A HANDBOOK OF SUSTAINABLE BUILDING DESIGN AND ENGINEERING

An Integrated Approach to Energy, Health and Operational Performance

EDITED BY DEJAN MUMOVIC AND MAT SANTAMOURIS

SECOND EDITION

A HANDBOOK OF SUSTAINABLE BUILDING DESIGN AND ENGINEERING

The second edition of this authoritative textbook equips students with the tools they will need to tackle the challenges of sustainable building design and engineering. The book looks at how to design, engineer and monitor energy efficient buildings, how to adapt buildings to climate change, and how to make buildings healthy, comfortable and secure. New material for this edition includes sections on environmental masterplanning, renewable technologies, retrofitting, passive house design, thermal comfort and indoor air quality. With chapters and case studies from a range of international, interdisciplinary authors, the book is essential reading for students and professionals in building engineering, environmental design, construction and architecture.

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PREFACE TO THE SECOND EDITION (2018)

Welcome to the second edition of *A Handbook of Sustainable Building Design and Engineering: An Integrated Approach to Energy, Health and Operational Performance*. Faced with the challenges of carbon, health, wellbeing, comfort and productivity, we continue to provide evidence-based chapters on the sustainable building design, engineering and operation.

The book is divided into four parts: (1) Introduction to urban environments; (2) Energy and buildings; (3) Buildings and environment; and (4) Operational performance of buildings. Each part has been updated with emerging themes such as environmental masterplanning, compliance and performance energy modelling, energy performance gap, ventilation and indoor air quality for health and productivity. Also, new 'hands on' case studies, such as one retrofit to near passive house standards, provide lessons learned from live projects.

In producing this edition of the book, the aim was to provide guidance not only for the building services engineers and architects but also other members of the design team who have an influence on the design outcomes. This book also aims to be a solid starting point for all students interested in sustainable building design, engineering and operation.

Enjoy.

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PREFACE TO THE FIRST EDITION (2009)

In the EU the issue of carbon has risen to the top of the political agenda. The current aspiration is to provide zero-carbon buildings in the foreseeable future, which might prove to be more challenging than initially anticipated. Although energy is the dominant factor due to its role in tackling the most urgent sustainability issue, i.e. climate change, some of the other equally important issues concerning sustainable building design and engineering have also been addressed in this book:

- Health and wellbeing, i.e. the provision of acceptable thermal comfort for occupants and good indoor air quality while maintaining adequate (day)lighting and indoor ambient noise levels.
- Adaptability to climate change, i.e. improving the capacity of buildings to operate successfully under various climate change scenarios.
- Operational performance of buildings, i.e. post occupancy evaluation of various aspects of building design.

All these challenges cross the boundaries of traditional disciplines and professional routes. The next generation of professionals will require an ability to work more closely with different disciplines and professionals if these challenges are to be met. The subjects covered and the depth to which they are analysed are more than sufficient to meet various syllabus requirements of undergraduate and multi-disciplinary postgraduate courses in building services engineering, architecture and facility management. Furthermore, the aim of this book is to challenge the 'silo mentality' approach to building design, while promoting awareness of the technical options available to engineers and architects and their suitability for various building-related applications. As such, this book is essential reading for both young and experienced professionals looking to broaden their knowledge.

We hope that you will find this book very useful.

Dejan Mumovic, *University College London, UK*
Mat Santamouris, *University of Athens, Greece*

SETTING THE SCENE

Dejan Mumovic and Mat Santamouris

The aim of this introduction is twofold:

- to set the scene and to show that each building with its surrounding represents a complex built environment system; and
- to highlight that sustainable building design and engineering requires an integrated approach to energy, health and the operational performance of buildings.

It was Winston Churchill who once famously remarked that: 'We make our buildings, and afterwards they make us.' For example, in the case of university campuses built in the nineteenth century it is absolutely conceivable that in the minds of the architects there was a link between outward expressions of grandeur and the importance of the learning that was going on within. One of the many examples could be the main University College London (UCL) building designed by William Wilkins, a leading architect of the Greek Revival in England (Figure 0.1). With steps leading up to an enormous Corinthian portico reminiscent of the British Museum and a dome behind, this building expressed the underlying character and value system fostered by UCL at that time.

Designing buildings in order to make some kind of statement is as important today as ever before. However, instead of grand architectural gestures, the new generation of buildings will have to show the extent to which both the client and, more importantly, the government (through standards and building regulations) take seriously the commitment to transform each of our countries into low carbon economies

Within just a few hundred metres of the previously mentioned Wilkins building lies a relatively new addition to the UCL campus – The School of Slavonic and East European Studies (Figure 0.2). The client (UCL) required a low energy, naturally ventilated and naturally lit building with low cost in use. Partially due to the reduced summer night cooling potential caused by the London urban heat island, and partially because the UK design guidelines required the use of a near-extreme weather year for the design of naturally ventilated buildings, this building designed by award-winning architects Short & Associates employed passive downdraught cooling operating from the top of a central well (see chapter on Sustainable Cooling Techniques for more details). As the world's first passive downdraught cooled public building in a city centre, theoretically speaking it employs an extremely energy efficient way of maintaining comfort within the urban heat island. It also demonstrates the UCL commitment to reduce the carbon footprint of its own buildings.

This example indicates that clients increasingly require building professionals to provide advice on sustainability. Many large organisations, such as UCL in this case, have been developing sustainability commitments in an attempt to become 'socially responsible'. Some of the large organisations have set up objectives and targets relating to measurable environmental performance concerning issues such as waste, water consumption and carbon emission.

Figure 0.1 Wilkins building.

However, the major driver to considerable change in the construction and refurbishment of buildings is still government commitment to sustainability issues. For example, in the UK changes are implemented through various mechanisms such as:

- Part L (Energy) of the Building Regulations, which is concerned with the prevention of carbon emission from buildings.
- Energy Performance of Buildings Directive which requires buildings to obtain two energy ratings: an operational rating and an asset rating. It also requires public buildings to display their certificates showing the energy efficiency of the building and requiring inspections for air conditioning systems. Furthermore, the member states have to ensure that meters and systems measure customers' actual energy consumption both accurately and frequently. This has resulted in the increased use of smart meters that provide frequent or real-time information on actual energy consumption.
- Climate Change Bill which sets legally binding targets to reduce carbon emissions by 80% by 2050.

Figure 0.2 The School of Slavonic and East European Studies.

- Local planning policies often require new developments to make the fullest contribution to the mitigation of, and adaptation to, climate change by incorporating energy efficiency and renewable energy measures, targeting in particular heating and cooling systems within developments. Developments are expected to reduce their energy needs in the first instance and then supply that energy efficiently with a proportion from renewable sources.

To complicate the issue further, the buildings are often complex bespoke systems which are difficult to control, with little feedback available on their real operation and actual performance. Evidence provided in this book suggests the gap between 'as designed' and 'in use' performance can be very large. This has considerable implications for the previously mentioned regulatory programme, as the closer standards get to zero carbon the more important the gap will become. The implications of this for the required research effort over the coming years are considerable, since building professionals must not only select new technology at the design stage (for example, opting for electrically driven heat pumps instead of low-temperature water heating systems) but also ensure that a huge change in construction practices (i.e. improved airtightness, thermal bridging, etc.) takes place. This presents a considerable challenge in the wide-ranging implications for all parts of the industry and its supply chains.

Even if the building engineering community had the answers on all technical issues, a building may be built to the most advanced sustainable standards but if the occupants are not using it in a sustainable way then the benefits may not be apparent. For example, it is very likely that in the next decade electrically driven heat pumps will provide the lowest carbon emitting space heating in the UK, while also providing cooling to prevent summertime overheating. However, the increased use of comfort cooling by occupants may mean that heat pumps provide no net reduction in carbon emissions. Therefore, the time has come when we need to engage the building occupants, owners and facility managers in operating their buildings in a sustainable and more environmentally responsible way.

The importance of the facility manager in ensuring a building's services are used to their optimum cannot be over-emphasised. Almost all new buildings have been equipped with state of the art building management systems (BMS), providing an opportunity to balance energy consumption and ventilation requirements to some extent. However, it is well documented that neither facility managers nor the caretakers are fully conversant with the BMS. This raises an important issue – training the relevant people (at least caretakers and facility managers) how to operate building effectively. The information on the building services systems, including logbooks, is usually 'buried' within dozens of thick folders, and even then, included no guidelines about how to get the most out of the system. Building information modelling (BIM) might be a solution.

Even at this stage it is obvious that buildings are actually complex built environment systems. However, there is more. Although building occupants are not passive recipients of the indoor/outdoor thermal environment but play an active role in creating their thermal environment by behavioural adjustments such as adjusting clothing, rescheduling activities still living in high-density urban areas, such as London, may be an important risk factor for heat-related mortality and morbidity. For example, the effects of the 2003 heat wave were greatest in London and many of the summer excess deaths that occurred during the August heat wave event may be attributable to the urban heat island effect. Furthermore, recent studies have shown that the costs of poor indoor environment for the employer, the building owner, and for society as a whole are often considerably higher than the cost of the energy used in the same building. It has also been shown that good indoor environmental quality can improve overall work and learning performance, while reducing absenteeism.

After reading this brief 'setting the scene' introduction, we hope that you are convinced that sustainable building design and engineering require an integrated approach to energy, health and the operational performance of buildings.

Enjoy the book.

PART 1

Introduction to urban environments

Introduction

Dejan Mumovic and Mat Santamouris

In this book we argue that understanding what makes a city sustainable requires a dialogue between a variety of researchers. Engineers, geographers, architects, planners, designers, ecologists and sociologists all conduct research in an effort to better understand the sustainable cities and communities. Chapter 1.1 states that multidisciplinary research can help us to analyse how sustainability of the urban environment is framed, while disciplinary knowledges can complement each other in producing a perspective of the subject. Chapter 1.1 also describes both the process and outcomes of developing a conceptual and methodological framework to investigate sustainable communities within a multifarious research team: combining social and physical perspectives. Equally broad, Chapter 1.2 focuses on offering a description of an integrated approach to developing strategies at an initial stage of the masterplanning process. It outlines the need to carefully consider the contextual issues of a given urban area that can inform the development of a vision for the masterplan. The authors claim that this vision, which is informed by the various actors within the development process, goes to setting out the objectives to which an environmental strategy must respond. These objectives are in turn embodied in targets that can be measured under a set of defined metrics. This authors further argue that environmental masterplanning process must emphasise the integration of the dynamic urban systems in order to achieve both synergy and resilience.

Adapting to and ameliorating the effects of urban heat islands on energy use, comfort and health will require appropriate policies for urban planning, housing and transport. However, before these policies can be developed, quantitative tools are required to identify and quantify the net effectiveness of mitigation and adaptation strategies. Chapter 1.3 advocates that the wider picture should be considered. The authors explain that in summer, urban heat islands in the UK will tend to result in an increased cooling load and an increased number of excess deaths due to overheating. Conversely, in winter the urban heat islands will tend to result in reduced heating loads and a reduced number of cold-related excess deaths. This chapter therefore explains that the net effects of these impacts must be borne in mind when considering large-scale urban modifications. Taking into account the growing concerns related to the exposure of urban dwellers to air pollution, Chapter 1.4 aims to summarise air flow and air pollution patterns in urban environments and discuss possible implications to building design. The authors address the fundamental principles related to urban indoor/outdoor air quality modelling and monitoring, which are of importance to both building design and urban planning professionals.

This part of the book provides only a starting point for readers who are interested in urban environments. It will develop with the rapidly increasing body of knowledge, which will form a science of cities.

1.1
BUILDING SUSTAINABLE COMMUNITIES
Combining social and physical perspectives

Gemma Moore, Irene Perdikogianni, Alan Penn and Mags Adams

Introduction

Sustainability has moved from a goal to a necessity in the urban environment. The recent focus of urban planning and urban regeneration practice has been to create sustainable, healthy and viable communities with positive neighbourhood identities. Visions of thriving, mixed-use, economically stable and socially inclusive cities with clean, green, safe neighbourhoods have been presented as the possible future of many urban areas. However, how to actually create such areas and communities is not entirely clear. Realistically, an answer to this question can only be reached using empirical evidence drawn from the functioning of an urban area and its dwellers' experience of everyday life within it. Understanding what makes a city sustainable therefore requires a dialogue between a huge variety of researchers. Engineers, geographers, architects, planners, designers, ecologists and sociologists all conduct research in an effort to better understand the sustainable cities and communities. Multidisciplinary research can help us to analyse how sustainability of the urban environment is framed, while disciplinary knowledges can complement each other in producing a perspective of the subject. This chapter describes both the process and outcomes of developing a conceptual and methodological framework to investigate sustainable communities within a multifarious research team: combining social and physical perspectives.

Historically the social and physical infrastructures of the city have coevolved and are interdependent; yet we do not fully understand their interaction (see Hommels, 2000). On the other hand, earlier studies conducted by academics such as Martin (1972) or Hillier and Hanson (1984) suggested that the way in which the physical environment of a city or a neighbourhood is arranged forms news possibilities for the way in which people choose to live and work. However, to date, the focus of research has either been on individual perceptions and attitudes toward specific 'places' or on more generalized design features of urban areas. In this chapter we describe multidisciplinary research that marries these two approaches. Focusing on Clerkenwell in London, UK, as a case study of a vibrant urban community, we present a new way of thinking about contemporary urban communities. To illustrate the wide range of complex interactions between the physical, social and economic processes of the urban mechanism, our study combines quantitative analysis of Clerkenwell's street layout (incorporating information on its usage and the historical formation and transformation of the urban fabric of the area) with qualitative information on perceptions and behaviours of city centre residents.

Background: What is a sustainable community?

The concept of a sustainable community is inherently a spatial construct, focusing on place-based communities. Sustainable communities are now central to UK developmental policy; for instance, Living Places (ODPM, 2002), Sustainable Communities Plan (ODPM, 2003) and Planning Policy Statement 1: Delivering Sustainable Development (ODPM, 2004a) all refer to this notion, presenting an intertwining of the discourses of sustainable development and sustainable communities. The government's definition of a sustainable community clearly embodies the key principles of sustainable development; it states that sustainable communities are ones which:

> . . . meet the diverse needs of existing and future residents, their children and other users, contribute to a high quality of life and provide opportunity and choice. They achieve this in ways that make effective use of natural resources, enhance the environment, promote social cohesion and inclusion, and strengthen economic prosperity.
>
> (ODPM, 2004b, p. 35)

Within urban spatial policy, the government promotes that a sustainable community has seven essential, balanced and integrated components (an active and cohesive community; well run in terms of governance; is environmentally sensitive; is a well-designed built environment; is well connected; has a thriving economy; and is well serviced), which should underpin planning and design processes.

The definition of a sustainable community describes a particular 'type' of neighbourhood, with a well-designed built environment, a range of employment opportunities, and a certain degree of social interaction and social cohesion that facilitates social order. Nevertheless, the formation of a neighbourhood involves a social–psychological experience with a physical space; therefore, the defined spatial area of a neighbourhood can be seen as subject to how people use and feel about the built environment. The geographer Doreen Massey has explored and strived to explain the complexities of this relationship throughout her work (see Massey, 1994). Massey argues that a person's development of place is an ongoing formation of social relations, interconnections and movements. Both Jacobs (1961) and Lynch (1960, 1984) have been instrumental in exploring spatial layouts and components that influence the prosperity of neighbourhood life (i.e. central points; clear flows in and out; places for people; a visual identity; shared open spaces; common eye on space; detailed design features). In particular, the street combined with the social activity that takes place on its frontage emerges as one key element of analysis in this stream of research. For Jacobs (1961), Appleyard (1981) and Sennett (1994), street layout and its properties affect the possibility and form of encounters between people. In contrast, Barton, Grant and Guise (2003) put people at the heart of creating sustainable neighbourhoods and communities. Barton suggests that while urban form can influence patterns of movement and interaction, so too can factors such as the way in which schools are designed or the existence of local associations. Barton looks at the social, economic and environmental factors that influence people's quality of life and illustrates that to understand how sustainable communities can actually be achieved and maintained is a multifaceted, complex issue requiring an approach that is likewise multifaceted and complex.

A multidisciplinary research strategy

As multidisciplinary work thrives, innovative methods of data collection and measurement are slowly emerging within and between many disciplines. We outline an excellent example of how methodologies can be moulded and experimented with. VivaCity2020: Urban Sustainability for the 24 Hour City is a large multidisciplinary research project within the Engineering and Physical Sciences Research Council (EPSRC) Sustainable Urban Environments (SUE) consortium, aiming to develop an in-depth understanding of human behaviour in urban environments and to create new innovative tools and techniques to support sustainable design decision-making. A research strategy was developed to explore both the more experiential side of city centre living alongside the collection of quantitative data on the urban layout and form.

Example case study

An area within Clerkenwell in the London Borough of Islington, to the north-east of central London, was selected as a case study area. Clerkenwell is one of 16 wards located within the London Borough of Islington (see Figure 1.1.1). Parts of the ward (including Clerkenwell Green, the historical heart of the area) are designated as conservation areas by Islington Council, meaning that special planning policy applies to protect the diverse character of the ward. This area is residentially diverse, incorporating social housing alongside privately owned flats and houses, and is economically diverse with a variety of shops, workshops, wholesale, offices and entertainment facilities. The area was selected as an example of a diverse and viable urban neighbourhood.[1]

An examination of the way in which this area has evolved and been transformed throughout its history clearly shows that its diverse character, protected under its current status as a conservation area, is an outcome of Clerkenwell's lack of economic success. This paradox in its development could be better understood in comparison with its adjacent thriving central business district: the City of London. The latter has developed and redeveloped its buildings over the years, and in doing so has readjusted the alignment

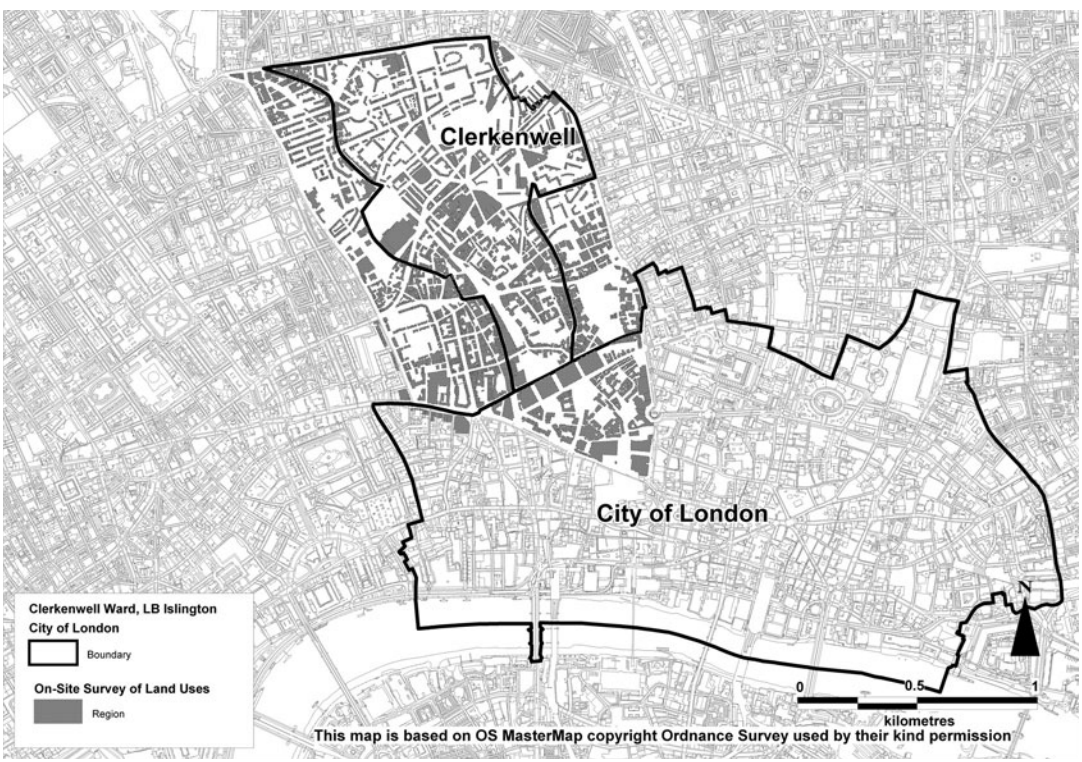

Figure 1.1.1 Map of Clerkenwell, Islington, London.[2]

Source: Based on OS Master Map, Ordnance Survey

of streets, amalgamated blocks and subdivided blocks, and radically changed its structure to accommodate new economic needs. Clerkenwell's spatial structure originated as an area of low-lying land traversed by the (now obsolete) River Fleet outside the walls of the City of London, used for the major cattle market for the city, and is broken up by a series of larger monastic properties and mansions (Pink, 2001). It prohibited its redevelopment following similar City of London mechanisms. Although nineteenth-century road improvement programmes constructed 'bypasses' in the area, such as Farringdon Road and Clerkenwell Road, to take people and traffic through the area on larger-scale trips, Clerkenwell remained a marginal area in the larger processes of change within the city as a whole (Perdikogianni and Penn, 2005).

Methodology

Thirty-four Clerkenwell residents took part in a photo survey, a sound walk and a semi-structured one-to-one interview in order to produce data on their perceptions of their local environment. An interview date was scheduled with each participant and approximately two weeks earlier a disposable camera (27 exposure, 35mm film, ISO 400 with flash), a photo survey log sheet, a return envelope and detailed instructions were sent out. Participants were asked to take photographs of their local area (incorporating both positive and negative aspects), noting the time, date, location and a short description of the photograph on the log sheet provided (the photo survey). Not wanting to be too prescriptive in telling participants what to photograph, the instructions simply stated: "We would like you to take photos that record both the positive and negative aspects of your area." This gave participants the freedom to take photographs of whatever they wanted at times and locations convenient to themselves. Cameras were returned to the research team after a week; the photographs were developed and catalogued according to the log sheet. At an agreed time, the researchers arrived at each participant's home. Participants were asked to complete a short questionnaire with general background information (personal data, household characteristics, residence details, local urban form and health details); they were also invited to identify a ten-minute walking route around their local area and to mark it on a large-scale map, centred on their home, supplied by the researchers. This map was then used as the basis for a sound walk of the local area. A sound walk is a walk around an area where the senses are directed toward the sounds that are heard, rather than the more commonplace sights that are viewed. On return to the participant's home, a semi-structured interview was conducted by one of the researchers. The interview was based upon a number of general questions about the urban environment, made specific to the resident's locality. Participants were asked to refer to their photographs and the sound walk at any stage during the interview.

This study also focused on assembling, describing, representing and analysing the multiple aspects of the physical and functional city. These were conceptualized as interdependent layers within the urban system and by using a geographical information system (GIS). An integrated spatialized database was created, bringing together primary data collected through observation-based surveys (of the use of buildings and public space) and pedestrian flow (on streets within the study area's boundaries). Physical space was considered to be the common framework for this study; hence, it was suggested that a comparative statistical analysis of this data with topological properties of the streets be made, considering the urban area as a spatial network. The land-use data gathered through on-site observation revealed the detailed activities that the buildings within the area accommodate. This enabled the investigators to identify any 'attractional inequalities' that may exist. This process was undertaken at a variety of spatial scales (the study area as whole, selected sub-areas, streets, and individual buildings or blocks) and was sensitive to temporal differences in usage. It was also acknowledged that each factor can be affected by and simultaneously have an effect on any other, both spatially and temporally.

The street morphology of the study area was analysed to identify regularities and irregularities in street layout that could account for any observed functional patterns. The analysis was enabled by a spatial model that represented all streets and public spaces as a line matrix of direct access in order to get from every location to every other possible location, following the rule of creating the longest and fewest lines (axial map)[3] (see Hillier, 1999, for details). The produced axial map was analysed in relation to its 'topological' properties by translating the line matrix into a graph and measuring the topological properties of the graph. All of the (axial) lines were differentiated or weighted in relation to their position in the global network. The measure of integration (developed during several empirical studies) quantified the syntactic properties of (axial) lines by measuring their mean topological distance (depth) from every other (axial) line considering the (urban) system as a whole[4] (see Figure 1.1.2).

Pedestrian flow was observed on 132 predefined locations by a group of 16 trained observers. Pedestrians passing by each location for a five-minute period were counted. The locations on main streets were observed for 2.5 minutes. Pedestrians were classified as locals working within the area and tourists based on their dress code, distinguishing between men and women. Overall, pedestrians were observed periodically in pre-decided nine time slots between 8.00 am and 8.00 pm during one weekday and one weekend day. For the land-use survey, the study area was divided into 12 sub-areas and data was collected through observation for each building and open space by a group of seven trained observers. Uses of the ground floor, first floor, the main use above first floor and the number of floors for all 3618 premises were recorded. Some additional information on the names and the opening hours of the retail and commercial premises was also recorded for capturing the temporal aspect of city life. The land uses were classified using an adaptation of the National Land-Use Database (NLUD) Classification.[5] Detailed multilevel land-use maps were created for the study area.

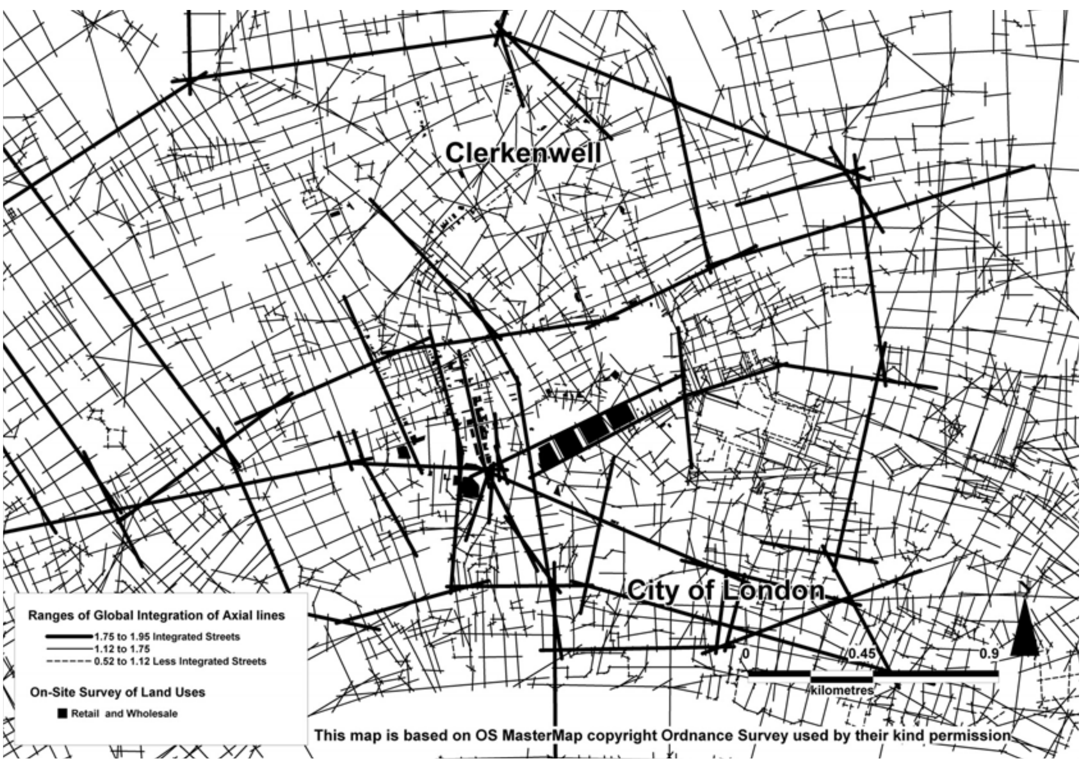

Figure 1.1.2 Axial map of Clerkenwell overlaid on the surveyed retail and wholesale within study area.

Source: Based on OS Master Map, Ordnance Survey

Investigating the role of space in the construction of place

We have combined physical and social perspectives in order to explore the degree that space and spatial structure affects the way in which the area is used and experienced today by people who choose to live within it.

The term spatial structure describes the way in which streets and public space are built in the overall street network. The land-use map for the ground floor use for all premises and open space revealed that there are a variety of uses within Clerkenwell, with an underlying structure in the way that these are assimilated within the overall spatial pattern. There is a clear spatial separation of residential and more mixed-use environments. There are mono-functional residential sub-areas in the north of the study area with a limited range of other uses (i.e. newsagents, local shops or pubs) often located on street corners, whereas the mixed-functional sub-areas were located in the southern sector of the case study area with a higher number of offices and retail uses. This structural separation of different uses can also be observed in a detailed examination of the area. Streets such as Exmouth Market, a thriving a semi-pedestrianized street full of restaurants, cafés and sandwich bars, is located next to Farringdon Road, dominated by housing blocks (largely rented) and commercial offices. This mix of different uses is not arbitrary; but one needs to change direction to find different spatial qualities. The axial map described in Figure 1.1.2 captures this by attributing different topological values for every change of direction. This framework describes that these two streets are one axial line (or step) away. In other words, residential and retail uses co-exist in Clerkenwell; however, they are located one step away (Figure 1.1.3).

Figure 1.1.3 Around Exmouth Market: The axial map is overlaid on shops, restaurants and houses located on the ground floor.

Source: Based on OS Master Map, Ordnance Survey

The same pattern of spatial separation between the different land uses is reinforced by the density of pedestrian flow observed in these environments. Streets such as Exmouth Market, as emerged from the observed predefined locations, attracted a high number of pedestrians (total daily mean per hour adult flow n = 1635), while the north end of Farringdon Road attracted a smaller number of pedestrians (daily mean per hour adult flow n = 467). The repetition of these phenomena in several empirical studies suggested that attributed topological values of streets (if we represent the street system as an axial map) have an effect on how different land and building uses are assimilated within urban systems, initiating a feedback process from land uses to the street system with the aid of pedestrian flows. Shops and restaurants occupy strategic locations that feature easy access and thus are well connected with the rest of the system (these are on streets with high global and local integration values). This is because they seek to benefit from passers-by since people tend to move on streets that are well connected to the rest of the street system (small mean distance from all other streets and, thus, a high integration value). On the other hand, residential uses benefit from privacy, so they tend to form quieter zones in more secluded areas (streets with low global or local integration values). If we think of this as an eternal dynamic feedback process, then we understand that the busy areas become busier and the quiet ones become quieter (Hillier, 1996).

Previous empirical findings have shown that a substantial proportion of people movement patterns in cities are generated by the structure of the street system itself (Hillier, Penn, Hanson, Grajewski and Xu, 1993). The correlation analysis between the pedestrian flow and topological measures – namely, the local integration values of all street axial lines, suggested that instead of one entity, Clerkenwell is a structured

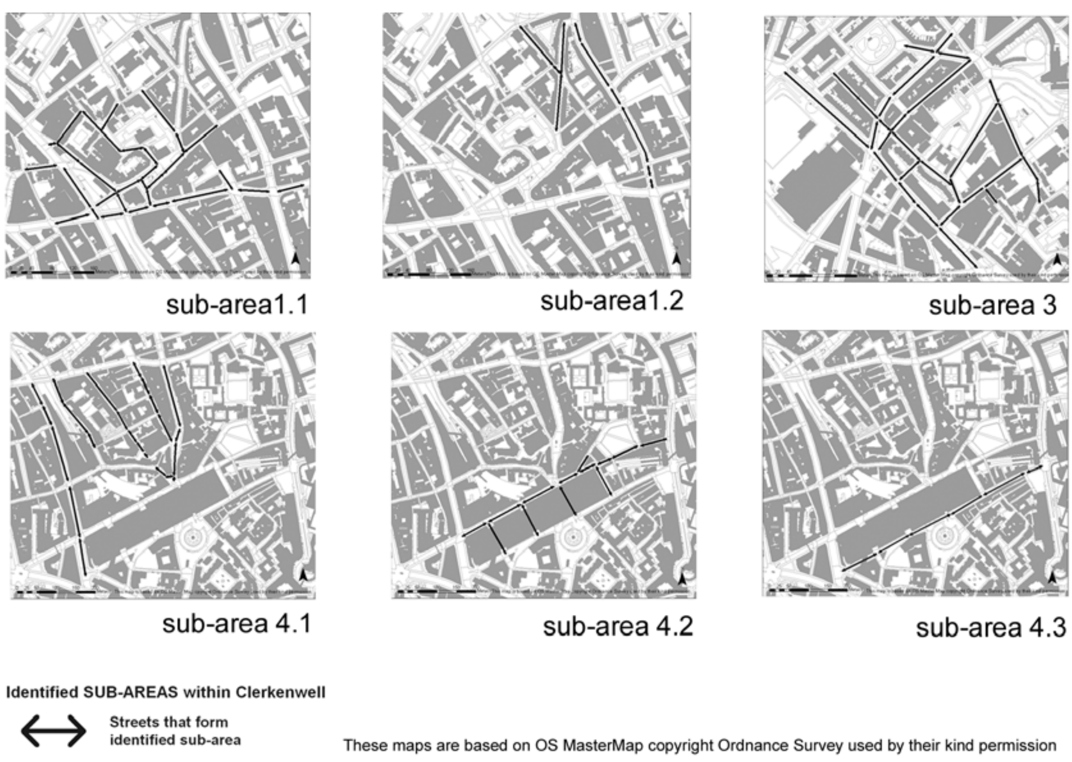

Figure 1.1.4 The identified sub-areas within Clerkenwell's boundaries.

Source: Based on OS Master Map, Ordnance Survey

system of smaller sub-areas. The strict localism of pedestrian movement patterns suggests that Clerkenwell is a fragmented system of six sub-areas that function as independent urban systems within the city and, as a whole, are relatively poorly related to one another (Figure 1.1.4). This spatial structure is, on the one hand, at the root of Clerkenwell's failure to redevelop (remaining a marginal area in the general process of change); but at the same time, it is itself a major factor since it is considered a 'well-working' diverse area that maintains its local residential, employment and leisure activities, as well as social and economic networks.

The combination of different uses (retail, commercial, residential and services) and networks within the built environment was a key element of residents' perception of their local area. The functionality of the neighbourhood was a crucial facet for residents when describing Clerkenwell. The provision of shops, restaurants, offices, doctors, pubs and transport within their wider neighbourhood was commonly referred to as a positive aspect of the area, with participants noting the convenience of having such amenities and facilities within close proximity of their home. This is illustrated by quotes from one participant, Luke,[6] who used the word convenient to describe Clerkenwell and was subsequently asked to elaborate further:

> It's close to work, close to transport; it means I don't have to use any tubes, trains to get to work, I can walk to work. Friends live close and that means I can get to my friends. And even if they don't live close, it's easy for them to get here. Easy for friends and family to get round. There are loads of facilities around. When they come over it's always nice; we've got hundreds of restaurants to pick [from] when we want to go and eat. We've got shops, we can go and buy something to make at home. We've got absolutely everything else that you need; so it's just convenient, that's it . . . It's fun. Fun, cause there's just so many things to do around here. It makes . . . your life easier when things are convenient and you can get people together and there's loads of things to do round here. It's just, you know if, if you're bored with one thing there's always something else to do.
>
> (Luke)

Luke's quotes illustrate the advantages that 'co-existence' can bring – multiple facilities in close proximity – raising issues such as convenience, accessibility and diversity. Alongside the benefits of having a multitude of shops and restaurants within the wider local neighbourhood, he, like many other participants, points out the degree of ease with which it is possible for people to reach the neighbourhood from other locations or for him to access elsewhere. In describing neighbourhood life, many participants took photographs of, and described in depth, specific aspects of the built environment that were significant to them. These included physical aspects (facilities, amenities, places to use, places to visit), visual aspects (things to see – i.e. views and architectural features) and social aspects (people – i.e. neighbours, groups and commuters). For instance, the quotes below from one participant, Ben, demonstrate this. In explaining the photographs he took as part of the photo survey, Ben expresses his delight at being able to have access to pubs and bars within his neighbourhood. Interestingly, like many other participants, Ben not only raises the issues of provision, but also the benefits brought about by having diversity in choice:

> And then I also took pictures of nice places and, and sort of things to do, which is another thing that Clerkenwell's great for. I used to live in Bermondsey and there was nothing to do, and there were no bars really at all, sort of All Bar One and a Brown's and one or two locals, the sort of . . . very soulless chain bars which just are all the same wherever you go. And what I love about Clerkenwell is its kind of diversity of . . . venues, and so it's got lots of kind of interesting little pubs.
>
> (Ben)

Despite the positive aspects of convenience and vibrancy brought about by the wider spatial connections, participants spoke of the disadvantages that come with living in such a mixed-use area:

> They're the pluses, these are the absolute negatives, this lot here [referring to his photographs], it says itself, doesn't it? That's an incredible amount of pollution down the alleyway . . . there's always people throwing up everywhere around this area.
>
> (Colin)

The quote from Colin succinctly captures what many referred to: the localized, direct, negative impacts of the urban spatial system. Local doorstep issues, such as rubbish, fly-tipping, anti-social behaviour, vomiting and noise, were all mentioned as aspects of urban living that residents disliked. Noise was predominately mentioned; particular sounds (such as traffic, drunken behaviour, people and sirens) became a noise nuisance to participants when they 'invaded' the participants' homes at particular times of day (i.e. late evening or early morning). The quotes below from Clive are used as an example to explain the auditory and visual experience of having non-residential neighbours 'one step away'. Clive lives very near to Exmouth Market:

CLIVE: And, the final one is early morning deliveries, which is an absolute pig.
INTERVIEWER: What time early morning?
CLIVE: It's normally between 5.30 and 6.30 in the morning and it's early morning deliveries and those kind of metal things on the front of the shops. They're sort of rolled up and make a hell of a racket.
INTERVIEWER: The shutters.
CLIVE: The shutters, and then they put the goods in and then they drive off. And invariably, I suppose once every three months, somebody leaves their van with the keys in and it gets nicked, and that happens quite regularly. You always hear: 'Oi, get out of my van', and then you hear a van go 'EEEEr' down the road and you come out half an hour later and you see there's food all over the road because it's come out of the back of the van and the thief has made off with it and it happens quite regularly in Exmouth Market. And that, I would say, is the major noise issue.

All participants spoke in depth about the interactions and conflict brought about from the differing needs of multiple uses (i.e. working times, access, services and deliveries). When the differing uses impact upon the direct locality, these are predominantly referred to as disadvantages of urban living. Despite the noted disadvantages, all participants had something positive to say about living in Clerkenwell. For most, the benefits of living in the city centre (the wider spatial issues of accessibility and proximity to neighbouring amenities) outweighed the negatives (localized problems such as crime, pollution, rubbish, etc.). Some commented upon the relationship between the benefits and disadvantages, noting that the negative aspects came in hand with the positives – what Healey (2006, p. 130) describes as the conflicts within ourselves. For example, when asked to describe the quality of the environment in Clerkenwell, Linda and her partner responded thus:

INTERVIEWER: How would you describe the environmental quality of the area?
LINDA: Not bad, I suppose, not bad.
LINDA'S PARTNER: I think, I think, I can see, I can see it could . . . be a lot worse. I don't think it's as bad as it could be, but it's not good either you know . . . It's what I would expect to live in an area like this; it's safe and . . . it's central and almost the same; the advantages contradict the disadvantages.
LINDA: So, it's noisy and polluted.

LINDA'S PARTNER: Yeah.
LINDA: So it's not good. But just . . . you can't have it, you can't have a lively central area with clean air and calm; it just doesn't exist. So it's one or the other.

Reflecting upon both the benefits and disadvantages of their local area enabled participants to consider the exchanges and trade-offs that they make within the urban environment. Participants commented upon compromising with the negative aspects to appreciate the benefits. The quote by another participant, Tina, clearly illustrates this: Tina spoke in detail about tolerating the negative aspects of city living (particularly the noise brought about by living next door to commercial premises), while recognizing the overall benefits brought about by the wider neighbourhood:

> But now I've actually . . . come to appreciate living in, sort of in London and all that it offers, you know, cause I can sort of, you know, I'm close; I like going to exhibitions and this and that, so . . . I'm . . . on the spot; I don't have to make big tube journeys or anything, and, as I say, I've . . . sort of learned to tolerate. It's not that I like the traffic and the, you know, various noises and stuff, and I don't like the commercial neighbours, you know I get fed up of them; but I've kind of seemed to overcome, able to tolerate it somehow.
>
> (Tina)

The participants' accounts of their experience of urban living alongside the detailed analysis of the urban form illustrate the complex interconnection and interaction between spatial scales and context for creating successful 'places' where people like to live and work. There is a clear difference between perceptions of the wider neighbourhood and the immediate locality. The relationships and interactions between these scales appear to be largely ignored, to date, in urban research; but as we have demonstrated, this has numerous implications for how we can make vibrant sustainable communities in which people choose to participate.

Reflections on processes and outcomes

Understanding and assessing the certain qualities or issues within the built environment is often a difficult, intangible process. Multidisciplinary projects can give rise to exciting research opportunities, innovations in methodologies and wide-ranging analytical approaches. Within this chapter we present a project that explores sustainable communities through combining different disciplinary approaches.

The multidisciplinary and interdisciplinary turn is now well recognized across disciplines; but further debate is necessary to fully understand the impact of moving in this direction, for researchers, for knowledge transfer and for academic disciplines themselves. However, within this chapter we highlight that through combining varying approaches and accounts, a comprehensive knowledge base for certain urban issues can be constructed. Making connections between residents' perceptions of the urban environment and the physical layout assisted understandings of the trade-offs made by city residents living in urban areas. Understanding how the identity of a neighbourhood is formed is extremely important in appreciating the functioning of this area as an urban system; our evidence in the case study of Clerkenwell reinforces this suggestion. Furthermore, our findings suggest the importance of understanding the complex interconnection and interaction between spatial scales and context for creating successful 'places' where people like to live and work. For instance, a city centre resident's local environment could be the house in which they live, the surrounding neighbourhood or even the city itself. There is a complex interconnection between each of these environments – a house in an urban area does not exist in isolation. It is part of a wider neighbourhood, which is in itself part of the city network. Perceptions of each may also vary (and, in turn, influence each other). We have found that these spatial scales are particularly noticeable in people's accounts of their experiences and the trade-offs that they make in order to live in the city centre.

Considerations

This chapter has described both the processes and outcomes of developing a conceptual and methodological framework to investigate sustainable communities within a multifarious research team combining social and physical perspectives. From our experience we would like to raise a number of aspects for consideration for future research within this field:

- There is a need to understand urban communities both from a physical and social perspective (i.e. what it means to co-exist in shared mixed-use spaces and how places can be made out of such spaces).
- Building sustainable communities requires a coordinated joined approach involving a range of academics and practitioners (i.e. engineers, planners and sociologists).
- Combined disciplinary knowledge can complement each other in producing a larger perspective and richer understandings of sustainability within the built environment.
- People other than official 'experts' may have insights into research, particularly with regard to social and physical aspects. In the context of research within specific geographical areas, residents may be considered 'local experts' about aspects of their neighbourhood and its conditions.
- Putting people in groups representing different academic disciplines, professions or expertise does not necessarily guarantee interdisciplinary practices – integration of different domains of research and forms of knowledge requires thoughtful and strategic facilitation.

The ability of designers to make more sustainable decisions relies upon their having accurate and relevant information to do so. Although the social accounts outlined in this chapter are very different from the analysed physical urban form combined together, they provide a detailed comprehensive knowledge base on the current conditions within the case study area. We urge that decision-makers take a holistic approach when exploring sustainability in the built environment, thinking about the wider relationships and connections between the physical environment and society. Effective sustainable decisions require designers to consider a range of knowledge and understandings (i.e. disciplinary, academic, professional, expert and lay) to be used at different stages of the design process. We highlight that local residents have valuable understandings of their local environment that would be beneficial to urban designers if they were listened to. However, key deliberations about building design often do not adequately involve local people. This requires the use of various targeted recruitment and public engagement practices. Recruitment is a time-consuming process; but with effort a diverse range of participants can be mobilized. We argue that using a combined qualitative (social) and quantitative (physical) methodology would give built environment designers a better understanding of a given environment or building. For instance, we have illustrated that residents' perceptions of their environment may be significantly improved by addressing door-step localized issues such as noise, rubbish and fly-tipping at the design stage by providing mechanisms for preventing or minimizing the impact of such issues.

Acknowledgements

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Notes

1 For further exploration of the location and wider context of the case study area, please use the search terms 'UK, London, Farringdon Road' in online maps such as Google Maps.
2 This map is based on data provided through EDINA UKBORDERS with the support of the ESRC and JISC and uses boundary material that is copyright of the Crown.
3 The axial map is based on Ordnance Survey Master Map data (courtesy of Ordnance Survey) for the EPSRC-funded project VivaCity2020.
4 Global integration (or radius n integration – INT R(N)) measures the mean depth (distance) of all axial lines in a plan from the line in question and then normalizes this for the number of lines that are present in the plan. Local integration (or integration radius 3, INT R (3)) accounts for the relationship between each line and all other lines restricted to two changes of direction away from it (Hillier and Hanson, 1984).
5 NLUD Classification Version 3.2.
6 The participant names quoted within this chapter are pseudonyms that were given to each participant.

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1.2
ENVIRONMENTAL MASTERPLANNING

Ian Hamilton and Aurore Julien

An environmental approach to masterplanning

Cities and urban environments are fast becoming the dominant human habitat and their impact on the local and global environment is significant. This impact of urban places, whether it is through the effect of increased hard surfaces on the surface energy balance and the formation of the urban heat island, the emission of particulate matter from transport exhaust, or the impact of tall buildings on the pedestrian environment, needs to be better understood so that the negative impacts of city building can be minimised. Urban environments have been described as complex systems that are continuously evolving, acting, and reacting to internal and external factors and engaging in dynamic exchanges (da Silva, Kernaghan, & Luque, 2012). Urban environments can be regarded as dynamic and ever-changing interactions between people, systems and environment. Urban systems comprise physical infrastructure, social institutions, and local understanding and practices that interact to create a 'system of systems'. These interactions may even be seen as being chaotic, i.e. that they are strongly dependent on initial conditions, but occur within the constraints of the system boundaries that are the physical and technical components, e.g. infrastructure, landscape, and climate. Existing urban environments provide an opportunity to understand how urban spaces impact on the surrounding climate, physical systems, and social environment. By examining these urban environments and critically assessing what and how services are provided, the technologies used, and their interactions with a range of users, it is possible to identify those systems that are able to meet the needs of urban inhabitants, while ensuring the needs of future generations are met.

The masterplanning scale is one of multiples of buildings and spaces. This might be a district, neighbourhood or a city block, or several, but more than just a single building. The masterplan scale provides the environment within which the multitude of urban activities takes place. Sharifi and Murayama say that the

> Neighbourhood is the scale at which land development takes place and new buildings and facilities are proposed, debated and constructed.
>
> (Sharifi & Murayama, 2013)

Environmental masterplanning is framed within an interdisciplinary context that attempts to address sustainability by harnessing the skills of those disciplines working at a masterplan scale. Engineers, planners, urban designers, policymakers, and citizens will all have a range or priorities, objectives, and (often time competing) demands that will shape urban processes. Drawing together their expertise and insight in order to build better urban environments is essential to the on-going development and redevelopment of the urban system. The environmental masterplanning approach emphasises the use of methods and best practice techniques that are underpinned by technical rigour and informed by a thorough understanding of contextual issues. This chapter places environmental masterplanning into the realm of urban systems and considers how the development of strategies for a range of interacting urban elements, i.e. energy, water, waste, place making, transport, and ecology for the urban community form, can help to achieve more 'sustainable' urban environments.

The chapter focuses on offering a description of an integrated approach to developing strategies at an initial stage of the masterplanning process. It outlines the need to carefully consider the contextual issues of a given urban area that can inform the development of a vision for the masterplan. This vision, which is informed by the various actors within the development process, goes to setting out the objectives to which an environmental strategy must respond. These objectives are in turn embodied in targets that can be measured under a set of defined metrics. The environmental masterplanning process emphasises the integration of the dynamic urban systems in order to achieve both synergy and resilience.

The need for the approach

As an underlying motivation for development, sustainability is often used as a guiding principle, though it may be rarely challenged in terms of what it exactly means. Developments that use the concept are often criticised because they are seen as not fulfilling what is implied by the use of the term. However, the features of a sustainable development are generally poorly defined and as a result may be interpreted in a number of different ways that will fuel criticism and potentially impact on delivering what might otherwise be an environmentally sound development. Despite its motivational and aspirational quality, sustainable development has been described as being 'plastic' and can be interpreted to suit any number of needs (Bebbington, 2009). Criticisms include practical execution failure whereby developments do not meet or failed to deliver on the targets are objective set, or they may be excluded altogether (Biddulph, Franklin, & Tait, 2006), or they may be excluded altogether. Another is the mismatch between defined sustainable principles and the development site itself, which may be set to take place on greenfield land and be reliant on traditional transportation systems for site access (Biddulph et al., 2006; Talen, 2000). A further criticism of these sustainable developments is the potential for socio-economic segregation whereby only those in a higher income level can only afford the sustainable development premium (Bulkeley, Broto, & Hodson, 2011). Understanding these criticisms and the real and perceived failures of the sustainability agenda provide a useful starting point from which to develop the environmental master-planning approach.

Among urban development and planning there is a general agreement on the definition of what sustainable development embodies despite there being no agreed upon method set of conditions or metrics (Garde, 2009). Features of sustainable development are typically diverse and wide-ranging, though will often include plans to limit greenhouse gas (GHG) emissions along with some attempt to meet a balance between economic, environmental and social factors. However, because the elements of what might be included in the term sustainability are wide, it is important that projects develop their own sustainability objectives against which they may be assessed. In doing so, they may perhaps avoid being challenged and criticised against an undefined concept and instead be assessed against real performance. However, given the wide variation in the term sustainability it is necessary to account for this throughout the life of the development project. Even if sustainability principles are defined at the outset of the project, it is entirely possible that they face practical limitations or setbacks that mean the envisioned objectives may not be met. Reasons for 'failing' to meet initial sustainability objectives may range from changes in technologies, cost, funding streams and priorities. This means in addition to spending initial effort at the outset to define objectives of sustainability, it is vital that the initial objectives are assessed and suitably revised throughout the development process.

Standards and sustainability indicators are widely used as a means for account or guiding sustainable development and are often used to set objectives. Assessment systems can provide a useful set of indicators to help guide the selection of sustainability objectives, but they are very often inflexible and subject to criticism of being overly simplistic (Kyrkou & Karthaus, 2011). Further, they can lead to inappropriate strategies for a site due to their inflexibility and inability to account for site-specific contextual issues, leading designers and developers to play the 'rating' game. While good designers and project professionals will reject simply designs that solely attempt to gain higher ratings, policymakers, investors and clients who are not part of the development process may be too attracted to the idea of a 'high boiler' plate rating. Despite this, standards and assessment tools have helped to draw sustainability into the development process and can help to inform a sustainability framework.

There are numerous drivers behind the actions that seek to create a highly sustainable development but that despite good intentions, the framework within which goals are defined and shaped and worked toward is failing. The examination of common criticisms of the urban development sustainability agenda highlighted the need to develop objectives that are suitable to the specific development context. This means understanding that in any situation a number of viewpoints exist and success in setting and achieving objectives comes through a pragmatic approach.

Masterplans are developed within a complex interaction of actors and their vision, goals, designs and outputs are a synthesis of both reality and ideals. However, a leading cause of failure for adopting proposals that seek to meeting sustainability objectives is that the objectives were set without reference to context and subsequently were unachievable. A study of masterplan developments in England identified a number of issues that acted as barriers to addressing sustainability, including: a sustainability measure was not considered by stakeholders, a measure was not required by the client, limited purview (i.e. the objectives sat outside the scope of the development team), a trade-off between objectives occurred, an objective was restricted by regulators, that meeting the objective cost too much, and that a proposed measure was untested or untried (Williams & Dair, 2007).

Summary of the approach

An environmental approach to masterplanning, therefore, uses context as its starting point, i.e. the social, physical, and environmental context, to inform the development of suitably sustainable objectives. Sustainability assessment guides and tools can act to inform and inspire the setting of objectives by offering as a framework within which to identify issues and challenge project actors. To address the barriers to sustainable development the capacity to gather together insight and consider a wide range of viewpoints, along with an understanding of the context, needs to be integrated into the development process. An understanding of context is used to set out a vision that will act as an over-arching guide and will be used, along with the context, to set the objectives against which the masterplan will need to respond. The objectives are used to set specific targets that may be bespoke for the project, drawn from an appropriate assessment standard, or a combination. Initial strategies are then developed that can support meeting the objectives and can be measured to support the targets.

Understanding the context

To initiate the process, information on the site-specific features of a development area are gathered in order to define the sustainability objectives. This information describes the context or the 'environment' within which a masterplan will be developed. The term 'environment' is used here in its broadest sense. The concept of environment transcends the physical features of place; it embodies the natural bio-physical and climatic features, the technological infrastructure, the socio-cultural interactions of human activity and institutional processes, and the wider values and ethics of the community. An environmental approach to masterplanning is, therefore, one that uses context as a basis of opening the development dialogue and define these and prioritises objectives.

Consideration of the social context is vital to building sustainable communities. In Chapter 1, Moore et al. examines the development of a methodological framework to investigate sustainable communities and their importance in developing sense of place and the importance of understanding social accounts.

An examination of the local climate can provide an indication of the site conditions that can support a more bioclimatic approach to the design. Bioclimatic design seeks integrate the local climatic conditions in order to minimise the impact of the built environment and also to make use of passive means to improve thermal comfort and reduce resource demand (Gaitani, Mihalakakou, & Santamouris, 2007). In the urban context, consideration of bioclimatic conditions involves examining the climate conditions by means of characterising the local environment through the use of data. Table 1.2.1 describes a number of climate and local site conditions that should be assessed as part of the bioclimatic analysis. Climate data is available from a number of sources, including national and local observatories.

Characterising the typical local climate and site conditions provides a method of understanding the opportunities and constraints that need to be considered as part of the background context. Where existing background conditions present risks that must be mitigated against (for example landforms prone to flooding) or opportunities that could be used to reduce the reliance on external resources. Box 1.2.1 provides an example of describing the local bioclimatic and site conditions of the University College London (UCL) Bloomsbury campus in central London. In this example the sunpath, incoming solar radiation (insolation), air quality (PM10) and background noise levels are provided as part of the analysis of the annual site conditions.

Developing a vision

In setting out toward a sustainable masterplan, it is vital to have a vision for what this masterplan will seek to achieve. A vision should be aspirational and acts as a point around which to coalesce and inform the development strategies and activities. For example, Masdar City, UAE is described by its developers as "One of the most sustainable communities on the planet". Its vision offers a conceptualisation of what it hopes to achieve through its development and completion and identifies the features around which it focuses (see Box 1.2.2).

The development vision is not derived from a single source but is developed in an iterative process. Often, an opportunity is identified for a space or place, either as a potential for a new development, or redevelopment that attempts to meet a need, generate an interest, foster enterprise or social connections, or any number of other demands. A well-defined vision is one that offers a sufficient condition around

Table 1.2.1 Local climate and site conditions for consideration in bioclimatic analysis.

Climate data:	Local conditions:
• Temperature	• Air quality
• Heating and cooling degree days	• Sources of noise
• Relative humidity	• Urban heat island
• Wind conditions (direction and speed)	• Soil conditions
• Solar angles and shadows	• Groundwater quality
• Insolation and solar irradiation	• Ecological integrity
• Precipitation	

Source: Chapter authors

Box 1.2.1 University College London (UCL) site conditions

An initial site analysis was undertaken for the UCL main campus in the Bloomsbury area in central London. Figure 1.2.1a shows solar characteristics in summer solstice (22 Jun) has 62.19° of solar access angle, compared with 15.19° in winter solstice (22 Dec). Based on the factors, some local shading from surrounding buildings and on the UCL campus building block itself may present challenges for passive solar design, especially for winter season.

Figure 1.2.1b shows average annual incoming solar radiation levels (insolation) per m^2 mapping. Based on solar characteristics, solar insolation can be used for natural gains (where desired) and for solar thermal and photovoltaic (PV) systems. UCL buildings are obstructed from solar access by each other; the distance between buildings is only 5m in the worst case in terms of solar accessibility, therefore façade has a limitation to install PV system; while the roofs have considerable solar potential.

Air pollution levels in most areas of London are sufficiently small to be classified as low according to the air quality index. Figure 1.2.1 c) shows the annual average daily PM10 levels around the campus. Higher concentrations are seen around the When this index was created these levels were considered unlikely to cause any adverse health effects. Much of the pollution in London is associated with traffic and zooming in to show individual roads will usually reveal locations where pollution levels are higher. (London Air).

Noise maps (such as Figure 1.2.1d) presented on this site provide an overview of the ambient noise environment. The maps allow the determination of the number of people affected by different levels of ambient noise, the source of that noise (i.e. road, rail, air, or industry). According to CIBSE guide A, the suggested noise rating (NR) for education facilities is 25–35NR, which can converted to 31–41dB. As the noise mapping around the site shows that the majority of the campus may experience noise levels in excess of 55dB(A).

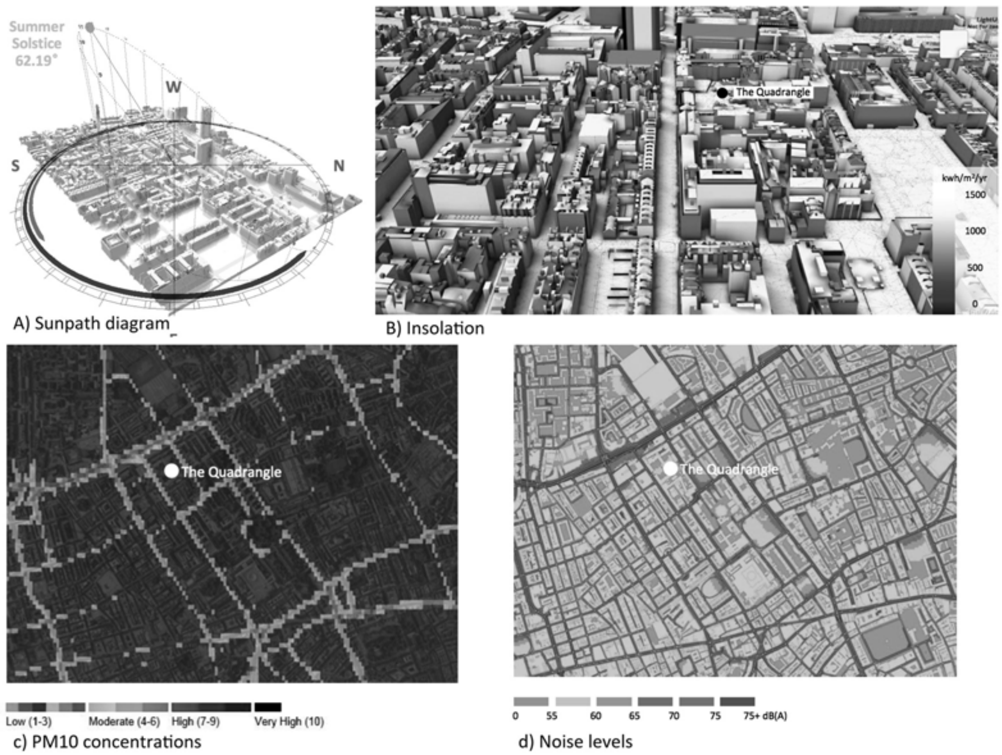

Figure 1.2.1 Selection of UCL campus site conditions.

Source: Courtesy of So Hyun, 2013

Box 1.2.2 Vision for Masdar City

A place where businesses can thrive and innovation can flourish, Masdar City is a modern Arabian city that, like its forerunners, is in tune with its surroundings. As such, it is a model for sustainable urban development regionally and globally, seeking to be a commercially viable development that delivers the highest quality living and working environment with the lowest possible ecological footprint.

Source: http://masdarcity.ae/en/27/what-is-masdar-city-/

which principles of action can be generated. Shipley & Michela (2006) outlines the importance visions have in motivating action from decision makers and stakeholders and that undergoing a visioning process assists the democratic process of development and city building. They go on to point out that alongside a vision must sit the notions and proposals of how the vision can be achieved (Shipley & Michela, 2006). As in the Masdar example, the ideal of creating and fostering a smart business hub in a sustainable manner is the vision that is then embodied in a set of objectives and principles.

Developing objectives and setting targets

As part of the initial strategy development process, a set of objectives should be set out in response to the site context and to the vision statement. The objectives should cover the range of different elements that can be used to attain the vision and are designed with regard to the leading principles of the design or approach. In Environmental Masterplanning, the emphasis is on the minimisation of the impact on the physical environment and supporting social activities. An objective is a qualitative aspiration that will be sought; it should of a sufficiently specific nature so that the objectives can be used to inform or develop targets. An example of an objective would be, say, minimising site water demand and runoff.

Targets are specific and quantifiable and should be measurable or clearly shown through some recognised means. The targets are used to help meet the objectives by providing the end at which to direct the means. This involves considering the multiple facets of an objective and coming up with a number of methods by which to measure progress, outcomes and by which to judge success and failure. For example, the objective of reduce water demand and runoff could involve several targets that assist in this task, such as: using 100% low flow water devices and appliances, providing user education to associate constrained water resources with their actions (i.e. dripping taps or long showers). It could also mean making choices on the type of water infrastructure on site and the potential of using alternative water sources, for example by reducing peak flow storm runoff by 40% or sourcing 80% of non-potable water demand from alternative low-impact sources.

Standards and guides

To assist in the development of objectives or identify targets that can be used to meet the overall vision and guiding principles of the development, assessment standards and guides, criteria and benchmarks are often used in Environmental Masterplanning. There are a number of such standards and guides available for a range of principles and visions, many focusing on broader issues and elements that are commonly drawn under the sustainability concept. Sharifi and Murayama describe these tools as:

> Neighbourhood sustainable assessment tool (also sometimes referred to as: district sustainability assessment tool, neighborhood sustainability rating tool, sustainable community rating tool) is a

> tool that evaluates and rates the performance of a given neighborhood against a set of criteria and themes, to assess the neighborhoods' position on the way toward sustainability and specify the extent of neighborhoods' success in approaching sustainability.
>
> (Sharifi & Murayama, 2013)

The main purpose of these assessment standards and guides is to offer some method of identifying issues or checklists and offer a standard against which a proposal or outcome can be graded. There are many standards that are being applied to masterplanning scale developments. Table 1.2.2 offers a brief overview

Table 1.2.2 Masterplan scale assessment tools.

Masterplan assessment tool	*Guiding principles*
LEED-ND	Low impact neighbourhood design and construction.
ECC	Responsibly designed and constructed communities, promoting smart growth, sustainable development and healthy communities.
BREEAM communities	Identify a range of issues and certify sustainability of early planning stage project proposals.
CASBEE-UD	Focuses on outdoor and off-site environment that focuses on enhancing sustainability of urban plans.
Qatar Sustainability Assessment System (QSAS) neighbourhoods	Assesses environmental performance of neighbourhoods' buildings and systems with a focus on smart growth.
Green star communities	Uses benchmarks and ratings for five principles (liveability, economic prosperity, environmental responsibility, design excellence, strong governance).
Green mark for districts	Assessment criteria that focuses on environment impact and performance of district level projects using specific features and practices.
Green Building Index (GBI) for townships	Promotes liveability and minimising environmental impact for developments with an assessment criterion for planning stage.
Neighbourhood sustainability framework	Provides a framework to improve existing and planned sustainability of neighbourhoods that through observation and rating.
HQE2R	Uses three tools to assess development project sustainability, including: long term impacts, environmental impacts, and economic and environment assessment.
Ecocity	Self-assessment that uses indicators and benchmarks focusing on evaluation of urban structure and transport.
SCR	Measures planned performance of residential communities including: new development, urban renewal and rural.
EcoDistricts performance and assessment toolkit	A performance standard and process that prioritises district-scale projects focusing on community themes (e.g. equitability, health and wellbeing, community identify, access, and mobility) through goals, objectives and measures of success.
Sustainable Project Appraisal Routine (SPeAR)	A sustainability decision-making tool that appraises projects on key themes throughout project planning and development.
One Planet Living (OPL)	A 10-principle framework that supports sustainable living and affordability focused on achieving a global equitable use of resource.

Source: Adapted from Arup, 2013; BCA, 2013; Beacon, 2014; BioRegional, 2014; EcoDistricts, 2011; GBCA, 2014; GBI, 2011; GORD, 2014; Sharifi & Murayama, 2013 of these standards and their guiding principles. Regardless of the decision to use any given standard or criteria, what is important is that the approach is sufficiently flexible and thoroughly considered. Not all approaches will be appropriate for every site and tools should be sensitive to the local conditions and context within which they are applied (Kyrkou & Karthaus, 2011; Sev, 2011). Applying a standard, such as zero energy, to a development that it would be impractical or include negative effects on other parts of the development should be avoided. As should 'green washing' a development, whereby a standard is being applied for the sole purpose of achieving it. The use of any standard should be to inform the development of the site features and design approach.

In the wider context of sustainable development these tools can offer policymakers an invaluable approach for including and considering the natural, physical and social systems within which development takes place, along with a method of summarising and simplifying complex streams of information to simplify the decision making process (Gasparatos, El-Haram, & Horner, 2009). They can be used to integrate the multitude of diverse issues that interact when progressing toward a vision of sustainability into a manageable set of discrete and understandable targets. They also provide a way for project actors (designers, engineers, developers, planners) to monitor their progress and understand their achievements (and challenges). This is particularly important for communicating these achievements and challenges to the wider public (in particular the vision). However, it is vital that the application of any standards is undertaken in a thoughtful manner, that they are not used simply as reductionist standards or checklists.

Building a strategy

In moving from the visioning and setting of objectives and deciding whether an assessment tool is used, the next steps in the process is to identify themes and issues around which a development strategy responds. This process of identifying themes and their priorities acts to begin outlining what features a strategy should include. As the strategy is developed and refined, the objectives themselves and the use of standards and their metrics should also be refined. It may be that during the process of responding to a development issue, it is no longer practical or appropriate to seek a particular standard (or element within that standard). Or it may be appropriate to select another metric of assessment.

Identifying themes

Regardless of whether a particular assessment standard or checklist is used, it is often the case that objectives and strategies are built under a set of themes or categories that help to delineate tasks, determine priorities, identify experts and specialists, and define the scope of work. These themes should aim to reflect and wider project stakeholders and actors that are involved and will be affected by a masterplan development. The current underlying principle of holistic sustainable development is driving the low-carbon society paradigm, i.e. that there is a need to reduce the impact that human activities have on local and global environments and to mitigate climate change (Skea & Nishioka, 2008). In these terms, urban masterplanning development has been tasked with drawing together collective actions to minimise the impact that existing and new urban developments have on local environment and also act to address the wider climate change mitigation needs. In addressing these issues, environmental masterplanning seeks to fit with the concepts of sustainability, including locality, embodied energy and CO_2 emissions, and renewable resources, and environmental impact, to name a few. The themes most often captured under a holistic approach for masterplanning are wide ranging and cover environmental, social, economic, institutional, and legacy issues. These themes are often identified under current sustainability frameworks – see Box 1.2.3 for common sustainability themes.

These themes and issues are by no means a comprehensive list, but rather offer commonly identified issues that are considered in research and practice. What is vital, however, is that contextually based,

Box 1.2.3 Common sustainability themes

- Community engagement
- Health and quality of life
- Economy and employment
- Transport and accessibility
- Energy supply and demand
- Water resources & sewerage
- Wildlife and biodiversity
- Food
- Agriculture
- Recreation and open space
- Land use and amenity
- Urban design and architectural character
- Heritage and culture

or site-specific issues are also included and may otherwise sit outside of these themes. For example, these may range from practical issues associated with: riparian erosion, site contamination, and brownfield redevelopment, to community space regeneration, technology innovation, and smart communication.

Using objectives informing the initial strategy

Once the visioning process is at a point where a set of objectives have been defined and a development brief and its themes and issues are set, it is possible to begin developing options that can attain the objectives and support the vision.

At an early stage, strategy development should wholly be focused on developing options that respond to the identified issues. At the options stage, the practice of designing and engineering is a process of distillation, which begins by identifying preferred designs, techniques or technologies. The purpose of identifying a number of design options within a strategy development is so that they may be judged against a multi-criterion, with strengths, weaknesses, opportunities, and challenges can be identified. During this time more information is gathered and objectives are refined, thus influencing the choices made on whether to pursue a given strategy.

A common approach is for strategies to be developed by the respective design team's project actors and brought together for discussion and consideration during project meetings. While this approach is necessary for the development and consideration of techniques and technology options and their feasibility, it is essential that when the teams are brought together that they are able to challenge and integrate their designs. This can only be done if there the vision and objectives are sufficiently strong, understood and, crucially, endorsed.

Development strategy options are not developed in isolation, though they may often be under the purview of a given project actor. While it may be that the urban designer considers the form (volume and massing) and the spaces between buildings, the options for transportation, access and circulation are not developed without integrating with the urban design principles (and vice versa). This initial stage is the point where options are set in context with one another and the influencing factors are discussed. For example, an objective that improves access and walkability around a development would need to consider the implication of pedestrianised spaces on the options for waste pickup and storage, the options for available for motorised vehicle access and maintaining the site features (such as landscaping) or actions to address climate (e.g. snow clearance). For examples of initial considerations in developing environmental strategies see Box 1.2.4.

Integration needs to be a driving force in developing strategies that address sustainability. If strategies are developed in isolation it is unlikely they will either be well-informed, flexible or sufficiently open to meeting the needs of the many stakeholders who will one day interact with the development. This

Box 1.2.4 Initial environmental masterplanning considerations for a selection of issues

Develop an appropriate strategy for each of the following sections within which certain issues should be covered, but are not limited to:

Landform, land use and density

- Consider how the site's landform influences the massing and layout of the buildings on the site.
- Examine densities, and mixture of services available onsite and consider changes necessary to achieve objective.

Energy and comfort

- Consider energy strategy options that are likely to address the sustainability objectives and targets, and also to respond to technical and environmental site conditions under future scenario.
- Consider built form issues such as orientation, use of thermal mass and materials, building envelope, solar access as appropriate and consider approaches to reduce energy demand.
- Review options to provide low carbon and/ or renewable energy at a strategic level and put forward preferred solution for the site.
- Consider the long-term operation of the suggested energy systems and related drawbacks and benefits and issues of comfort.

Water

- Consider approaches to reduce onsite water demand and water run-off.
- Identify strategies for meeting water consumption demands as sustainably as possible.
- Identify appropriate methods of water supply for the site and wastewater treatment and disposal that are suitable for the site and sustainability standard.

Waste

- Consider operational waste management issues with respect to waste minimisation, collection, diversion and treatment.
- Outline onsite waste strategies, consider: waste hierarchy, collection, storage, integration, treatment, and any necessary disposal.
- Consider how proposals will be influenced by perceptions.

Transport

- Consider on modes of transport appropriate for the site that would satisfy the anticipated needs of those living, working, visiting the development.
- Consider how the strategy might make connections with existing transport links; consider the implications from and for site design and layout.

Greenspace and local food

- Consider options for greenspace provision and requirements to strengthen biodiversity and ecological value of the site within its local environment.
- Identify whether alternative greenspaces, could be integrated into the site for both pleasure and ecological benefits.

Box 1.2.5 Integrated strategy mapping

In developing an integrated environmental masterplanning strategy, the development strategy for a low-carbon community sought to integrate a number of issues and themes together to maximise the potential opportunities for reducing impact on the local environment. The process of mapping out the features of the strategy offered an early day's assessment of what features the development strategy might pursue and appraise.

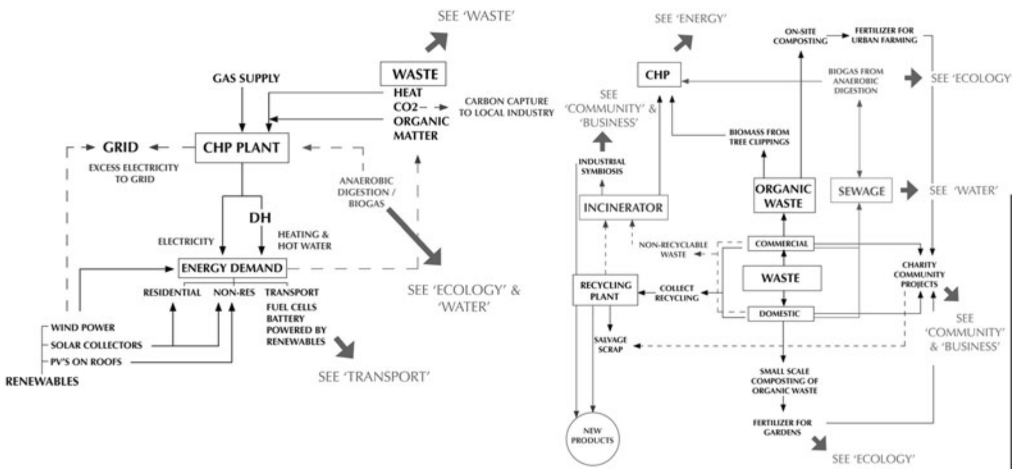

Figure 1.2.2 Integrated environmental design mapping.

Source: Courtesy of Carrie Behar, 2010

requires considering integration throughout the strategy development process by linking together interacting features. For example, Box 1.2.5 offers an example of mapping out the interaction between strategies that might occur and offer opportunities to improve the sustainability (i.e. by reducing resources and maximising symbiotic relationships).

Moving towards implementation

In order that the environmental masterplan strategies are robust and have a high level of 'buy in', it is imperative that the development process include a creative and interactive process that draws in experts and non-experts alike. Further, feedback throughout the design process is fundamental to ensuring the strategies are appropriate and flexible to the reality of the development process.

Charrette process

A method that is commonly used to refining the strategy development process is through the charrette, a process that draws together experts and non-experts into an interactive environment that seeks to allow options to be discussed and considered. Within a charrette, project actors (engineers, planners, designers, etc . . .) offer their ideas to elicited discussion and seek feedback and alternative options to inform the strategy process. The process is meant to allow for constructive and creative interactions to occur between the stakeholders in developing strategies and often occurs at an early stage in the environmental masterplanning process and again as more concrete options are developed. In advance of the charrette, the project team clarifies the brief, objectives and the initial opportunities and constraints that could be addressed. By inviting a wide range of stakeholders, e.g. local residents, institutions, community organisations, and interest groups (all of whom will have vested interests), many viewpoints will be offered that can help strengthen the development. The process begins to open a dialogue between the project actors to present and seek information from wider stakeholders on their initial concepts.

The purpose of the charrette is to allow for experts to engage with the wider community stakeholders to (a) develop and refine the masterplan vision; (b) identify and prioritise objectives; (c) identify relevant themes and issues; and (d) discuss and develop strategy options. The approach is commonly used in the USA and Canada. Sutton and Kemp have found that the process can "broaden the knowledge base [and bring forward] new understandings and perspectives" (Sutton & Kemp, 2006).

The benefit is that this process can strengthen the relationship between the design and development team and local community and stakeholders. It is a challenging process of discourse; within the charrette environment, development clients are faced with community voices, designers with technical experts, and technical experts with creative and social challenges. The charrette offers a process by which to balance the technical, social and aesthetics of the development process. It can strengthen the approach to achieving more realistic and a higher degree of environmental, social and economic sustainability.

The feedback loop

As strategies are refined with techniques and technologies identified, appraised and selected, it is important that the initial environmental masterplanning vision and objectives are re-examined and reconsidered. There is a risk that throughout the journey of a lengthy development process, with many interacting project actors, community stakeholders, institutions and organisation that new objectives will be revealed, and others dispensed with. By introducing feedback loops to different parts of the strategy development process, it is possible for the process to ensure pragmatism is offered alongside aspirations. For some, this may dilute the level of ambition sought; however, the alternative are lofty and possibly unattainable goals for the masterplan that are uninformed or developed outside of the context or environment.

The environmental masterplanning process

The environmental masterplanning process is predicated on an open framework within which to identify issues to inform and develop a definition of sustainability (see Figure 1.2.3). By undertaking an assessment of the environment, or context, within which the masterplan is being developed, will provide a deeper understanding of the inter-related conditions that must be considered as part of defining sustainability. Through this process, and also drawing on environmental paradigms and principles, a vision of what might be achieved is put forward. In support of this vision are the objectives, which are developed through an understanding on the context but also informed by the local community and interested stakeholders. In support of the vision and informed by the objectives, it might also be appropriate to use, or draw from, an environmental assessment standard. These standards, of which those for the masterplan scale are growing, provide both a set of themes that should be considered, along with indicators and metrics that can help in the strategy development. The strategies themselves should be developed in an integrated and iterative process, whereby each strategy is informed by the design principles, can support the objectives and also any standards being sought. Integration provides a way of achieving both parsimony and can offer efficiency in resource use or resilience in the design. In developing these strategies, the process of going out to the interested community stakeholders and engaging in a creative and constructive charrette process can help to bring forward new ideas, challenge the existing or common approach and help to improve the buy so that higher levels of sustainability may be achieved.

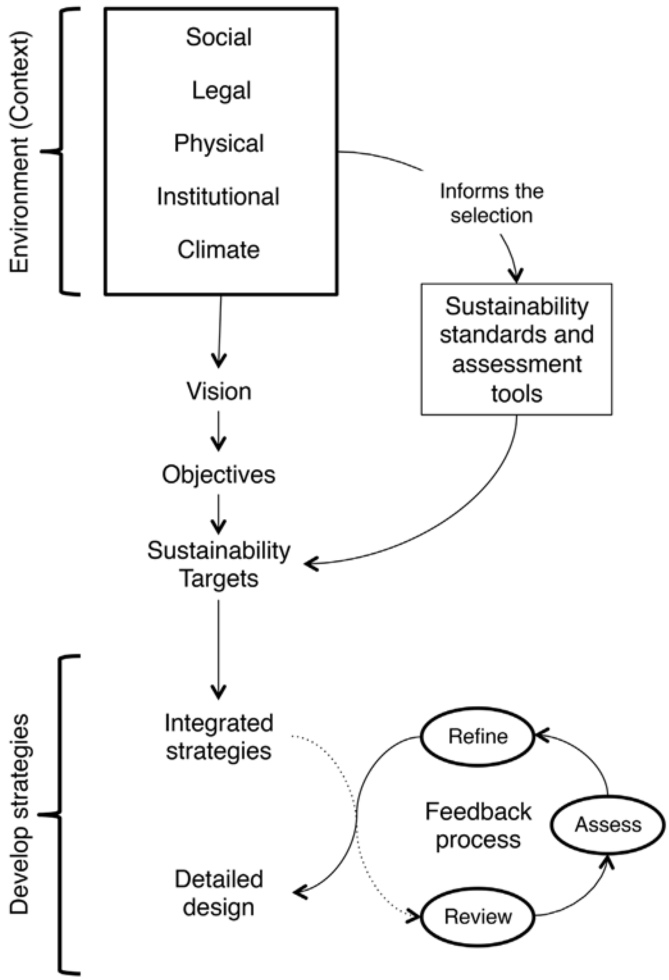

Figure 1.2.3 Environmental masterplanning process.

Source: Chapter authors

Considerations

It is not enough to simply ‘make plans’ that comprise visions, objectives and targets, and strategies. Achieving a long-lasting change in the city building process that considers the physical and social environmental conditions requires actions that are derived from a process that harnesses the expertise and collaboration of the disciplines that interact at the masterplanning level.

Throughout the design and development process, constructive collaboration and critical thinking is essential to develop interdisciplinary designs that are able to deliver integrated and sustainable built environment. Depending on the training process of the various disciplines involved, practitioners are more or less used to collaborative interdisciplinary working environments. The development of strategies, the use of techniques and delivery of systems separately by individual disciplines is no longer appropriate and generally falling out of practice. The interdisciplinary approach is slowly becoming a part of the teaching curriculum in engineering, architecture, urban design, urban studies and planning. However, it is impossible for every student, researcher or practitioner to be a cross-disciplinary expert. The integrated approach can only thrive in an environment that is open to question, constructive criticism and collaboration with recognised benefit from collaboration and multi-disciplinary contributions. This means that the different disciplines involved in the environmental masterplanning process are able and comfortable to discuss priorities and strategies openly and with pretence or defensiveness. It also means that the different disciplines need to be feel confident to ask those sitting around the table questions on how to improve strategies proposed from one discipline and how they can create links to their own.

In summary, a number of final points are offered here that students, research and practitioners can consider during the environmental masterplanning process:

- Developing an inclusive vision for the development that will act as guide to setting out the objectives and targets that will drive the strategy development requires entering into a discussion with the project client early on. This will ensure that an integrated approach to the strategy development is put in place from the beginning of the process and will assure both the client, the design team actors and the eventual occupants or tenants that the development was not singularly focused.
- Initiating an integrated environmental planning process requires that at least one member of the development design team holds a role with sufficient responsibility to direct the scope of the different project actors to engage in an inter-disciplinary design process. Some clients might recognise the value of a creative and collaborative design team for setting out and achieving sustainability or environmental goals. However, if this belief is not present, it takes a strong member of the design team to advocate the benefits of an integrated design approach.
- Improving the design and delivery of a development to meet environmental and sustainable objectives is largely an incremental process. While every project requires a thoughtful and creative approach that is based on critical thinking on how to achieve multiple goals, not every project is suitable for the most advanced technologies or innovative techniques. It might be that in order to build acceptance and elevate environmental priorities of a development that these issues are progressively tackled, building trust between the design team, stakeholders and showing that the process can support advanced practices.
- The environmental design process requires practitioners that are able to think critically, evaluate options and judge benefits and risks in order to achieve multiple goals. Thinking through the dynamic process and interactions that the urban environment comprises provides a means of recognising the potential opportunities that exist and barriers that must be overcome. Entering into a constructive process of developing ideas, discussing techniques and technologies and services with a range of stakeholders allows for this environment to be better understood and therefore increase the chances of creating a more enjoyable and environmentally sensitive urban place.
- The period of single disciplines delivering their 'parts' of the masterplan is coming to an end because the process of developing and delivering integrated environmental masterplanning strategies requires well-designed and thoroughly considered services with inputs from different disciplines. Consider how your activities can contribute to this process.

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1.3
URBAN CLIMATE
Impacts on energy use, comfort and health

Michael Davies, Philip Steadman and Tadj Oreszczyn

Introduction

One of the best-known effects of urbanisation on the local climate is urban warming – this phenomenon is commonly referred to as the 'urban heat island' (UHI). A range of factors vary between rural and urban areas and contribute to the UHI – for example the thermal properties of materials, the height and spacing of buildings and air pollution levels. These factors result in more of the sun's energy being captured, absorbed and stored in urban surfaces compared to rural surfaces during the day and a slower loss of this energy at night thus resulting in comparatively higher air temperatures. In addition, less evaporation (with the consequent reduction in associated cooling) takes place in the typically drier urban areas. Finally, urban areas such as London (Figure 1.3.1) also have greater inputs of heat as a result of the high density of energy use in cities. All this energy (used in buildings and for transport) ultimately ends up as heat. Strategic planning is therefore required which takes account of the above factors, particularly in the context of climate change.

Figure 1.3.1 London.

Source: UCL

The value of the UHI in any city will have significant spatial and temporal variations – the maximum intensity is typically reached several hours after sunset (Oke, 1987). With regard to the UK, in London during the August 2003 heat wave, the maximum temperature difference between urban and adjacent rural locations reached 9°C on occasions (Greater London Authority, 2006a). Watkins, Palmer, Kolokotroni and Littlefair (2002) reported on an extensive series of measurements, made in London in the period 1999–2000, which demonstrate in detail the behaviour of London's UHI.

It should be noted that for certain cities a 'negative' UHI can instead be dominant. In arid regions, cities with large amounts of irrigated greenspace may actually be cooler than the surrounding dry areas (Grimmond, 2007). UK cities however, appear to exhibit features of a 'conventional' UHI (as would be expected) and it is such cities that this chapter focuses on.

The concept of the 'urban heat island' is now well established. However, the distribution of local temperatures within the urban environment and their relation to land use and building form is much less well understood. These variations in temperatures are important for several reasons. Firstly, populations typically display an optimum temperature range at which the (daily or weekly) death rate is lowest. Mortality rates rise at temperatures outside this optimal zone. The temperature–mortality relation varies greatly by latitude and climatic zone. People living in urban environments are at greater risk than those in non-urban regions (McMichael, Woodruff and Hales, 2006). Adapting to and ameliorating such dangerous conditions, whose effects have been experienced, for instance, in Chicago in 1995 (Klinenberg, 2002), in Greece in 2001 and in France in 2003, will require appropriate policies for urban planning, housing and transport (Hunt, 2005). But before these policies can be developed, quantitative tools are required to identify and quantify the net effectiveness of mitigation and adaptation strategies. For example, while the lowering of urban temperatures in summer is likely to reduce rates of heat-related mortality, the number of cold-related deaths is far higher in the UK than the death toll due to excessive summer heat. This should be borne in mind before any major intervention in a city is contemplated.

Increased mortality represents an extreme consequence of rising temperatures. However, it is clear that the proportion of the time that people will feel 'uncomfortable' has the potential to increase. This raises the possibility of a large increase in the use of mechanical cooling systems and a consequent rise in energy use, particularly in urban areas.

The urban environment then has an impact on energy use, comfort and health. It is possible to modify this environment in an attempt to address these issues. The next section describes some options that are available.

Modifying factors

A range of physical scales apply to the strategies that may be used in an attempt to modify the urban climate. The UHI is a city scale effect and research is currently being undertaken to examine modification strategies that can be implemented at levels ranging from street to city wide. At a local scale these include the modification of surface properties ('cool roofs', 'green roofs' and 'cool pavements') planting trees and vegetation and the creation of green spaces.

The geometry of the built environment and anthropogenic (man-made) heat emissions are also issues to consider. A useful guidance document is available that provides further details of these issues with a specific focus on London (Greater London Authority, 2006b). A brief discussion of all of these factors follows – anthropogenic heat emissions are reviewed initially.

Several studies have shown the effect of anthropogenic heat emissions on the urban climate (see Coutts, Beringer and Tapper, 2007; Ichinose, Shimodozono and Hanaki, 1999; Taha, 1997; and Klysik, 1996). The Ichinose et al. (1999) study of Tokyo quantified the increase in temperatures within the urban environment, on the basis of a detailed survey of energy consumed, to be up to 1.5°C within areas of high anthropogenic heat emission. The influence was strongest during winter months and weakest during summer, as the shortwave radiation varied along with seasonal daily temperature profiles. The Taha (1997) analysis of several American, Canadian and European cities indicated that anthropogenic heat emission was strongest in cold-climate city centres but was nearly negligible in suburban areas. The study suggested that an increase of 2–3°C could be seen due to the impacts of anthropogenic heat.

A 2008 study (Hamilton, Davies, Steadman, Stone, Ridley and Evans 2008) estimated the anthropogenic heat emission from buildings in London at a range of spatial and temporal scales – an example of the data is shown in Figure 1.3.2 and refers to the emissions per m^2 of ground area. A wide spread of annual average heat emissions was identified with 50% of London emitting less than 10W/m^2, 25% emitting between 10–18W/m^2, 20% emitting between 18–30W/m^2, and 5% emitting above 30W/m^2. The annual average building related heat emission for the whole of London is estimated at approximately 9W/m^2. In comparison, the London Energy and CO_2 Emission Inventory (LECI) database (Greater London Authority, 2006a) estimates the annual average energy delivered for transport in London as approximately 2W/m^2.

The highest levels of annual heat emission from buildings in London are concentrated in central London although there a few isolated pockets of high emitting areas in outer London. The pattern follows the concentration of domestic and non-domestic buildings, their clustering, and the density of the development

The study also compared the anthropogenic heat emissions and total incident net shortwave solar radiation balance of four representative London sites. In those urban areas with deep canyons and high

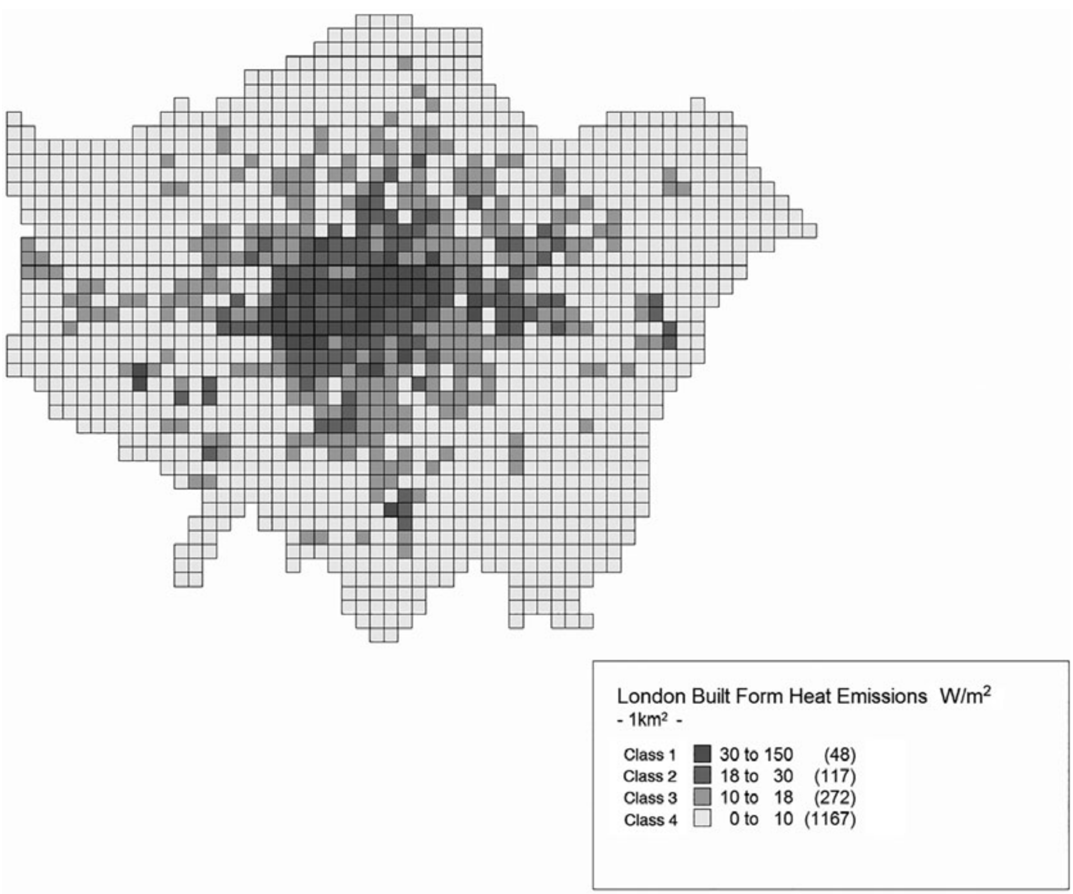

Figure 1.3.2 Annual average anthropogenic heat emission from buildings in London.

Source: Hamilton et al. (2008)

densities, the anthropogenic energy constitutes a significant portion of the total energy input. A study of London's UHI phenomenon indicated that the centre of the island sits above the Old Street and Farringdon Road area within the City of London (Watkins et al., 2002). This location is also where the anthropogenic heat emission is greatest. It indicates that the reduction of energy use within such areas may be particularly relevant with regard to the UHI.

In the future it is likely that not only will our use of energy reduce but that the sources from which this energy is supplied will alter due to the pressures of meeting our climate change obligations and to maintain security of supply. This may involve the decentralised distribution of energy as greater use is made of combined heat and power and local authorities increasingly demand that new buildings generate a percentage of their energy locally, e.g. the 'Merton Rule' (a policy adopted in 2003 by the London Borough of Merton that stated: "All new non-residential developments above a threshold of 1,000 square metres will be expected to incorporate renewable energy production equipment to provide at least 10 per cent of predicted energy requirements").

These changes may have an impact on anthropogenic heat emissions. If conventional power stations were moved into cities, then this would clearly have an impact in raising the local emission of heat but if the power stations were instead used for combined heat and power generation then the effect on heat emissions may be negligible. Notice that the future move to decarbonised electricity in its own right is unlikely to make a major change since it does not matter how power is generated. The energy, whether low carbon or high carbon, all ends up as heat at the place of use. However, it is worth considering the implications resulting from a widespread move to solar heating because of the potential impact that this will have on the reflectance of roofs.

The reflectance (albedo) of a roof surface will have a significant impact on the resultant temperature of that surface. Modifications to the albedo will then impact on the resultant energy flows, both directly to the building and indirectly to the nearby environment. Green roofs will have a similar impact but with the additional potential benefit of associated evaporative cooling (assuming appropriate access to water). Large scale urban solar collection of energy may make it difficult to reduce the impacts of future climate change on urban areas – there may be a potential conflict between solar panels and the desire for highly reflecting roofs to mitigate the UHI.

Just as a modification to the albedo of roofs will impact on the energy balance of that surface and the surrounding environment, the same issues apply to other urban surfaces such as pavements and parking areas. If this modification to the albedo is also combined with improved water permeability, then evaporative cooling will also be enhanced. Highly reflective roads and pavements may also be advantageous for night-time street lighting.

Other options for modification strategies can make use of the fact that air temperatures in and around green spaces can be several degrees lower than their surroundings (e.g. Spronken-Smith and Oke, 1998). Trees and vegetation are good modifiers of climate, as they not only provide shade but offer enhanced evaporative cooling – assuming appropriate water availability. Gill, Handley, Ennos and Pauleit (2007) demonstrate the potential of green space using Manchester as a case study.

Finally, a key factor that differentiates the energy balance of rural and urban areas is the ability of the urban area to reduce the emission of long wave radiation at night. This is due to the reduced view of the sky of the urban surfaces. The orientation of streets will also impact on local wind velocities. Issues of sky view and orientation could be considered and addressed at the planning stage. However, clear evidence needs to be provided of the potential impact.

Energy use

There has been much work in this area and hence only a brief summary is provided in this chapter.

Energy impacts of the UHI

In general, the UHI would be expected to result in an increased cooling energy demand in summer and a reduced energy demand in the heating season – the literature supports this view. With regard to the UK, measured air temperature data have been used (Kolokotroni, Zhang and Watkins, 2007) as inputs to a building energy simulation computer program to assess the heating and cooling load of a typical air-conditioned office building positioned at 24 different locations within the London UHI. It was found that the urban cooling load is up to 25% higher than the rural load over the year, and the annual heating load is reduced by 22%. For this particular building and set of assumptions, the absolute gains due to the heating load reductions were outweighed by the increased cooling loads. For non-air-conditioned buildings, the UHI as described by this dataset would tend to result in net energy savings albeit coupled with higher summer temperatures.

Elsewhere, Landsberg (1981) compared heating and cooling degree days for several American cities and at airports outside them. A modified table was published by Taha (1997) – see Table 1.3.1. The relevant data for London has also been added to the table for the purposes of this chapter. The heating and cooling degree days are both calculated to a base of 18.3°C.

The data for London in Table 1.3.1 are the average heating and cooling degree days (1993 to 2006) for the London Weather Centre (central London) and Northolt (near to and at a similar radial distance from the centre of London as Heathrow Airport). Theoretically, the heating and cooling energy used should be a linear function of the number of cooling and heating degree days provided that the correct base temperature is used. Although the percentage change is much greater for cooling degree days than heating, the absolute change in heating degree days is greater for heating than cooling in most of the locations in Table 1.3.1 and the difference becomes greater the further north the location.

Energy impacts of modifications to the urban environment

Strategies for the intentional modification of the urban climate can be effective and hence can have a significant impact on the energy used by buildings. The effect on energy use may be usefully split into two components – direct (i.e. modifying the energy use of an individual building via the application of a cool roof for example) and indirect (i.e. modifying the energy use of all buildings via the impact that the methods outlined in section 2 – if applied on a large scale – may have on the ambient conditions).

Table 1.3.1 Heating and cooling degree days.

Location	*Heating degree days*			*Cooling degree days*		
	Urban	*Airport*	Δ	*Urban*	*Airport*	Δ
Los Angeles	384	562	–178	368	191	+177
Washington DC	1300	1370	– 70	440	361	+ 79
St. Louis	1384	1466	– 82	510	459	+ 51
New York	1496	1600	–104	333	268	+ 65
Baltimore	1266	1459	–193	464	344	+120
London	2419	2779	–360	248	207	+ 41
Seattle	2493	2881	–388	111	72	+ 39
Detroit	3460	3556	– 96	416	366	+ 50
Chicago	3371	3609	–238	463	372	+ 91
Denver	3058	3342	–284	416	350	+ 66

Source: data from Taha, 1997

One study (Synnefa, Santamouris and Akbari, 2007) looked specifically at the direct impact on an individual building from using cool roof coatings on the cooling and heating loads and the indoor thermal comfort conditions of residential buildings for various climatic conditions. For the locations studied (27 cities worldwide), the heating penalty (0.2–17 kWh/m^2 year) was less important than the cooling load reduction (9–48 kWh/m^2 year).

Akbari and Konopacki (2005) developed summary tables for approximately 240 locations in the USA, sorted by heating and cooling degree-days, based on simulations to quantify the effect of a range of strategies (i.e. solar-reflective roofs, shade trees, reflective pavements and urban vegetation).

The tables provide estimates of savings for both the direct and indirect effects for three building types – residences, offices and retail stores. The study found significant energy savings. For all building types, over 75% of the total savings were from direct effects of cool roofs and shade trees.

Both the UHI and relevant modifications to the urban environment have the potential to impact significantly on energy use. However more analysis is required into what happens in practice. Research is currently being undertaken at University College London (UCL) to examine the impact of climate change on energy use and analysis of monitored energy use with external temperature suggests that the effect is more complex than previously thought. For example, as temperatures rise the benefits of warmer external conditions are not always taken as reduced energy use but as higher internal temperature and increased levels of ventilation. Energy use in cities is highly complex. For instance, the requirement for air conditioning in cities is often driven more by traffic noise and pollution than the UHI. Also, some new feedback mechanisms could be foreseen in the future. For example, lightweight electric cars could be quiet and less polluting while contributing less heat to the urban heat island and this could encourage the use of natural ventilation instead of energy intensive air conditioning.

Health and comfort

With regard to the UHI, issues of health and comfort are inevitably linked. Higher summer temperatures will result in increased discomfort, but prolonged elevated temperatures cause significant increases in mortality rates. In the summer of 2003, much of Europe experienced a persistent heat wave. In England, there were 2,091 excess deaths (17 per cent increase) during the heat wave. The impact was greatest in the southern half of England, particularly in London, where deaths increased by 42 per cent (Johnson et al., 2005).

The elderly (over 75s) are most vulnerable to heat related mortality, particularly those living alone. However, other groups are also at risk – children and sick adults (e.g. those with chronic cardiorespiratory disease).

The design of dwellings can also play a critical part in modifying the risk of death. A study that considered the impact of the August 2003 heat wave in France (Salagnac, 2007) noted that:

> . . . thermal insulation plays a considerable role as a risk reduction factor: the odds ratio is decreased by a factor of 5 between non-insulated and insulated dwellings. A bedroom under the roof leads to an increase by a factor of 4 or more the risk of death. Surroundings with a high vegetation index also considerably reduce the risk.

As well as temperatures, pollutant concentrations are an important factor during heat waves in England. Ozone has been linked with increased hospital admissions for respiratory diseases (Anderson, Ponce de Leon, Bland, Bower and Strachan, 1996). In the 2003 heat wave excess exposure to ozone and PM10 were recorded for all regions in England, most notably in London and the South East. A significant proportion of the excess deaths in the 2003 heat wave could be attributed to ozone and PM10, (Stedman, 2004) although this study assumed no interaction between high temperatures and high pollutant exposures

Work is under way via the EPSRC funded 'LUCID' ('The Development of a Local Urban Climate Model and its Application to the Intelligent Design of cities') project to assess vulnerability to the health impacts of heat waves in the London setting and to address any synergistic effect of pollutants and temperature. An element of the project, led by the London School of Tropical Hygiene and Medicine (LSHTM) initially aims to quantify the degree to which micro-variations in the temperature and pollution have influenced mortality during past heat waves, and then apply this evidence to models of future heat waves under a range of assumptions about climate change and urban development. This work will extend research currently being undertaken as part of a range of other projects on heat-related mortality in the UK funded by the MRC and the European Commission. It will entail linkage of four principal data sets:

1 Modelled micro-variations in (a) temperature and (b) airborne pollutants (principally PM10, ozone) for past heat wave periods.
2 Daily mortality data for London geo-referenced using the full postcode of residence.
3 Small-area socio-demographic characteristics derived from the 2001 census at Super Output Area (SOA) level, including population age-structure and an index of socio-economic deprivation.
4 Data on the characteristics of domestic properties combined with new relationships being developed by UCL to predict summer time overheating in dwellings based on both field data and modelling.

The project will then specify a number of illustrative policies relating to urban planning and for each one use the LUCID urban climate model to predict temperatures and pollution levels under future climate change scenarios. With these urban policy-scenario combinations, the work will apply the evidence derived from analysis of past temperature-mortality patterns in London to estimate the future numbers of heat-attributable deaths in London.

While increased mortality represents an extreme impact of overheating, the issue of discomfort is also a critical one. A full treatment of comfort issues is given elsewhere in this book, so discussion of the relevant factors will be limited here to a short summary. A paper by Watkins, Palmer and Kolokotroni (2007) also provides a detailed treatment of this issue with a focus on London.

For the purposes of this chapter it is sufficient to note that many factors (air temperature, clothing, activity level, relative humidity, radiant exchange and air speed) are involved in the perception of comfort. It is certainly possible, in principle, for societies to adapt to elevated temperatures and indeed the future temperature projections for London for example are currently the norm for some lower latitude countries. The greater challenge for urban societies may be in dealing with the adaptation to the mitigation strategies relating to the reduction of CO_2 emissions. An element of the EPSRC funded 'PUrE Intrawise' (Pollutants in the Urban Environment: An Integrated Framework for Improving Sustainability of the Indoor Environment) project that the authors are part of will consider such issues. In an attempt to reduce the energy use of buildings and hence the associated heat emissions, the impacts of increased insulation and reduced air change rates may – in poorly designed buildings – lead to overheating and poor indoor air quality. The associated health risks need to be borne in mind.

The issue of discomfort is closely linked to that of increased energy use for cooling. Two projects (Orme and Palmer, 2003; Hacker, Belcher and Connell, 2005) have demonstrated via computer modelling the effect that ventilation could play in reducing the take-up of air conditioning. Higher temperatures associated with the urban heat island are expected to make the challenge more difficult. In particular, one strategy for passive cooling of buildings is through storing heat within the building fabric during the day and cooling through ventilation at night. But this method relies on the night-time temperatures being sufficiently low. The UHI is typically most pronounced at night, and so it is important to know whether or not this method remains viable. In general, strategies which may have served historic buildings well may no longer be appropriate. Buildings both respond to and contribute to the local microclimate. Effective building design requires a knowledge of, and ways of dealing with, this microclimate.

Conclusions

The local character of the built environment can have a strong influence and generate a localised microclimate, which leads to variation in the strength of the urban heat island across a city. We have seen, for example, how green space interspersed into the urban landscape can substantially reduce undesirable impacts of buildings on the microclimate. In this and other ways, intelligent master planning of large-scale development can alleviate overheating in urban areas. However, at present there are no suitable quantitative tools available to architects, planners, and designers to analyse the impact of urban development on the microclimate – and hence health, comfort and energy use – across this range of scales. What is needed is a robust and appropriate model that can reliably predict localised urban temperatures – a 'weather forecast' model for the urban environment. This would mean a move away from 'traditional' generic weather files that are currently utilised within building engineering, toward 'tailored' predictions specific to the local environment. To address each of the concerns requires local environmental prediction - on scales from whole city scale down to hundreds of metres. In the UK, for example, there are no established practical methods or tools for assessing the impact of local planning decisions (land use; building layout, orientation and design; size of open spaces or parks) on the fine details of the local climate. Widespread and immediate modification of the relevant properties of the urban environment in order to impact on the UHI is not feasible for UK cities on a large scale. However, the collective effect of many smaller changes may be significant at a variety of scales.

A number of projects have begun to investigate these issues with a particular focus on the UK, in particular two EPSRC funded projects 'SCORCHIO' (Sustainable Cities: Options for Responding to Climate cHange Impacts and Outcomes) and, as noted earlier, 'LUCID'. The authors of this chapter are involved in the LUCID project that will develop, test and apply state-of-the-art methods for calculating local temperature and air quality in the urban environment. The impact on energy use and the consequences for health of changes to the urban climate will then be explored. The implications for urban planning will be considered in detail. Such methods applied to urban areas would contribute greatly to the generation of guidance in planning process and indeed modelling is seen as essential to estimate and predict the transition from the present unsuitable practices to more sustainable communities.

There is much current interest in attempting to ameliorate potential summer overheating – i.e. a focus on the consequences of heat waves. However, the wider picture should also be considered. In summer, in the UK, the UHI will tend to result in an increased cooling load and an increased number of excess deaths due to overheating. In winter conversely, the UHI will tend to result in reduced heating loads and a reduced number of cold related excess deaths. As noted earlier, the net effects of these impacts must be borne in mind in the consideration of large scale urban modifications.

In the UK it would be possible to hypothesise that the UHI may actually have a net positive energy, health and comfort effect over the year. The research challenge is to test this hypothesis both for the present day and also for the future taking into account climate and other social and technical changes. Detailed studies of these issues with regard to the UK are now under way and the results of this research should be fully understood before any major changes to the urban infrastructure are undertaken which may impact on the UHI.

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1.4

AIR POLLUTION AND URBAN BUILT ENVIRONMENT

Dejan Mumovic and James Milner

Introduction

Breaches of the prescribed air quality standards in cities are frequently associated with the need to travel from residential suburban areas to the city centres for business, shopping, entertainment and leisure facilities, universities and historical heritage sites. Although most of European cities have a well-developed rail networks, much of the commuter traffic is by motor vehicles, which concentrate pollutant emissions as they converge on, or diverge from the city centre. Recently, the local authorities in the UK have started supporting the creation of new multi-storey residential developments within the city centres, which will inevitably lead to creation of deeper street canyons and a reduction of natural ventilation. The inhabitants of these new residences are likely to be subjected to higher pollutant concentrations, and for longer periods than the commuters, who spend more time in the less-polluted suburbs.

Taking into account the growing concerns related to exposure of urban dwellers to air pollution this chapter aims to:

- define a basic outdoor air quality modelling practices used to identify locations where health-based air quality standards might be exceeded;
- classify air quality sampling locations according to characteristics of urban microenvironment;
- analyze sitting consideration for permanent stationary air quality monitoring stations;
- summarize air flow and air pollution patterns in complex built environments and discuss possible implications to building design;
- highlight the main factors influencing penetration of outdoor air pollutants into buildings; and
- highlight pros and cons associated to use of multi zonal and CFD modelling in assessing outdoor-indoor air quality relationships in urban environments.

Note that this chapter is aimed to address the fundamental principles related to the urban indoor/outdoor air quality modelling and monitoring. Specific details of ever changing air quality standards and regulations could be found elsewhere. The UK National Air Quality Archive is recommended as an excellent source of information.

Urban air quality management areas

Local authorities in the UK and throughout the EU are required by law to review and assess air quality in their areas and to identify locations where health-based air quality standards are likely to be exceeded. These responsibilities have been introduced as a consequence of policy developments in late 1990s, notably:

- the EU Framework Directive on Ambient Air Quality Assessment and Management (96/32/EC), which defined the general legislative structure, supplemented by four related daughter directives (1999/30/EC, 2000/69/EC, 2002/3/EC, 2004/107/EC) which define standard air quality thresholds and prescribe minimum requirements for the assessment of air quality levels in urban areas; and
- the UK Environment Act 1995 required the development of a National Air Quality Strategy, which, after consultation, was published in 1997 (revised in 2000, 2002 and 2007), setting challenging health-based targets for eight main air pollutants and laying the foundations of local air quality management.

Local air quality management plays a key practical part in the strategy to achieve air quality objectives in urban areas. Following the first review and assessment of air quality in the UK, almost 130 local authorities have declared Air Quality Management Areas (AQMAs) (Woodfield, Longhurst, Beattie, Chatterton and Laxen, 2006). The designation of an AQMA is a statutory requirement and local authorities are required to identify all areas where the standard air quality thresholds are likely to be exceeded (Table 1.4.1). Note that the objectives defined in the Strategy apply at locations outside buildings or other natural or man-made structures, above or below ground and where members of the public are regularly present and might reasonably be expected to be exposed over the relevant averaging period (Longhurst, Beattie, Chatterton, Hayes, Leksmono and Woodfield, 2006). The assessment of public exposure to air pollution would ideally follow a cohort of representative individuals throughout their day, integrating exposure to chosen pollutants. This should include exposure within the home and place of work or

Table 1.4.1 Air quality objectives for protection of human health in England and Wales (2007).

Pollutant	*Concentration*	*Measured as*
Benzene	5.00 $\mu g\ m^{-3}$	Annual mean
1.3-Butadiene	2.25 $\mu g\ m^{-3}$	Running annual mean
Carbon Monoxide	10.0 $mg\ m^{-3}$	Maximum daily running 8-hour mean
Lead	0.25 $\mu g\ m^{-3}$	Annual mean
Nitrogen Dioxide	200 $\mu g\ m^{-3}$ not to be exceeded more than 18 times a year	1-hour mean
Particles (PM10) (gravimetric)	50 $\mu g\ m^{-3}$, not to be exceeded more than 35 times a year	24-hour mean
Particles (PM2.5) (gravimetric)*	25 $\mu g\ m^{-3}$ (target)	Annual mean
Sulphur Dioxide	266 $\mu g\ m^{-3}$, not to be exceeded more than 35 times a year	15-minute mean
PAH*	0.25 $ng\ m^{-3}$	Annual mean
Ozone*	100 $\mu g\ m^{-3}$ not to be exceeded more than 10 times a year	Daily maximum of running 8-hour mean

* not included in regulations at present

Source: UK National Air Quality Archive

recreation and during travel as well as any exposure within an AQMA. Those at work or in shops within an AQMA will be subject to ventilation with outdoor air and the position of the air intake will have a strong influence on its quality. Those passing through the AQMA on foot or in a vehicle will follow a trajectory in space and time with exposure to a highly variable concentration field. Direct monitoring of individuals using exposure meters is a possibility, but this would be costly and impractical. The alternative is to use an exposure model, which predicts pollutant concentrations in space–time and which could be used to calculate exposure for individuals and cohorts. Many of the large local authorities with considerable air quality problems, such as Glasgow City Council, have adopted this balanced approach, combining air quality monitoring and modelling. It should also be noted that measured concentrations are only available at points in the AQMA, whereas modelled values are available throughout the AQMA.

Air pollution modelling practices – regulatory and research approaches

The most widely used approach to regulatory air quality modelling in urban areas includes the modelling screening tool DMRB and more complex, commercially available packages, such as ADMS-Urban, AEOLIUS and OSPM (Woodfield, Longhurst, Beattie and Laxen, 2003). All these models take into account three different factors:

- the contribution from the pollutant flow from the source to the receptor (a plume model);
- the recirculation component due to vortex formation within an urban street (a simple box model); and
- the urban background contribution.

Although quite advanced, all these models use a number of predetermined parameters in relation to size of the wind vortex within the street, the rate of exchange of pollutants across the boundaries of the recirculation zone and the wind profile above and within urban canopy. However, all three models ignore the effects of junctions and non-flat roofs, leading to the conclusion that they are incapable of describing the microenvironment in urban street canyons.

In the UK, a Technical Guidance Note, LAQM TG (03) was introduced to provide local authorities with advice on air quality management in built areas but both computational fluid dynamics (CFD) and wind tunnel modelling were disregarded as too complex to use, except in very contentious cases. However, this advice is overly pessimistic in our view and through this chapter we set out to demonstrate that modelling can be a very useful addition to the monitoring and management of urban air quality. In the highly complex geometry of city centres, the wind flows are characterized by a multitude of recirculation regions, overlapping with complex wake structures. The fluid motion governing the dispersion process is highly turbulent and influenced by meteorological conditions and local scale effects, and these issues could be better addressed using CFD. In the short term, further development of existing advanced Gaussian based models is worth pursuing. However, in the medium to longer term, there is no doubt that these simpler models will be superseded by CFD models, with their much superior fundamental basis, aided by further developments in computing power.

Air pollution monitoring practices

The present monitoring programmes are usually based on two main systems:

- a relatively small number of continuous monitors at fixed sites, located away from the roadside, which give instantaneous background values and can identify pollution episodes; and
- a rather larger number of diffusion tube samplers which give a crude average exposure.

LOCATION: St. Enoch Square	DISTANCE FROM THE ROAD: 10m
TYPE: urban centre	TRAFFIC FLOW: 20,000 vehicles/day
	DESCRIPTION: pedestrian area of the city centre; the surrounding area is open with city centre business and retail premises surrounding the site from three sides; the monitoring station has been operational since 1996; monitored pollutants: O_3, CO, SO_2, PM_{10}, and NO_x.
LOCATION: City Chambers	DISTANCE FROM THE ROAD: 2m
TYPE: urban background 	TRAFFIC FLOW: 12,000 vehicles/day DESCRIPTION: the monitoring station is located on the second floor to the rear of the City Chambers building, at the junction of Montrose Street and Cochrane Street; both streets are subject to frequent congestion; the manifold inlet is approximately 20 metres above ground level; the surrounding area is urban and comprises street canyons with retail and business outlets; the monitoring station has been operational since 1987; monitored pollutants: CO, NO_x.
LOCATION: Hope Street	DISTANCE FROM THE ROAD: 1m
TYPE: urban kerbside	TRAFFIC FLOW: 25,000 vehicles/day
	DESCRIPTION: the nearest road is subject to frequent congestion during peak traffic flow periods; the manifold inlet is at a height of three metres above ground level; the surrounding area is adjacent to the junction and has a more open aspect than previously mentioned sites; the monitoring station has been operational since 1997; monitored pollutants: CO, PM_{10} and NO_x

Figure 1.4.1 Summary of the main characteristics of permanent air quality monitoring station.

However, intensive kerbside research studies have shown that the pollution levels experienced by pedestrians might be 2 to 3 times greater than background concentrations and that the pollution climate varies enormously in space and time and with meteorological conditions (Hassan and Crowther, 1998). Therefore, the questions of network design and the location of monitoring stations are very important, due to the cost as well as the representativeness of the chosen location. General guidance for monitoring network design is given by the European Commission, and for an AQMA like Glasgow, three sampling points for continuous measurement are required to assess compliance with limit values for the protection of human health (Figure 1.4.1).

In general, the following types of air quality sampling locations are characteristic of urban micro-environments:

- urban kerbside (sites with sample inlets within 1m of the edge of a busy road and sampling heights between 2 and 3m);
- urban centre (non-kerbside sites located in an area representative of typical population exposure in town or city centre areas, e.g. pedestrian precincts and shopping areas; with sampling heights typically between 2 and 3m); and
- urban background (urban locations distanced from sources and broadly representative of city-wide background concentrations, e.g. elevated locations, parks and urban residential areas).

Taking into account the large size of the designated air quality management area in cities such as Glasgow, an additional monitoring campaign could be carried out using an environmental monitoring trailer (Figure 1.4.2). The trailer used by one of the authors of this chapter was equipped, for example, with instruments for the continuous monitoring of carbon monoxide (Gas Filter Correlation CO Analyser, API model 300), oxides of nitrogen (API Model 200A chemiluminescent $NO/NO_2/NO_x$ analyser) and PM10 (TEOM Series 1400a, Rupprecht & Patashnick Co.). In addition to air quality monitoring equipment, the trailer was equipped with an anemometer providing an indication of wind speeds within the street canyons. In these cases, twenty-four hourly samples are usually collected daily during the four-week period at each of the chosen monitoring sites. The locations should be carefully chosen according to traffic

Figure 1.4.2 Mobile air pollution station.

flow data in order to give more detailed information on local pollution level differences within street canyons in a designated AQMA.

Different siting considerations for permanent air quality monitoring stations

Taking into account the capital and operating costs of permanent air quality monitoring stations, it is of paramount importance to determine their best location. The different siting considerations for the permanent air quality monitoring stations were discussed in two comprehensive monitoring studies carried out in central areas of London and Paris. The first study was carried at the Bartlett (Croxford and Penn, 1998) and provided an insight into both temporal and spatial variations of carbon monoxide distribution in the Bloomsbury area of central London. The area was largely homogeneous in terms of building height, with most streets having a canyon type profile with an aspect ratio (height to width) ranging from 0.7 to 1.7. All the measurement points were at the same height (2m) and as far from any street junction as possible. Radical variations were observed between monitors located at sites within a few metres of one another, prompting a simple protocol on positioning of air quality monitoring equipment within urban areas. The second study (Vardoulakis, Gonzalez-Flesca, Fisher and Pericleous, 2005) detected the strong spatial and temporal variability of traffic-related air pollution in the vicinity of a permanent monitoring station in central Paris. Diffusive BTX samplers were exposed to ambient air for 28 consecutive 7-day periods, placed at 2.6-metre intervals at the 10 roadside locations (horizontally and vertically). Comparing with additional data from the permanent air quality monitoring station, it was concluded that the measurements from this site do not give a representative picture of air quality in the surrounding area and are, therefore, inappropriate for population exposure studies.

Using both monitoring and modelling it has been shown (Mumovic et al., 2006) that the dispersion of air pollutants within street canyons is controlled primarily by the micro-meteorological effects of urban geometry. Therefore, when discussing different sitting considerations for the permanent air quality monitoring stations, one should address the issue of local concentration gradients within urban street canyons. Although not a perfect tool, that study has certainly shown that CFD may help to resolve a number of questions related to local concentration gradients in complex-built environments. The study concluded with a call for the use of CFD in decisions relating to the positioning of permanent air quality monitoring stations within urban areas where the costs justify the approach advocated that practicality and local turbulence also have to be considered when deciding if a location is suitable for air quality monitoring. By satisfying the following requirements one can determine an appropriate location for positioning of air monitoring equipment (Figure 1.4.3):

- analysis of local concentration gradients;
- practicality of the location in the real physical domain; and
- turbulence intensity at the chosen location.

Siting monitoring equipment in this way will allow a more meaningful comparison between different sites in AQMAs and between modelled and measured concentrations. The adoption of this approach will tend to avoid the pollution hot spots, which are often close to areas of high concentration gradient. However, the exposure of individuals moving through an AQMA will be averaged over position and time, yielding a value between urban background and the hot spot values. When comparing the numerical modelling results and field measurements in urban street canyons, it has to be recognized that the controlled approach flow conditions assumed in that study, and to some extent simplified geometry tend to provide modelled flows with strong wind speed and concentration gradients. However, the wind flow disturbances in a real complex configuration of street canyons, caused by observed large variation of instantaneous wind direction and speed, might have a smoothing effect on the flow irregularities.

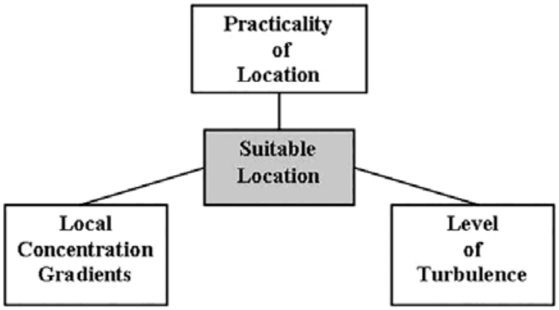

Figure 1.4.3 Different factors which have to be included when positioning air quality monitoring equipment in urban street canyons.

Therefore, a smaller spatial variability of mean flow, turbulence field, and consequently of pollutant concentration may be observed if measured within a real urban built environment.

Air flow and concentration patterns in complex-built environments

To address this issue the distribution of air pollutants has been analyzed using the developed integrated air quality model of Glasgow's AQMA. Figure 1.4.4 illustrates the distribution of carbon monoxide within the designated AQMA in the City Centre of Glasgow. The results are obtained at the height of 1.75 metres, assuming that the prevailing wind is a westerly, blowing at 6 m/s. For the purpose of this study, the numerical modelling was done for two prevailing wind directions, and five different wind speeds, as follows: (a) wind speed: 2, 5, 6, 11 m/s; (b) wind direction: westerly and south-westerly. The wind velocity vectors are representative of the meteorological patterns observed in the area. The aspect ratio of street canyons in the computational domain varies from 0.8 to 1.1. Note that the results of the analysis of local concentration gradients have been generalized.
Qualitatively, the results are very similar to those obtained in wind tunnel experiments:

- lower concentration at the windward-facing side of street canyons which are almost perpendicular to the wind direction;
- higher concentration at the leeward-facing side of street canyons which are almost perpendicular to the wind direction; and
- wash-out and accumulation effects along those canyons whose axes are parallel to the wind direction.

In addition, comparison of the distribution of the pollutant for the same wind direction, but different wind speeds: 2 m/s, 5 m/s and 11 m/s shows that considerable differences can be observed in concentration values:

- during low wind periods the convective transport of the pollutant is greatly reduced, causing higher concentration at the very lower levels of street canyons; and
- during periods of very high wind speed, the wash-out effect increasing significantly, generally lowering the concentration levels within the city centre.

Analysing the flow field patterns, it has been showed that flow within the streets is the vector sum of a channelling and a recirculation vortex and that a relatively short distance from an intersection the flow

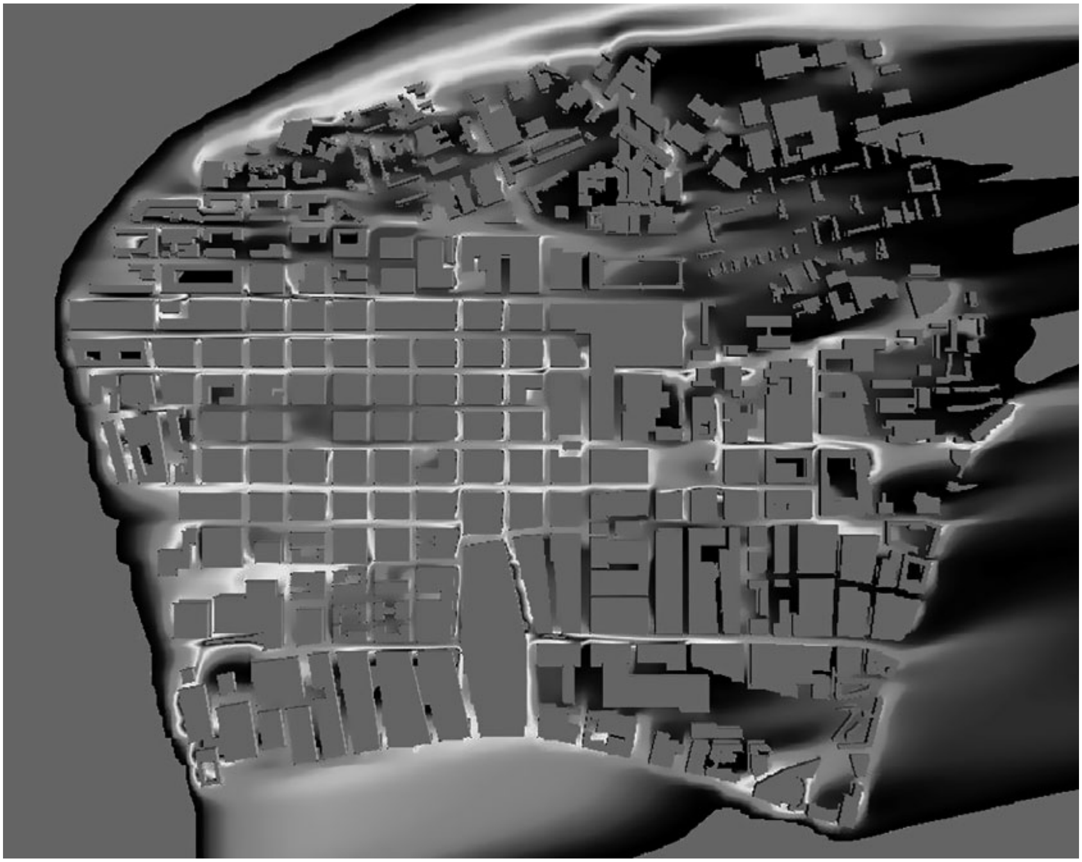

Figure 1.4.4 Distribution of CO in the air quality management area – Glasgow city centre.

seems to be characterized by the main large-scale features – along street channelling and an across-street recirculation vortex. This is in agreement with comprehensive flow field measurements carried out in the proximity of an urban intersection in London (Dobre et al., 2005). Furthermore, the model observations show that centrally located vortices are not formed when the wind is incident obliquely to the street canyon axis (south-westerly wind) and the wind speed is lower than 6 m/s. However, due to elevated kinetic energy when the wind speed is set to 11 m/s, the expected centrally located vortex has been formed. As in the previous cases, it has been shown that increased levels of pollution occur near the leeward-facing side but, when the wind speed is very low, and the wind direction is oblique to the axis, it can be observed that the large local concentration gradients exist only at the bottom of the street canyon. Furthermore, it is observed that for low wind speeds, the change of vertical concentration gradients tends to be very small, preventing the pollutant from dispersing all over the cross-section of street canyon. In contrast to this, the very high wind speed of 11 m/s increases the natural ventilation, especially in the case of the oblique wind direction. In relatively long canyons without connecting streets, field measurements have shown that maximum street-level concentrations are more likely to occur when the synoptic wind is parallel to the street axis. The summary of the results is given in Table 1.4.2.

Finally, an analysis of local concentration gradients with street canyons will be described, assuming that the observed cross sections are located away from crossroads and that the height of buildings on both sides of the analysed canyons is the same. Note that this problem has been thoroughly researched over

Table 1.4.2 Assessment of local concentration gradients.

Wind incident	*Local concentration gradients*	
	Small	*Large/medium*
Perpendicular	upper leeward side vortex centre lower windward side	lower leeward side (large) bottom of the canyon (large)
Oblique	upper leeward side vortex centre lower windward side	lower leeward side (medium) bottom of the canyon (medium)

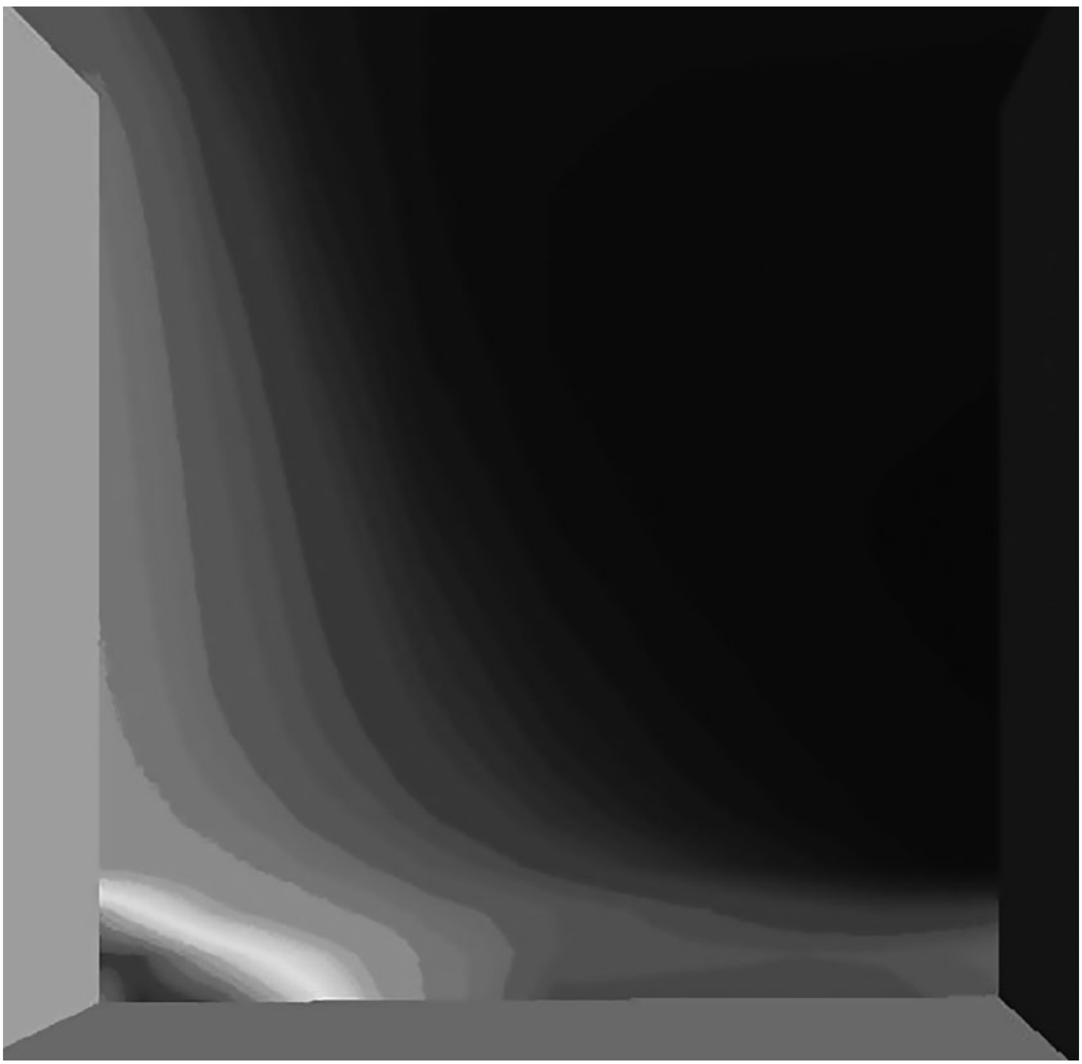

Figure 1.4.5 A typical distribution of CO within Glasgow's street canyons for perpendicular wind incidents.

the last ten years but never before using a realistic CFD model of an actual AQMA. A number of street canyons have been analysed and a typical distribution of carbon monoxide within a canyon is shown in Figure 1.4.5.

It seems that very steep concentration gradients exist at the leeward lower corner of the street canyon. Consequently, small differences in monitoring station positioning may yield significant variations of measured mean concentration, due to large values of horizontal, $\partial C/\partial x$, and vertical, $\partial C/\partial y$, local concentration gradients. These results have significant implications for positioning of monitoring equipment, not just in street canyons, but probably in wind tunnel experiments as well. Generally speaking, it suggests that monitoring stations should not be positioned at the lower leeward-facing side of a street canyon. By contrast, one can observe relatively smooth concentration gradients at the windward-facing side, at the upper leeward side of street canyon, and possibly in the central part of a vertical cross section of the street canyon. These figures clearly show the formation of three regions of relatively smooth concentration gradients, as was observed in the previous sections:

- in the vicinity of the vortex centre;
- in the lower corner of the windward-facing wall; and
- in the upper part of the leeward-facing wall.

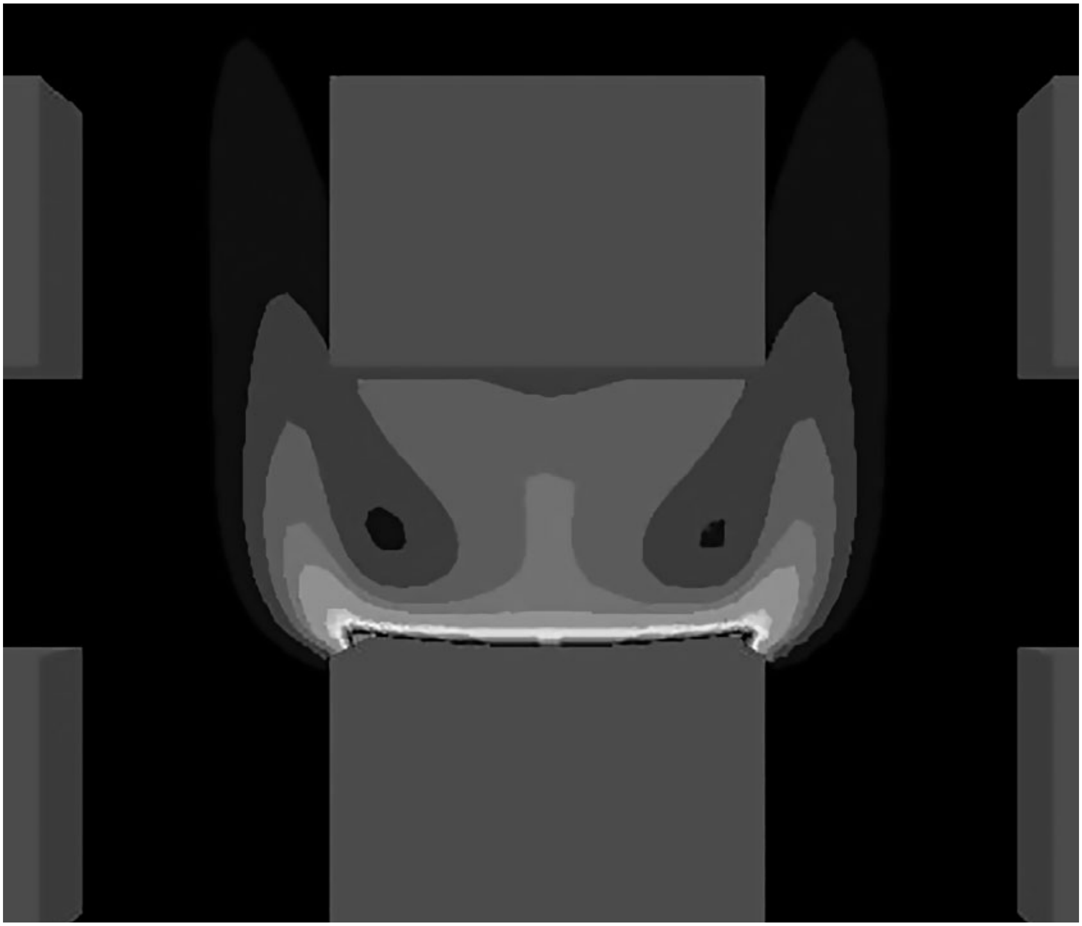

Figure 1.4.6 Examining the effect of crossroads: the source was placed at leeward side of the studied street canyon.

The effect of crossroads on horizontal local concentration gradients is shown in Figure 1.4.6. Note that the source of pollution was placed at the leeward side of the studied street canyon. This was done in order to compare the modelling results with available experimental results. However, the formation of the vortices and consequently the prediction of pollutant concentrations in street canyons are subject to considerable uncertainty. It has to be stressed that the mentioned local wind field within the canyon is unlikely to occur if the wind direction changes rapidly in time. Note that the developed integrated air quality model does not take into account differential across-road traffic count.

Relationships between outdoor and indoor air pollution

In the absence of indoor sources, indoor air pollutant concentrations are generally lower than outdoors due to attenuation by the building. However, in the presence of indoor sources, indoor concentrations may well exceed the local outdoor levels. People who live and work close to busy streets in urban areas may experience a large part of their total exposure to air pollution while indoors. As such, it is vitally important that this contribution to overall exposure is properly understood. Unfortunately, most research on urban air pollution has focussed only on outdoor air with far less work considering exposure in the indoor environment.

Penetration of pollutants into urban buildings

In urban areas, a significant proportion of indoor air pollution can be due to penetration through the building façade of pollutants generated outdoors. Pollutant levels within a building, resulting from outdoor sources, depend on:

- complex dispersion processes around the building (as discussed elsewhere in this chapter);
- the ventilation strategy of the building (i.e. natural or mechanical);
- the locations of air intakes (for mechanically ventilated buildings);
- the airtightness of the building (affecting the rate of infiltration); and
- the specific pollutant and its physical and chemical properties.

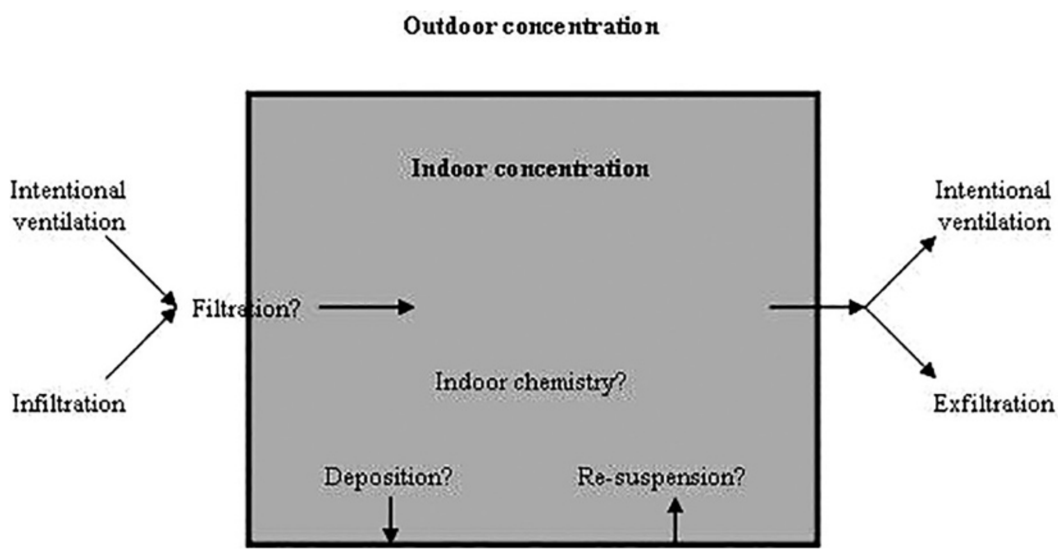

Figure 1.4.7 Factors determining indoor air pollution concentrations.

Other environmental parameters, such as the local meteorology, also play important roles in influencing indoor pollution concentrations in indirect ways. Once indoors, the concentration may be decreased by indoor chemical reactions, by deposition onto indoor surfaces and through ventilation back to the outdoors (Figure 1.4.7). Although indoor sources (especially cooking and smoking activity) should be taken into account, these are out of the scope of this chapter.

A key distinction is between long-range and short-range sources of air pollution. For far-off releases (say, more than 500m away), the concentration in the envelope surrounding the building may be assumed to be relatively constant due to vertical and lateral spreading of the plume. However, for closer releases (less than 500m) the outdoor concentration close to the building may not be assumed to be constant. For such sources, concentrations are usually high at short ranges and vary considerably over the surface of the building, fluctuating over time periods as short as seconds.

Peak penetration of pollutants into buildings occurs at points of both high pressure and high contaminant concentration, the patterns of both of which can become extremely complex in urban areas due to the close proximity and configuration of surrounding buildings (Kukadia, Hall and Sharples, 1999). It is, thus, also true that internal concentrations in an urban building close to busy roads can be highly spatially and temporally variable. Both indoor and outdoor concentrations measured at single, fixed locations may not be sufficiently representative of the overall distribution of concentrations and the actual exposure experienced by the occupants of the building (Milner, Dimitroulopoulou and ApSimon, 2006b).

Simultaneous indoor and outdoor measurements

The relationship between the indoor (I) and outdoor (O) air pollution level for a building at a given time is usually expressed in terms of the I/O ratio. The I/O ratio gives an indication of the protective effect of a building for a given pollutant. However, I/O ratios are affected by many factors, such as ventilation rates and the local meteorology. In fact, I/O ratios have been shown to vary greatly, even for an individual building.

Since monitoring work can be technically difficult and expensive, it is often not practical to sample in multiple locations. For single or relatively few sampling locations, it is therefore important to give careful consideration to the siting of equipment. The aim is to find a location that is as representative of the exposure of building occupants as possible. Depending on the situation, this is likely to be in the centre of the room, at head height of a seated adult and away from internal pollution sources (unless the source is of particular interest). In reality, it is often necessary to compromise when choosing a suitable location.

Ideally, multiple measurement locations will give a clearer picture. An example of this is provided by Milner, ApSimon and Croxford (2006a) who monitored carbon monoxide (CO) concentrations in different locations within an office building in central London and at an external location close to the building. The building was flanked by two heavily trafficked streets and two quiet streets. In general, the data suggested that:

- Indoor CO concentrations were greater on the lower floors of the building (Figure 1.4.8);
- Indoor CO concentrations on the same floors were greater closer to the busier roads; and
- Correlation between the outdoor and indoor data decreased within the building with distance from the outdoor site and were found to improve with introduction of a time lag.

These findings imply that the protection offered by the building shell may be increased further away from the busiest roads. For this particular building, the highest I/O ratios were observed for north-westerly winds, although the highest internal and external concentrations were for south-easterly winds. This suggests that a higher rate of penetration of low ambient concentrations occurred during north-westerly winds and demonstrates how complex the situation may be in an urban setting.

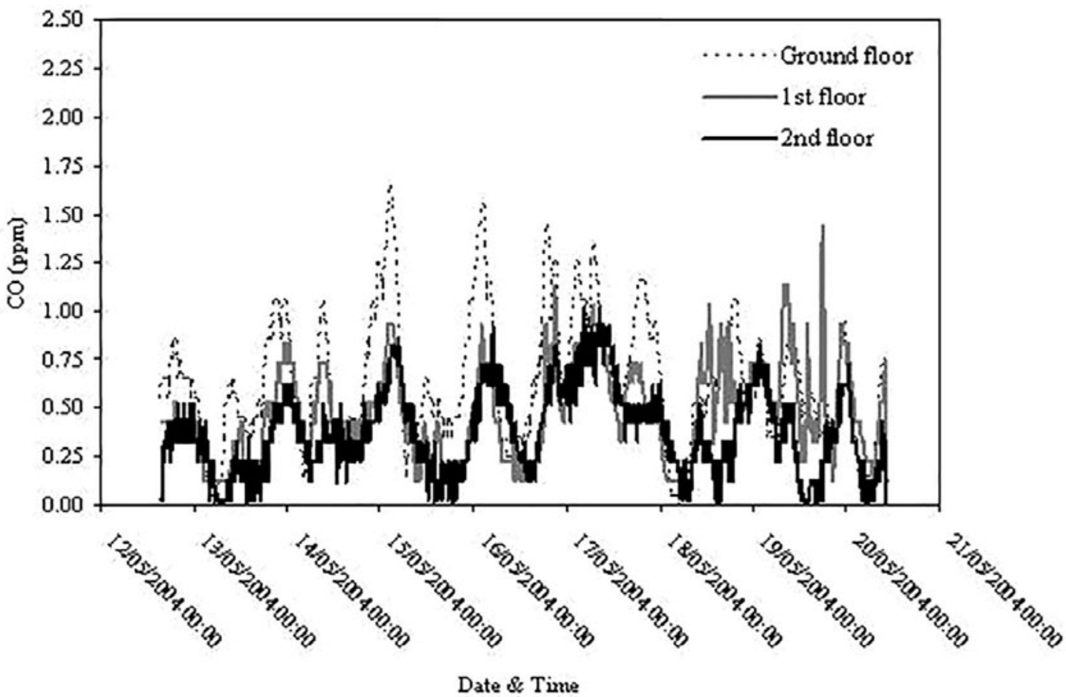

Figure 1.4.8 15-minute average CO concentrations on different floors of an office building in central London.

Table 1.4.3 COMEAP recommended indoor air quality guidelines for NO_2 and CO.

Pollutant	*Averaging period*				
	Annual	*8 hour*	*1 hour*	*30 minutes*	*15 minutes*
NO_2	20ppb ($40\mu g/m^3$)		150ppb ($300\mu g/m^3$)		
CO		90ppm ($100mg/m^3$)	50ppm ($60mg/m^3$)	25ppm ($30mg/m^3$)	90ppm ($100mg/m^3$)

Differences in I/O ratios for a particular building will also occur depending upon the type of pollutant. The I/O ratios of three of the most common indoor pollutants resulting for outdoor sources will now be discussed in more detail: particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2) and carbon monoxide (CO). These pollutants (among others) were considered for guideline limits in indoor air by the UK Department of Health (COMEAP, 2004). However, the committee decided it was not currently feasible to define a satisfactory guideline for indoor particle concentrations. The guidelines for NO_2 and CO are shown in Table 1.4.3.

Particulate matter

The results of a US Environmental Protection Agency project, the Particle Total Exposure Assessment Methodology Study (PTEAM) (e.g. Özkaynak, Xue, Spengler, Wallace, Pellizzari and Jenkins, 1996), suggest that transport from outdoors to indoors is the primary source of particles in the indoor environment.

In general, most studies find that, under normal ventilation conditions and in the absence of indoor sources, indoor particle concentrations follow closely the concentrations outdoors, with indoor levels lower than outdoors. However, great variations in I/O ratios for particulate matter are reported in the literature. For particles, predicting indoor levels based on observed outdoor concentrations is complicated by the sizes of the particles, since the penetration and deposition rates of smaller and larger particles will vary.

Nitrogen dioxide

Indoor NO_2 is more greatly influenced by indoor sources than either CO or particulate matter. Sources of NO_2, such as gas cookers, lead to considerably raised indoors levels and also to increased variation in these levels. However, when no internal sources are present, indoor NO_2 is usually below ambient levels due to chemical reactions and deposition on internal surfaces. Due to the importance of internal sources on indoor levels, contributions from outdoor sources will clearly be relatively less important for NO_2.

Carbon monoxide

As a non-reactive pollutant, of which more than 85% in the atmosphere is traffic-related, indoor CO concentrations have been shown to follow outdoor levels closely, especially near busy roads (see, for instance, Chaloulakou, Mavroidis and Duci, 2003). Theoretically, pollutants that are non-reactive with little or no filtration and negligible deposition, such as CO, should have an I/O ratio close to 1 in the absence of indoor sources. The only occasion in which indoor concentrations of CO may become higher than outdoors is following a concentration peak, since the indoor gas is enclosed and, hence, has a longer residence time. However, indoor sources (such as faulty gas appliances) can lead to potentially dangerous levels of CO in buildings.

Modelling air pollution in urban buildings

Both monitoring work and physical (wind tunnel) modelling may be difficult, costly and time consuming. Furthermore, the results may only be valid for the specific conditions in which the experiment was carried out. So, monitoring studies report a wide range of indoor concentrations and I/O ratios due to the complexity of indoor-outdoor transport, indoor sources and the wide range of variable parameters that may have an effect.

As such, there are two modelling techniques that are commonly used for predicting indoor air pollution concentrations from outdoor sources: mass-balance modelling and CFD modelling. The former is relatively simple to apply but have the important disadvantage that they assume spatially uniform external and internal concentrations, while the latter are highly complex and used primarily as research tools.

Mass-balance models

Mass-balance models, which may be sub-divided into microenvironmental models and more complex multizone models, are used to simulate average indoor air pollutant concentrations as a function of outdoor concentrations, building and pollutant characteristics and indoor sources. These models consider transport of air pollutants between outdoors and indoors, as well as between indoor compartments, which are assumed to be instantaneously well-mixed. They are widely used due to the simplicity of the mathematics involved. The concentration within a compartment at steady state, C, is usually written as an ordinary differential equation, such as:

$$\frac{dC}{dt} = S - LC$$

where S is the sum of all sources and L is the sum of all sinks in the compartment. The above equation may include further parameters, such as a deposition loss rate (if the pollutant readily deposits), a filtration factor (to account for losses in the building shell) or a mixing factor (to approximate the proportion of the indoor space that is well-mixed). For an example of mass-balance modelling, see Dimitroulopoulou, Ashmore, Hill, Byrne and Kinnersley (2006), which describes the application of the INDAIR model to studying indoor air pollution in UK homes.

The main strength of these models is the simulation of air pollutant concentrations that may be well compared with results from experimental measurements. Mass-balance models can be used to identify the key building factors that influence indoor concentrations of air pollutants and to estimate the relative importance of different pollutant sources. In this way, mass-balance models, in conjunction with exposure models, can relatively quickly evaluate the potential benefits of measures to reduce indoor air pollutant levels and the implications of policy decisions on population exposure.

Mass-balance models also have some significant limitations, the most important of which are the assumption of a spatially uniform concentration outside the building and the internal well-mixed assumption. As discussed previously, the concentration in the envelope surrounding an urban building may be extremely variable, especially due to sources close to the building. Using a single value to represent the outdoor concentration at a given time may lead to serious inaccuracies in the results produced. The use of internal well-mixed zones is only generally appropriate for average-sized residential buildings since intra-room mixing is usually orders of magnitude faster than inter-room exchange and physical walls act as partitions. However, in very large rooms with localized ventilation and/or many internal source locations, a significant spatial concentration gradient may persist, and a single, well-mixed compartment may be inappropriate to represent the room.

CFD models

CFD modelling takes a microscopic view by simulating the detailed air flows and concentration distributions within a room or between rooms. Although these techniques have been used in this context since the 1970s (e.g. Nielsen, 1973), most whole-building analysis currently relies on multizone mass-balance modelling. Despite this, the rapid development of computational speed and power over recent years has led to growing popularity of CFD methods.

CFD models have been applied extensively to simulate pollutant dispersion in urban areas and in indoor spaces. Given the highly variable nature of urban air pollution, to model accurately indoor air pollution due to external sources it is first important to model the external concentration pattern. As discussed earlier in this chapter, CFD is well suited for this, while operational street canyon models such as those described in section 2.1 have considerable limitations (e.g. see Vardoulakis, Valiantis, Milner and ApSimon, 2007) and cannot sufficiently account for variability in external air pollution close to buildings. However, most CFD studies of indoor airflow and pollutant transport concentrate only on the indoor environment and not on the transport of pollutants from outdoors to indoors. Much further research is needed in the area of combining indoor and outdoor CFD modelling (Figure 1.4.9). Combined indoor and outdoor CFD modelling has rarely been performed and only then for natural ventilation modelling rather than contaminant transport. In one of the few published examples, Jiang, Alexander, Jenkins, Arthur and Chen (2003) compared CFD simulations with and wind tunnel data for three ventilation strategies and found that the numerical results were in good agreement with the experimental data.

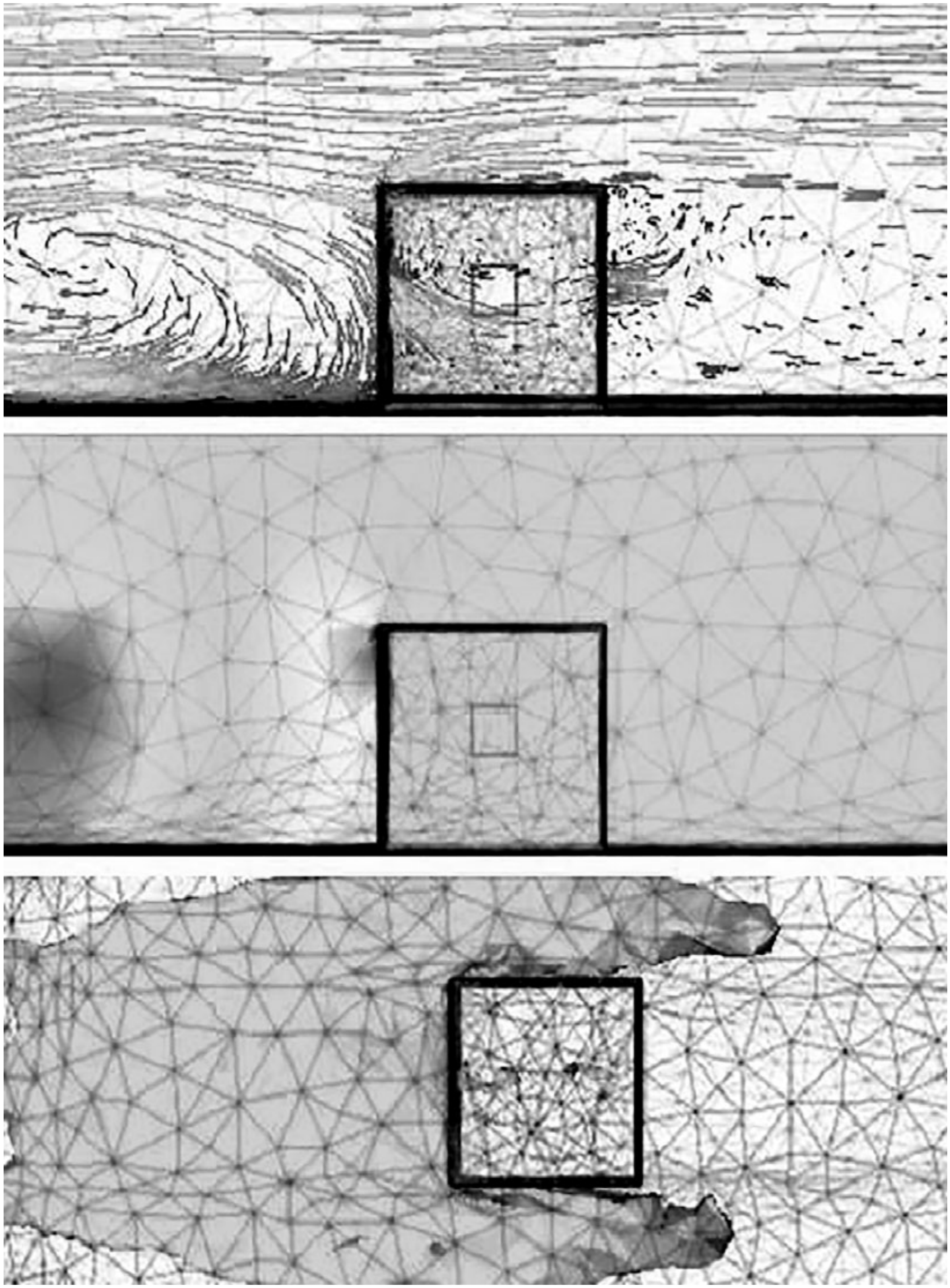

Figure 1.4.9 Example visualizations of combined indoor and outdoor CFD modelling (taken from Milner, ApSimon and Pain, 2005). Shown are flowvectors (top), pressure distribution (middle) and plan view of constant pollution concentration 'iso-surface' (bottom).

In contrast to mass-balance models, CFD simulations are highly specific and complex to use, requiring powerful computers and lengthy run times. As such, the method is currently used primarily as a research tool. Although the complexity of CFD models can be problematic, the technique allows the model user control of far more parameters and variables, as well as providing a quantitative description of the situation that the user may visualize. As computational power increases, CFD has the potential to become a viable alternative to wind tunnel methods for modelling both outdoor and indoor air pollution.

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PART 2

Energy and buildings

Introduction

Dejan Mumovic and Mat Santamouris

Chapter 2.1 gives an overview of building physics and highlights the importance of energy saving houses to sustainable building engineering and design. Several forms of energy saving buildings, such as low-energy houses, three-litre houses, passive houses, zero-energy houses, energy self-sufficient houses, plus-energy houses have been defined.

Chapter 2.2 defines various energy rating indexes (operational rating, calculated rating, design rating, asset rating and tailored rating) used for the assessment and prediction of energy use in buildings and describes both heating and cooling energy monitoring procedures. In the Chapter 2.3, we define energy modelling as the key element of the broader discipline called building simulation, a domain that, apart from thermal aspects, also studies (day)lighting, moisture, acoustics, air flow and indoor air quality. After an overview of various aspects of energy modelling, the need for full co-disciplinary energy modelling, allowing HVAC system experts, control system developers, architectural designers to add model components to a shared multi-domain responsive energy model during full concurrent real time collaborative design of all the systems has been highlighted. Implementing energy modelling through the use of computational simulation tools for the demonstration of compliance with building energy performance regulations, the issuing of energy certification and assessment of sustainability ratings is collectively often referred to as 'compliance modelling'. Taking into account raising importance of the compliance modelling we provide detailed background and context in the Chapter 2.4.

Chapter 2.5, in a straightforward, no-nonsense way, describes various strategies in which the energy consumption of buildings can be reduced at design stage. This chapter discusses the ways to reduce energy for heating (i.e. optimize the building envelope), reduce energy for cooling (i.e. optimize the use of natural climate features), reduce energy for lighting (i.e. integrate daylight with artificial light), reduce energy for equipment/ processes and investigate the use of renewable and integrated energy sources.

There are many technologies used by buildings to help provide thermally and visually comfortable indoor environments using ventilation, heating, cooling, and artificial lighting services. Rather than listing a large number of technologies and discussing their relative merits, Chapter 2.6 offers a more structured approach and asks two fundamental questions: what are environmental technologies and why they are necessary?

At the end, Chapter 2.7 explains that the life cycle of a building as well as of other systems (processes, services, etc.) follows like the life time of biological organisms a circle. In the same way that the biological organisms originate, reproduce and finally die, the buildings are constructed, used and finally demolished and disposed. This chapter critically discussed both positive and negative aspects of life cycle assessment

(LCA) of buildings including the most important one – the LCA cannot take into account or predict future changes in the current technology or demand.

Last but not least, at the end of Part 2 of the book we have included three case studies:

- Case Study 2A: Energy and environmental monitoring. The aim of this chapter is to guide researchers along a practical methodology for energy and environmental monitoring studies both to address fully the specific research questions under investigation and underpinned by benchmark methods, and to recognise the potential for wider supplementary research that can add considerable value to the original monitoring study. The topics are illustrated via a case study of 29 dwellings in Milton Keynes (UK).
- Case Study 2B: Energy modelling – Building stock modelling. There are two principal approaches that can be used to forecast the energy use and CO_2 emissions of a particular sector of the economy, namely: 'top-down' or 'bottom-up'. The aim of this case study is to describe in detail the development of DECARB, a physically based model of the UK housing stock that is capable of forecasting the energy use and CO_2 emissions attributable to this sector, under a range of possible futures.
- Case Study 2C: Retrofitting to near Passivhaus standard. This 'story telling' case study describes a general approach taken by the team to retrofit a house near Passivhaus standard, including insulation of the external envelope to Passivhaus standard; reduction of the infiltration rate to as near Passivhaus standard as possible; and installing suitable low carbon systems to provide heating and hot water with an aim to achieve an overall energy consumption reduction of 80% compared to an estimate for the original house. This is not a traditional book chapter; instead it provides very practical insight and solutions of importance to practitioners.

2.1
ENERGY EFFICIENCY AND THERMAL ENVELOPE

Anna Mavrogianni, Jurij Krope, Darko Goričanec and Hector Altamirano-Medina

Building envelope design as a response to environmental factors

> "A great building must begin with the unmeasurable, must go through measurable means when it is being designed and, in the end, must be unmeasurable."
>
> Louis Kahn

> "If you cannot measure it, you cannot improve it."
>
> Sir William Thomson, Lord Kelvin

Since the advent of human civilisation, the medium of architecture has served a multitude of functions, both pragmatic and hedonic. By configuring physical materials and bounding space, the process of architectural synthesis encompasses a wide range of inextricably linked environmental, functional, technical, economic, sociocultural, physiological, psychological, aesthetic, symbolic and spiritual considerations. Some examples of such closely intertwined, yet often conflicting, requirements are:

- sheltering against the external climate;
- privacy and security against outsiders;
- durability and structural integrity;
- indoor environmental quality, which includes hygrothermal, visual and acoustic comfort aspects, as well as the provision of fresh, clean air;
- ergonomically functional spaces and furnishings;
- aesthetic delight; and
- symbolism, representation and communication of meaning.

One of the main functions of the building envelope is, thus, to act as a *filter between the external and the internal environment*. If clothing is our 'second skin', buildings are considered our '*third skin*'. The building envelope operates as *a modifier of exposure* to the external climate, and associated health and safety risks. It should simultaneously be permeable to light and fresh air and able to 'breathe'. The construction of building envelopes and their operation with the aim to optimise indoor environmental conditions require the utilisation of energy, materials and other natural resources. In other words, "*the dream of architecture, among other things, is to escape entropy*" (Bois and Krauss, 1997).

In traditional architecture, where energy and resources were often scarce, their use was judicious. Building envelopes were shaped to maximise the use of solar energy and natural materials. As a result, they were highly responsive to local climatic conditions. They were also intrinsically tied to a specific place, a literal product of their surroundings. However, following the Industrial Revolution at the end of the eighteenth century, architecture became increasingly reliant on the consumption of fossil fuels. This engendered a shift toward engineered and highly controlled indoor environments provided by auxiliary, mechanical means (Hopkins, 1998). As a consequence, the link between building envelope and place weakened. This shift was not devoid of adverse impacts. Chief among these was the creation of energy-hungry buildings with large ecological footprints and side-effects on the indoor environment, such as Sick Building Syndrome (Tong and Leaman, 1993).

The oil crises of the 1970s, followed by increased awareness about climate change, energy security and the depletion of finite natural resources in the years that followed were instrumental in making built environment professionals (re)adopt a holistic approach toward building design and construction with an emphasis on *total building performance*. Pivotal to this goal is the shift to a new paradigm of *passive* buildings, i.e. buildings that do not rely on the burning of fossil fuels to meet their energy demands.

It is estimated that residential and commercial buildings in the US and the UK consume 40% of total national energy use (approximately 50% of which is consumed for space conditioning) and generate around 40% of CO_2 emissions (DoE EERE, 2012; CCC, 2013). The emergent need to mitigate and adapt to climate change generates creative tensions and opportunities for built environment professionals. Energy efficient buildings are now reprioritised, and more weight is given to the interactions between location, external climate, form, materials, the building envelope and the systems and controls for space and water heating, cooling and ventilation. This new paradigm lends itself to the creation of platforms to enable interdisciplinary cooperation between architects, engineers, builders and building inhabitants within all stages of a building's construction.

This chapter will first briefly investigate the various ways in which energy is consumed during a building's lifetime. It will then go on to examine the energy and mass exchange processes occurring between the building envelope and its surroundings. Following this, it will explore design principles that could help reduce the energy use of a building through the optimisation of its form and materials. Last, different types of low energy buildings will be described.

Energy use in buildings

Based on the point in time it occurs during a building's lifetime, building energy use is classified into the following categories:

- *Initial embodied energy* comprises the energy utilised during the *construction phase* of a building. It involves energy consumed during the extraction and processing of materials, the manufacture of construction components, and finally their transportation and assembly on the construction site.
- *Operational energy* is the total amount of energy required during the in-use phase of a building's lifetime to maintain a functional and comfortable indoor environment through the operation of any active, i.e. fossil fuel-powered systems, such as space and water heating, cooling, ventilation, lighting, cooking and any other electrical appliances and equipment.
- *Maintenance energy* is the energy required to maintain the building, including the replacement of individual system components, e.g. heating system, and refurbishment of the building envelope, e.g. plastering, addition of insulation.
- *Demolition energy* is the energy consumed to dismantle, demolish and dispose the components of a building during the *post-use* phase of its lifetime.

The relative magnitude of each energy use component varies with location and construction practices. The main focus of current energy saving, and carbon reduction regulations and initiatives is on operational energy use. Figure 2.1.1 below illustrates the average breakdown of energy end-uses in typical UK and US dwellings. Space conditioning (heating and cooling) is currently the main consumer of energy. As building fabrics become increasingly insulated and airtight, this component is expected to be minimised in the future. As a result, other end-uses such as water heating, cooking and use of appliances, which are highly dependent on occupant behaviour, are expected to become more prominent (EIA, 2010).

However, the reduction of a building's environmental impact should not be limited to measures that decrease its operational energy use. It is essential that the energy consumed throughout the entire lifetime of a building, i.e. *from cradle to grave* (McDonough and Braungart, 2002), should be examined. Table 2.1.1 below presents the embodied energy and carbon coefficients for commonly used building materials.

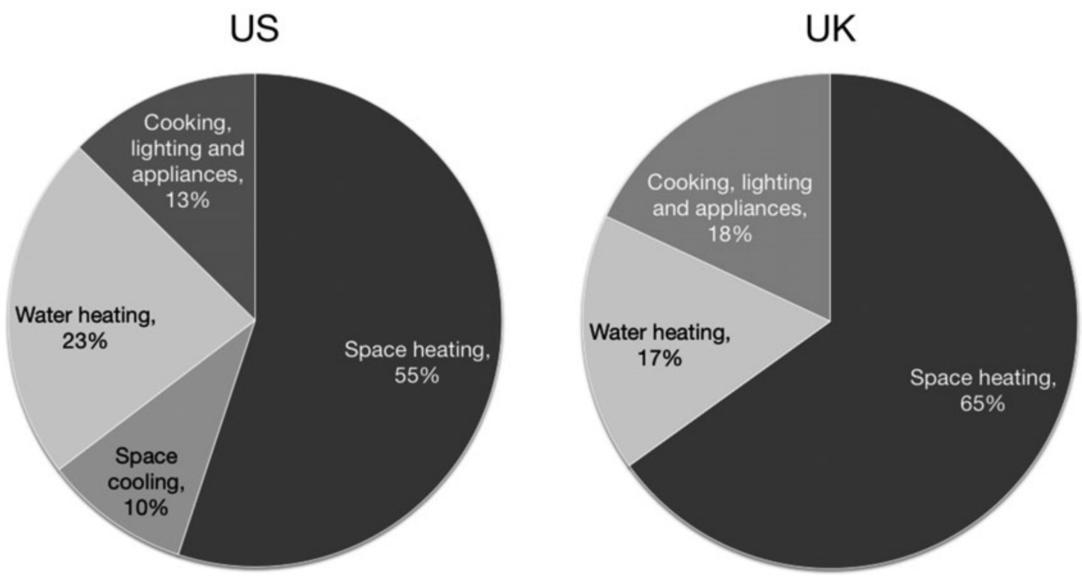

Figure 2.1.1 Energy consumption in a typical home in the UK and US broken down by end-use.

Source: DECC, IEA

Table 2.1.1 Embodied energy and carbon coefficients for typical building construction materials.

Material	*Embodied energy (MJ/kg)*	*Embodied carbon (kC/kg)*
Bricks	3.00	0.060
Cement	4.60 ± 2.00	0.226
Concrete	0.95	0.035
Glass	15.00	0.232
Steel	24.40	0.482
Timber	8.50	0.125

Source: Hammond and Jones, 2008

Arguably, the embodied, maintenance and demolition energy consist significant components of the overall energy use throughout a building's life cycle. For example, even if the operational energy use of a building is low, the energy consumed, and gases emitted for the manufacture and transportation of artificial, inorganic, non-locally sourced construction materials could potentially be higher than the energy and emissions saved by the building throughout its lifetime. This realisation provided an impetus to move from a *cradle-to-grave* to a *cradle-to-gate* and, even further, a *cradle-to-cradle* approach. This new approach encourages the creation of lean construction and retrofit supply chains, in conjunction with the use of low embedded carbon construction materials that can be reused or recycled at the end of the building's lifetime.

There is, therefore, a significant potential for carbon reduction if locally and ethically sourced, renewable, organic, relatively unprocessed, eco-friendly, reusable and recyclable materials are used. Examples of environmentally friendly materials include:

- sustainably sourced timber from well-managed forests;
- rammed earth or clay brick-shaped products, which have a high capability of controlling the humidity and conserving the heat or delay overheating indoors; and
- straw, which can be compressed into bales with polypropylene strings or wires and can offer high levels of thermal insulation.

Building heat transfer processes

To improve our knowledge of the way energy is consumed within building envelopes, we need to enhance our understanding of *heat and mass transfer processes* occurring in a building. *Heat*, or otherwise called *thermal energy*, is a form of energy, often an intermediate stage in the production of other energy forms (e.g. mechanical, electrical etc.). It is essentially an internal molecular property of a material body (McMullan, 2012) representing the kinetic energy of its particles. *Temperature* functions as an indicator of whether heat shall flow from one body to another, with heat flowing from warmer to cooler bodies according to the *Second Law of Thermodynamics*. In buildings, heat exchange usually takes place by one of the following modes (Figure 2.1.2):

- *Conduction*: Through contact between the materials but without molecules changing their basic positions, e.g. conductive heat loss through the opaque building envelope elements (walls, ground floor, roof).

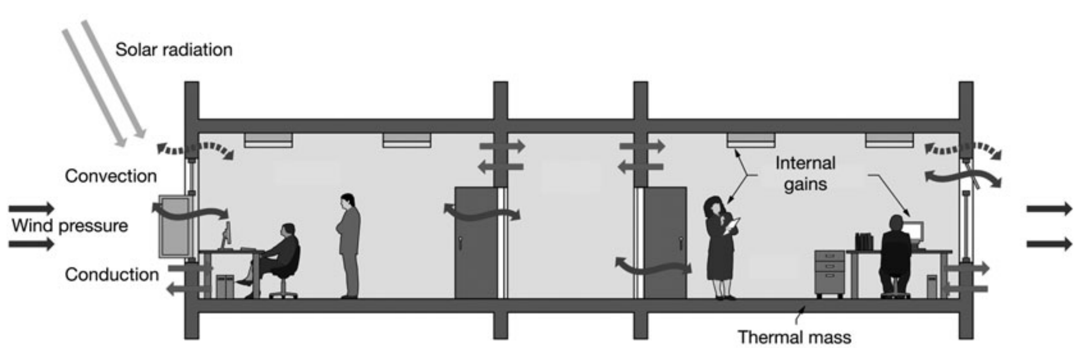

Figure 2.1.2 The building envelope as a thermal moderator between the inside and outside environments.
Source: CIBSE, 2013

- *Convection*: Through motion of fluids, e.g. convective heat loss through controlled (purpose provided ventilation through windows) and uncontrolled (infiltration and exfiltration through cracks) air movement between the indoors and outdoors.
- *Radiation*: Through electromagnetic waves without contact or molecular movement, e.g. in a building, solar shortwave radiation (visible light) is transmitted through the windows and then absorbed and re-radiated as longwave (infrared) radiation by the internal building surfaces.
- *Phase change*: Through absorption or release of latent heat, e.g. cooling of the surrounding environment by a water pond through the evaporation of water molecules.

An infrared camera image of a typical UK office building during winter is demonstrated in Figure 2.1.3; the main heat loss areas are observed around the windows, the roof and thermal bridges.

The net heat exchange between a building and its surroundings under steady state conditions, ΔQ, is calculated using Equation (1):

$$\Delta Q = Q_f + Q_v + Q_s + Q_i \tag{1}$$

where:

Q_f – heat flux between the internal and external surface of the building fabric (W)
Q_v – heat flux through purpose provided ventilation and uncontrolled infiltration (W)
Q_s – solar heat gains (W)
Q_i – incidental internal heat gains by occupants, lighting and appliances (W)

The estimation of Q_f, Q_v, Q_s and Q_i is discussed below.

Figure 2.1.3 Heat leak paths in the façade of an early 1960s office building with prefabricated wall panels as demonstrated by an early morning thermography survey during the heating season, highlighting thermal bridges (Point A) and air leakage (Point B).

Source: CIBSE, 2013

According to the *First Law of Thermodynamics*, the overall heat flux through a building fabric construction by conduction and convection, Q_f, should be proportional to the internal–external temperature differential. This relationship is determined by Equation (2):

$$Q_f = U_f \times A_f \times (T_i - T_e) \tag{2}$$

where:

Q_f – heat flux between the internal and external surface of the building fabric construction (W)
U_f – overall heat transfer coefficient of the building fabric construction (W/m^{2}K)
A_f – surface area of the building fabric construction (m^2)
T_i – internal air temperature (K)
T_e – external air temperature (K)

The *overall heat transfer coefficient*, *U*, or *U-value*, includes both the convective heat transfer taking place at the external and internal surface of the building envelope construction, and the conductive heat transfer occurring through the various homogeneous layers of the construction. It is calculated using Equation (3):

$$\frac{1}{U} = \frac{1}{\alpha_i} + \sum_{i=1}^{n} \frac{\Delta x_i}{\lambda_i} + \frac{1}{\alpha_e} \tag{3}$$

where:

U – overall heat transfer coefficient of the building envelope construction (W/m^{2}K)
a_i – internal heat convection coefficient (W/m^{2}K)
n – number of homogeneous layers of the building construction
Δ_{xi} – thickness of the homogeneous layer (m)
λ_i – thermal conductivity of the homogeneous layer (W/mK)
a_e – external heat convection coefficient (W/m^{2}K)

The *overall thermal resistance*, *R* or *R-value*, of a building envelope construction is defined as the reciprocal of the *U-value* and is expressed in m^{2}K/W.

Convective heat loss due to ventilation and infiltration is calculated by Equation (4):

$$Q_v = 0.33 \times N \times V \times (T_i - T_e) \tag{4}$$

where:

Q_v – heat flux through purpose provided ventilation and uncontrolled infiltration (W)
N – number of total air changes per hour within the zone (h^{-1})
V – internal volume of the zone (m^3)
T_i – internal air temperature (K)
T_e – external air temperature (K)

The overall solar gains of a building are a function of a building's geographical location, orientation, size and physical properties of its transparent and opaque elements. The solar gains through the glazed openings of a building, Q_s, are calculated using Equation (5).

Table 2.1.2 Benchmark allowances for internal heat gains in different building types.

Space function	*Occupation density (m^2/person)*	*Sensible heat gain (W/m^2)*			*Latent heat gain (W/m^2) People*
		People	*Lighting*	*Equipment*	
Office	12	6.7	8–12	15	5
	16	5	8–12	12	4
Retail stores	5	16	25	5	12
Teaching spaces	1.5	53	12	10	40

Source: Table 6.3, p. 6-2 and Table 6.2, p. 6-3, CIBSE, 2007

$$Q_s = \tau \times g_n \times FF \times Z \times A_w \times S \tag{5}$$

where:

Q_s – solar heat gains through glazed openings (W)
τ – a factor representing the ratio of typical average transmittance to that at normal incidence
g_n – the total solar energy transmittance factor of the glazing at normal incidence
FF – the glazed fraction of the opening
Z – the solar access factor
A_w – the area of the opening (m^2)
S – the solar flux on the surface (W/m^2)

The overall internal gains inside a building, Q_i, are estimated based on our knowledge about occupancy density and patterns, and default values given for appliances. For example, a seated person carrying out moderate office work emits 130 W on average (75 W sensible and 55 W latent heat). A personal computer uses on average around 55 W on continuous mode and 20 W on energy saving mode. Benchmark allowances for internal heat gains in different building types are demonstrated in Table 2.1.2.

Energy efficient building form

An energy saving rationale should be prioritised during the decision-making process and not be an afterthought. Crucially, although the efficiency of materials and individual systems can be improved in later stages, the core characteristics of the built form, inevitably, cannot be altered to increase its energy efficiency once its geometry and orientation have been fixed. Early stage energy conscious design decisions may include:

- the selection of the building site;
- the positioning, configuration and massing of building volumes on site;
- the geometrical characteristics of the building envelope;
- the orientation of spaces and the external surface areas that surround them; and
- the ratio between opaque and transparent elements etc.

Early literature in this field describes the concept of the *Socratic House*, an archetype for a solar building (Figure 2.1.4). Named after the ancient Greek philosopher Socrates, the form and construction materials of the Socratic House are largely influenced by the path of the sun movement at the specific location. Its plan is a trapezoid and the main openings are located on the south side. Its roof is inclined toward the

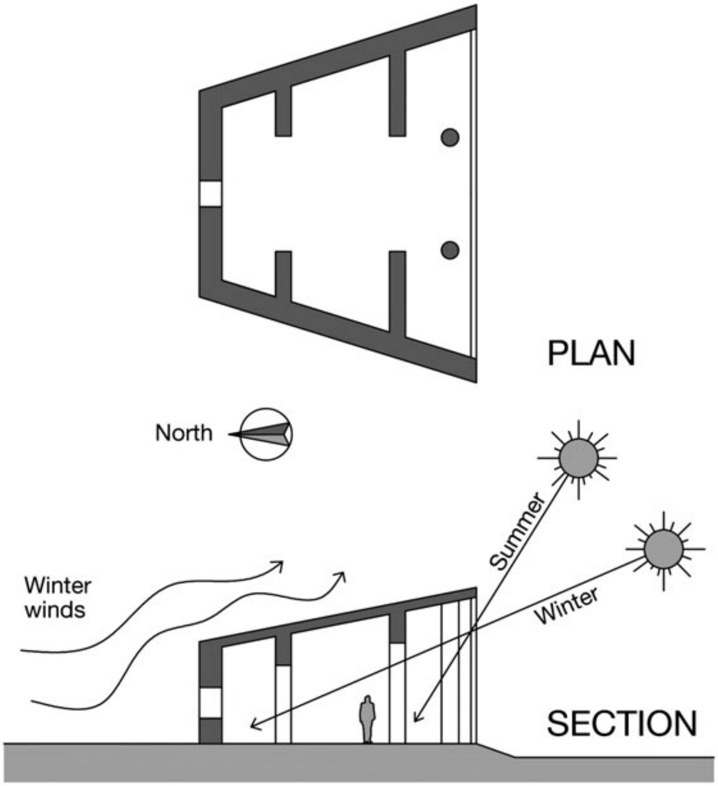

Figure 2.1.4 Environmental design principles of the Socratic House.

north; the angle and length of the south-facing overhang is designed in such a way so as to offer solar protection in the summer when the sun is high in the sky but maximise the penetration of solar radiation indoors during the winter when the sun is lower. Heat losses are minimised through the roof inclination which shelters the building from prevailing winds and the thermal insulation provided by the increased thickness of the north-facing wall, i.e. the side of the building that receives the least amount of solar gains. In this archetypal configuration, the exploitation of readily available natural energy resources, building geometry and materials are profoundly interwoven through a seamless design decision process.

Designers should ideally optimise a built form by applying a combination of the following principles:

- Conductive and radiative heat loss by longwave radiation from the external building envelope can be reduced if exposed surface areas are minimised. For example, compact forms, which are characterised by lower external surface to internal volume ratio, e.g. square-, circle-, ellipse-, and octagon-shaped buildings, tend to lose less heat and are, therefore, easier to heat. The internal layout could also be configured in such a way that intra-zone convective heat transfer is reduced.
- Convective heat loss through controlled ventilation can be reduced if the location of inlets and outlets is carefully considered in relation to the position of heating sources and occupants. On the other hand, it can be increased, e.g. for cooling purposes, if inlets and outlets are strategically located in relation to predominant summer winds. The internal layout should also be configured in combination with ventilation openings in such a way that enables pressure-driven cross ventilation. It is essential, however, that ventilation does not occur when external temperatures are above the internal as this

would not offer a cooling benefit. Temperature-driven ventilation paths could also be achieved through the creation of stacks or atria.

- Convective heat loss through uncontrolled infiltration and exfiltration can be reduced in winter if the direction of predominant winds are identified. The main living spaces should be sheltered by placing them toward the leeward side. Spaces not frequently occupied, e.g. storage spaces, can be placed toward the windward side so as to function as buffer spaces, and their external surfaces should be adequately insulated. Furthermore, construction discontinuities in the building envelope, e.g. when two different materials meet, should be minimised in order to limit the creation of thermal bridges.
- Net solar radiative heat gains, can be maximised in winter if the transparent elements of the building are orientated toward the south in buildings located in the northern hemisphere and toward the north in buildings located in the southern hemisphere. The optimum ratio between opaque and transparent building elements (glazing ratio) should be specified for the specific climatic region, to ensure that the solar gains trapped through glazed elements are overall higher than the heat lost through these elements. The geometry and inclination of openings and glazed surfaces could be further optimised to facilitate the transmission and storage of solar heat gains. Highly glazed spaces, e.g. (unheated) conservatories, when attached to the main living spaces could function as thermal buffers that preheat the internal building surfaces as well as the air entering the building.
- To avoid summertime excess internal temperatures, opaque and, especially, transparent building elements should be protected from undesired summer solar radiation. Shading could be provided by adjacent buildings or structures, trees, the building geometry itself (e.g. overhangs), externally or internally placed shading systems (e.g. external louvres/awnings or internal blinds, respectively). In general, external shading is preferable to internal as it 'switches off' solar gains before they enter the building.

It is, of course, crucial that the built form design decisions are combined in such a way that they render the building adaptable to all seasons. The design of the Socratic House roof offers a simple example of such year-round optimisation; its inclination allows the penetration of solar radiation during winter when it is most needed and offers solar protection during the summer when it is undesired. Another example of such a win–win measure is the planting of deciduous trees to offer shading of a building during the summer and allow the transmission of solar energy when they have lost their foliage in winter.

Energy efficient building materials

The careful selection of building construction materials should be an integral part of the design process, alongside the definition of built form and function. With regard to the thermal efficiency of the building envelope, building practitioners should not only carefully consider the optimum levels of *thermal insulation* but also its impact on overheating, *water vapour* movement in the building envelope, and the accidental fabric heat losses due to poor construction (*air permeability* and *thermal bridges*). Attention should be also put on the *thermal mass* of materials and the appropriate design and selection of the *transparent elements* of the building envelope, e.g. glazing.

Thermal insulation

Thermal insulation materials are used in building construction in order to reduce conductive heat loss through the building envelope by thermally decoupling the interior from the exterior thermal environment. The majority of materials used for insulation purposes feature small pockets of air between fibres or inside foam. In this way, they exploit the low heat conductivity of air. They can be of organic or inorganic nature and they are produced in different forms, such as loose fill, spray foam, blankets and panels. Alternative building insulation technologies include vacuum insulation materials, which do not contain any air or gas pores and, thus, significantly eliminate convective heat losses. Thermal insulation materials need to be light, easy to install and replace, durable, water resistant, low carbon and cost efficient. Different types of popular organic and inorganic insulation materials are presented in Table 2.1.3.

The overall heat transfer coefficient, *U-value*, is the primary indicator of insulation quality: the lowest the U-value of a material, the highest its insulating ability. By way of illustration, the heat losses of a non-insulated, 9 inches thick single brick wall with internal plaster with a U-value of 2.10 W/m^2K can become five times less by applying a plasterboard/insulation laminate with an insulation R-value of 2.90 m^2K/W, together with a protective render, so that its U-value is decreased to 0.30 W/m^2K (Energy Saving Trust, 2006).

Minimum acceptable U-values for different elements of a new building envelope according to the English Building Regulations are given in Table 2.1.4 below (DCLG, 2013a, 2013b). Highly efficient building envelopes, such as buildings compliant with the Passivhaus standard, which will be presented in the following section, are characterised by even higher thermal insulation ability.

The optimum insulation thickness for a building depends on the local climatic conditions, the building form and the internal heat loads. It can be calculated for a given demand internal temperature, *Ti*, using the heat balance Equation (2) presented earlier. The cost of insulation, fuel prices and associated payback periods of the investment should also be taken into consideration. For instance, it is likely that, after a certain point, energy savings do not increase linearly with insulation thickness and, thus, any further

Table 2.1.3 Popular building construction insulation materials.

Inorganic materials		*Natural and organic materials*	
Mineral fibres	*Foam materials*	*Plant and animal fibres*	*Foam materials*
Slag wool	Expanded glass	Coconut fibres	Polyester foam
Glass wool	Vermiculite	Cellulose fibres	Extruded polyester
Rock wool	Perlite	Wood flax	Polystyrene foam
	Expanded clay	Wool	Polyurethane foam
		Straw	Foamy formaldehyde tar
		Cotton	
		Paper	
		Cork	
		Hemp	

Table 2.1.4 Minimum acceptable fabric performance values for new buildings in England.

Building element	*Heat transfer coefficient, U (W/m^2K)*	
	Dwellings	*Non-domestic buildings*
External walls	0.30	0.35
Floor	0.25	0.25
Roof	0.20	0.25
Windows, roof windows, glazed roof lights, curtain walling and pedestrian doors	2.00	2.20

Sources: DCLG, 2013a, 2013b

increase of insulation may have diminishing returns. The actual U-values achieved in situ will also vary due to differences in workmanship.

Thermal insulation is required not only in winter to prevent heat loss but also during the summer period to reduce the occurrence of excess temperatures indoors. Taking into account that our climate is changing, a future rise in ambient temperatures is likely to exacerbate the risk of overheating inside buildings even in previously heating dominated climates (DCLG, 2011). The existing building stock in these regions has not been designed to cope with extreme heat and it is hence an imperative that it adapts to a warming climate. However, while insulation is generally found to be beneficial for the mitigation of overheating, internal insulation in buildings heavily occupied during the daytime could potentially result in an increase in overheating due to excess heat being trapped indoors if no sufficient ventilation is provided. Consequently, externally rather than internally applied insulation may be preferable for buildings with high internal heat gains. The impact of insulation on the year-round performance of a building should be, therefore, carefully evaluated prior to installation using dynamic thermal simulation in order to avoid any unintended consequences.

Vapour permeability

The process of selecting insulation materials may involve the balancing of conflicting requirements, such as having an envelope that is both air tight but also being able to *'breathe'*.

In residential spaces, in particular, a large amount of *water vapour* is formed by occupant breathing, sweating, cooking and other processes taking place indoors. The installation of insulation layers is of great significance for vapour permeability and, as a consequence, indoor microclimate. It is hence crucial to ensure controlled heat and water vapour transfer routes from the interior to the exterior of the building. This could be achieved in two ways:

- a vapour impermeable but diffusion closed envelope; or
- a vapour permeable and diffusion open envelope.

In the first case, the building is tightened with foils that do not, or only slightly, let through water vapour. The effect is similar to a windjacket, which occasionally has to be opened for the air to get inside. Similarly, in a building we need to open the windows from time to time for the fresh air to get in. In the second case, we build in vapour permeable foils that enable water vapour formed inside the building to be evenly transferred throughout the building envelope while simultaneously enabling the air exchange between indoors and outdoors.

Air permeability

Building envelope *air permeability* is the uncontrolled leakage of outside air into the building space. This can occur at numerous points: through cracks, gaps around doors and windows, as well as through the roof, floor and gaps around pipes and ducts. Air can also leak through porous construction materials, such as brick or blocks. Air leakage through the building envelope contributes to ventilation, heating and cooling costs and has an impact on moisture migration and indoor air quality. Leakier homes are, thus, characterised by higher space heating needs and, as a consequence, higher CO_2 emissions.

Thermal bridges

Structural *thermal bridges* can occur at gaps and discontinuities between different building construction layers. They are usually found at the junctions of walls and floors, walls and roofs, external and internal

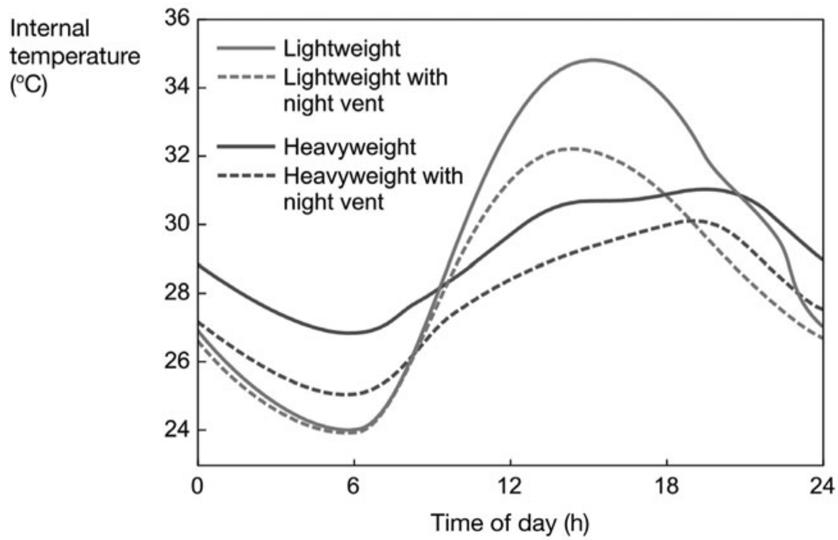

Figure 2.1.5 Temperatures in non-insulated and insulated corners of two walls.

Source: Zbašnik Senegačnik, 2007

walls, or around openings where the insulation is disrupted (doors, windows, piping etc.). Thermal bridges can be responsible for increased heat losses in a building and the occurrence of condensation and mould, as well as defects on the building itself after a certain period of time. Although it may be impossible to construct a building without thermal bridges, they can be eliminated through very careful detailing and high-quality workmanship. As an example, in a window–wall junction, special attention needs to be paid to the contact between the window jamb and the insulated wall. The in-building of the window shelf has to be made together with the insulation of the part of the brick wall below the shelf.

The temperatures in non-insulated and insulated corners of two walls, with external temperature of 10°C and internal temperature of 20°C, are shown in Figure 2.1.5.

Thermal mass

Thermal mass is a term used to describe the ability of a physical material to absorb and store thermal energy. It is a function of the material's:

- density (dense materials tend to store more heat); and
- specific heat capacity (materials with high specific heat capacity need a lot of energy for their temperature to change).

Table 2.1.5 lists the thermal properties of common construction materials, including their effective thermal mass.

Materials of high thermal mass have been historically used in building construction to decrease and stabilize internal temperatures, therefore reducing the cooling needs of buildings in a passive manner. This strategy was commonly applied in the traditional architecture of hot and dry climates that are characterized by high diurnal external temperatures. Thermally heavyweight exposed materials that absorb and retain heat during the daytime were combined with small but strategically placed openings that allow cross purge

Table 2.1.5 Thermal properties of common construction materials.

Building material	*Density (kg/m^3)*	*Thermal conductivity (W/mK)*	*Specific heat capacity (J/kgK)*	*Effective thermal mass*
Timber	500	0.13	1600	Low
Steel	7800	50.00	450	Low
Lightweight aggregate block	1400	0.57	1000	Medium-high
Precast and in-situ concrete	2300	1.75	1000	High
Brick	1750	0.77	1000	High
Sandstone	2300	1.80	1000	High

Source: Concrete Centre, 2012

ventilation through the building envelope in the night time. This enabled the reduction of the magnitude and delay of the peak of internal temperatures. Indoor thermal comfort was hence achieved without air conditioning despite the excess ambient temperatures. High thermal capacity materials are often used today as part of energy saving strategies in low energy buildings. Increased exposed thermal mass may also be beneficial in mixed-mode buildings as it could potentially reduce and delay the peak air conditioning loads. The stabilising effect of exposed thermal mass on indoor temperature is illustrated in Figure 2.1.6.

A series of issues need to be factored in, however, during the design of a heavyweight building:

- High density materials tend to be quite heavy and, therefore, the structural integrity of the building needs to be carefully considered. Thermal mass elements should preferably form part of the load bearing structure of the building envelope.
- Similarly to insulation, there are diminishing effects of increased thermal mass as only a certain portion of the exposed mass will be acting as a heat store in a diurnal cycle. The active penetration depth of concrete, for example, is usually found to be around 10 cm.

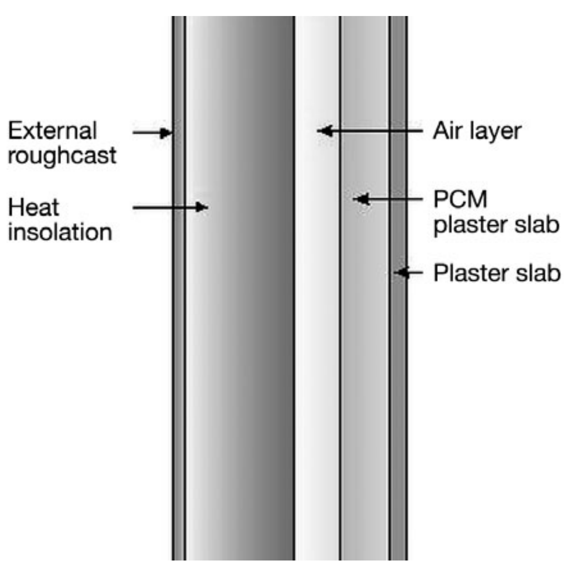

Figure 2.1.6 Effect of thermal mass and ventilation rate on peak indoor temperature.

Source: CIBSE, 2005

- As explained previously, the advantage of heavyweight building envelopes is that they smooth indoor temperature profiles and shift the occurrence of peak temperatures later in the day. This delay in heat build-up indoors may, nevertheless, not be desirable during the heating period. In particular, this may be the case in spaces that are used intermittently and for short periods of time, such as educational spaces, theatres and halls. A more lightweight structure may be preferable for this type of buildings.
- A whole lifecycle assessment of the building should ideally be undertaken in order to determine whether the typically high embodied carbon of high thermal mass materials, such as concrete, will be offset by the reduction of space conditioning needs due to the presence of thermal mass over the course of the building's life span.

Technological advances in the area of building construction material science have led to the development of new, energy saving technologies, such as *phase change materials* (PCMs). PCMs are substances that need relatively large amounts of heat to change their state from solid to liquid and vice versa. As a result, they are capable of accumulating or releasing large amounts of latent heat. Similarly to thermally heavyweight

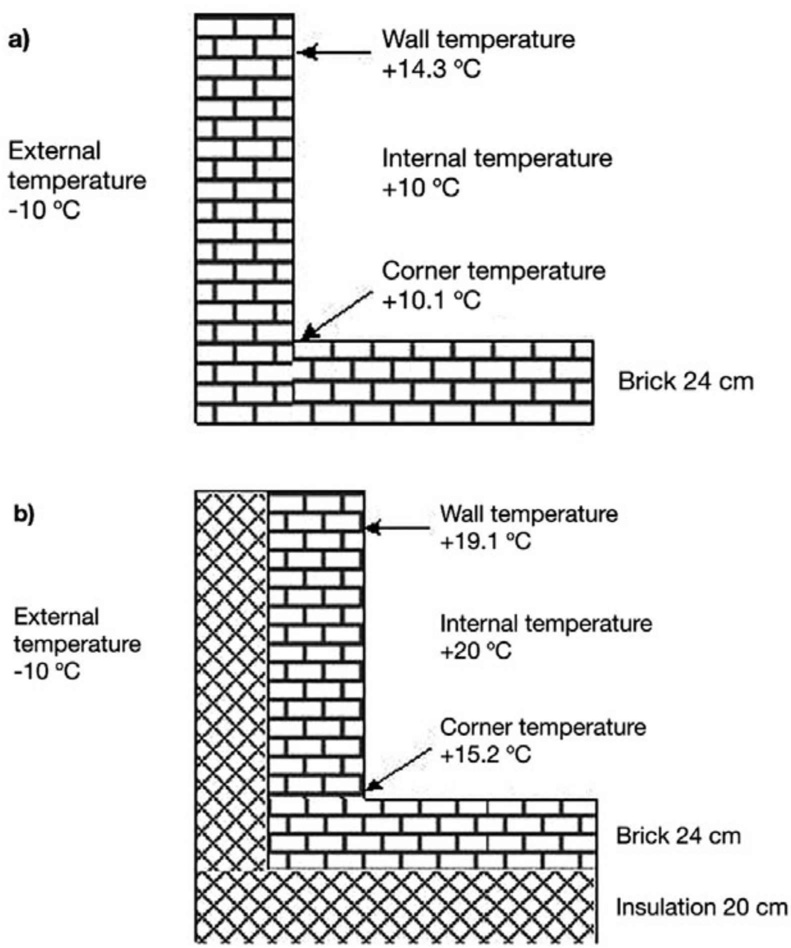

Figure 2.1.7 Wall with embedded PCM.

materials, such as concrete and brick, PCMs act as heat storage units. They store 5 to 14 times more heat per unit volume than conventional storage materials such as water, masonry, or rock. A 15 mm thick plaster plate with built-in PCM micro grains (Figure 2.1.7) is, for example, equivalent to a 12 cm thick brick wall or a 9 cm thick concrete wall. Improvements in their durability have led to their wider use in construction in recent years. Popular PCMs used in building construction include inorganic hydrated salts and organic paraffin or fatty acids. They are usually manufactured in the form of micro or nano balls contained in cassettes as part of ceiling tiles, or in the form of wax contained in tiny hard plastic capsules (microencapsulation) that can be embedded in walls or other building envelope elements.

Transparent elements

The windows and other transparent elements of a building envelope have multiple functions: providing natural light, ventilation and weather protection. Due to its optical properties, the presence of glass in the building envelope creates a greenhouse effect: Glass is highly transparent at wavelengths of sun light ($0.3 < \lambda < 3$ μm) and almost opaque for infrared waves, which are emitted by house interior objects. As a result, on sunny days, shortwave solar radiation penetrates the building envelope through glazed elements and is absorbed and re-emitted by interior surfaces as longwave radiation, a large percentage of which is trapped indoors. However, when the opaque elements of the building envelope are well insulated, the transparent elements are generally found to contribute the most to energy losses. High performance, energy saving transparent elements could be used in order to limit building envelope heat losses. Energy saving windows consist of two or three glass layers with inert gases, such as argon, krypton etc., in the interspaces. The mechanism of heat transfer through a window with multiple glass panes involves:

- radiative heat transfer between the glass panes;
- conductive heat transfer of gas between the glass panes; and
- convective heat transfer of gas between the glass panes.

Approximately 2/3 of heat loss through a conventional double-glazing window is due to heat radiation ($e \sim 0.85$) and only 1/3 is the result of conduction and convection in the interspaces of the window. To reduce the longwave heat radiation transmission that can pass through glass without compromising the transmission of visible light, glass panes are often covered with thin layers of low emissive (low-e) film on the inner surfaces. Covering either one of the two glass surfaces with a low-e film reduces thermal

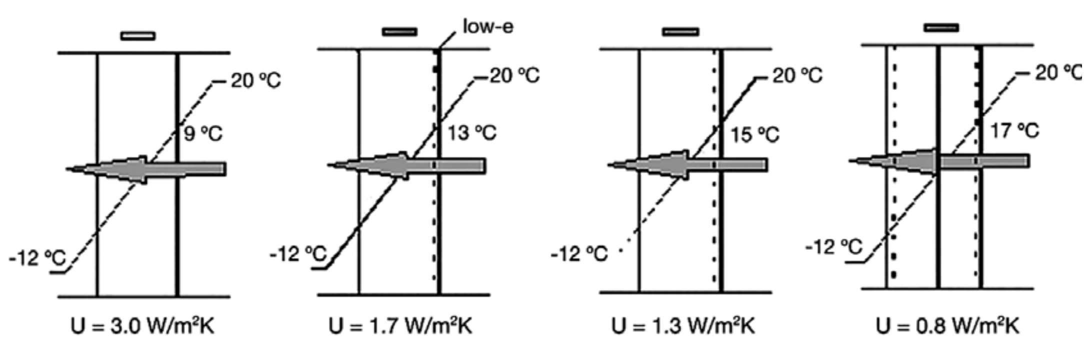

Figure 2.1.8 The temperature of glass surfaces in heat insulated windows.

Source: Umberger, Krope and Krope, 2006

radiation practically to zero, and any further heat loss is only due to conduction and convection. Insulation films need to fulfil the following requirements:

- high degree of total light transmittance;
- natural light reflectivity; and
- low value of radiation.

Typical heat transfer coefficients for low energy double glazed window panes are between 1.2 and 2.2 W/m^2K. Triple glazed windows usually have U-values below 1.0 W/m^2K. This reduces the temperature difference between the room air and the window surfaces (Figure 2.1.8), hence ensuring higher indoor thermal comfort.

Types of low energy buildings

The shift toward sustainable, energy conscious architecture has generated a wide range of terms used to classify energy efficient buildings on the basis of energy performance, greenhouse gas emissions, and other sustainability aspects. Definitions are not standardised and tend to vary widely from country to country, as do the types of energy demand these terms refer to and the benchmarks they are often accompanied with. As of 2008, 17 different terms commonly used to describe such buildings across Europe were identified (Erhorn and Erhorn-Kluttig, 2011). Broad definitions for key such terms are provided below.

Low energy or *energy saving* or *high energy performance building* is a loosely applied term used to describe a building with energy demands that are considerably lower (usually by at least 25%) than the national average or national building code standards and requirements for buildings of a similar type, size and climatic region. In most central European countries, for instance, houses would be characterised as low energy if their heating demand is around 40–60 $kWh/m^2/year$ (EC, 2009). This is usually achieved through the optimisation of the building form (orientation, glazing ratio) and materials (insulation, thermal mass, air tightness), in conjunction with the use of efficient active systems.

A passive or *passive solar* or *free running building*, not to be confused with the more specific *Passivhaus* standard, is a type of low energy building where indoor thermal comfort conditions can be achieved through passive means (exploitation of solar gains, natural ventilation etc.) and, thus, does not require the use of mechanical heating, cooling or ventilation systems.

A building designed and constructed according to the *Passivhaus* standard, as initially developed in Germany, is a type of low energy building that achieves indoor thermal comfort conditions by post-heating or post-cooling of fresh air through the recuperation of heat from used air using a Mechanical Ventilation with Heat Recovery (MVHR) system and, thus, is not heated or cooled in a conventional way (Figure 2.1.9). Owing to its highly performing envelope and systems, the majority of the time the gains from solar energy and inner sources are sufficient to keep indoor temperatures within the comfort range. As a result, the active heating season of a Passivhaus building is significantly shorter than that of conventional buildings.

For a newly constructed building in a central European climate to comply with the Passivhaus standard the following are required (Passivhaus Trust, 2012):

- The total annual space heating and cooling demand should be equal to or below 15 kWh/m^2 each (or the heating and cooling load should be equal to or less than 10 W/m^2 each).
- The total annual primary energy demand, including space and water heating, space cooling, fans, lighting and appliances, should be equal to or lower than 120 kWh/m^2.
- The overall air change rate should be equal to or below 0.6 air changes per hour @ 50 Pa.

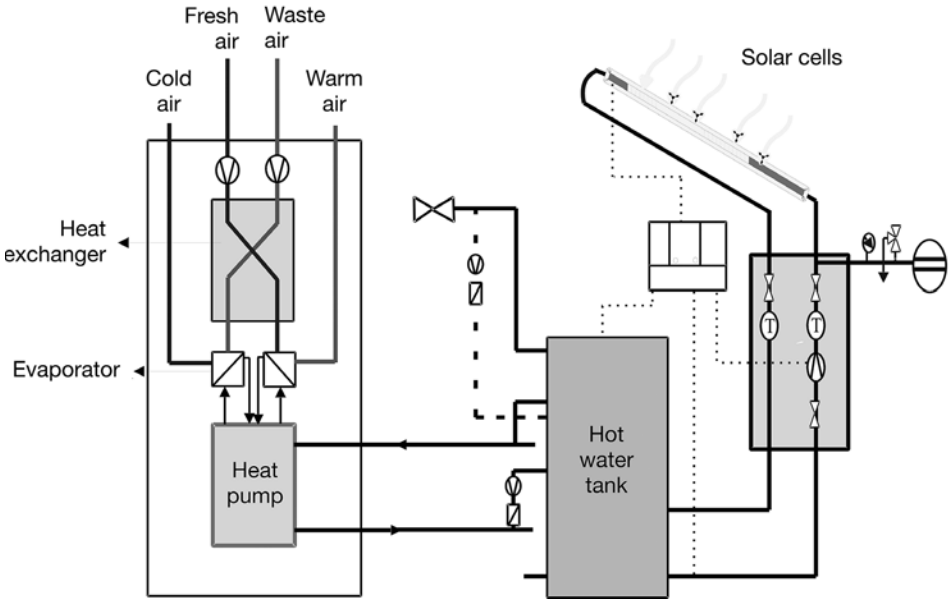

Figure 2.1.9 Passivhaus heat recovery system.

Source: Umberger, Krope and Krope, 2006

For a newly refurbished existing building in a central European climate to comply with the Passivhaus retrofit standard, EnerPHit, the following are required (Passivhaus Trust, 2012):

- The total annual space heating demand should be equal to or below 25 kWh/m^2.
- The total annual primary energy demand should be equal to or less than 120 kWh/m^2, plus the heat load factor.
- The overall air change rate should be equal to or lower than 1.0 air changes per hour @ 50 Pa.

Buildings constructed according to the Passivhaus standard usually include large south-oriented glazed surfaces and an airtight, thermal bridge free, thermally efficient building envelope. To achieve the Passivhaus standard, it is suggested that the U-values of the walls, floors and roof are equal to or below 0.15 W/m^{2}K and of the glazed elements equal or below 0.75 W/m^{2}K (BRE, 2011). An average heat transfer coefficient for the entire external envelope equal to or below 0.20 W/m^{2}K is also recommended.

A *zero energy* or *zero carbon* building is a type of low energy building all energy needs of which, including space and water heating, space cooling, ventilation, lighting and appliances, are covered with passive means and/or renewable energy sources or other carbon free energy sources. This means that the building is:

- either energy autonomous or self-sufficient throughout the whole year and potentially not connected to the energy grid supply,
- or that it alternates between energy importer and supplier mode depending on the season, i.e. on an annual basis, its energy imports from the grid are balanced with the energy it generates and then returns to the grid.

Summary

The continued use of conventional, fossil fuel-based energy sources is no longer justified from a social, economical and ecological perspective. The design and construction of energy efficient building envelopes that simultaneously optimise the indoor environment and maintain the desired levels of living standard and comfort is an emerging need. To achieve this, building designers need to employ a combination of traditional environmental design principles and innovative solutions that are technically feasible, economically viable and sustainable from environmental and social standpoints.

A holistic approach toward truly sustainable built environment design encourages the integration of energy conscious design principles from the initial stages of architectural synthesis. Efforts to reduce the energy demand and resulting environmental impact of buildings should follow a fabric-first approach. The building geometry and physical properties of the construction materials, such as air tightness, thermal conductivity and capacity, should ensure the creation of a building envelope that minimises heat losses and maximises heat gains in winter, and vice versa in summer. Such demand-focused energy reduction strategies need to go hand in hand with supply-based solutions. Active elements that exploit solar and wind energy, ground, ambient or waste heat could be incorporated in the building envelope to further reduce its energy needs.

This chapter highlighted the importance of interdisciplinary approaches toward the design of a low energy built environment. The design and operation of energy efficient building envelopes necessitates new ways of thinking and working. It lends itself to a truly integrated approach toward building design that breaks the silos of different built environment professional fields and creates a shared vocabulary and vision toward the creation of low energy, low carbon, healthy buildings.

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2.2
ENERGY BENCHMARKING AND MONITORING

Stefano Paolo Corgnati, Vincenzo Corrado, Ilaria Ballarini and Cristina Becchio

Introduction

Since Directive 2002/91/EC on the energy performance (EP) of buildings was adopted, there has been a strong increase in the interest in rationalization of energy consumption in both new and existing buildings. The introduction of the energy performance certification of buildings have resulted in development of various methodologies, i.e. diagnostic tools which may assist to facility managers and energy monitoring professionals to detect faults or malfunctions in the energy behaviour of buildings. Furthermore, as underlined by the Directive, the energy consumption monitoring may contribute to the development of building energy performance classification and more comprehensive energy benchmarking systems.

A further impulse was given by European Directive 2010/31/EC (EPBD recast) which requires Member States (MS) to introduce a comparative methodology framework at national level in order to define cost-optimal levels of minimum EP requirements for buildings and building elements (EPBD recast, art. 4.1 and 14), and compare them with the national requirements set in building codes. According to the comparative methodology framework provided by the European Commission, the MSs have proceeded to define reference buildings (also named benchmark buildings, both residential and tertiary sectors, both existing and new), representative of the building stock in terms of function and climatic conditions, to define the energy efficiency measures (EEMs) to be assessed for the reference buildings, extended to the whole building or to building elements, to evaluate the final and primary energy need for the reference buildings before and after the realization of EEMs, and to calculate the costs of EEMs applied to the reference buildings in the expected economic life-cycle.

The main purpose of a reference building is then to represent the typical and average building stock since it is impossible to calculate the cost-optimal situation for every individual building. *Reference building* means a hypothetical or real reference building that represents the typical building geometry and systems, typical energy performance for both building envelope and systems, typical functionality and typical cost structure and is representative of climatic conditions and geographic location. The use of reference buildings allows to set reference energy demand/consumption and predict future energy resource needs on a regional, national or international scale, by assessing the energy and economic impact of different energy efficiency measures, also considering future EP requirements and/or financial subsidies.

A similar approach has been followed in the US, through the introduction the benchmark building models. These models are reference buildings aimed to represent the American commercial stock and derive from some research conducted by US DOE with regard to energy efficiency for new buildings and energy dynamic simulation. They represent 70% of the energy supplied for commercial buildings.

In this chapter, different approaches for benchmarking building energy performance are presented, considering also energy and indoor climate classification through monitoring.

Energy assessment methodologies

The energy classification and the certification of buildings require an assessment methodology which can be applied without distinction both to new and existing buildings. To this end, the standard *EN 15603: Energy performance of buildings – Overall energy use, CO_2 emissions and definition of energy ratings* presents several assessment methodologies enabling to:

- obtain the same results for different data sets;
- estimate the missing data and calculate a "standard" energy consumption for air-conditioning (heating, cooling, ventilation), production of domestic hot water and lighting; and
- assess the effectiveness of possible energy efficiency improvements.

EN 15603 identifies the end-uses to be considered in order to evaluate the energy performance of new and existing buildings. The energy performance evaluation is based on the weighted sum of the calculated or measured consumptions by primary energy source (natural gas, oil, electric energy, etc.).

According to the circumstances, we can determine the energy performance of a building through a calculation model based on the known building characteristics (*direct approach*) or assess the energy consumption through the actual consumption measurement (*inverse approach*).

In EN 15603 the following classification of energy assessments is proposed:

- *operational rating* – is obtained by measuring and summing up (after appropriate weighting) all amounts of delivered energy by each energy source (electricity, oil, natural gas, etc.);
- *calculated rating* – is obtained by measuring and summing up (after appropriate weighting) all amounts of delivered energy both by use and energy source. This assessment can be further differentiated according to the method adopted to collect the data, the climate and use conditions;
- *design rating* – is based on calculations using the data coming from design results and design values estimated for a building under construction;
- *asset rating* – is the value based on calculations using the existing building data (the data are obtained from field surveys and deductive rules), and input standard values concerning indoor/outdoor environments and occupancy; and
- *tailored rating* – it is based on calculations using actual data of a building and actual climate and occupancy data. The data concerning the building may be rectified after a comparison between calculated and measured consumptions (*validated rating*).

The asset rating represents the intrinsic potential of a building under standardized conditions of use and can be applied for the energy certification. On the other side, the operational rating, is a measure for the in-use performance of the building and can be useful to certify the actual performance of the building-user system. Obviously, in order to obtain an operational rating, it is essential to implement monitoring strategies which would enable us to measure the actual energy consumption of the building.

The EN 15603 underlines that it is impossible to compare directly the energy performance indexes obtained from an asset rating and an operational rating. However, the differences between these two ratings can be useful to evaluate the cumulative effects of the actual conditions of the building in comparison with the standard conditions. The following methods should be considered:

- to assess the compliance with technical and operational rules representative of energy targets
- to compare the energy performances of various design alternatives for a new building
- to set an energy performance benchmark for existing buildings
- to evaluate the effect of possible energy saving actions on an existing building, through the analysis of the pre-intervention consumption and the estimation of the possible post-intervention savings;
- to predict the future energy requirements of a building, or a building stock, on the basis of the actual trend of energy consumptions of different buildings representative of the building stock in question.

Energy benchmarking through reference buildings

The reference building concept

The assessment of the energy performance of existing building stocks by means of an asset rating should be carried out on "reference buildings" that represent the typical and average buildings of the stock (Corgnati, Fabrizio, Filippi and Monetti, 2013). The "reference building" concept has been introduced by the EPBD-recast for the development of the so-called *cost-optimal* analysis, to set energy performance requirements for the refurbishment of existing buildings "*with a view at achieving cost optimal levels*". Thus, the assessment of the present energy demand and the potential energy savings attainable on the existent building stock should be performed on "reference buildings" in order to obtain general results consistent with the characteristics of the analysed stock.

According to the Commission Guidelines accompanying the Commission Delegated Regulation No. 244/2012, it is recommended that reference buildings are established in one of the two following ways: (1) selection of a real example, representing the most typical building in a specific category (e.g. type of use and reference occupancy pattern, floor area, compactness of the building expressed as envelope area/volume ratio, building envelope constructions with corresponding U-values, etc.); (2) creation of a "virtual building" which, for each relevant parameter, includes the most commonly used materials and systems. The choice between these options should depend on expert enquiries and statistical data availability. It is possible to use different approaches for different building categories, to have (real or virtual) reference buildings able to represent the characteristics (geometry, envelope, systems, etc.) of each specific building category.

At international level one of the largest database of benchmark building models for commercial buildings is the one of the Department of Energy (DOE) of United States, where reference building models are defined for 16 building typologies across 16 locations (representative of US climate zones) and three construction periods (pre-1980, post-1980, new buildings). The purpose of these models is to represent new and existing buildings. The reference building models will be used to set reference consumption and to assess optimize designs and energy retrofit measures.

Reference buildings for energy benchmarking

The creation of a harmonized structure for "reference building" definition at European level has been the objective of the European research project TABULA (Typology Approach for Building Stock Energy Assessment, 2009–2012). The project concerned the definition and the application of "European building typologies" to estimate the energy demand of residential building stocks at national level and to assess the impact of retrofit actions on the same building stocks.

Each participating country developed a national "building typology", that is a set of reference buildings, or "building types", each of them with its specific energy related properties. The building typology is classified according to three specific parameters: location (related to the climatic area), construction period (related to the constructive principles and materials) and building size (e.g. single-family houses, terraced houses, multi-family houses, apartment blocks).

Each national building typology is displayed through the "Building Typology Matrix", differentiated by region/climatic area. Each cell in the matrix contains a building type, considered representative of a specific construction period and building size. An example of "Building Typology Matrix" is shown in Figure 2.2.1 for the Italian Middle Climatic Zone (2100–3000 heating degree-days).

Three different methodological approaches have been applied in TABULA for the identification of the building types: (1) the "Real Example Building" approach identifies the building type by means of experience; (2) the "Real Average Building" approach identifies the building type as a real building showing characteristics similar to the mean geometrical and construction features of a statistical sample; (3) the "Synthetical Average Building" approach identifies the building type as an "archetype" based on the statistical analysis of a large building sample.

The building typology concept can be applied for the energy benchmarking of the building stock. In fact, since each building type is considered representative of a suitable portion of the residential building stock, the energy performance of each building type – assessed through an official calculation method –

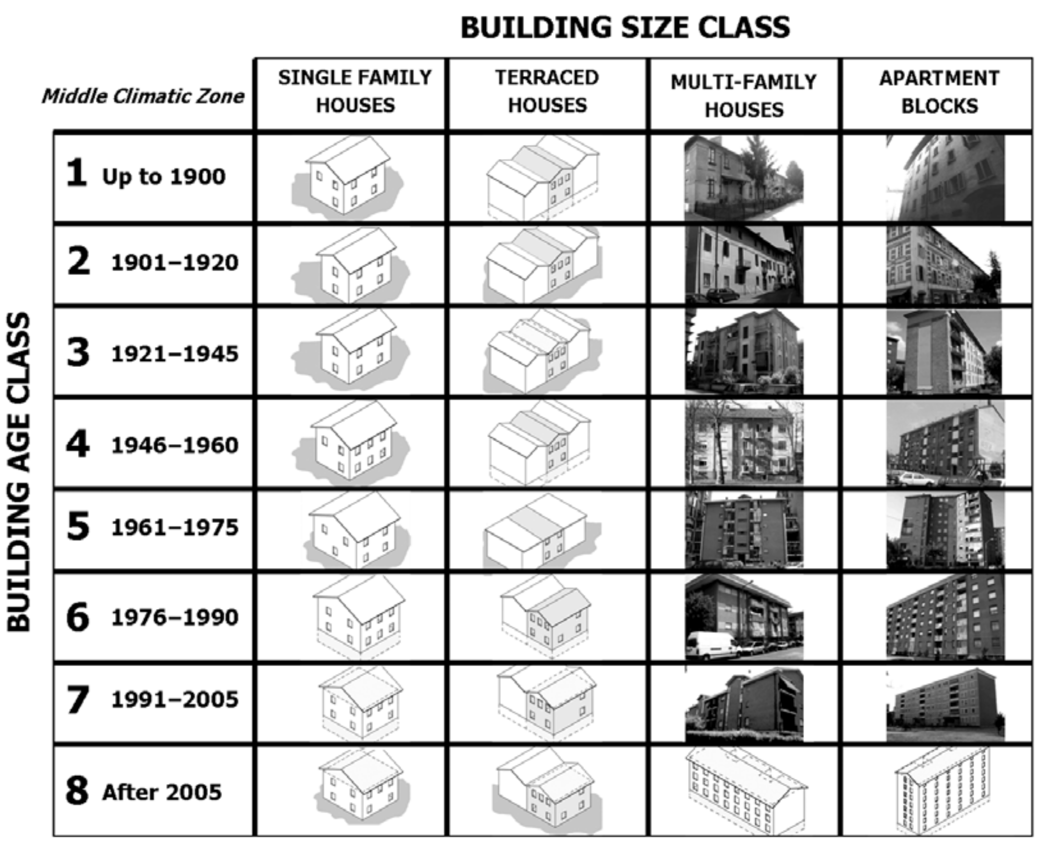

Figure 2.2.1 The Italian "Building Typology Matrix" developed in the TABULA project.

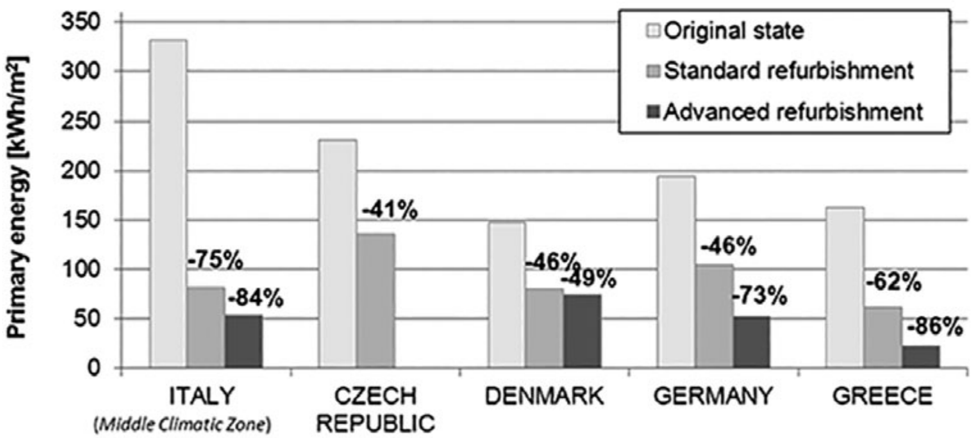

Figure 2.2.2 Annual energy saving potentialities of some residential building stocks analysed in the TABULA project.

can be enlarged to the building stock according to the frequency of each building type in the stock. Consistent statistical data are necessary to perform the projection from the building type to the building stock.

Besides this application, the building types can be also used either by consultants for initial energy advice activities, or by housing companies to assess the energy performance of a building portfolio, or for the evaluation of subsidy programmes.

In TABULA, among the possible application of the reference buildings, it has been investigated the evaluation of the potentialities of energy savings and CO_2 emission reductions from the present state to a renovated state ("standard" and "advanced" retrofits) of the residential building stocks of some European countries. An example of the obtained results is shown in Figure 2.2.2.

Energy and cost benchmarking: the cost optimality approach

As mentioned, according to the cost optimal methodology "reference buildings" can be exploited as a basis for analyzing national building stock and the potential impacts of energy efficiency measures (EEMs) in order to select the most energy and cost-effective strategies for upgrading existing buildings. In particular, a measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure. The cost-optimal level, that is a is a special case of cost effectiveness, represents a specific retrofit action or combination of actions that minimized the global cost during the estimated economic lifecycle. According with EN 15459:2007, the global cost is determined by summing up initial investment costs, periodic and replacement costs, annual costs and energy costs (the calculation of which is thereby fed by the results of the energy performance calculations) and subtracting the final value; all the costs are referred to the starting year by applying an appropriate present value factor. After the analysis phase, in order to find the cost-optimal level, the primary energy consumption (x-axis) was plotted versus the global cost (y-axis). Both quantities are then divided per the net conditioned floor area of the building. From the variety of specific results, a cost curve can be derived.

In order to check the reliability and stability of the results some sensitivity analyses are necessary. In this way the impact of important framework conditions are tested, such as discount rate, energy price development and fiscal tool consideration. If the sensitive analyses confirm the same cost optimal level, it means that the results are solid.

Energy benchmarking through monitoring

Heating energy consumption

This section focuses on the monitoring, standardization, and analysis of primary energy consumption for heating in existing buildings. In this case, the monitoring is defined as a continuous measurement during the whole heating season of those parameters which are significant to describe the energy consumption for heating in a building (for example, the amount of the fuel consumed), and essential for standardization of the energy consumption (for example, total heated volume of the building).

In order to attribute a specific consumption index to the building, able to define its energy performance, an *operational rating* procedure is applied for the following purposes:

- to monitor and control continuously the actual building consumptions;
- to set reference consumption values for the building;
- to predict the energy consumption for the future heating seasons.

The attribution process of reference energy consumptions to each building is particularly important. These data can be effectively used to define costs in energy service contracts. Moreover, the attribution of such energy index to the building is in compliance with the European Directive 2002/91/EC on the energy performance of buildings. As already mentioned, it highlights the need to attribute energy performance indicators to existing buildings, even through the analysis of the actual consumptions.

According to the specific purposes, it may be more significant either to use energy performance indexes obtained from theoretical consumptions, on the basis of the known characteristics of the building-plant system (*calculated rating*), or to refer to the actual metered energy consumptions (*operational rating*). The indicators obtained from this second approach are particularly suitable to represent the consumptions of an operating building as a result of the "building-plant-user" system dynamics.

In particular, the *operational rating* procedure is based on the estimation of an index of "conventional specific energy consumption for heating purposes" (Corgnati, Corrado, Filippi and Maga, 2004). Basically, this estimation procedure provides for the development of the following two phases:

1 data collection
2 definition of the consumption index

The first phase consists of collecting data concerning building characteristics (both typological and geometrical), local climate conditions, heating use conditions, energy consumption, and in particular:

- location of the building
- shape and type of the building
- geometrical characteristics (gross heated floor area, useful heated surface, etc.)
- actual degree days (*DD*), on a yearly and, if possible, monthly basis
- fuel type
- actual primary energy consumption for heating (*CE*), on a yearly and, if possible, monthly basis
- actual consumed energy delivered by the heat generator (*QP*), on a yearly and, if possible, monthly basis
- duration of the heating period, expressed in hours, on a monthly and yearly basis
- indoor thermo-hygrometric conditions (*T* and *RH*)

In order to analyse a sufficiently significant data sample, it is necessary to collect monitoring data representative of at least three heating seasons. The duration of the heating period is represented by the hours during which the heat generator supplies the consumed energy *QP*. However, other data can be in some cases more appropriate to evaluate the *d* parameter. For instance, in case of a heating management service contract, the purchaser can consider more significant to identify with d the number of hours during which the appropriate minimum temperature conditions must be maintained in order to ensure the occupants' comfort (i.e. 20°C during occupancy hours). In this case, the aim of the heating management company is to define a heating strategy which enables to minimize the consumption and satisfy the minimum required level of environmental quality (that is the above mentioned 20°C).

The second phase consists of defining the consumption index (Corgnati, Filippi and Perino, 2007). For example, in the case of a heating management service based on the purchase/supply of thermal energy delivered by the heat generator, the consumption index referred to the actual energy delivered by the heat generator (*QP*) is obtained from the following expression:

$$QP_{s,c} = \frac{QP}{V} \cdot \frac{DD_c}{DD} \cdot \frac{d_c}{d} = QP_s \cdot \frac{DD_c}{DD} \cdot \frac{d_c}{d}$$

The $QP_{s,c}$ index represents the "conventional specific energy consumption for heating purposes", given by the ratio of the delivered thermal energy (measured by heat meters) to the gross heated volume, with reference to the conventional degree days in the examined area (DD_c), and the conventional duration of the heating period (d_c). The fuel consumption, or in this case the useful delivered energy, is first of all divided by the volume, in order to obtain a specific value. The mutual relation between consumption and volume is well known.

The proposed model for the $QP_{s,c}$ index assessment provides, in accordance with the European Standard EN 15203 and former authors' works (Corrado, Corgnati and Maga, 2004), a linear dependence between the energy consumption for heating and:

- the local degree days
- the duration of the heating period of the building

One can plot a graph of the monthly metered fuel consumptions in a given building (expressed in m^3 of natural gas per m^3 of gross heated volume) as a function of the corresponding actual monthly degree days. This will typically show how consumption is influenced by stochastic factors and deviates from perfect linearity. In particular, the users' behaviour may significantly influence the size of endogenous heat supply, the ventilation rate, the incoming solar radiation, etc. Once the monitoring data have been collected, it is always convenient to make an accurate analysis, in order to assess how decisive the influence of the above mentioned stochastic variables is on the actual consumption of an examined building.

With reference to the other parameter, that is the duration of the heating period (*d*), it is important to note that its actual value is strongly related not only to the occupation time of the building, but also to the thermal dynamics of the "building envelope-plant" system (the difference between light and heavy buildings is an example).

While assessing the $QP_{s,c}$ index, it is important to estimate the reliability of the metered energy consumption values. The heat meters, in fact, may often give approximate values due to possible malfunctions and measurement inaccuracies. On the contrary, the metered fuel consumptions values are typically more reliable. The reliability of the metered *QP* values is estimated by calculating, on a monthly and seasonally basis, the efficiency of the heat generator:

$$\eta_p = \frac{QP}{CE}$$

The evaluation procedure for generation efficiency has been amply dealt with in a former authors' publication (Corrado et al., 2004). As already mentioned, the index of conventional specific energy consumption for heating purposes $QP_{s,c}$ can be defined using monitored consumption data representative of at least three heating seasons, and can be useful to define consumptions and costs for a heating management service, or simply evaluate or predict the energy consumption of future heating seasons. The evaluation procedure presented above has been validated by the authors (see Corgnati and Corrado, 2006).

The procedure is mainly applied to compare the predicted consumption (on the basis of the specific energy consumption $QP_{s,c}$) with the actual consumption for a given heating season.

A chart should be used to collect data concerning both the building and its consumption, and the climate conditions. It can be divided into three main sections:

- general information;
- monthly energy and climate data; and
- diagram of comparison between predicted and measured consumptions.

The general information includes general data concerning the building (plant code, building name, city, and address), climate data (average monthly outdoor temperature, monthly degree days, climatic zone, and duration of the heating period), and the main characteristics of the building (category, gross heated volume, and fuel type).

The monthly data section includes a table showing conventional and measured quantities. The climatic zone where the building is located is defined on the basis of the number of degree days. The time interval for the conventional duration of the heating period is identified according to the climatic zone. For instance, with reference to a building in an Italian climatic zone E (number of degree days below 3000°Cd), the heating season extends from 15 October to 15 April. The conventional daily number of hours used to calculate the conventional duration of the heating period is set on the basis of the building use (i.e. 6 hours a day for schools and offices, 14 hours a day for residential buildings).

In order to compare the measured and calculated values, it is necessary to correct the "conventional data", according to the climate conditions and actual operating hours. To this end, the "corrected conventional specific heat supply" can be defined:

$$QP_{c*} = QP_c \frac{DD_r}{DD_c} \frac{d_r}{d_c}$$

A comparison between measured and calculated values is fundamental to evaluate the accuracy of the consumption prediction. In the above example, we plotted a graph showing corrected conventional heat supply (axis x) and the measured specific heat supply (axis y) for the heating of 117 schools during one entire heating season in climatic zone E. Obviously, in case predicted and measured data are perfectly coincident, the dots representing the examined sample would fall along the bisector of the first quadrant of the Cartesian coordinate system (y = x). This diagram showed that the dots, although scattered around the bisector, tended to concentrate mainly in the lower part of the quadrant, which revealed that the predictive model tends to slightly overestimate the actual consumptions.

It is evident that, in case the above mentioned predictive model is not applied to the consumption of every single building, but of an entire sample of buildings (i.e. for heating management service in a real estate), the comparison between total measured consumptions and total predicted consumptions is more significant.

The histogram in Figure 2.2.3 shows an example of comparison between metered and predicted heat supply for a mixed-use group of buildings where a heating management service is carried out. The real estate is basically composed of school buildings, representing over 95% of the real estate consumptions,

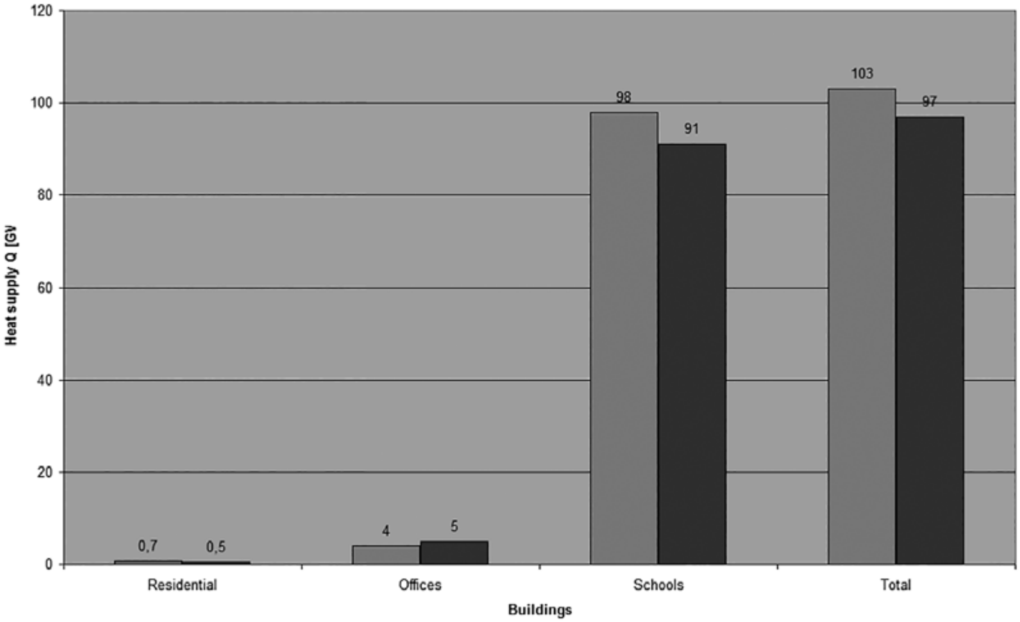

Figure 2.2.3 Measured specific useful heat supply vs. corrected conventional specific useful heat supply for a sample of buildings used for different purposes.

and some office and residential buildings, covering the remaining 5% of the consumptions. It is evident that the total estimated consumption predicts with reasonable accuracy the total metered consumption. The difference of 6% is an acceptable value, if we consider the number of stochastic factors which may interfere between predicted and actual consumptions, such as first of all the users' behaviour.

Energy labelling of heating energy consumptions

The assessment methodologies for the actual energy consumptions can be a useful starting point to carry out diagnostic processes on the examined real estates. In particular, the consumption analysis enables to identify anomalies and critical issues in buildings (i.e. in terms of overconsumption in comparison with the average behaviour of the examined sample of buildings).

The first step of the diagnostic process is the energy classification of the real estate. From the operative point of view, this means first of all defining the correlation between consumption and volume, in order to identify any possible cases which do not reflect the statistical trend of the sample.

The frequency distribution of the specific consumptions is then expressed, as a basis of the energy classification (consumption class A, B, C, etc.) which may lead to plan and develop energy requalification interventions. Obviously, priority will be given to high consumption buildings (in terms of both absolute and specific values). Therefore, the aim of these analyses is to examine the distribution of both absolute and specific consumptions and carry out an energy classification in order to identify those subgroups of the sample which present more critical issues in terms of energy.

As a case example, we studied primary heat consumption for the heating of a school complex, with the volume of most of the buildings below 40,000 m^3. However, higher volume buildings, despite their small number, have a significant impact on the total consumption. Again, we plotted our results in a graph, in which we found a large number of buildings fall above the regression line (passing through the origin) representative of the sample consumptions. This indicates that a number of specific consumptions are significantly higher than the sample trend.

These results must be integrated with frequency distribution and cumulated frequency of the specific consumption, expressed in kWh/m^3, for the examined real estate. About 60% of the values were lower than 40 kWh/m^3, which is a reference value set slightly below the average specific consumption value of the sample. Moreover, it was evident that in some cases the specific consumption significantly exceeded the average: 11% of the sample showed consumption above 80 kWh/m^3 (that is the double of the sample average value), and 7% showed consumption above 120 kWh/m^3 (that is the triple of the sample average value). It was therefore necessary to deepen the diagnostic analysis on the buildings presenting such critical issues, in order to identify the causes (which may be related to the building envelope, the plant technology, the plant management, the users' behaviour, etc.) and propose corrective solutions.

A further in-depth analysis can be carried out by classifying the energy efficiency of the real estate as function of the specific consumption value, set as an index for the characterization of the consumption in existing buildings. The following methodology providing for the definition of a dimensionless indicator of the actual consumption is adopted:

$$I_c = \frac{CEs}{CE_{rif}} \quad \text{(consumption index)}$$

where the value of CE_{rif} [kWh/m^3] (reference specific energy consumption) is obtained from the statistical analysis of the specific energy consumptions (*CEs*) of the sample of buildings characterized by the same use (school buildings). In this case, CE_{rif} correspond to the average value of the examined sample of buildings. On the basis of the I_c index value, four classes are defined, as shown in Table 2.2.1.

Each of the four above mentioned classes corresponds to an assessment of the I_c index (see Table 2.2.2). The aforementioned approach emphasizes an important aspect: it is evident that intervention priority is given to high consumption buildings (in comparison with the average consumption of the estimated sample of buildings), although general improving interventions on the building-plant system must not be excluded for classes A and B either. Therefore, the proposed diagnostic method defines the guidelines for the assignment of intervention priority within the specific examined sample of buildings. For this reason, the CE_{rif} value is not aprioristically defined on the basis of literature data, but it represents a studied characteristic datum of the real estate.

Our analysis showed that it is possible to define a clear and objective subdivision of the examined real estate into energy efficiency classes. At first, the diagnostic investigation was carried out on high consumption buildings. In this case, 10% of the buildings fell into class D (= specific consumption index above 2), therefore they were assessed as "non-classifiable".

Table 2.2.1 Variation intervals of the I_c index.

Index	*Variation interval*	*Class*	*Index assessment*
Consumption index	≥ 0.5	A	Excellent
I_c [−]	$0.5 > I_c \geq 1$	B	Good
	$1 > I_c \geq 1.5$	C	Mean
	$1.5 > I_c \geq 2$	D	Poor
	$I_c < 2$	Non classifiable	

Table 2.2.2 Assessment classes of the I_c index.

I_c	*Assessment*
Class A	Building consumption far below the average consumption of the reference statistical sample. No intervention is needed.
Class B	Building consumption slightly below the average consumption of the reference statistical sample. No intervention is needed.
Class C	Building consumption above the average consumption of the reference statistical sample. Intervention aimed at reducing heating consumption is recommended.
Class D	Building consumption significantly above the average consumption of the reference statistical sample. An urgent intervention aimed at reducing heating consumption is recommended.

The aforementioned tools are useful for the energy classification of real estates, which is a preparatory activity for the diagnostic investigation on high (absolute and specific) consumption buildings. Moreover, these procedures are a particularly effective support tool for planning extraordinary maintenance activities in real estates, which implies the definition of criteria for the assignment of intervention priorities.

Cooling energy consumption

In order to carry out an accurate monitoring of cooling energy consumption, direct measurements on individual items of equipment (chiller for example) or energy use (lighting for example) are preferable instead of overall utility energy bills. The total electricity bill, which may relate to time periods that are not ideal for monitoring purposes, combines energy consumption by numerous end-uses: lighting, ventilating and small power appliances (kitchen or office equipment, hi-fi etc. . . .) and sometimes process loads such as air compressors, pumps, fans etc.

Interpretation of electricity bills requires the listing of each type of electrical appliances whose consumption is included in the energy bill.

The analysis of air conditioning performances using global energy bills will be accurate only if the share of air conditioning energy consumption in the bill is significant. If energy consumption for cooling is submerged by that from other uses, accurate estimation will be impossible without sub-metering.

Several parameters have effects on air conditioning energy consumption and more generally on all thermal energy consumption. It is possible to distinguish four types:

- **Building parameters** are intrinsic to the construction of the building. The building envelope thermal characteristics, the glazing surface, heated/cooled areas and their location are part of them.
- **Policy parameters** depend only on the current building owner's decisions and his will to save energy. Equipment choices and investments, operational parameters such as temperature and humidity set points (if building centralized), the time of operation or maintenance and follow-up policies are among them. The sensitivity of energy consumption to these parameters is really important.
- **Behavioral parameters** depend on the occupants' choices. Operational parameters such as temperature and humidity set points (if room localized) or the natural uneconomic behaviour of occupants are part of them. Their influence on energy consumption can be large although the duration of the "good practice" behaviour can be short.
- **Activity parameters** depend mostly on the use of each space. These are largely determined by the business needs of the organization. They have an important influence on energy consumption, but a building owner or energy manager cannot usually change them.

- **Climatic data** Obtain values of external temperature and solar irradiance from the meteorological station that is most representative of the location of the building and of the time period used for energy metering. Solar irradiance shall be available for all main orientations of the building envelope that include transparent elements or elements covered with transparent insulation.
- **Internal temperature** The actual internal temperature should be assessed, since it often differs from design temperature and has a significant influence on the energy use for cooling or heating. Possible methods are: (a) in buildings with mechanical ventilation, the air temperature in the exhaust duct upwind of the fan can give an estimate of the average temperature of the ventilated zone when exhaust fan is on, (b) In many large buildings, a building automation and control system controls all the energy systems, and records the internal temperature and other energy related characteristics at several places, (c) the temperature can be measured or monitored (using small single-channel data loggers) at some representative places during representative days, i.e. days that have meteorological characteristics that represent the corresponding month or season, (d) the heating or cooling systems are controlled by thermostats, their set points could be used, provided that the calibration of the thermostat is checked.
- **Air infiltration and ventilation** External airflow rate shall be estimated as well as reasonably possible. Ways to do this include: (a) assessments of the airflow rates of air handling units where appropriate and (b) use of the tracer gas dilution method.
- **Internal heat sources** The occupancy (number of occupants) and presence time should be assessed from a survey or from the building management. The internal sources from artificial lighting and electrical appliances are at best assessed from electricity bills where there are no heating or cooling systems on the same meter. EN 15193 can also be used when no field data are available for lighting.

Table 2.2.3 Annual use of electricity in dwellings with energy efficient equipment (kWh).

Number of rooms	1	2	3	4	5	6
Number of occupants	1	1.5	2	3	4	5
Refrigerator	250	250	270	270	170	170
Freezer	0	0	0	0	200	200
Dishwasher	110	150	210	260	320	330
Oven	30	40	80	80	80	80
Washing machine	70	100	130	200	270	330
Dryer	130	200	260	390	525	660
Cooker	220	240	260	300	340	380
Other equipment	130	150	180	220	270	290
Total in kWh	940	1130	1390	1720	2175	2440
Floor area	40	60	80	110	140	170
Total in kWh/m^2	24	19	17	16	16	14

Table 2.2.4 Annual use of electricity for office equipment per work place in kWh and per conditioned area in kWh/m^2.

	Per work place	*Per m^2 conditioned area*		
Floor area per person		10 m^2	15 m^2	20 m^2
With energy efficient equipment	120	12	8	6
With typical equipment	230	23	15	12

- **Hot water use** Where a separate meter is installed, hot water use is obtained from the difference of two readings at the beginning and end of the assessment period.
- **Artificial lighting** Electricity bills may be useful to assess energy use for lighting, provided there are no other systems (cooking, heating, cooling systems or other appliances) on the same meter.

Energy and microclimatic labelling

The maintenance of particular thermo-hygrometric comfort levels is linked to certain energy consumption and a consequent energy cost (Corgnati, Fabrizio and Filippi, 2006). This apparently obvious statement leads to a deep reflection: it is useless to express the energy consumption for the microclimate control in a building, without relating such consumption to the microclimatic quality assessed for the environment (Corgnati, Filippi and Fabrizio, 2008). The aim of a thorough management of the building-plant system is to satisfy the thermo-hygrometric and air quality requirements with the minimum possible consumption of non-renewable resources, and therefore minimize the costs.

The first step is the clear definition of the thermo-hygrometric quality expected and measured in the environment. In fact, it is not rare that contracts for heating management services set standard values for temperature, relative humidity, and air quality with narrow tolerance intervals, often without considering that narrow thermal tolerance intervals lead to unavoidable high energy consumptions. Moreover, it is often forgotten that modern theories on adaptive thermal comfort allow wider tolerance intervals, and modifications of the environment parameter values enable to reduce energy costs.

From the normative point of view, the indoor environment classification in terms of microclimatic quality is dealt with in the draft standard EN15251, which is being developed by the European Committee for Standardization. This draft deals in general terms with the theme of indoor environmental quality, therefore including thermo-hygrometric, visual, and acoustic comfort, and air quality. With reference to the thermo-hygrometric comfort aspects, and in particular the classification used for the thermo-hygrometric quality assessment, the draft provides for the subdivision of comfort into classes, corresponding to three different levels of environmental quality (class 1 or A is characterized by the narrowest tolerance interval and the highest thermo-hygrometric comfort; the attribution of a number or a letter to the class is being discussed). In particular, the draft standard defines the thermo-hygrometric parameters, divided according to the building use, which have to be adopted at design stage, in order to measure the building-

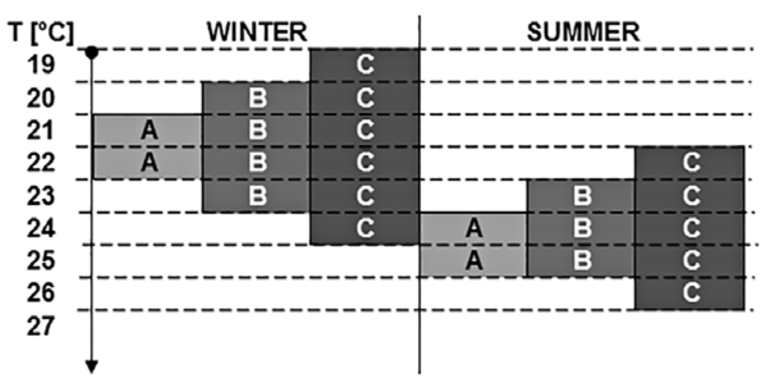

Figure 2.2.4 Operating temperature intervals recommended for the design of fully mechanically controlled office spaces, during summer and winter seasons.

plant system during summer and winter seasons. Figure 2.2.4 shows the temperature intervals with their respective classes, proposed for air-conditioned office spaces.

Figure 2.2.4 clearly shows that the acceptable temperature variation interval increases progressively from A to C class: the interval is of the order of 2°C for class A (both in winter and in summer), while for class C it extends to 6°C in winter and to 5°C in summer. Obviously, the extension of the interval has a direct impact, not particularly on the set-point temperature value which must be maintained in the environment, but on the acceptable regulation bands.

Therefore, it is clear that the purpose of maintaining a certain temperature level must be supported by equipment able to achieve the objective. For instance, it is impossible to keep an office space in class A during the whole year without installing an air-conditioning system able to control the temperature within the narrow pre-set intervals. However, in many cases the requirement of mechanical climate control is limited to only one particular period of the year (i.e. schools just need a heating plant), or more periods of the year alternated with natural climate control periods (i.e. offices need heating in winter, cooling in summer, and natural climate control in mid-season). The intervals proposed in Figure 2.2.4, as clearly indicated, refer to the design of fully mechanically controlled environments.

What happens when we want to examine the actual microclimatic quality of an indoor operating environment throughout the whole year?

The in-situ study of microclimatic quality through long-term measurements was carried out according to a research design guide (ASHRAE RP884), focused in particular on the theme of thermal quality levels. The obtained results gave an impulse to a number of further in situ case studies, which led to the so called "adaptive comfort" theory, particularly suitable for describing the thermal comfort conditions in non-fully mechanically controlled environments (deDear and Brager, 1998).

This theory comes from the assumption that the comfort sensation can't only be explained by the thermal balance equation between the human body and the surrounding environment (as per Fanger's

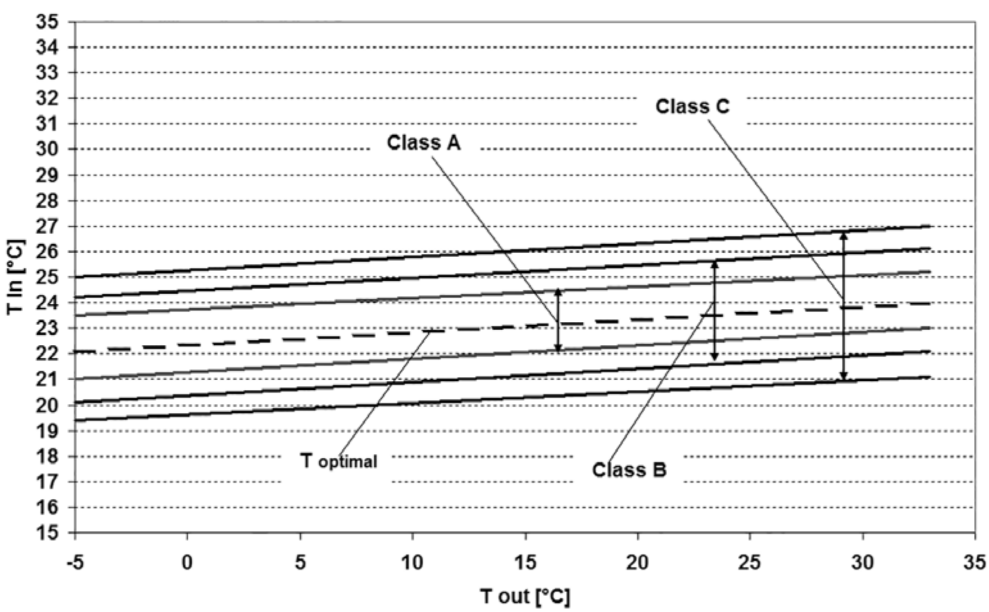

Figure 2.2.5 Intervals for thermal quality classes in "fully mechanically controlled" environments (as per ASHRAE RP884).

classic comfort model (1982), perfectly suitable for fully mechanically controlled environments), but it must also consider other factors (behavioural, cultural, social, contextual) which may affect the thermal sensation (deDear and Brager, 2002).

The impact of such factors increases in a "naturally" controlled environment, where the microclimate is not "artificially" created and controlled by a plant (fully mechanically controlled) but is the result of the user's direct action (even just partially, if we consider natural ventilation) (Brager and deDear, 2000). The conducted studies have demonstrated that people have a higher tolerance to "less narrow" microclimatic conditions (in terms of extension of the acceptable temperature intervals) in naturally ventilated environments. In fact, people can activate behavioural, physiological, and psychological regulation mechanisms which lead to a wider acceptability of thermo-hygrometric conditions.

One of the main results of ASHRAE RP884 research project is represented by the diagrams showing how the operating temperature intervals for the thermal quality classes (class A, B, and C) vary according to the average monthly outdoor temperature, both in "fully mechanically controlled" and "naturally ventilated" environments (Figures 2.2.5 and 2.2.6).

These diagrams can be opportunely used as a basis to represent the thermal monitoring results of an indoor environment (i.e. an office or a classroom), and consequently to assess the thermal quality during occupancy hours.

The example in Figure 2.2.7 shows the results of a long-term microclimate monitoring of a "hybrid" environment: heating by radiators and natural ventilation by opening windows in winter season, and cooling by natural ventilation and opening windows in mid and summer season (Ansaldi, Corgnati and Filippi, 2006). For this type of environment, typical of many Italian buildings, a hypothesis of temperature intervals and microclimatic quality classes was proposed, according to the aforementioned research methods (Corgnati, Ansaldi and Filippi, 2008b). In particular, Figure 2.2.7 shows the results of a monitoring campaign, therefore it displays the indoor temperature values measured in relation to the thermal quality classes (A and B). Two parts are clearly distinguished in the figure: the left side of the

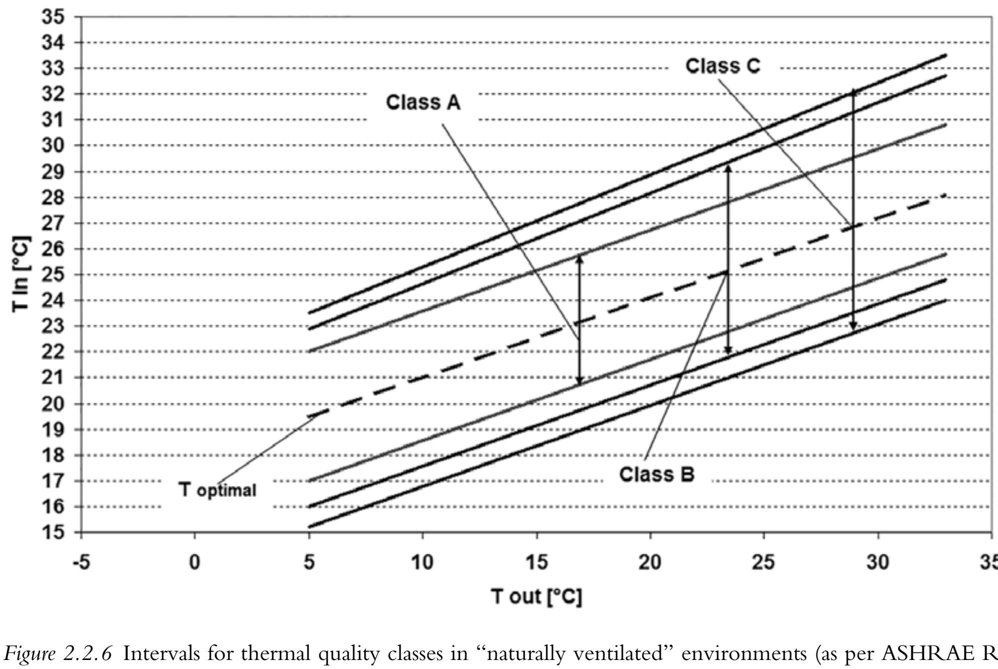

Figure 2.2.6 Intervals for thermal quality classes in "naturally ventilated" environments (as per ASHRAE RP884).

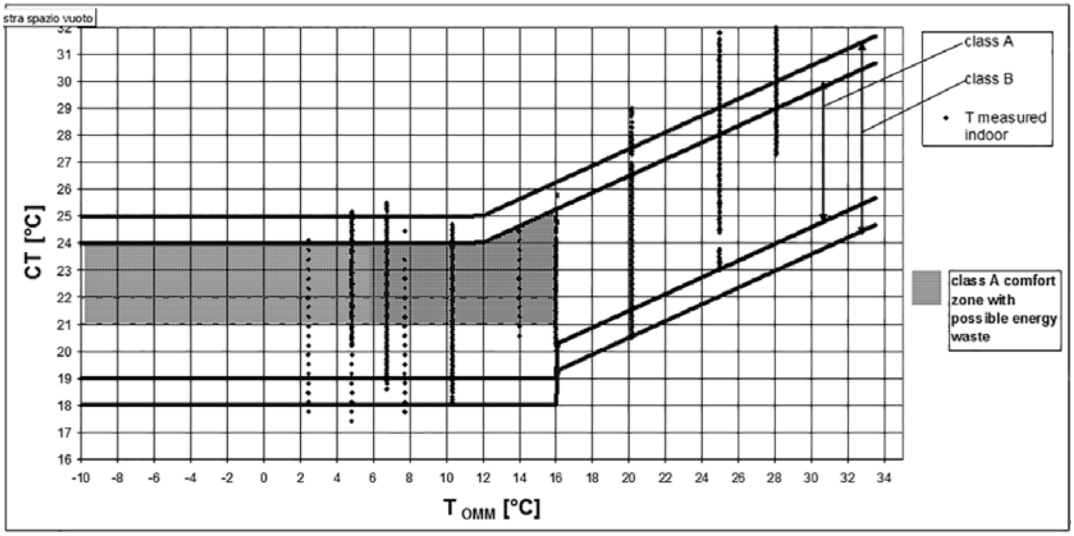

Figure 2.2.7 Temperature values and thermal quality classes proposed in the hypothesis of a thermal model for hybrid environments (as in Corgnati, Filippi and Perino, 2006b). CT = operating comfort temperature; TOMM = average monthly outdoor temperature.

diagram (mechanical climate control during the heating season) shows that values and microclimate class intervals remain constant despite varying outdoor temperature, while the right side of the diagram (no mechanical climate control) shows that values and microclimate class intervals vary according to outdoor temperature variations.

Therefore, such diagrams can be opportunely used as a basis to represent the thermo-hygrometric monitoring results, and consequently to assess the obtained environmental quality.

The thermal quality assessment of the environment can be expressed by a synthetic index called "performance index", PI (Corgnati et al., 2006b), which represents the percentage of measured values falling within the acceptability interval of a given class. Therefore, this parameter indicates how often the examined environment is exposed to acceptable thermal conditions.

With reference to the measurements shown in Figure 2.2.7, the performance index of class A intervals is 84% during the heating period, and decreases to 69% if we consider the whole analysis period (from October to July). This methodology of data representation and analysis is very effective as it ensures representation clarity and easy comprehension of the thermal quality index. The microclimatic quality analysis described above can be conducted while monitoring the energy consumption for air-conditioning, in order to prove their correlation with the obtained thermal quality level.

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2.3
ENERGY MODELLING

Pieter de Wilde and Godfried Augenbroe

Introduction

Energy modelling is the discipline that models the energy flows in buildings and between a building and its (local) environment, with the aim of studying the heat and mass flow within buildings and their (sub)systems under given functional requirements that the building must satisfy. Most of the current models are computational in nature. This means that the models are implemented in the form of a computer simulation that replicates a part of physical reality in the machine. To do this efficiently, energy models idealize, quantify and simplify the behaviour of real world systems like buildings by describing them as a set of internal variables, distinct system boundaries, and external variables. The application of physical laws leads to a set of relations between the variables of this physical model which together constitute the mathematical model. This is then coded in some programming language and subsequently run as a computer program (commonly named tool). In energy modelling the area of interest is the thermal behaviour of buildings, especially in terms of energy efficiency and thermal comfort.

Energy modelling is a key element of the broader discipline called building simulation, a domain that, apart from thermal aspects, also studies (day)lighting, moisture, acoustics, air flow, and indoor air quality. The discipline of building simulation first emerged during the 1960s. In this period research efforts focused on the study of fundamental theory for building simulation, mostly for energy transfer. During the 1970s the new field matured and expanded, driven by the energy crisis of those years. Most research was devoted to the development of algorithms for heating load, cooling load and energy transfer simulation. In the 1980s the effects of the energy crisis waned. However, this effect was compensated by the advancements in personal computers, which made building simulation widely accessible. As a result, research efforts now concentrated on programming and testing of computational tools. In the same period, natural selection set in: only tools that had active support from their makers (maintenance, updating, addition of desired new features) were able to survive. In the late 1980s and the 1990s the field of building simulation broadened with the development of new simulation programs that were able to deal with lighting, acoustics and air-flow problems. The last decades have shown progress on a range of advanced aspects, such as inclusion of uncertainty and sensitivity analysis in simulation, run-time coupling of programs, equation-based modelling, and district or city scale modelling. In 2014, the ever-increasing availability of monitoring data is starting to change the discipline. The advent of Automated Meter Reading (AMR) seems to promise an era where for the first-time measurement and data mining techniques might become a viable alternative to modelling for buildings that already have been constructed and are in actual use.

Buildings can be modelled on three distinct fidelity levels, often referred to as 'black box', 'grey box' and 'glass box'. This latter can be subdivided into 'milky white glass box' and 'true glass box'. Each indicates a specific level of model fidelity, user transparency and modelling capacity.

Black box (or statistical) models have been developed to predict the energy consumption of buildings taking into account climate profiles at the regional scale. Since statistical models are mostly based on historical information, data collection is typically intense. Regression analysis and neural networks are the most commonly used techniques for developing statistical energy consumption models.

Grey box (or normative) models are based on simplified normative calculations, such as described by the CEN-ISO 13790 Standard (CEN-ISO, 2008). These models are based on a first order principle energy balance of a building, typically at a monthly resolution. They use quasi stationary calculations of all energy flows with internal utilization factors for heating and cooling and system efficiency factors that were calibrated on a large sample of similar buildings. The energy performance is calculated on three separate levels: energy load, delivered energy and primary energy use. It should be kept in mind that normative models have been made for the specific purpose of comparing buildings of a certain type (officially termed functionally equivalent) under similar and well defined (hence normative) usage conditions. The simplified models underlying the normative tools have found some employ in regular building energy prediction by substituting the normative usage conditions by the actual usage and occupancy scenario and specific condition parameters of the design (Lee, Zhao and Augenbroe, 2013a). If one is interested in aggregate (e.g. monthly) energy outcomes, this is usually acceptable. One should however pay extra attention to checking whether the utilization factors are calibrated on the type of building considered and in the local climate.

Figure 2.3.1 Biomes at the Eden Project, Cornwall.

Source: Chapter authors

The milky white box (or dynamic simulation) models consist of the current state-of-the-art transient tools for deep and dynamic energy assessment. These tools offer a wide range of pre-configured models that allow to simulate the behaviour of key components such as façades, windows, and typical building (HVAC) services. However, the aspect of pre-configuration also limits the amount of flexibility that these tools allow.

True glass box (or open) models have rich modeling features and virtually unlimited configuration capabilities, either through the use of modules and API (application programming interface) levels, or by building each model from scratch in new expressive environments like Modelica (Wetter, 2009)

While energy modelling remains the most prominent field within building simulation, it is closely related to modelling the aspects that have a direct impact on energy use and thermal comfort. This is particularly so for the study of air flow and lighting, since air flow impacts on ventilation and infiltration losses, daylighting is coupled with solar gain, and artificial lighting contributes to internal gain and thus impacts heating and cooling loads. Such interaction becomes especially interesting within innovative buildings like the biomes of the Eden Project (see Figure 2.3.1), where a large space is subject to a mix of natural ventilation and mechanical ventilation, novel building skin elements are used, and indoor air criteria are different from normal, in this case catering for plant comfort rather than human comfort.

An in-depth discussion of the basics of energy modelling is provided by Hensen and Lamberts (2011); more advanced topics in simulation are discussed by Malkawi and Augenbroe (2004). Recent progress is published in the *Journal of Building Performance Simulation* (Taylor and Francis) and *Building Simulation: An International Journal* (Springer), as well as in the more generic building science journals such as *Energy and Buildings, Building and Environment, Automation in Construction, Advanced Engineering Informatics* (Elsevier) or *Building Research & Information* (Taylor and Francis). A good and well-known treatises on heat and mass transfer in general is Incropera, DeWitt, Bergman and Lavine (2007); for more detail on building services, see the ASHRAE handbooks (e.g. ASHRAE, 2012) and, for an overview of building equipment, refer to Stein and Reynolds (2006).

Energy modelling tools

There are currently many tools available for building energy modelling and analysis. Tools often featured in the literature mostly fall into the category of 'milky-white box' and include, among others, ESP-r, EnergyPlus, TNRSYS, eQuest, DesignBuilder and IES-VE. A good overview of building energy software tools remains the directory provided by the US Department of Energy (2014). This directory lists well over 400 tools, ranging from software that is still under development to commercially available software.

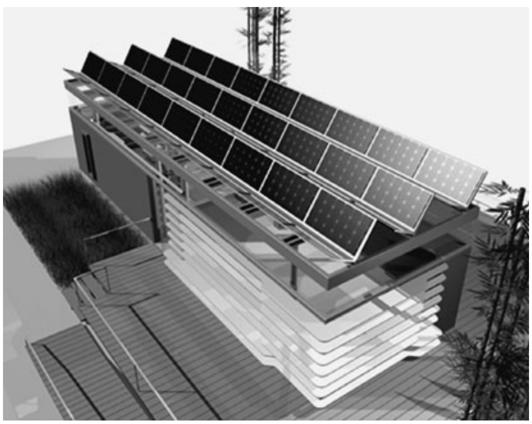
Many of these tools have over the years fostered a community that continues to develop new components or modules that can be added to a growing library. This has produced a rich palette of component types for the major tools in the current market place. For the average user, who is not interested in adding customized modules the use of the tools is rather straightforward but requires training and a basic level of understanding of the physical principles that underlie the simulations.

There is general consensus that the current generation of tools is mature, robust and of high fidelity, i.e. accurate enough for most applications. User interfaces are continuously improving and data transfer with other up and downstream applications is being automated, thus avoiding tedious preparation of (mostly geometric) input data and cumbersome parsing of output data by hand for post-processing or design decision making. The latter is part of providing interoperable solutions, which have a much wider scope than energy modeling software (Bazjanac, 2007). Notable examples are Simergy and Open Studio. Simergy is a user interface for EnergyPlus under development, with among others drag-and-drop editing facilities for HVAC schemes (LBNL, 2014a). Open Studio originated as a plug-in to link Google Sketch-Up to EnergyPlus but has now been developed into a platform that allows communication between a range of tools that include EnergyPlus as well as the lighting simulation engine Radiance (NREL, 2014a).

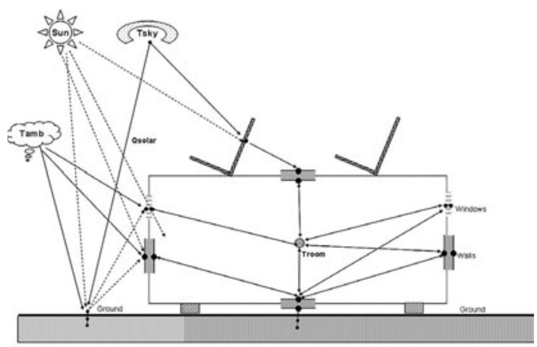
Figure 2.3.2 shows an example of the typical energy modelling steps, going from (a) a design representation to (b) an idealization that is relevant to the investigation at hand to (c) a diagrammatic representation of the computational model, to (d) the output of a computation. The core part of energy modelling is choosing the right idealization (b) which then more or less automatically leads to an appropriate choice of computational model and level of resolution (c).

It is interesting to note that the current generation of closed tools 'collapses' stages b and c into one stage, as users do not (and mostly cannot) interact with the computational model; the physical idealization generates the computational model automatically. Open tools like Matlab on the other hand give the user explicit access in stage c which obviously comes at the expense of more work and more advanced skills that are expected of the user.

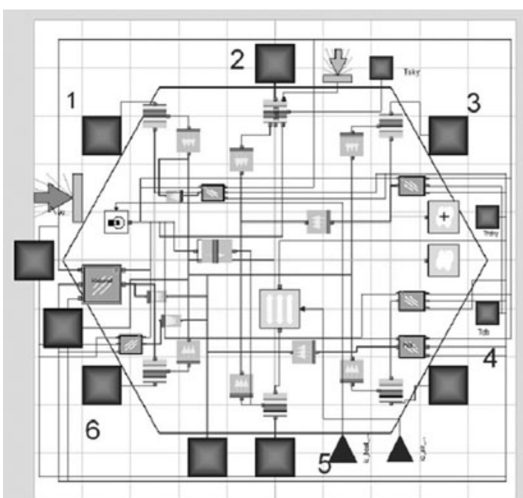
In spite of the successes and growing user base of current tools, there is little reason to become complacent about the state of building energy modelling tools. Most of the current (second generation) toolset



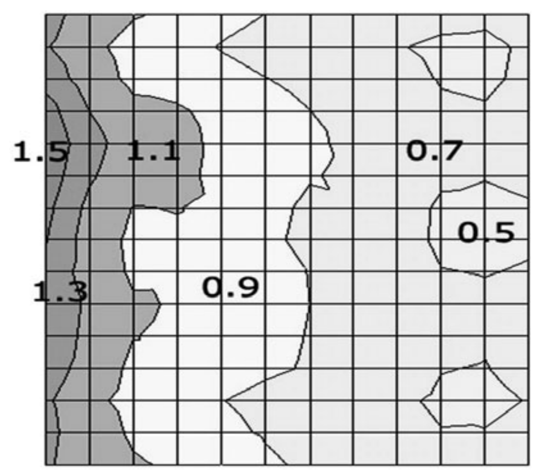
(a) The design model



(b) Idealization



(c) Diagram of computational model



(d) Generated output

Figure 2.3.2 The life cycle stages of energy modelling.

use old-style imperative programming techniques, and their computational kernel uses quite outdated techniques. Although this software is more than adequate for routine applications, its outdated basis will eventually become a roadblock when far reaching extensions are attempted and new application areas are entered. A future, third generation toolset might offer:

- functional integration of energy modeling in building design (CAD) systems; and
- full co-disciplinary energy modeling, allowing HVAC system experts, control system developers, architectural designers to add model components to a shared multi-domain responsive energy model during full concurrent real time collaborative design of all the systems.

Several research projects over the years have set this development in motion, notably EKS (Clarke et al., 1992), SEMPER (Mahdavi, Mathew, Kumar and Wong, 1997), SPARK (Sowell and Haves, 2001), IDA (Sahlin, Eriksson, Grozman, Johnsson, Shapovalov and Vuolle, 2003), and others. A breakthrough toward the third-generation tools is expected from the use of Modelica (Fritzson, 2004), which promises to deliver the generic declarative simulation language substrate on which configurable applications could be built. The latest development employs the best of both worlds, i.e. both the large semi-closed simulation tools for the conventional modelling of the building as a whole and the experimental open simulation languages for complex components or systems. The most immediate applications of the latter are control systems which are typically hard to specify in the conventional energy models. Early work in this direction was first reported by Wetter and Haugstetter (2006), and the first industry strength application is now available in the form of the Building Control Virtual Test Bed or BCVTB from Lawrence Berkeley Labs (LBNL, 2014b) and a Modelica Buildings Library is under development (Wetter, Zuo, Nouidui and Pang, 2014).

In the meantime, more generic solutions to co-simulation have received quite a bit of attention (Nouidui, Wetter and Zuo, 2013). The typical way that co-simulation is implemented is through a standardized construct that uses master-slave communication between two modules that are added to the both simulation tools that are running in the co-simulation. It is to be expected that the current simulation tools will be offering the facilities to add these co-simulation plug-ins without requiring deep programming expertise.

Application in energy efficient buildings

In the engineering of sustainable buildings, energy modelling is closely integrated with the design of energy efficient buildings. Different drivers have been pushing the construction industry to make buildings more energy efficient: first the oil crisis of the 1970s, then the aim for sustainable development (Brundtland, 1987), and more recently the concerns about the depletion of fossil fuel reserves, peak oil (Bentley, 2002) and climate change (Stern, 2006).

As a consequence, building requirements have evolved to include increasingly stringent energy saving demands. Recent buildings are required to meet a minimum level of overall energy performance, which can only be achieved by using holistic design approaches that minimize heating and cooling demands, integrate advanced high efficiency building systems that utilize renewable energy sources, and make the best use of any fossil fuels through application of highly efficient energy conversion technologies. Within such buildings, all different kinds of systems interact to make buildings more energy efficient (ASHRAE, 2012). This makes ensuring the overall performance of the building a much more complex task, that rather than deferring it to the final stages of the design, needs to be undertaken during all stages of design. Designers and engineers therefore are becoming more reliant on the use of advanced dynamic building simulation tools which require special skills for the preparation of idealized or schematic models and a computational representation as explained above. Acquiring these special skills typically takes a degree in architectural or mechanical engineering with at least two graduate courses that teach these skills. In addition, it usually requires training courses and/or a training workshop provided by the tool vendor.

The domestic state-of-the-art in the UK is demonstrated by advanced dwellings like the Kingspan Lighthouse, a BRE showhome which is designed to meet the legislative standards anticipated to be in effect in 2016. It incorporates a complex set of interacting energy saving measures: PV array, phase change materials, windcatcher for passive cooling and ventilation, passive solar windows, structural insulation panels, heat recovery for ventilation, biofuel boiler, and solar shading (Kennett, 2007), as shown in Figure 2.3.3. Internationally, homes built to the 'passive house' standards demonstrate the prospects of realising extremely efficient domestic buildings with a heating requirement of less than 15 kWh/m^2 per year through a combination of passive solar design, superinsulation, advanced glazing systems, a good balance of air tightness and ventilation, energy efficient lighting, and high-efficiency heating systems like heat pumps (Feist, Peper and Görg, 2001).

Commercial and public buildings, like for instance offices, hospitals, educational buildings, shopping centres and factories, are more complex than houses by their very nature. They use a palette of interventions that range from passive architectural features to added active systems. Many have high-tech façades and building services. In the UK, a good example of a straightforward yet sustainable office is the Home Office Headquarters in Sheffield, which utilizes solar protective glass, local ventilation and heat reclaim systems, maximal use of daylighting, occupancy sensors, and extensive monitoring of energy use patterns ('Home Office goes green', 2007). On the active systems side of the spectrum, an internationally acclaimed project is Council House 2 in Melbourne, Australia, the CIBSE 'sustainable building of the year 2007', which combines chilled ceilings, thermal night cooling, solar panels and wind turbines (World Green Building Council, 2008).

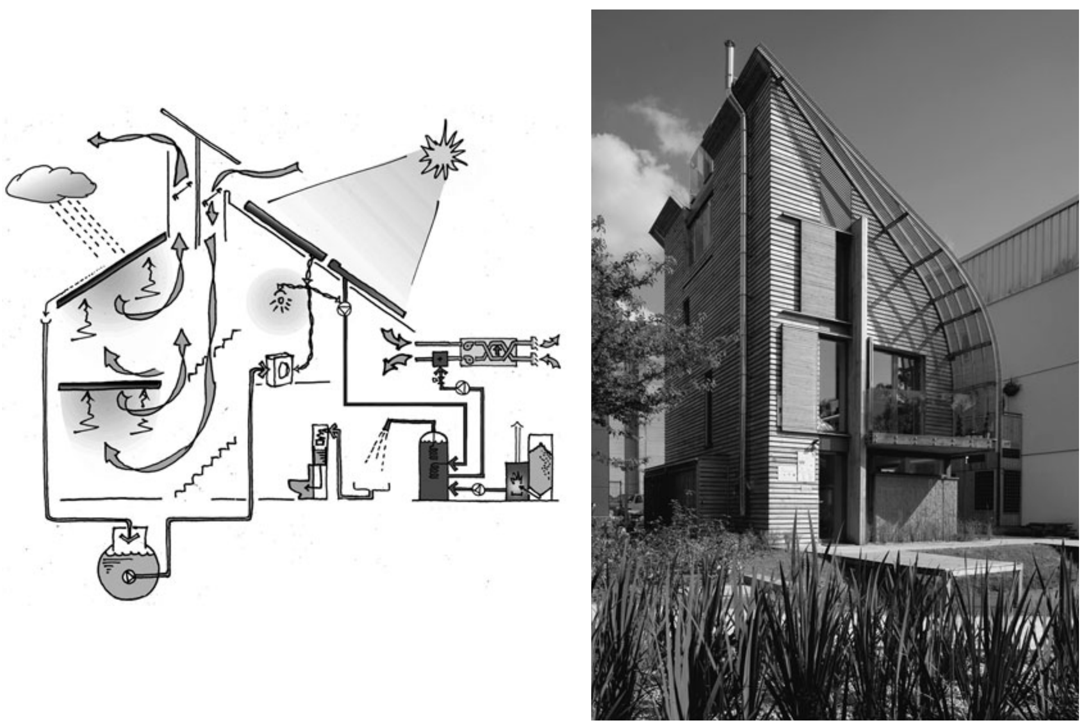


Figure 2.3.3 Kingspan Lighthouse: concept sketch (left) and finalized building (right).

Source: SheppardRobson, Hufton + Crow

Obviously, the engineering of such buildings, whether domestic or commercial/public, requires that the design team is able to ensure that energy targets are being met, while maintaining thermal comfort in both summer and winter. Energy modelling can help this process in various ways, e.g. by supporting the evaluation of alternatives, system configuration, sizing and arrangement, and optimal system control strategies and set points. However, the process is a complex one, requiring many trade-offs and weighting of performances for sub-systems.

Within the construction industry, sustainability rating methods are gaining momentum. The current voluntary schemes, like BREEAM, GBTool, and LEED, offer a quality label like 'excellent' or 'gold', which offers status and is seen as desirable by many clients. However, it must be noted that energy use is only one of the categories considered, on average making up 10–20 % of the total score. Furthermore, energy performance is represented as improvements against a current-practice base case. This makes these rating methods rather blunt when striving for high energy performance.

It is important to note that specific energy efficiency targets cannot be seen in isolation from an associated measurement principle. For managers of building portfolios (corporate owners, university campuses etc.), targets will often be related to actual meter readings, like annual consumption (often per square meter). For buildings that are yet to be constructed, targets will be related to the performance predictions based on standardized calculation recipes. In novel design concepts, or non-routine system concepts, standard calculations will provide an estimate of the demand but how this demand is met by the systems, and how the systems interact with occupants and other building systems can only be derived through advanced dynamic simulation of the building behaviour, or, in short through expert driven building energy modelling.

Challenges in thermal building engineering

A review of earlier research efforts that focussed on the uptake of simulation on building design (de Wilde, 2004) listed a number of plausible barriers to the integration of building simulation in building design. Many of these remain in place today. McElroy, Cockroft and Hand (2007) reiterate that the main issues facing the application of building simulation in design practice are the training of the 'simulationists', trust in the accuracy of models, (mis)interpretation of results, and the role of uncertainties. Authors like Attia, Hensen, Beltrán and de Herde (2012) and Bleil de Souza (2013) focus on the different paradigms and backgrounds that are perceived to divide architects and engineers. Bazjanac (2005) reports progress in the development of data exchange (interoperability) but concedes that some of the current software is not compatible, or that existing interfaces need fixing. At the same time, Schwede (2007) notes that current simulation tools still view buildings in a simplified manner, and do not allow for a full 'simulative investigation'.

Yet given the complexity of modern buildings, as described in the previous section, energy modelling needs to be a crucial instrument in the engineering of sustainable buildings. Indeed, it is already used in many projects and now plays a major role in the work of services engineers, energy systems designers and building physics consultants. The energy modelling that specialized firms provide or architectural firms do in-house is diverse. It ranges from early conceptual design support, relying mostly on the expertise and inventiveness of the energy consultant, to detailed simulations in the final stages of the design. In early design the emphasis is on creating meaningful schematic models of the proposed design concept and managing different criteria by which suggested design options can be judged. This work is not well supported by simulation tools; rather the early stage requires deep insights and expertise supported by mostly simple calculations. In later design stages the emphasis shifts toward deep inspection of all the systems and their dynamic interactions. This requires expert skills in simulation, reflecting a shift from insight informed by simple schematics toward brute force simulations that replicate physical model behaviour as accurately as possible in the computer. The energy simulation models represent the physical behaviour of components and their dynamic interactions recognizing all intricate phenomena in these interactions. Interpreting the outcomes and aggregating them into meaningful measures that support the dialogue with the design team becomes the crucial, expert driven after-stage of the simulation. Both types of energy modelling and their intermediate manifestations require different types of expert knowledge, and indeed very different tools to support them. It is often stated that the early conceptual stages are lacking adequate tool support, which is then always declared a critical deficiency because of the far-reaching consequences of early decisions through ensuing design evolution. This raises the question where a concerted effort to generate energy models that support conceptual design should focus. The authors of this chapter argue that true conceptual design support requires one to show which design option has a statistically high(er) chance of impacting the energy performance of the eventually resulting final design. Very few, if any, of the past research efforts in this area has framed the objective of their research in this way. A renewed effort is therefore needed to predict energy performance as an approximation of the probability distribution of the relevance of different design options. The underlying energy models that are needed to achieve this will be mostly normative, putting less emphasis on quantification and more on explanation. It should be stressed that the best intermediary between conceptual design decisions and an energy assessment is the trained mind of the energy modelling expert. This puts the burden of better early design support squarely on the shoulders of the educators that stand at the cradle of the emerging guild of 'energy design modellers'.

In the meantime, few, if any, buildings are delivered without a detailed energy model and simulation of the energy consumption of the consumers in the building (heating, cooling, fans, pumps, hot water, lighting, appliances). Yet at the same time there are also many instances of buildings not living up to the expectations of the clients and design teams. Often, actual buildings require more energy to run than anticipated during the design stage, showing a significant gap between predictions of building energy use at the building design and engineering stage and measurement results once buildings are operational (Bordass et al., 2001; de Menezes et al., 2012), and complaints about occupant discomfort persist (Karjalainen and Koistinen, 2007). This 'energy performance gap' erodes the credibility of the design and engineering sectors of the building industry and leads to general public scepticism of new high-performance building concepts. A couple of observations can be made. First of all, energy simulation models are typically based on 'idealizations' that assume that buildings are built and operated according to specification. Moreover, they assume 'perfect knowledge' about physical properties, occupant and operator intervention, operating schedules etc. This is hardly realistic however when one realizes that buildings exist in an unpredictable environment, where deteriorating systems, bad workmanship, unforeseen use and adaptations are the rule, rather than the exception.

Researchers have started to look at the role that these uncertainties play in predicting energy performance. Figure 2.3.4 shows an example of a small study into the effect on monthly cooling demand of a single office space (Augenbroe, McManus, Zhao, Li, Heo and Kim, 2008). As the figure shows, the expected mean average is around 140 kWh/month, but the uncertainty ranges from 120 to 165, roughly plus or minus 20%. In this case only a subset of all uncertainties was taken into account whereas user behaviour was not included.

Other deficiencies of current energy modelling result from the fact that our models are in some cases only abstractions of real behaviour. Advanced control strategies for example can look good on paper and their dynamic simulation can be carried out cleanly. However, their actual implementation is complex and plagued by all kinds of practical issues such as sensor errors, cycle times, activation delays etc. Not surprisingly, it can take up to a year to get the building controls to perform close to expectations. In general, it is not uncommon that buildings under-perform the predicted energy performance by as much as 30%. The main reason is deviation from the idealized assumptions embedded in the energy model, unexpected circumstances, malfunctioning of system components and bad workmanship. Continuous commissioning is often seen a way to restore the energy performance of a building to its expected

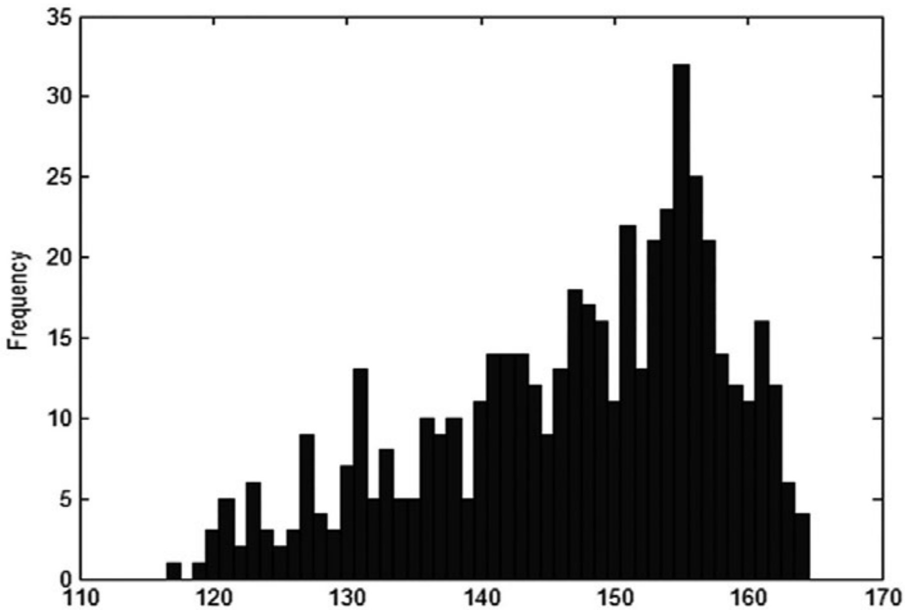


Figure 2.3.4 Example of monthly cooling demand calculation with uncertainty.

Source: Chapter authors

levels, but it should be well understood that a large part of the discrepancy may originate from too optimistic assumptions in the first place. Only the explicit modelling of uncertainties in model parameters and model assumptions will reveal the extent (probability) to which the energy model outcomes predict reality.

When looking at the role of energy modelling in building engineering, it is also important to note that the building design process itself is changing. The use of digital media is leading to new approaches to design. In these approaches not only do designers work with new ways of representing the developing building design but they also develop new ways of generating forms, and they increasingly analyze the performance of their designs (Oxman, 2006). In developing new tools and design systems, it therefore is important to ensure a fit with the cognitive way in which designers work (based on design reasoning and thinking) while at the same time being aware that the design practice (tools, products, process) might change in the future (Kalay, 2006). The current – as of 2014 – status in thermal building engineering practice, as informally conveyed by numerous consultants active in the industry in the UK, is one of buoyancy. Performance requirements for energy efficiency are becoming increasingly stringent, boosting the work volume of the consultancy companies. An uptake in the economy is presently driving a multitude of construction projects, so skilled modelling and simulation workers are again in high demand. However, this situation leaves little room for a fundamental review of the practices in the consultancy office, and for improving the state-of-the-art from within the industry.

Recent initiatives and outlook

The work on integration of energy modelling in the building engineering process focusses on one or more of the challenges mentioned in the previous section. These efforts augment continuous work on the improvement of building performance simulation tools in general, including work on better input data (climate files, user behaviour, system control), algorithms, data post-processing, data mining and result visualization techniques.

While the major tools are getting bigger, user friendlier and feature richer, a grass roots community is developing extensible Matlab libraries/toolboxes (Riederer, 2005). Due to the large proliferation of Matlab in the engineering curricula, this opens the door to the introduction of research-oriented energy modelling in graduate class exercises and PhD research projects. Whether this will grow out into a Matlab based open source 'energy modelling research community' remains to be seen. Rather it is to be expected that the grass roots development of Matlab and Modelica libraries will be leveraged in existing and growing co-simulation environments.

On the input side of the major energy tools, one category of research and development efforts attempts to integrate simulation with early or conceptual design by linking emerging CAD sketching tools with energy simulation engines, see for instance (Rizos, 2007). However, as is demonstrated by the example of the link between Sketchup and EnergyPlus, such linking is depending on interoperability, as reported by Bazjanac (2005). A more fundamental approach, which looks at scalable and reusable spatial models, has been described by Suter and Mahdavi (2004). It is interesting to note that in the adjacent discipline of lighting modelling, simulation has already been fully integrated with CAD systems for a while: Desktop Radiance operates from within AutoCad 14, using pull-down menus (Mistrick, 2000) whereas the Radiance based DIVA grasshopper plug-in for Rhino has enjoyed a growing user base. No similar tool has been demonstrated for energy simulation thus far, which underlines how difficult it is to map unconstrained design models into energy models. It will be more likely that energy modelling environments like OpenStudio will constrain the generation of models by positioning gbXML as the neutral format for energy model generation and combining this with design contextual wizards that prompt the designer/modeller to add contextual and run time data to the model. This is not unlike the push-pull model of data population suggested in the exploratory DAI project discussed later in this section.

On data post-processing and visualization, recent work at the University of Strathclyde by Morbitzer (2003) and Prazeres (2006) has focussed on the presentation of simulation results by means of an Integrated Performance View. This tailors simulation output toward specific aims like design exploration, analysis, representation and reporting, while providing flexibility to match individual preferences. It employs data mining and clustering techniques to filter through a range of simulation results. A related area under development is the use of uncertainty and sensitivity analysis (UA/SA) to guide design, as previously discussed. A prototype of an UA/SA workbench has been launched (Lee, Sun and Augenbroe, 2013b). It contains a standard uncertainty repository that can be easily imported in other simulation environments and pre-processors. It is to be expected that the integration of this repository and mainstream UA/SA functionality will take place in the next 3–4 years. Most large simulation platforms already offer parametric simulation options for optimization or parameter sensitivity studies. This is either an embedded function such as offered with tools such as ESP-r or as an add-on such as GenOpt (Coffey, Haghighat, Morofsky and Kutrowski, 2010), BEopt (NREL, 2014b) or JEPlus (Zhang, Tindale, Garcia, Korolija and Tresidder, 2013) for EnergyPlus. In the most recent developments these functions are being generalized and offered as seamless part of simulation environment, such as for instance promised by the ongoing development of the OpenStudio environment (NREL, 2014a). Once these developments have come to fruition it will be easy for third parties to slot in new optimization approaches, expanding UQ repositories from different research projects and UA workbenches as addressed above. Finally, it is worth to mention the work on the coupling of energy modelling with the realm of intelligent computing. Here advanced search and visualization techniques can be applied to the field of energy simulation, allowing to push the boundaries of what is currently undertaken in the design office. As an example, Figure 2.3.5 shows two clusters, A and B, of energy efficient solutions obtained from a 9-dimensional search space using a genetic algorithm (de Wilde, Beck and Rafiq, 2008).

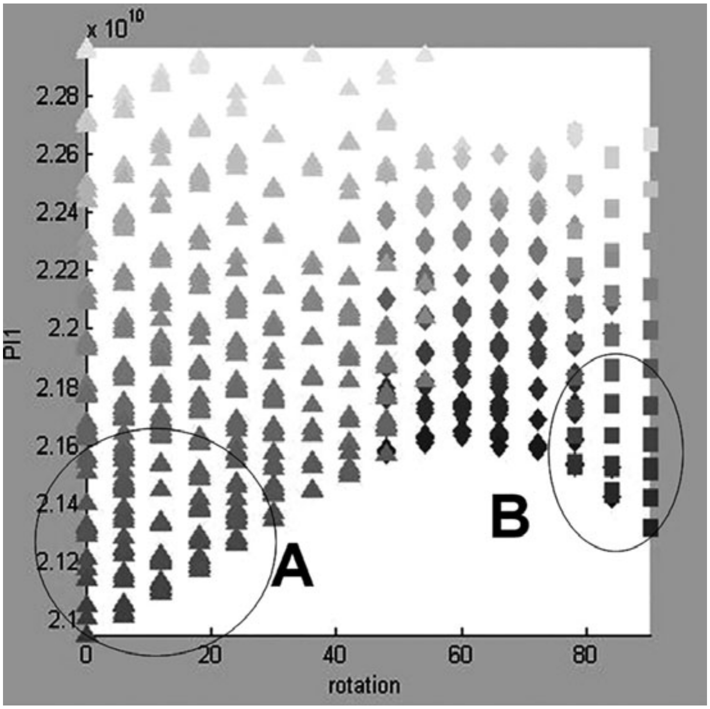


Figure 2.3.5 Visualization of results of searching in a multi-dimensional space.

Source: Chapter authors

Meanwhile, there is still a community aiming at the integration of simulation in building design, and more specifically CAD software tools. While the idea of an open unconstrained co-operation of different design software tools seemed attractive but very hard to accomplish, several attempts emerged to structure the derivation of simulation models. The Design Analysis Integration (DAI) Initiative (Augenbroe, de Wilde, Moon and Malkawi, 2004) was one of these efforts, aimed at addressing problems perceived in the ongoing efforts toward tool interoperability. The project built on the recognition that current solutions suffer from two major shortcomings: (1) they assume an idealistic structured data context, which allows perfect mapping between design information and analysis needs, and (2) they are data driven, neglecting the process dimension of design – energy modelling interaction, where there is a clear 'analysis request' and where modelling results must be useful to the professionals that are involved in the building engineering process. To overcome these issues the DAI-Initiative suggested a modular approach that starts from the premise that a set of recurring design analysis requests can be identified. These requests would represent the main questions that repeatedly are asked from modelling experts, say 80%, leaving room for another 20% of highly specialised requests that cannot be automated and need first-principle modelling of a specific problem from scratch. The recurring 80% of requests would then allow the modelling of structured, if needed scalable 'analysis functions' which uniquely define the quantification of specific building performance aspects in terms of Performance Indicators (PIs). A prototype software environment was developed and demonstrated to experts in the field; follow-up initiatives are currently under development. Current efforts to streamline the mapping from CAD to simulation models take an approach that is characterized by a set of upstream constraints and (naming) conventions during the generation of the design model. These constraints are typically embedded in native software that runs inside the CAD environment. The constraints and conventions are chosen such that the mapping rules can process the design model into an unambiguous and valid simulation model. Although this method can lead to a working design analysis interface, the resulting platform lacks openness (emerging solutions tend to be tied in with proprietary CAD software) and lacks modellers interaction with the mapping process. Robust mapping of unconstrained instances of a building information model (e.g. according to the current IFC standard, as generated by current CAD tools) to a valid simulation model have only been accomplished under specific conditions, i.e. typically assuming that the CAD model is defined by an experienced energy modeller, rather than the typical "free style" designer. A practical and instructional application of the resulting "semi-automatic" mapping can be found in (O'Donnell et al., 2013).

Summary

The role of energy modelling in building engineering has co-evolved with the technology. Increasingly stringent regulations on energy efficiency, carbon emissions and more energy conscious clients have yielded a buoyant consultancy sector which is a major factor in today's collaborative design of buildings. Yet while energy modelling now has become an important ingredient of the engineering of sustainable buildings, a set of important challenges remain. Full integration of energy modelling and building design requires further process integration, which is a non-trivial issue due to the highly unstructured nature of the current building design process. Further investigation of how designers make decisions, and how modelling results can help to make those choices, is needed, but such research needs to take into account that design practice itself is subject to change. Process integration also requires better collaboration between the actors, including improvements in data exchange, communication, and the pursuing of common objectives. Furthermore, the trust in modelling outcomes, the role and impact of uncertainties, and the training of simulation experts are fields that need addressing to move the discipline forwards.

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2.4
ENERGY MODELLING FOR COMPLIANCE

Building regulations, energy certification and sustainability rating schemes

Rokia Raslan

Introduction

Building regulations (also referred to as building standards or codes) are minimum requirements that aim to ensure that buildings achieve important regulatory objectives such as the provision of adequate levels of health, safety and wellbeing of occupants. To ensure their enforcement, building regulations are typically established by the government and are mandated by law.

The control of the energy performance of buildings and the promotion of the uptake of energy efficient technologies through regulatory control came into prominence in the mid 1970s (Lee and Yik, 2004). Since then, energy efficiency has become an increasingly important regulatory objective (Pilzer, 2005). Beyond regulatory compliance, energy performance efficiency can also be promoted through the use of Energy Certification, which assesses the comparative energy performance of a building based on a calculated "rating" (usually compared to similar buildings). Furthermore, energy efficiency is also a key driver of Sustainability Rating Schemes which are (mostly voluntary) industry adopted standards that refer to national regulations and can set comparatively higher performance targets.

Implementing energy modelling through the use of computational simulation tools for the demonstration of compliance with building energy performance regulations, the issuing of energy certification and assessment of sustainability ratings is collectively often referred to as "compliance modelling" (Hensen and Nakahara, 2001; Pilzer, 2005). During the past few years in particular, building regulations and sustainability assessment and rating schemes around the world have undergone major changes in an aim to improve occupant wellbeing and – more recently – address the global call to improve the energy performance of buildings. As a result, the use of computer simulation tools has become an integral part of this process.

Demonstrating energy compliance

Historically, building regulations were based on a prescriptive approach, whereby specific prescribed requirements were followed to achieve compliance. For example, structural compliance was deemed to be achieved when the dimensions of various structural elements were at least equal to specific prescribed dimensions. This prescriptive approach was often criticised as lacking the flexibility required to promote innovation and reducing freedom of design (Hamza and Greenwood, 2009). Consequently, in recent years there has been an increasing international shift to a more flexible performance-based approach (Figure 2.4.1). Here, only performance goals are specified and flexibility in the selection of the materials and processes utilised to achieve them is allowed (Sorrell, 2003; Thomas, 2003).

Energy efficiency is considered a key domain in a performance-based approach. As a performance category, it describes and assesses the building's features and characteristics relevant to its impact on the environment and considers the effects on both the local and global environment (Lützkendorf, Speer, Szigeti, Davis, le Roux, Kato and Tsunekawa, 2005). In recognition of the particular benefits it provides in the promotion of energy efficiency, a number of national building regulations around the world now include energy performance standards (e.g. Hitchin, 2008; Huovila, 2007; Janda, 2009). These regulations have various objectives that include conserving fuel, decreasing energy consumption and reducing GHG (in particular CO_2) emissions (Parsons, 2004).

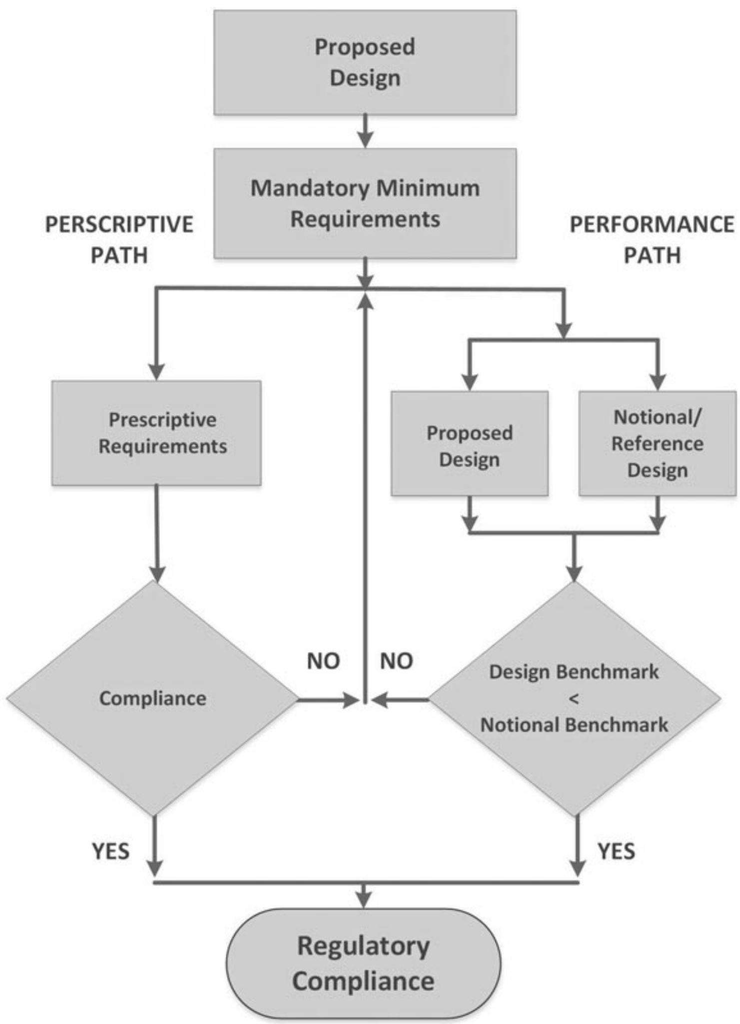

Figure 2.4.1 Prescriptive and performance paths.

Source: Adapted from Pérez-Lombard, Ortiz, Coronel and Maestre, 2011

One of the main challenges associated with the decision-making process in the performance-based approach is how to predict and assess performance, and ultimately, determine compliance based on a proposed (yet to be built) building design (Spekkink, 2004). Here, building energy performance modelling can provide the ability to objectively assess the overall performance of design proposals (e.g. Crawley, Hand, Kummert and Griffith, 2005; Hensen and Nakahara, 2001; Wilde, 2004) and allow designers to explore innovative approaches to satisfying performance requirements. In most countries, compliance modelling is now an important domain within the larger field of energy modelling that is not only confined to the later stages of the design process but may take place throughout the building's lifecycle.

General modelling methodology for performance-based compliance

In compliance modelling, the procedure defined to demonstrate compliance is referred to as the "compliance methodology". For the majority of energy compliance related applications in countries that employ the performance-based approach, this is generally a comparative process, where the design is modelled using a simulation tool and compared to a generated benchmark. Figure 2.4.2 describes a simplification of this process, which includes the following key elements:

- Compliance methodology: The general approach and calculation procedures (solution techniques) that should be implemented and the benchmarks that must be generated and compared against to demonstrate compliance.
- Modelling/simulation tool: Various methodologies for demonstrating compliance/or assessing ratings often entail the use of accredited/approved modelling simulation tools.

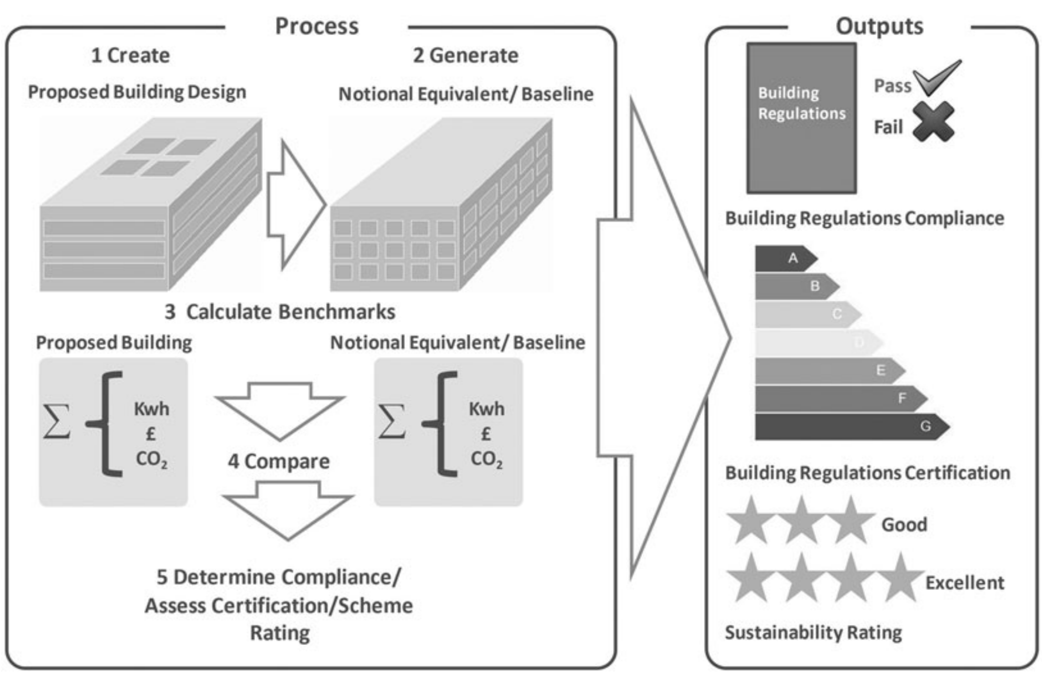

Figure 2.4.2 General compliance modelling approach.

Source: Chapter authors

- Proposed design: The computational/mathematical model used to represent the geometrical properties and physical processes in the proposed actual building.
- Notional/baseline/reference building: The virtual "equivalent" building generated from the proposed design. In most cases this is based on the shape, size and usage of the proposed design, but includes building systems, construction elements, glazing ratios . . . etc. that comply with certain reference standards.
- Compliance benchmark: The benchmark values that are used for comparison and are derived from the baseline building generated from the proposed design. These refer to key energy performance indicators or "metrics" such as energy consumption, CO_2 emissions rates, costs . . . etc.

Compliance modelling tools

For compliance modelling, the simulation tools used must be able to perform the specific calculation (and analytical) procedures required to implement the compliance demonstration methodology defined. As a result, they are in most countries subject to accreditation procedures or schemes that aim to assess their "fitness for purpose" for undertaking specific modelling tasks and validate their use for implementing the methodologies defined. In most countries with mandatory energy efficiency building regulations, a simplified free compliance demonstration tool is usually made available in addition to an array of commercially developed tools.

In categorising compliance demonstration tools, it is important to note that while some simulation tools are specifically developed for the sole purpose of compliance demonstration, it is often the case that simulation tools that are used for general energy performance modelling may incorporate additional functionality that allows them to implement specific compliance demonstration methodologies or interface with the compliance tools. As such, it is important to recognise the overlap that exists between energy modelling and compliance modelling tools (Figure 2.4.3).

In terms of calculation approaches, as is the case with general energy modelling, compliance demonstration tools may range from simplified to fully comprehensive (Doyle, 2008). While simplified approaches attempt to generate an exact solution of an approximation of the real problem, comprehensive methods attempt to approximate a solution of an "exact" representation of the problem (Hensen, 1994). Consequently, the tool selected to implement compliance modelling will together with other factors such as user competence therefore impact the results produced and ultimately the compliance outcome.

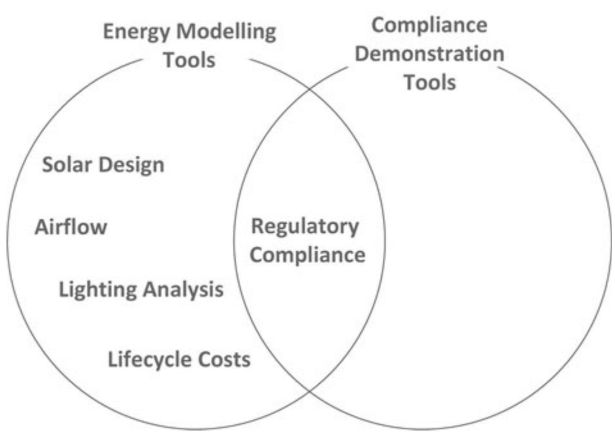

Figure 2.4.3 Compliance demonstration and energy modelling tools.

Source: Chapter authors

Comparing Compliance Modelling and Design Modelling

It is important to differentiate compliance modelling from energy modelling that is undertaken primarily for design development. It should be recognised that the purpose of compliance demonstration methodologies is not to develop an accurate prediction of annual energy use for the building, but to develop fair and consistent evaluations of the effects of deviations from the prescriptive requirements.

In general, compliance demonstration methodologies generally rely on simplification and standardisation of assumptions and often on the use of simplified methods to undertake calculations. The term "simplified" denotes that certain assumptions are applied to the underlying model, where some energy or mass flow paths that interact in a dynamic fashion may either be approximated or entirely omitted (Hensen, 1994). In addition, compliance modelling may only focus on "regulated" energy uses and does not include "unregulated" loads as highlighted in Figure 2.4.4 (Menezes, Cripps, Bouchlaghem and Buswell, 2012).

Compliance Modelling for Energy Regulations and Certification

As mentioned, on an national level a number of national building regulations around the world now include energy performance standards (e.g. Hitchin, 2008; Huovila, 2007; Janda, 2009). Furthermore, on a regional level instruments such as the European Union's Directive on the Energy Performance of buildings (EPBD) have become catalysts in the process of adopting performance-based energy standards for buildings throughout member states. Table 2.4.1 summarises the modelling requirements, approaches and tools used for demonstrating compliance with building regulations for a number of key countries. The procedures for the UK and the USA are discussed in further detail below.

The United Kingdom

Similar Countries: EU member states, Australia

As an EU member state, UK building energy efficiency legislation is heavily influenced by the EPBD. In terms of implementation, the UK is based on a devolved administrative structure subdivided (as of 2011) into four jurisdictions (England, Wales, Scotland and Northern Ireland). However, the single compliance methodology in all jurisdictions follows the general modelling approach described for compliance and is referred to as the National Calculation Methodology (DCLG, 2008a, 2008b, 2010). The relevant second tier regulatory documents that provide the technical guidance on the implementation of procedures (Part L: The Conservation of Fuel in England and Wales, Technical Booklet Part F in Northern Ireland and Power or Section 6 in Scotland) are subdivided to distinguish between various building types (domestic and non-domestic buildings) and in some cases further divided to also distinguish between new or existing buildings.

In accordance with EPBD recommendations, regulatory target benchmarks have since the major amendments of 2006 been primarily based on carbon emissions metric (commonly referred to as "Carbon

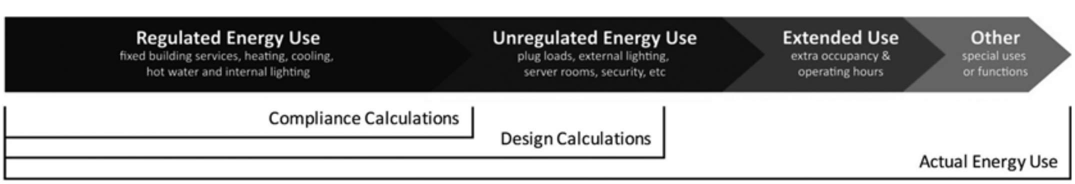

Figure 2.4.4 Parameters accounted for in compliance modelling.

Source: Adapted from Menezes et al., 2012

Compliance"). Additionally, several other metrics have been added with each regulatory revision (to a variable extent in each jurisdiction) in an aim to provide a more realistic approach that accounts for other factors which contribute to energy efficiency. For the domestic sector, the target benchmarks include the Target CO_2 Emissions Rate (TER) in addition to the Dwelling Fabric Energy Efficiency (DFEE) and the Carbon Emission Rate (CER). For the non-domestic sector these include the Target CO_2 Emissions Rate (TER) and the Target Primary Energy Consumption (TPEC) in Wales.

Table 2.4.1 Modelling approach for compliance with building regulations.

Country	*Compliance guidance/ requirements*	*Modelling approach*	*Examples of modelling tools*
UK – England	Approved Document Part L1/L2	National Calculation Methodology (NCM)	SAP/ NCM Approved Tools
UK – Wales	Approved Document Part L1/L2	National Calculation Methodology (NCM)	SAP/ NCM Approved Tools
UK –Scotland	Technical Document Section 6	National Calculation Methodology (NCM)	SAP/ NCM Approved Tools
UK –Northern Ireland	Technical Booklet Part F	National Calculation Methodology (NCM)	SAP/ NCM Approved Tools
The Netherlands	Energy Performance Standards (EPN)	NEN 7120:2011 method	EPCheck & other commercial tools
France	La Réglementation Thermique (RT)	RT methodology	Th-CE & other commercial tools
Germany	EnV	DIN V 18599	DIN V & IBP Kernal based tools
Spain	Reglamento de instalaciones térmicas en edificios (RITE)	RITE methodology	CALENER GT
USA	Variable (e.g. ASHRAE, IECC)	Variable (e.g. ASHRAE, IECC)	ResCheck, ComCheck & other commercial tools
Australia	Building Code of Australia (BCA)	JV3	AccuRate & other commercial tools
Canada	MNECB & NECB	Part 9 - NCB & Part 8 (Division B) NECB	EE4, HOT . . . etc.
China	National Building Energy Standard	Whole building performance approach	PKPM-Energy, TianZheng, Si Wei Er, Tangent BEC & THS BECS
Hong Kong	Building Energy Efficiency Ordinance (BEEO)	Performance-based Building Energy Code (Section 9)	Any software tools fulfilling specified requirements
India	Energy Conservation Building Code (ECBC)	Whole Building Performance (WBP) method	ECOnirman & any software tools fulfilling specified requirements
Japan	Rational use of energy within buildings & Criteria for clients on the rationalisation of energy use for buildings 2010 (CCREUB)	Simplified, basic & professional methods	BEST (Building Energy Simulation Tool)

With regard to energy certification, the UK introduced Energy Performance Certificates (EPCs) which record the building "Asset Rating" (when a building is constructed, sold or rented) and Display Energy Certificates (DECs) which record the "Operational Rating" to measure in-use performance of the building based on metered energy consumption. The contents of the certificate and the format will vary slightly in different jurisdictions and for different building sectors.

The process for determining the EPC rating for the domestic sector is based on the application of the SAP methodology. For the non-domestic sector, the method for determining the EPC rating is similar to that described for NCM compliance however instead of the TER a Standard Emission Rate (SER) is calculated from the Reference Building. The Asset Rating is calculated on the basis of the following equation, where the result normalised such that the SER is equivalent to an Asset Rating of 50 (the calculated AR is rounded to the nearest whole number (DCLG, 2008b, 2010).

$$AR = 50 \times BER / SER$$

The operational rating (OR) is a measure of the annual (CO_2) emission per unit of area of the building caused by its consumption of energy, compared to a value that would be considered typical for the particular type of building (DCLG, 2008a). The values are determined based on actual metered data for energy use and the calculation equation used is:

$$OR = (\text{Building } CO_2 \text{ emissions/Building area}) \times (100/\text{Typical } CO_2 \text{ emissions per unit area})$$

In terms of modelling tools, five main tool types are currently available for the implementation of compliance calculations in the UK. A review of their main features and guidelines for their applicability is summarised in Table 2.4.2 and as part of the accreditation program for commercial tools, the approved list of accredited tools is constantly updated and can be found at:

- DCLG notices of approval (domestic and non-domestic, all jurisdictions) www.gov.uk/government/publications/department-for-communities-and-local-government-approved-software-for-the-production-of-non-domestic-energy-performance-certificates-epc
- www.bre.co.uk/sap2012 (domestic, all jurisdictions)
- www.scotland.gov.uk/Topics/Built-Environment/Building/Building-standards/techbooks/sectsixprg (Specific Information for Scotland Section 6 Software)
- http://projects.bre.co.uk/sap2005/pdf/SAP2005_9–81_software.pdf (domestic, all jurisdictions)

A number of studies (e.g. Garmston and Pan, 2013; Pan and Garmston, 2012; Raslan and Davies, 2012) have assessed the extent of the success of the various aspects relating to the implementation of the UK approach to regulating energy efficiency in the building sector. Among the various positive aspects identified, it is important to acknowledge that the current approach has been a key factor in raising the profile of energy legislation in comparison to the pre-2006 regulations. Further positive impacts include the expansion of the core group of highly skilled experts in the field and the change in the operational strategies of many organisations that have encouraged the consideration of energy performance compliance from the earlier stages.

Table 2.4.2 Modelling tools for the NCM – Compliance and certification.

Option	*Input method/data*	*Calculation methodology*	*Outputs*	*Applicability*
Standard Assessment Procedure (SAP)	Non-graphical, Microsoft Excel based input work sheet.	Steady-state monthly average calculation incorporating various BS EN standards.	• SAP outputs/rating • Data reflection reports • EPC Certificates	All domestic buildings <450m^2
Reduced Data Standard Assessment Procedure (RdSAP)	Non-graphical, Microsoft Excel based input work sheet. Includes defaults & inference procedures for data completion.	Steady-state monthly average calculation incorporating various BS EN standards.	• SAP outputs/rating • Data reflection reports • EPC Certificates	Existing domestic buildings
Simple Building Energy Model (SBEM)	Non-graphical, Microsoft Access based input forms. Data includes geometry, thermal characteristics of constructions, HVAC properties & renewable energy systems. Contains some default values such as HVAC efficiencies.	Quasi steady-state monthly average calculation based on the Dutch methodology NEN 2916:1998 (Energy Performance of Non-Residential Buildings).	• BRUKL/SBEM outputs • Data reflection reports • EPC Certificates	Theoretically applicable to all non-domestic buildings. Best used where buildings have uncomplicated geometry/recurring floor plans & simplified systems. Used for domestic buildings >450m^2
Front-End Interfaces to the Simple Building Energy Model (FI-SBEM)	Type A: A front-end graphical interface is used only for building geometry input, & then interfaces with iSBEM where additional data is entered. Type B: A front-end graphical interface is used for building geometry & information input. Data generally conforms to iSBEM standard; degree of detail varies due to individual tool capabilities.	Both types interface with SBEM calculation engine, relying on the same algorithms to implement a quasi steady-state monthly average calculation method.	• BRUKL/SBEM outputs • Data reflection reports • EPC Certificates	Theoretically applicable to all non-domestic buildings. Best used where buildings have simplified systems. Used for domestic buildings >450m^2
Dynamic Thermal Modelling Tools (DTM)	3D CAD front-end modules allow building geometry to be input &/or imported from CAD packages, 3D BIM & other software. Includes more detailed input options /extensive databases for materials & systems.	Dynamic detailed hourly calculation method using each tools own algorithms.	• BRUKL/SBEM outputs • Data reflection reports • EPC Certificates • Load calculations, energy performance analysis results	Applicable to all non-domestic buildings. Most effective where buildings have complicated geometry & systems. Used for domestic buildings >450m^2
Operational Rating Calculation Tools (ORcalc)	Simplified calculation tools for the production of DECs	Simplified calculation methodology with various interfaces.	• DEC Certificates • Advisory reports	Applicable to mostly non-domestic buildings.

A number of concerns surrounding the use of compliance benchmarks that primarily relate to carbon emissions have been highlighted. While carbon compliance provides a degree of design flexibility, one of its main limitations is the fact that the actual impact of a building may be misrepresented due to the use of average conversion rates for compliance calculations (Berry, Davidson and Saman, 2014). Furthermore, the use of a purely carbon-based compliance metric may be restrictive in terms of delivering the multiple policy goals that are often the aim of regulatory control (Riedy, Lederwasch and Ison, 2011). Finally, it has been pointed out that the use of the notional building as the comparative benchmark for assessment can make it difficult to track the level of emissions reductions being achieved in real terms over time (Greenwood, 2010).

While one of the most positive outcomes associated with the introduction of the NCM has been the encouragement of the market-based driven development of various commercial software tools to support implementation, the considerable limitations in the technological capability of the majority of accredited tools were found to impact the usability of the NCM methodology (Raslan and Davies, 2012). In addition, an inter-model comparative analysis of accredited tools found a large degree of predictive variability between results produced and, more importantly, a lack of consistency in granting approval (a pass/fail result) for the same building (Raslan and Davies, 2009).

The United States of America

Similar Countries: Canada, Hong Kong, India

The regulatory framework is markedly different from that in most EU member states (Pérez-Lombard et al., 2011). Instead of a national building energy code or standard, the United States applies energy codes at the state and local government levels. The majority of the USA states have energy codes and standards which use the ASHRAE Standard 90.1 for the non-residential (commercial) sector and International Energy Conservation Code Model Energy Code (IECC-MEC) for the residential sector (VanGeem, 2012). In California, the 2008 Building Energy Efficiency Standards (comprising Title 24, Parts 1 and 6) are used. These are more energy efficient than ASHRAE 90.1 (DOE, 2012).

For the commercial sector, the ASHRAE 90.1 standard sets out three paths for compliance (ASHRAE, 2010), where he energy cost budget method (ECB) is the performance-based approach. The ECB compares the design performance "Proposed Design Model" (PDM) (also referred to as the "Design Energy Cost") with a baseline building "Budget Building Design" (BBD) (also referred to as the "Energy Cost Budget") of the same shape and type but with the ASHRAE 90.1 minimum prescriptive requirements for component performance (ICC, 2009). Compliance is achieved if the requirements of all mandatory sections and the design energy cost (DEC) does not exceed the energy cost budget (ECB). In addition, the energy efficiency level of components specified in the building design must meet or exceed the efficiency levels used to calculate the design energy cost.

Similarly for the residential sector, the IECC 2012 standard sets out a performance-based compliance method (section R405.3) (ICC, 2011). This requires that a proposed residence be shown to have an annual energy cost that that is less than or equal to the annual energy cost of the standard reference design. Energy prices are taken from a source approved by the code official (e.g. DOE). Compliance is achieved if this requirement – in addition to all mandatory section requirements of the code – are met (ICC, 2011).

The performance paths in energy codes generally allow the use of a computer-based "trade-off" tool or a detailed energy budget method. Free simplified tools have been developed for the purposes for compliance demonstration (DOE, 2012) and a number of software tools have been certified for use in various states. In general, the more complicated compliance tools allow more design flexibility and the exploration of trade-off also allow for innovation in design and materials. Detailed computer-based energy analysis programs calculate yearly energy consumption on an hourly basis and are more useful when using the energy budget method as the simpler compliance tools do not take into account special features of the building or its components (VanGeem, 2012).

Compliance modelling for sustainability rating schemes

In the built environment, in addition to policy-driven legislative mitigation measures, a number of building assessment rating systems have been developed by independent bodies. Although numerous rating systems have been developed around the world, the UK-developed Building Research Establishment – Environmental Assessment Method (BREEAM) and the US-developed Leadership in Energy and Environmental Design (LEED) have emerged as the leading systems in terms of worldwide use (Schwartz and Raslan, 2013).

An integral component of sustainability rating systems requires the implementation of compliance checking with national building regulations and standards for their allocation of credits. For example, BREEAM awards credits depending on a building's performance as defined by its Energy Performance Certificate rating. In a similar approach the LEED system awards credits when a building performs better than the target defined by the above mentioned ASHRAE standard. Table 2.4.3 provides an overview of the various Green Building Assessment and Certification Schemes used across the globe and where the information to undertake the analysis can be found.

Leadership in Energy & Environmental Design: LEED

LEED, or Leadership in Energy and Environmental Design was developed by the U.S. Green Building Council (USGBC) in 2000. The LEED rating systems are developed through an open, consensus-based process led by LEED committees and cover a number of building typologies. As a points-based system, projects must satisfy particular prerequisites and earn LEED credits by meeting specific green building criteria, which are grouped into seven credit categories. Certification is available in four progressive levels (Certified, Silver, Gold and Platinum), determined by number of points the project earns. For the LEED rating systems that cover existing buildings, new buildings (New Construction, Schools, Commercial Interiors, Core & Shell) as well as the specialised retail and healthcare versions, building energy performance assessment is the main focus of two credits. These are the Prerequisite EAP2 – Minimum Energy Performance and Credit EAc1 – Optimize Energy Performance.

While both prescriptive based for compliance demonstration and points calculation are available, performance-based methods (when applicable) are considered to be the most flexible and widely used as they allow for a greater degree of design innovation. For existing buildings, the methodology compares the energy performance of the building with the national average for similar building type. For other rating systems, the Building Performance Rating Method (PRM) described in Appendix G of the ASHRAE 90.1 standard is used and substantially exceeds the requirements of the ASHRAE standard that represents standard practice.

In general, PRM involves the implementation of a whole building energy simulation to demonstrate energy savings of the proposed building with all its designed energy enhancements over a baseline building. In the Performance Rating Method:

- ***The proposed case*** is defined based on the actual building design characteristics (with the exception that all conditioned spaces must be modelled as being both heated and cooled).
- ***The baseline building*** is identical to the proposed case in terms of its form, infiltration and proportion of windows per façade but designed according to characteristics specified in ASHRAE 90.1 – Appendix G.

Table 2.4.3 Green building assessment and certification schemes.

A – International schemes		
Coverage	*System*	*Further information*
North America, South America, Asia, Europe	LEED	www.usgbc.org/
Europe	BREEAM	www.breeam.org/
B – Country specific schemes		
Australia	NABERS	www.nabers.gov.au
	Green Star	www.gbca.org.au/
Brazil	AQUA	www.vanzolini.org.br/
	LEED Brasil[1]	www.gbcbrasil.org.br/
Bulgaria	Bulgaria GBC	www.bgbc.bg/
Canada	LEED Canada[1]	www.cagbc.org/
	Green Globes	www.greenglobes.com/
China	MOHURD Three Star	N/A
Egypt	The Green Pyramid Rating System (GPRS)	www.egypt-gbc.gov.eg/ratings/index.html
Finland	PromisE	www.vtt.fi/
France	Le bilan carbone chantier	www.r-co2.com
	HQE	www.assohqe.org/
Germany	DGNB	www.dgnb.de/
Hong Kong	BEAM Society	www.beamsociety.org.hk
India	GRIHA	www.grihaindia.org/
	LEED India[1]	www.igbc.in/
Indonesia	Greenship	www.gbcindonesia.org/
Israel	SI-5281	www.iisbeisrael.org/eng_SI_5281.htm
Italy	Protocollo Itaca	www.itaca.org/
	LEED Italia[1]	www.gbcitalia.org/page/show/leed-italia—3
Malasyia	Green Building Index (GNI)	www.greenbuildingindex.org/
Mexico	Consejo de Edificación Sustentable	www.mexicogbc.org/
Netherlands	BREEAM NL[2]	www.dgbc.nl/
New Zealand	Green Star NZ	www.nzgbc.org.nz/
	Homestar	www.homestar.org.nz/
Norway	BREEAM NOR[2]	www.ngbc.no/
Japan	CASBEE	www.ibec.or.jp/CASBEE/
Philippines	BERDE	http://philgbc.org/
Portugal	LiderA	www.lidera.info/
Qatar	GSAS/QSAS	www.gord.qa/index.php?page=qsas
Singapore	Green Mark	www.bca.gov.sg/GreenMark/green_mark_ buildings.html
	CONQUAS	www.bca.gov.sg/professionals/iquas/conquas_ abt.html
South Africa	Green Star SA	www.gbcsa.org.za/home.php
South Korea	Greening Building Certification System	www.greenbuilding.or.kr/eng/html/sub02_1.jsp
Spain	GBC Espana-Verde	www.gbce.es/
	BREEAM ES[2]	www.breeam.es/
Sri Lanka	GREEN SL	http://srilankagbc.org/
Sweden	Miljöbyggnad	www.sgbc.se/certifieringssystem/miljoebyggnad
Switzerland	Minergie	www.minergie.ch/
Taiwan	EEWH	http://green.abri.gov.tw
United Arab Emirates	Estidama Pearl Rating System	http://estidama.org/pearl-rating-system-v10.aspx
United States	LEED	www.usgbc.org/
	Green Globes	www.thegbi.org/green-globes-tools/
United Kingdom	BREEAM	www.breeam.org/
Vietnam	LOTUS	www.vgbc.org.vn/

Notes:
[1] Based on the original LEED scheme originating in the USA
[2] Based on the original BREEAM scheme originating in the UK

With regard to the simulation tools used, while USGBC does not certify or formally approve "qualified" simulation software packages for compliance with ASHRAE requirements or for generating an appropriate baseline model, "qualified" tools should conform to the requirements stated in ASHRAE 90.1–2007, Section G2.2.1. The tool used needs to be approved by the rating authority and as part of the LEED submittal, the project team is required to document that the building inputs for any software package conform to the baseline and proposed case modelling requirements.

Building Research Establishment Environmental Assessment Method: BREEAM

BREEAM is an environmental assessment method developed by the Building Research Establishment (BRE) in 1990. The BREEAM systems cover a number of building typologies and awards a sustainability rating (Pass to Outstanding) based on a series of credit points. If a building does not fit into a particular scheme, the BREEAM Other Buildings scheme which includes bespoke ratings developed on a case by case basis to suit the development can be used.

In BREEAM, building energy performance assessment is the main focus of one credit Ene01 Reduction of CO2 emissions. In BREEAM 2011 the Ene01 credits are based on the performance of the actual building against each of three performance indicators which are derived from the building regulations compliance calculation (Part L). These parameters include energy demand, consumption and CO_2 emissions generated. A notional building is generated, and the percentage improvement is calculated using simulation tools. Relative weights are then assigned to each of the performance indicators to reflect the maximum that each can contribute to the overall Energy Performance Ratio for New Constructions (EPR_{NC}).

The EPR_{NC} achieved is compared with the relevant of benchmarks (as determined by the specific BREEAM system) to award the corresponding number of BREEAM credits (BRE, 2011). In the UK, the BREEAM Ene-01 credit calculation procedure requires the use of any the approved building energy calculation software used for NCM (Part L) calculations.

Challenges and future directions in compliance modelling

Research work undertaken in the field of compliance demonstration has highlighted that while the requirement for the use of modelling for compliance and certification has played an important role in encouraging the development of various software tools to support implementation a number of challenges still exist. It should be acknowledged that in reality, the way in which a building operates in practice is extremely complex. The modelling of this process to obtain accurate estimates is both difficult and prone to error (Mason, 2003) and the issue of the resulting "Performance Gap" between actual and predicted/modelled behaviour has been highlighted by such initiatives such as the PROBE studies (Post-occupancy Review of Buildings and their Engineering) (Cohen, Standeven, Bordass and Leaman, 2001), the CarbonBuzz database (CarbonBuzz, 2013) and the Energy Performance Analysis of LEED accredited buildings (Turner and Frankel, 2008).

Furthermore, while compliance targets can themselves be challenging, they are invariably limited to determining the performance of the design in a given set of pre-defined conditions of use restricted by the approved calculation method. This means that the energy performance of a proposed design is only compared against a typical building of its type under a single climatic condition and a single usage scenario, which may not necessarily lead to an optimised design. Since regulations and environmental standards are increasingly influencing the design process, it is therefore important to acknowledge that if used in isolation, regulations and standards may lead to inefficient design of buildings.

As a result, various research and industry initiatives are continually looking to improve available tools through the exploration of various topics such as:

- Increased use of dynamic thermal models (DTMs)
- Model integration into BIM to integrate the design and certification processes
- Increased use of more user-friendly/portable GUIs for software
- Increased development of web-based certification and compliance modelling applications
- Development of cloud-based computing facilities for analysis and storage of data to streamline application processes and document submission

Conclusions

As building regulations and sustainability assessment and rating schemes have become increasingly important and more widespread, the implementation of "compliance modelling" through use of computer simulation tools has become an integral skill that is required from today's sustainability specialists.

While the implementation varies in its details on the national level, a common "general" approach or methodology forms the basis of compliance modelling around the world. This relies on a comparative approach that utilises simulation tools that are able to generate notional or benchmark buildings and calculate target benchmarks to compare against. These refer to key energy performance indicators such as energy consumption, CO_2 emissions rates, costs . . . etc.

Finally, while it shares some commonalities with general energy modelling it is important to differentiate compliance modelling from energy modelling that is that undertaken primarily for design development and understand its limitation in the interpretation of compliance modelling results.

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2.5
CARBON REDUCTION IN BUILDINGS

Ian Ward

Introduction

Worldwide almost 40% of the energy used is for heating, cooling, lighting and ventilating buildings and in the UK it is almost half of the energy used. This emphasizes the fact that buildings are important in the drive to reduce both national and global consumption of resources.

The general way in which the energy consumption of buildings can be reduced is to pay attention to the following design issues.

Reduce energy for heating – Optimize the building envelope

The design of the building envelope can have a significant effect on the overall energy performance of the building and care should be taken in the design of the façades. By careful design the demand for heating can be significantly reduced.

- Compact plan forms reduce fabric losses.
- Exceed Building Regulations requirements for U values.
- Optimize glazing ratios for heat gains, day lighting and artificial lighting.
- Investigate the use of shading systems remembering east west orientations will require different treatment to south elevations.
- Use thermal mass to reduce fluctuations in internal air temperatures – also can have an influence on the cooling requirements.
- Detail junctions between fabric components to prevent the ingress of unwanted air.

Reduce energy for cooling – Optimize the use of natural climate features

The demand for cooling can be reduced by careful consideration of the climate features of the site as well as by consideration of the internal loads. Using daylight reduces the dependence on artificial light which reduces electrical energy used and natural winds can be used to ventilate buildings and provide a degree of "free cooling". If possible zone the internal spaces to:

- Maximize the opportunities to use solar energy.
- Maximize the view of the sky to allow daylight to enter the building.

- Maximize the potential use of natural wind forces for natural ventilation.
- Shelter the building from strong cold winds – this reduces the unwanted cold air infiltration.
- Shield windows from unwanted solar gain in hot periods of the year.
- Consider reducing the internal loads or zone areas of high loads together – this can help in minimizing the spread of cooling services throughout the building.

Reduce energy for lighting – integrate daylight with artificial light

The provision of good quality lighting not only enhances the ability of the occupants to carry out their tasks more efficiently but can also reduce the energy demand for electric lighting. Electricity is a high-quality fuel and its production efficiency from fossil fuels is rarely more than 30–40%.

- Maximize the amount of daylight entering the building by providing windows with a view of the sky zenith – the sky is generally 3 times as bright at the zenith compared to the horizon.
- Where possible use clearstory, light pipes and roof glazing systems.
- Use light shelves to "bounce" daylight deeper into the occupied space.
- Keep internal decorations of walls, floor and ceiling light to reflect as much light as possible.
- Plan artificial lighting switching systems to switch off lights progressively as they become further away from the windows.
- Use electronic control systems to modulate the lighting switching and levels in response to available daylight levels.
- Select glazing systems with high transmission factors for daylight.

Reduce energy for equipment/processes

Boilers, chillers, fans, pumps and motors all use energy to provide the energy systems to keep the inside conditions within comfortable ranges. These systems can be designed to minimize the energy used.

- Use equipment with high efficiency ratings.
- The efficiency of particularly boilers and chillers depends on the load imposed on them – the higher the load the better the efficiency. To maximize the efficiency of the whole system, use modular units as they will work at full load for longer periods of time therefore the system efficiency will be greater.
- Use heat recovery, energy storage and desiccant dehumidification to reduce heating and cooling energy usage.
- Use variable volume air systems to respond to the demands of the users – low occupancy will need less air than when full occupancy, however, care should be taken to prevent air stagnation and moisture build up.
- Use variable flow pumps and variable speed drives.
- Use zero CFC based refrigerants.
- Use white goods with high energy efficiency rating.

Investigate the use of renewable and integrated energy sources

One way to reduce the demand on fossil fuels is to use renewable or integrated energy sources which in theory will not run out – unlike fossil fuels.

- Look at the use of PVs to produce either electricity to be fed into the building or used as direct current to charge batteries – for cars, computers, emergency lights etc.

- Investigate the use of the heat generated by PVs to supplement space heating systems in mid seasons.
- Consider the use of wind generators.
- Consider the use of heat pumps – generally for every kWatt of energy fed into a heat pump 3 kWatts of energy are produced. If the two units are free i.e. from ground water, river water air or other source then high efficiencies are obtained.
- Consider co-generation of heat and electricity.
- Consider the use of wood burning stoves supplied from harvested cuttings from forests.

To reduce the carbon emission from buildings it is essential that consideration is given to these issues as early on in the design process as possible. Design decisions made at concept stage are often easy to implement as the building details have not been decided and therefore there are no cost implications. However, if design decisions are made late on in the project then there are likely to be cost involved and the modifications could result in less of a saving compared to decisions made at concept stage.

Carbon reduction issues to be considered at the early stages of design

The main issues, which are of importance when designing an energy efficient building, are:

- Site analysis.
- Fabric design with respect to heat gains/ losses, thermal mass.
- Provision of appropriate services.
- Type of control systems to be used and operational programmes.

Each of the above topics will be considered in more detail in the following sections.

Site analysis

Before carrying out a site analysis it is necessary to establish the priorities. For example if the site is in the middle of a city then the scope to deal with solar access will be severely limited due to the surrounding buildings and it may therefore not be possible to do much about it. On the other hand on a green field site there will be more scope to maximize solar assess.

A site analysis dealing with carbon issues should take into consideration the following points:

- Solar access.
- Local wind environment.
- Availability of daylight.

Solar access

Good solar access is important if a building is to make use of the suns energy to help in producing a passively heated building. By keeping the south elevation free from obstructions in the northern hemisphere (NH) and the north elevation free in the southern hemisphere (SH) then solar access is possible. The simple rule governing layout of buildings to maximize the benefits of sunlight can be taken as:

- Ensure that there are no obstructions within a 30-degree angle from the south/north elevation.
- Ensure that there is no other building obstructing the window within an elevation angle of 25 degrees.

Local wind environment

Wind shelter can be provided by several means – other buildings, natural vegetation or artificial wind breaks. Providing wind shelter may also be in conflict with the desire to provide solar access. For passive solar buildings facing south (NH) or north (SH) with planted shelter to the south and west (NH) or north and west (SH) good solar access for winter sun is maintained if the shelter is at least 4 times the height of the building distant from it for latitudes up to 550N/S and 5 times the height of the building distant up to 600N. Shelterbelts at the edge of an estate or groups of buildings should be about twice the height of the buildings away from them to protect daylight availability (although some sunlight will be sacrificed). Shelterbelts protecting open spaces will be effective at reducing wind speed by the amounts shown in the Table 2.5.1.

Table 2.5.1 Shelterbelts and reduction of wind speed.

Distance from belt in belt height (H)	*% Reduction in wind speed*
2	60
5	40
10	20
15	10

Daylight

If it is desired to let the internal spaces be day lit it is first necessary to establish the desired daylight factor.

- Daylight factors between 2 and 5% would be desirable.
- If a window is to be used for providing daylight then obstructions should not be higher than 250 above the horizon.
- A room can have a daylit appearance if the area of the glazing is at least 1/25th of the total room area.
- Areas of a room from which there is no direct view of the sky are likely to have a low level of daylight.
- Surfaces closer to a window than twice the height of the window head above desktop level are likely to receive adequate daylight for most of the working year.
- It is possible to establish the likely percentage of the year when daylight would be adequate for defined levels of illuminance. Normal conditions of clear or tinted glass, light interiors and working day 9am to 5pm can be assumed.

A general equation which can be used to estimate the likely daylight factor is:

$$DF = \frac{\Sigma WT\Phi M}{A(1-R^2)}$$

where

W = Total window area m^2
T = Transmittance of glazing system (usually 0.7 for double glazed clear glass)
Φ = Vertical angle of sky seen from each window

M = Maintenance factor (usually taken as 1)
A = Total internal surface area m^2
R = Area weighted average reflectance of surfaces

Fabric design

Once the issues relating to the site have been established, the next issue to consider is the design of the building fabric. At the initial stages of a design it is important to consider how the massing of the building will affect the carbon emissions requirements. The following simple guidelines can help to reduce the emission rate:

- Narrow buildings use less energy in total as they can be more effectively day-lit which leads to a reduction in electrical load which outweighs any slight increase in fabric losses due to a large façade area.
- Courtyard buildings do not perform as well as shallow buildings as they have less daylight and natural ventilation.
- Atrium buildings perform in a similar way to courtyard buildings, although the ventilation is better than courtyard (due to stack effects). There may be a need to have mechanical ventilation to the upper floors due to the low stack pressures at higher levels.
- Buildings with very small glazing ratios will produce significantly more carbon than buildings with larger glazing ratios.
- Increasing glazing ratios much above about 50% will produce little extra benefit.
- The optimum glazing ratio is in the region of 30–50% for vertical surfaces.
- The optimum glazing ratio for roof-light is no more than 20%.

Plan form

Plan form has a very significant role in the design for carbon efficiency. Deep plan forms will result in the building requiring a larger proportion of the floor area to be artificially lit and more reliance on mechanical cooling. It is generally accepted that a space up to about 6m deep from a window will be able to take advantage of natural lighting and natural ventilation and if natural ventilation is a prerequisite of the design than about 14m deep is regarded as the upper limit for the floor slab.

Orientation

Building orientation can play a significant role in determining the solar gains received. A building facing east or west will be more susceptible to receiving adverse low altitude sun in the morning and evening, which will contribute to the possibility of overheating of these zones within the building. Low altitude sun is always more difficult to deal with than the higher altitudes during the mid-part of the day and therefore by minimizing glazing on the east west façades and providing solar shading of the south (NH) or north (SH) the potential adverse effects of solar penetration can be minimized.

Glazing ratios

Glazing ratios have an important role to play in the design of building façades. Windows let in light and solar heat and loose heat to the outside. The larger the window the more daylight and solar gain will enter and the larger the losses will be. There is an optimum design of glazing systems, which attempts to provide a balance between these energy flows. This balance is a function of the orientation, location, obstructions and user requirements. Generally, between 25 and 50% ratios are regarded as being optimum depending of the above factors.

Window design for:

- Solar protection
  - To prevent overheating windows should always be protected from direct solar gains and external shading is recommended. Internal shading only serves to re-direct the gains to the space as they are already in the space having passed through the glass.
- Daylight
  - The qualities of daylight are such that it should always receive serious consideration in any design analysis, as there is strong evidence that occupants prefer to work in a day lit environment. Daylight also offsets the need for artificial lighting.
- Natural ventilation requirement
  - Windows are the main source of natural ventilation and if this is required in the design then the choice of window can significantly affect the provision of ventilation. Windows that open in such a way as to provide drafts are to be avoided. Tilting windows generally are regarded as being the best type to use. Also, if night cooling is required then some form of trickle ventilation is required and these can be provided either by devices such as perma-vents or small clear story openings.

Thermal insulation

Building regulations require that high standards and integrity of thermal insulation are provided, and it should be normal practice to carry this out. However, with the move to even tighter thermal regulation standards designers should be actively thinking of designing buildings with thermal insulation standard in excess of the current ones as their buildings will (it is hoped) have a life span of sever tens of years and over that time the likelihood of the standards being improved is very strong.

Thermal mass

Thermal mass is an important aspect of design when the specification requires that the amount of mechanical cooling be minimized. Exposed thermal mass in a building is able to absorb a proportion of the heat gains produced during the working period and to remove them at night by allowing the cooler outside air to pass over the surfaces. Generally, it is accepted that by exposing the thermal mass in a building a 2 to 4 degree drop in the inside peak internal air temperature experienced during the day can be achieved. It is important, however, to consider other factors when exposing the thermal mass. The main factor being the possibility of internal noise being transmitted along the space, which can be disturbing to other users of the building.

Thermal mass can be used anywhere in a building but the most effective locations are those where it is easy to absorb heat. Exposed ceilings are perhaps the best location as warm air rises and can therefore easily be absorbed into the surface. Also, a warm ceiling (in winter) will help to keep the radiant temperature slightly higher, which will help in promoting thermal comfort. The removal of heat from a ceiling can either be through passing cooler air over the surfaces (above, through or below) or by passing cooled water through the structure. There is no one solution to the position of or removal of heat from thermal mass – each application is specific to that building. Vertical walls can also be used but they can be covered in decorations or paintings, which will detract from their effectiveness.

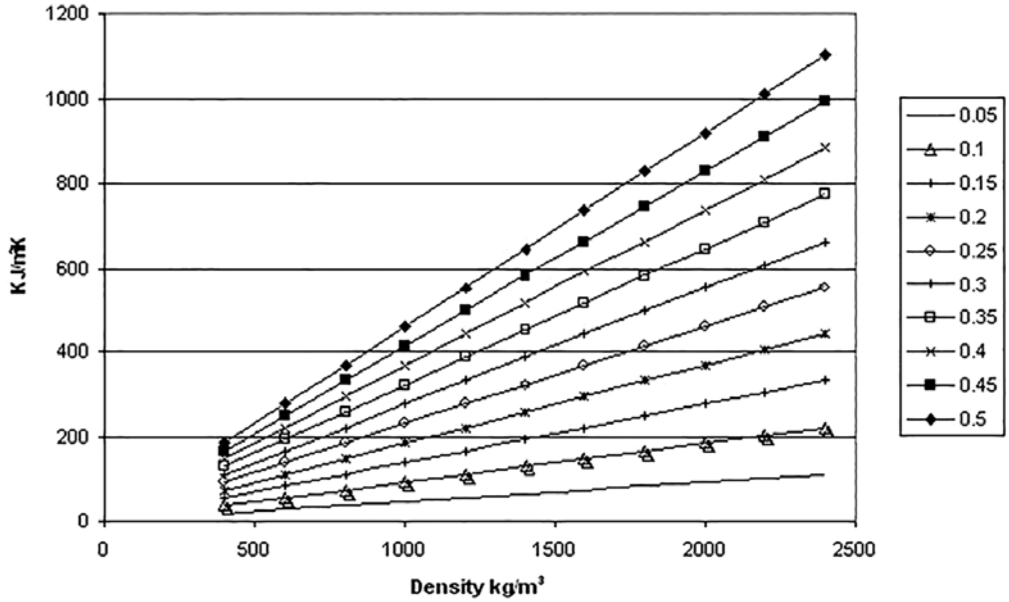

Figure 2.5.1 Thermal storage capacity of concrete for a range of densities and thicknesses per degree kelvin rise in temperature.

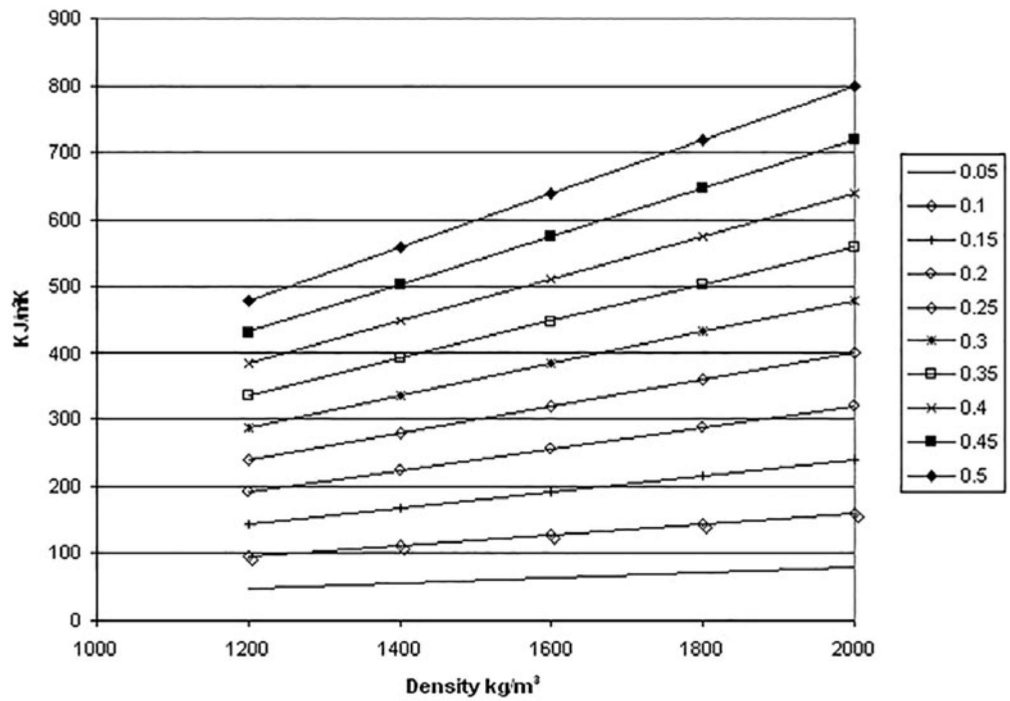

Figure 2.5.2 Thermal storage capacity of brick for a range of densities and thicknesses per degree kelvin rise in temperature.

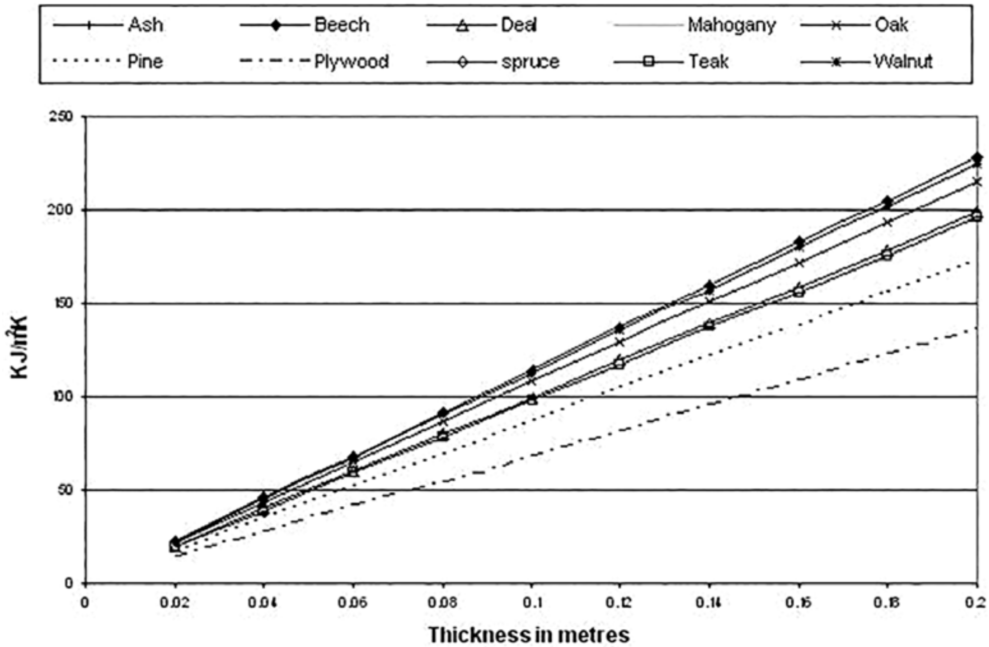

Figure 2.5.3 Thermal storage capacity of a selection of timbers for a range of densities and thicknesses per degree kelvin rise in temperature.

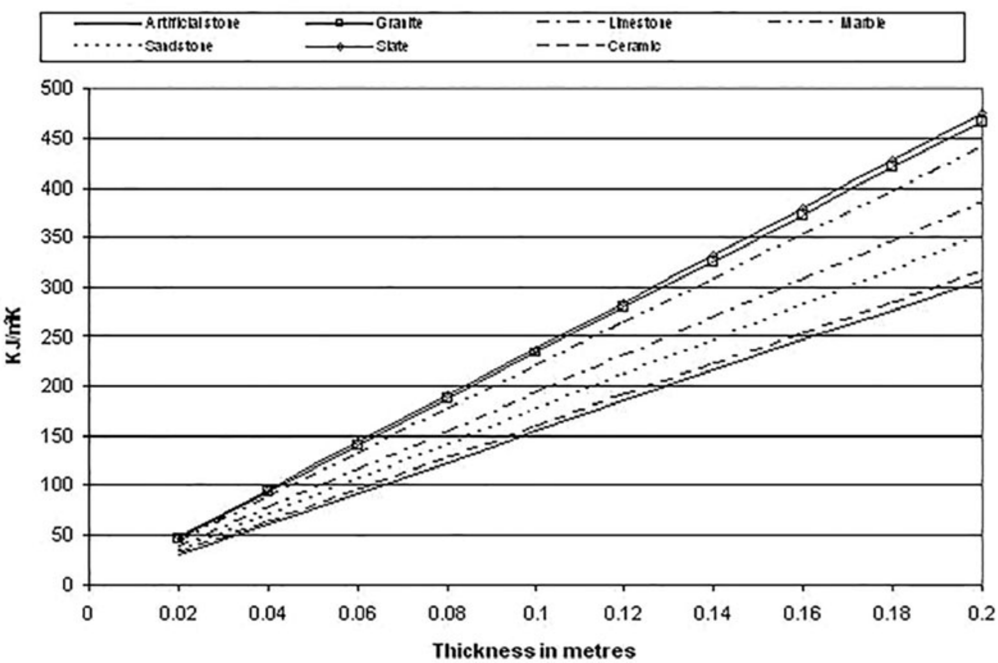

Figure 2.5.4 Thermal storage capacity of a selection of stones for a range of densities and thicknesses per degree kelvin rise in temperature.

In order to help in determining the amount of thermal mass to include in the design, Figures 2.5.1, 2.5.2, 2.5.3 and 2.5.4 give an indication of the amount of heat which could be stored for a range of materials and thicknesses.

Natural ventilation

By ensuring that a building can be naturally ventilated it is possible that the demand for air-conditioning can be minimized or at least reduced in capacity. This means that the carbon footprint of a building could be lower. Accepted figures for a typical high-quality air-conditioned office block are in the region of 9.5 kg/CO_2/m^2 treated floor area while for a naturally ventilated building the value is zero.

Services

As buildings become more energy efficient pressure will be put on the design of the services to meet the lower requirements. Even with housing, using the current UK Building Regulations normal radiators are becoming so small that they look out of place in a room, Figure 5 shows an example from a low energy social home.

In the non-domestic sector, there are similar pressures to reduce the demand for services and to make the service systems more energy efficient. Table 2.5.2 indicates typical values of CO_2 emissions from the four main systems of servicing non-domestic buildings which illustrates quite clearly that the appropriate design of the building and its services can have a significant impact on the levels of CO_2 emitted.

The systems used to supply energy to buildings are also of importance and there are pressures not only to improve the efficiency of these services but also to look at new and innovative ways of providing energy.

By insulating the supply and extract ducts/ pipes it is also possible to make significant improvements in the energy losses of systems – typically these can be up to about 20% of the potential losses.

Minimizing energy demands of building services

Ventilation services

Some systems are now using localized mechanical ventilation systems as it is possible to design the pressure losses in the ducts to be very low resulting in significantly lower fan power for example the fan power used by such systems can be as low as 0.8 W/L/s compared to the normal values of 2 W/L/s.

The air velocity rate of air within ductwork is also of importance as the power required to deliver a specific amount of air increases as a cube function of velocity. To minimize this power requirement, it is advisable to ensure that the air is supplied as slow as possible. Typical duct velocities are in the region

Table 2.5.2 Typical range of carbon dioxide emissions from office buildings (kgCO_2/m^2 treated floor area).

	Typical			*Good practice*		
	Heating	*Cooling*	*Fans/Pumps*	*Heating*	*Cooling*	*Fans/Pumps*
Prestige air conditioned office	11	5.8	9.5	5.9	3	5.1
Standard air conditioned office	9.8	4.4	8.5	5.3	2	4.3
Naturally ventilated open-plan	8.3	0.3	1.1	4.3	0.1	0.6
Naturally ventilated cellular	8.3	0	0.8	4.3	0	0.3

of 6 m/s, but if this can be reduced then significant energy savings can be achieved. On the negative side by reducing the velocity the duct area increases, which could place an extra burden on the space allocation for such services.

Heating and cooling services.

Boilers and chillers are the type of equipment covered by these services. For boiler plant to maintain the maximum efficiency as possible it is advisable to install boilers which can operate at near their maximum output for the longest period of time. This often requires that modular boilers are installed so that as the load varies boilers can be switched on or off as necessary. The most inefficient way of supplying heating services is to install one large boiler capable of delivering the maximum load. It is normal that in most cases the average load is around 50% of the maximum and therefore a single boiler will operate at well below its capacity (and hence efficiency) for a significant period of time.

A similar argument can be put forward for cooling services as being able to schedule on or off of plant to maintain their maximum output is the best strategy to use to minimize inefficiencies.

Alternative energy supply systems

Micro combined heat and power plants

These systems can be used to provide heat and power to either an individual home or a small community. These units produce lower values of CO_2 than traditional boiler plants while also producing electricity. Current technologies for these systems are capable of providing the same comfort levels in a home as a traditional boiler while at the same time reducing the carbon dioxide emissions by about 1.5 tonnes per year (around 25%). Such systems produce between 1–5 kW of peak electricity. However, in summer periods when there is little demand for heating energy then the electricity produced is at a lower efficiency which could make such systems uneconomic.

Micro CHP plants can be powered by a range of fuels some of which produce little or no CO_2 (such as bio-fuels).

Biomass fuels

Biomass fuels are often regarded as fuels which take carbon out of the atmosphere while it is growing and returns it as it is burned. If it is managed on a sustainable basis, biomass is harvested as part of a constantly replenished crop. This is either during woodland or arboricultural management or coppicing or as part of a continuous programme of replanting with the new growth taking up CO_2 from the atmosphere at the same time as it is released by combustion of the previous harvest. This maintains a closed carbon cycle with no net increase in atmosphere CO_2 levels.

The realities of the economics involved in biomass fuels means that high value material for which there is an alternative market are unlikely to become available for energy applications. However, there are large resources of residues, co-products and waste that exist world-wide which could potentially become available, in quantity, at relative low cost, or even negative cost where there is currently a requirement to pay for disposal.

There are five basic categories of material:

1 Virgin wood: from forestry, arboricultural activities or from wood processing.
2 Energy crops: high yield crops grown specifically for energy applications.

3 Agricultural residues: residues from agriculture harvesting or processing.
4 Food waste: from food and drink manufacture, preparation and processing and post-consumer waste.
5 Industrial waste and co-products: from manufacturing and industrial processes.

Renewable energies – solar and wind

Solar and wind energy have a role to play in providing renewable energy to support the demands of a building.

Solar energy can be utilized in one of two ways:

1 The generation of electricity.
2 The generation of hot water.

For the generation of electricity Photo Voltaic devices are utilized. There is a wide range of types on the market but that all currently have efficiencies in or around 10–20% in the conversion of solar energy into electricity. Typical payback periods for such devices are in the region of 20 years which can make them an unattractive option. They produce low voltage DC electricity which often cannot be directly used in the building and therefore has to be converted into higher voltage AC power – this involves more equipment and there are inefficiencies associated with the conversion process.

On the other hand, the use of solar energy to produce hot water is a much better option as the initial costs are lower and the efficiencies higher. In the UK it is conceivable that around 30–40% of the hot water requirements of a domestic home can be supplied by solar panels. In lower latitudes this figure can be significantly increased which makes this type of solar collection a more attractive proposition.

Wind energy is provided by turbines and the larger the turbine the more electricity can be produced. It is also possible to install small generators on a particular building but often their efficiency is compromised by the local wind environment ant there is evidence that such small turbines are not generating anything like their potential. The most efficient way of using wind energy is to use a large turbine located away from the building. These turbines often produce more energy than is required by the building and therefore these give the opportunity for exporting electricity to the grid.

Methods of approach to reduce carbon emissions

With the move toward low carbon emitting buildings taking hold throughout the world there are many ways in which this can be achieved. Some methodology being promoted in Europe for domestic buildings is the German "Passiv Haus" principals. These essentially involve ensuring that the following design issues are strictly adhered to:

- A design which ensures that air leakage is kept to a minimum – the standard is a leakage rate of 0.2 air changes per hour at a pressure test value of 50Pa.
- Super insulated structure – typically 300–400mm giving "U" values less than 0.15.
- Good quality windows and doors with "U" values in the region of 0.6–1.0 W/m^{2}K.
- No thermal bridges in the structure.
- Use passive solar gains which typically supplies about 1/3 of the heating requirement.
- Heat recovery whole house ventilation with high efficiency DC electric motors.
- Ability to use hot water solar systems to supplement the demand for heating and domestic hot water.
- Space heating requirements – 16 kWhr/m^2 year.
- Domestic appliances are "A" rated.

Some examples of passive Houses in Hannover – Germany

EXAMPLE A: These homes (Figure 2.5.5) use 300mm of thermal insulation on the outside walls (Figure 2.5.6), grass roof with solar water heating panels. The heat recovery ventilation unit is located in the loft space (Figure 2.5.7).

Figure 2.5.5 Social passive housing.

Figure 2.5.6
Section of the external wall showing the thickness of the thermal insulation.

Figure 2.5.7
Heat recovery ventilation unit in the loft space.

EXAMPLE B: The design principals for this private block of flats (Figures 2.5.8 and 2.5.9) were the same as those applied to the social housing project. The details of the construction were:

- Concrete core and floors.
- External walls render, timber support, 300mm sheep's wool insulation, internal plasterboard and skim.
- Windows – 3 layers of glass with low e coatings. Frames coated aluminium and timber (on inside). Mechanical ventilation system giving 3 air changes per hour with heat recovery.
- Heating supplied by pre heat of ventilating air and low-level radiator in bedroom.
- Energy supply for the block is by a wood burning boiler – this also provides hot water as a back-up to the solar water heating system.
- Occupants say that in winter the inside temperature never drops below 22°C and in summer the flats never get warmer than 25°C (they do have external blinds).

Figure 2.5.8 Internal view of one of the flats.

Figure 2.5.9 South elevation of the block of flats.

EXAMPLE C: Again, this house (Figures 2.5.10 and 2.5.11) uses the same constructional details to achieve the low heating demand.

Within the UK there has been a great deal of work carried out on the design strategies to be used to produce a house which uses 40% less energy than is currently used. The main strategies to be adopted to produce such a dwelling by 2050 are:

- Electricity consumption for lights and appliances to be reduced by nearly 1/2 to around 1600 kWh per household.
- New build homes will have to have close to zero heating demand.

Figure 2.5.10 Private house.

Figure 2.5.11 Internal view of the house.

2.6

ENVIRONMENTAL TECHNOLOGIES IN THE BUILT ENVIRONMENT

Benjamin Jones, Phillip Dale, Wu Yupeng, Parham Mirzaei and Christopher Wood

There are many technologies used by buildings to help provide thermally and visually comfortable indoor environments using ventilation, heating, cooling, and artificial lighting services. Rather than listing a large number of technologies and discussing their relative merits, we offer a more structured approach and ask two fundamental questions: what are environmental technologies and why they are necessary?

The answers to these questions highlight why sources of low-carbon energy are needed but are not the sole solution, why it is useful to store energy when it isn't required so that it can be used at a time when it is, and how the demand for energy can be reduced. Five specific examples are used here, but we readily acknowledge that there are other technologies. The approach is designed to help practitioners identify other environmental technologies that can meet a particular need.

What is an environmental technology?

The built environment is responsible for the conversion of a significant proportion of all generated and supplied electrical and chemical energies (in the form of oil and gas) into other useable forms, such as thermal (heating and cooking), electromagnetic (lighting and visual systems), or mechanical (washing and sound systems). Accordingly, it is currently responsible for a correspondingly significant proportion of national carbon emissions.

If we are to develop sustainably, concurrently preserving our quality of life and environment, then the built environment has to do two things. Firstly, there is a long term need for it to reduce its dependence on forms of energy that are responsible for the emission of carbon dioxide equivalents when they are generated or used. Therefore, a readily available zero-carbon supply of energy is explored in Section 2.6.2. Secondly, there is a general need for it to use less energy. In the short term this will reduce its dependence on carbon intensive forms of energy and in the long term it means that other available forms of energy can be stored and used responsibly by systems that improve human health and wellbeing. Technologies that store and release energy and reduce energy use are explored in this chapter.

It is particularly important to note that our ability to provide these services is bound by physical limits. Over time, the efficiency of everyday building technologies will approach a thermodynamic limit. Some, such as the electric motor, are already highly efficient (~ 90%) and so further improvements will be incremental and will only make minimal energy savings. Other technologies, such as the light bulb, have recently experienced dramatic efficiency improvements so that they now use only 10% of the energy that they did a few years ago and last up to 10 times longer. Nevertheless, such reductions are uncommon and most of the radical improvements have been made so we cannot assume that energy savings can be achieved solely by increasing the efficiency of technologies.

We are also bound by other physical limits, such as the thermal properties of air and water. In the built environment their temperatures are manipulated to heat and cool buildings, yet their properties remain constants. This emphasizes the need to minimize the total mass of air and water that is heated or cooled, and this is explored below.

With these factors in mind, we define an Environmental Technology as one that is capable of making a significant contribution to the reduction of energy used by the built environment. This chapter gives an overview of technologies that are capable of making such a contribution. It does not attempt to explore each technology in depth but is designed to give the reader an overview and to provide a list of references that facilitates further study. An assessment of embodied energies is deemed to be outside the scope of this chapter.

Zero-carbon energy: Solar energy

Every day the earth receives enough solar irradiation to meet current human energy needs. If this energy could be harnessed and stored, the world could rely solely on renewable solar energy. Solar irradiation can be used directly to warm air or other fluids, or it can be converted into electrical energy, a primary energy source. A device that converts solar energy to electrical energy is a photovoltaic (PV) device. Once the solar irradiation has been converted to electrical energy it can either be stored in a battery as chemical energy or be used directly.

Photovoltaic principles

A photovoltaic device converts solar radiation into electricity energy. Photons of light are absorbed in the device creating excited electrons and holes. Holes are simply the vacancies left by the vacated excited electron. The photovoltaic device separates the excited electron and hole charge carriers, normally through the use of a p–n semi-conductor junction and allows them to flow around an external circuit doing useful work before they meet and re-combine. A semi-conductor is described using a band model where electrons move from a valence band to a conduction band. The energy difference between the valence and conduction bands is known as the band gap. Only photons with a particular energy are absorbed by the semi-conductor and those photons must have a higher energy than the semi-conductor's band gap. The output voltage of the device is proportional to the size of the band gap, the output current is proportional to the number of photons of light that have an energy level that is greater than the band gap, and the output power is a product of the current and voltage. In a photovoltaic module, commonly observed on building roofs, devices are often placed in series to allow a much larger output voltage than a single device could provide. The electrical output of a module is direct current, and so if it is desirable to feed the power directly into the electricity grid an inverter is used to convert it to alternating current. Photovoltaic modules are optimally installed on southern facing roofs in the northern hemisphere and tilt angles are adjusted by latitude.

Photovoltaic types

The various types of photovoltaic device technology each use a different semi-conductor to create the p–n junction. Each has its own advantages and disadvantages. Normally there is a trade-off between power conversion efficiency and the cost of making the semi-conductor. Table 2.6.1 is a selected list of the power conversion efficiencies of the main technologies, both the best laboratory efficiency based on a

Table 2.6.1 Maximum power conversion efficiencies (as of the end of 2013) reported for laboratory scale and module sized devices.

Technology		*Power conversion efficiency at end of 2013 (%)*		*EPT (years) [Peng13]*
		Small area ca. 1cm [Green14]	*Module > 800 cm²* *[Green14]*	
Bulk	⋆Crystalline silicon	25.0	22.4	1.7–2.7
	⋆Polycrystalline silicon	20.4	18.5	1.5–2.6
Thin film	GaAs	28.8	24.1	–
	⋆CdTe	19.6	16.1	0.75–2.1
	⋆$Cu(In,Ga)Se_2$	19.8	15.7	1.5–2.2
Molecular	Dye sensitized	11.9	–	–
	Organic	10.7	–	–

⋆ Indicates that the technology is readily commercially available. EPT is calculated for southern Europe.

1 cm^2 device, and the best module efficiency with an area greater than 800 cm^2. The theoretical maximum power conversion efficiency of these technologies, known as the Shockley-Queisser limit, is around 33% (Siebentritt, 2011). However, the realistic engineering limit is considered to be around 26%. The laboratory efficiency reflects what is scientifically possible, whereas the module efficiency reflects the difficulty in reproducing this over large areas. The higher efficiencies of the silicon and Gallium Arsenide (GaAs) technologies reflect, in part, the greater research effort and time spent on them, and the fact that they are used in technologies other than photovoltaics. Contrarily, Cadmium Telluride (CdTe) and $Cu(In,Ga)Se_2$ technologies are relatively new and are only used in photovoltaics, but have a greater potential to be produced at a lower cost than the silicon or GaAs technologies. The newest technologies apply a low temperature molecular based processes that can be fabricated on a roll-to-roll manufacturing system at high speed and at low cost. Their efficiencies show that there are still many challenges to overcome. Both the thin film and molecular technologies may be produced on flexible substrates, unlike the bulk silicon technologies, and so have the potential to be used on moderately curved surfaces.

Annual energy

A rough upper estimate of the maximum number of kW.hr per year generated by an optimal south facing residential roof photovoltaic system can be estimated. First, the installed power generating capability under standard conditions[1] is calculated, with units of kW_{peak} or kW_p. Second, the number of kW.hr generated per installed kW_p per year for the given location is assessed. The product of the two numbers together gives an estimate of the total energy production in one year. The best commercially available photovoltaic modules have an efficiency of approximately 21%, which under standard irradiation conditions give 210 $W.m^{-2}$. If one assumes a 30m^2 array, the total power under standard conditions is $210 \times 30 = 6.3$ kW_p. In northern Europe, the total annual irradiance is approximately 1200 $kW.hr.m^{-2}$, which if one assumes an overall performance ratio of 0.75 $m^2.Wp^{-1}$ gives $1200 \times 0.75 = 900$ $kW.hr.kWp^{-1}$. Therefore, the total electrical energy output of the array in one year is approximately $900 \times 6.3 = 5700$ kW.hr. To put this in context, the average European household electrical use in 2009 was 4200 kW.hr (EEA, 2013). Using low energy appliances and light bulbs can reduce the annual electrical use of a family of four to 2000 kW.hr.

Energy payback time

The energy payback time (EPT) of photovoltaic systems depends heavily on the level of solar irradiation. A photovoltaic array installed in southern Europe instead of northern Europe could conceivably generate double the electrical energy. The EPT is roughly defined as the time required to generate the same energy that it takes to make, use, and then recycle the array (Peter, 2011). EPT estimates are given in Table 2.6.1 for some of the technologies in a southern European context. Photovoltaic systems are usually guaranteed for 20 years or more, and here the EPT is around three or less. The EPT does not include the manufacturer's markup or the installation costs (Peng et al., 2013).

Building applied and integrated photovoltaics

Photovoltaic installations added to a building after it is built and that have no other function than to produce energy are called Building Applied PV (BAPV) (Jelle et al., 2012). BAPV forms the majority of installations. However, if the photovoltaic installation is an integral part of the building providing some other function, such as weather proofing, then it is known as a Building Integrated PV (BIPV) (Jelle et al., 2012). BIPV products are integral to a building's structure and, in addition to generating electrical power, can provide savings in materials and electricity costs by also providing a colourful façade or roof, giving partial shading, or providing extra daylight illumination (Jelle et al., 2012). Shading or illumination can be achieved by either allowing transparent spaces between individual cells that make up a module, or by using a continuous semitransparent solar cell, such the amorphous silicon-based devices (Pagliaro et al., 2010). Accordingly, they can facilitate natural space heating during winter and increased daylight illuminance.

One of the most exciting developments of BIPV is their harnessing of the thermal energy generated by the photovoltaic component during operation. Normally, the incoming irradiation unconverted to electricity raises the temperature of the solar cells by up to 40°C. In turn, this reduces their efficiency and their electrical power output and so it is desirable to cool them. The absorbed thermal energy can transfer away to power a thermovoltaic device, or more simply to heat air or a fluid, which in turn may be used for other applications, such as drying processes, heating water, or air conditioning (Saloux et al., 2013).

The major barriers to the adoption of BIPV are low efficiency coupled with high cost. Well known examples of architectural integration include the Pompeu Fabra Public Library in Mataró, Spain, and the De Kleine Aarde building in Boxtel, Netherlands.

Solar concentrators

Although significant efficiency and cost gains have been made in recent years another promising advance is the integration of PV with solar concentrators (CPV); see Figure 2.6.1. Their aim is to increase the electrical output per unit area of relatively expensive solar cells by concentrating available solar irradiation using low cost reflecting or refractor optics.

CPVs can be categorized into three groups: (i) High concentration PV systems ($C > 100$, where C is the geometrical concentration ratio defined as the ratio of the aperture area of the concentrator and the solar cell), (ii) Medium concentration PV systems ($10 < C < 100$) and (iii) Low concentration PV systems ($C < 10$). High and Medium concentration PV systems are usually large in size and require very accurate tracking; for example, high concentrating systems require tolerances below 0.2°C. As such they are more difficult to integrate into building components and so they are often installed on flat roofs.

Most of the low concentration systems such as flat reflectors and compound parabolic concentrators (CPC), with a geometrical concentration ratio of less than 3 can be static and so no tracking is required. Therefore, they are suitable for integration into many different locations on a building's façade. The use

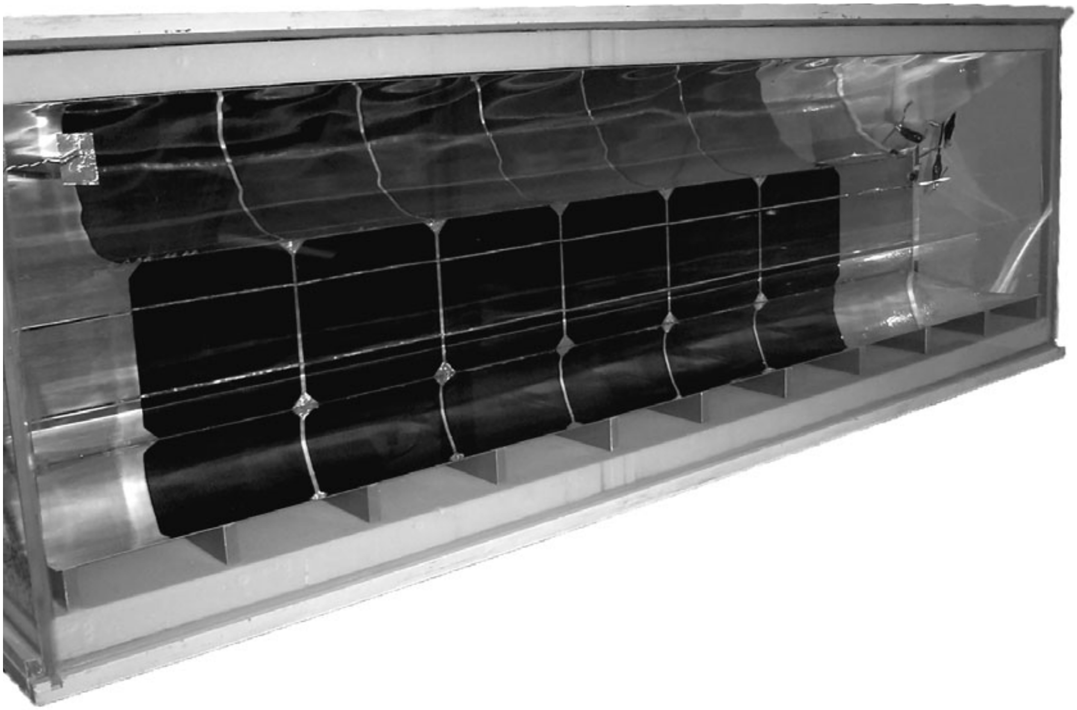

Figure 2.6.1 Integrated PV and solar concentrator.

of conventional flat reflectors with PV modules has been studied since the 1970s. CPCs have also been widely investigated because they can achieve their theoretical maximum geometric concentration ratio within their acceptance angles, the maximum angle at which incoming sunlight can be captured by a solar concentrator. The typical power output of flat reflectors and CPC PV can be 1.6 to 2 times greater than that of non-concentrating PVs. Luminescent concentrators are also suitable for building integration; however, their performances need to be further optimized; for example, the photostability over prolonged periods of UV exposure for organic dyes-based concentrators still needs to be further investigated and the Quantum dots based luminescent concentrators exhibit relatively low luminescent quantum efficiency.

Final thoughts

There is a wide choice of commercial photovoltaic technologies that may be added to existing buildings or even directly integrated into new buildings. The technology is now sufficiently mature that enough electrical energy may be generated to cover the average European household electricity use and perhaps some of the heating requirements as well. From a materials and energy perspective, photovoltaic modules pay for themselves within two years when located in southern Europe and normally guaranteed to generate electricity for over twenty years.

Storing energy: Phase change materials

The supply of renewable energies to a building is not always compatible with its demand. The sun doesn't always shine, and the wind doesn't always blow. This implies that these energy forms should be stored when available and managed so that they can be used when required. Thus, a process is required to respectively store and utilize the energy during the off-peak and peak periods. Phase change materials (PCM) are a widely accepted method of storing these energies due to their large latent storage capacity during an almost isothermal (constant temperature) process. This means that PCMs provide a large storage density in a very small temperature interval. Away from buildings PCMs have been used for years to heat and cool food and examples include ice in drinks or reusable wine bottle coolers. PCMs have been widely integrated into buildings because they have the potential to increase energy efficiency, to shift load from peak to off-peak periods, to provide emergency heating/cooling loads, and because they make an economic and environmental impact (Mirzaei and Haghighat, 2012).

Characteristics of the PCM for building integration

When choosing a material for the thermal storage purposes, it should have a large latent heat (the energy required to convert it from a solid into a liquid) and a high thermal conductivity. Its melting temperature should also be adapted to a practical range of operations. The super-cooling effect (where its liquid state is retained well below its freezing temperature) should be minimal, and it should be chemically stable. Moreover, the material should be inflammable, low or non-corrosive, nontoxic, and cheap. Some of the most widely used PCM materials are salt hydrates, paraffin waxes, fatty acids and eutectics (a mixture of substances that melt and freeze at a single temperature that is lower than that of its constituents) of organic and non-organic compounds (Farid, Khudhair, Razack and Al-Hallaj, 2004). Each type of the PCM has its own advantages and disadvantages, and the selection should be based on four major properties of the PCM: (1) thermodynamic, (2) nucleation, (3) chemical, and (4) economic. Important properties include the melting point that assures the storage and extraction of heat, the heat of fusion required to obtain a high storage density, the thermal conductivity to perform a suitable charging/discharging process, the material density, the need for congruent melting (when the composition of the melted fluid is the same as the solid, as opposed to incongruent melting when it is not), minimal volume change following phase change to ensure installation practicality, and a high specific heat to ensure a significant sensible storage capacity (Cabeza, Castell, Barreneche, de Gracia and Fernández, 2011).

Application of PCM in buildings

Various techniques are utilized to integrate PCMs into the buildings, such as micro, macro, composite, and structure encapsulation. In the microencapsulation process (mainly smaller than 1mm) the small PCM particles are encapsulated in a thin, high molecular weight, polymeric film. The coated particles can then be placed in a building integrated matrix. The main advantages of this technique are heat transfer and stability improvements. The larger scale encapsulation technique (mainly larger than 1cm) is known as macro-encapsulation. The PCM is enclosed in a container that can be used in building products. Thus, the products can easily be integrated in building applications without the problems such as phase-change volume adjustments. An example of a low energy cooling and ventilation system that uses PCM thermal batteries and is located in a roof void is shown in Figure 2.6.2. Building integrated PCMs can be also manufactured as composite materials (with another compatible material) to improve its characteristics. Furthermore, the structural encapsulation or impregnation of PCMs into building materials such as plaster, concrete, vermiculite, wood, or cement, is another popular technique of integrating PCMs (Zhang, Zhou, Lin, Zhang and Di 2007).

Impregnated PCMs are installed in buildings using a range of strategies. They can directly incorporate into the buildings' ceiling, flooring, or walls (Kuznik et al., 2011) for heating and cooling purposes, or they can be stored in tanks for until required (Agyenim, Hewitt, Eames and Smyth, 2010). PCMs can

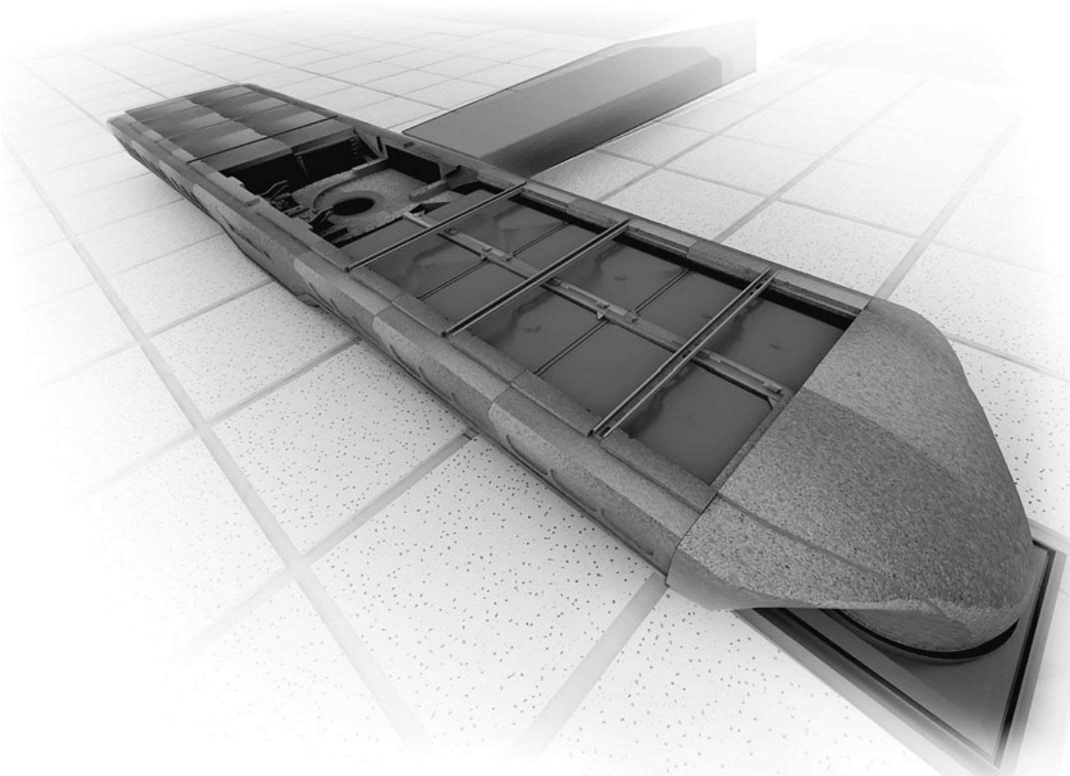

Figure 2.6.2 Cooling and ventilation system using PCM thermal batteries.

Table 2.6.2 Main advantages and disadvantages of organic and inorganic PCMs.

	Advantages	*Disadvantages*
Organic PCM	• Large temperature range • Low super-cooling • Non-corrosive • High congruency in melting • Highly compatible with building materials • Chemically stable • High fusion heat • Recyclable	• Low thermal conductivity • Low volumetric latent heat storage capacity • Flammability
Inorganic PCM	• High volumetric latent heat storage capacity • Low cost and easy availability • High thermal conductivity • Non-flammability	• High volume change • Super-cooling

Source: Cabeza et al., 2011; Kuznik, David, Johannes and Roux, 2011 also be indirectly integrated with solar collectors (Hasan, McCormack, Huang and Norton, 2010) or heat exchangers.

PCM modelling and future challenges

To understand the economic factors (such as capital outlay and payback periods) and the optimal design criteria (such as PCM type and integration technique) of a PCM integrated technologies, many mathematical and experimental tools have been developed (Verma, Varun and Singal, 2008; Dutil, Rousse, Salah, Lassue and Zalewski, 2011) and integrated within building energy simulation (BES) software tools. The mathematical approaches are mainly use numerical techniques (such as the finite difference, element, or volume methods). The limitations of these modelling approaches comprise their high computational cost and limited accuracy (Mirzaei and Haghighat, 2012).

The future PCM challenges include the need to enhance PCM characteristics (such as cost and thermal conductivity), to make their integration in buildings more efficient and practical, to development faster and more accurate design approaches, to provide improved calculation and optimization tools, and to prepare practical guidelines for end-users.

Reducing heat transfer: Super insulators

The need to increase the energy efficiency and thermal comfort of buildings has resulted in a *fabric-first* approach in modern construction and a large increase in the use of insulation materials. The primary function of any insulation material is to reduce the heat flow through construction elements and is achieved by virtue of the material's inherent low thermal conductivity λ (W/m.K), compared to those of surrounding construction materials. Insulation materials can generally be split into two categories; conventional and super insulation. A super insulation material is defined as one having a $\lambda < 0.020$W/mK. Presently, super insulation materials are rarely used due to their comparatively high cost as a function of their thermal performance. In terms of market share, the most widely used insulators are conventional and take the form of organic foams or inorganic fibres. Expanded polystyrene and polyurethane are examples of typical foam materials, while mineral wool is the most readily used fibre. The λ of these materials range from as low as 0.020W/mK for polyurethane to as high as 0.045W/mK for the fibrous materials (Cuce, Cuce, Wood and Riffat, 2014). In contrast, superinsulation materials such as aerogel and vacuum insulated panels (VIPs) can achieve λ as low as 0.013W/mK and 0.004W/mK respectively (Kalnæs and Jelle, 2014).

Optimum thermal conductivity

The thermal performance of super insulation materials can be understood by considering the physics of heat transfer through a material. The heat transport through an insulation material can be divided into three distinct processes; conduction in the solid, conduction in the gas phase, and radiation through the pores. The overall λ of the material is influenced by all three processes; for example, solid conduction increases with material density, and conversely as density decreases the influence of radiation increases (although non-linearly). An optimum point therefore exists where the sum of these two components are at a minimum. For most insulants the thermal conductivity of air (≈ 0.025W/mK) is the limiting factor and tends to limit the thermal conductivity to around 0.030W/mK (Cuce et al., 2014). Materials such as mineral wool and polystyrene are both limited in terms of their lower range thermal conductivity values due to this factor. By either removing air or at least limiting its fraction and ability to move and also by producing a solid component of low thermal conductivity it is possible to produce an insulant with extremely low heat transfer properties.

Aerogel achieves its low thermal conductivity by means of a structure, with an extremely low pore size; typically 5–70nm for silica aerogel. This has the effect of constraining the movement of air molecules to within the order of their mean free path, thereby reducing the effective thermal conductivity of the air within the structure. The high porosity structure of silica aerogel structure has a very low density, which can be as low as 3kg/m^3, but typically for building applications will be around 100kg/m^3 (Cuce et al., 2014). At ambient pressure the silica aerogel is typically 0.0135W/mK. Aerogels are produced via the Sol-gel process, where a gel is created, and the liquid is removed to leave the solid aerogel micro-porous shell.

VIPs also achieve low thermal conductivity with a structure consisting of very small pores; typically 30–100nm. The VIP core tend to be fumed silica and unlike the aerogel insulation material the core is 100% open and is evacuated to a pressure of 30–100nm. The vacuum is maintained within the core by shrouding the material in a film envelope. Thermal conductivity is typically in the range of 0.003–0.006W/mK when the core is under a pressure of 20–100mbar and with a mass density of around 200kg/m^3. As the VIP panel is held at a very low pressure compared with the atmosphere, a function of the core is to resist the pressure exerted by the surrounding air, which amounts to 101kPa. Other materials, such as aerogels and polyurethane can be used for the core, but fumed silica is by far the most common material for VIPs in the building sector due to its advantageous credentials, of being non-toxic, incombustible and recyclable. As gas conduction in the VIP is extremely low the contribution of radiation heat transfer is proportionately much higher. To overcome this, opacifiers are added to the fumed silica (Kalnæs and Jelle, 2014). The film envelope is an extremely important component of the VIP and is critical to the overall 'effective' thermal conductivity of the panel and the longevity of the vacuum inside the panel. The films used are multi-layer, which have overall thicknesses in the range of 100–200μm. Metal foils, metallized and polymer films are all currently used for VIPs. The use of an aluminium layer is also very common because of its very low gas and water permeation. However, its disadvantage is its relatively high thermal conductivity, which creates high heat fluxes at the edges of panels (Baetens et al., 2010). Edge effects are critical consideration in the design of such panels, as the flow of heat via the edge along the side of the panel will have the effect of reducing the overall aggregated thermal resistance of a number of panels applied to a wall.

Superinsulation materials currently have a very small market share due to their high cost when compared against the conventional insulants. However, superinsulation has most relevance in the retrofitting of older buildings due to their higher thermal resistance and therefore much slimmer construction. In the drive toward making the building stock more energy efficient, the improvement of thermal performance of the building fabric is of key importance. For most buildings heat transfer through the fabric is one of the largest components of the energy demand for the building. By retrofitting insulation this energy demand can be substantially reduced; however, in many cases insulation can only be performed on the internal surface of the property due to external aesthetics. The addition of this type of internal insulation can lead to overheating without appropriate mitigation measures, such as solar shading. It can also reduce the floor area inside a dwelling, which is often undesirable. Superinsulation can minimize this problem because its thermal resistance requires only a thin layer to be used.

Reducing demand: Controllable ventilators

A successful ventilation strategy must deliver clean air at a rate that maintains adequate indoor air quality (IAQ), at a temperature that maintains occupants' thermal comfort, and in the most energy efficient manner. Accordingly, the amount of energy used is dependent on the airflow rate, required air conditioning, and the energy used by devices such as fans, pumps, and control systems.

The need to meet this triumvirate of requirements suggests that there isn't one solution applicable to all ventilation problems, but there are a number of technologies that can ensure that these conditions are met.

However, it is first important to avoid using technologies when they aren't required by eliminating known sources of poor IAQ, utilizing freely available forms of energy such as solar heat gains, minimizing the thermal conductivity of the fabric, and by increasing fabric airtightness. The measurement of an air leakage rate is discussed on page 245 of this volume and shown to be an invasive steady state technique at a pressure differential that is an order of magnitude higher than that which occurs under operational conditions, and uses a power law model that can lead to significant uncertainty. The pulse technique (Cooper, Etheridge and Smith, 2007) is emerging as a non-invasive (see Figure 2.6.3) alternative that measures the air leakage rate at a pressure differential of 4Pa with an accuracy that has not previously been possible.

The next step is to ensure that a well design ventilation system is used as efficiently as possible by using fine control. Occupants are notoriously bad at controlling ventilation openings efficiently and so a demand-control strategy compares indoor air temperature and CO_2 concentration inputs against IAQ and comfort criteria to amend airflow rates. Even the humble window can be controlled using actuators and this can be a distinct advantage because occupants are poor moderators of their ventilation. Nevertheless, they must be given the opportunity to override and control technology.

An energy efficient ventilation strategy may be solely mechanical, only driven by natural forces, or a mixed-mode combination of the two; all have their own advantages and disadvantages. The occupants of naturally ventilated (NV) buildings, which require no mechanical input, are often found to be more satisfied with their indoor environment than those who occupy air-conditioned spaces. Smaller devices are often found in public buildings, such as schools, and in houses. Windows are the most common NV opening but airflow rates through them can be increased significantly by using a stack, a covered chimney used to extract air at a high level. The split-duct ventilator (also known colloquially as a wind-catcher) (Jones and Kirby, 2009) is a modern derivative of rectangular cross-section that is diagonally divided into four separate quadrants so that each is connected to a louvred vertical face. Those faces incident to the wind channel air into a room under the action of its pressure, while those that are leeward simultaneously

Figure 2.6.3 Clarke Rebel 60 air compressor.

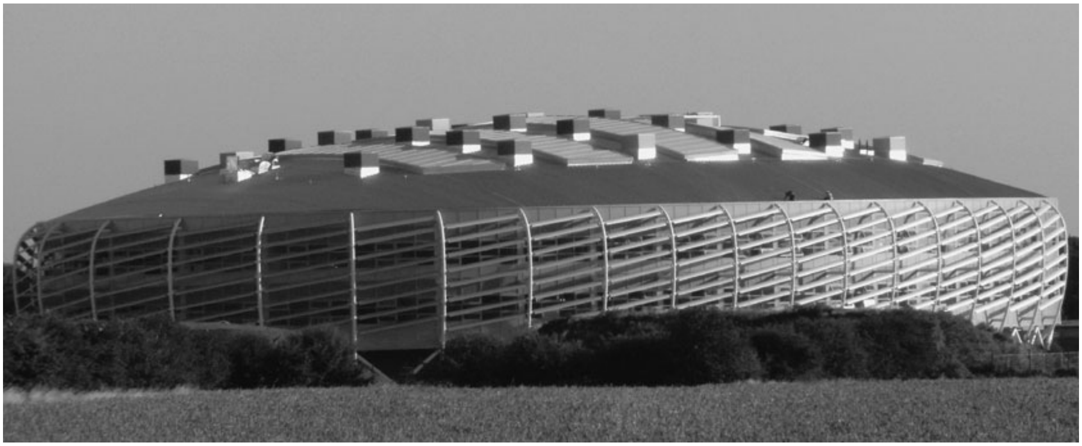

Figure 2.6.4 Breathing Buildings ventilation system, Monkseaton High School, Whitley Bay, UK.

draw air out of the room by virtue of a low-pressure region created downstream of the wind-catcher element. They can operate autonomously where airflow through windows is either undesirable or impossible or can augment airflow through windows or other purpose-provided vents. A wide number of other wind driven devices are discussed by Khan et al. (2008).

Some NV systems facilitate high heating season energy losses. However, another derivative of the stack (see Figure 2.6.4) achieves significant reductions in heating season heat loss by only supplying air from roof level and by incorporating fans into the device that tempers the incoming ambient air by mixing it with room air; see Linden (1999) for a discussion on mixing ventilation. In the summer the fans can be used to augment night cooling techniques, demonstrating the advantages of a mixed-mode system.

In houses, balanced mechanical ventilation systems that are capable of transferring over 80% of thermal energy from the extract airflow path to the supply path are becoming increasingly common. However, a failure to provide high air tightness and the perfect balancing of the supply and extract airflow streams can significantly increase their energy consumption.

Note

1 Standard conditions are AM 1.5 radiation with a power density of 1 $KW.m^{-2}$.

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2.7
LIFE CYCLE ASSESSMENT OF BUILDINGS

Christina Diakaki and Denia Kolokotsa

Introduction

The life cycle of a building, as well as of other systems (processes, services, etc.) follows like the life time of biological organisms, in a circle. In the same way that the biological organisms originate, reproduce and finally die, the buildings are constructed, used and finally demolished and disposed.

At each stage of their life cycle, the building systems interact with other systems, and thus, their life cycle is actually an open cycle. Their construction, demolishment and disposal interact with the wider natural, economic and social environment since raw materials and energy, labour, technology and capital are required. The developed relations and interactions are dynamic and in some cases, they may become even competitive. For example, the construction of a green building usually requires an increase of the related cost. Therefore, in order to get globally acceptable solutions, all the factors involved during the life cycle of a considered building should be studied. To this end, several methods and tools may be used, and life cycle assessment (LCA) is one among them (IEA, 2004).

LCA refers to the environmental impact study for each stage of a system's life cycle. It constitutes generally of a set of systematic procedures that quantify the inflows and outflows of energy and other resources throughout its total life cycle. Based on this quantification, LCA, then, evaluates and identifies any potential environmental impacts aiming to determine appropriate improvement actions.

LCA is not the only approach for analyzing the environmental impacts of a system, it is probably, however, the most comprehensive one (IEA, 2004). When applied to the building sector, LCA may focus on building materials and component combinations, single buildings, building stocks (i.e. groups of buildings), specific aspects of a building system (e.g. the air-conditioning system), or specific stages of a building's life cycle (e.g. the construction stage) (Kotaji, Schuurmans and Edwards, 2003; IEA, 2004). It is the aim of this chapter to present the main characteristics of the LCA approach with particular emphasis in its application to the building sector.

The chapter starts with a short review of the evolution of LCA from its roots, dating back in the decades of 1960s and 1970s, until today, discussing also the efforts of different international organizations to standardize the overall procedure. Then, the goal and scope of the approach is presented followed by a description of the LCA procedures. The chapter concludes with a few final remarks and a discussion of its main topics.

The evolution and standardization of the life cycle assessment method

LCA has a life of almost 40 years. The roots of the method lie into the early studies of the 1960s and '70s that became known as Resource and Environmental Profile Analyses (REPAs) in USA and Ecobalance in Europe (Ciambrone, 1997). During these decades, several studies were conducted by research institutes and consulting firms addressing issues mainly concerning the private sector (Assies, 1993; Tan and Culaba, 2002).

As their title indicates, the early LCA studies place the emphasis in the energy and raw material demand, as well as, the waste production. The oil crises of 1973 and 1979 advanced further the conduction of such studies focusing on fuels and energy related issues and analyses (Boustead and Hancock, 1979; Sørensen, 2004).

At the end of the '80s, the production and disposal of packages with negative environmental impact is acknowledged as an issue of major importance and a recycling trend spreads around the world – a further advancement emerges for LCA that is now recognized as one of the most important methods for the analysis of environmental impacts (Ciambrone, 1997).

The modern LCA methodology is based on the standards developed during '90s. More specifically, in 1991, the Society for Environmental Toxicology and Chemistry (SETAC) published a guide for the conduction of LCA studies (SETAC, 1991). A few years later, the International Organization for Standardization (ISO) released the standard series ISO 14040 on LCA, as supplement and expansion of the ISO standard series 14000 on Environmental Management. The new version of ISO 14040 series has been since released (ISO 14040, 2006; ISO 14044, 2006).

Although the ISO 14040 series standards are quite similar with the SETAC guide, they have superseded the SETAC guidelines due to the dominant position of ISO in the development of international standards.

Goal and scope of life cycle assessment

Life cycle is a concept underlining several environmental oriented approaches. These approaches, also called a "cradle to grave" way of thinking about products, services or processes, can generally be split into analytical and practical (UNEP, 2005). Independent of the category to which they belong, all life cycle-based approaches are steered by concepts such as sustainable development, ecology and eco-efficiency, which are guiding principles on how to achieve a life cycle economy. Moreover, their application is based on the availability of data and information such as databases with specifications on resource use, emissions and toxic substances, or demographical data.

The analytical approaches are used to assess, in a scientifically sound way, the effects of planned actions and decisions, while the practical approaches aim to put the results of the analytical approaches into practice. The LCA approach addressed herein, is an analytical life cycle approach (UNEP, 2005) that may contribute in (Tan and Culaba, 2002; Kotaji et al., 2003; ISO 14040, 2006; Nebel, 2006):

- Formulation of environmental laws.
- Decision making by the industry, as well as by governmental or non-governmental organizations.
- Development of business strategies including investment plans.
- Identification of opportunities for the improvement of the products' environmental aspects at several points during their life cycle.
- Selection of indicators for surveillance, evaluation and/or measurement processes.
- Marketing, including the ecological labelling and the improvement of corporate image.
- Benchmarking.
- Purchasing decisions.

The wide range of possible applications implies also the wide range of stakeholders who may use and benefit from the LCA results (Nebel, 2006):

- Industry and other commercial enterprises.
- Governmental and regulate bodies.
- Consumer organizations and environmental groups.
- Consumers.

When applied to buildings, LCA aims to assess the environmental loadings and impacts, throughout their entire life cycle that includes the following main stages:

1 Design.
2 Materials and components production.

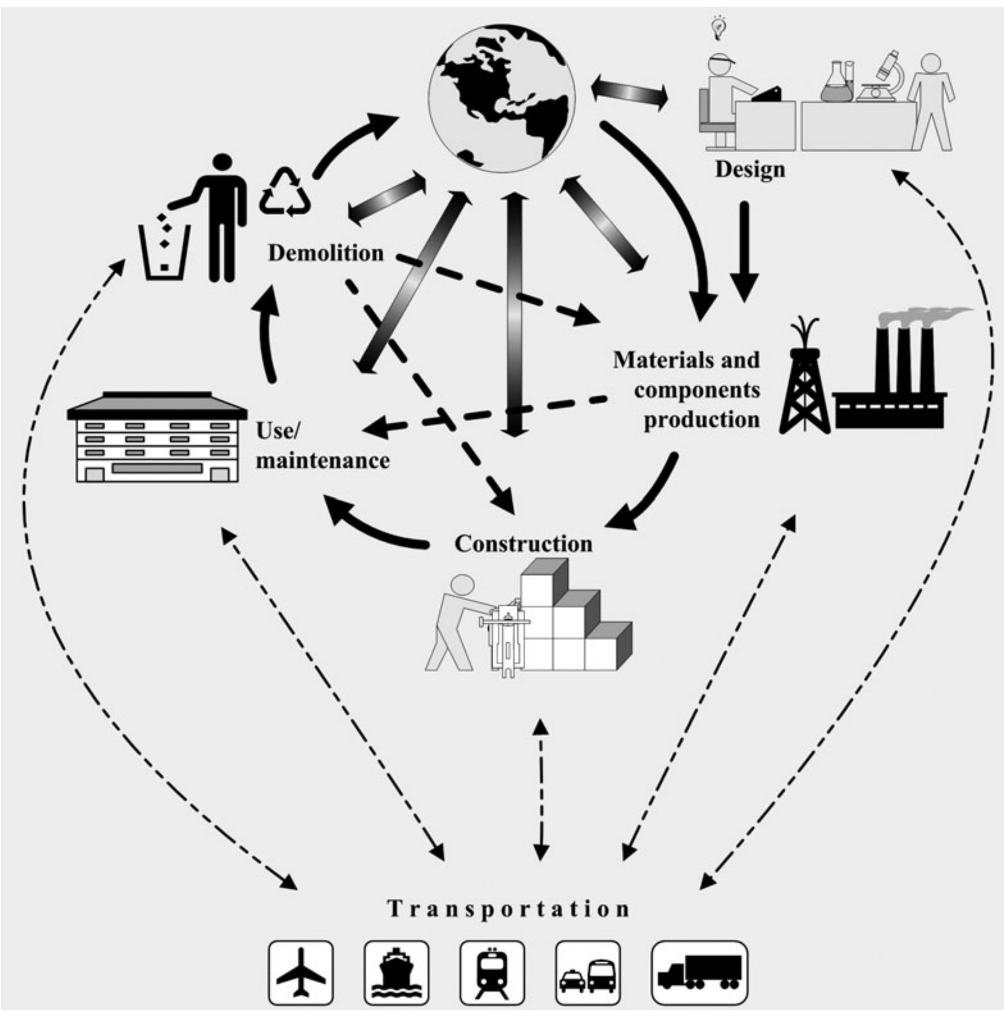

Figure 2.7.1 The life cycle of a building.

3 Construction.
4 Use and maintenance.
5 Demolition.

A process that should also be considered within all the aforementioned stages of a building's life cycle is transportation. Usually, the loadings from transportation are considered separately from the other processes due to several difficulties that may arise. The most significant difficulty (IEA, 2004) is the attempt to account for transportation during the use stage of a building's life cycle. At this particular stage, it is necessary to predict the building occupants' behaviour and to formulate transportation scenarios, thus to perform tasks that are not at all trivial and depend upon several factors that cannot be anticipated during the design and construction stage (e.g. the building location and the transportation infrastructures).

The LCA method recognizes that all the aforementioned stages of a building's life cycle have environmental impacts that need to be identified, quantified, analyzed and improved. Areas of concern usually include resource use, human health and ecological consequences (SETAC, 1991). Depending upon the goals of each particular study, a building may be viewed in many different ways (IEA, 2004). It may be viewed as a product that is manufactured, used/maintained and finally disposed. It may also be viewed as a process intended, through its operation, to provide a number of services to users as well as appropriate conditions for living, working, studying, etc. Finally, it may be viewed as a place to live thus putting the emphasis in the comfort and health of its users. Therefore, LCA requires to be customized accordingly so as to include or exclude specific life cycle stages, or specific loadings and impacts.

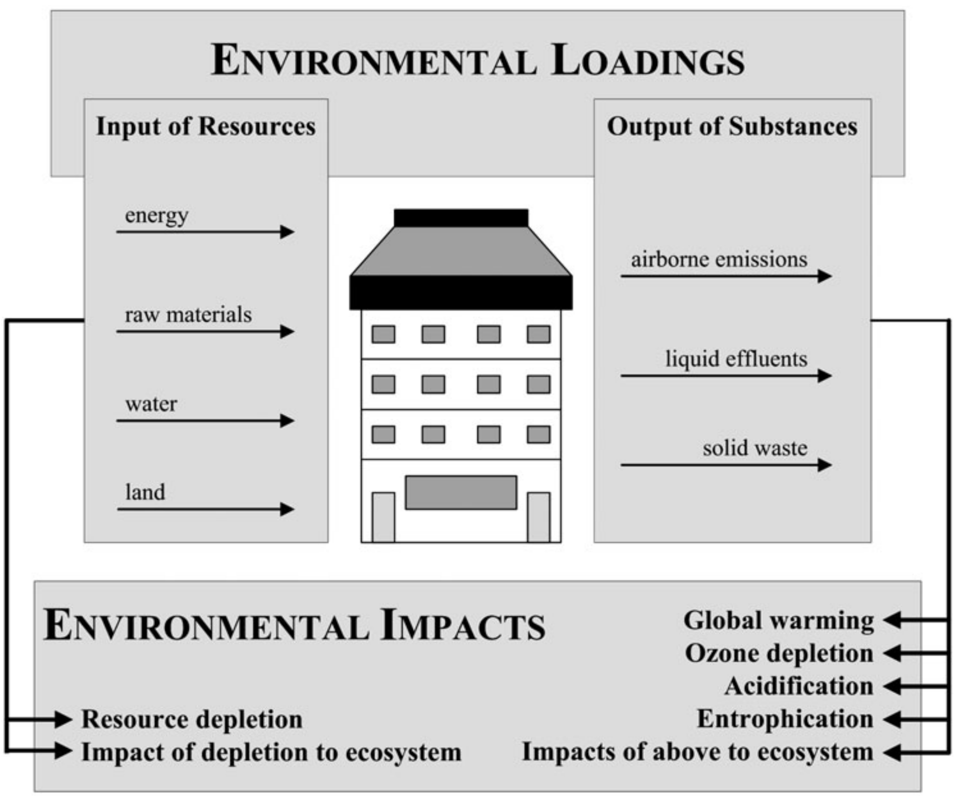

Figure 2.7.2 Environmental loadings and impacts of a building.

Generally, the environmental loadings of a building include the input of resources (e.g. energy) and the output of substances (e.g. liquid effluents), while its environmental impacts include resource depletion, global warming, ozone depletion, etc., as well as their associated impacts to the ecosystem (see Figure 2.7.2). The self-evident advantage of LCA application is that it enables the revealing of potentially significant though well-hidden environmental effects. However, the buildings are very distinctive systems with characteristics that may complicate or frustrate the application of the method (Kotaji et al., 2003; IEA, 2004):

- The lifetime of a building is long and unknown; often more than 50 years. During this lifespan, the building may undergo many changes, even more significant than the original construction that can be hardly predicted accurately.
- The location of a building is specific. As a consequence, many of its impacts are in local level, in contrast to the global effects considered by LCA.
- The buildings are complex systems comprising several distinctive subsystems and products. As a consequence, numerous data are needed in order to perform an LCA study that may also differ from one location to another. This means that the LCA results for a building located in a specific area are, usually, substantially different from the LCA results extracted by placing the same building in another area.
- The environmental consequences of a building are substantially affected by the behaviour of its users, services' operators and other third parties.
- The indoor environmental quality improvement that is expressed in terms of comfort and health usually has significant impacts to its external environment.
- The buildings are closely integrated with various elements of their external environment such as roads, pipes, grids, etc. that formulate the urban infrastructure. As a consequence, if a building's LCA is isolated from these elements, the analysis may provide misleading results.

Despite these problems, however, many applications of LCA may be found in the related bibliography covering different issues and aspects. Table 2.7.1 provides an indicative list of such applications along with their particular characteristics.

The methodology of life cycle assessment

Introduction

The application of the LCA methodology (Figure 2.7.3) follows four phases (Ciambrone, 1997; Guinée et al., 2001; ISO 14040, 2006; Sørensen, 2004):

1. Goal and scope definition. This phase is responsible for the determination of the system to be studied and the desired/required depth of analysis.
2. Life Cycle Inventory Analysis (LCI). This phase is responsible for the identification and quantification of the environmental loadings (inflows and outflows) of the system under study during its entire life cycle.
3. Life Cycle Impact Assessment (LCIA). This phase is responsible for the analysis and assessment of the environmental impacts of the system under study.
4. Interpretation (according to ISO 14040) or Improvement Assessment (according to SETAC). This final phase is responsible for the analysis, assessment and synthesis of the results of all previous LCA phases with the aim to identify any potential actions and policies that support the reduction of any identified environmental impacts of the system under study.

Table 2.7.1 Indicative building-related LCA studies.

Goal and scope	*Functional unit*	*System boundaries*	*Considered impacts*	*Source for further information*
Study of a residential home to determine total life cycle energy consumption of materials fabrication, construction, use and demolition	A whole home building with its auxiliary areas (i.e. garage, etc.) of specific structural characteristics and functions, with 4 occupants and 50 years lifespan	Extraction of raw materials and production of engineered materials, manufacturing of building components, transportation of materials from extraction to fabrication and from fabrication to the construction site, on-site building construction including site earthwork, energy consumption during use-stage, embodied energy of maintenance and improvement materials, demolition and transportation of demolished materials to recycling centres or landfills	Primary energy Global warming potential Other impacts such as life cycle cost	Blanchard and Reppe, 1998
Comparison of three houses: the present construction standard in France (reference), a solar and a wooden frame house	A whole building, built in a given site and planned for a specified use (dwelling, office, etc.), generally occupied, assumed comfortable and healthy (a unit of living area $1m^2$ can be used as functional unit under the same conditions)	Direct fluxes caused by external processes (e.g. energy use for transportation of materials) were considered without taking into account the effects created by making available their infrastructure, processes which could also be located in a building (e.g. water treatment) making their infrastructure available were taken into account, the infrastructure of the used energy for hot water production by fossil fuel (for fuel oil extraction, transport and refinery) was also taken into account	Energy consumption Water consumption Depletion of abiotic resources Waste creation Radioactive waste creation Global warming potential Depletion of the ozone layer potential Acidification potential Eutrophication potential Aquatic ecotoxicity potential Human toxicity potential Photochemical oxidant formation potential Malodorous air potential	Peuportier, 2001
The energy and environmental implications of applying different conservative technologies in school buildings in arid Andean regions of Mendoza-Argentina	The environmental impact of the implementation of a given technology in the school building (together with all the additional materials required), including the reduction of heat losses over its operative lifetime	Only locally available technologies were taken into consideration, the environmental aspects included in the study accounted only for external effects, construction and operation stages were considered but with the exception of some factors such as the people transportation during the operation phase, etc.	Global warming potential Acid rain potential Photo-smog Resource consumption Eutrophication potential Toxicity	Arena and de Rosa, 2003

Assess the environmental impacts of residential ventilation units over a 50 year life cycle in a Finland area of 120-150m^2 or a typical three-bedroom house in Canada	Providing an outdoor ventilation airflow of 50l/s, corresponding to the recommended ventilation rate of 0.5ach in Finland for a 1-floor house	Production of materials and use of the ventilation unit in single family house in Helsinki, Finland for a life cycle of 50 years. (the ventilation unit was assumed to operate 24h/day, 365days/year)	Global warming potential Acidification potential Potential for the photochemical formation of oxidants (smog)	Nymana and Simonson, 2005
Analysis (concerning energy and environmental performance) and comparison of different types of fuel intended either for direct use (e.g. domestic boiler combustion) or indirect use (production of electricity that will be consumed) in order to satisfy the energy requirements of a typical apartment building in Thessaloniki, Greece	A whole apartment building, built in a given site (city) and equipped to provide specific comforts and facilities (a unit of living area 1m^2 can be used as a functional unit under the same conditions)	Emissions of light heating oil refining, transportation and combustion, for natural gas, transportation and combustion in the building's boiler and other domestic appliances	Energy consumption Light heating oil Natural gas Electricity Global warming potential Acidification potential Eutrophication potential Winter smog potential Heavy metals potential	Theodosiou, Koroneos and Moussiopoulos, 2005, 2007
Environmental, economic and social analysis of materials for doors and windows based on their use in school buildings	The area of doors that is required to provide access and the area of windows that is required to provide sufficient light and ventilation for a 20ft long and 20ft wide room which is located in a single storey school building, for 50 years	All processes in the life cycle of timber and aluminium doors and windows from extraction of raw materials to disposal	Embodied energy Global warming potential Acidification potential Nutrification potential Other impacts such as economic viability, and social concerns (thermal comfort, good interior aesthetics, ability to construct fast, strength, durability)	Abeysundra, Babel, Gheewala and Sharp, 2007
Evaluate in terms of energy usage and air emissions the wood and steel reinforced concrete for housing construction	1kg of emission per year per m^2 during the design life of a house	All stages of life cycle	Global warming potential Acidification potential Eutrophication potential Human toxicity	Gerilla, Teknomo and Hokao, 2007

Table 2.7.1 continued.

Goal and scope	*Functional unit*	*System boundaries*	*Considered impacts*	*Source for further information*
Identify key issues associated with the life cycle of brick produced and used in Greece	A brick of dimensions 17 × 14 × 28cm weighting 5.945kg after baking process	Raw material acquisition, industrial production, packaging and transportation	Greenhouse emissions Acidification potential Eutrophication potential Winter-smog Summer-smog Solid waste	Koroneos and Dompros, 2007
Model selected energy systems that provide space heating and cooling, electricity for lighting and equipment, and domestic hot water in commercial buildings to assess the potential life cycle environmental impacts that might result from the production and use of energy	1kWh of energy consumption	Extraction of raw materials and energy resources, transportation, production, combustion/conversion and use	Global warming potential Acidification potential Tropospheric ozone precursor potential Primary energy consumption	Osman and Ries, 2007
Define the energy and environmental profile of an insulation product based on a natural fibre composite material	The mass (kg) of insulating board, which involves a thermal resistance R of $1m^2K/W$ during the insulation life time	Cultivation and crop of kenaf, transports along all phases, kenaf fibres refining and manufacturing of the insulation board, use (installation and maintenance impacts were neglected), incineration during disposal stage	Gglobal energy requirement Global warming potential Acidification potential Nutrification potential Phochemical ozone creation potential Ozone depletion potential Water consumption Waste generation	Ardente, Beccali, Cellura and Mistretta, 2008
Evaluate the environmental impact of a bore-hole based system taking into account its entire life cycle	An air-conditioning system which conditions and distributes a variable airflow volume of a maximum $5m^3/s$, including the cooling and the air distribution systems	Production of materials, energy use for the operation of the systems, removal and air distribution system in the building	Acidification potential Eutrophication potential Global warming potential Photochemical ozone creation potential	Heikkilä, 2008

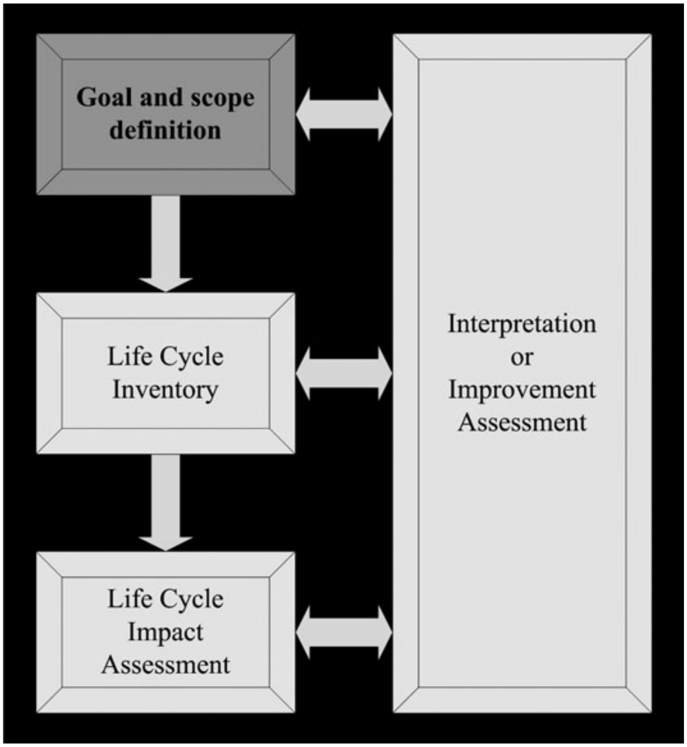

Figure 2.7.3 The application phases of the LCA methodology.

The following sections describe in more detail the goals, the methodology and the contribution of each one of the aforementioned phases of the LCA methodology. Moreover, Table 2.7.2 provides a list of software packages that may support the application of LCA in buildings. More information on LCA-related software may be found in Jönbrink et al. (2000), Kotaji et al. (2003), IEA (2004), as well as at the European Platform on Life Cycle Assessment (http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm).

Goal and scope definition

The first phase of LCA is responsible for the definition of the goal and scope of the study. This includes the determination of the system's space and time boundaries as well as its purpose and life cycle. In addition, under this phase, the pursued results and the methodology for the conduction, reviewing and reporting of the study are specified. Moreover, the data and information necessary for the accomplishment of the subsequent phases are identified and located in order to be compatible with the general aspirations of the study.

LCA requires also, especially for comparison purposes, the definition of a common reference base called functional unit or comparison basis. The functional unit refers to one or more of the functions of the system to be assessed and to the duration of its utilization. When referring to buildings, this choice is not a trivial task since, due to their multifunctional nature, a unit that is suitable for one function may be unsuitable for the others (Kotaji et al., 2003; IEA, 2004).

Table 2.7.2 Building-related LCA software.

Name	*General information*	*Inventory data*	*Impact indicators*	*Available at*
ATHENA	Covers material manufacturing (resource extraction and recycled content), related transportation, on-site construction, regional variation in energy use Building type and assumed lifespan Maintenance, repair and replacement effects Demolition and disposal Operating energy emissions and pre-combustion effects	Natural resources, energy and water inputs to processes, emissions to air, water and land for the manufacture, transportation and use of all of the individual building products	Embodied primary energy use Global warming potential Solid waste emissions Pollutants to air Pollutants to water Weighted resource use	www.athenasmi.ca/
BEES	Focuses on environmental performance of building products by using the environmental life-cycle assessment approach specified in ISO 14040 standards All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management	230 building products across a range of functional applications	Life-cycle environmental and economic performance scores for various building product alternatives Physical flow quantities for each environmental impact (carbon dioxide for the global warming impact), embodied energy, and first and future costs	www.bfrl.nist.gov/oae/bees.html
BREEAM Tools	Focus on different stages of the construction process (manufacturing of building materials, i.e. life cycle analysis of materials in BREEAM Specification: The Green Guide, design stage, i.e. BREEAM Envest and BREEAM Buildings, construction stage, i.e. BREEAM Smartwaste and post construction, i.e.BREEAM Buildings) BREEAM Buildings assesses the operational and the embodied environmental impacts of individual buildings	Available with each tool	Energy: operational energy and carbon dioxide emissions Transport: location issues related to transport Pollution: air and water pollution (excluding carbon dioxide) Materials: environmental implications of materials selection, recyclable materials Water: consumption issues Ecology and land use: ecological value of the site, greenfield and brownfield issues Health and well-being: internal and external issues relating to health and comfort	www.bre.co.uk

ECO-BAT	Focuses on environmental impacts produced during the building life span, from its construction to its demolition, including fabrication, replacement, waste management and transport The impacts are evaluated at different levels: materials, elements and the whole building	Ecoinvent database (www.ecoinvent.ch)	Non renewable energy, global warming potential, acidification potential, and photochemical ozone creation	http://ecobat.heig-vd.ch
EQUER	Evaluates environmental impacts during the different phases (fabrication of materials, construction, utilization, renovation and demolition) Combines life cycle analysis and energy calculations The functional unit considered is the whole building over a certain duration	Building model	Primary energy consumption, water consumption, acidification, eutrophication, global warming 100 years, non radioactive waste, radioactive waste, aquatic ecotoxicity of polluted water, human toxicity, photochemical ozone (smog)	www-cenerg.ensmp.fr/english/themes/cycle/index.html
GABI	Focuses on Design for environment, Life cycle assessment (LCA), Life cycle costing (LCC), Life cycle impact assessment (LCIA), Life cycle inventory (LCI), Life cycle management (LCM), Life cycle sustainability assessment (LCS), Supply Chain Management, Substance/material flow analysis.	Comprehensive database including 110 European Reference Life Cycle Data System (ELCD) and Life Cycle Cost information	All environmental impact indicators such as: Primary energy demand Global warming potential (100 years) Eco-indicator score Waste generation Water consumption	www.gabi-software.com/
LEGEP	Focuses on design, construction, surveying and evaluation of new or existing buildings or building products Covers all life cycle phases from construction, maintenance, operation, refurbishment and demolition	Ecoinvent database (www.ecoinvent.ch)	Cost, energy, mass flow, global warming potential 100 years, acidification, photochemical ozone creation potential, ozone depletion potential, eutrophication potential, primary energy consumption, renewable and non-renewable	www.legep.de/
LISA	Focuses on identifying key environmental issues in construction and design that are based on whole of life cycle of buildings	Data per building are entered by the user	Resource energy use, tonnes of equivalent CO_2, SPM, NMVOC, Water, NO_x, and SO_x	www.lisa.au.com

To obtain true functional equivalence when comparing buildings, the whole structure over its entire life cycle, defined according to a series of pre-established performance characteristics such as conformity, location, indoor conditions, adaptability, safety, comfort, etc., should be considered (Kotaji et al., 2003). Other basis of comparisons may include criteria such as m^2 or m^3 of the building area over a typical year, or the number of occupants or households (IEA, 2004). It might also be useful, sometimes, to analyse a building in terms of rooms or services provided (IEA, 2004). On the other hand, when comparing building materials and component combinations, the functional unit used should be a part of a functional unit that corresponds to the whole building (e.g. per tonne unit for a material such as mortar, per installed unit such as $1m^2$ wall with thermal resistance $2.5m^2K/W$) (Kotaji et al., 2003).

The choices for the functional unit are many, involving trade-offs that should be carefully considered and the final decision should only depend upon the particular processes, products, activities, services and geographical scale defined for the building to be analysed (Kotaji et al., 2003; IEA, 2004). Examples of functional units used in building-related LCAs can be found in Table 2.7.1.

Another issue that arises during this stage is the pinpointing of the hypotheses and limitations that should be taken into account while performing the study. In case of long lived products such as buildings, several assumptions or estimates are necessary for (Kotaji et al., 2003; IEA, 2004):

- their service life time, as well as the service life time of their constituent components that determines the number of repair and replacements;
- their use and maintenance scenarios;
- their major refurbishment or renovation scenarios;
- their adaptation to changing expectations, users and technologies (many buildings are vacated or demolished long before their useful life due to lack of adaptability); and
- the demolition and recycling scenarios, i.e. the end-of-life scenarios that divide waste streams into streams sent to landfill, incineration or recovery.

All these assumptions and estimates may significantly affect the LCA results.

This phase is potentially the most important. It provides a guide for the conduction of the entire study. It also ensures that the obtained results will be compatible with the goal and scope of the study. It should be noted, however, that this guide is not static. LCA is an iterative procedure. It starts with some initial choices and requirements that may be revised and adapted later in the light of new evidence from the analyses. Such revisions and adaptations, however, should be made only after serious and careful consideration.

Life cycle inventory analysis

The second LCA phase is perhaps the most demanding (Goedkoop and Oele, 2007). It concerns all the activities/processes that are involved in the system under study and include the direct and/or indirect use of energy and/or mass.

Inventory analysis is the phase, where the system under study must be specified in detail. This includes (Guinée et al., 2001):

- the refinement of system boundaries, i.e. the definition of its precise boundaries in relation to the natural environment and other systems,
- the development of a building model including all process and sub-processes that will be considered, and, finally,
- the collection, quantification, recording and validation of all relevant data, based on the developed building model.

The building constitutes of a set of processes, interconnected via energy and/or mass exchange, which perform a specific task. The building is also separated from the rest of the world, which constitutes its environment, via existing or virtual boundaries. There are three types of such boundaries (Guinée et al., 2001; UNEP, 2005); boundaries separating the system under study from the natural environment, boundaries defining the sub-processes relevant to the system (allocation) and boundaries separating the system from irrelevant processes (cut-off).

The first type of the aforementioned boundaries defines the type of environmental and financial processes that are considered or excluded from the study and affect directly the LCA results.

The second type of boundaries concerns the way that the several environmental impacts resulting from a multifunctional process, i.e. a process that produces more than one product, are allocated in its several sub-processes. Consider for example, the total energy required in a factory that produces metal products for the automotive and building industries, but no records exist to discriminate the amounts of energy required for each type of product. There are several ways to allocate energy (e.g. according to the product weight), with a single, however, objective, to ensure that each product will receive its fair share of environmental interventions originating from the shared processes (Kotaji et al., 2003; IEA, 2004). Similar problems and careful allocation procedures are also needed in the case of using recycled products.

Finally, the third type of boundary determines which particular processes of the system under study will be excluded from the LCA, for reasons of simplicity or lack of relevant data. Obviously, the impacts of the excluded processes should comprise a negligible part of the total impacts of the system.

Setting system boundaries for buildings is critical for achieving valid and comparable results. Comparative studies implementing different LCA tools have shown that the majority of the variations observed in the results come from differences on the considered system boundaries (IEA, 2004). Unfortunately, boundaries can be established in all areas (life cycle stages, geographical scale, resources, groups of concern, impacts of concern, etc.) and there are no specific rules on where to draw them beyond the fact that they should generally reflect the type of LCA that is to be conducted and its intended use. For example, the comparison of two different buildings may require more inclusive boundaries than the comparison of alternative technologies for the same building project. Examples of system boundaries set for building-related LCAs can be found in Table 2.7.1.

The output of the inventory analysis phase is an inventory table that includes all the quantitative data collected with respect to the inflows and outflows of the system under study. It should be noted, however, that in parallel to the quantitative data, several other qualitative data and information may be collected that cannot be quantified. However, they may be proved particularly useful and necessary during the last LCA phase (i.e. during interpretation). For this reason, any qualitative data and information potentially collected should also be reported, in order to be available during the interpretation of the analysis results (Sørensen, 2004).

Life cycle impact assessment

The third LCA phase aims to evaluate the environmental impacts of the system under study based on the inventory results, in relation to the goal and scope of the study. To this end, the inventory results are further processed with respect to the pre-established environmental impacts and social preferences (Guinée et al., 2001).

The impact assessment is a quantitative and/or qualitative process that is used to characterize and interpret the negative consequences of the environmental impacts identified during the inventory phase. Five steps are followed for the impact assessment: classification, characterization, normalization, grouping and weighting (Guinée et al., 2001; ISO 14040, 2006; Goedkoop and Oele, 2007). The last three steps are optional but are frequently followed, as their results facilitate the interpretation of the results of the whole analysis during the fourth LCA phase.

In the classification step, the impact categories to be taken into account are refined and finalized, taking into account the degree of required detail that has been specified during the first LCA phase. Then, the inventory data are assigned to the defined impact categories. During this process, it is possible that some data are allocated in more than one impact category. The impact categories that are usually taken into account concern the degradation of the ecosystem, the waste of natural resources, the degradation of the quality of human life and the consequences for human health (see Figure 2.7.2). Examples of impact categories considered in building-related LCAs can be found in Table 2.7.1.

In the special case of building-related LCAs where site-specific environmental impacts are also involved, the following site-specific impacts may be at least also considered, (Kotaji et al., 2003; IEA, 2004):

- Neighbourhood impacts (e.g. micro-climate, glare and solar access).
- Indoor environment (e.g. indoor air quality and thermal comfort).
- Local ecology (e.g. land surface occupation and ecologically sensitive areas).
- Local infrastructure (e.g. water supply and transport systems).

Moreover, during the construction stage, several types of substances can affect the health of workers (Kotaji et al., 2003). Traditional LCA aggregates all the loadings and calculates impacts at the regional or global scale, thus not addressing local impacts such as those mentioned above and are connected with a building. In order therefore, to apply LCA to buildings, either the site-specific impacts are excluded from the assessment by appropriately setting the system boundaries or are inventoried and classified separately (Kotaji et al., 2003; IEA, 2004). In the second case, a more extensive data collection is needed at the LCIA stage, however, a more balanced view of the building performance is obtained. Unfortunately, the currently available LCA models and tools are not able to account for most of the site-specific impacts and the best available alternative is to combine LCA with more passive and qualitative evaluation tools in order to obtain a generic and balance view of the building performance (Kotaji et al., 2003; IEA, 2004; Blom, 2006).

During the second step of impact assessment, i.e. characterization, the inventory data are quantified and summarized within each impact category. To this end, appropriate characterization methods are specified to enable the assessment of the inventory data' contribution, in the impact category or categories they have been assigned. There are several methods that may be employed (e.g. the eco-indicator method) (Goedkoop and Spriensma, 2001; Goedkoop and Oele, 2007). However, since the results of this phase are particularly important for the overall outcome of the LCA study, it is essential that the characterization method selected for each impact category is explicitly reported and analyzed.

The specification of the characterization method is followed by the calculation of the category indicators based on the inventory data that are quantified and aggregated through the use of appropriate characterization factors that reflect the relative contribution of the LCI results into a single result for each impact category. This result, called category indicator result, expresses the contribution of the specific impact category in terms of equivalent amount of an emitted reference substance (e.g. the global warming potential impact indicator result is expressed in terms of emitted kg of CO_2 equivalents). The set of all category indicator results comprises the environmental profile of the system under study.

Normalization, i.e. the third step of impact assessment, is used to assess the magnitude of the effect that a particular impact category has upon the wider environmental problem. According to ISO 14040 (2006), normalization is the calculation of the category indicator results in relation to a base case. The base case may refer to a particular geographical area (e.g. Greece, Europe, etc.), a person (e.g. Greek citizen, European citizen, etc.), or another system for a given time period. Additionally, other types of information may be taken into account like for example a future desirable state. The main aim of the category indicator results' normalization is the better understanding of the relative importance as well as the magnitude of the results, as far as the system under study is concerned. Normalization is also used for the compatibility check of the results and the preparation of data for the next phases. The outcome of this step is an alternative environmental profile for the system under study called normalized environmental profile.

During the grouping step of the impact assessment, the different impact categories are aggregated into one or more sets. Grouping may be based either on the classification of the impact category indicators according to a nominal scale (e.g. specific emissions) or on the sorting of the impact category indicators according to an ordinal scale (e.g. high, medium and low priority).

Finally, at the last step of impact assessment that is weighting, specific weights are defined for the impact category indicators' results that have been assessed during normalization. The weights reflect the relative importance of each category indicator's result according to some given social values and preferences. Then, the category indicator results are multiplied with their weights and aggregated, resulting in a new alternative profile for the system under study, called the weighted environmental profile.

Weighting is especially helpful when attempting to reduce LCA to a single score, as far as the environmental impact is concerned, and make comparisons between alternative buildings or designs. Such a reduction is certainly useful when someone does not have the time or interest to get into the involved details. However, the performed aggregation may lead to isolation from the reality that is included and can be recognized through specific details. Moreover, weighting is not allowed across impact categories for public comparisons between products, according to ISO 14040 (2006), due to the fact that the utilized weights are largely based on subjective views.

Interpretation

This particular LCA phase is neither specific for buildings (Kotaji et al., 2003), nor does it present any particularities when applied in this field. Moreover, it is very difficult to be standardized in the sense that there are no strict and rigorous rules applicable to each case.

Generally, during interpretation, the results of all previous analyses are interpreted and used as a basis for decision making regarding actions that are expected to improve both the system under study and the environment and human welfare. Moreover, the results of all previous analyses, all choices that were made and all hypotheses assumed are assessed through sensitivity analyses to ensure consistency, completeness, soundness and robustness (Guinée et al., 2001).

Based on the aforementioned analyses and assessments, conclusions are drawn, and recommendations are made for the decision making regarding the system under study.

Concluding remarks and discussion

LCA was not originally conceived as a tool for analyzing buildings or other so complex and long-living products or processes. Nevertheless, its applicability in this sector is accelerating fast, and is currently considered as one of the major tools supporting the efforts toward achieving sustainable buildings (Kotaji et al., 2003; IEA, 2004). Moreover, although LCA has an obvious significant contribution in the nowadays environmental concerns, it has at the same time several limitations due to its complexity.

To perform a detailed LCA of a system, all the related processes and environmental impacts should be identified and analysed. This results to an extremely complex and time-consuming procedure, with increased data and specialized knowledge requirements.

Other problems result from the fact that LCA cannot take into account or predict future changes in the current technology or demand. This limits the validity of LCA results versus time. Moreover, it does not take into account the effects caused by possible changes in methodological choices or decisions regarding the boundaries set or the considered system. As a consequence, LCA is limited to the analysis of impacts that are known and can be quantified, and in practice it must be combined with sensitivity analyses and/or other approaches to account for the effects of the choices and assumptions considered.

Generally, the application of LCA may be limited by the following factors (UNEP, 2005):

- Lack of the acknowledgement of its necessity/utility.
- Lack of specialized knowledge.
- Lack of necessary budget.
- Lack of appropriate data and methods.

In addition, when applied in buildings, adaptation is needed for LCA to account for the long lifespan, local impacts, wide boundaries, maintenance, renovation and replacement needs, adaptation to changing expectations, users and technologies, occupant's behaviour and diverse interests of the involved stakeholders of the buildings.

However, if a clear justification is provided for the reasons adopting this particular assessment method, if the principles of the method are adapted consciously in the building applications, if the way, the analyses' results are to be communicated both internally and externally, is clearly defined and if a reasonable budget is available, LCA may become a powerful tool toward the development of sustainable buildings leading to a more environmental-friendly building sector.

Acronyms and abbreviations

ACLCA	American Centre for Life Cycle Assessment
CML	Centre of Environmental Science – Leiden University, The Netherlands
ECBCS	Energy Conservation in Buildings and Community Systems Programme
ELCD	European Reference Life Cycle Data System
ENHR	European Network for Housing Research
IEA	International Energy Agency
ISO	International Organization for Standardization
LCA	life cycle analysis or life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCM	life cycle management
LCS	life cycle sustainability
REPA	resource and environmental profile analysis
SETAC	Society for Environmental Toxicology and Chemistry
Sirii	Swedish Industrial Research Institutes' Initiative
UETP-EEE	University-Enterprise Training Partnership in Environmental Engineering Education
UNEP	United Nations Environmental Programme
VROM-DGM	Ministry of Housing, Spatial Planning and the Environment, The Netherlands

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Case Study 2A
ENERGY AND ENVIRONMENTAL MONITORING

Alex Summerfield, Hector Altamirano-Medina and Dejan Mumovic

Introduction

Building research, particularly with respect to energy performance, appears to be undergoing a transformation not seen since the first oil crisis. Governments have begun to recognise the scale and urgency of the challenge presented by climate change and that buildings can make a substantial contribution to reducing national carbon emissions (DTI, 2007). Thus, building research is likely to focus increasingly on climate change mitigation and adaptation strategies across the built stock. In research terms this translates into a rapid shift from more familiar small-scale projects, such as exemplar or prototype buildings of design and academic interest, to field studies that generate the kind and scale of empirical evidence that can inform energy policies at the national level.

The dynamic interactions between people and their built environment form a complex system that renders research of any detail or duration in this area a major challenge. These are not clinical trials, laboratory bench studies, or just occupant questionnaires, but involve extensive environmental monitoring, detailed building and social surveys, and sometimes require major interventions in people's homes, such as replacing heating systems or refurbishment. So apart from dealing with participant recruitment, ethical issues, and the often-intrusive nature of the work, the sheer logistics and organisation of such studies represent a major undertaking within typical resource and financial constraints. On the other hand, it is people living and working in buildings that essentially make this fieldwork interesting; they can highlight the limitations and confound the predictions of purely technical or physical models. They are essentially why we still need to do this type of research.

The aim of this chapter is to guide researchers along a practical methodology for these studies both to address fully the specific research questions under investigation and underpinned by benchmark methods, and to recognise the potential for wider supplementary research that can add considerable value to the original study. There are numerous related issues, such as statistical methods of recruitment to obtain representative samples or detailed energy analysis, that have been dealt with elsewhere and moreover would require a volume in their own right (BRE, 2005; Fowler, 2009). Hence this chapter focuses on the underlying principles and techniques to guide the selection and implementation of methods to undertake this type of research.

The topics are illustrated via a case study of 29 dwellings in Milton Keynes, situated about 75km northwest of London, that were originally monitored for hourly energy and temperature from 1989–1991. The dwellings essentially follow conventional UK housing design but were constructed to higher standards of energy performance than required by building regulations at that time. They incorporated energy efficiency features, such as increased floor and wall insulation, double-glazing, and condensing boilers, so that they broadly complied with building standards of a decade later (Edwards, 1990). In 2005–2006, a follow-up study was undertaken in 14 of the gas centrally heated homes from the original study, to determine if internal temperature or energy consumption had changed over the intervening years. The original and follow up studies are referred to as MK0 and MK1 respectively (Summerfield, Lowe, Bruhns, Caeiro, Steadman and Oreszczyn, 2007).

The chapter comprises three main parts. First, we describe the process of planning a research project, in translating precise research questions into protocols for monitoring temperature and energy; as well as using building and occupant surveys. Second, we discuss issues of analysis and communication of results. This is illustrated by the approach taken to analyse the MK0–MK1 comparison. The last section illustrates supplementary research, not necessarily considered as part of the original research agenda, but that can greatly enhance its scientific value. The work uses the MK0 and MK1 data to investigate the environmental conditions that lead to mould growth.

Research methodology

The renewed focus on building research has been accompanied by rapid technological developments that greatly facilitate monitoring and data collection, for instance via wireless remote loggers, and at a far more practical and cost-effective level than previously. Thus, it is now possible to consider studies that would have been almost inconceivable only a few years ago. However, recruitment and on-going contact with households for what may amount to a major intervention and monitoring spell, such as installing and monitoring new technology, remains a considerable barrier. For this reason, energy studies may be conducted conjointly with other projects that focus on issues from disparate fields, such as issues of sociology or epidemiology across households (Hong, Oreszczyn, Ridley and Warm Front, 2006). There is considerable incentive to seek out opportunities for collaboration where recruitment has already been incorporated into the logistics, since for minimal additional cost the value of a project may be extended greatly by including the energy research component. If this is the case, then it is all the more important that the methodology is well thought through, so that the work is not unwittingly compromised by the priority of other research agendas.

Study planning

It is not unlikely for researchers in the built environment to find themselves in ambitious collaborative projects with tight budgets, timelines, and multiple or even conflicting objectives. Therefore, it is imperative that considerable effort is invested in determining precisely a set of core research questions, that may be augmented later, but here serve as a basis around which the study can be designed. These should remain a central focus during the inevitable compromises and adjustments that take place during the planning an implementation phase of the project. Research questions have typically moved on from being merely descriptive (such as finding the level of roof insulation in the building stock) to relational investigations (or determining the effect of this insulation on energy usage for different building types). Studies may be used to evaluate the potential of a particular technology or efficiency improvement and to identify the relationship between various operational parameters that effect performance or its impact on the environment. Studies often take the form of determining the changes across time within the same dwelling or household, such as before and after the installation of efficiency improvements.

Relational studies therefore implicitly involve a series of comparisons and the critical point to planning the study is to determine precisely as possible on what basis the comparison is drawn, so that any effects are not confounded by other factors that may have also changed. As well as defining the research questions or hypotheses, it is worthwhile writing a hypothetical sentence about the results as if each hypothesis were affirmed. Thus, an initial and broad hypothesis with respect to the MK1 study was that household energy consumption has increased since 1990 (due to building fabric deterioration, more appliances, and higher internal temperatures). This might be translated into a hypothetical result along the lines of:

> In a sample of 'low-energy' homes in Milton Keynes (under standardised daily external temperature conditions), it was found that gas/electricity consumption has increased by Y% to ZkWh/m^2 since 1990, even after allowing increases in floor area due to extensions. This is consistent with trends seen in national statistics on UK dwellings and may be due to increased internal temperatures.

Regardless of whether this is found after analysis to be the case, the detailed nature of hypothetical results helps to clarify the content required of the study. Specifically, the study must obtain data on:

- composition and attributes of the sample, e.g. the dwelling type, location, construction;
- external conditions included in the monitoring period (over the heating season);
- internal temperature (and placement of loggers and frequency of readings);
- energy usage by fuel (and frequency of readings); and
- measurements that permit comparison with other studies and national statistics.

Thus, there are two main sets of criteria driving the research agenda within the resource constraints: those aspects prescribed by the primary research objectives and then the underlying need to fit into existing methods and collect 'benchmark' parameters, such as dwelling type or number of occupants. This will allow the results to be placed in a wider scientific context, for instance by comparison with previous studies, so that their significance can be properly gauged. In terms of providing guidance for models or policies, this often means knowing to what extent these dwellings/occupants are typical of those in the stock/population or, if not typical, what proportion they might represent. So, data needs to be gathered on all the main aspects that define representativeness, from dwelling type to socio-economic level of the occupant, and done so in a standard way. This debate between what is required to meet project specifics and the standard measurements needs to be engaged fully as the planning of equipment and logistics are developed. Resource constraints mean that limitations in the ambitions of research projects are inevitable, particularly so when investigating complex systems that exist in the built environment, but these limitations should be understood and acknowledged early on, rather than arising as an unexpected consequence of omissions in the methodology.

If budgetary and time issues appear to be the most obvious constraint on the scope and scale of monitoring, it should be noted that these largely reflect the time costs of installation and data retrieval (due to arranging appointments and visiting houses) rather than of the physical equipment itself. But there is a further consideration of good survey protocol, in not disturbing the occupants too frequently to reset equipment and possibly alter their behaviour. In the end, such decisions also reflect cultural norms and the exact situation of each dwelling, for instance if energy meters are located outside it may not be necessary to disturb occupants. A different level of acceptability may apply for private homes with working families, whereby access inside may be largely restricted to a brief appointment at the weekend, than say for social housing for the elderly, where not only is someone at home and available at most times but they may welcome the social contact of a regular visitor. There is also a role for quid pro quo, so if the project is providing a free heating system then it might be negotiated that this is in exchange for the opportunity to monitor performance – so long as the implications are clearly stated at the outset. Remote logging, where data may be retrieved wirelessly or via the household internet connection, can reduce costs and disturbance of the occupants, while providing an early alert of problems. Whatever the approach chosen, ethical considerations regarding the occupants and good survey practice should remain paramount.

Monitoring temperature

The purpose of monitoring is to collect sufficient data to provide information to address the research objectives (and beyond a minimum required by standard methods). But this statement of the obvious often belies the numerous issues raised when we consider a protocol for implementation across many sites. The general point is well illustrated by quantifying internal temperature in the dwelling, an essential part of most energy surveys. The difference between internal and external temperature is fundamental to parameterise the fabric heat loss and to understand any heating or cooling demand in terms of meeting occupant comfort. So, the task is to identify the most appropriate spatial and temporal arrangement for monitoring that captures this effective internal temperature across the whole dwelling, in a way that is applicable and consistent across the entire sample and where little knowledge may be available beforehand.

Temperature and relative humidity (RH) data loggers are compact devices usually about the size of a pack of cards that can be programmed in various ways, in terms of start time and frequency of reading. The unit illustrated in Figure 2A.1 has 4 channels: temperature, relative humidity, illuminance and a spare channel to take the input from other detectors, such as for CO_2 levels. The readings are instantaneous measures rather than cumulative, which would be needed for energy usage. The capacity of this unit is 43,000 readings, or about 150 days for 10-minute readings in 2 channels. The logger takes about a minute to download via USB cable to computer and re-launch. The ability to check battery status is an essential feature to ensure at the outset that sufficient charge remains to last over any proposed monitoring period. It may well be used more than once in any study. Each should be labelled with a unique code and a return address. It is crucial to have adequate systems in place to download, reprogram, and administer, the hundreds of loggers that may well be required.

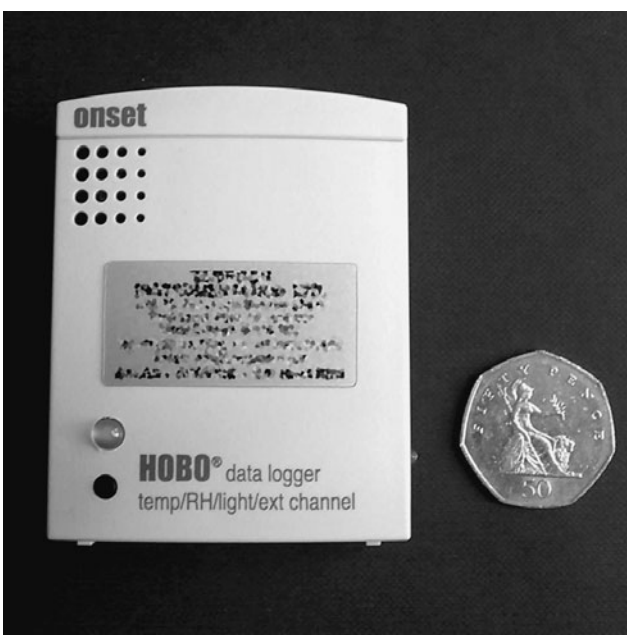

Figure 2A.1 Example of a portable data logger used for measuring temperature and RH.

For quantifying space heating demand, the effective internal temperature will be a weighted combination of average temperatures from each heating zone in the dwelling – where these are defined by the design of the home, heating system, and by occupant living patterns. Typically, this means that the living area is defined as Zone 1, where the main thermostat or room controller is located. Note that separate lounges may not be part of the living space, especially if they are reserved just for certain activities, such as formal socialising. Zone 2 is usually represented by occupied bedrooms, which may have a substantially different daily heating profile to the living space corresponding to differences in the occupancy patterns. If necessary, Zone 3 can describe indirectly heated areas and mostly unoccupied spaces such as hallways and other circulation spaces, spare bedrooms, and so on. There may be specific rooms worth monitoring, such as studies with large amounts of electrical equipment; utility rooms where the boiler or heating system is located; and sunspaces or conservatories, where these may assist with understanding the indirect and solar gains occurring. This is also the kind of detail that might useful for validating any dynamic computer modelling of temperature.

The overall design of the dwelling also has a bearing on the monitoring required, for instance a two or three storey house may exhibit considerable temperature gradient, with the higher temperatures at the top leading to greater heat losses through the roof space than might be anticipated from the average overall temperature. In contrast, well insulated homes are likely to have far more uniform temperatures across the dwelling – reducing the difference between zones and potentially the number of loggers required. Given the complexity of deciding and administering all this on a dwelling by dwelling basis with limited prior information, a generic protocol may be adopted:

- Over part of the heating season at least, monitor every room in the dwelling.
- If resources are tightly constrained (and given that for space heating summer months are less critical), this could be reduced at other times to a three monitoring points, one for each zone: living room, main bedroom, and hallway.
- Include one or two extra loggers for rooms of special interest, such as sunspaces or conservatories.

There remains the issue of locating each logger within each space to obtain a representative reading of temperature and RH on a daily basis. In MK1 we positioned loggers according to the following protocol:

- On a shelf or ledge, between 1 and 2m high away from direct sunlight.
- If possible out of sight, such as behind ornamental objects, so that loggers had less chance of being moved and that any LED flashes from the logger would not disturb the occupants (an important issue in bedrooms).
- Away from potential heat sources, such as mantle pieces (over fireplaces) and bookcase lamps and electronic equipment.
- Additional loggers are placed in large open plan spaces.

Regarding the frequency of reading programmed in each logger, for meaningful analysis most studies – including MK1 – require at least average daily temperature. Typically, this is achieved with hourly measurements to calculate average temperature with a minimum of 24 samples. But if the researcher wishes to detect finer grain changes as a result of occupant activity, such as window opening, then the interval between measurements should be a least half the expected length of the activity period for the change to be detected with 2 measurements – otherwise the change can occur between measurements or just appear as a spike (so an event may be detected but no indication of the length of change). The instrumentation of the loggers also imposes constraints, since its response to rapid change in conditions (say 5 degrees) may mean that it takes several minutes to stabilise. Logger data storage capacity will limit the frequency of sampling if site visits for replacement (or data downloads) are kept to a minimum. In MK1 sites, we initially logged at 10-minute intervals for the first month and thereafter at half hourly readings with replacement of the logger every three months.

To address more involved research questions, additional temperature loggers may be placed next to radiators, as a means of indirectly identifying heating system operation, or even on specific appliances of interest. But the overall benefits of using a generic protocol as a benchmark methodology, a minimum standard, are that it can be applied across a range of dwelling types and across studies. With rapidly advancing technology, in the medium term the benchmark for new developments may be to incorporate monitoring devices as part of their building management systems and installed prior to occupancy.

External temperature is a critical data stream as it serves to standardise the environmental conditions and permit comparison across studies. Not only is there considerable variation from years to year, but the UK like many countries has had a generally warmer climate over recent years, leading to redefinitions in standard year weather conditions. If energy consumption were compared without correcting for differences in external conditions, then simply due to warmer winters in the UK we would expect dwellings to use less energy than in 1990 with no need to ascribe the reductions as being due to improvements building performance.

Monitoring external temperature and RH can be done on site, if equipment is located away from the dwelling, for instance in its garden, by placing a logger in a Stephenson Screen – a vented container that shields instruments from direct radiation and precipitation but permits air circulation. For studies where all dwellings are located in the same neighbourhood, this can be achieved with a single measurement location. If the dwellings are geographically dispersed, then finding reliable places for each site and having sufficient Stephenson Screens may become problematic. An alternative is to use official metrological data, which depends both on the location of weather stations and the availability of data. Universities and other such institutions often monitor weather conditions as part of other scientific research may also be willing to provide accurate and reliable data. In MK1 local monitoring was done, as well as using data from the UK Meteorological Office for the nearby city of Bedford. This hourly dataset provided a single source of measurement that spans the MK0 and MK1 studies, from the 1980s onwards.

Monitoring energy

With the decline in the use of solid fuels in the UK domestic sector, monitoring for energy usage has been simplified in most urban settings by having just two sources of energy: gas and electricity. Monitoring usage of other fuels poses considerable difficulties. Oil use for central heating may at least be read from storage tank levels, or more accurately by installing flow meters, but to quantify biomass and other solid fuel usage in a reliable manner is highly problematic. The energy content of such materials varies greatly, from waste wood and pellets to coal, as does the efficiency of stoves and fireplaces in which they are burnt. These monitoring issues would need to be resolved on a case by case basis. Fortunately, the MK1 sample comprised gas centrally heated homes.

Gas and electricity are frequently metered externally for ease of access by the utility companies. Unfortunately, in the UK, numerous types of meters remain in use and these differ in age, technology, and method of reading. Electricity usage in kilowatt hours (kWh) requires two readings if the occupant has *economy* 7 tariff, whereby there is a peak and off-peak or night rate. Gas readings are provided in cubic metres or cubic feet and converted to energy using calorific values provided in the UK on a monthly and regional basis by the national gas grid. Calorific value may also appear on utility bills. Staff resources permitting, anything from monthly to weekly (or even daily) manual meter readings on site is probably the most straightforward and robust method. It should be noted that some occupants may have more than one meter, and sometimes a single meter serves more than one household. For the MK1 study gas and electricity meters were read manually on a semi-regular basis, varying from weekly to monthly, according to external conditions and with more frequent winter readings in order quantify space heating.

Alternatively, high resolution monitoring of electricity usage can be obtained by a current clamp placed around the live wire and data logger and combining this with meter readings. Another option is for an optical sensor to count revolutions of the spinning meter disk. Since gas suppliers usually object to the presence of any electrical devices within the meter box, such optical devices may need to be placed outside strapped to the glass window of the meter box. For detailed research on appliance usage, individual circuits can be monitored, and sophisticated equipment can be installed that identifies specific appliance types based on the 'signature' they leave in the demand profile. Such systems are sufficiently complex and expensive to remain an unlikely option for medium or large-scale studies. With the potential roll-out of *smart* meters across the UK domestic sector by utility companies, where relatively high-resolution data can be provided to both the occupants and suppliers, many of current monitoring issues may be resolved, so long as researchers can reach a cooperative agreement between all parties to obtain and analyse the data.

Dwelling and occupant surveys

To make sense of energy usage data requires key dwelling characteristics. The study must consider the detail and scope of information, as well as the method of collection. This includes generic characteristics such as type, size, and age, as well as specific attributes such as construction and glazing types, boiler age and model, type of control systems being used, and set point temperatures (that is the room thermostat setting). All this data is gathered primarily to estimate the thermal performance or U-values of the building fabric (including windows), the efficiency of the heating systems, and ventilation rates. Often as part of logger installation or replacement, skilled researchers can conduct a building survey regarding the key building attributes. Occupants may also provide useful information about the dwelling and particularly regarding any extensions or renovations.

Ideally such data should comply with a standard or accepted classification systems, to avoid the proliferation of incompatible data across studies. By remaining consistent with the inputs to national benchmarks, provides researchers with the means to compare results across standard categories and typologies, and hence judge the relevance of their sample the national stock or to the results of other studies. For instance, where other information is lacking, building age can often be used to help infer construction type and hence U-values; this may not be identified as a specific year of construction but by an age band, such as '1985 to 2000'. The question is: what age bands would be best to choose? Another point is the definition of floor area of the dwelling, from the external to internal dimensions or to considering heated areas only or including all enclosed areas. Such differences can amount to a variation of more than 20% of the area. The best policy is to seek out definitions that are used as part of a national standard. One starting place in the EU is the data behind the Energy Performance Certificate that is increasingly mandatory across the building stock. For the domestic sector in the UK, the Standard Assessment Procedure (SAP) lies at the heart of carbon emission calculations used to comply with building regulations (BRE, 2005; ODPM, 2006a,b). The reduced SAP uses a simpler set of items, combined with typical assumptions, to estimate the SAP and annual energy usage. In MK1 we were fortunate in already having construction details and plans from MK0, that it was relatively straightforward for MK1 to note changes to layout or the heating system.

These methods are sufficient but by no means comprehensive. They can always be augmented or refined, so long as this is not done in a way that leads to incompatibilities. In SAP calculations, while conservatories or sun spaces are noted, they are only considered integral to the heated space as an addition to the dwelling they have a substantial impact by increasing floor area and affecting average U-values (otherwise they simply serve to reduce the exposed wall area). Yet previous surveys have indicated that it is not uncommon in the UK for occupants to leave internal doors to conservatories open, or to occupy and heat conservatories through winter (Oreszczyn, 1993). Similarly, variations in appliance ownership and usage, which largely determine electricity consumption, are not noted on a dwelling by dwelling basis. Yet for researchers, it might be precisely this area that is of most interest. Standard occupant surveys that capture such issues are still being researched (Leaman, 2008) and currently none have been sufficiently validated to warrant recommendation. However, it should be noted that for basic sociodemographic variables in the UK, a series of harmonised questions are available from the Office of National Statistics (ONS, 2004). In the MK1 survey, we used a combination of questions taken from the original survey (to maintain compatibility) and standard questions from the ONS and the English House Condition Survey (ODPM, 2003).

Energy analysis

To describe the full range of statistical analyses possible with energy and temperature data is beyond the scope of this chapter and would entail a volume in its own right. Calculating conventional annual performance statistics often pose problems for research due to attrition of occupants over the period, for reasons such as moving house, and insufficient monitoring data. Annualised results also contain such variability in seasonal weather and occupancy patterns, key underlying factors for energy consumption, so that unravelling usage patterns from such aggregated indicators is difficult. Standardised weather on an annual basis is usually achieved via a comparison of the number of degree days experienced by each dwelling to that of nominated standard year. For many outside the field of energy analysis, degree days are an unfamiliar concept which creates a further disadvantage in communicating results to policymakers.

Instead, we illustrate this energy analysis with an alternative strategy adopted for the MK01 project that is both easily understood and requires minimal winter data (Summerfield et al., 2007). By normalising energy usage under daily external conditions of T_{ex} = 5°C, close to average temperatures over the heating

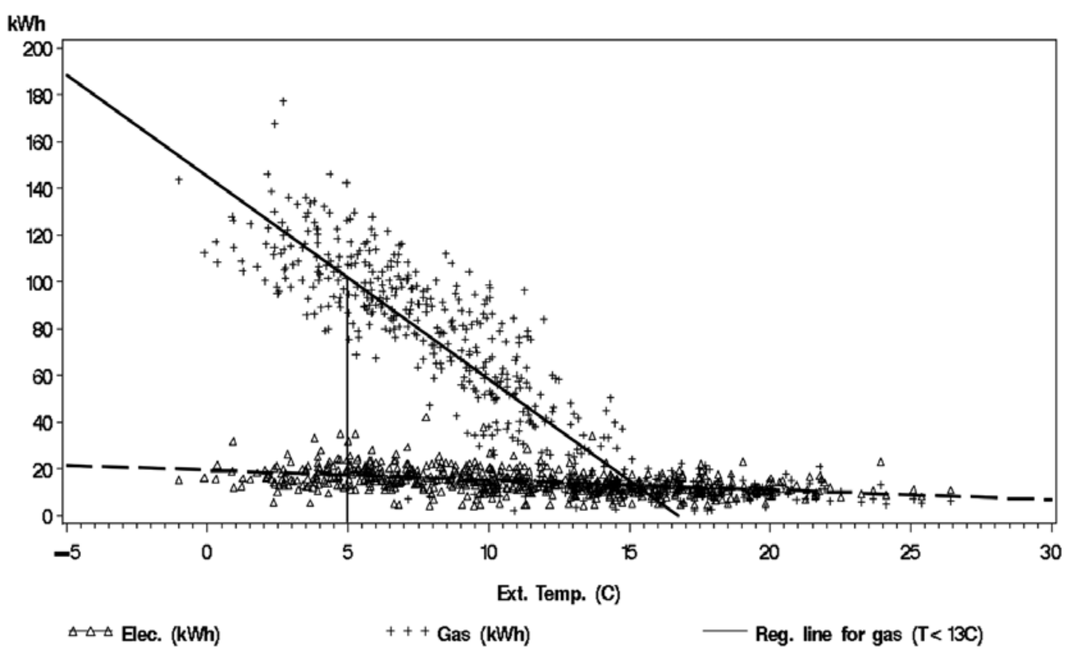

Figure 2A.2 Daily electricity and gas use vs. external temperature for an example dwelling from MK0.

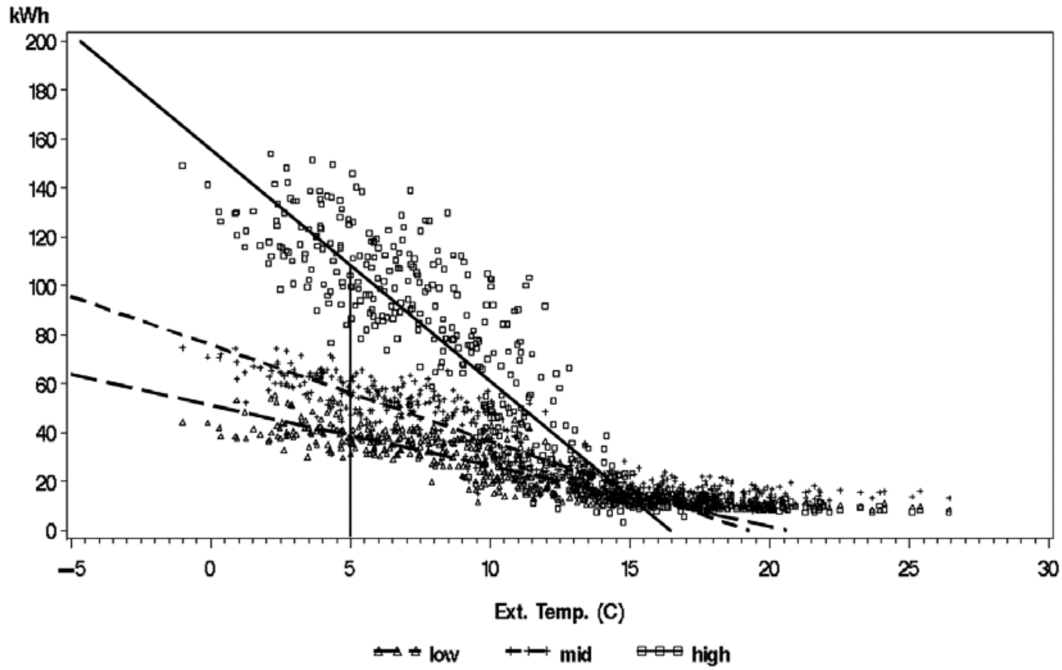

Figure 2A.3 Daily gas use vs. external temperature in MK0 for each energy usage group.

season in the UK. Such conditions are immediately familiar to people living in temperate climates like the UK and daily usage is easier to comprehend in terms of scale than annual data. For MK0 we used daily data, but weekly data can also be used to allow for occupant variability in usage from weekdays to weekends and other patterns, such as shift work. Simple linear regression models were fitted for each dwelling, with mean daily external temperature as a predictor of gas and electricity usage (Figure 2A.2). The regression model was fitted when T_{ex} < 13°C for gas usage, with parameter estimates, defined by slope and intercept, used to obtain values for both gas and electricity usage under the standardised conditions of T_{ex} = 5°C. A similar process was carried out for the MK1 data, except using mean T_{ex} over intervals corresponding to the meter readings of usually between two weeks to one month.

Since the distribution of energy consumption was found to be highly skewed, dwellings were then grouped into thirds based on their total energy consumption in the 1990 study and referred to as the low (n = 5), mid (n = 5) and high (n = 4), energy groups. Once a dwelling had been classified according to its energy consumption in 1990, it remained in the same group throughout the subsequent analysis to simplify interpretation of the results. Thus, any change detected in a group has occurred to the same group of dwellings from baseline to follow-up studies. This classification process could have been done separately by gas and electricity, however it was found that essentially the same groups were formed in all cases (in other words high gas usage was likely to be accompanied by high electricity consumption). As previously, regression models were then used to obtain estimated energy consumption of each group (Figures 2A.3 and 2A.4) when T_{ex} = 5°C. The process was repeated for MK1 data. The regression data output from SAS 9.1 provides confidence intervals for these estimates, and hence a test for whether statistically significant change has occurred.

A key part of analysis is the communication of the results. With these estimates of energy usage under specific conditions it was possible to generate a series of charts that succinctly summarise the key point about differences in energy consumption between baseline and follow-up studies. A consistent pattern

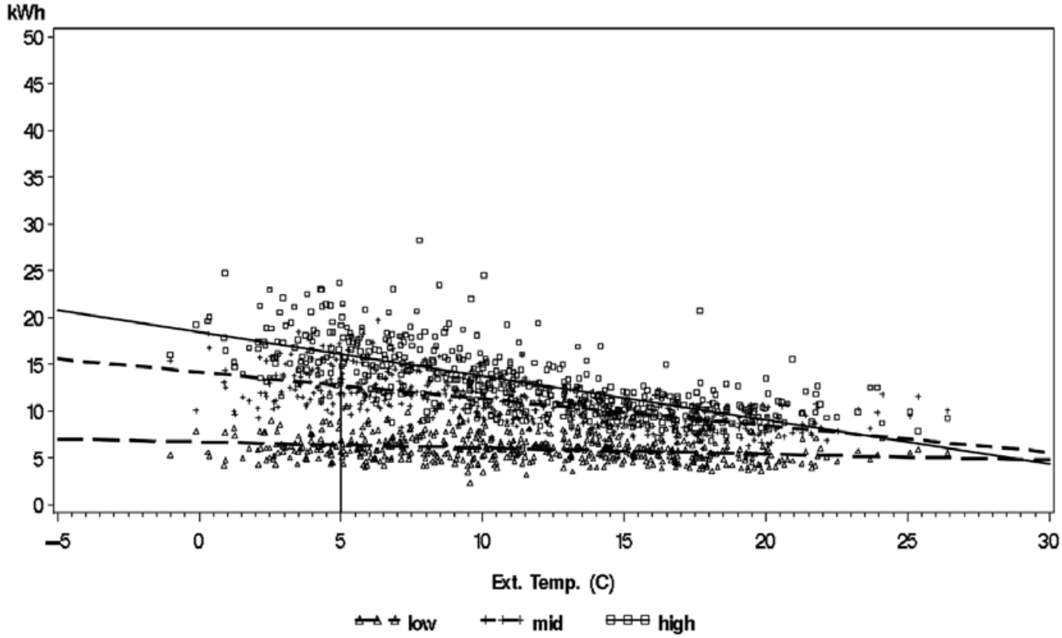

Figure 2A.4 Daily electricity use vs. external temperature in MK0 for each energy usage group.

emerged whereby high energy users accounted for almost all of the increases only weakly apparent in the overall statistics. There was only weak evidence that across all dwellings the gas use rose by 10% to 71 kWh/day (95% Confidence Interval (CI): 63 to 80), whereas for the high energy group alone the increase was 20% to 130kWh (95%CI: 110 to 150). When gas consumption is normalised for floor space (Figure 2A.5), the change is no longer statistically significant, giving no indication of deterioration in the building performance for any group. So, the rise in space heating in the high group is instead accounted for by increased floor area or extensions to these dwellings (9%), and which had not occurred in other groups.

Overall electricity usage was 30% higher at 15 kWh/day (95%CI: 13.5 to 16.5). But compared to the other groups, electricity usage has jumped in the high group by 75% to 28 kWh (95%CI: 25 to 31). This high energy group not only accounts for more than half (57%) of the total energy used in 2005 but this is three times more than the low group (47kWh/day, 95%CI: 42 to 52) and double that of the middle group (68kWh/day, 95%CI: 64 to 73) (Summerfield et al., 2007). Although not necessarily representative of changes in dwellings across the UK building stock, these findings highlight issues regarding the importance of effective targeting of energy conservation measures both to where consumption is greatest and where it is increasing most rapidly.

Supplementary research: Indoor environment and mould

The MK1 datasets have also provided an invaluable opportunity to undertake supplementary research on the occurrence of indoor mould. It is well established that indoor environments contaminated with mould can adversely affect the health of occupants, and individuals with respiratory problems and asthma are among those most likely to be affected (Burr et al., 2007; Bush, Portnoy, Saxon, Terr and Wood, 2006; Mazur, Kim and Committee on Environmental Health, 2006). The prevalence of respiratory symptoms and asthma in the UK is one of the highest in the world (Janson et al., 2001), with more than 1500 deaths reported annually from asthma alone (Denning, O'Driscoll, Hogaboam, Bowyer and Niven, 2006).

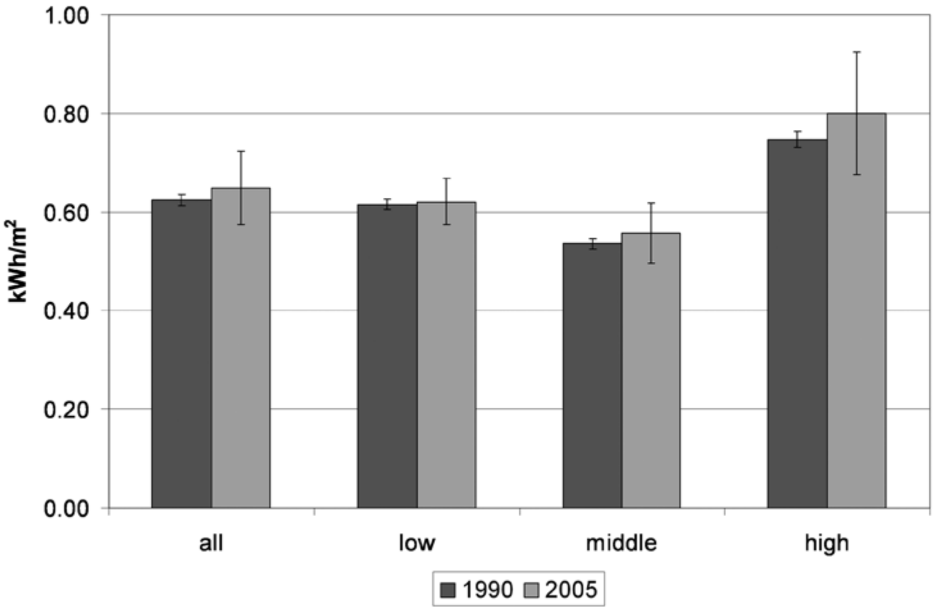

Figure 2A.5 Daily gas usage per unit floor area for 1990 and 2005 by energy group (at T_{ex} = 5°C).

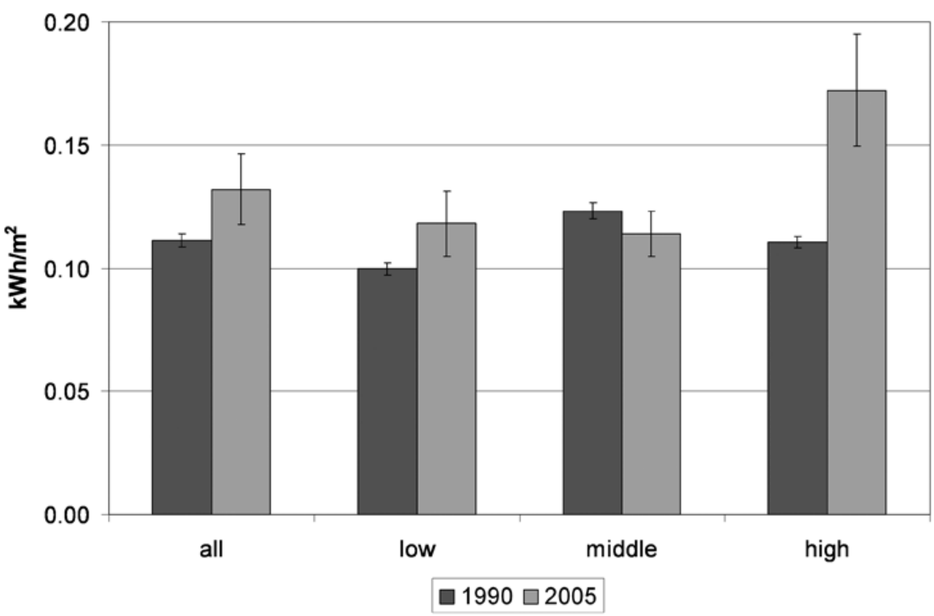

Figure 2A.6 Daily electricity usage per unit floor area for 1990 and 2005 by energy group (at T_{ex} = 5°C).

Moreover, a high proportion of UK homes affected by mould, condensation and damp has been reported during the last 20 to 30 years (DETR 1991, 1996; RSHA, 2001; Sanders, 1989; Sanders and Cornish 1982a, 1982b).

Primarily based on laboratory measurements, it has been shown that mould growth occurs when wall surface relative humidity (RH) is above 80% for a period of several weeks, or even for some species when relative humidity is as low as 70%. These results have led to a number of guidelines being proposed to avoid the occurrence of mould. However, in buildings RH is continually fluctuating due to changes in internal temperature, moisture generation, external vapour pressure, ventilation (natural and occupant controlled), and moisture transport through the building envelope. Mould growth in indoor environment is a complex problem and even though it has been studies for many years analysis the details remains unclear. So, these guidelines need further verification and possibly amendment depending on the results of laboratory work and field data.

Data requirements

This supplementary research aimed to investigate the relationship of various indoor parameters, such as air tightness of the house and household moisture production, with the development of indoor mould. Ideally the information specifically related to mould should include the following:

- Physical condition related to the environment where mould is present (building materials, building age, etc).
- Temperature and RH: hourly measurement of indoor and external conditions. In view of the time required for mould spores to germinate and *Mycelium* to grow, these parameters should be for at least 4 to 6 months or a complete season.
- Occupancy behaviour and indoor moisture production via a questionnaire.
- Visible mould occurrence: a simple index can be used where two or three categorisation levels can be used, (e.g. no visible mould, small spots, hand size patches and large patches).
- Indoor air quality, ventilation and air tightness.
- Identification of potential thermal bridges and damp problems via visual inspection and measurement.

For the MK1 study this information took the form of:

- Air tightness of the house calculated with fan pressurisation tests (Figure 2A.7).
- Information on occupancy, moisture production and mould occurrence from a questionnaire survey.
- Thermal bridges and damp problems identified through infra-red (IR) images and visual inspection (Figure 2A.8).
- Hourly measurement of temperature and RH (indoor and outdoor conditions).

Derived parameters

Temperature factor

The standard BS EN ISO 13788:2002 details a method for assessing the thermal quality of each building envelope element. The thermal quality is characterised by the temperature factor at the internal surface:

$$f_{Rsi} = \frac{\theta_{si} - \theta_i}{\theta_i - \theta_e}$$

Figure 2A.7 Electric blower door for fan pressurisation tests.

where θ_{si}, θ_i, θ_c represent temperatures at the internal wall surface, for internal air temperature, and external air temperature respectively. The internal surface temperature will depend on the nature of the structure, especially in the presence of thermal bridges causing multidimensional heat flow, and the value of internal surface resistance. The temperature factor, *fRsi*, calculated for all MK1 properties fluctuated between 0.69 to 0.73. Note that it should be close to 1 for well insulated buildings, however, to avoid mould growth a temperature factor of 0.75 and higher is considered sufficient.

Figure 2A.8 IR image of MK1 dwelling; note signs of thermal bridging around the window frames.

Vapour pressure excess (VPX)

The standard BS5250 (BSI 2002) gives details of typical moisture production rates as a function of occupant numbers and behaviour. The occupancy is defined as dry (up to 300Pa) where there is proper use of ventilation and it includes those buildings unoccupied during the day. Where internal humidity is above normal, possibly a family with children who do not ventilate the dwelling sufficiently, the occupancy is defined as moist. If VPX exceeds 600Pa the occupancy is defined as wet. For each dwelling, regression of indoor VPX with outdoor temperature was used to obtain estimates of daily indoor VPX under standardised conditions (T_{ex} = 5°C and RH = 80%).

Mould severity index (MSI)

Since each dwelling was assessed for the occurrence and extent of mould on windows, walls and ceilings, we assigned it a value according to the mould severity index (MSI), as developed for the English House Conditions Survey (DETR, 1996).

Modelling

Transient thermal modelling

The steady state method of calculation defined in BS EN ISO 13788:2002 was used to obtain the surface temperatures of the selected 'as designed' construction details for the identified thermal bridges in MK1 dwellings. The modelled results have then been compared with surface temperature readings obtained from the thermal images for the same boundary conditions. In order to achieve the similar severity of the thermal bridges identified, the effect of the build quality had to be taken into account which led to deterioration of thermal performance of the 'as designed' construction details; this iterative process of progressively adjusting the 'as built' construction details were carried out until comparable results were obtained.

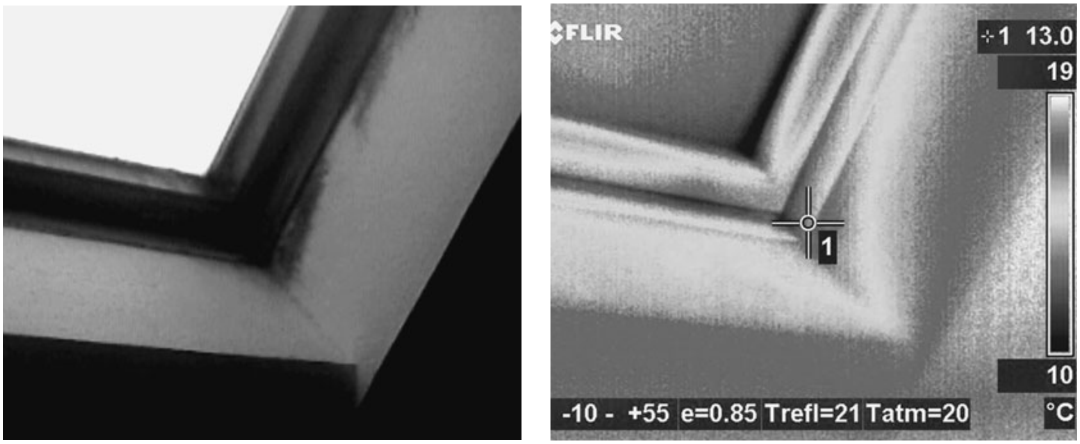

Figure 2A.9 Detail of mould growth by window frame (left) and IR image of same area (right) indicating thermal bridging in the same area.

Boundary condition for mould growth

The modelled surface temperatures were then used to obtain boundary conditions for the mould growth assessment model – WUFI Bio. This model is based on WUFI, a validated advanced model which is able to predict moisture balance under realistic transient boundary conditions.

The monitoring and modelling results used to analyse the causes of mould growth were divided into three categories:

- Boundary conditions (external temperature and RH).
- Occupant behaviour (inside temperature, moisture generation and ventilation).
- Building construction and design (building form/layout, thermal performance of building envelope, moisture buffer capacity, presence of preferential condensation surfaces and type of finish).

Results

Factors for mould

Mould was identified in 4 out of 12 houses studied. In all cases the reasons for mould growth are a combination of one or more previously mentioned factors. However, the main factors that seem to have an effect on the development of mould are:

- Thermal bridging – poor thermal performance of building envelope (in 4 out of 4 cases where the mould was identified the thermal bridging was of significant importance for mould growth).
- Moisture generation – high vapour release at source (in 4 out of 4 cases the mould grew either in the bathrooms or in the adjacent bedrooms).
- Insufficient ventilation – reduced adventitious ventilation (in 2 out of 4 cases).
- Building form/layout – rooms with more than one external surface and located to high moisture generation sources such as en-suite bathrooms (in 1 out of 4 cases).

Table 2A.1 Four dwellings with mould and the presence of factors for mould growth.

Influencing parameters	*Dwell. A*	*Dwell. B*	*Dwell. C*	*Dwell. D*
Internal temperature	–	yes	–	–
Thermal bridging	yes	yes	yes	yes
Moisture generation	yes	yes	–	yes
Building form	–	yes	–	–
Ventilation	yes	–	–	yes

Thermal bridges

It was evident the association of mould with thermal bridges usually located either on external corners of the room or around the windows. The most severe thermal bridges are located at room corners where the minimum temperature factor calculated was 0.68. Besides, it was possible to identified three types of external bridges:

- Detailing around roof lights.
- Detailing at wall/ceiling intersection.
- Gaps in roof insulation.

Water vapour

Water vapour is usually generated locally within house in wet processes areas such as kitchens and bathrooms. The dominant mechanism for transporting this water vapour to other drier and usually colder areas is the airflow to the building. This is the case for MK1 as the mould grew either in bathrooms or in bedrooms with en-suite bathrooms.

Insulation and ventilation

Although mould growth is usually associated with non-insulated houses, this study has shown that mould can also occur in well insulated modern dwellings. However, this is usually due to combined effect of a few factors most notably thermal bridging coupled with the high moisture generation and/or insufficient ventilation. Important is the fact that thermal bridging coupled with insufficient ventilation and that higher moisture generation is the most likely reasons for mould contamination in studied Milton Keynes houses.

Although not all the main observations required of a mould study were available from MK1, it has still been possible to develop a new methodology that included the calculation and simulation of new parameters. This accounted for the deficiency of the building envelope in localised areas (i.e. the accurate modelling of fluctuating temperature conditions at the 'deficient' building surfaces) which significantly increases the likeliness of mould growth. This detailed case-study analysis based on the monitored data in real dwellings, the physical surveys, and the consequent modelling work has provided insight into identifying the parameters of most importance for mould growth in buildings. Alongside the results of other studies, it will help inform guidelines for avoiding mould in well insulated UK dwellings.

Discussion

More than just a case study, the MK0 study has been a highly invaluable sample to select for follow-up research. This specific group of dwellings represented best practice in the UK domestic sector for the symbolically important year – in Kyoto Protocol terms – of 1990 and which were roughly a decade ahead of their time with respect to building regulation standards. Hence, they also provide an indication of what might be expected a decade from now, from dwellings of an equivalent standard. Our results found no evidence for any decline in the building fabric that has significantly affected building energy performance, though there was evidence of construction issues and thermal bridging in places, particularly around window frames – and leading in some dwellings to mould growth. The general increase in gas use for space heating was accounted for by the increased floor space in the MK1 sample, but specifically in the top third of energy users in 1990. These tended to be larger dwellings and were where extensions had been added. This high group also had a substantial rise in electricity usage, and by 2005 they used more energy than the other two groups combined. Although not representative of the UK dwelling stock, this work has pointed to the need for further research to help policymakers refocus specifically on where energy is used and where change is occurring the most.

With the supplementary research, the MK1 study has also proven its usefulness for research on mould growth on UK dwellings. A methodology that combined modelling with detailed data of temperatures and RH, has clarified the role of four factors, including thermal bridging and moisture production. This information will contribute to the analysis and results for other studies and ultimately improve guidelines for avoiding mould. It is also the case that with some minor additions and improvements on the initial data collection methodology for MK1, it would have been possible to investigate mould growth with an even more sophisticated and informative analysis.

In summary, the MK0 and MK1 studies provide a useful illustration for some of the issues and possibilities of energy and environmental research in the domestic sector. We have outlined the various considerations that need to inform the planning process for the study, while ensuring that the primary research objectives are met and being aware of the potential that good research methods have in enabling supplementary work to add-value to the original dataset. We have also highlighted the importance of referring to existing standard methodologies of data collection and classification to maintain compatibility and permit the results to be set within an appropriate scientific context. By describing in some detail, the range of options associated even with the basic objectives, such as monitoring temperature and RH, we have endeavoured in portray the numerous considerations to be addressed, from maximising reliability and accuracy to minimising costs and occupant disturbance. Complex or even chaotic it may be on a large scale, but worthwhile research in this field must cope with the unpredictable and messy world of people and buildings as they are, rather than just how we imagine things should be in a laboratory or computer simulation.

Acknowledgements

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Case Study 2B
ENERGY MODELLING

David Johnston

Introduction

The aim of this case study is to describe in detail the development of DECARB, a physically based model of the UK housing stock that is capable of forecasting the energy use and CO_2 emissions attributable to this sector, under a range of possible futures. This model has been used to develop a number of illustrative scenarios for the UK housing stock, in order to explore the technical feasibility of achieving CO_2 emission reductions in excess of 60% within this sector by the middle of this century. Reductions of this order are likely to be required across the industrialised countries in order to stabilise the atmospheric CO_2 concentration and mitigate the effects of climate change.

Forecasting energy use and CO_2 emissions

In recent years, a variety of models have emerged that are capable of analysing and developing various strategies that are designed to achieve the long-term goals associated with climate stabilisation. These models have the ability to model the complex interactions that occur between the energy use and the CO_2 emissions associated with a particular sector of the economy, examine the effect of various CO_2 abatement strategies and policies, and suggest the possible impact that these strategies and policies may have on future energy use and CO_2 emissions. Consequently, these models are required in order to help us understand which strategies and policies are important, when such strategies and policies should be implemented, and the potential effects of their implementation.

There are two principal approaches that can be used to forecast the energy use and CO_2 emissions of a particular sector of the economy, namely: '*top-down*' or '*bottom-up*'. Top-down methods tend to start with aggregate data and then disaggregate this data as far as they can. They focus on the interaction between the energy sector and the economy at large, using econometric equations to model the relationships that exist between the energy sector and economic output. They also rely on aggregate economic behaviour (which is based on past energy-economy interactions) to predict future changes in energy use and CO_2 emissions (IEA, 1998). Data input into these models largely comprises econometrically based data, such as Gross Domestic Product (GDP), fuel prices and income. Various other factors that can have an important influence on energy use can also be incorporated into top-down models, for instance: technological progress, saturation effects and structural change.

The use of econometrically based data within top-down models means that these techniques are capable of modelling the interactions that occur between various economic variables and energy demand, ensuring that macroeconomic factors are taken into consideration and are not ignored, and providing feedback from the economy. Thus, top-down models are particularly appropriate for modelling the societal cost-benefit impacts of various energy and emissions policies and scenarios (MIT, 1997). However, their reliance on past energy-economy interactions to predict future changes in demand, makes it difficult to use top-down methods for predictions that incorporate structural change or novel technologies, unless of course they adhere to past energy-economy interactions. They also tend to lack technological detail, so are inappropriate for adequately identifying differences in the energy efficiency of various end-use technologies or taking into account technological changes to end-use systems or changes to the energy efficiency of such systems.

Bottom-up methods, on the other hand, tend to start with disaggregated data and then aggregate this data as far as they can. They focus on the energy sector alone, using highly disaggregated physically based engineering-type models to model in detail the energy demand and supply sectors. Data input into these models largely comprises quantitative data on physically measurable variables, such as the energy consumption of a refrigerator, and this data is used to describe in detail the past, present and future stocks of energy using technologies within particular sectors of the economy. The use of such data acknowledges the fact that over time, the current stocks of energy using technologies will be replaced with new ones, as their useful lifetime is reached. The physically measurable data, along with other relevant information on factors such as usage patterns, saturation effects, appliance replacement cycles and alternative technological options, is then used to determine the demand for energy within various sectors of the economy. The use of detailed physically measurable data enables bottom-up models to adequately take into account technological changes to end-use systems or changes to the energy efficiency of such systems, identify and include the complex interactions that exist between the different end-uses of energy, and incorporate changes in ownership, substitution effects and saturation effects. Thus, bottom-up models are particularly appropriate for suggesting the likely outcome of policies, or to identify a range of technological measures that are intended to improve end-use efficiencies (Shorrock, 1994).

DECARB (Domestic Energy and Carbon Dioxide Model)

Bottom-up modelling techniques have been used to develop DECARB, a physically based bottom-up energy and CO_2 emission model of the UK housing stock that is capable of exploring the technological feasibility of achieving CO_2 emission reductions in excess of 60% from the UK housing stock by the middle of this century. DECARB has been developed from work previously undertaken in this area by Shorrock et al. (2001) using the Building Research Establishment's Housing Model for Energy Studies (BREHOMES). The structure and form of DECARB is illustrated in Figure 2B.1.

As Figure 2B.1 indicates, DECARB has been constructed around two separate but inter-related components: a data module and a calculation module. The data module contains internally and externally generated data on a wide range of factors that are likely to influence the energy use and CO_2 emissions of the UK housing stock, such as population projections, mean household size data, levels of insulation, and the ownership and usage of various appliances. Where possible, this information has been obtained from relatively uncontentious external data sources. In addition, a number of logistic functions (s-curves) devised by the Building Research Establishment (BRE) have been used to determine the likely uptake rate and ownership of various insulation measures (see Shorrock, Henderson, Utley and Walters, 2001). Other information, which is required as input into the data module, has been generated internally, either by manipulating the existing data sets, or by deriving the data based upon the results of other modelling studies or practical case studies. For instance, information contained within the English House Condition Survey has been taken as being representative of the UK, and the experience gained from a number of exemplar case study dwellings has been used to determine the sorts of technological measures that can be implemented into the UK housing stock.

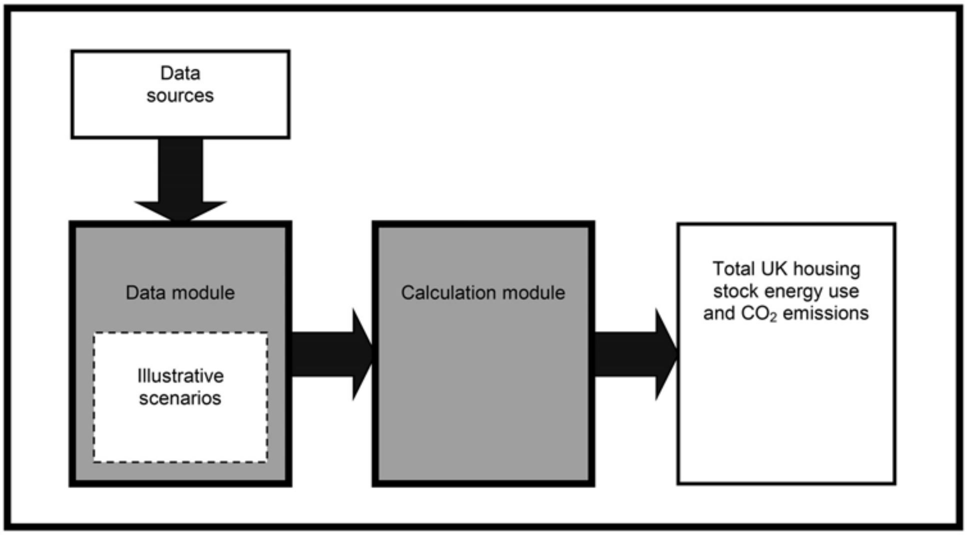

Figure 2B.1 Structure and form of DECARB.

Since it would be impractical to attempt to obtain or generate all of the relevant data for all of the existing dwelling types in the UK, transparency within DECARB has been preserved by adopting a parsimonious approach to detail. Thus, a selectively disaggregated approach has been adopted when constructing the model. This approach has enabled the model structure and the data collection to be biased toward those sectors that dominate domestic energy use and CO_2 emissions and those sectors where energy efficiency measures are likely to be implemented. For instance, space heating not only dominates domestic energy use and CO_2 emissions, but there are also a large number of energy efficiency measures that could be applied to this sector to reduce its energy use and CO_2 emissions. Therefore, space heating has been disaggregated down to a level where different types of building envelope construction are capable of being described (cavity walls and solid walls). This has enabled a variety of measures, such as retrofitting existing uninsulated cavity walls with blown fibre insulation or externally insulating solid walls, to be incorporated within the model. Such an approach has resulted in the main emphasis of DECARB being concentrated upon the demand side of the domestic sector.

One of the major features of adopting a selectively disaggregated approach has been the incorporation of just two 'notional' dwelling types[1] into the data module of DECARB. The physical properties of these 'notional' dwellings are based upon an average of the currently available fully disaggregated data and take into account the likely effects of new-build rates, demolition rates, refurbishment cycles, heating system and appliance replacement cycles and so on. A two-dwelling approach is justified on two accounts. First of all, data on and projected trends in insulation ownership, the use of lights and appliances and stock replacement cycles can only be identified at the level of the whole housing stock (see for example Shorrock and Dunster, 1997). Secondly, at the whole stock level, the impact of dwelling type on energy use and CO_2 emissions is very small, in comparison with the impact of the thermal characteristics of the building fabric and system efficiencies. Therefore, in the long-term, what is important is the average performance of a wall, a roof, a space heating system and a lighting system across the stock, rather than the individual differences in geometry, thermal performance and energy use of the various individual dwelling types.

The two 'notional' dwelling types have been deemed to be representative of pre- and post-1996 construction respectively. The distinction between pre- and post-1996 dwellings was undertaken for a number of reasons. First of all, 1996 is the base case year used within DECARB. This year was chosen since it is the most recent year where a fairly comprehensive breakdown of the various factors that are likely to influence UK housing stock energy use and CO_2 emissions are available. Therefore, the ability to be able to distinguish between pre- and post-1996 construction gives a convenient way to look at new (post-1996) and existing (pre-1996) construction. Secondly, the distinction between new and existing construction is important, because of the distinct differences in the average performance of these two separate categories of dwellings, apart from at the margin, and the limitations they impose on the application of various technological measures. For instance, the average external wall U-value of a new dwelling will no doubt be much lower than the average external wall U-value of an existing dwelling. Consequently, various strategies and technologies that are aimed at improving the performance of one particular category of dwelling may not always be appropriate for the other. Thirdly, such a distinction represents an absolute minimum categorisation of the stock in terms of their age-related structure.

The information that is contained within the data module is then used, along with a number of assumptions, to formulate a number of detailed illustrative scenarios for the UK housing stock, for each 'notional' dwelling type. Relevant scenario-specific information relating to each of the scenarios, on factors such as the number of households, dwelling size, thermal and ventilation characteristics of the building envelope, type and seasonal efficiency of the space and hot water heating systems, information on lights, appliances and cooking, occupancy details and the effects of global warming, is then fed into the calculation module. The calculation module is based upon a modified worksheet version of the Building Research Establishment's Domestic Energy Model (BREDEM) Version 9.60 (DETR, 1998). Various modifications were made to BREDEM 9.60 in order to simplify the model where applicable, reduce the required input data, and enable the model to utilise additional disaggregated data from the illustrative scenarios. For instance, BREDEM 9.60 has been modified to include detailed disaggregated information on the internal heat gains associated with lights, appliances and cooking. This data replaces the existing algorithm contained within BREDEM 9.60, which assumes that these heat gains are a function of the dwelling's total floor area. In addition, BREDEM 9.60 has also been modified to incorporate a very simple energy supply side model. The supply side model is based around just two fuels, natural gas and electricity, with the carbon intensities of these fuels being used to describe the performance of this sector. A BREDEM-based energy and CO_2 emission model was utilised for a number of reasons. First of all, BREDEM is capable of taking into consideration the complex interactions that take place both between and within the different end-uses of energy within dwellings. Secondly, utilising a model that predominantly models space heating energy use has been undertaken because space heating is currently the largest energy demand and CO_2 emission category within the domestic sector, and the potential for reducing the space heating energy requirement of dwellings is extremely large. Furthermore, since the fabric of the UK housing stock is the most important determinant of space heating energy use and has a very long physical life, it is also one of the most difficult areas to change. Finally, BREDEM is not only the most widely used approach to modelling the space heating energy requirement of dwellings in the UK, but it has also been extensively validated against monitored data (see Shorrock, MacMillan, Clark and Moore, 1991; Dickson, Dunster, Lafferty and Shorrock, 1996).

The scenario-specific information that is contained within the calculation module is then used to calculate the delivered energy use and CO_2 emissions attributable to each 'notional' dwelling type, for the particular year in question. This process is undertaken from the base case year 1996 to 2050 inclusive. The year 2050 was chosen because this year is commonly referred to in climate stabilisation calculations. Furthermore, undertaking detailed projections of the UK housing stock over this sort of time-scale, almost 60 years, has a number of important advantages. First of all, 60 years corresponds to a time-scale over which long-term policies can be expected to operate. Secondly, many energy-using devices in the domestic sector, such as boilers and electrical appliances, will be replaced at least once, if not several times, over a 60 year time period. Thirdly, the lifetime of many electricity generation systems is around 30 to 50 years, so undertaking projections over this sort of time-scale should see at least one complete replacement cycle within the electricity generation sector. Finally, information on the total number of 'notional' dwellings available in each in year is then combined with information on the performance of these dwellings, in order to scale the delivered energy use and CO_2 emissions up to the level of the whole UK housing stock.

The illustrative scenarios

So far, DECARB has been used to develop and evaluate three illustrative scenarios for the UK housing stock. These scenarios have been constructed to explore the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the middle of this century. Reductions of this order are likely to be required across the industrialised countries in order to stabilise the atmospheric CO_2 concentration and mitigate the effects of climate change. The remainder of this case study presents a broad overview of the results of these scenarios. A much more detailed discussion of the results and the insights gained form the scenarios can be found within Johnston (2003).

The three developed scenarios are exploratory in nature and assume the application of currently available technology only. They have been termed the 'Business-as-Usual', the 'Demand Side' and the 'Integrated' scenario. The 'Business-as-Usual' scenario represents a continuation of current trends in fabric, end-use efficiency and carbon intensity trends for electricity generation. The 'Demand Side' scenario represents what may happen if the uptake of energy efficiency measures within the demand side of the domestic sector were to be increased. Finally, the 'Integrated' scenario shares the same demand side assumptions as the 'Demand Side' scenario but represents what may happen if the carbon intensity of electricity generation were to fall even further.

In addition to internally and externally generated data, a wide range of assumptions have also been used to develop the 'Business-as-Usual', the 'Demand Side' and the 'Integrated' scenarios. Unfortunately, it is not possible to present all of these assumptions here. However, a brief description of some of the assumptions that have been incorporated within each of the illustrative scenarios can be found within Table 2B.1. Further details concerning the various assumptions that have been used to develop each of the illustrative scenarios can be found within Johnston (2003).

The results of the illustrative scenarios

Figures 2B.2 and 2B.3 illustrate the delivered energy use and CO_2 emissions attributable to the UK housing stock under each of the scenarios. The results show that by the year 2050, considerable reductions in delivered energy use and CO_2 emissions are expected to occur within all of the scenarios. All of these reductions are expected to occur despite a number of opposing trends. These trends include: a substantial increase in the total number of UK households; an increase in thermal comfort standards; and a substantial increase in the ownership and usage of central heating systems and various electrical appliances.

The scale of the projected reductions in delivered energy use and CO_2 emissions varies between each of the scenarios (see Figures 2B.2 and 2B.3). Under the 'Business-as-usual' scenario, which assumes a continuation of current trends, building fabric improvements, increases in end-use efficiency and a continued reduction in the carbon intensity of electricity generation, result in a 21% and a 33% reduction in delivered energy use and CO_2 emissions respectively, by the middle of this century. These reductions in delivered energy use and CO_2 emissions could be reduced by a further 29 and 25 percentage points respectively, if the current rate at which fabric and end-use efficiency measures are being implemented into the demand side of the UK housing stock are increased to the levels that have been identified within the 'Demand side' scenario. Figure 2B.3 also illustrates that a further 7 percentage point

Table 2B.1 Description of some of the assumptions incorporated within the illustrative scenarios.

	Scenario		
	'Business-as-usual'	*'Demand side'*	*'Integrated'*
Building fabric	80% of pre-1996 cavity walls insulated by 2050. 10% of uninsulated pre-1996 solid walls insulated by 2050. All pre-1996 glazing replaced at least once by 2050. 10% of pre-1996 dwellings undergo post-construction airtightness work by 2050. Building Regulations wall U-values fall to $0.25W/m^2K$ by 2009, to $0.23W/m^2K$ by 2015, $0.20W/m^2K$ by 2020 and $0.15W/m^2K$ by 2025. Building regulations window U-values fall to $1.8W/m^2K$ by 2009, $1.5W/m^2K$ by 2015, $1.3W/m^2K$ by 2020 and $1.0W/m^2K$ by 2025. Air leakage rates are introduced into the Building Regulations in 2005 at 10 ac/h @ 50Pa and fall to 5.0 by 2015, 3.0 by 2020 and 1.0 by 2025.	All pre-1996 cavity walls insulated by 2050. All pre-1996 uninsulated solid walls insulated by 2050. All pre-1996 glazing replaced at least once by 2050. 30% of pre-1996 dwellings undergo post-construction airtightness work by 2050. Building Regulations wall U-values fall to $0.25W/m^2K$ by 2005 and $0.15W/m^2K$ by 2010. Building regulations window U-values fall to $1.5W/m^2K$ by 2005 and $1.0W/m^2K$ by 2010. Air leakage rates are introduced into the Building Regulations in 2005 at 10 ac/h @ 50Pa and fall to 5.0 by 2007 and 1.0 by 2010.	As 'Demand side' scenario.
Mean internal temperature	Pre- and post-1996 dwellings saturate at 21°C by 2040 and 2020, respectively.	Pre- and post-1996 dwellings saturate at 21°C by 2040 and 2020, respectively.	As 'Demand side' scenario.
Space and water heating systems	All dwellings have a central heating system installed with an average seasonal efficiency of 88% by 2050.	All dwellings have a central heating system installed which is fuelled by a gas-fired condensing boiler (seasonal efficiency of 91%) or an electrically driven heat pump (seasonal efficiency of 230%).	As 'Demand side' scenario.
Lights, appliances and cooking	Ownership of the majority of lights, electrical appliances and cooking appliances saturate around 2020. Appliance efficiencies rise over the period 1996 to 2050.	Ownership of the majority of lights, electrical appliances and cooking appliances saturate around 2020. Appliance efficiencies rise over the period 1996 to 2050, resulting in higher efficiencies than experienced within the 'Business-as-usual' scenario.	As 'Demand side' scenario.
Carbon intensity of natural gas	Remains constant at $51kgCO_2/GJ$ over the period 1996 to 2050.	Remains constant at $51kgCO_2/GJ$ over the period 1996 to 2050.	Remains constant at $51kgCO_2/GJ$ over the period 1996 to 2050.
Carbon intensity of electricity	Reduces to $92kgCO_2/GJ$ by 2050.	Reduces to $92kgCO_2/GJ$ by 2050.	Reduces to $51kgCO_2/GJ$ by 2050.

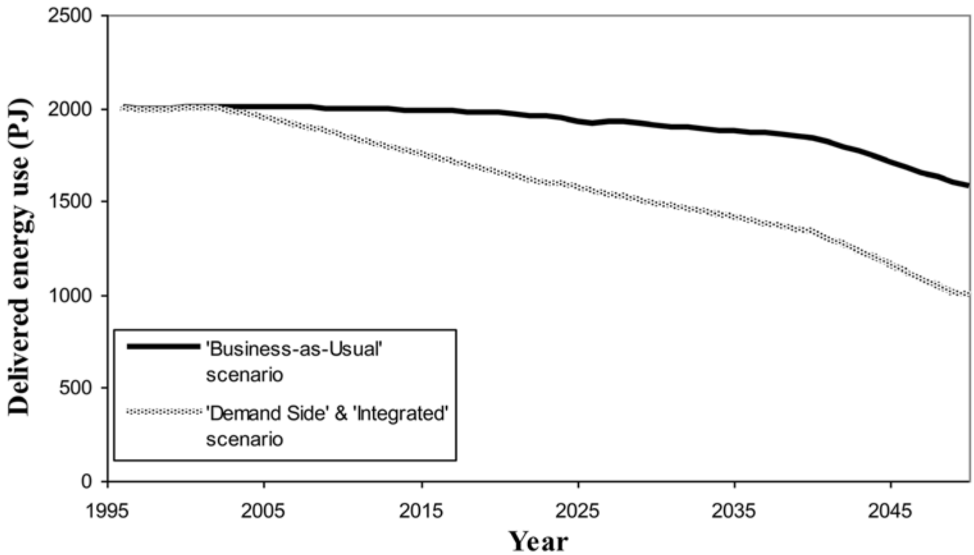

Figure 2B.2 Total delivered energy use attributable to the developed scenarios over the period 1996 to 2050.

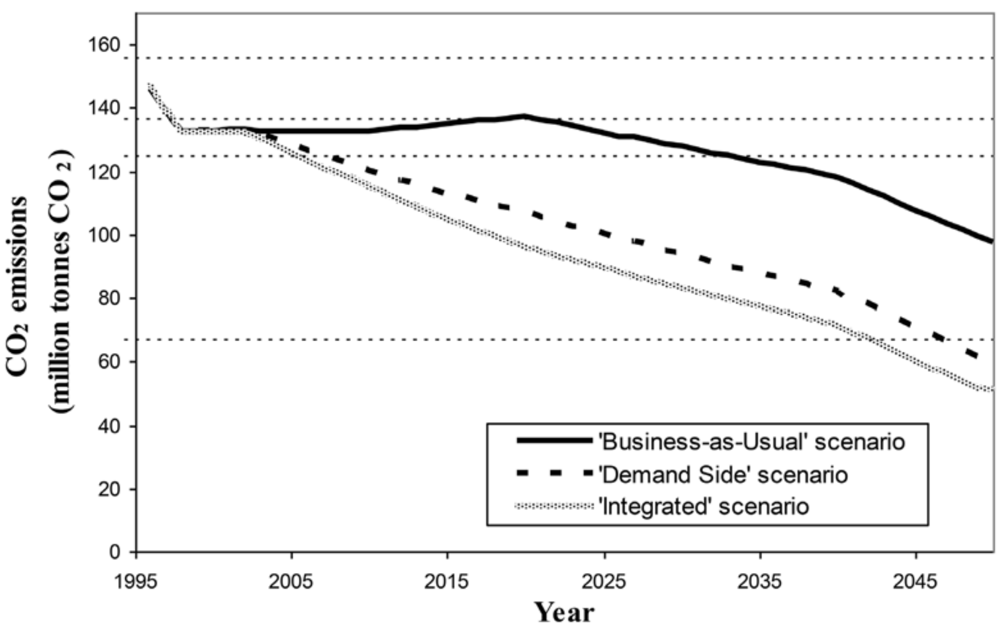

Figure 2B.3 CO_2 emissions attributable to the developed scenarios over the period 1996 to 2050.

reduction in CO_2 emissions could be achieved if various measures are also applied to the electricity generation side of the energy supply sector.

The CO_2 emission trajectories of all three illustrative scenarios have also been compared against the UK's Kyoto target of a 12.5% reduction in CO_2 emissions between 2008 and 2012, the UK Government's domestic target of a 20% reduction in CO_2 emissions by 2010 (DETR, 2000), and the UK Government's Energy White Paper target of a 60% reduction in CO_2 emissions by 2050 (DTI, 2003). Relative to the 1990 baseline,[2] Figure 2B.3 indicates that although all of the scenarios are likely to achieve the UK's Kyoto target, only the 'Demand side' and the 'Integrated' scenario are likely to achieve the UK Government's domestic target. More importantly, the results also suggest that the RCEP target of a 60% reduction in CO_2 emissions by the year 2050 could be achieved under both the 'Demand side' and the 'Integrated' scenario. However, achieving these sorts of emission reductions will require a considerable increase in the current uptake rate of efficiency measures within both the demand side and the supply side of the UK housing stock.

Conclusions

This case study has described the development of DECARB, a selectively disaggregated physically based bottom-up energy and CO_2 emission model of the UK housing stock and illustrates how this model has been used to explore the technical feasibility of achieving CO_2 emission reductions in excess of 60% within the UK housing stock by the middle of this century. This has been achieved by constructing and evaluating three illustrative scenarios for this sector, namely: a 'Business-as-usual' scenario, which represents a continuation of current trends in fabric, end-use efficiency and carbon intensity trends for electricity generation; a 'Demand side' scenario, which represents what may happen if the current rate of uptake of fabric and end-use efficiency measures were to be increased; and an 'Integrated' scenario which shares the same demand side assumptions as the 'Demand side' scenario, but represents what may happen if the carbon intensity of electricity generation were to fall even further.

The scenario results indicate that it is technically feasible, using currently available technology, to achieve the sorts of CO_2 emission reductions that are likely to be required to stabilise the atmospheric CO_2 concentration and mitigate the effects of climate change, under the 'Demand side' and 'Integrated' scenarios. These reductions appear feasible despite a substantial increase in the total number of UK households, an increase in thermal comfort standards and a significant increase in the standards of service that occupants are likely to expect. However, achieving these sorts of emission reductions will be technically demanding, and will require a considerable increase in the current rate of uptake of energy efficiency measures within both the demand side and the supply side of the UK housing stock.

Notes

1 In this context, dwelling types refer to a very broad range of dwellings, rather than dwellings of a particular size, form, tenure or age-related category.
2 The year 1990 has been used as a baseline as it is commonly referred to in climate change scenarios.

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Case Study 2C
RETROFITTING TO NEAR PASSIVHAUS STANDARD

Ben Croxford and Fran Bradshaw

Introduction

The UK Technology Strategy Board (TSB) launched a competition to help increase the capacity of the UK construction industry to carry out domestic refurbishments aimed at reducing carbon emissions in 2009. The team led by Metropolitan Housing Partnership (MHP) and Anne Thorne Architects Partnership (ATAP), won funding to carry out such a refurbishment on 10 Hawthorn Road in North London, UK. The overall principle of the refurbishment and of the TSB Retrofit for the future project was "to improve the performance of the entire property with a goal to make deep cuts in carbon emissions" (LEB, 2010; TSB 2010).

The house selected by MHP was unoccupied (void) and arranged as two flats; the top flat had been burnt out, with holes in the roof space, first floor flooring and in the ground floor. Several of the windows were also boarded up. There is no energy consumption data from before refurbishment that can be used to compare with the refurbished house and no meaningful air change testing was possible prior to refurbishment.

The first project meetings of the team were in 2009, and the refurbishment of the house was completed just before Christmas 2010. Finishing touches were made around the New Year period 2010–2011 (Figure 2C.1) and the previously selected occupants moved in during the last weeks of January 2011.

The general approach taken by the team was to insulate the external envelope to Passivhaus standard; to reduce the infiltration rate to as near Passivhaus standard as possible, and to install suitable low carbon systems to provide heating and hot water with an aim to achieve an overall energy consumption reduction of 80% compared to an estimate for the original house. The Passive House Planning Package (PHPP, 2007) was used throughout the design process to ensure the building fabric would meet Passivhaus standards.

Building description

The house is a late Victorian/Edwardian terrace house typical of London, it now has 3 bedrooms with a bathroom and WC upstairs; downstairs there is a kitchen, living room and extra WC, the low energy systems are fitted into a utility cupboard in the downstairs toilet. The total floor area is 109m^2, with a total volume of 250m^3.

The house was originally split into two flats, as part of the refurbishment these were deconverted into a single terrace house, high levels of insulation were added, and high performance, triple glazed, Passivhaus

Figure 2C.1 The refurbished house.

certified windows were fitted. Mechanical ventilation with heat recovery (MVHR) was installed to extract warm, moist air from kitchen and bathroom and to supply warmed, fresh, dry air to all other rooms, this unit also has a small heater battery. A Rotex gas-solar unit was installed to provide hot water and back up central heating, the unit is a gas boiler, and hot water tank combined with solar thermal panels. To complete the project, low flow taps, low energy light bulbs and low energy white goods were installed.

The next section covers the refurbishment in some detail and is split into three sub-sections: Building fabric, infiltration and low carbon systems.

Building fabric

Different strategies were used for different parts of the building with the aim of achieving a U-value of 0.15 W/m^2.K for opaque parts (roof, wall and floor), and 0.8 W/m^2.K for the windows. The house is in a conservation area, and the front façade could not have external insulation fitted. The approach taken was then to insulate the front façade internally with a moisture permeable wall construction using sheep's wool (Thermafleece) as the primary insulation material and woodfibre board.

The suspended wooden floor was replaced with a solid floor using expanded polystyrene (EPS) for insulation. External insulation of EPS could be used on the rear façade with a finishing render. Except for the staircase, the party walls were also insulated, using woodfibre board. Lime plaster was used for the internally insulated walls.

Actual U-values and constructions of the as-built house are given in Table 2C.1 below. Triple glazed windows with wood frames, reaching Passivhaus standard (U =0.77W/m^2.K) were used throughout (Drewexim). A triple glazed inner door, also to Passivhaus specifications was used; the original outer door was kept, to comply with the conservation of the external façade of the house.

Table 2C.1 U-values of constructions (figures from PHPP model).

Element	*Construction*	*U-value (W/m².K)*
Ceiling – main house	350mm Thermafleece PB20, plasterboard	0.122
Ceiling – rear part of house	300mm Thermafleece PB20, plasterboard	0.142
Wall – interior insulation	2 × 100mm layers of Thermafleece PB20, 60mm Gutex woodfibre, lime plaster	0.162
Wall – external insulation	250mm Jablite EPS, render	0.134
Wall – party wall	100mm Gutex woodfibre, lime plaster	0.307
Floor – main house	250mm Jablite, OSB	0.129
Floor – rear kitchen	150mm Jablite, OSB	0.206
Windows	Drewexim triple glazed	0.77

Careful detailing was required throughout to minimise any thermal bridges, these are discusses in the design issues section later on.

Infiltration

A key part of the refurbishment was to install an air tight layer completely enclosing the occupied areas; on internal walls this was formed by wet plaster; on external surfaces by a vapour permeable, air tight membrane. The membrane used was Intello (from www.proclima.com), and joints were taped with Proclima tape, and sealing glue Orcon F. The Intello membrane has properties that vary with humidity, with low diffusion in winter and high diffusion in summer.

The requirements for Passivhaus certification is 0.6 air changes per hour at 50Pa pressure difference (ach@50Pa). For the slightly less stringent EnerPHit rating the requirement is 1 ach@50Pa. Pre-refurbishment the house had large holes due to fire damage, so the infiltration rate before refurbishment is not relevant, however it was measured by Chiltern Dynamics at 16.47m^3/m^2.h@50Pa, on 14/8/2009.

After the first fix of the refurbishment the infiltration rate was measured at 5.29 ach@50Pa; after final completion this was reduced to 2.08 ach@50Pa (note the permeability was measured as 2.53 m^3/h.m^2 façade @50Pa, this is an average of pressurisation and depressurisation, test carried out on 17/1/2012 by Chiltern Dynamics). A further test with the utility cupboard sealed off completely was carried out, this showed a further reduction in permeability (1.76 m^3/h.m^2 façade @50Pa). This indicated that the connection of the MVHR system and associated pipework were where leaks were occurring, but these were physically impossible to reach post installation.

It is possible that air leakage in the utility cupboard was routed from where the staircase was fixed to the wall. To solve this air leak, would have required the removal of the staircase and the sealing of the wall where it was fixed. Because of these issues it was unfortunately the house was not sealed to either EnerPHit or Passivhaus requirements.

Low carbon systems

This section covers the different systems installed in the house; namely a combined gas-solar unit, for domestic hot water (DHW) and back up space heating, and an MVHR system for providing sufficient warmed fresh air. A shower waste water recovery unit was also installed.

Rotex Gas-Solar Unit

Domestic hot water (DHW), and wet central heating is supplied from a combined hot water cylinder, condensing gas boiler and solar thermal panels. The unit installed is the Rotex GSU 320E (see Rotex 2010 for more details).

The gas boiler is fitted directly on top of the pre-insulated, hot water tank thus minimising heat losses. Along with the cold-water supply to the tank and the DHW supply from the tank, there are two other pairs of pipes to the cylinder; one for the solar, the other for central heating.

Five small radiators all with thermostatic valves (TRVs) are supplied from the central heating circuit (one in the kitchen, two in the living room, and one in each of the main bedrooms upstairs). The central heating pump is driven by the Rotex controller, unusually there is no thermostat for the Rotex, the system relies on the difference in flow and return temperatures to ensure set point is reached.

The gas boiler can modulate down to provide just 4kW of heating. The details of the system (from the manufacturer) are below:

- Gas boiler (4–20kW) Modulating
- Solar: 2 x Daikin solar flat plates (V26 P) @ 2.36m^2 = 4.72m^2 (min yield 535kWh/m^2)
- 300 litre tank
- Electrical power consumption = 30–130W
- Estimated heat loss at 60°C: 1.7kWh per day

Mechanical ventilation with heat recovery (MVHR): Maico Aeronom WS250

A Passivhaus certified MVHR unit, with a stated efficiency of 85% (Maico 2010) was installed to preheat incoming air using heat from outgoing, extracted air from kitchen and bathroom. A low-profile duct system was installed passing through holes in the joists of the ceiling of the ground floor and rising up into the roof space where ducting was installed underneath the roof space insulation. The system was balanced according to the manufacturers' specifications, to supply 30.5l/s and extract 30.3l/s at the normal setting, which corresponds to ~109m^3/hr, or approximately 0.4ac/h.

The unit has a frost protection circuit which is a small electrical heater, and also a post-heat exchanger, heater battery which can add a small amount of heat to the air supply (Maico, 2010). It is installed into the utility cupboard in the downstairs toilet. The unit has 4 silencers, one on each main duct to the unit.

There is a thermostat for the unit in the hallway which controls the heater battery, and a programmer/control unit in the kitchen to control summer/winter mode and ventilation speed. The three fan settings are stated to provide 100/150/250m^3/hr. Maximum power consumption is 130W. Summer mode bypasses the heat exchanger.

Shower waste water heat exchanger (Recoh-vert)

This quite simple device, from Shower-save, is a long waste water tube with a thin copper supply water tube bonded to the outside of it. Incoming cold, supply water is warmed by outgoing warm waste water and fed back into the shower thermostatic mixer thus reducing hot water supply requirements. Its installation demands that the shower is installed on the first floor, or higher, leaving a clear, long straight drop for the waste water tube. The tube is designed so that warm waste water from the shower "sticks" to the walls of the tube ensuring maximum heat exchange. This product only works while showering and the effect is that it will reduce the amount of hot water used.

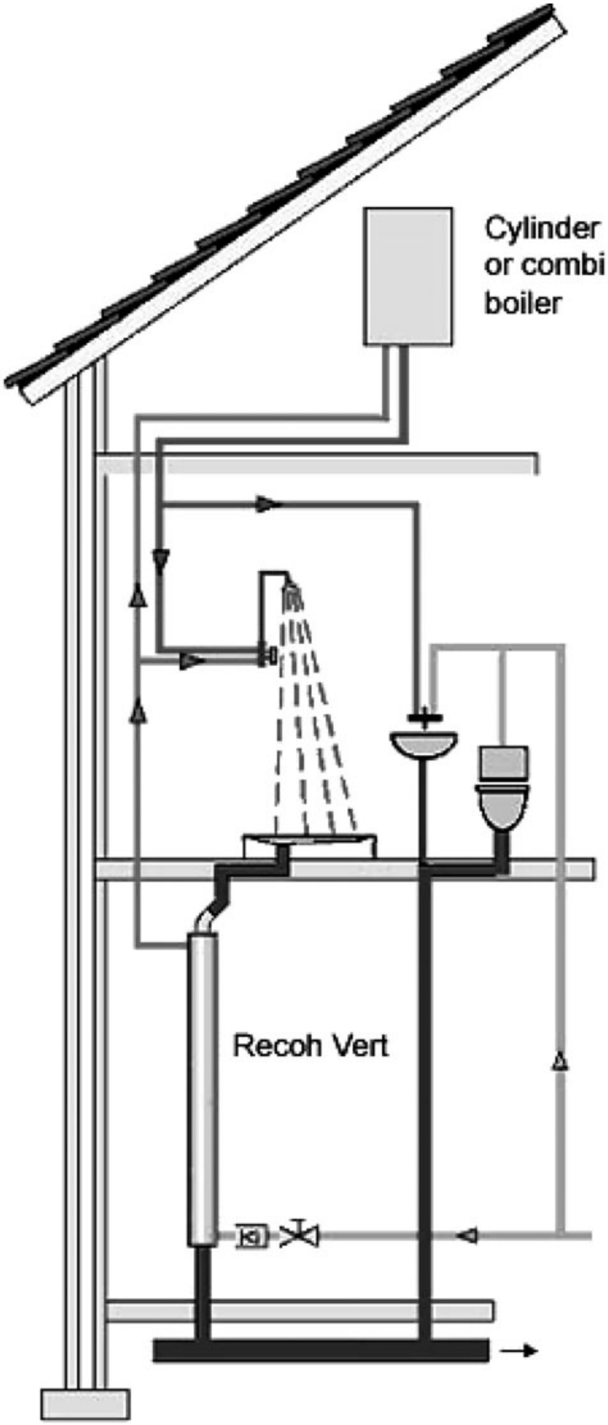

Figure 2C.2 Layout of shower waste water heat reclaim unit.

Source: Recohvert, 2012

Occupant controls

The house is designed to have a very low heat loss so needs very little heat input. The occupants can choose to have space heating via hot air using the MVHR system, or via the Rotex and radiators, or both. The MVHR is electric heating and the Rotex is gas–solar. The householders have been asked to not use the MVHR heating, and this has been switched off.

The radiators are small and run with relatively low temperatures of about 55°C. The thermostat is set in the Rotex gas solar unit to provide a whole house temperature of 21°C with a setback of 19°C at night. For space heating, the Rotex has three main time programmes, the occupants have chosen the time programme best suited to their schedule. It is designed to keep the house at 21°C during daytime and 19°C at night. In summer mode the space heating is off.

For DHW the occupants use the solar programme which provides DHW at a minimum of 55°C, allowing solar top up to 70°C. Maximum benefit from solar occurs if DHW draw off occurs during times of high insolation.

There is no room thermostat for the Rotex, the heat provision is based on return flow temperature and was commissioned at installation, thermostatic radiator valves (TRVs) on the radiators can be adjusted by the occupants as necessary.

The MVHR unit has a main control in the kitchen and a room thermostat in the hallway. The hallway thermostat can be adjusted by the occupants and will call for heat if the MVHR system is in winter mode. In summer mode the heat exchanger is bypassed. If the occupants want to boost the ventilation when cooking they can use the control in the kitchen to choose setting 2 or 3; normal setting is 1.

The shower waste water unit has no controls and occupants can open all windows as required.

Design issues

The design issues considered for this project are grouped into three sub- sections; building fabric, infiltration, and systems.

Building fabric

The difficulties of retrofitting insulation are extensive. In this case certain constraints dictated the approach, and required very careful detailing to avoid thermal bridges and potential problems with interstitial condensation.

In this mid terrace house with internal front façade insulation, there was a danger of a thermal bridge along the party walls. The insulation was then brought back along the party wall sufficiently far so that surface temperatures would remain above 17°C.

Similar detailing was required at points where the rear extension joined the main house both at roof level and at floor level, and also at the base of the rear wall.

If impermeable internal insulation were to be installed, the junction between the existing wall and the new insulation could be cold enough to be at high risk of interstitial condensation, periods of driving rain can force water vapour deep into the wall from the outside where it could lead to mould growth. By using a breathable wall construction, moisture can move both from inside to out and from outside inwards without reaching a barrier where condensation could form. Impermeable external insulation is less at risk as the junction temperature between wall and insulation will be much higher than for internally insulated walls.

Lime plaster was used on all breathable construction walls and is permeable to water vapour. This also can act as a buffer stabilising relative humidity in a room by absorbing moisture at times of high humidity and releasing this later.

Initial designs planned to keep the floor void and install insulation under the floorboards, however the contractors were happier with a solid floor using EPS. This solution was also cheaper and has less risk of the insulation failing, due to a leaking washing machine for example.

In retrofit terrace houses such as this one, the existing chimney flues are not required and can be a major source of air infiltration. Ideally, they would be removed however this is expensive, and can reduce the structural integrity of the house, so are generally only removed if absolutely necessary. In this case the flues were filled with expanded clay balls, which act as insulation and buffer humidity levels.

Infiltration

The careful detailing of the insulation included the installation of an air tight layer. This is compromised at many points and these penetrations need to be carefully handled and ideally tested after completing each one. All services into and out of the house go through the air tight layer and need to be taped and use gaskets where possible. All joists that go through the air tight layer also need taping.

In this house the 'stringer' that fixes to the wall and that the staircase is fixed to, provided a leakage path for outside air into the house and in this case was too expensive to solve. It also appeared that there was a source of air leakage in the utility cupboard that was too difficult to reach after installation. In this refurbishment as the project was finishing, it was obvious that to reach Passivhaus standards of infiltration was too expensive.

The internal air distribution ducts for the MVHR system were mainly inside the air tight layer; except for the extract and supply from outside and a riser to the roof space with first floor ducts above the ceiling but below the insulation layer.

Systems

If Passivhaus specifications were achieved, then the house could have been heated using the heater battery of the MVHR system. However, it was likely that a back-up heater would be required. The UK is very used to gas fired, wet central heating systems and these are relatively cheap. The choice of the Rotex gas-solar unit meant that, solar thermal panels and a hot water cylinder were included with the gas boiler. The engineer liked this system and it has benefits of reduced heat loss from the cylinder, seamless integration with the solar thermal panels, unified controls for DHW and space heating and also there was the possibility of using hot water for the MVHR heater battery (in the event this proved too difficult to develop and was omitted).

One issue that could have been considered in more detail, was the positioning of radiators. The low heat loss of the building fabric, meant that pipe run length could be minimised and radiators didn't need to be placed by windows.

An important consideration for the systems were the volume that they required. The installers made mock-ups out of cardboard to check how the systems would fit into the small space available and to work out the sequencing for installation. After this process, the silencers for the MVHR had to be shortened slightly to enable installation. The main ducts were insulated after installation, this made it difficult to insulate them optimally.

Performance

Monitoring of the house over the two years post completion has shown a significant reduction in energy use and CO_2 emissions compared with the pre-refurbishment estimated values. Table 2C.2 shows these in more detail.

Temperatures in the house are very stable throughout the year and humidity is kept within acceptable limits of 40–60%RH almost all of the time. Air quality is very good with CO_2 levels not high and occupants noting that their house is the only one they know that doesn't smell of "central heating" in the winter. (This smell is often burnt dust occurring with radiator temperatures as high as 80ºC). Interviews with the tenants have confirmed that they are happy with their comfort levels in the house.

The MVHR can provide a small amount of heat using an integral electric heater which is installed after the heat exchanger, this is a high CO_2 option as grid electricity has a high carbon content, 0.54kg CO_2/kWh (Carbon Trust, 2012) and is estimated to be unable keep the house comfortable if the external temperature is below about 0°C. The occupants were asked not to use this heater but to use the gas central heating which has much lower CO_2 emissions at around 0.19kg CO_2/kWh.

The detailed performance of the Rotex gas-solar unit is determined by solar availability and occupant behaviour. If occupants use DHW early in the day and late at night, then gas is used to recharge the energy stored in the cylinder rather than solar energy.

Maintenance information suggests regular replacement of both the coarse filters and of pollen filters (Maico Manual, 2010). There are two sets of filters that need maintenance, one needs washing approximately every 3 months (coarse filter class G4), the other (pollen filter class F7) needs vacuum cleaning approximately every 6 months, and both should be replaced annually. In addition, the heat exchanger itself should also be carefully cleaned once a year using soapy water.

The shower waste water heat recovery system was performing well, saving around 600kWh/yr. The unit is estimated by the manufacturer to save >1000kWhrs/yr. Overall the product is quoted as being 61% efficient at 7.5l/s.

Overall water consumption was similar to expected, but the proportion of this that was hot water was higher than expected. Passivhaus predicts an average usage of 25 l/p/day, compared to an estimated actual consumption of around 90 l/p/day.

No problems with the building fabric itself have been found. All the walls and surfaces are warm, an infra-red survey (not reported here) found no internal surface lower than 17°C on a cold morning.

Table 2C.2 Overall household energy consumption (per m^2) for 10 Hawthorn Road for 2011–2012.

		Existing ($kWh/m^2/yr$)	*Proposed ($kWh/m^2/yr$)*	*Actuals ($kWh/m^2/yr$)*
Gas	Heating	617	26	52
Gas	Hot water	23	11	41
Electric	Total	27	18	49
OVERALL	Total	668 (100%)	55 (14%)	142 (27%)

The initial finish of the lime plaster was a little rough in places and required remedial work to smooth to an acceptable finish.

A leaking gutter was found to be raising moisture levels inside the front façade. This is a common problem in housing and one that can cause considerable damage. In heavy rain, water can run down the face of the brickwork. The internally insulated wall is colder than that for uninsulated homes and will dry out slower. This is likely to damage the brickwork over time especially if a hard frost occurs before the brickwork can dry.

The initial PHPP results forecast a low energy consumption for the house; in retrospect, the assumptions used; in particular those for, air tightness, living room temperature, and DHW were too optimistic.

Passivhaus design assumes occupants will gain some energy from solar radiation during the year to offset losses. In practice this gain can be affected by the use of blinds or net curtains and also by overshadowing which is not thoroughly considered in the PHPP file.

In hot weather there is likely to be a problem with overheating, the occupants need to adapt, by reducing solar gains and by using night ventilation, on warm nights the house will be hard to keep cool by passive means.

This is a complicated building in terms of the systems present and the occupants are not confident to read the manuals and work out how to adjust the systems on their own. Even with the manuals it is a complex system to adjust.

The occupants often dry clothes in or near the utility cupboard in the downstairs WC as this is the warmest room of the house. A drying area for clothes would have been a good idea.

Summary

The main conclusion that can be drawn from the retrofit is that it has massively improved both the fabric of the dwelling, reducing the average U-value from around 1 to around 0.15W/m.K, and it's air tightness from an estimate 15 down to 2.1ach@50Pa.

The house is now easy to keep warm even in cold weather, however optimal use of energy is less easy to achieve and optimal carbon emissions even less so.

The householders need to understand the operation of several complex pieces of equipment. Some of these have controls that are not obvious and ideally would need frequent adjustment to ensure optimal performance.

This house is kept warm all of the time, to the taste of the householders, and has a very stable temperature, day or night, winter or summer. With the price of gas being much cheaper than electricity there is less cost pressure on them to turn the temperature down. The household prefer the house to be warmer than we predicted, this is quite a common finding and is reported by Hong et al. (2009).

More hot water is used than expected, and at a higher temperature, this again is the choice of the householder; the water temperature restrictor wasn't liked and was removed, (apparently this is a common request for plumbers). To reduce energy consumption due to hot water, the householders will have to choose to use less hot water.

Keeping infiltration below 3@50Pa should be sufficient to ensure the MVHR has a positive benefit on energy consumption (Lstiburek, 2011), however lower infiltration rates will result in lower space heating consumption.

Electricity consumption was much higher than expected also, despite having AAA rated major appliances (washing machine, fridge freezer, dishwasher, tumble dryer) the householders used much more electricity than forecast. The reasons for this are affected by householders having more appliances than expected, having more electric chargers and having all of these operating more than expected.

With limited budgets, it is often not possible to achieve Passivhaus standards with retrofits; a compromise is therefore essential. Complex systems can require complex commissioning procedures and more detailed monitoring to ensure correct operation. Even with this closely monitored case study, it took several months to understand and find some key commissioning errors. Regular servicing of the various systems in the house is necessary. This should include checking the settings with the occupants and ensuring they are at their optimum, and that the different systems are set to work together with each other rather than in opposition. Occasional maintenance is also required and the responsibility for arranging servicing and carrying out maintenance needs to be made clear at handover.

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PART 3

Buildings and environment

Introduction

Dejan Mumovic and Mat Santamouris

Humans in developed parts of the world spend 85–95% of their time indoors (at home, work, school or when commuting). Chapter 3.1 describes how indoor environment quality can affect humans, without discussing the energy consequences for creating high-quality indoor environments (energy-related issues are explained in Part 2 of this book). Emphasis is placed on the thermal environment and air quality, and their effects on health, comfort and performance. Chapter 3.2 provides a review of methods to assess thermal comfort, followed by a discussion on the psychosocial aspects of thermal comfort which are often overlooked, ending with an overview of the health impacts of thermal conditions, followed by conclusions.

This is followed by a detailed discussion of state of the art indoor air quality and ventilation monitoring (Chapter 3.3) and modelling tools (Chapter 3.4) that are available to building design and academic communities. More attention is paid to moisture, which is responsible for 70 to 80% of all damage in buildings. Thus, correct moisture control is a prerequisite for achieving sustainable buildings. Chapter 3.5 explains that adequate control is only possible if we know how moisture is transferred to and moves in building assemblies, and how assemblies degrade when staying moist over prolonged periods of time.

Chapter 3.6 gives an overview of natural ventilation in non-domestic buildings and describes more advanced natural ventilation strategies and technologies available to optimise the performance of naturally ventilated systems. Special attention is paid to urban areas as lower wind speeds, the existence of heat islands, and the potentially high ambient noise and air pollution levels represent a serious challenge to designers of naturally ventilated buildings. As natural ventilation is based on pressure differences created by temperature differences and wind, in some conditions it will not be possible to maintain the adequate temperature and/or to provide ventilation at the rates predicted at design stage. Therefore, it is crucially important to familiarise ourselves with the state of the art mechanical and mixed-mode ventilation systems for city centre buildings. Due to supply and exhaust air fans, these ventilation systems are more flexible with respect to building design, and often more energy efficient than other systems if heat recovery means are used. These issues are covered in Chapter 3.7.

While Chapter 1.1 in Part 1 focuses on the impact of urban climate on energy use, health and comfort, Chapter 3.8 here discusses the potential impacts of climate change (temperature, precipitation, wind and subsidence) on buildings and offers options for changing building design to make buildings more resilient to future climates. Both chapters are based around two large EPSRC projects which have begun to investigate these issues, with a particular focus on the UK – 'LUCID' (The Development of a Local Urban Climate Model and its Application to the Intelligent Design of Cities) and 'SCORCHIO' (Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes). To highlight possible building services solutions for changing climate, Chapter 3.9 provides an overview of sustainable cooling strategies for urban buildings.

Last but not least, at the end of Part 3 of the book we have included three case studies:

- Case Study 3A: Ventilation and indoor air quality in naturally, mechanically and hybrid ventilated buildings in the urban environment. This case study focuses on the experimental investigation of the impact of the urban environment on the effectiveness of natural and hybrid ventilation, since the efficient design of these ventilation systems is the determinant for thermal comfort, indoor air quality and energy savings.
- Case Study 3B: Indoor air quality and health – The psychrometric control of house dust mites and its impact on childhood asthma. This case study describes a number of measures for allergen (pet and mite) removal and avoidance, including tailored advice aimed at reducing mite population growth via changes in moisture production, heating and ventilation habits.
- Case Study 3C: Ventilation and air quality modelling. This case study provides a general guide to the use of CFD for assessing thermal comfort and air quality in and around buildings. Within this framework, relevant experimental and theoretical problems are also briefly discussed. The case studies include: (a) urban air quality modelling for regulatory purposes in Glasgow (Scotland); (b) assessment of the impact of a new building on air flow and pollution distribution in a district of Copenhagen (Denmark); and (c) assessment of indoor air quality and thermal comfort in a typical medium-sized mechanically ventilated theatre.

3.1
VENTILATION, THERMAL COMFORT, HEALTH AND PRODUCTIVITY

Pawel Wargocki

Introduction

Indoor environmental quality (IEQ) plays an important role for human health, comfort and performance. One of the main reasons is that humans in developed parts of the world spend 85–95% of their time indoors (at home, at work, at school or when commuting). Indoor environmental issues received much attention in the mid nineteenth century and a renaissance of indoor environmental sciences was observed after the energy crisis in the 1970s when the tightening of buildings, use of new building materials and dramatic reductions of energy use resulted in numerous complaints from occupants of indoor spaces. A similar situation is likely to occur in the 2000s when the issue of climate change is being reflected in the trend to again reduce energy used to create indoor environments as it constitutes 30–40% of the total energy use in buildings. To overcome this threat, emphasis is placed on maintaining IEQ as high as possible when energy reductions have been implemented (EPBD, 2002). This chapter will describe how IEQ can affect humans, without discussing the energy consequences for creating high quality of the indoor environments. Emphasis will be placed on the thermal environment and air quality and their effects on health, comfort and performance. Although light and noise are also important constituents of IEQ, they will not be discussed here. Health is understood very broadly, reflecting the basic definition of the World Health Organization (WHO, 1948) which states that health is a state of complete physical, mental and social well-being and not merely absence of disease or infirmity. Comfort expresses satisfaction with the environment. Performance is related to the ability of an individual to perform different mentally and physically demanding tasks. Often the term productivity is used instead of performance; however, it is a wider economic term including a volume measure of output (e.g. performance of several individuals) in relation to input (e.g. the costs relating to the work of these individuals). Health, comfort and performance (productivity) can be influenced by physiological, behavioural and psychological factors, while performance (productivity) can be influenced also by personal, social and organizational variables. The impact of these factors is not discussed in the present chapter which deals solely with the effects of IEQ.

Thermal environment

Thermal comfort

The most important variables that affect thermal comfort are air temperature, mean radiant temperature, relative air velocity, water vapour pressure in ambient air, activity level (heat production in the body) and the thermal resistance of the clothing (clo-value). These six variables are included in the comfort model developed by Fanger (1970) based on extensive American and European experiments involving over a thousand subjects exposed to well controlled environments. The premise of the comfort model is that the body must be in thermal balance so that the rate of heat loss to the environment is equal to the rate of heat production in the body, that the mean skin temperature should be at the appropriate level of comfort, and that there is a preferred rate of sweating related to metabolic rate. Based on the model and its assumptions, two thermal comfort indices were created to describe the effects of the thermal environment on humans, the predicted mean vote (PMV) which predicts the mean vote of a large group of persons on the seven-point scale (Figure 3.1.1), and the predicted percentage of dissatisfied (PPD) providing the percentage of persons dissatisfied with the thermal environment. The relation between PMV and PPD is illustrated in Figure 3.1.2 and forms the basis of many international standards (e.g. ISO 7730, 1994).

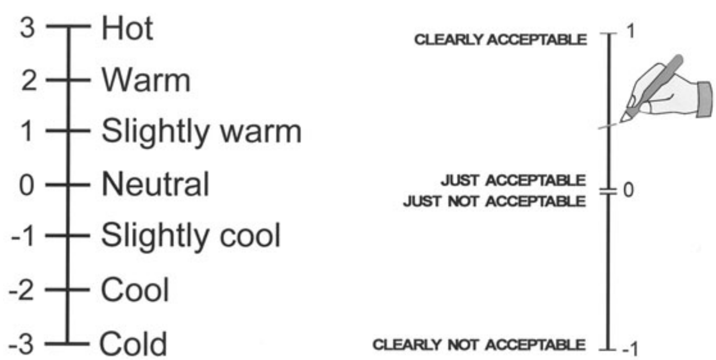

Figure 3.1.1 The seven-point scale for thermal comfort (Fanger, 1970) and the continuous acceptability scale (Gunnarsen and Fanger, 1992; Clausen, 2000).

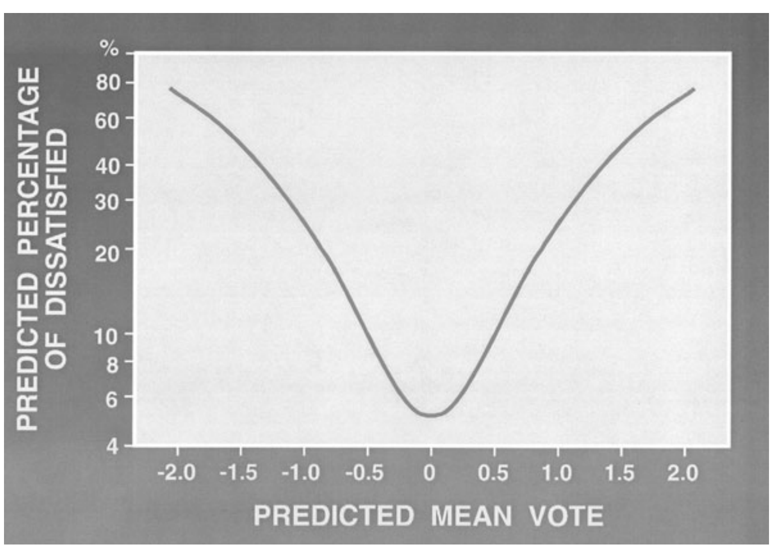

Figure 3.1.2 Predicted percentage of dissatisfied (PPD) as a function of the predicted mean vote (PMV).

Source: FANGER, 1970

The PMV model predicts well the thermal response when the person is not experiencing unwanted heating or cooling of a particular part of the body. This issue should be considered separately and therefore parameters describing local thermal discomfort have been introduced. They include draught risk, asymmetric thermal radiation, vertical air temperature difference and contact with warm or cold floors. Draught is an unwanted local cooling of the body caused by air movement. Dissatisfaction due to draught is caused by air velocity and turbulence intensity; thus, cooling is caused not only by the air velocity but also by fluctuation in the air stream. For people in thermal neutrality the draught risk model was developed predicting the percentage of persons dissatisfied due to draught (Fanger, Melikov, Hanzawa and Ring, 1988). An example of the practical application of the model is shown in Figure 3.1.3, indicating the combination of air temperature, turbulence intensity and air velocity that will cause 20% of persons to be dissatisfied with draught. The model is used in international standards (e.g. ISO 7730, 1994).

Asymmetric thermal radiation can be caused by cold/hot surfaces such as windows, exterior walls, ceilings, etc. It is defined as the difference between the plane radiant temperatures of the two opposite sides of a small plane elements. Based on the work reported by Olesen (1985), the limits for radiant asymmetry were established. Environments are expected to cause less than 5% dissatisfied due to asymmetric radiation if the difference between the plane radiant temperature is below 10K for vertical surfaces and below 5K for heated ceilings (ISO 7730, 1994). Stratification of indoor air can result in the vertical temperature gradients that can contribute to local thermal discomfort. The work by Olesen et al. (1979) indicates that the percentage dissatisfied with the vertical temperature difference will be below 5% if the temperature difference between ankles (0.1m above the floor) and the head (1.1m above the floor for a seated person) will be below 3K. Floor temperature can also result in local thermal discomfort, especially

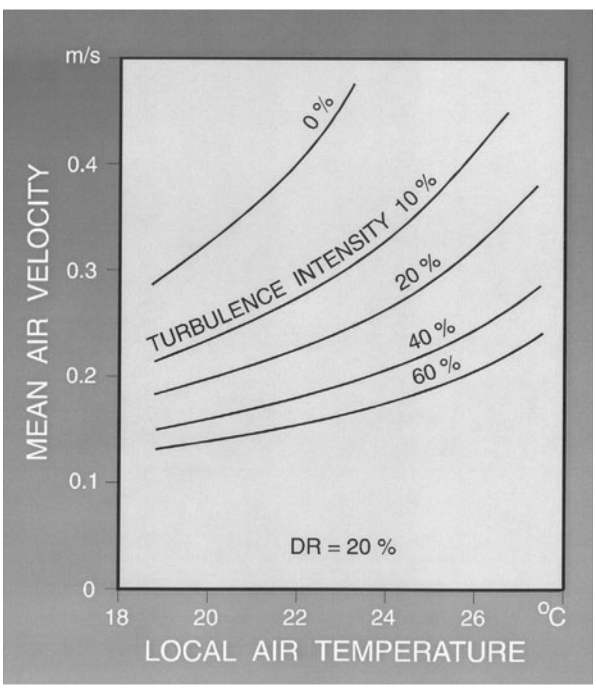

Figure 3.1.3 The combination of air temperature, turbulence intensity and air velocity causing 20% to be dissatisfied with draught.

Source: ISO 7730, 1994

in winter, causing cold feet. The general requirement is that floor temperatures should be between 19°C and 26°C for light mainly sedentary activity in winter and a floor heating system design temperature of 29°C.

While the PMV model predicts thermal sensation well in buildings with heating, ventilation and air-conditioning (HVAC) systems, field studies in warm climates in buildings without air-conditioning have shown that it predicts a warmer thermal sensation than the occupants actually feel (Brager and de Dear, 1998). The reason for this discrepancy could be that thermal perception is affected not only by heat balance of the body but also by other factors such as behavioural adjustments, physiological and psychological adaptation. Since the PMV model was developed on the basis of studies in climate chambers, these influences could have been overlooked. The impact of these other factors on thermal response form the premise of the adaptive model of thermal comfort, which relates the neutral temperature indoors (temperature at which people are thermally neutral according to the seven-point scale in Figure 3.1.1) to the monthly average temperature outdoors (de Dear and Brager, 2001). Figure 3.1.4 shows the application of the model suggested by EN15251 (2006). The basic assumption of this model is that building occupants are not passive recipients of the thermal environment but play an active role in creating their thermal environment by behavioural adjustments, such as adjusting clothing, opening windows or rescheduling activities. Furthermore, their thermal responses are modified by acclimatization, habituation and expectation. Fanger and Toftum (2002) proposed an extension to the PMV model including an expectancy factor (e) which should be multiplied by the PMV. The expectancy factor depends on whether the

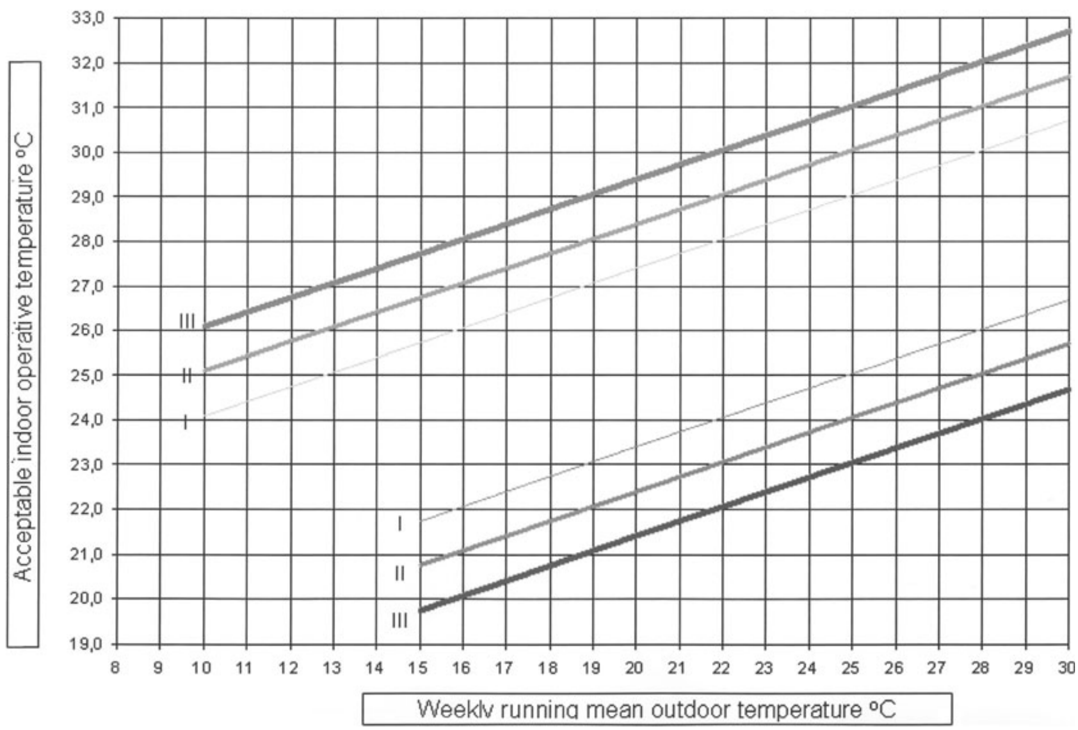

Figure 3.1.4 Indoor operative temperature as a function of the outdoor temperature. Upper and lower limits of the operative temperature are shown for design different categories resulting in PPD < 6% (Category I), PPD < 10 (Category II) and PPD < 15% (Category III).

Source: Adapted from EN15251, 2006

non-air-conditioned building is located in regions where air-conditioning is common (e = 0.9–1.0) or where there are few air-conditioned buildings (e = 0.5–0.7). With this adjustment, the PMV seems to provide a reasonable estimation of thermal comfort in non-air-conditioned buildings.

The existing thermal comfort models refer to steady-state conditions. There have been numerous efforts to describe transient effects of thermal sensation and comfort (e.g. de Dear, Knudsen and Fanger, 1989; de Dear, Ring and Fanger, 1993; Goto, Toftum, Fanger and Yoshino, 2003; Goto, Toftum, de Dear and Fanger, 2006) but there is a need for further data on this issue. For example, Goto et al. (2003) investigated transient effects on the human thermal response of clothing adjustments, the most common behavioural thermoregulatory action. They showed that, independently of the activity level, the thermal sensation votes respond immediately (within 5 minutes) after up-step or down-step of the adjustments of clothing insulation. The effect of metabolic step-changes on thermal sensation was investigated by Goto et al. (2006). They suggested weighting factors to estimate a representative average metabolic rate with varying activity levels, using steady-state comfort models: 65% to weight the activity during the most recent 5 min, 25% during the prior 10–5 min and 10% during the prior 20–10 min.

Thermal conditions affect also the perception of air quality, as discussed later in this chapter.

Thermal environment and health

Thermal conditions affect health. This is best illustrated by the rates of mortality in nursing homes (Marmor, 1978) and ordinary households (Rogot, Sorlie and Backlund, 1992) during hot weather. When thermal conditions are less extreme, elevated temperatures have been associated with increased prevalence of symptoms typical of Sick Building Syndrome (SBS), non-specific building-related symptoms of headache, chest tightness, difficulty in breathing, fatigue, irritation of eyes and mucous membranes which are alleviated when the individual leaves the building (WHO, 1983). The survey by Burge et al. (1990) in six office buildings showed that the occupants in buildings with lower dry bulb air temperature experienced fewer SBS symptoms. An intervention study by Burt (1996) showed that reducing the temperature from 22 to 20.4°C reduced SBS symptoms. High air temperatures were found to be a risk factor for work-related general symptoms (headaches, difficulty in concentration) in 14 office buildings studied by Skov et al. (1990). In an intervention study by Krogstad et al. (1991) virtually all SBS symptoms increased with temperature from a minimum of 20–21°C up to 24°C among office workers performing computerized work; the prevalence of headaches and fatigue increased from 10% to 60% and effects of similar magnitude were observed for other symptoms. These field data are supported by experiments in chambers. Fang et al. (2004) observed that the intensity of headaches and difficulty in thinking clearly increased when thermal conditions were increased from 20°C/40%RH to 26°C/60%RH. Similarly, Willem (2006) observed that a temperature of 26°C tended to elevate neurobehavioural symptoms among subjects in tropical regions compared to 20°C. These studies indicate that it is beneficial to keep the temperatures in buildings at the lower level of thermal comfort.

Thermal environment and performance

Thermal conditions can affect the performance of work by several mechanisms (Wyon and Wargocki, 2006a): (i) thermal discomfort distracts attention and generates complaints that increase maintenance costs; (ii) warmth lowers arousal (the state of activation of an individual) (Willem, 2006), exacerbates SBS symptoms and has a negative effect on mental work; (iii) cold conditions lower finger temperatures and thus have a negative effect on manual dexterity; (iv) rapid temperature swings have the same effects on office work as slightly raised room temperatures, while slow temperature swings merely cause discomfort; and (v) vertical thermal gradients reduce perceived air quality or lead to a reduction in room temperature that then causes complaints of cold at floor level.

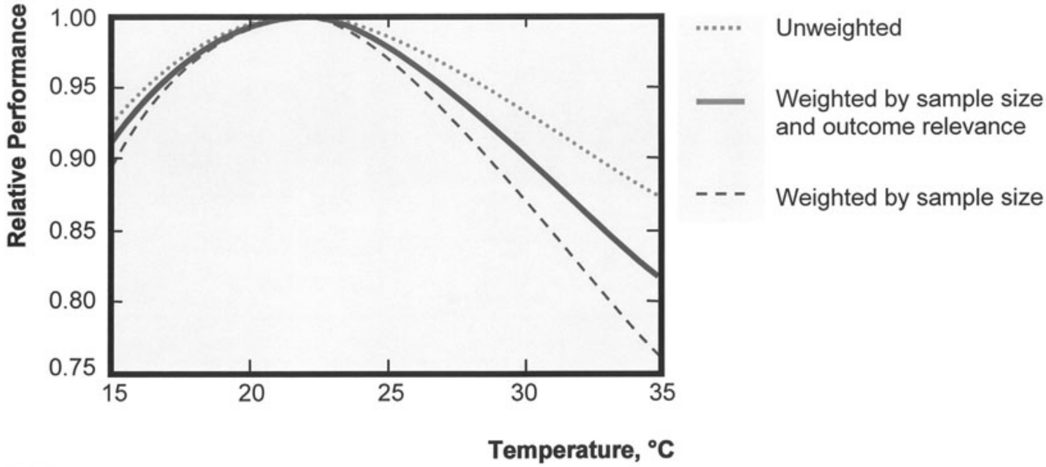

Figure 3.1.5 Relative performance as a function of temperature.

Source: Seppänen et al., 2006a; figure adapted from REHVA Guidebook 6 (2006)

The evidence obtained so far shows that thermal conditions within the thermal comfort zone can reduce performance by 5% to 15% (Wyon, 1996). Based on the results from 24 studies investigating the effects of temperature on performance of office work, Seppänen et al. (2006a) created the relationship between temperature and work performance (Figure 1.5), suggesting a reduction of performance by about 1% for every 1°C change.

The data points presented in Figure 3.1.5 were obtained mainly in laboratory experiments with human subjects; however, three studies in buildings with normal office employees provide quantitative estimates similar to the magnitude of effects observed in the laboratory. Niemelä et al. (2002) showed that the operator performance was better (average talk-time was 5–7% lower) when temperatures remained below 25°C in a telecommunication call-centre. Federspiel et al. (2002) showed that qualified nurses providing medical advice in a call-centre worked 16% more slowly when writing up their reports after the call was over when temperatures were above 25.4°C. Tham et al. (2003) showed that the average talk-time of the call-centre operators in the tropics was reduced by 4.9% (performance improved) when the air temperature was decreased by 2°C from 24.5°C. Moderately elevated temperatures affect also the performance of schoolwork by 10–12-year-old children. Reducing the temperature by 1°C in the range from 24–25°C to 20°C would improve the performance of language-based and numerical tasks typical of schoolwork by 2–4% (Wargocki and Wyon, 2006). It should be noted that the data presented in Figure 3.1.5 do not include the results from studies in which people were asked to judge themselves whether the thermal conditions affect their work (so-called self-estimated performance). The studies of Preller et al. (1990) and Raw et al. (1990) in office buildings indicate that self-estimated performance is higher when individuals can control their own thermal climate.

An attempt to relate thermal discomfort to performance was made by Roelofsen (2001) who correlated Fanger's PMV model (Fanger, 1970) with Gagge's two-layer model (Gagge, Fobelets and Berglund, 1986). No verification of the model has been obtained so far but studies in which subjects were clothed for comfort under different thermal conditions indicate no effect on performance (Wyon, Fanger, Olesen and Pedersen, 1975; Fang et al., 2004).

Indoor air quality

Quality of indoor air can be defined as the level of the contaminants/pollutants in indoor air. These pollutants comprise organic species such as volatile organic compounds, inorganic species such as particles, fibres, allergens, radioactive gases such as radon, or species of microbiological origin such as moulds or fungi. The contaminants can originate from outdoor sources, e.g. urban traffic, combustion, or from indoor sources, e.g. people, their activities, tobacco smoke, building and furnishing materials, as well as electronic equipment, cleaning products or HVAC systems. The criteria for acceptable levels of these pollutants can be set based on the effects on health and performance as well as sensory effects on humans. To mitigate the air quality problems, the following methods are usually applied: filtration, air cleaning, avoidance/reduction of sources of pollution or ventilation. Often indoor air quality is closely associated with ventilation, considering that ventilation is the process of exchanging indoor (polluted) air with outdoor (presumably fresh and clean) air. Thus, ventilation is considered as a surrogate or proxy of the indoor air quality, and many studies have expressed the effects of indoor air quality on health, comfort and performance in relation to ventilation. The use of proxies for indoor air quality is necessitated by the fact that indoor climates are multifactorial environments and often it is not known which of the pollutants indoors are responsible for the effects observed.

Perceived air quality

The quality of the air indoors may be expressed as the extent to which human requirements are met. There are, however, quite large differences between the requirements of individuals. Some people are rather sensitive to an environmental parameter and are difficult to satisfy, whereas others are less sensitive and are easier to satisfy. To cope with these individual differences, the environmental quality can be expressed by the percentage of persons who find an environmental parameter unacceptable (= % dissatisfied). If there are few dissatisfied, the quality of the environment is high. If there are many dissatisfied, the quality is low. Prediction of the percentage dissatisfied is used to establish ventilation requirements for reaching a certain level of air quality. This approach is illustrated in Figure 3.1.6 showing the relationship between ventilation rate per standard person and the percentage dissatisfied with air quality. Three different categories of indoor air quality are presented causing 15%, 20% and 30% dissatisfied (CEN, 1998). The relationship presented in Figure 3.1.6 is used by many ventilation standards and is based on the experiments in which human subjects assessed the air quality immediately upon entering the rooms polluted mainly by the emissions from humans (bioeffluents) (Fanger and Berg-Munch, 1983; Berg-Munch, Clausen and Fanger, 1986). These studies were carried out in Europe but similar experiments in Japan (Iwashita, Kimura, Tanabe, Yoshizawa and Ikeda, 1990) and in the USA (Cain et al., 1983) showed very similar results.

The percentage of persons dissatisfied with air quality cannot yet be measured directly with an instrument although there are attempts to create such instruments (Wenger, Miller and Quistgaard, 1993; Müller, Müller, Knudsen, Wargocki, Berglund and Ramalho, 2007). Panels of subjects judging the air quality are the only feasible way at present. The subjects render a judgment of indoor air quality immediately upon exposure (within 15s, unadapted vote) independently of other observers. Usually an untrained panel of at least 20 impartial subjects is used. The subjects judge whether the air quality is acceptable or not (ASHRAE Standard 62 (2007)) usually using a continuous acceptability scale (Gunnarsen and Fanger, 1992; Clausen, 2000), Figure 3.1.1; based on the assessments the percentage dissatisfied with the air quality is estimated. A panel of 10–15 trained judges is sometimes used (Bluyssen, Kondo, Pejtersen, Gunnarsen, Clausen and Fanger, 1989) judging the degree of annoyance with the air quality due to perceived odour and irritation, compared to well-defined reference exposures of 2-propanone.

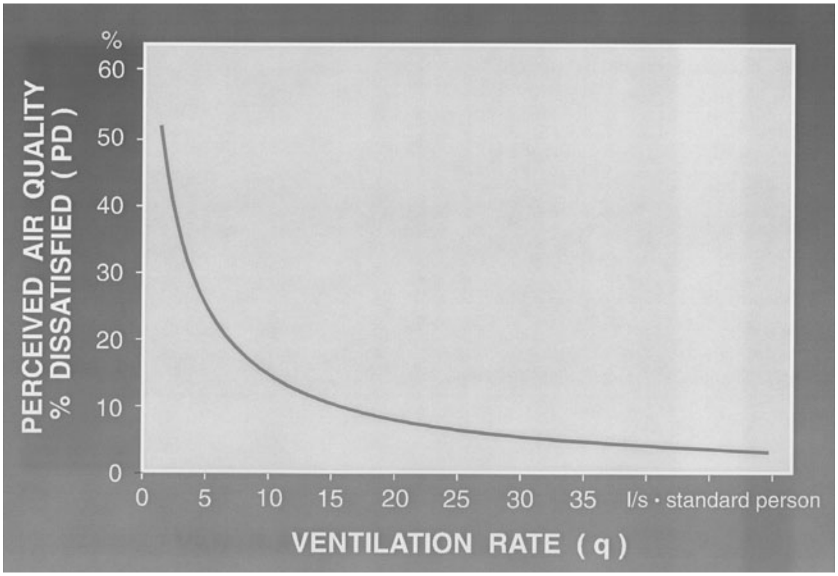

Figure 3.1.6 Percentage dissatisfied with air quality as a function of ventilation rate per standard person.
Source: FANGER, 1988

The assessment of indoor air quality is influenced by stimulation of the olfactory sense (sensitive to >1/2 mil. odorants) and the general chemical sense (sensitive to >100 thousand irritants). Studies by Berglund and Cain (1989), Fang et al. (1998a,b) and Toftum et al. (1998) show that the perception of air quality is also influenced by the humidity and temperature of the inhaled air even when the chemical composition of the air is constant, and the thermal sensation for the entire body is kept neutral. Keeping the air dry and cool reduces the percentage dissatisfied with the air quality (Figure 3.1.7) and causes the air to be perceived as fresh and pleasant. This effect is probably due to stimulation of the thermal sense as a result of convective and evaporative cooling of the respiratory tract if only the temperature is different from the mucosal temperature which is ~30–32°C.

It should be noted that some harmful pollutants are not sensed by humans at all, e.g. radon or carbon monoxide which have negative effects on health. This means that any health risk should be considered separately from the sensory effects. Although some harmful pollutants cannot be sensed, the sensory effects may in many cases also provide a first indication of a possible health risk since human senses have an important warning function against danger in the environment.

Indoor air quality and health

Health effects of indoor air quality include allergies, irritation of mucous membranes, SBS symptoms, toxic reactions, infections, inflammation, cancer and mutagenic effects. In the case of industrial environments, these hazardous effects are handled by defining maximum acceptable concentrations, or threshold limit values (TLV) for individual substances. In the case of non-industrial environments, the situation is more complicated as the pollutants are at concentrations much lower than TLV levels and the effects can be caused by interactions and mixtures of pollutants. One of the most comprehensive discussions on the effects of the indoor environment on health was proposed by NORDWORKS (EUROWORKS) (Sundell and Bornehag, 1999). They created an interdisciplinary consensus on the state-of-the-art of air quality effects

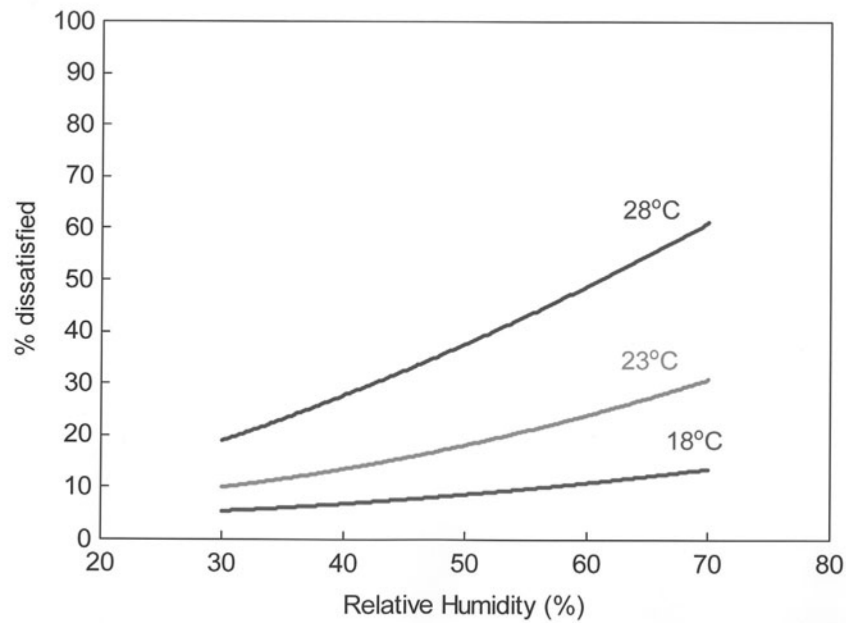

Figure 3.1.7 Percentage of dissatisfied with air quality as a function of temperature and relative humidity of inhaled air.

Source: Fang et al., 1998b

on health by reviewing the scientific peer-reviewed literature within specific areas. The review was carried out by an invited multidisciplinary team of scientists, experts in different disciplines related to indoor air research. The reviews showed in general no association between total concentration of volatile organic compounds, microbially produced matter and particulate matter indoors and health effects (Anderson et al., 1997; Bornehag et al., 2001; Schneider et al., 2003). The lack of the effects of particulate matter is worth noting as it was observed in spite of the reliable epidemiological evidence showing that the particles found in outdoor air do have negative health effects for both adults and children (e.g. Ward and Ayres, 2004; Dominici et al., 2006). Nevertheless, studies in schools tend to confirm the absence of effects of particles indoors (Mattsson and Hygge, 2005; Wargocki, Wyon, Jensen and Bornehag, 2008). The NORDWORKS (EUROWORKS) reviews showed a clear relation between working in a damp building, ventilation and health. Working in a damp building was associated with cough, wheeze, allergies and asthma, and there are indications that general SBS symptoms such as fatigue and headache and airway infections are also associated with dampness (Bornehag et al., 2001). The relative risk of experiencing health problems when staying in a damp building is 40% to 120% higher compared to a building with no dampness problems. In spite of this high risk, it is still unclear which pollutants/agents are responsible for the health effects observed in damp buildings. Ventilation was found to be strongly associated with health: SBS symptoms, inflammation, infections, asthma, allergy, short-term sick leave (Wargocki et al., 2002a). The scientific evidence indicates that outdoor air supply rates below 25 L/s per person increase the risk of SBS symptoms and increase short-term sick leave while ventilation rates below 0.5 h^{-1} in homes increase infestation of house dust mites in Nordic countries and thereby may increase the risk of allergies. These conclusions correspond with other literature reviews on the effects of ventilation on health, showing that the ventilation rates at or below 10 L/s per person can significantly aggravate SBS symptoms (Mendell, 1993; Godish and Spengler, 1996; Menzies and Bourbeau, 1997; Seppänen, Fisk and Mendell, 1999) and that there is an indication that increasing the ventilation rate from 10 to 20 L/s per person may further reduce SBS symptoms (Seppänen et al., 1999). A study on the relationship between indoor air quality and asthma supports the conclusions obtained in a review (Bornehag, Sundell and Weschler, 2004). By comparing air quality in 200 homes with asthmatic children and 200 homes with healthy children in Sweden it was found that lowering the ventilation rate (in a range from 0.62 h^{-1} to 0.17 h^{-1}) increased the risk of allergic symptoms; the risk was also increased by the presence of phthalates emitted from polyvinyl chloride, including plasticizers in children's rooms. Similar results were observed in a repetition of the study in Bulgaria (Kolarik, Naydenov, Larsson, Bornehag and Sundell, 2008).

When discussing the effects of ventilation on health it is worth mentioning that the literature indicates that occupants of many buildings with air-conditioning systems may be subject to an increased risk of SBS symptoms compared with occupants in naturally or mechanically ventilated buildings (Seppänen and Fisk, 2002; Wargocki et al., 2002a). Potential causes of adverse health effects due to HVAC systems comprise: poor maintenance, poor hygiene of the HVAC systems; intermittent operation of the HVAC systems; lack of moisture control; lack of control of HVAC system materials and used filters. Other causes may include recirculation, draught, noise and fibres but there is little information on these issues in the scientific peer-reviewed literature (Wargocki et al., 2002b).

Li et al. (2007) reviewed the literature on the role of ventilation in airborne transmission of infectious agents, similar to the work performed by NORDWORKS (EUROWORKS) described above, and concluded that there is strong and sufficient evidence that ventilation and air movement in buildings are associated with the spread and transmission of infectious diseases such as measles, tuberculosis, chickenpox, influenza, smallpox and the severe acute respiratory syndrome (SARS). These results emphasize the importance of indoor air quality and ventilation for health especially considering the risk of an avian influenza pandemic.

Indoor air quality and performance

The mechanisms by which indoor air quality affects performance are not well understood, but it seems reasonable to assume that people who do not feel very well and experience SBS symptoms such as headaches and difficulty to concentrate and think clearly when the air quality is poor will not work very well. Other possible mechanisms for an effect of poor air quality on performance include distraction by odour, sensory irritation, allergic reactions, or direct toxicological effects. Studies of adult subjects performing simulated office work (Bakó-Biró, Wargocki, Wyon and Fanger, 2005) provide further information on the effects of indoor air quality on performance. They showed that increased air pollution caused by gaseous emissions from typical building materials, furnishing and office equipment caused subjects to exhale less carbon dioxide (CO_2). This must either be a consequence of reduced metabolic rate due to reduced motivation to perform work in polluted air, or a consequence of physiological changes leading to inefficient gas exchange in the lungs when polluted air is breathed. The latter mechanism would lead to an increased CO_2 concentration in the blood, which is known to cause headaches.

There are fewer studies showing the effects of indoor air quality on performance than for the effects of thermal environment on performance (Wyon and Wargocki, 2006a,b). In the study by Wargocki et al. (1999) performance of text typing improved as typing speed improved by 6.5% and the error rate was reduced by 18% when the proportion dissatisfied with the air quality was reduced from 70% to 25% by removing a 20-year-old carpet. A repetition of this study with the same carpet showed that performance of text typing improved by 1.5% and the number of errors in addition reduced by 15% when the proportion dissatisfied with the air quality was reduced from 60% to 40% (Lagercrantz, Wistrand, Willén, Wargocki, Witterseh and Sundell, 2000). In the study by Bakó-Biró et al. (2004) performance of text processing improved by 9% when the proportion dissatisfied with the air quality was reduced from 40%

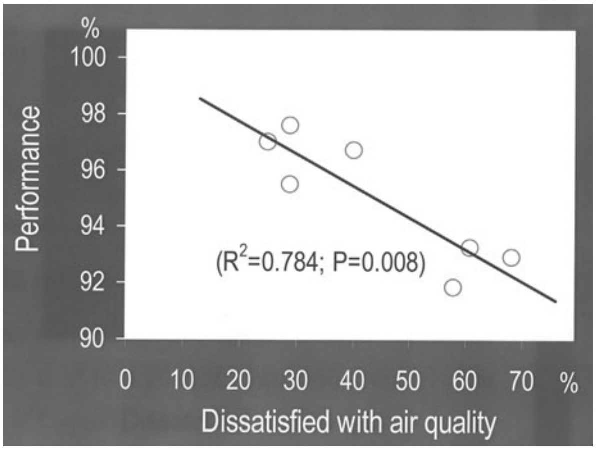

Figure 3.1.8 Performance of simulated office work as a function of the percentage dissatisfied with the air quality.

Source: Wargocki et al., 2000c

to 10% by removing personal computers. In the study by Wargocki et al. (2000a) performance of text-typing improved by about 1% for every two-fold increase in the outdoor air supply rate in the range between 3 and 30 L/s per person, causing the proportion dissatisfied with the air quality to be reduced from 60% to 30%. The laboratory experiments described above were summarized by Wargocki et al. (2000b,c) who showed that the performance of office tasks improves linearly following the reduced proportion dissatisfied with the air quality upon entering a space: a 10% reduction in the percentage dissatisfied with the air quality corresponds to about a 1% increase in the performance of office work (Figure 3.1.8).

No field measurements were carried out in which the performance of office work was quantified and at the same time the air quality was measured by quantifying the proportion dissatisfied. In one study performed in the field by Wargocki et al. (2004), replacing the used bag ventilation filter with a new one improved the performance of call-centre operators by 10% because the pollution load in a space was reduced, similar to the interventions made in the laboratory studies described above, and consequently the air quality was improved. But the percentage dissatisfied with the air quality was not measured.

There are few studies in which the ventilation rate was modified, and the performance of office work was measured. Considering that increasing the ventilation rate improves the perceived air quality (Seppanen et al., 1999; Wargocki et al., 2002a), it is reasonable to assume that the effects on performance due to altering the ventilation rate observed in field experiments are due to improved indoor air quality. Wargocki et al. (2004) showed that the performance of call centre operators improved by 6% when the outdoor air supply rate was increased from 2.5 to 25 L/s per person but only when new ventilation bag filters were installed; with used bag filters the increase of the ventilation rate reduced the performance by 8%. In a study by Federspiel et al. (2004) the performance of operators improved by 2% when the ventilation rate was increased from 8 to 94 L/s per person, but an increase to 20 and 53 L/s per person reduced the performance, probably because used bag filters were installed, similar to the observation by Wargocki et al. (2004). Tham et al. (2003) showed that the performance of call-centre operators improved by 9% when the ventilation rate was increased from 10 to 23 L/s per person in an office building with no bag filters (electrostatic filters were used instead). In a study by Milton et al. (2000) short-term sick leave was 35% lower in office buildings ventilated with an outdoor air supply rate at 24 L/s per person compared with buildings ventilated at 12 L/s per person.

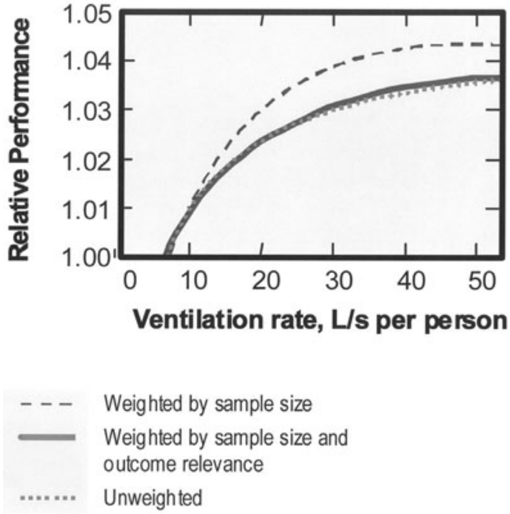

Figure 3.1.9 Performance as a function of ventilation rate relative to the performance at a ventilation rate of 6.5 L/s/person.

Source: Seppanen et al., 2006b; adapted from REHVA Guidebook 6 (2006)

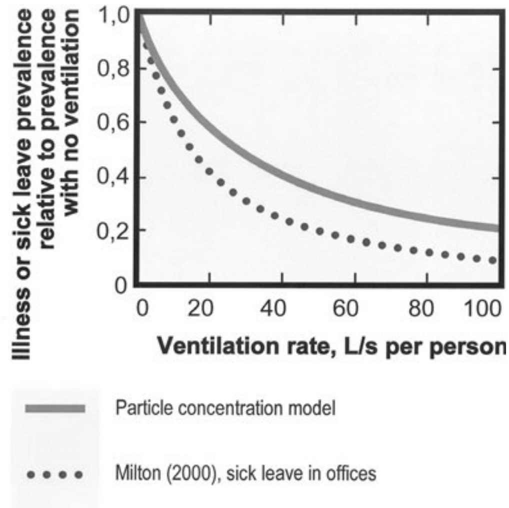

Figure 3.1.10 Predicted trends in illness or sick-leave as a function of ventilation rate.

Source: Fisk et al., 2003; adapted from REHVA Guidebook 6 (2006)

Based on the results of the studies investigating the effects of ventilation on performance of office work, Seppänen et al. (2006b) suggested the quantitative relationship of office work and ventilation rate (Figure 3.1.9) showing that work performance will on average increase by approximately 1.5% for each doubling of the outdoor air supply rate.

It should be noted that when developing the relationship presented in Figure 3.1.9 no data on the effects of ventilation on self-estimated performance were included. These data also suggest the benefits of increased ventilation on performance as for example in a study by Kaczmarczyk et al. (2004) providing a personalized ventilation system increasing the amount of unpolluted air supplied to the breathing zone of people. The relationship in Figure 3.1.9 is based on studies in which the performance of office work was measured. Studies in schools suggest that increasing the outdoor air supply rate in classrooms will also be beneficial for schoolwork by 10–12-year-old children, including language-based and numerical tasks - doubling the ventilation rate (in a range from 3 to 9.5 L/s per person) would improve the performance of school tasks by 8–14% (Wargocki and Wyon, 2006).

As ventilation seems to affect short-term absenteeism, Fisk et al. (2003) attempted to create the relationship between sick-leave and ventilation rate (Figure 3.1.10). This relationship was estimated on the basis of studies using sick-leave or short-term illness as outcomes. The analysis suggests a 10% reduction in illness or sick leave when doubling the outdoor air supply rate.

Economic implications

There are enormous potential benefits from improving the thermal environment and air quality in relation to the investments required, considering that worker salaries in offices typically exceed building energy and maintenance costs by a factor of approximately 100 and they exceed the annual amortized cost of construction or rental by almost as much (Woods, 1989). Even a 1% increase in performance (productivity) will justify the expenditure. The results presented in previous sections show that the effects of improved IEQ can be much higher than 1%. Crude estimates of benefits from improving indoor environments for the U.S. suggest that potential annual savings and productivity gains can be from $29 to $168 billion (Fisk and Rosenfeld, 1997). Implementation of all improvements to indoor air quality in the U.S. buildings that do not meet ASHRAE 62 and ASHRAE 55 Standards (ASHRAE, 2005, 2007) result in an annual benefit of $62.7 billion due to improved health and productivity and a simple payback time of 1.4 years for investments (Dorgan, Dorgan, Kanarek and Willman, 1998). Seppänen (1999) estimated that the value of improved productivity in Finnish offices resulting from a reduction in the prevalence of SBS symptoms is annually ca. €330 per worker. The reduction in absenteeism due to improved ventilation would produce net savings of $400 per employee per year (Milton et al., 2000).

In spite of the above benefits it must be emphasized that indoor environments should be improved, accepting the principles of sustainable design while decreasing energy. New and energy-efficient technologies are required for this purpose and their development may require an understanding of the mechanisms by which IEQ affects humans.

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3.2
THERMAL COMFORT AND OVERHEATING
Assessment, psychosocial aspects and health impacts

Marcella Ucci, Stephanie Gauthier and Anna Mavrogianni

Introduction

Environmental conditions can potentially have an impact on comfort, performance/productivity and health – as well as on resource use such as fossil fuels. Therefore, important issues underpinning environmental design and engineering are: (1) identifying the environmental parameters which affect these relationship(s); (2) establish, for each of these parameters, what levels should be maintained to ensure comfort, productivity and health; (3) how to balance trade-offs, if needed, between various conflicting criteria/requirements, for example health, comfort and energy use. This chapter addresses primarily the first two questions with a focus on thermal conditions (mainly in indoor environments within buildings) – except for the issue of productivity/performance, which is discussed elsewhere in the book. In particular, the next section provides a review of methods to assess thermal comfort, followed by a discussion on the psychosocial aspects of thermal comfort which are often overlooked, ending with an overview of the health impacts of thermal conditions, followed by conclusions.

Review of methods to assess thermal comfort

Thermal comfort assessment: Overview of study design

The research approach for assessing thermal comfort is twofold:

- Identifying the key parameters to be addressed.
- Determining methods to collect and assess each parameter.

The key parameters could either be environmental variables or occupant characteristics. Having identified those, this section will review typical and emerging data collection methods, focusing on the type of data gathered, their practicalities, and the approaches taken to the data analysis.

In order to establish how people feel thermally and how this is affected by various variables, surveys are commonly conducted. As environments are ever changing, these surveys should be systematic, and enable the monitoring of local conditions and behaviours. The current standard assessment methods are

Table 3.2.1 Key factors to be recorded in thermal comfort studies.

	Environmental parameters	*Occupants parameters*
Typical	Internal dry-bulb air temperature (*Ta*) Internal mean radiant temperature (*Tr*) Internal relative humidity (*RH*) Internal mean air velocity (*va*) External hygrothermal conditions Building location and type	Activity level (ISO 8996, level 1 and 2) (*M*) Thermal insulation level (observed or self-reported) (*Icl*) Thermal perception (self-reported, ISO 10551)
Additional	Internal vertical hygrothermal stratification Internal variation in air velocity and turbulence intensity Building layout Building fabric Building systems	Socio-demographic factors (incl. age, gender, income, education level, etc.) Physiological conditions (incl. heart-rate, skin temperature, core temperature, etc.) Activity level (ISO 8996, level 3) (*M*) Thermal insulation level (monitoring) (*Icl*) Affective assessment and thermal preference (self-reported, ISO 10551) Air movement preference Perceived control Typical reported response to discomfort (incl. change of clothing level, activity, or location, intake of warm drink, etc.) Occupancy schedule Observations (incl. automated visual diary)

drawn from three body-of-sciences – building physics, physiology and psychology, and include the record of environmental variables, individual variables and participants' subjective assessments. These variables are measured or estimated at the time of the survey or through continuous periods of time. The core set of recordings common to most thermal comfort studies is summarised in Table 3.2.1; studies should collect information regarding the 'typical' factors and may gather additional information to address any specific research questions.

During the study design, the researcher should consider the group of participants to be surveyed, the sample size, and the sampling strategy (i.e. how and why participants are recruited/selected) – whereby most thermal comfort studies are carried out with a case study approach and a convenience sample. The researcher should also define the environment in which the study will be carried out; i.e. controlled or free-running. These two practical constraints – sampling strategy and experimental settings, will have great implications in the choice of assessment methods, in particular the use of monitoring equipment and social surveys.

Assessment of environmental factors in thermal comfort

To assess thermal comfort within buildings, one might adopt the adaptive approach and aim to compare monitored indoor operative temperature against standard benchmarks in relation to outdoor conditions. Field study researches (Humphreys, Rijal and Nicol, 2010) report that preferred indoor operative temperature is associated with outdoor temperature, and that their relationship is linear. In this approach, it is important to note that the levels and variations in external temperature are associated with the local climate, and also with the neighbourhood-built form and density. Therefore, in addition to temperature recording, it is important to gain insight into the local site morphology.

Thermal comfort assessment may also use the framework of the predictive approach (ISO 7730:2005) – also known as the heat-balance or PMV model – where occupants' comfort is assumed to be a function of physical and physiological parameters. This framework is applied especially to mechanically conditioned buildings (heated and/or cooled), and generally aims to provide uniform environments. The four indoor environmental parameters (Table 3.2.1, top four 'Typical') should be recorded, and the study design should ideally account for their variations in location and through time – although the predictive model is primarily based on steady-state conditions. When the environment is considered heterogeneous, the four variables shall be measured at several locations. In particular the sensors should be placed at standard heights (Table 5 in ISO 7726:2001), defined as ankle, abdomen and head level, set at:

- Sitting position: 0.1m, 0.6m and 1.1m.
- Standing position: 0.1m, 0.6m and 1.7m.

The sensors should be placed in occupied zones where the participants carry out their activities, while avoiding the obstruction of usual circulation in the rooms. Moreover, the potential effect of thermal radiation (e.g. from a heat source such as heaters) and incident solar gains should be taken into account when locating the sensors. With regard to the measurement period, ideally this should be set at 5 minutes or less for at least 2 hours (section 7.3 in ASHRAE 55:2013). Figure 3.2.1 shows an image of equipment typically used for measuring environmental parameters within thermal comfort studies.

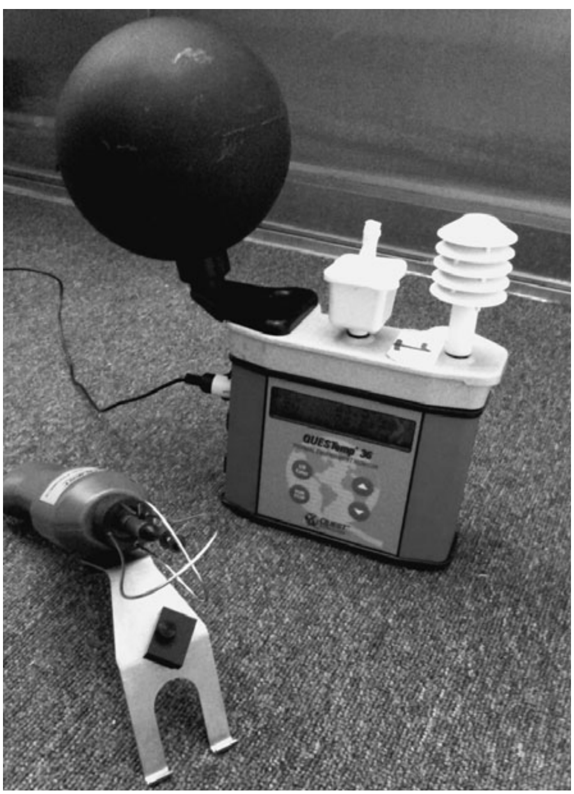

Figure 3.2.1 Image of equipment monitoring wet bulb temperature, dry bulb temperature, globe temperature, relative humidity and air velocity.

Source: Authors' own picture

With regard to the instruments chosen to record the four variables, their measuring range, accuracy and precision should comply with the requirements of ISO 7726:2001. However, in practice most studies only deploy one set of sensors in one location; this limits the accuracy of the environmental monitoring results, with assumptions made that the room and/or building retain homogeneous conditions and overlooking the potential for any air turbulence or thermal asymmetry – the latter being explicitly mentioned in the predictive approach as an issue affecting thermal comfort. To address these limitations, recent advancements in more accurate and affordable sensing technologies may allow for the monitoring of building and people, while using 'discreet' observatory systems (Spataru and Gauthier, 2014). Recent studies have used wireless sensor networks to record, store, compute and communicate monitoring data (Khan, Khan Pathan and Alrajeh, 2013), which allows to monitor and control environments in real time.

Assessment of individual factors in thermal comfort

In addition to environmental parameters, the assessment of individual factors is also important for evaluating thermal comfort, which involves addressing the following aspects:

- Estimation of clothing insulation and activity level (the main individual factors for the predictive approach).
- Subjective assessment of thermal comfort using questionnaires, interviews or focus groups.
- Behaviour observation.

These approaches may be used as 'stand-alone' methods or concurrently to environmental monitoring. As described in ISO 8996:2004, a person's metabolic rate (M) is a measure of activity level and is defined as the rate at which the human body utilises oxygen, food, and other sources to produce energy, per surface area of the body. Methods to estimate or to monitor human energy expenditure range from direct to indirect methods with varying levels of accuracy, complexity and cost. ISO 8996:2004 provides the methodological framework to estimate metabolic rate. It includes four levels:

- Level-1: screening of the participant's occupation or activity.
- Level-2: observation of the participant's activities at specific times.
- Level-3: analysis of the participant's heart-rate.
- Level-4: use of expert methods such as direct calorimetry.

These four levels of estimation can be divided into subjective and objective recordings. The subjective methods – Level-1 and Level-2 – are used in most thermal comfort studies, where the metabolic rate is based on reference tables, which provide typical metabolic levels for various types of activities (this assumes that the participant's body has a standard surface area). However, these methods often provide a biased assessment and are associated with a great risk of error. Over the past few years, sensing technologies have enabled the development of people's activity assessment (Trost et al., 2005). One of the most noticeable has been the rapid uptake of accelerometry, which measures movement as biomechanical effect. Another emerging tool is the use of wearable location sensing technologies, namely inertial navigation system (Shala and Rodriguez, 2011) or Wi-Fi signals processing (Xiong and Jamieson, 2013).

With regard to determining thermal insulation of clothing, the researcher may choose to estimate the clothing insulation for a given combination of garments, or the sum of individual garments, from reference tables. Although prone to observation bias, this is the most commonly used method in the field studies. Emerging methods include the use of infrared cameras (Revel, Sabbatini and Arnesano, 2012) and wearable sensors measuring the temperature gradient between the inner and outer layer of clothing (Gauthier and Shipworth, 2014).

Reported responses from participants are also collected using questionnaires, interviews or focus groups, in order to gather their thermal comfort perception. The standard assessment framework is described in ISO 10551:2001. Questionnaires may be filled-out by the respondent (self-completed questionnaire), or by the researchers themselves. The information is all recorded within the questionnaire-form, so the analysis could be systematic and requires little time, in particular if computer coding is used. Questionnaires are relatively easy to implement, as the same template is used for all participants, and the data collected is pre-formatted. However, some opinions may not be captured, as the format may have omitted some aspects, which are relevant to some participants. Also, as a subjective assessment method, questionnaires might introduce some bias in the choice of responses. In recent studies, additional types of subjective assessment have been carried out, and include the use of the following:

(1) Focus groups aim to interview several participants at the same time to carry out an in-depth exploration of a specific topic. This method is often used to develop an understanding of why people feel and behave the way they do. Limitations of this method include 'group-effect' where participants' opinions may be prone to culturally expected views rather than individual ones; and 'moderator-effect' where participants feel the 'need' to please the moderator. Moreover, the analysis relies on subjective coding and interpretation.
(2) Interviews with individual subjects encourage the formulation of ideas by studying the interviewees' own opinions and understanding of events. As the format is flexible, the discussions provide an opportunity for participants to express how they feel and why, giving an in-depth view of their range of experience and opinions. Interviews also allow the researcher to interact directly with respondent; this provides opportunities for the clarification of responses, and follow-up questions. Limitations of this method include bias caused by the interviewer affecting some responses ('interviewer-effect').
(3) Observation of participants may be carried out directly by the researcher or via a visual device, such as video. Participants may be observed at different times of a day or a week and in different contexts or performing different activities. The observer may join the participant-group, observe it, take some records, then develop an understanding of practices or behaviours, and finally report on the observation through a detailed written account by categorising participants and events. Limitations of this method include the 'observer-effect' (i.e. participants changing their behaviour as they are aware they are being observed), and bias in the observer recording. Observations may also be carried-out through the use of automatic diary methods. This objective technique enables the review of activity, for periods of time representative of a person daily practice, and with minimal impact and discomfort. Analysis of the diary is carried out through automatic segmentation to identify events or activities. As the analysis is automated little bias is introduced, only in the subjective interpretation of the reason(s) for an event to occur.

Evaluation of thermal comfort: Summary

Much progress has been made in recent years in the tools and techniques to monitor buildings and people. The forensic level of investigation will be determined by considerations such as the research question, the budget, and the programme. Field monitoring may be categorised into different classes according to the level of accuracy required, and the standard of instrumentation and procedures used. In summary, the following aspects should be reviewed:

- Practical constraints of the data collection, i.e. sample size and characteristics.
- Multi-disciplinary approaches giving different weighting to the factors, i.e. objective measurements versus self-reported information.

- Precision and accuracy of the recordings, i.e. estimation of clothing insulation and activity levels, and non-uniformity of environmental measurements.

Social and psychological aspects of thermal comfort: The missing link?

Approaches to psychosocial aspects within mainstream thermal comfort models

As mentioned in the earlier section, the predictive model of thermal comfort mainly focuses on physical and physiological mechanisms, whereby thermal comfort is considered primarily as a heat balance problem with adaptive mechanisms (e.g. clothing levels, eating/drinking, etc.) conceptually treated as 'noise' in the system – i.e. maintained at fixed levels in the chamber experiments which were used to develop the model. On the other hand, the adaptive thermal comfort theory frames the building occupant as capable of 'adaptation' and thus potentially tolerant of wider thermal conditions. These adaptive processes were classified as: physiological (acclimatisation), behavioural (e.g. opening windows, changing clothes, etc.) and psychological (e.g. expectations) (de Dear and Brager, 1998). Despite the reference to these three factors, the main focus of adaptive thermal comfort research has been to demonstrate that, especially in free-running buildings, there is a quantifiable link between outdoor conditions and preferred indoor conditions – with the latter being a wider range than typically assumed when using the predictive model. Critics of this interpretation of the adaptive model highlight that it is essentially a 'black box' where the relative contribution of physiological, behavioural and psychological mechanisms is neither understood nor explicitly addressed. In fact, the psychosocial component of thermal comfort has been relatively under researched, with limited evidence from qualitative and quantitative studies. It should also be highlighted that there is the potential for some confusion regarding the exact nature of some terminology and associated thermal comfort mechanisms. For example, some behavioural adaptations could be a direct response to physiological needs, while it could be argued that 'psychological adaptation' could refer to both individual and social mechanisms, as presumably thermal comfort 'expectations' are a combination of both individual and cultural/social factors. On the other hand, some aspects of 'expectations' may be caused by acclimatisation, which in turn could have a physiological component (involving a change in the physiological response to thermal conditions) as well as a psychological one (involving a change in the perception of and reaction to environmental stimuli) (Candido, de Dear and Ohba, 2012).

A review of published literature on the factors influencing human comfort indoors (Frontczak and Wargocki, 2011) highlighted that there is some evidence of thermal comfort being affected by factors such as: the level of education of building occupants, their relationship with superior and colleagues, and time pressure. However, these findings are based on a very small number of studies and some of these factors (e.g. education level) could be a proxy for other mechanisms. Some studies have also found that occupants' actual or perceived control of one's environment can improve the acceptability of comfort conditions (Leaman and Bordass, 2001). In the case of actual availability of controls, the mechanisms at play are primarily behavioural (i.e. possibility of opening windows, fan use, etc.) but psychological aspects could also be involved in the case of perceived control, which could increase the occupants' tolerance of wider thermal conditions. This type of phenomenon has been described by some as 'cognitive tolerance', where users are more tolerant of stimuli when they are sympathetic to its cause (Healey, 2014). In principle, several factors could affect occupants' perceptions of indoor thermal conditions, thus making them more/less tolerant of such conditions. However, very few studies address this issue and often they do so by considering environmental comfort overall (rather than solely thermal comfort). For example, some studies suggest that occupants' environmental attitudes may be linked to cognitive tolerance, with 'greener' occupants being more tolerant of environmental discomfort (Deuble and de Dear, 2012; Lakeridou, Ucci, Marmot and Ridley, 2012). As an example of potential cognitive tolerance, Figure 3.2.2 shows the results from an intervention study where both control and intervention participants were given a building

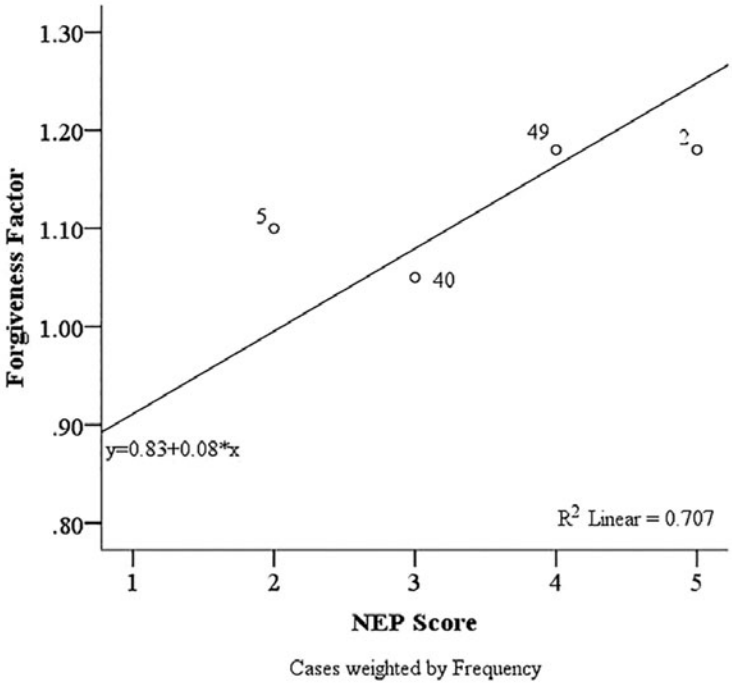

Figure 3.2.2 Association between tolerance of environmental conditions (Forgiveness Factor) and environmental attitudes measured via the New Ecological Paradigm (NEP) score.

Source: Lakeridou et al., 2012

evaluation questionnaire asking for an overall vote for comfort, as well as for individual parameters such as temperature, light, noise, etc. Participants also had to express their environmental attitudes using the New Ecological Paradigm (NEP) scale, where a higher NEP score represents a greater level of concern/interest with environmental issues. From the building evaluation questionnaire, a 'Forgiveness Factor'[1] can be calculated as a ratio of the overall comfort level with the individual comfort factors. The graph shows that there is a correlation between environmental attitudes and forgiveness factor, although the authors also highlight that analysing the results as a scatter plot shows a weaker correlation between the two variables – which suggests the need for further research in this field. In relation to the issue of perception of environmental conditions, some authors have also highlighted the importance of acknowledging the difference between sensation (i.e. cold, hot) and comfort (i.e. like or dislike), whereby the use of the 7-point thermal sensation scale (from very cool to very hot, with mid-point being 'neutral') in the predictive model is based on the assumption that people like being at a neutral state of comfort – which is not necessarily true in all cases (de Dear, 2011).

Psychosocial factors in thermal comfort: the contribution of human sciences

In parallel with mainstream thermal comfort research (i.e. research underpinning current approaches in thermal comfort Standards and Technical Manuals), the last 10–15 years have witnessed the development of debates on the nature of thermal comfort, initiated by scholars from disciplines traditionally not involved in this field, such as sociology, geography and history. Such debates highlight that comfort is '*a highly negotiable socio-cultural construct*' and that current trajectories in mainstream thermal comfort thinking could not only result in overreliance on (or even addiction to) mechanical cooling/heating systems, but also that such trajectories are by no means irreversible, precisely because of such negotiable nature of comfort (Chappells and Shove, 2005). Within this line of thinking, some scholars have highlighted the importance of studying thermal comfort in context (Hitchings, 2009), with a fuller understanding of some dynamics via qualitative studies, for example via semi-structured interviews with occupants. While these methods are time consuming, they can provide some new insights into the psychosocial aspects of thermal comfort. The benefits of such approaches were highlighted in a pilot study involving interviews with a small number of office workers in a naturally ventilated building in Brisbane, Australia (Healey and Webster-Mannison, 2012). The study found a number of cultural and contextual factors affecting the perceptions of thermal comfort and of adaptive opportunities, including the role of 'negotiations' for preferred thermal conditions among workers, which is also intertwined with the person's self-identified 'thermal disposition' (i.e. the person's perception of his/her typical thermal state relative to those around them). The study found, for example, that "*Whether someone identified as a 'hot person' or a 'cold person' emerged as an important factor, with most participants having a well-developed view of how they identified both themselves and those around them*" (Healey and Webster-Mannison, 2012, p. 171). However, humanities-based qualitative studies of thermal comfort in buildings are, for now, not only limited in number, but also based on approaches such social practice theory whose conceptual framework and terminology can be obscure to mainstream thermal comfort researchers/practitioners. Since the practical implications of such qualitative studies can be difficult to grasp (e.g. role of psychosocial factors not easy to quantify), their value can be underestimated.

While much thermal comfort research efforts have focused on the identification of the exact range/combination of environmental parameters which create 'perfect' and 'universal' thermal comfort conditions, an alternative line of thinking questions the 'homogenisation' of the indoor environment, or even the very notion of thermal comfort as a necessity (Healy, 2008). Some scholars have highlighted how the development of thermal comfort standards seeking to establish universally applicable (and in many cases narrow) comfort conditions has coincided with the rise of air-conditioning technology and low fuel prices. A book on "America's romance with air-conditioning" (Ackermann, 2010) describes various aspects of this 'romance', attributing part of air-conditioning's success to starting as an aspirational status-symbol for the American middle-class and then becoming a 'must have' within a consumerist economy. The contextual and negotiable nature of thermal comfort is also debated by sociologists such as Chappells and Shove (2004), who refer to comfort as a commercial and political achievement demonstrated by the mass marketing and diffusion of Westernised standards across the world. They also highlight how issues such as lifestyle, fashion, convention or convenience affect both comfort expectations and accepted strategies for thermo-regulation (e.g. clothing conventions or sweating as being less socially acceptable than other cooling strategies). They conclude that "*the task ahead is to redefine meanings of comfort so as to prevent unsustainable expectations taking hold or becoming a self-fulfilling prophecy*" (ibid., p. 27).

Psychosocial factors in thermal comfort: Summary

In summary, research on the role of psychosocial factors in thermal comfort has highlighted the role of some intriguing mechanisms, but it is still at its infancy. A new field of thermal comfort research is now growing, led by disciplines such as sociology or geography, contesting the notion of universally applicable thermal comfort principles and emphasising the need for re-contextualising comfort needs, whereby for example the role of groups (e.g. household, work community) should be better understood in addition to individualised comfort approaches. For now, however, it is unclear if and how this new research field will intersect with current engineering-based approaches to thermal comfort. A key exponent of thermal comfort research and founder of the adaptive theory wrote a review on thermal comfort research over the last twenty years (de Dear, 2013). Perhaps surprisingly, the review does not explicitly discuss the role of psychological and social factors on thermal comfort (other than the issue of perceived control). This omission could be due to the scarcity of psychosocial studies in the field and to the lack of quantitative evidence which could be translated into practical guidance, but it might also reveal a fundamentally different viewpoint. In fact, rather intriguingly the aforementioned review paper gives a great emphasis to physiological mechanisms and to the role of air movement – suggesting that perhaps some branches of adaptive thermal comfort thinking may end up intersecting with some aspects of the predictive model, which it had originally aimed to contest.

Health impacts of thermal discomfort and the modifying effect of the built environment

Impacts of extreme temperature exposure on morbidity and mortality

As shown by numerous thermal comfort studies, human populations are acclimatised to their local climatic conditions through physiological, behavioural and cultural processes. While it has been hypothesised that increased exposure to a thermoneutral environment could potentially be linked to undesired effects, such as weight gain (Johnson, Mavrogianni, Ucci, Vidal-Puig and Wardle, 2011)[2], exposure to temperatures outside the comfort range has detrimental effects for human comfort and health.

The physiological effects of extreme temperatures on the human body have been widely investigated. Human exposure to very low temperatures could lead to hypothermia, which in turn may cause the clinical symptoms of uncontrollable shivering, memory lapse, drowsiness, frostnip and frostbite; it may also trigger or worsen asthma and cold sores, cause increased blood pressure and freezing and non-freezing injuries – such as chilblain, immersion foot, etc. (Parsons, 2002). Extreme heat exposure, on the other hand, could lead to hyperthermia, which may cause the symptoms of heat stress and, in particular, heat stroke, heat exhaustion, heat syncope and heat cramps (Kilbourne, 1999). Extreme cold and heat exposure could even result in death although the majority of temperature-related deaths do not directly arise from hypothermia or hyperthermia, but rather from temperature effects on disease, primarily cardiovascular and respiratory – in particular Chronic Obstructive Pulmonary Disease (COPD) in the case of cold-related mortality (Wilkinson et al., 2001; Vardoulakis and Heaviside, 2012). Among the most severely affected during a heatwave or extreme cold episodes are expected to be the elderly (above 65 years old), the chronically ill (in particular individuals suffering from cardiovascular, cerebrovascular, renal and respiratory diseases), and the socially deprived population groups of the inner cities (Kovats and Hajat, 2008).

Excess seasonal mortality is generally defined as the short-term increase in the numbers of deaths above the average historic mortality figure recorded during an extreme weather episode in a given period and region (Basu and Samet, 2002). This is illustrated for the London 2006 heat wave in Figure 3.2.3.

There is nowadays a well-established relationship between external climate and excess temperature-related mortality risk at the population level. In most cities around the world, daily mortality is generally characterised by a U-shaped relationship with external ambient temperature (Hajat, Kovats and Lachowycz, 2007; McMichael et al., 2008).

Temperature-related health risk determinants

Determinant factors of temperature-related health risk can be classified in one of the following categories (WHO, 2009):

a) exposure;
b) sensitivity;
c) ability to adapt.

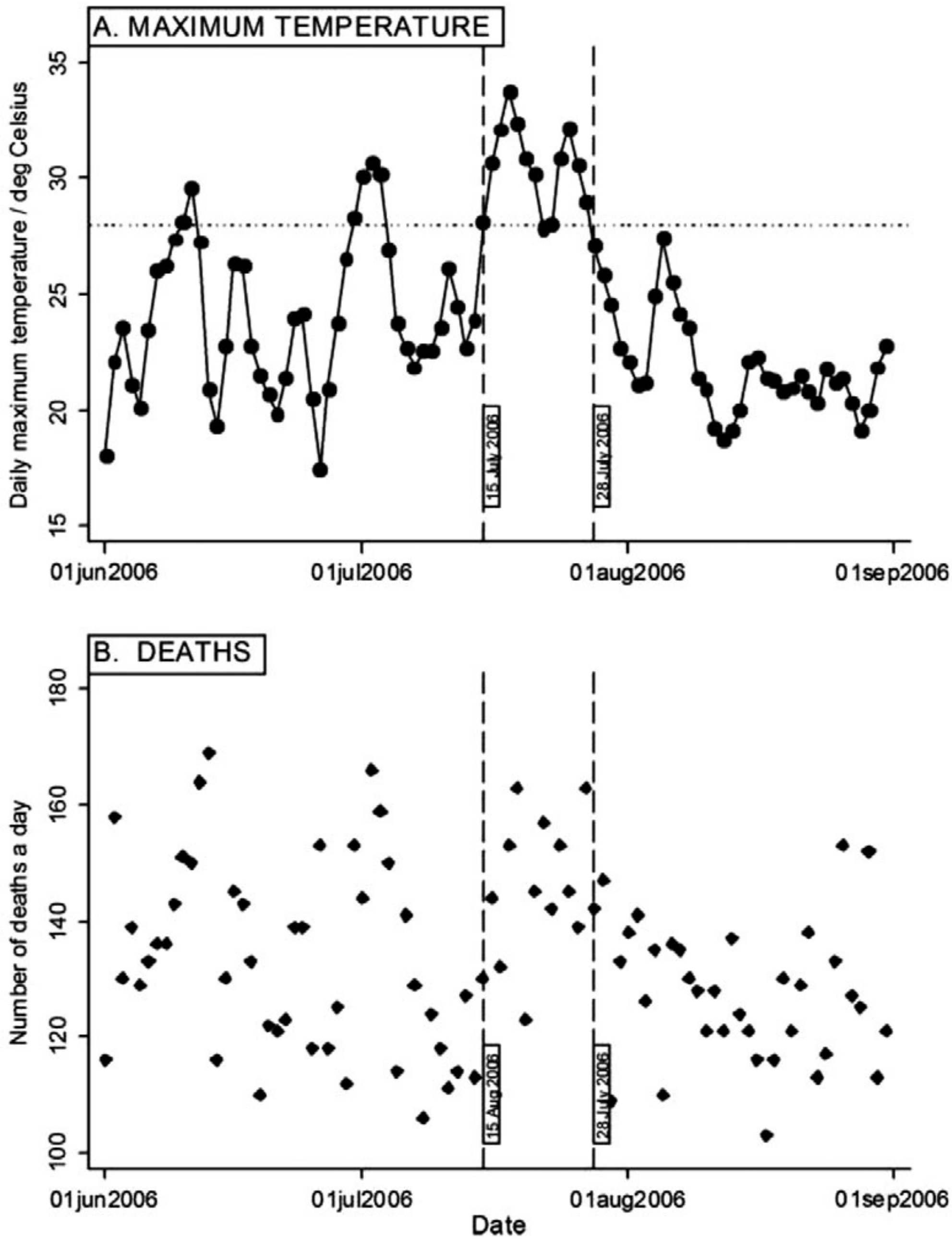

Figure 3.2.3 (a) Daily maximum temperatures, London, 1 June–31 August 2006. The period defined as the heatwave (15–28 July inclusive) is indicated by the vertical dashed lines. The horizontal dotted line indicates 28°C. (b) Daily deaths for the same period.

Source: Mavrogianni, Davies, Chalabi, Wilkinson, Kolokotroni and Milner, 2009

These factors may be determined by both physiological, as well as social/environmental parameters. While heat-related health risks are projected to increase in the future due to climate change, cold-related mortality is still projected to be a major public health concern in mid- and high-latitude countries, at least by the middle of the century. For instance, the highest excess winter mortality of recent years in the UK was observed in the winter of 2008–2009 (more than 36,000 excess deaths), 18 times higher than the approximately 2,000 excess heat-related deaths that were attributed to the 2003 heat wave. It is essential to note that excess winter mortality is not solely linked to the outdoor climate; a large number of deaths occur every year during the winter in heating-dominated climates. A large proportion of these is characterised as 'preventable' (Marmot Review Team, 2011), as they are partially attributed to: fuel poverty, thermally inefficient building stocks, inefficient use of public health infrastructure, lack of population acclimatisation etc. By way of illustration, countries such as Finland, Germany, and the Netherlands appear to suffer considerably less from excess winter deaths compared to warmer countries such as the UK, Portugal, Spain and Greece (Healy, 2003).

The interplay of thermal processes within the built environment, in conjunction with the heterogeneity of building fabrics and socioeconomic structures, may markedly affect the distribution of cold and heat vulnerability across the city. This is particularly pertinent in urban environments, where climatic changes induced by regional warming trends could be exacerbated by urban heat island effects. As discussed earlier, there has been a wealth of literature to date examining the relationship between external temperatures and mortality, but little attention has been paid to the potential impact of the indoor climate on temperature-related health risk. Given that populations in mid- and high-latitude countries tend to spend the majority of their time indoors, this is an issue of significant importance.

Inter-city differences in temperature-related mortality risk are likely to be observed due to heat island effects, site microclimate and individual building properties. A time-series study of daily mortality in all regions of England and Wales between 1993 and 2003 found that while mortality risk was observed for heat exposure in all regions, the strongest heat effects were in London (Kovats, Johnson and Griffiths, 2006). It is, however, likely that heat islands offer some protection from cold-related deaths during winter. Interestingly, it has been indicated that variations in individual building geometry and fabric physical characteristics may have a larger influence on internal temperatures compared to the location of a dwelling across the London heat island (Oikonomou, Davies, Mavrogianni, Biddulph, Wilkinson and Kolokotroni, 2012). A number of studies have investigated the role of housing characteristics as potential determinants of cold-related morbidity and mortality in England (Wilkinson et al., 2001). A statistically significant relationship was found between excess winter mortality and the construction age of the property, thermal efficiency ratings, indoor temperatures, tenure type and presence of central heating, with deaths more likely to occur in older, more inefficient, colder, privately owned properties without central heating. Analysis of evidence from the Paris 2003 heatwave suggests that summer heat-related mortality risk might have been higher in thermally heavyweight or uninsulated structures, top floor flats and houses with limited means of ventilation (Vandentorren et al., 2006).

Climate change impacts and future research in temperature-related health risks

Climate change is linked to a series of interconnected impacts on the thermal comfort, energy demand and health risk levels of human populations worldwide. It could also potentially lead to a rise in heat-related morbidity and mortality. By way of illustration, in the UK, heat-related mortality is expected to increase by around 70% in the 2020s, 260% in the 2050s, and 540% in the 2080s, compared with the 2000s baseline, assuming no acclimatisation of the population to a warmer climate (Vardoulakis and Heaviside, 2012). During winter, however, current warming trends are likely to decrease the space heating loads. This is likely to be associated with a decline in the cold-related death toll. A 2% and 12% reduction of cold-related mortality compared with the 2000s baseline is projected by the 2050s and the

2080s in the UK (Vardoulakis and Heaviside, 2012). It is hence crucial that the wider picture ought to be considered and the net effects of such phenomena need to be better understood before proceeding to the implementation of climate change adaptation and mitigation strategies (Davies and Oreszczyn, 2011).

From the above, it can be concluded that there is a wealth of studies that have addressed the individual specific determinants of weather-related vulnerability risk factors, i.e. age, disease, disability. There is also sufficient evidence on the impact of extrinsic factors, such as the ones related to the built environment (e.g. urban heat island effects and building fabric quality), on temperature-related health risk during winter. The relationship between the indoor climate and heat-related health risks are, however, less understood. Deepening our understanding of these issues is expected to increase the efficiency with which vulnerable populations are targeted and mitigation and adaptation strategies are applied in community settings. A first step toward achieving this goal could be the large scale, high resolution, longitudinal monitoring of indoor thermal conditions across nationally representative building stock samples.

Conclusions

This chapter has highlighted a number of key issues and implications for the design of thermal comfort in buildings:

- The evaluation and design of thermal conditions in buildings is a key aspect of environmental design and engineering, and a thriving research field, which is continuously uncovering almost as many unanswered questions as finding answers. As a result, standards, guidelines and technical manuals on the design/evaluation of thermal comfort are being regularly revised in an attempt to provide practical guidance, based on a snapshot of the 'best evidence' available at that time. While the invaluable role of these standards/guidelines is undeniable, architects and engineers should avoid an uncritical application of such tools in the search for 'perfect' and 'universally applicable' thermal conditions. Rather, a holistic and contextual view of the interactions between environment, resources, people, culture and buildings is needed.
- Greater importance is being increasingly placed on local and/or personal control of thermal conditions, which can have a deep impact on the design philosophy of buildings and their systems. This trend is partly due to a greater awareness of personal control as an important factor in thermal comfort, and partly thanks to technological changes in HVAC and control systems. Within this context, it is important to consider building occupants as 'inhabitants' who may play an active role in the dynamics of the building's thermal conditions (rather than as 'occupants', passive recipients of predetermined comfort conditions) (Cole, Robinson, Brown and O'Shea, 2008). Again, current technological advances (e.g. ubiquitous and pervasive sensing; participatory platforms, etc.) can facilitate this two-way dialogue between the building and its inhabitants. However, a further challenge here is how to move away from an exclusively individual notion of comfort, and first understand then exploit psychosocial mechanisms – such as 'negotiations' of temperatures and comfort settings within multi-occupancy buildings.
- Partly linked to the issue above, recent advances in thermal comfort research point toward the potential for a greater focus on the 'dynamic' nature of thermal comfort. A new line of thinking suggests that the role of temporal and spatial variations in thermal conditions could be exploited and explored, rather than avoided (de Dear, 2011; van Marken Lichtenbelt and Kingma, 2013). If one considers thermal comfort evaluation from a person-centric perspective of exposure to thermal conditions over time and space (rather than in terms of averages occurring in building zones), this could have the potential for generating new experimental design philosophies where 'building inhabitants' can dynamically experience the 'delights' of thermal conditions, rather than their 'absence' via 'neutral' temperatures.

- While temperature can have a negative and even deadly effect on human beings, the impact of indoor temperatures on health is not fully understood, especially with respect to the interplay – given certain outdoor conditions – between building characteristics, individual characteristics (including behaviour), social/cultural factors and the wider geographical context (e.g. urban design features). The health impacts of thermal conditions are possibly one of the biggest challenges within the context discussed here. It may be argued that the 'entitlement' or the 'need' for thermal comfort is a relative notion (e.g. why or to what extent does it matter if someone is thermally uncomfortable in a building?), which could therefore be balanced against the needs of energy saving and climate change mitigation/adaptation. However, it is harder to argue against the design of safe (health-wise) thermal conditions. Nevertheless, in the absence of a clear understanding of the mechanisms underpinning 'safe indoor temperatures' (especially for overheating), one may need to apply the precautionary principle – which could in turn results in resource wastage. In this situation, the best designers can do is to consider the adaptive capacity of their buildings, providing flexibility of uses (e.g. access to cool areas) especially for the most vulnerable populations. At the same time, the issue of health, comfort and energy must be addressed at the policy level as a continuum where the context (physical, psychological and social) needs to be further understood. In this sense, building designers can help via a greater understanding of how their buildings are being used, rather than 'walking away' post-construction. Overall, this may raise the question: 'Is there the need for a new generation of building designers (or even a new profession) who take at least as much interest in the design as in the operation of their buildings?'

Notes

1 The building evaluation questionnaire and the Forgiveness Factor used by Lakeridou et al. (2012) are based on the widely used post-occupancy evaluation method BUS (www.usablebuildings.co.uk).
2 The potential links between temperature exposures and weight gain are still unclear as recent studies have found contradictory results.

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3.3

INDOOR AIR QUALITY AND VENTILATION MEASUREMENT

Lia Chatzidiakou, Benjamin Jones and Dejan Mumovic

Introduction

Indoor air quality (IAQ) and thermal comfort are important aspects of indoor environmental quality, as they can significantly affect health, comfort and performance of building occupants (Chapter 3.1). IAQ in non-industrial environments is often evaluated in terms of estimated ventilation rates and carbon dioxide levels (CO_2). Over recent decades, building design has increasingly needed to address the competing requirements of reducing operational energy demand while having to provide adequate IAQ in addition to thermal comfort. Extensive natural or controlled ventilation intended to remove internally generated air pollutants, is likely to affect energy performance of buildings by increasing cooling or heating consumption for the provision of required thermal comfort conditions. The construction of more air-tight buildings has reduced uncontrolled background ventilation, and also led to the introduction of new materials in buildings that may significantly impact on IAQ. With the growing recognition of the problem of indoor air pollution, the need for clearly defined guidelines and thresholds for specific indoor concentrations became evident. This chapter is intended as an aid to planning indoor air pollution measurements, and guidance on cost-effective and convenient sampling strategies for IAQ monitoring.

Measuring ventilation

At a fundamental level, ventilation is the exchange of air between a building and its local environment through openings in its thermal envelope. These openings are both purpose provided (intentional) and adventitious (unintentional) and the energy consumption and IAQ of a building are closely related to the ventilation rates through them. In practice, one may need to determine a particular ventilation rate or airflow pattern for commissioning, design, or diagnostic purposes using in-situ measurement techniques. Accordingly, this section provides an overview of common methods used to estimate the total ventilation rate through both adventitious and purpose provided openings in concert, the airflow rates through specific purpose provided ventilation elements or components, and the airflow rate through adventitious openings that indicates the airtightness of a building.

Measuring total ventilation

The total ventilation rate (TVR) is the sum of the ventilation through purpose provided and adventitious openings. The most accurate and commonly used techniques to measure the TVR involve the injection of a tracer gas into the atmosphere of a test zone and the subsequent measurement of its concentration over time. The rate at which air, free from the tracer gas, is brought into the zone is determined from the concentration history. Three techniques are commonly applied. (i) The Decay Method (*multipoint* and *two-point*) requires the injection of a small amount of tracer gas into a single zone and its exponential decay is monitored over time. (ii) The Constant Concentration Method moderates the rate of injection of a tracer gas into a single zone so that a near constant concentration of the tracer gas in maintained. The volume flow rate of the tracer gas is proportional to the overall ventilation rate through the zone. (iii) Finally, the Constant Emissions or Injection Method releases a tracer gas at a steady rate and mixes it into the local atmosphere so that an equilibrium concentration is reached. This concentration is also proportional to the overall ventilation rate through the zone.

Assumptions

All techniques assume that the air in the test zone is homogeneous, that the tracer gas is perfectly mixed, and that the ventilation rate is constant. Dead spaces should be illuminated by leaving open internal doors to cupboards and closed rooms. Errors increase when actual conditions deviate from those assumed. Their effect is best considered using an example of the multipoint decay method, where many measurements of a tracer gas are taken over the measurement period, as opposed to the two-point variant that only takes measurements at the beginning and end of the measurement period. Figure 3.3.1 shows the decay of a tracer gas over time in a single zone. Regression of the natural log of the concentration gives a gradient whose modulus is the air change rate, which in this example is $2.75h^{-1}$. The coefficient of determination (R^2) indicates the precision of the measurement and the degree of exponential decay, which in this case are both high. In turn, R^2 also indicates the degree to which the assumptions of perfect mixing, air homogeneity and a constant ventilation rate have been met, and in this case, they have. If exponential decay is not observed, the two-point method should be employed whereby the first and last measurements are used to estimate the time-mean specific ventilation rate for the measurement period.

As a rule-of-thumb, the error in the accuracy of the measurement is predicted to be up to ±20% (Jones and Kirby, 2012) although in skilled hands it can be <10% (Sherman, 1990). The technique should be

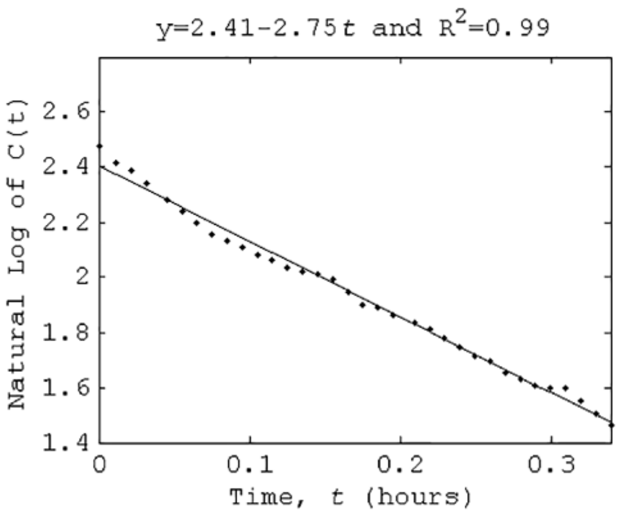

Figure 3.3.1 Example of the tracer gas decay method (Jones and Kirby, 2012).

C(t): Tracer gas concentration (ppm) as a function of time limited to test zones with a volume of less than 500m^3 (Liddament, 1986) to minimize mixing errors. In order to reduce bias, the time allocated to each test should the inverse of the air change rate. For example, the optimum time for the test in Figure 3.3.1 is 22 minutes (0.36 hours).

Limitations

When interpreting a measurement of a ventilation rate, one should be clear about its limitations. It is impossible to isolate the proportion of air exchanged between the test zone and the outside and that exchanged between the test zone and adjacent zones unless a unique tracer gas is deposited in each zone. Furthermore, one cannot predict the air change efficiency (an indicator of the mixing behaviour of air or the distribution of contaminants within a space) unless multiple samples are taken from different parts of the test zone. Moreover, a measurement of a ventilation rate in a test zone using a single tracer gas and a single sampling point indicates the time averaged air exchange between it and all adjacent spaces, both internal and external.

Equipment

Necessary equipment includes a tracer gas, dose apparatus, gas concentration measuring equipment, and a mixing fan. While the fan choice is noncritical its application is important. For example, some practitioners use mixing fans for the duration of the measurement to ensure that the tracer gas is well mixed within the test zone. However, it is argued that they create artificial airflow paths so that the measured conditions deviate from those normally experienced (Liddament, 1986).

The gas concentration analysis equipment makes use of a specific identifying property of a tracer gas. Infrared (IR) detection exploits the ability of a tracer gas to absorb IR radiation of a particular characteristic wavelength. Gas Chromatography (GC) separates the different gases in a sample before their concentrations are measured using an electron capture detector (ECD) or a thermal conductivity detector (TCD). ECDs and TCDs use a gases ability to capture electrons or to amend its thermal conductivity, respectively. Not all tracer gases share the same identifying property and so the equipment should be chosen according to the tracer gas; see Table 3.3.1. Analysis equipment should have a measuring error of no more than ±5% and should be calibrated (BSI, 2012).

The dose apparatus may be a simple regulator attached to a portable hand-held gas canister. It may also contain a heater to prevent cooling and freezing during release. When using the constant concentration or emissions methods, a more advanced dosing device is controls the volume flow rate of the tracer gas.

Tracer gases

The choice of tracer gas is important and should be appropriate for the measurement task. However, all tracer gases should have a several common characteristics. A tracer gas should be safe, inert, unique, measurable, and should not affect the airflow rate in, or the air density of, the test zone. EN ISO 12569 (BSI, 2012) proposes six tracer gases (see Table 3.3.1), of which three have a high global warming potential (GWP) relative to that of CO_2. The remaining unique tracer gases are helium and ethylene. The former has a significantly lower density than air and so should be well mixed using fans throughout the test period, although this could adversely affect the measurement of buoyancy-driven natural ventilation. Ethylene is a flammable gas and so it should be handled with great care. Standard 12569 also identifies CO_2 as a tracer gas, and although it is not unique in the atmosphere, dissolves in water, and is absorbed by building materials, it is an acceptable tracer gas when a high degree of accuracy is not required. Other tracer gases (not included in Table 3.3.1), such as nitrogen (non-unique), carbon monoxide (toxic to humans), ethane (flammable), methane (flammable), and isobutene (flammable) are indicated by Standard

Table 3.3.1 Types of tracer gas.

Type of gas	*Helium*	*Carbon dioxide*	*Sulphur hexafluoride*	*Perfluoro carbon*	*Ethylene*	*Nitrogen monoxide*
Chemical symbol	He	CO_2	SF_6 C_2F_6 (PFC-16)	SF_4 (PFC-14) C_2H_4	 N_20	
Maximum permissible concentration	—	$5×10^{-3}$	$1×10^{-3}$	—	—	$25×10^{-6}$
Density relative to air [-]	0.138	1.545	5.302	Example, PFC-14: 3.06 PFC-16: 4.80	0.974	1.53
GWP relative to CO_2	—	1	23900	Example, PFC-14: 6500 PFC-16: 9200	—	310
Measurement method	GC-TCD	IR-GA GC-ECD	IR-GA GC	GC-ECD	IR-GA or FID GC	IR-GA

GC: Gas Chromatography, with or without a Thermal Conductivity Detector (TCD). GC-TCD: GC using Thermal Conductivity Detection. GC-ECD: GC using Electron Capture Detection. IR-GA: Infra-red gas absorption (both transmission and photo-acoustic spectroscopy)

Source: BSI, 2012

12569. Their properties should be checked to ensure that they share have the common characteristics of an appropriate tracer gas.

Passive methods

The three main tracer gas techniques all require expensive and bulky equipment and are invasive. Low cost passive techniques were developed in the 1980s (Liddament, 1986) that use volatile per fluoro tracer (PFT) gases that are emitted over a long period of time in small quantities from an emission tube with an approximate length and diameter of 30mm and 5mm, respectively. The PFT gas is then detected by a second sample tube (of similar dimensions) and the time averaged air change rate is calculated from amount of tracer gas emitted and collected by each tube. The analysis is not instantaneous and must be done in a laboratory using gas chromatography and electron capture detection. As a rule of thumb, one tube should be allocated per 25–30m^2 of test zone floor area (Sherman, Walker and Lunden, 2013). It is possible to use multiple tracer gases and tubes to measure inter-zonal airflow rates.

This technique is also limited by the assumptions of a constant air change rate and good mixing. Under ideal conditions it is predicted that there is an uncertainty of at least 10–15% in measurements but in variable imperfect conditions a measurement might be out by a factor of 2 from the right answer (Sherman et al., 2013) making careful experimental design an imperative.

Measuring airflow through components

It is often necessary to determine the airflow rate through specific ventilation components, such as a terminal diffuser of an air conditioning system. This is done using a terminal hood flow meter that contains a small fan. When placed over the diffuser, the rate of rotation of the fan is varied until there is no pressure drop through the device. The airflow rate is determined from the fan speed.

To estimate the airflow through a duct, several methods may be employed. The first is to use a tracer gas and the constant emissions method where the airflow rate is then proportional to the concentration of the tracer gas in the duct. Secondly, an orifice plate or nozzle, with a known relationship between the airflow rate and pressure drop, is attached to the duct in series and the pressure drop is measured. Thirdly, an air velocity measuring device, such as a hot-wire anemometer or pitot static tube array, is used to measure the air velocity at specific points in a duct's cross-section. The airflow rate is estimated by the integrating the measurements. By calculating the difference between the duct and the terminal airflow rates, an estimation of the duct leakage rate can be determined.

Air leakage and air permeability

The direct measurement a building's infiltration rate is technically difficult, invasive, and expensive. Therefore, the leakiness of a building is often assessed from a measurement of an air leakage rate (ALR), a physical property of a building that indicates the resistance of its fabric to airflow. The airflow through the thermal envelope $\dot{V}$ (m^3/s), is often related to the pressure difference across it ΔP (Pa), by a power law relationship,

$$\dot{V} = C\Delta P^{n} \tag{1}$$

where C ($m^3/s/Pa^{-n}$) is a flow coefficient and n is a flow exponent. Natural forces create a pressure differences across its thermal envelope of 1^{-4}Pa. To overcome these, the internal air pressure is artificially raised at intervals between 10Pa and 60Pa when $\dot{V}$ is recorded and the values of C and n are be determined by regression (CIBSE, 2000). Equation (1) is used to extrapolate the airflow rate at a reporting pressure. In some circumstances $\dot{V}$ is reported at 4Pa when it is used to calculate an effective leakage area, the area of an opening with a discharge coefficient of unity that would have the same airflow rate at the same pressure difference. However, it is more common to report $\dot{V}$ at ΔP = 50Pa when is known as an ALR or $\dot{V}_{50}$ (BSI, 2001). Although Equation (1) is the most commonly applied relationship between $\dot{V}$ and ΔP, it should be noted that a quadratic relationship is shown to reduce errors when extrapolating measured data to operational conditions (Etheridge, 1998).

Normalized parameters

It is difficult to compare ALRs for different buildings and so they are often normalized. In academic circles it is common normalize $\dot{V}_{50}$ using building volume when it becomes an air change rate, ACH_{50} (h^{-1}). EU standard 13829 (BSI, 2001) normalizes $\dot{V}_{50}$ using the thermal envelope area and is known as an Air Permeability, Q_{50} ($m^3/h/m^2$). This area includes the total area of all floors, walls, and ceilings bordering the internal volume of the building. In a terraced house or apartment surfaces shared with adjacent dwellings are included.

Equipment and procedure

A significant amount of equipment is required to measure an ALR (BSI, 2001; CIBSE, 2000). Firstly, an air-moving device, such as a fan, is connected to a convenient external door. The fan must operate at a number of speeds to vary the pressure differential. Otherwise dampers are used to control the airflow rate. An airflow rate measuring system (accuracy of ±7%) measures the airflow rate through the air-moving device. A manometer measures the difference between the internal and external air (gauge) pressure (accuracy of ±2Pa between 0 and 60Pa), a barometer measures the ambient air pressure, and an anemometer measures the wind speed. Finally, a temperature-measuring device (accuracy of ±1K) measures the air temperature inside the building. At least one sensor is required on each floor.

Before a test the building is prepared by switching off all combustion appliances and by sealing their flues. All internal doors are opened, while all external doors, windows, and ventilation openings are shut. Finally, all mechanical ventilation systems are turned off and sealed.

When the average wind speed is below 3m/s, the fan is temporarily sealed, and the gauge pressure is measured in the building. With the fan uncovered, it is used to provide a pressure differential of 55 to 60Pa. If this unachievable, perhaps because the building is very large, the maximum pressure difference is reduced to 25Pa. With the fan speed constant, the pressure difference and airflow rate are recorded. The fan speed is reduced and at least 5 further readings are taken between the maximum value and a minimum of 10Pa (CIBSE, 2000).

Values of C and n are be determined by regression using Equation (1) and C is corrected to a standard temperature and pressure of 20°C, and 101,324Pa, respectively, in accordance with national and regional standards (CIBSE, 2000; BSI, 2001; ASTM, 1999). The flow exponent should be $0.5 \geq n \geq 1$. Values outside this range indicate a problem with the measurement, such as a high wind speed. Typically, uncertainty in the measurement of air leakage is below 15% for still conditions and up to 40% when windy (BSI, 2001).

The conjoined conundrum

A measurement of air leakage in a conjoined or multi-family dwelling, such as an apartment, does not allow one to differentiate between the infiltration of unconditioned ambient air that may require heating or cooling, and the infiltration of conditioned air from an adjacent dwelling that may not (Jones et al., 2013). The Guarded Zone technique uses multiple fans and tests to isolate a single conjoined dwelling (Fürbringer, Roecker and Roulet, 1988) and to determine the air leakage through its shared walls.

Monitoring IAQ

The reliance on ventilation rates and CO_2 levels for IAQ assessment reflects the relative difficulty and expense of collecting measurements of specific pollutants. In most circumstances, the interpretation of collected measurements is assisted by the use of guideline values for acceptable indoor pollution levels. WHO 2006 and 2010 guidelines focus on chemicals often found indoors in concentrations of health concern (Table 3.3.2). The guidelines are based on a comprehensive review and evaluation of the accumulated scientific evidence from toxicological and epidemiological studies.

Sampling strategy and instrument selection requires a firm understanding of the goals of the planned monitoring campaign. Two general approaches are generally used for the determination of indoor pollution levels: (a) Sampling on site may be performed with direct-reading instruments, or (b) sampling is performed on-site, but further analysis is required in the laboratory. In both cases, selected instruments must be as simple and manageable as possible.

Indoor investigations are mainly undertaken because of occupants' complaints about poor air quality, observed or suspected health effects, the need to determine the exposure of occupants to certain substances, compliance of indoor concentrations with standards and guidelines, or the efficiency of remedial measures. When selecting a monitoring approach, it is essential to take into account the variation in the concentration of air pollutants with time. The sampling duration of the measurement may be determined in relation to health effects, emission characteristics of the source, the limit of quantification of the chosen analytical method, available resources, costs and the time available for carrying out the study. Other considerations

Table 3.3.2 Summary of indoor air quality guideline values for selected pollutants, health effects and methods of determination.

Pollutant	*Averaging time*	*AQG value (reference)*	*Health effects*	*Methods for determination*
Carbon monoxide (CO)	15minutes 1 hour 8 hours 24 hours	100 μg/m^3 (WHO, 2010) 35 μg/m^3 10 μg/m^3 7 μg/m^3	reduction of exercise tolerance ischaemic heart disease	non-dispersive infrared spectroscopy (BS EN 14626:2012)
Ozone (O_3)	8 h, daily maximum	100 μg/m^3 (WHO, 2006)	Mortality, lung function and lung inflammation	Instrumental: Ultraviolet absorption photometry (BS EN 14625:2012) Diffusive sampling: Nitrate method analysis with ion chromatography
Nitrogen dioxide (NO_2)	1 year 1h	40 μg/m^3 (WHO, 2010) 200 μg/m^3(WHO, 2010)	Respiratory symptoms, airway inflammation, increased susceptibility to respiratory infection	Instrumental: Chemiluminescence (BS EN 14211:2012) Diffusive sampling: TEA principle analysis with ion chromatography (BS EN 16339:2013)
Particulate matter $PM_{2.5}$	1 year 24h (99th percentile)	10 μg/m^3 (WHO, 2006) 25 μg/m^3 (WHO, 2006)	cardiopulmonary and lung cancer mortality	Gravimetric measurements (BS EN 14907:2005) Optical photometer
PM_{10}	1 year 24h (99th percentile)	20 μg/m^3 (WHO, 2006) 50 μg/m^3 (WHO, 2006)		
Radon		100 Bq/m^3 300 Bq/m^3 depending on local conditions	Lung cancer	Alpha-track method (BS ISO 11665–4:2012)
VOCs benzene	.	no safe level of exposure can be recommended (WHO, 2010)	genotoxic carcinogen	PID (photo-ionization detector) FID (flame-ionization detector) Passive diffusive sampling (BS ISO 16017–2:2012)
Formaldehyde	30-minute average	100 μg/m^3 (WHO, 2010)	Sensory irritation	PID (photo-ionization detector) FID (flame-ionization detector) Passive diffusive sampling (BS ISO 16000–4:2011)
TVOCs		200 to 600 μg/m^3 (Salthammer, 2011)	Sensory irritation	PID (photo-ionization detector) FID (flame-ionization detector)
Allergens Cat allergen (Fel d 1)		Allergic sensitization: 1.0μg/g Asthma symptoms in sensitized individuals: 8.0μg/g	Asthma exacerbations and allergic sensitisation	Settled dust sampling and analysis with molecular cultivate-independent methods
Dog allergen (Can f 1)		Allergic sensitization: 2.0 μg/g Asthma symptoms in sensitized individuals: 10.0 μg/g		

Table 3.3.3 Indoor and outdoor sources, building design and remedial measures.

Pollutant	*Main indoor sources*	*Main outdoor sources*	*Building design and remedial measures*
Carbon monoxide (CO)	Combustion processes (heating, cooking), open fires, gas appliances,	motor-vehicle exhaust gases	Installation of electrical apparatus for CO detection in domestic premises Inspection of heating, cooking and gas appliances Introduction of reduced-traffic zones around buildings accommodating susceptible groups
Ozone (O_3)	Photocopier, laser printers	photochemical reaction	Local extract in rooms with ozone producing equipment Avoidance of ventilation during peak traffic
Nitrogen dioxide (NO_2)	Combustion processes (heating, cooking), open fires, gas appliances	motor-vehicle exhaust gases	Introduction of reduced-traffic zones around buildings accommodating susceptible groups Detached building compound for food preparation/ boiler room (schools, hospitals etc.)
Particulate matter $PM_{2.5}$, PM_{10}	Cooking, fungi spores, humans, bacteria, viruses, construction materials	Fuel combustion, pollen, soil	Filtration of outdoor air Reduction of indoor dust reservoirs (carpeting textiles) Detached building compound for food preparation/boiler room (schools, hospitals etc.)
Radon	Building materials	Soil contaminant	Installing a radon sump system Sealing floors and walls Increasing underfloor ventilation Installing a whole house positive pressurization or positive supply ventilation system Improving the ventilation of the house
VOCs benzene	Open fires, tobacco smoke, garage	motor-vehicle exhaust gases, filling stations	Detached garage
Formaldehyde	Open fires, tobacco smoke, chipboards, insulating materials, disinfectants		Introduction of low emitting furniture Selection of low emitting construction materials
TVOCs	cleaning agents, paints and varnishes, wood preservatives, adhesives, printing ink, printing products, solvents, personal care products,	motor-vehicle exhaust gases	Introduction of low emitting cleaning supplies Storage of solvents, pesticides etc in airtight containers away from main use spaces Purge ventilation in the beginning of the occupied period Zoning of ventilation systems and local extraction in special use spaces (laboratories, artwork)
Biological parameters Cat allergen (Fel d 1) Dog allergen (Can f 1)	Occupants with pet ownership through clothing	Domestic animals	Reduction of indoor dust reservoirs (carpeting, upholstery furniture) Introduction of special clothing to protect susceptible occupants Deep cleaning of spaces
Fungal and bacterial groups	Condensation, water damage, water leakage, humans,	spores	Avoidance of damp, visible mould growth Reduction of indoor dust reservoirs (carpeting, upholstery furniture) Maintenance of HVAC systems

when planning a monitoring strategy include the sampling location in the building, and simultaneous outdoor measurements.

This section aims to offer comprehensive guidance for forensic investigations on indoor non-industrial environments, and in line with WHO 2006 and 2010 guidelines, it focuses on methods for Particulate Matter (PM), nitrogen dioxide (NO_2), ozone (O_3) and Volatile Organic Compounds (VOCs) quantification. Moreover, methods for the determination of Total VOCs, fungal and bacterial groups and allergens are proposed, as high concentrations of these pollutants may have health implications and are suspected to cause non-specific symptoms known as Sick Building Syndrome (SBS) (Chapter 3.1).

Airborne particles

In addition to its gaseous components, indoor air may contain a variety of contaminants that occur as airborne particles. Conventionally particles are classified by their aerodynamic diameter (usually referred to as particle size) because these properties govern the transport and time of suspension in the air, their deposition in the lungs, and they are generally related to their chemical composition (Morawska and Salthammer, 2003).

There are many different measurement techniques for physical characteristics of airborne particles of different sizes in indoor environments, such as mass and number concentration, number and mass distribution and particle area. In this subsection, only mass concentration obtained with filter-based and direct-reading methods will be presented.

Mass concentration is the most commonly measured characteristic of airborne PM. Gravimetric method is considered the most accurate way to determine aerosol mass concentration and involves passing a known amount of air through a filter, and then determine the increase in mass of the filter due to aerosol particles collected (BS EN 14907:2005). This is done by weighing the filter before and after the sampling with a microbalance in controlled temperature and relative humidity conditions. The filter shall be conditioned before and after weighing to normalize absorbed water content that may affect the measurement. There are different types of filters in use, each with different properties and different collection efficiencies, the choice of which depends quite significantly on the size of the collected particles. Collected filters after weighing can be further analysed to determine the chemical or biological composition of the aerosol. The filter is placed in a filter holder, most commonly are circular and common dimensions include 13, 23, 37 and 47mm. An impactor or a cyclone can be adjusted on the inlet of the air drawn in order to collect

Figure 3.3.2 A commercially available photometer with an impactor adjusted on the inlet and an open filter cassette with a support mesh. The photometer can be fitted in an environmental exposure for outdoor measurements.

particles smaller than a specified diameter. Note that the noisiest part of all instruments is the pump, and in gravimetric measurements it may be possible to locate the pump outside.

The most commonly used direct-reading aerosol instruments that are commercially available are photometers. These instruments have many advantages over the traditional gravimetric sampler, as they provide real-time data, they are highly automated and easy to use, and in the long term are affordable. Photometers obtain concentration of airborne particles by light scattered by all particles passing through the sensing region of the instrument. Therefore, the typical laser used in many photometers limits these instruments for particles smaller than 0.25 μm (smallest detectable particles being about 0.1 μm).

A further limitation of these instruments is that the instrument does not calculate mass concentration directly, but infers the concentration based on a given particle density (most photometers are factory calibrated against a gravimetric reference using the respirable fraction of standard Arizona test dust). Therefore, without prior calibration to the specified aerosol, the quantity measured must be regarded as a very crude approximation. Gravimetric measurements can be used to define the density of the aerosol of interest. Some commercially available laser photometers incorporate a filter cassette to facilitate gravimetric measurements (Figure 3.3.2).

Radon

Residential epidemiological studies have shown consistent statistically significant increases of lung cancer risk due to exposure to radon in dwellings at moderate levels of exposure, and a strong synergism with cigarette smoking. The excess relative risk, based on long-term (30-year) average radon exposure is about 16% per increase of 100 Bq/m^3, and on this relative scale does not vary appreciably between current smokers, ex-smokers and lifelong non-smokers. On this basis WHO 2010 proposes a reference level of 100 Bq/m^3 to minimize health hazards due to indoor exposure, and 300 Bq/m^3 if the reference level cannot be achieved in the specific country's conditions.

Figure 3.3.3 A solid-state nuclear track detector (SSNTD) can be used for integrated measurement for determining average activity concentration using passive sampling and delayed analysis.

Radon activity concentration may exhibit multiple orders of magnitude over temporal and spatial variations. Exposure to radon concentrations and its decay products depends firstly on the amount of radon emitted by the soil and the building materials in each area and, secondly, on weather conditions in the areas where individuals are exposed.

Standardized methods for measuring radon-222 activity concentration and the potential alpha energy concentration of its short-lived decay products in the air are described in ISO 11665, and fall into three categories: (a) spot measurement methods (less than one hour); (b) continuous measurement methods; and (c) integrated measurement methods over a period of few days or over a period of few months.

Integrated long-term measurements are often used to assess human exposure and can be performed with a solid-state nuclear track detector (SSNTD). The method offers a cheap and reliable method applicable to large-scale investigations. Alpha particles from radon and its decay products striking the detector cause damage tracks (ISO 11665–4). The detector is a piece of special plastic or film inside a small container (Figure 3.3.3). At the end of the exposure period the container is sealed and returned to a laboratory. The plastic or film detector is treated to enhance the damage tracks (etching). Then the tracks are counted using a microscope or optical reader. The detector then shows the tracks as etching holes or cones, in a quantity proportional to the number of alpha particles that have passed through the detector. Exposure of alpha track detectors is usually 3 to 12 months, but because they are true integrating devices, alpha-track detectors may be exposed for shorter lengths of time when they are measuring higher radon concentrations.

Biological parameters

The large surface area to mass ratio of particles provides opportunities for them to act both indoors and outdoors as sinks for a variety of organic species. Bioaerosols contain allergens, viruses, bacterial, fungal cells and cellular fragments as well as by-products of microbial metabolism. The complexity of the microbial exposure assessments has probably contributed to the lack of generally applicable threshold levels for fungi and bacteria in indoor environments. There are multiple methods for air sampling for determination of biological parameters including natural deposition on a surface, rotating arm impactor, suction impactor, centrifugal sampling, and filtration sampling. Traditionally, cultivation-based analyses methods, typically in combination with short-term air sampling have been (filtration or impaction).

However, current efforts in indoor microbial exposure assessment have been developed toward using long-term integrated samples, such as settled dust, and analysis with molecular cultivation-independent methods. Settled dust offers a valuable tool for non-destructive and cost-efficient screening of indoor pollutants. Bases of methods for collecting settled dust include suction-based methods, wiping and adhesives. This subsection focuses on determination of allergen and fungal and bacterial groups in settled-dust collected with suction-based methods from surfaces above floor level, which can be considered a measure of long-term airborne exposure. The selected methods are convenient as sampling of settle dust can be performed easily by occupants with a household vacuum cleaner. The samplers can be mailed from the laboratory and mailed back without risk of material loss or contamination.

Fungal and bacterial groups

Fungi colonies may release individual spores, clusters of spores or small fungal fragments. Fungal spores constitute a significant fraction of bioaerosol microbial particles and are often 100 to 1000 times more numerous than other bio-particles.

Similarly to inorganic airborne particles, fractions smaller than 10 μm are of primary concern as they can penetrate deep in the lower airways and lungs and cause allergic reaction or infect tissues. There is strong scientific evidence linking indoor dampness, fungal growth, and health effects, such as upper respiratory tract symptoms, asthma symptoms in already sensitized asthmatic individuals, hypersensitivity pneumonitis, and SBS symptoms and increased dissatisfaction with IAQ.

Water leakage, moisture damage (Chapter 3.5) and dampness are well documented factors positively affecting microbial growth in buildings. Building characteristics, such as increasing age of building, ventilation system, and indoor finishing (such as presence of carpeting) and occupancy density may positively affect indoor microbial levels (Chatzidiakou, Mumovic and Summerfield, 2012). Therefore, environments with high occupancy density shall be investigated for microbial growth. Indoor environmental parameters that were positively associated with higher microbial concentrations were higher temperatures, CO_2 levels and RH.

In temperate climates, *Cladosporium* is the predominant outdoor fungus (accounting for 50% of the total) followed by *Penicillium*, *Aspergillus*, *Alternaria* and yeasts. The order of the last four groups may vary with location. In healthy indoor environments fungal groups are generally affected by outdoor levels, therefore, the indoor/outdoor ratio is lower or slightly higher than unity, and *Cladosporium* is the predominant fungal group. Indoor investigations for air quality may be assisted by fungal determinations, as in buildings with moisture damage and microbial growth, the ratio is much higher than 1, and *Penicillium* and *Aspergillus* are largely dominant (Figure 3.3.4).

A convenient sampler for determination of fungal and bacterial groups in settled dust is the 'sock', a nylon conical bag that can be adjusted on the nozzle of a household vacuum cleaner. The method has been used in large scale campaigns and showed high reproducibility.

Allergens

Although the role of indoor allergen exposure in the development of allergic sensitization and asthma remains unclear, there is strong evidence that indoor allergens play a key role in triggering and exacerbating allergic and asthmatic symptoms. In indoor environments where pets are not present, clothing is the primary transfer mechanism and source of pet allergens. For example, school settings can be a significant site of exposure to cat (Fel d 1) and dog allergens (Can f 1), particularly to susceptible individuals (e.g. sensitized children who have no pets at home). The number of pet owners in a room is one of the strongest predictors of increased cat and dog allergens in these settings. Additionally, cat and dog allergens have generally been found higher in carpeted floors and upholstered areas (Chatzidiakou et al., 2012). Other allergens commonly detected indoors are dust mite allergens (Case Study 3B), cockroaches, and rodent allergens, which are detected more often in low income inner-city populations.

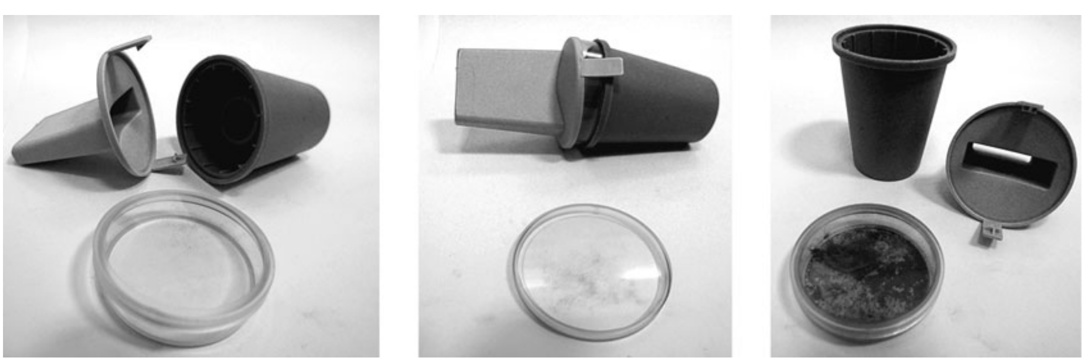

Figure 3.3.4 The ALK sampler. The collector adapted in the nozzle consists of a Petri-dish-like filter holder with the cover lid, the filter and perforated filter support at the bottom.

As seasonal variations of allergens are limited, annual investigations of indoor concentrations shall be performed, especially in indoor environments accommodating susceptible individuals. The most common sampling method for the determination of allergens is in settled dust samples. A convenient suction-based method for dust sampling is the ALK sampler (Figure 3.3.4). The ALK sampler consists of a disposable nozzle that fits on to any vacuum cleaner hose. High spatial variability among adjacent spaces requires sampling of each space individually.

Chemical parameters

Sampling of gases can be performed with commercially available direct-reading instruments, passive diffusive or active diffusive sampling. Passive diffusive sampling utilizes the process of physical or chemical adsorption on a sorbent over a period of time. Active diffusive sampling is based on the diffusion of the molecules on a sorbent undertaken by means of a suction pump to draw air through a collection medium; therefore, sampling period is much shorter (from less than an hour to a few hours). Analysis stages are essentially the same between passive diffusive sampling and active diffusive sampling. The method of choice for analysis depends on the type of pollutant. Chromatography (supplemented with different kind of detectors) and spectroscopy are generally used.

Advantages of passive diffusive sampling are the independency from mains supply, low limits of quantification, small size and noise-free operation. Moreover, installation of the samplers can be performed relatively easily by unskilled occupants and samplers can be posted to the lab for analysis.

Carbon monoxide

There is considerable evidence on human environmental and occupational CO exposure, on consequent levels of the specific biomarker COHb in blood, and on dose-effect relationships with regard to the most important health effects. The organs and tissues that are mostly affected include the brain, the cardiovascular system, exercising skeletal muscle and the developing foetus.

Carbon monoxide is produced by the incomplete combustion of carbonaceous fuels. Low levels of carbon monoxide can occur outdoors near roads, as it is produced by the exhaust of petrol- and diesel-powered motor vehicles. Parking areas can also be a source of carbon monoxide. Indoor concentrations of CO follow outdoor levels, with approximately 1h lag and a tendency not to reach either the extreme high or low values that are found outdoors. In developed countries, the most important source of exposure to carbon monoxide in indoor air is emissions from faulty, incorrectly installed, poorly maintained or poorly ventilated cooking or heating appliances that burn fossil fuels. Therefore, buildings shall be investigated for potential indoor sources.

A standard method for measurement of the concentration of carbon monoxide indoors and outdoors is by means of non-dispersive infrared spectroscopy (BS EN 14626:2012). Water and CO_2 have broad bands that can interfere with the measurement of CO. Different technical solutions have been developed to suppress cross-sensitivity including dual-cell monitors, and gas correlation spectrophotometers, which are less sensitive to the influence of interferences.

Nitrogen dioxide and ozone

NO_2 is a traffic related pollutant, and is often used as a proxy for traffic intensity in epidemiological investigations. Indoor NO_2 levels may be affected by indoor (heating and cooking with solid fuel) and outdoor sources. Outdoor levels exhibit strong spatial variations depending on the proximity to pollution sources, and temporal variation as they are affected by complex meteorological phenomena. Further decomposition reactions are aided by indoor materials and concentrations may affect indoor NO_2 levels.

In the general population there is moderate evidence that long-term exposure to an annual mean above 40 μg/m^3 of NO_2 is associated with respiratory symptoms/diseases, hospital admissions and mortality. As several recent studies reported adverse health effects below the current exposure limits for NO_2 particularly among susceptible populations (the elderly, asthmatics and children) regarding long-term exposure, it is essential to monitor personal exposure to NO_2 over long periods of time.

Ozone is formed in the atmosphere by photochemical reactions in the presence of sunlight and precursor pollutants, such as the oxides of nitrogen (NO_x) and VOCs. Several studies have shown that ozone concentrations correlate with various other toxic photochemical oxidants arising from similar sources. Collectively, epidemiological longitudinal studies have revealed positive associations between daily mortality and ozone levels. Based on evidence from these studies, provide a good case for reducing daily maximum 8-hour mean values below 100 μg/m^3. It is possible that health effects will occur below the new guideline level in some sensitive individuals.

Short-term measurements of NO_2 are generally performed with a continuous analytical monitoring instrument based on the principle of chemiluminescence (BS EN 14211:2012). Relatively few options are available for monitoring O_3 in the indoor environment, with ultraviolet absorption photometry considered as the reference-grade technology (BS EN 14625:2012). Low detectable limit makes the method suitable for concentrations in rural and urban areas. Commercially available units for instrumental sampling of NO_2 and O_3 are generally expensive, too bulky for portable operation and noisy operation could discourage their use indoors.

A cost-effective, convenient alternative for the determination of NO_2 and ozone is passive diffusive sampling with Palmes-type tubes (Figure 3.3.5). One limitation of the method is that it gives integrated measurements over a certain period (few hours to weeks) and does not provide information on peak concentrations that may have important health implications. The standardized method for passive sampling of NO_2 is based on the reaction of the compound with TEA (Tri–Ethanol–Amine) (BS EN 16339:2013) analysed with Ion Chromatography. Although standards are yet to be developed for the passive sampling of ozone, the nitrite method analysed with ion chromatography showed high correlation with ultraviolet absorption photometry in field studies.

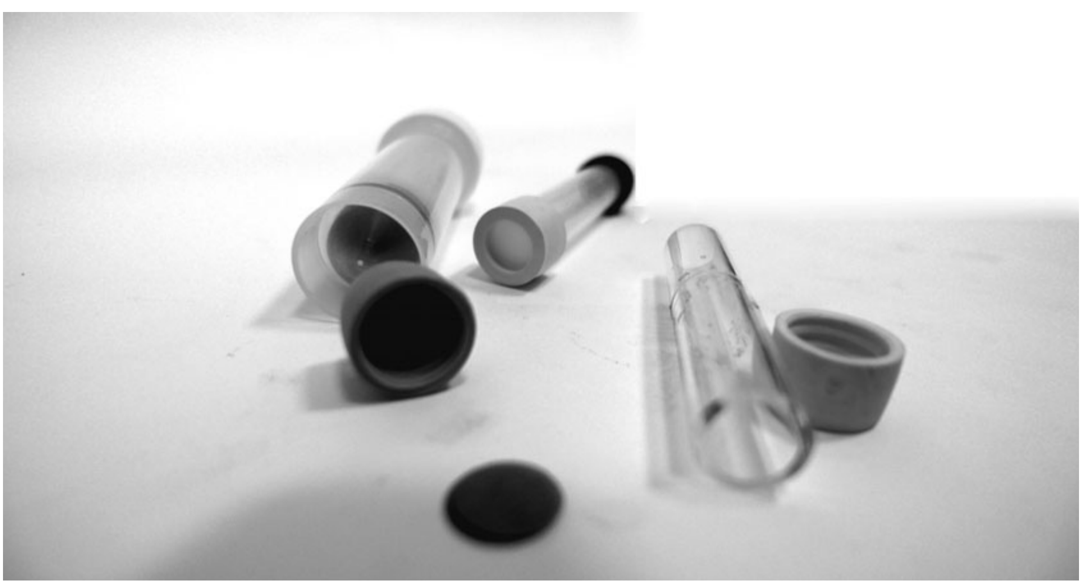

Figure 3.3.5 Palmes-type tubes for diffusive passive sampling of nitrogen dioxide and ozone.

Volatile organic compounds

There is sufficient evidence from both human and animal studies to believe that some VOCs have carcinogenic and mutagenic effects on human health. VOCs are acutely and chronically toxic at low concentrations, so symptoms may not become completely manifest for years. For example, benzene is classified as a carcinogen and no safe limit of exposure can be recommended (WHO, 2010).

VOCs include a variety of organic chemicals that are emitted as gases from certain solids and liquids. Indoor sources may be continuous or intermittent. The most important indoor continuous sources are building construction materials, furniture and textiles. Intermittent sources include occupants and a number of their activities, such as smoking and cooking. Indoor concentrations can be diluted with increased ventilation. Purge ventilation can reduce indoor concentrations to outdoor levels. Outdoor VOCs contribute to indoor air pollution, but concentrations are generally much lower.

VOCs can be up to 10 times more concentrated in indoor air compared with those in outdoor air. As it is possible to detect 50 different compounds indoors, each at a low concentration but higher than outdoors, the concept of total VOCs (TVOCs) has been introduced in existing literature (Molhave, 2009). Today, the TVOC value is widely accepted as screening parameter but is not recommended to be used as an indicator to health. Although in The UK there are not guideline values developed for indoor non-industrial environments, many countries have released threshold values in the magnitude of 200 to 600 $\mu g/m^3$.

Direct-reading TVOCs instruments are commonly performed with a flame-ionization detector (FID) or a photo-ionization detector (PID) (Figure 3.3.6). Advantages of direct-reading detectors include fast response time and ease of use. A high degree of variability of instrument performance was observed on instruments subjected to the variations of temperature, relative humidity, and concentrations. Although these instruments are useful to identify exposure sources or concentrations profiles, they should have frequent, careful calibration checks and should be validated using standards.

Figure 3.3.6 Commercially available photo-ionisation detector (PID) and environmental enclosure for outdoor measurements.

Figure 3.3.7 Radial passive diffusive samplers for quantification of volatile organic compounds.

Direct instrumental sampling does not give information on the composition of the mixture. Types of VOC samplers include badge, tube- or radial-type. Radial type samplers increase sampling rates (Figure 3.3.7). Sorbents commonly used for sampling VOCs include inorganic sorbents like silica gels, carbon-based porous materials (activated carbon) and porous organic polymers. The type of sorbent selected depends on the targeted pollutants to be determined. Recovery of the collected VOCs can be by thermal or solvent extraction. Quantification requires a Gas Chromatographer (GS) with an appropriate detector (usually mass spectrometry). Thermal desorption is easier automated and less labour intensive compared to solvent desorption.

Although formaldehyde is a VOC, it is normally sampled separately and analysed with High Performance Liquid Chromatography (HPLC), which is one of the most rapid and sensitive methods (ISO 16000-4: 2012). The formaldehyde vapour migrates into the sampler, which is impregnated with 2,4-dinitophenylhydrazine (DNPH). Although the method is designed to eliminate potential interference from other compounds, the risk of ozonolysis is increased at high ozone concentrations.

Conclusion

While currently regulations focus on energy performance of buildings, it is expected that in the foreseeable future evaluation of IAQ will be part of the standard requirements of Building Regulations. This chapter focused on cost-effective, non-disruptive screening methods for a forensic comprehensive investigation of IAQ. Selected pollutants are often found in indoor environment, and are known for their hazardousness to health, and they are reliable indicators of indoor and outdoor sources.

Estimated ventilation rates and CO_2 may provide a first indication of exposure and sensory irritations, as they are reliable proxies for the dilution of pollutants with indoor sources that built-up at lower ventilation rates. However, indoor CO_2 levels alone are poor predictors of traffic-related pollutants penetrating indoors and biological contamination. In line with previous epidemiological investigations, we propose long-term measurements of indoor NO_2 as an indicator of exposure to motor-vehicle emissions, particularly in buildings accommodating susceptible populations. A guide for radon management should include, in addition to the setting of a reference level, building codes, measurement protocols and other relevant components of a national radon programme. Determination of indoor VOCs levels with direct-reading instruments and passive diffusive sampling may contribute to the identification of potential indoor pollution sources. Finally, determination of fungal and bacterial groups in settled dust can be performed with molecular non-culturable methods and may provide a screening method of potential microbial growth. Annual allergen investigations determined in settled dust may raise the need for remedial measures to protect vulnerable groups.

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3.4

MODELLING VENTILATION AND INDOOR AIR QUALITY IN BUILDINGS

Ian Ridley

Introduction

Over the last 30 years two interrelated themes have become of increasing interest to those designing, commissioning and indeed using buildings; the need for energy efficiency and the provision of adequate indoor air quality. Both are intrinsically linked together via the ventilation regime of the building. The energy used to supply and condition fresh air to a building can be a significant contribution to the carbon footprint of a building, while the resultant ventilation rate along with the strength of pollutant sources will determine the level of indoor air quality (IAQ).

The ability to be able to predict building ventilation rates and the subsequent impact on both energy use and IAQ is therefore highly desirable. Computer-based simulation tools provide a suitable methodology of calculating air flows, in both naturally and mechanically ventilated buildings and their impact on pollutant concentrations, allowing the adequacy of designs and strategies to be assessed in terms of the energy and IAQ performance.

This chapter is intended to be a brief introduction to the use of such models, raising some issues that the novice practitioner should be aware of. For further information readers should refer to (Feustel, 1998; Liddament, 1986; Musser, 2001; Persily, 1998; Persily and Ivy, 2001; Persily and Martin, 2000).

Types of application

Building regulations and design briefs often demand that specific performance criteria are met by a building in terms of energy consumption and IAQ. Ventilation rates, temperatures, relative humidity and pollutant concentration targets all may need to be met. In naturally ventilated buildings, the ventilation rate will be driven by factors such, external and internal temperature, wind speed and direction, area of ventilation opening, all of which are subject to transient variation, as such the building will have a distribution of performance, with ventilation rate and IAQ levels varying throughout the year. As an example (modelled by the author), the distribution of predicted heating season air change rate in an air tight, naturally ventilated house with a background air permeability of $3m^3/m^2h$ @ 50Pa, located in the UK is given in Figure 3.4.1.

If performance-based standards are to be used to assess the success of a building design simulation can be used to predict how the building will perform under different weather conditions and with varying occupant use, both in terms of pollutant loads and interaction of the occupant with the ventilation system.

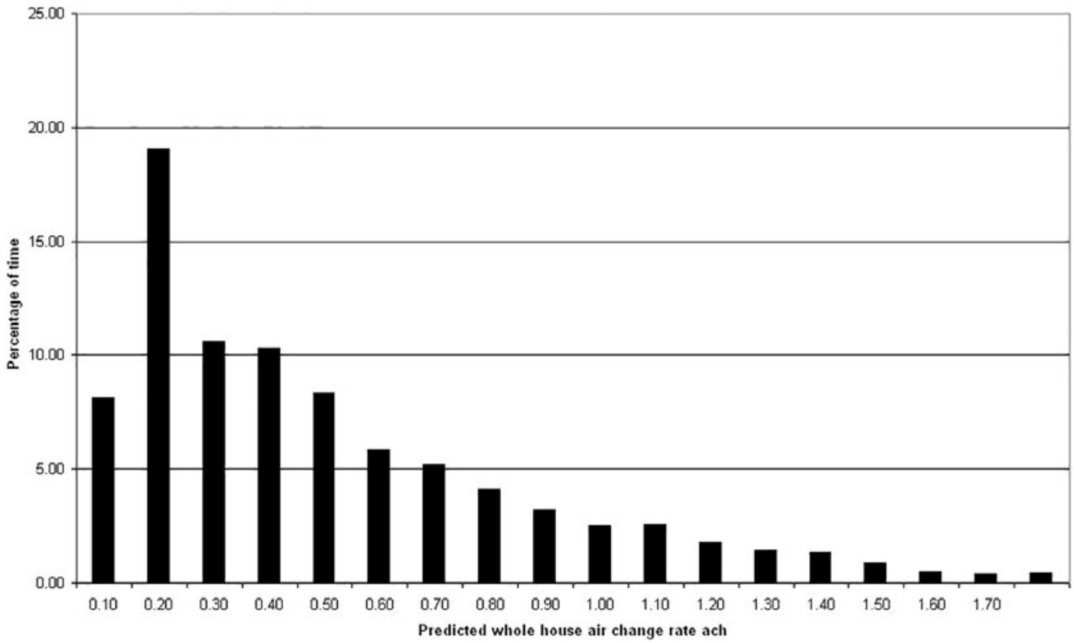

Figure 3.4.1 Distribution of predicted heating season air change rate.

The exposure of occupants to different pollutants under different scenarios of pollutant source strength and profiles in conjunction with varied patterns of available ventilation can be estimated and compared to recognised guidelines and recommended limits. Similarly, the risk of condensation and likelihood of mould growth or house dust mite infestation can be examined by predicting the relative humidity as a result of moisture production and achieved ventilation rate.

Demand controlled ventilation, which aims to reduce energy consumption by matching the ventilation rate to the actual need, by its very definition assumes that that ventilation rates will, vary according to the conditions within a building within a specific time. The need for simulation tools to include elements of control and feedback is therefore apparent.

Types of model

There are typically four types of models that can be considered to be of use in this area.

i) In their simplest form, thermal and energy simulation models, will predict the consequences of a pre-defined or specified ventilation rate on temperature and energy consumption, pollutant prediction will often be limited only to consideration of moisture.
ii) Airflow and contaminant models will predict, air flows and subsequent pollutant concentrations within zones, but will not predict energy consumption and zone temperatures will often need to be user defined.
iii) Integrated Airflow and thermal models, have greater capabilities to model the effects of temperature on ventilation rates and vice versa, allowing the energy consumption in naturally ventilated systems to be more accurately measured, however their contaminant modelling capabilities is not as advanced as type ii models.

iv) Finally, zonal models have the ability to model pollutant concentrations and temperature distributions within zones, predicting airflows in great detail at a high spatial and temporal resolution. In terms of complexity zonal models can be considered to lie between single node air flow and full CFD models, producing distributions of temperature and contaminants without the time penalty of full CFD treatment. The room, or zone, is sub divided into a number of small cells, to which the equations of conservation of heat and mass are applied.

Each type has advantages and disadvantages, for some applications where both energy and pollution concentrations are required a combination of using the different approaches may be necessary. In this chapter, we will focus on the use of airflow and contaminant models, and integrated thermal and airflow models. Examples of such models are CONTAMW (NIST, 2008), and Energy Plus (EERE, 2008). A comprehensive list of building energy and ventilation tolls can be found on the Building Energy Software Tools Directory (BESTD, 2008).

Multi zone indoor air quality and ventilation tools are typically designed to predict:

(a) Whole building infiltration and ventilation rates due to mechanical systems, wind pressures and stack effects, and air flow between zones.
(b) The concentration of pollutants, from both internal and external sources in each zone, the transport of pollutants between zones. The predicted concentrations may then be used to estimate occupant and artefact exposure to these contaminants.

Validation and testing

As with all simulation models it is important that that testing and validation studies are carried out to inform potential users of the confidence they can place on the results of such models and to identify and solve possible sources of error. Multi zone air flow and contaminant models have been subject to some validation and comparison exercises (Fiirbringer, Roulet and Borchiellini, 1996). It should be noted that the level of effort and instrumentation required to produce experimental data of sufficient quality to test ventilation models is a challenge even in highly controlled and monitored environmental chamber.

It is, however, important to note the need for further validation work, under a wider range of weather conditions and for a varied range of both systems and applications is still required. Analytical tests, comparing simulation results with exact analytical solutions are possible; however, they are limited to only the simplest of multi zone buildings. A series of inter model comparisons between a number of software tools have been undertaken to allow the relative consistency between models to be assessed. Empirical validation against experimental data has also been carried out for a small number of cases (Emmerich, 2001), such studies conclude that a knowledgeable user can make reasonable predictions of air change rates and contaminant concentrations for residential-scale buildings.

Creating the model

As with all simulation tools the reliability of the output of ventilation and contaminant models is intrinsically governed by the quality of input data used. The input required in order to model the air flow and subsequent contaminant concentrations in a building can be broken down into the following sub groups.

Building dimensions and orientation

The volume and floor area of each zone to be modelled are needed, as are the heights of each floor, and the orientation of each façade.

Weather file

The simulation is driven by a steady state or transient weather file, usually with hourly resolution. This file includes external temperature and relative humidity, wind speed and direction, and external pollutant concentration. As with weather files used to drive thermal and energy building simulation tools, test reference years for particular locations may be used. Historical hourly external pollution data from networks of automatic monitoring sites can now be readily downloaded to create external pollution concentration input files.

Openings and flow elements

Details must be given of the cracks, openings and ventilation, through and for which the airflow will be calculated. Openings and cracks may be defined in terms of an opening area and discharge coefficient or by a flow exponent and flow coefficient

Zonal infiltration models are based on an empirical (power law) relationship between the flow and the pressure difference across a crack or opening in the building envelope. If the flow characteristics, the flow coefficient and exponent, of a building element are known, either from experiment or from tabulated values, the air infiltration due to the element may be calculated as a function of pressure difference.

$$Q = C\{\Delta P\}^n$$

where:

Q = Flow (m^3/s)
C = Flow coefficient
ΔP = Pressure difference (Pa)
n = Flow exponent

The flow exponent should be entered with a value between 0.5 and 1.0, with larger openings commonly having a value of 0.5, and small gaps and cracks being given a value closer to 0.65. Similarly, if the flow element is defined in terms of its opening area and flow characteristic, the flow may be expressed by the following equation, where the discharge coefficient for openings with sharp edges is typically 0.6

$$Q = C_d A \left\{\frac{2\Delta P}{\rho}\right\}^{0.5}$$

where:

Q = Flow (m^3/s)
C_d = Discharge coefficient
ΔP = Pressure difference (Pa)
ρ = Air density (kg/m^3)

Simple mechanical systems such as extract fans can be defined in terms of a constant flow rate or in terms of performance curves. The height of the flow element in a zone must be provided.

A simple method of incorporating the gaps and cracks in a building which contribute to the background air permeability, is to distribute them equally around the building façade. The results of a fan pressurisation test or a target air permeability value may be used. The permeability can be distributed between zones according to the proportionate façade area. It is common practice to insert permeability at high and low level within each zone.

As an example, the flow characteristics of domestic ventilation devices such as background trickle ventilators are measured by a protocol outlined in CEN Standard (CEN TC 156), Ventilation for Buildings, more specifically prEN13141-1, refers to 'The performance characteristics of the components/ products for residential ventilation.' The flow exponent, flow coefficient and equivalent opening areas of such products are freely available from manufacture specification sheets.

Wind pressure coefficients

One of the aims of using zonal air flow models is to predict the air flow through cracks and openings, in the building, and hence the ventilation rate due to the action of wind. The wind pressure exerted on the façade of a building can be approximated using the following equation, using the wind speed in the weather file, modified by the local terrain, and wind pressure coefficients related to the form of the building (ASHRAE, 2001)

$$P_w = \frac{\rho V_{\mathrm{met}}^2}{2} A_{\mathrm{o}}^2 \left(\frac{H}{H_{\mathrm{ref}}}\right)^{2a} f(\theta)$$

where:

P_w = Wind pressure (Pa)
ρ = Air density (kg/m^3)
V_{met} = Reference wind speed (m/s)
A_o = Terrain coefficient
a = Terrain exponent
H = Wall height (m)
H_{ref} = Reference wind speed height (m)
$f(\theta)$ = Wind pressure profile
θ = Relative wind angle

Wind pressure coefficients are dimensionless and vary as a function of wind direction. For real buildings wind pressure coefficients can be measured on site by correlating the output of pressure sensors on the building façade, with locally measured wind speed and direction. Alternatively, wind tunnel studies of scale models may be used. In most simulation applications, a 'standard' set of wind pressure coefficients for standard building formats, will be taken from databases and tables (ASHRAE, 2001).

Zone temperature

The temperature of each zone is another important determinant of the airflow in the building, and as such needs to be defined by the user. The stack pressure exerted by cold air entering at low level rising and exiting at high level can be approximated using the equation

$$P_s(T_o,h) = \rho g\left(H_{NPL} - h\right)\frac{T_i - T_o}{T_i}$$

where:

P_s = Stack pressure (Pa)
g = Acceleration due to gravity (ms^{-2})
H_{NPL} = Neutral pressure level (m)
T_i = Internal temperature (ºC)
T_o = External temperature (ºC)

The main advantage of using integrated airflow and thermal models, such as Energy Plus, is precisely that the internal temperatures will be calculated as part of the simulation. Such software will of course require further input, at a level of details required to perform a full thermal and energy simulation. Therefore, the thermal properties of the fabric both opaque and transparent will be requires, along with details of any heating or cooling equipment. Similarly, a more detailed weather file including solar radiation data will be required to run such a simulation. When using air flow and contaminant models, such as CONTAM, which do not have an integrated thermal modelling capability, internal temperatures can be user defined, or the output of building simulation can be used as input.

Contaminants

Sources of individual contaminants can be defined in each zone. These may have a constant emission rate, or a variable rate which is controlled by a release schedule. Contaminants could come from the building occupants, the fabric and fittings or from appliances.

The most commonly considered contaminants from occupants are carbon dioxide, bio effluents, and moisture. The building fabric and its fixtures and fittings can be a source of volatile organic compounds. Combustion appliances such a gas cookers and boilers are sources of carbon monoxide, nitrous oxides, whereas appliances such a photocopiers and laser printers can be sources of ozone.

A large literature exists on the measurement of pollutant source strengths from building materials, often made in environmental chambers. In certain specific modelling tasks, a user may wish to enter user defined schedules based on a specific scenario. Often however a modeller may wish to assess the effectiveness or adequacy of a proposed building or ventilation design when challenged by a standardised contaminant emission rate. It should be recognised that the task of simulating and then assessing IAQ would be greatly aided if there was a consistent and recognised database or library of common pollutant source rates and schedules. As an example of how to approach the construction of a contaminant source schedule for a dwelling, the following examines the creation of a moisture production schedule for a three-bedroom house occupied by two adults and two children.

Moisture production schedule

The following tables present the results of an extensive literature review, of published academic and papers and national standards, designed to gather information on moisture production rates from domestic activities. The sources of moisture were, split by the following household activities:

- Occupant breathing and sweating (Table 3.4.1)
- Cooking (Table 3.4.2)
- Clothes washing (Table 3.4.3)
- Washing of floors and surfaces (Table 3.4.4)
- Washing dishes (Table 3.4.5)

Table 3.4.1 Moisture production due to occupant breathing and sweating.

Author	*Moisture production rate per person*
BS5250	Asleep 40g/h Awake 55g/h
Annex 27	Adult asleep 30g/h Adult awake 55g/h Child asleep 12.5g/h Child awake 40g/h
Finbow, 1982	0.752kg/day
BRE, 1985	Person asleep 0.25–0.5kg/day Person active 0.75–1.5kg/day
CIBSE, 2006	0.96–2.4kg/day 40–100g/h
Boyd, Cooper and Oreszczyn, 1988	0.7475kg/day
Angell and Olson, 1988	1.26kg/day
Stum, 1992	1.44kg/day
Lstiburek, 1993	65g/h
Hanson, 2002	180g/h
Trechsel, 2001	Light activity 30–120g/h Medium 120–200g/h Heavy activity 200–300g/h
Rousseau, 1984	50g/h
Yik, Sat and Niu, 2004	40–100g/h
Pretlove, 2000	Asleep 40g/h Awake 55g/h

- Drying clothes (Table 3.4.6)
- Bathing
- Indoor plants

It can be seen that the moisture production rates within each category although consistent, reflect a large range, dependent upon occupant activity and more fundamentally on the intensity of moisture production. When designing the schedule, the user must consider if an average or extreme scenario is to be considered. After gathering data on production rates associated with different household activities, the next step is to assign specific activities to the most relevant room or zone at a specific time. An example production schedule in dwelling that produces a relatively high daily moisture load of 9kg is presented by source in Table 3.4.7, and by room in Table 3.4.8.

In a similar manner schedules can be built up for gaseous pollutant from cooking or combustion appliances. First, the user goes to published databases on the relevant emission rates, and then a time specific schedule is produced.

As well as the sources of contaminants, the user should also be aware of contaminant sinks, which can act to remove pollution from buildings. As an example, the fabric and furnishings within a building will act as a buffer, absorbing and releasing moisture. This effect should be taken into account when modelling indoor relative humidity. CONTAM includes a boundary layer diffusion model, which may be used to take moisture buffering into account. The issue of moisture buffering in buildings has been covered in depth by Annex 41, Whole Building Heat, Air and Moisture Response (Woloszyn and Rode, 2008). Energy Plus incorporates an effect moisture penetration depth model (EMPD) to account for moisture buffering (Crawley et al., 2001).

Table 3.4.2 Moisture due to cooking.

Author	*Moisture production rate per person*
BS5250	Gas 3kg/day Elec 2kg/day
Annex 27 (includes dishwashing)	Breakfast 50g/h Lunch 150g/h Diner 300g/h
Finbow, 1982	0.6kg/day
BRE, 1985	0.5–1kg/day
CIBSE, 2006	0.9–3kg/day
Boyd et al., 1988	Gas 3kg/day Elec 2kg/day
Angell and Olson, 1988	Gas 1.35kg/day Elec 1.0kg/day
Lstiburek, 1993	Breakfast gas/elec 520/200g/day Lunch gas/elec 300/680g/day Diner gas/elec 700/1600g/day
Hanson, 2002	0.920kg/day
Trechsel, 2001	1.5kg/day
Rousseau, 1984	950kg/day
Pretlove, 2000	Gas 0.55kg per person per day Elec 0.38kg per person per day

Table 3.4.3 Moisture due to washing clothes.

Author	*Moisture production rate per dwelling*
BS5250	0.5kg/day
Annex 27	0.2kg/day
Finbow, 1982	1.0kg/day
BRE, 1985	0.5–1.0kg/day
CIBSE, 2006	0.5–1.8kg/day
Meyringer, 1985	0.15kg/day
Boyd et al., 1988	0.5kg/day
Stum, 1992	0.63kg/day
Hanson, 2002	1.96kg/day
Pretlove, 2000	0.5kg/day

Table 3.4.4 Moisture from washing floors/surfaces.

Author	*Moisture production rate per dwelling*
CIBSE, 2006	1.0–15kg/day
Angell and Olson, 1988	0.15kg/m^2 cleaned
Stum, 1992	0.14kg/day
Lstiburek, 1993	0.18kg/ m^2 cleaned
Hanson, 2002	0.15kg/m^2 cleaned
Trechsel, 2001	0.12kg/m^2 cleaned
Rousseau, 1984	0.13kg/m^2 cleaned
Yik et al., 2004	0.05kg/m^2 cleaned
Pretlove, 2000	0.22kg per person per day

Table 3.4.5 Moisture due to washing dishes.

Author	*Moisture production rate per dwelling*
BS5250	0.4kg/day
Annex 27	(included in cooking)
Burberry, 1994	0.4kg/day
CIBSE, 2006	0.15–0.45kg/day
Boyd et al., 1988	0.4kg/day
Lstiburek, 1993	0.15kg/day
Hanson, 2002	0.45kg/day
Rousseau, 1984	0.5kg/day
Yik et al., 2004	0.08kg/day
Pretlove, 2000	0.113kg per person per day

Table 3.4.6 Moisture due to drying clothes.

Author	*Moisture production rate per dwelling*
BS5250	1.5kg/day per person
Annex 27	2kg/day
CIBSE, 2006	5–14kg/day
Stum, 1992	1.5kg/day per person
Lstiburek, 1993	2.5–3.4kg/load
Hanson, 2002	11.9kg/day
Trechsel, 2001	2.2–2.9kg/load
Rousseau, 1984	1.74kg/day
BRE, 1985	3–7.5 kg/day
Yik et al., 2004	16kg/day
Pretlove, 2000	2.5kg/load

Table 3.4.7 Moisture production by source.

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Number of people	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1	1	2	2	2	3	3	3	3	3
Moisture gen. rate/person	40	40	40	40	40	40	40	40	40	55	55	55	55	55	55	55	55	55	55	55	55	55	40	40
Tot. moisture - people	120	120	120	120	120	120	120	120	120	55	55	55	55	55	55	55	110	110	110	165	165	165	120	120
Cooking									600					600					1000	1000				
Bathing								400													200			
Dishwashing									200												200			
Washing clothes											250	250												
Drying clothes indoors													250	200	150	100	100	100	100	100	100	100	100	100
Plants	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Tot. moisture(g)	130	130	130	130	130	130	130	530	930	65	315	315	315	865	215	165	220	220	1220	1275	675	275	230	230

Table 3.4.8 Moisture production by room.

Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Bed 1	80	80	80	80	80	80	80																80	80
Bed 2	40	40	40	40	40	40	40																40	40
Bathroom								400					83	67	50	33	33	33	33	33	233	33	33	33
Living room	10	10	10	10	10	10	10	93	93	38	38	38	121	104	88	71	98	98	98	126	126	136	43	43
Kitc								83	883	28	278	278	111	694	78	61	88	88	1088	1116	316	116	33	33
Tot. moisture (g)	130	130	130	130	130	130	130	575	975	65	315	315	315	865	215	165	220	220	1220	1275	675	275	230	230

Output and analysis

Having run the simulation, the output data must be analysed using a suitable set of metrics and criteria to assess if adequate ventilation and IAQ performance is being achieved. The output of the models may well be large in both size and temporal resolution. Typically, the user will be able to export the transient air flows predicted for each ventilation element, and the transient pollutant concentration in each zone. The air flows may be converted into zonal or whole building air change rates, which can be plotted as a frequency distribution, showing the expected range of ventilation availability achieved in a building on an annual or heating season basis. Such a distribution can be used to assess what percentage of time the building is under or over ventilated. If an integrated thermal and airflow model is being used, which does not have the ability to model pollutant concentrations, the predicted ventilation rate will be the basis of analysis. In dwellings the hourly air change rates can be compared against recommended domestic ventilation rates of 0.5–1.00 ach^{-1} as described in BS5250 (BSI, 2005) and CIBSE Guide B2 (CIBSE, 2006).

Ventilation rates achieved, represented by air change rates, or litres/person may be compared to those recommend e by local standards or targets. Some recommended ventilation rates are summarised in Table 3.4.9.

Another useful predictor of IAQ is indoor relative humidity, which will be commonly available as an output of integrated thermal and airflow models. Several criteria exist to predict the risk of mould as a result of indoor RH. The Building Regulations for England and Wales state that '*the moisture criterion will be met if the relative humidity (RH) in a room does not exceed 70% for more than 2 hours in any 12 hour period, and does not exceed 90% for more than 1 hour in any 12 hour period during the heating season*'.

IEA Annex 14 was an extensive body of work that looked in detail at the issue of mould growth in buildings. It suggests a 'long-term' (monthly) limit the average air RH 70% in line with BS5250. The condition under which mould germinates and grows may be represented by a series of isopleths (Sedlbauer, 2001). The predicted RH may be compared to these isopleths and used as input to mould prediction models such as WUFI-bio (WUFI, 2005), such an approach has been used to examine mould growth in UK dwellings (Altamirano-Medina, Davies, Ridley, Mumovic and Oreszczyn, 2008).

Table 3.4.9 Comparison of recommended domestic ventilation rates.

Country standard reference	*Whole building ventilation rates*	*Living room*	*Bedroom*	*Kitchen*	*Bathroom & WC*	*WC only*
Belgium (NBM D50–001 1991)	1l/s/m^2 of floor area with specific values for kitchen, WCs & bathrooms	Supply 1l/s/m^2 maybe limited to 150m^3/h	Supply 1l/s/m^2 maybe limited to 36m^3/h	Exhaust 1l/s/m^2 maybe limited to 75m^3/h	Exhaust 1l/s/m^2 maybe limited to 75m^3/h	Exhaust 25m^3/hr
Canada NBC 2005 based on (F326,1-M1989)	> 0.3 ach 5l/s/p		Prescribed principal exhaust "solutions" at rates based on number of bedrooms (like ASHRAE 62.2/2004)	Exhaust 50l/s Inter 30l/s cont.	Exhaust 50l/s Inter 30l/s cont.	
Denmark BR 2005	0.5 ach	Clear opening min 30cm^2 per 25m^2 floor area		Exhaust 20l/s	Exhaust 15l/s	Exhaust 10l/s
Finland Finland (NBC-D2, 2003)	Exhaust figures air flows can be reduced when the spaces are not in use provided that the whole dwelling is greater than 0.4 ach and min air flow rates in bedrooms and living rooms are fulfilled	0.5 l/s/m^2	6.0l/s/p or 0.35l/s/m^2 floor area	Exhaust 10l/s (cont.) 15l/s (boost)	Exhaust 7l/s (cont.) 10l/s (boost)	
France				Continuous: 20–45m^3/h Intermittent 75–135m^3/h	15–30m^3/h	15–30m^3/h
Netherlands Building Decree (NB dm^3/s~ l/s)		0.9 dm^3/s/m^2 floor area	0.9 dm^3/s/m^2 floor area	21dm^3/s	14dm^3/s	7dm^3/s
New Zealand (ASHRAE 62–1999)	0.35 ach min 7.5l/s/person			Continuous: 12l/s Intermittent 50l/s or openable window	Continuous: 10l/s Intermittent 25l/s or openable window	

Table 3.4.9 continued.

Country standard reference	*Whole building ventilation rates*	*Living room*	*Bedroom*	*Kitchen*	*Bathroom & WC*	*WC only*
Sweden (BFS 1988:00) Update 2006	Requirements: Rooms shall have continual 0.35l/s/m^2 floor area when in use		Recommendation: < 4l/s/bed place	Recommendation: Extract 10l/s	10l/s with openable window or 10l/s with high speed rate up 30l/s or 15l/s without openable window	
Switzerland SIA 180:00	15m^3/h/p (non-smoking)					
England and Wales ADF 2006	13l/s 1 bed 17l/s 2 bed 21l/s 3 bed 25l/s 4 bed 29l/s 5 bed Minimum ventilation rate not less than 0.3l/s per m^2 of floor area	Rapid vent: 1/20th of floor area Background vent: 8000mm^2	Rapid vent: 1/20th of floor area Background vent: 8000mm^2	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates 30l/s adjacent to hob or 60l/s elsewhere or PSV	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates 15l/s or PSV	Rapid vent: Opening window Background vent: 4000mm^2 Extract vent rates 15l/s or PSV
USA (ASHRAE 62–99 Amended 2005)	0.35 ach min 7.5.l/s/person			Continuous: 12l/s Intermittent: 50l/s or openable window	Continuous: 10l/s Intermittent: 25l/s or openable window	
German Passive House	Recommend a supply flow rate of 30 m^3/h per person (8.5l/s, person) and the system should also allow for a minimum air supply setting for times with no occupancy, with a corresponding air flow rate of 0.2h^{-1}					
Swedish Passive House	0.5 ach					

The concentrations of other pollutants, such as formaldehyde and carbon monoxide, should be compared against the recommended World Health Organisation (WHO) acceptable level of concentrations within the dwellings (WHO, 2000). The predicted level of carbon dioxide is often used as a proxy measure for the adequacy of IAQ, indoor levels of CO_2 > 1,000ppm suggest inadequate ventilation rates within an occupied space (Manson, 1995).

Summary

Ventilation modelling provides a valuable theoretical method for assessing the performance of domestic ventilation systems, both in terms of ventilation rates achieved and the resultant indoor air quality. For these models to become more widely used accepted as a reliable method of assessing IAQ and ventilation rates in buildings there is a need for continued testing and validation. The production of benchmarks and common exercises, which could be used as tutorials and learning material for novice modellers would be very welcome. The creation of common methodologies, accepted best practice, and competent person schemes, for the use of such models should also be promoted especially if such tools are to be used in the future as possible compliance tools to assess performance-based building and ventilation regulations.

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3.5
MOISTURE CONTROL IN BUILDINGS

Hugo L. S. C. Hens

Introduction

Moisture is responsible for 70 to 80% of all damage in buildings. Thus, correct moisture control is a prerequisite for getting sustainable buildings. True control, however, is only possible if we know how moisture is transferred to and moves in building assemblies and how assemblies degrade when staying moist.

Why is water such an aggressor? The reason is its asymmetric molecular structure, with the one oxygen atom and the two hydrogen atoms forming a very active dipole. That turns water into an effective solvent and explains why it adheres easily to surfaces. Water further-on has its triple point at 0°C, which means that freezing starts there, a phase change causing 10% volumetric expansion. The equilibrium between solid, liquid and vapour also causes condensation to appear at normal environmental temperatures.

Terminology

Before expanding on sources, transfer, damage and design, first some terminology is clarified (Hens, 2007).

The term 'density' is used for weight per m^3 of dry material. The many microscopic small voids in a material, fix its 'porosity'. Only part of these voids may be assessable for water molecules, quantifying the 'open porosity'.

The word 'moisture' relates to water in its three states (vapour, liquid, solid) with inclusion of all substances, such as salts, dissolved in it. Moisture in vapour form is present in all materials with open pores wider than 0.23 Angstrom. Liquid moisture demands larger open pores. In fact, water molecules form chains in the liquid phase with larger effective diameter.

To describe the presence of moisture in open porous materials, different definitions travel around:

Moisture content	kg/m^3	The mass of moisture per cubic meter of material
Moisture ratio	%kg/kg	The mass of moisture per unit mass of dry material
Volumetric moisture ratio	$\%m^3/m^3$	Cubic meter of moisture per cubic meter of material
Saturation degree	%	Ratio between moisture content and moisture content at saturation

Although pointing to a same reality, the numerical values may be quite different. Take a brick with density $1800kg/m^3$ and a moisture content of $200kg/m^3$. The moisture ratio than is: $100 \times 200/1800 = 11.1\%kg/kg$, while for the volumetric moisture ratio, one gets: $100 \times (200/1000) = 20\%m^3/m^3$.

11.1 is a smaller number than 20 and 200. As moisture worries, smaller looks better, so use it without units! For materials with density below 1000 kg/m^3, volumetric moisture ratio gives the smaller number and becomes the favourite. To avoid such confusion, following rules are forwarded:

- For open-porous, stony materials, use moisture content
- For timber-based materials, use moisture ratio in %kg/kg
- For extremely porous materials, use volumetric moisture ratio in %m^3/m^3

Water vapour in the air

Dry air and water vapour both behave more or less as ideal gasses:

For air: $p_a V = 287 m_a T$ For water vapour: $pV = 462 m_v T$

with V the volume considered (in m^3), m_a mass of air and m_v mass of water vapour in that volume (in kg) T temperature in Kelvin, p_a partial dry air pressure in Pa and p partial water vapour pressure in Pa, further called vapour pressure.

Humid air being a mixture of ideal gasses, total pressure obeys Dalton's law: equal to the sum of both partial pressures. Under atmospheric conditions the mixture is exactly defined when two state variables are known, for example temperature in °C and vapour pressure in Pa. As air is hardly soluble in water,

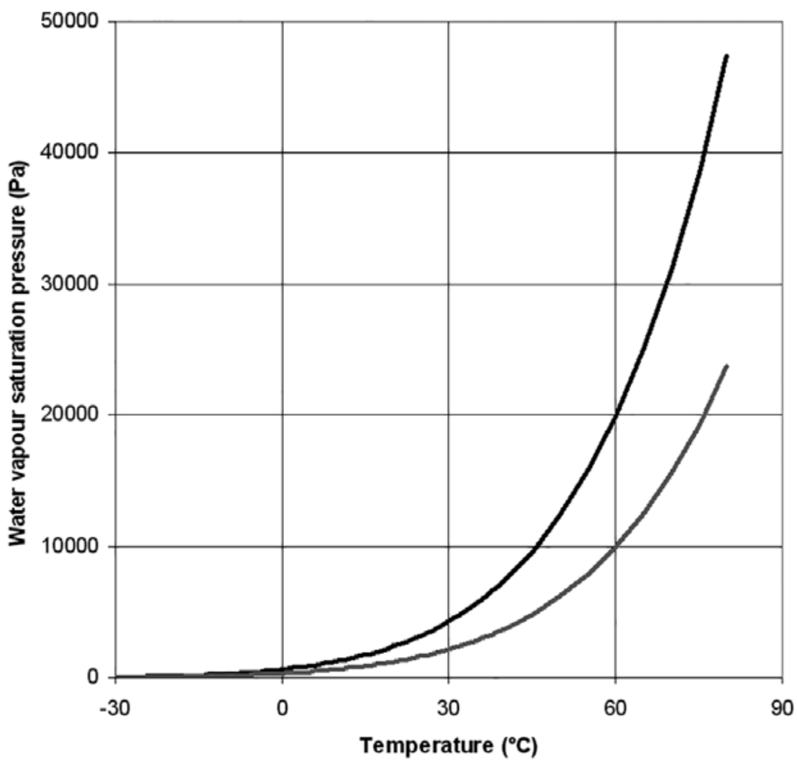

Figure 3.5.1 Water vapour saturation pressure as a function of temperature.

the mixture is characterized by a same vapour saturation pressure as in vacuum (Figure 3.5.1). Vapour pressure cannot attain a higher value in humid air at given temperature. Adding more water vapour than saturation allows, will cause condensation to happen.

Widely used as a concept is relative humidity: the ratio between the actual vapour pressure in the air and the vapour saturation pressure at the air's temperature:

$$\phi = \frac{p}{p_{\text{sat}}(\theta_a)}$$

A relative humidity 1 or 100% means saturation. The value may shift between 0% and 100%. In Figure 3.5.1 for example, the 50% line is drawn.

Two very specific changes of state could start condensation:

- Adding vapour to the air volume at constant air temperature. The starting point in Figure 3.5.1 then moves parallel to the pressure axis. At a given release, the saturation line is touched, and condensation

Table 3.5.1 The moisture and air saturation degree scale.

S_m %	S_a %	*Meaning*
0	1	**Dry material** Complete drying is physically impossible. Dry always means: nearly dry
$0 \geq S_m \geq S_{m,H}$	–	**Hygroscopic interval** Porous materials see their moisture saturation degree crossing that interval when in contact with humid air. Resulting moistening looks as sketched in Figure 3.5.2, with a hysteresis between sorption and desorption. Two phenomena shape the curve: molecular adsorption against all pore walls at low relative humidity and capillary condensation at higher relative humidity.
$S_{m,cr}$	–	**Critical moisture saturation degree** Marks the border between moisture in the pores transported from as vapour only and moisture transported in liquid form. The critical moisture saturation degree limits the moisture saturation degree in a porous material by interstitial condensation and helps explaining the transition from surface drying to drying from inside the material.
$S_{m,c}$	$S_{a,cr}$	**Capillary moisture saturation degree** Stands for the moisture saturation degree a porous material attains when remaining in contact with a water surface. Once capillary saturated the escape routes for all air pockets left are closed, shutting off outflow. The air saturation degree is therefore called critical.
$S_{m,c} \geq S_m \geq 1$		**Beyond capillary** The interval is reached when a material goes on contacting water without any drying possibility or when submersed in water. In fact, as time goes on, the air pockets left slowly dissolve in the sucked water. The critical moisture saturation degree for frost damage (Sm,cr,fr) sits somewhere in that interval Below, frost damage is unlikely, above, probability turns to 1.
S_m=1	S_a=0	**Saturation** Arriving there is only possible through special treatment, such as saturating the material while vacuum-sucked, or, boiling it in water. Anyhow, once saturated, i.e. once all open pores filled with liquid, the air saturation degree is definitely zero.

starts, while vapour pressure remains at saturation value. Such isothermal change of state more or less happens in a bath room during showering, when the mirror becomes misty.

- Keeping the amount of vapour in the air constant and lowering temperature. Crossing the saturation line happens then at a certain temperature. That temperature is called the dew-point, a word that reflects grass wetted during clear summer nights.

Of course, infinite other changes of state will cause condensation. Adiabatic humidification for example is used to measure humidity in the air as it forces the air temperature to drop to a value called wet bulb temperature (*θwb*). A psychrometer measures that quantity plus the air temperature. Transposition to vapour pressure gives:

$$p = p_{\text{sat}}(\theta_{wb}) - 66.71(\theta_{db} - \theta_{wb})$$

Air and moisture scale

As said, pores in building materials may be open or closed. Empty open pores are filled with humid air. Starting from dry, pores get filled stepwise with their moisture saturation degree (S_m) crossing some typical intervals and values, coupled with a changing air saturation degree (S_a).

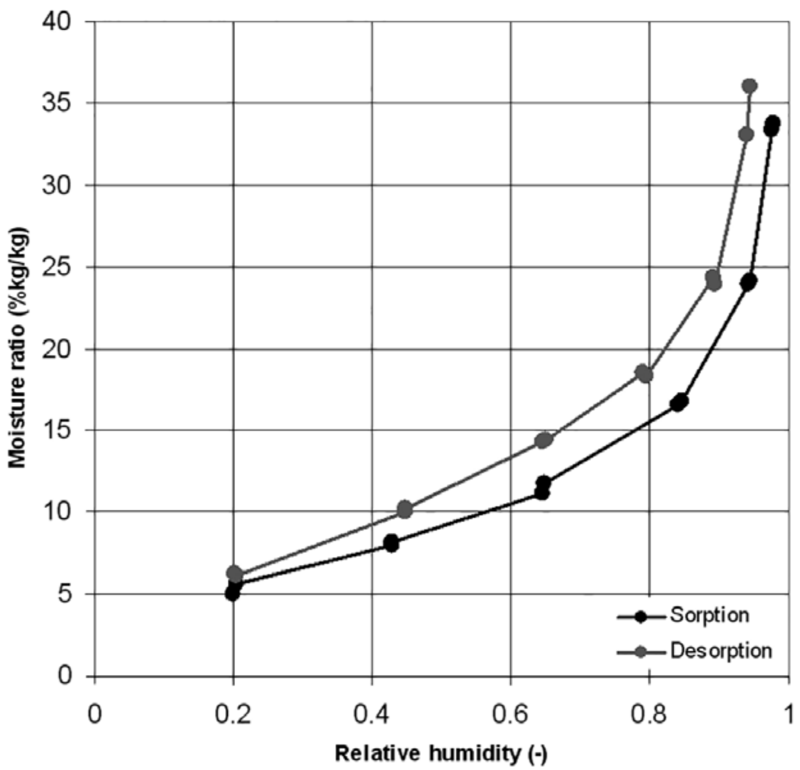

Figure 3.5.2 Hygroscopic curve.

In capillary-porous materials,

$$0 < S_{m,H} < S_{m,cr} < S_{m,c} < S_{m,cr,fr} < 1$$

In materials with wide pores only, critical moisture saturation degree moves to saturation till gravity starts draining the porous system. If the pores are too fine for capillary action, the same happens though without gravity drainage.

Moisture sources

A difference is made between liquid and vapour:

Liquid	
Accidental	Dripping pipes, leaky joints around a shower pan, etc.
Rising damp	Moisture sucked up from the bottom of a wall. Could be ground water, below grade capillary water, rain run-off and splashing rain.
(Wind driven) rain	In many climates the most important moisture source.
Water and air pressure heads	Present above and below the phreatic surface, wind induced.
Built-in moisture	All moisture present in the building fabric at the moment of decommissioning.
Vapour	
Humidity in the air	Many materials adsorb or desorb vapour in equilibrium with the relative humidity in the surrounding air.
Surface condensation	Stands for water vapour condensing on wall surfaces. Its presence indoors is seen as a problem, its presence outdoors not although surface condensation by under-cooling may generate as much moisture as wind-driven rain.
Interstitial condensation	Points to water vapour condensing inside a building part. Interstitial condensation may stay invisible for quite some time.

Moisture damage

The open pores in the materials composing a building assembly being filled with humid air do not harm. Only when that air moves while experiencing temperature differences, problems may arise. That some layers in a building assembly turn wet is even not a disadvantage by definition. Veneer walls for example are used as rain buffer. Their wetness should not be of concern in cold and cool climates, except if non-frost resistant bricks or mortars are used. The same holds for surface condensation against single glass. True, it is annoying, but does not damage unless so much condensate is deposited that run-off attacks the timber casings. Although many examples of tolerance can be given, moisture is a main cause of damage. Invisible or hardly visible degradation includes increase in thermal conductivity, more latent heat transfer, a decrease in strength and stiffness and swelling and shrinking as moisture varies. For certain wood-based materials, decrease in strength and stiffness plus volume change may be quite extreme.

Visible are:

Wood-based materials

- Hydrolysis of the resin keeping particle board, plywood, strawboard and OSB together.
- Bacterial rot, mould attack and fungal attack. Surely fungi are damaging as they convert cellulose into water. That way, timber loses its integrity, which may lead to collapses as shown in Figure 3.5.3.

Figure 3.5.3 Swimming pool, wooden roof girder collapsed by fungal attack.

Stony materials

- Mould, algae, moss and greenery growing. Is more an aesthetic problem, although the roots may destroy joints and organic acids produced may attack lime-based materials.
- Salt crystallizing and hydration. Surface drying stage gives efflorescence, drying from inside the porous system crypto-efflorescence. The last, with hydration/dehydration, induces tensile stresses in the material, which sometimes end in complete pulverization of the salt-attacked parts
- Frost damage. Demands a very wet open porous material and temperatures, oscillating around zero. The result may be spalling and pulverization.

Metals

- Most feared is corrosion. In many cases, the corroding volume expands, which is a reason why older reinforced concrete starts to spall around bars.
- Plastic materials.
- Hydration may plasticize the material, ending in loss of structural integrity.
- Plastic foams could show large irreversible expansion under thermal load, once the cells are partially filled with water.

Moisture displacement

Several driving forces cause moisture to move in and through open-porous materials. Looking to the vapour phase, two intervene: diffusion and bulk transport. Diffusion develops each time differences in vapour concentration exist in the humid air surrounding the material and filling its pores. For simplicity reasons, resulting moisture movement is considered to be Fickian, with the gradient in vapour pressure as driving force:

$$g_v = -\partial \text{ grad } (p)$$

δ is the vapour permeability of the open-porous material (in kg/(m^2.s.Pa)). Fickian of course simplifies things. In fact, many phenomena intervene. In extremely fine pores Knudsen diffusion governs movement. With capillary condensation happening, vapour moves between water islands with condensation/evaporation at each island. Above a certain relative humidity, surface flow develops in the adsorbed water layers between the water islands, etc.

Bulk flow reigns each time humid air infiltrates, exfiltrates and loops in and through assemblies:

$$g_v = -0.621\ 10^{-6}\, p g_a$$

with g_a the air flux in kg/(m^2.s). The amounts of water vapour transferred that way are a plural of those driven by diffusion, reason why bulk flow is the main player behind several damages. That reality was recognized decennia ago. Anyhow, many practitioners and experts still overlook it when detailing highly insulated envelope assembles or explaining damages.

Turning to the liquid phase, three main drives act together: suction, gravity and pressure differences. Suction is a direct consequence of capillarity, the fact that hydrophilic materials pick-up water each time they contact a water surface. That capillary force is inversely proportional to the equivalent pore diameter or crack width and proportional to the surface tension of water multiplied with the cosine of the contact angle between water and material:

$$s = -\frac{4\sigma \cos(\vartheta)}{d}$$

The smaller a pore and the closer the contact angle to zero, i.e. the more hydrophilic an open-porous material, the stronger it sucks. Displacement, however, is largely refrained in smaller pores, resulting in a bulk liquid flow proportional to the third power of the equivalent diameter or width. Materials with very small open pores hardly allow suction flow to develop. Important to know is that suction can never end in water outflow! A basement wall for example may turn wet by suction. However, when leakage is observed, the cause is gravity or flow driven by external pressure differences. Hydrophobic materials instead expel water with a force identical to the capillary one.

Gravity is only active vertically. It takes over from suction as soon as the weight of a water column in an open porous system exceeds capillary suction. The result is water displacement and outflow. External pressure differences do the same, although they mobilize all flow directions.

Moisture modelling

Moisture modelling is never an activity on its own. As temperature and air pressure differences act as driving forces, one always has to combine with heat and air transport, the whole being called hygrothermal modelling. All models start from the axioms of mass and energy conservation and combine these with the transport equations, commented above and equations of state. As shown, the first link moisture (vapour and liquid), heat and air fluxes to the driving forces (temperature, partial water vapour pressure, air pressure, suction, gravity and external pressures), while the second describe all thermodynamic equilibriums involved, such as enthalpy versus temperature, vapour saturation pressure versus temperature and moisture content versus relative humidity.

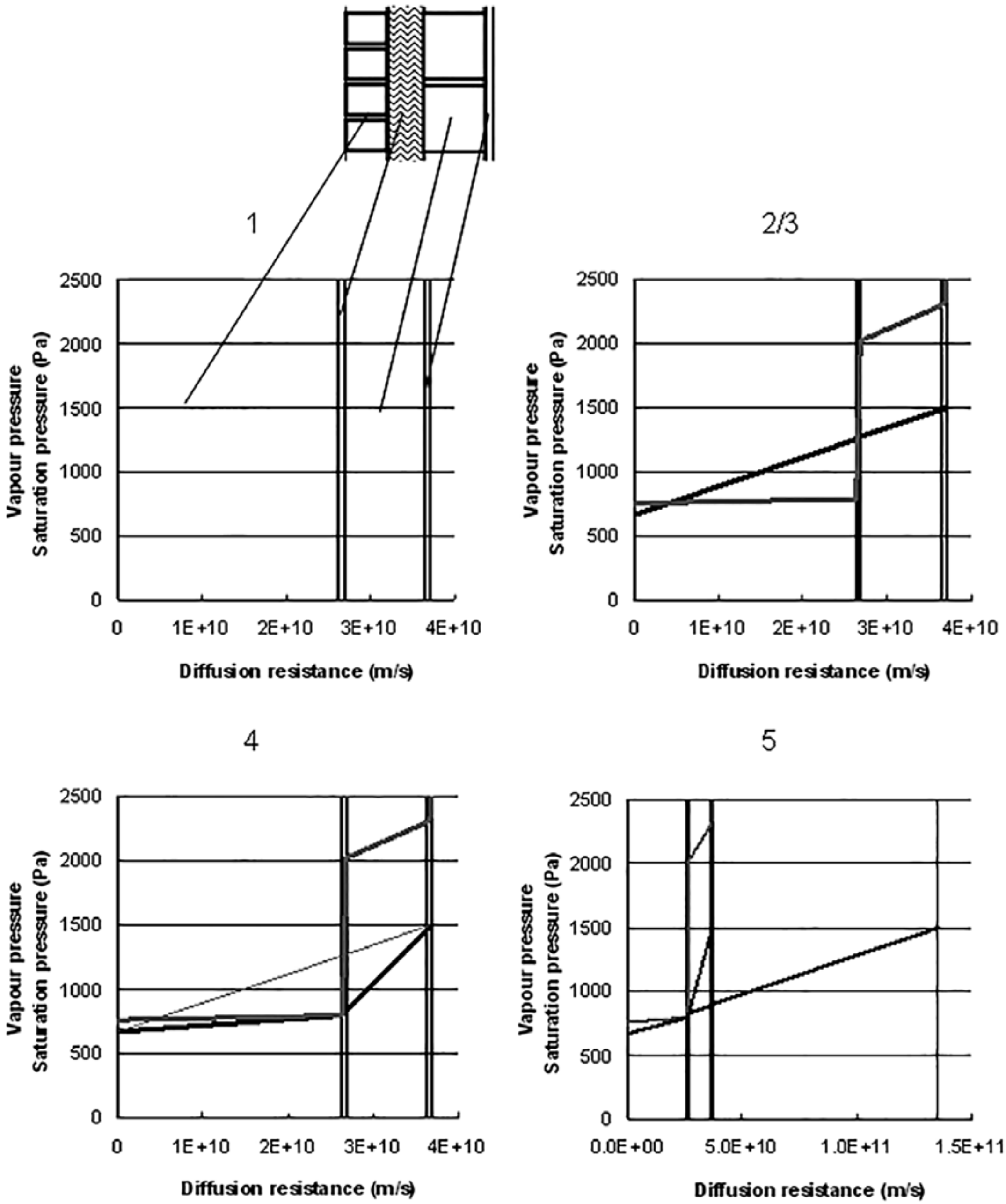

Figure 3.5.4 Example of a Glaser analysis. Successive steps: Redress the wall as a diffusion resistance versus vapour pressure image; Trace vapour (p) and saturation pressure (p_{sat}). If intersecting, interstitial condensation a fact; Vapour pressure replaced by the tangents; Diffusion resistance added at the warm side of the insulation to prevent interstitial condensation.

Solving a combined heat, air and moisture problem demands knowledge of the exact geometry of a building assembly, together with the starting conditions, the exterior and interior boundary conditions and the contact conditions between material layers. The exterior boundary conditions include temperature, relative humidity, wind, solar radiation, under-cooling, precipitation and wind driven rain. Each of them is influenced by the environment around the building, the building form, building orientation and envelope detailing. Temperature, vapour pressure and air pressure in turn shape the interior boundary conditions. Contacts between materials may be diffusion-only, capillary-only or a mixture of capillarity here and diffusion there. Contact surfaces may also have properties different from both materials in contact.

One simple model got standardized: Glaser's scheme. The assumptions behind are far-reaching. The building part should behave as one-dimensional assembly, air may not intervene as carrier for water vapour, the assembly must be dry enough for vapour diffusion to be the only transport mechanism, no material is hygroscopic and capillary, heat and water vapour flows are steady state and surface and interstitial condensation are the only moisture responses considered. Calculation starts at the coldest month. Vapour and vapour saturation pressures are calculated across the assembly. If both intersect, interstitial condensation is a fact. Correct vapour pressure is then found by constructing the tangents to the saturation line through the vapour pressure value inside and the one outside and linking the contact points with intermediate tangents if necessary (Figure 3.5.4). The condensate per time and surface unit in each contact point is then given by the difference in slope between in- and outgoing tangent. With interstitial condensation a fact, the points where moisture is deposited remain on saturation pressure until complete drying (Glaser, 1959).

Since Glaser published his method (which was conceived to evaluate cold storage room envelopes), several upgrades have been proposed, extending the method to assemblies with wet layers, allowing limit state analysis and introducing bulk water vapour flow as additional vapour drive (with far reaching consequences for moisture tolerant design) (Vos and Coelman, 1967; Hens, 1978; Hens, 2007).

From the 1980s on, full models were developed, first at building part level and recently at whole building level. They calculate the transient heat, air and moisture response with inclusion of latent to sensible heat conversion, sorption/desorption, bulk vapour flow and liquid transport by suction. Moisture sources were extended to include rain, built in moisture and rising damp. Most models, however, still struggle with gravity and pressure flows (Philip and De Vries, 1957; Luikov, 1966; Van der Kooi, 1971; Nielsen, 1974; Kießl, 1983; Kohonen, 1984; Pedersen, 1990; Künzel, 1994; Descamps, 1997; Küntz and van Mier, 1997; ASHRAE, 2005; Rode and Woloszyn, 2008).

Coupling with stress/strain calculations and the probability of crack formation has been achieved since (Carmeliet, 1992). Also salt transport with crystallization and hydration plus VOC-emission has been added, turning combined heat, air, moisture modelling into damage and IAQ prediction tools (Grunewald, Nicolai and Zhang, 2007; Nicolai, Grunewald and Zhang, 2007). Once so far, still, risk should be added as the ultimate refinement, allowing well balanced decision making on acceptability.

Moisture resilient design

Building component level

Staring point is the set of moisture sources, mentioned above and discussed in detail in Trechsel (2001) and Rose (2005).

Groundwater and seeping water pressure heads

Both act below grade. Leakage avoidance and thermal quality kept are the main performances to be guaranteed. If only seeping water has to be considered, tolerance is gained by a drainage around the basement in combination with a moisture barring layer against the basement walls and floor. If a moderate groundwater head has to be turned around, the basement could be constructed in watertight concrete with insertion of special profiles and adding injection tubes at all construction joints to inject curing resin if needed. In case large water heads have to be turned around, outside or inside water-tightening should be applied. Inside, floors and walls are typically rendered with a water tight mortar or covered with a PVC-membrane, which is stabilized by cast inside reinforced concrete walls and floor. Outside, a concrete floor 0.5m larger than the basement is cast first and covered with a multilayer watertight felt with very high tensile strength. Then, the actual basement floor is cast together with the walls. These are lined up at the outside with the same watertight felt, that is joined together with the horizontal felt. Finishing includes watertight perimeter insulation and extra mechanical protection.

Sloping terraces away from the building and adding a drain at the terraces head are additional aids in keeping the basement dry.

Rising damp

The performance requirement is straight forward: avoid. How, is simple in new construction: insert watertight membranes were needed in all walls above grade and respect continuity. Anyhow, still, things may go wrong as shown in Figure 3.5.5. There, rain penetrated the ground floor screed and the walls sucked up that water.

Floors on grade demand special care. Research showed that the ground below acts as a substrate on 100% relative humidity. If the contact temperature between slab and ground passes the temperature inside and non-water-resistant glue fixes the vapour retarding floor finish, it will slowly get moist and finally detach.

Figure 3.5.5 Rising damp.

(Wind driven) rain

Main performance requirements are: rain should neither moisten thermal insulation nor the layers behind. On low-slope surfaces, the only remedy to avoid is coverage with a water-tight roofing felt as rain may pond and create water pressure heads that way. Such solution is called a one-stage system.

On sloped surfaces, coverage with overlapping elements such as tiles or slates may create rain-tightness with rain flowing down from one element to the other. Water-tightness however is not achieved that way. High wind velocities may press run-off into the overlaps, causing leakage. For that reason, redundancy is sought in adding a second line of defence, the underlay. Roof elements and underlay must drain in the gutters which in turn transport the water to the downspouts.

In vertical wall assemblies, the layers caching the wind driven rain may act as drainage plane, buffer volume or transmission route. Their combination resulted in three systems of rain protection (Straube and Burnett, 1999):

- Usage of massive walls with such high buffer capacity that even the longest rain spell does not wet half of the wall thickness. Old masonry buildings are constructed that way
- The one-stage system. Walls are finished at the outside with a material acting as drainage plane. The layer hardly buffers rain and should not transmit it to the layers behind. Stuccoed buildings follow this road, although their effectiveness may be torn down by cracking.
- The two-stage system. In such case the airtight inside leaf with thermal insulation is protected by an external veneer with air cavity behind. That veneer functions as outside drainage plane and buffer layer. It also transports rain across cracks and voids to its inside, where the veneer's surface acts again as drainage plane, with the air cavity behind functioning as capillary break. That prevents rain from jumping to the inside leaf. Some non-capillary fibrous insulation materials may contact the veneer without causing leakage (Figure 3.5.6).

Figure 3.5.6 Example of a two-stage rain protection: cavity wall with water-repellent fibrous insulation touching the veneer. The inside leaf is still lacking its air-retarding plaster finish.

The three systems are not equivalent in terms of overall performance. Buffering only results in a loss of thermal quality, as wet materials conduct heat better than dry ones. At the same time, rain run-off is very unlikely to happen, which means that moisture load on joints, for example those between masonry and windows, remains modest.

A one-stage system keeps the wall behind dry but produces much more run-off with as a result heavier moisture loads on joints and a higher probability of leakage there.

The two-stage system is the best: the wall keeps dry while run-off is minimal. However, the rain drained at the veneers inside should be redirected to the outside. That demands cavity trays at the right spots with weep holes above. Even then, a problem remains: summer condensation. Veneers become wet by rain. When sunny weather follows, the moist veneer will heat up to 50/55°C. That produces very high vapour saturation pressures in the masonry, much higher than the vapour pressure inside, inducing a vapour drive to the inside with sometimes interstitial condensation against and in layers inside of the thermal insulation. Especially timber framed walls suffer from it.

Built-in moisture

The only performance requirement is: the wet construction must dry without harming thermal quality and durability. Drying may proceed to the inside as well as to the outside. If necessary, the insulation should be sandwiched between two air and vapour barriers as to avoid wetting by a vapour drive from the wet layers on. This for example is done in low-slope roofs, where the insulation is mounted on an air and vapour retarder and covered by the felt.

Hygroscopic moisture

The cause of hygroscopic behaviour is relative humidity in the air. Along surfaces, its value depends on local temperature. When much lower than the value inside a higher relative humidity will be measured than inside. If passing 80% for long periods of time, the likelihood for mould to germinate increases to one. Mould is more an aesthetic than a medical problem. Only sensitive people respond negatively. Yet, cleaning does not help. Mould spots look dirty. People believe they have moisture problems, etc. In cold and cool climates, mould is easily avoided by insulating properly, excluding thermal bridging when insulating, heating enough in winter and ventilating with an eye on healthy indoor conditions. In hot and humid climates, air drying is the only relief measure (Anon, 1990; Adan, 1994; Sedlbauer, 2001).

In museums, churches and monumental buildings with rich wooden ornament, also a too low and to fast changes in relative humidity is a problem, as timber will crack, and paints will end showing alligator skin. In cold climates, air humidification may be needed, while in cool climates, moderate heating already offers part of the solution.

Surface condensation

The performance requirement is simple: avoid or at least, keep the risk below 5%. Surface condensation happens each time the relative humidity at a surface touch 100%. Capillary surfaces suck the condensate. On non-porous surfaces tiny water droplets appear who, once big enough, run-off. Avoidance in cool climates, cold climates and hot and humid climates demands the same measures as for mould.

Interstitial condensation

The performance requirements are: lasting moisture built up must be avoided, annual winter moistening may be tolerated unless thermal performance degrades too much, durability gets attacked or water drips out.

Tolerance against interstitial condensation demands excellent air-tightness against infiltration and exfiltration and a correct balance between the vapour resistances at both sides of the thermal insulation. In cool and cold climates, highest vapour resistance should be found at the inside. In hot and humid climates, where cooling is needed, highest vapour resistance should sit at the outside. In mixed climates, where the vapour drive changes direction, the best is using an airtight mounted vapour retarding thermal insulation (Janssens, 1998).

Building level

When analysing wind driven rain patterns on buildings, the highest floors are typically hit more intensely than the lower ones, with the upper corners as most exposed parts. Overhangs may protect the envelope efficiently. Really critical are inclined surfaces. They are not only wetted by wind driven rain but also by precipitation.

Inside, temperature is a controlled comfort parameter. In many buildings relative humidity is not. Its value depends on the instantaneous balance between ventilation flows, air flows among rooms, water vapour produced by the building users and wet construction assemblies or removed by the HVAC-system, sorption/desorption behaviour of finishes, furniture and furnishing and air buffering. Yet the average relative humidity over longer periods solely depends on average vapour pressure outside (p_e in Pa), average water vapour production or removal inside ($G_{v,P}$ in kg/h), average ventilation ($\dot{V}$ in m^3/h), inside temperature (θ_i) and sometimes, surface condensation which helps removing water vapour:

$$\phi_i = \frac{1}{p_{\text{sat}}(\theta_i)}\left[p_e + \frac{462(73.15+\theta_i)\left(G_{v,P} - \max\left[0,\beta A_{\text{cond}}[\phi_i p_{\text{sat}}(\theta_i) - p_{\text{sat}}(\theta_{s,\text{cond}})]\right]\right)}{\dot{V}_a}\right]$$

with β surface film coefficient for water vapour diffusion in s/m, A_{cond} area affected by surface condensation in m^2 and p_{sat} ($\theta_{\text{s,cond}}$) saturation pressure on that surface in Pa. Peaks and valleys in inside relative humidity are dampened by sorption/desorption and air buffering. In extreme cases, such as libraries with numerous shelves filled with books, relative humidity may become very stable, even without air conditioning.

Air flows among rooms and between the building and outdoors are driven by stack, wind and fans. Some, carrying water vapour produced inside, could traverse air-permeable envelope parts, causing severe interstitial condensation problems sometimes. Flows infiltrating through rain buffering layers in turn transport extra water vapour to the inside (Rode and Woloszyn, 2008).

Case studies

Building with inclined walls

A university building had to house a very diverse program: underground parking, lecture theatres, library, smaller seminar rooms and individual office rooms. For that purpose, the design team proposed a building, which narrowed from basement to top. The lecture theatres were situated just above the parking and the library was posted in between these theatres and the seminar rooms and offices, which filled the top floors. The result was a building with oblique cavity walls composed of masonry veneer, partially filled cavity and reinforced concrete inside leaf with brick finish inside (Figure 3.5.7).

Once in use, complaints about large moisture spots inside and rain penetration along the window sills surfaced (Figure 3.5.8).

The diagnosis included calculation of the catch ratio patterns on the building envelope for wind driven rain coming from south west. That proved the heaviness of rain exposure. Observation of the run-off

Figure 3.5.7 The building with rain penetration inside.

Figure 3.5.8 Rain water run-off and missing sill step below the window frames.

learned that the oblique façades functioned as very active drainage planes with a concentration at the edges, a thing no model could predict. As the veneer received a water repellent treatment, run-off mainly loaded the small cracks between bricks and mortar joints, causing leakage into the cavity. There, the leaking water dripped on the insulation, ran-off, penetrated the joints between the boards and wetted the concrete inside leaf, where shrinkage cracks directed the water to the brick-finish inside. The sills in turn lacked step-ups below the window frames causing the direct rain penetration.

To solve the problem, the contractor first replaced one of the oblique veneer walls by a stepwise regressing veneer. That was not a success as the view was awful and the solution created thermal bridges who lifted the *U*-value of the wall from 0.49 W/(m^2.K) to 0.64 W/(m^2.K). Trays were also forgotten, leaving room for continued leakage. The final solution advanced was exchanging the brick veneers for a watertight zinc veneer on timber lathing. That also solved the sill problem.

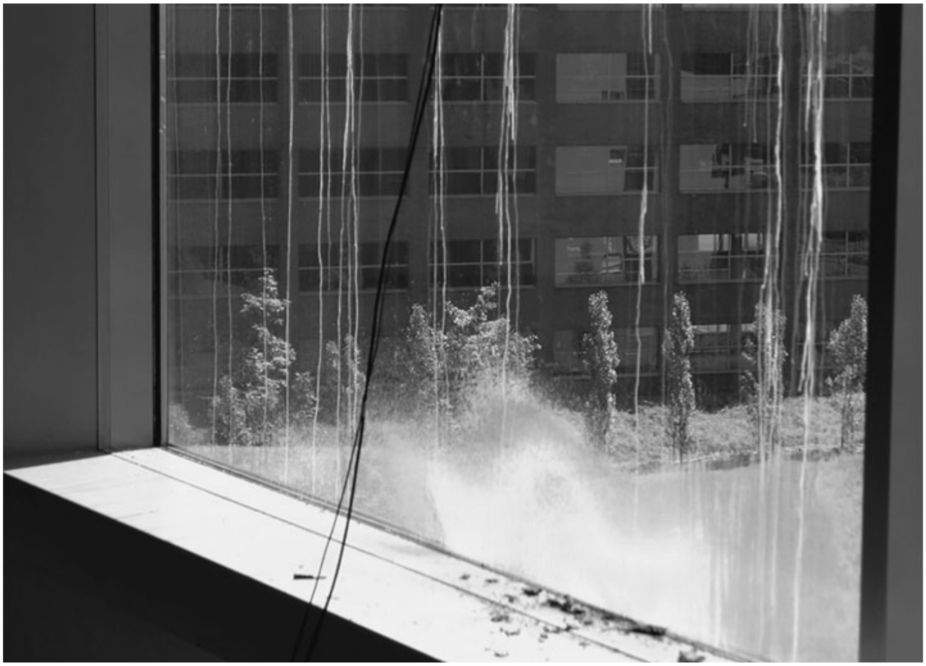

Figure 3.5.9 Dripping water and run-off along the inside face of the windows.

Summer condensation

A new office building counting 5 floors was inaugurated. Soon after, complaints about water running down the inside face of the windows at the highest floor, surfaced (Figure 3.5.9). Dripping became even so annoying that the top floor could not be leased anymore.

The contractor thought surface condensation was the cause, which of course was unlikely as run-off always happened during warm weather. An in-depth study revealed that the highest floor was heavily hit by wind driven rain (Figure 3.5.10). The envelope was comceived as a cavity wall with a veneer, constructed of dense bricks, a cavity filled with mineral fibre and an inside leaf in very dense, hardly capillary pre-cast concrete. The trays above windows were point-wise fixed to the concrete, leaving open joints in between, while the windows themselves were mounted in the veneer, ahead the filled cavity.

Each rain spell filled the joints in the veneer with water, giving a cavity side run-off that slowly moistened the bricks. When the sun shined, that moisture evaporated. The vapour traversed the mineral fibre fill and condensed against the concrete inside leaf, where it was not sucked, but ran down, passed the joint between the tray and the concrete and dripped down along the windows.

Three solutions were offered, from most risky to very safe:

1. Treating the bricks with a water-repellent agent
2. Bringing down the veneer at the fifth floor, gluing the tray correctly against the concrete leaf and rebuilding the veneer
3. Stuccoing the whole building with a water repellent lime-based mortar

Although 2 or 3 were advised as being least risky, the contractor decided for the most risky but cheapest solution 1.

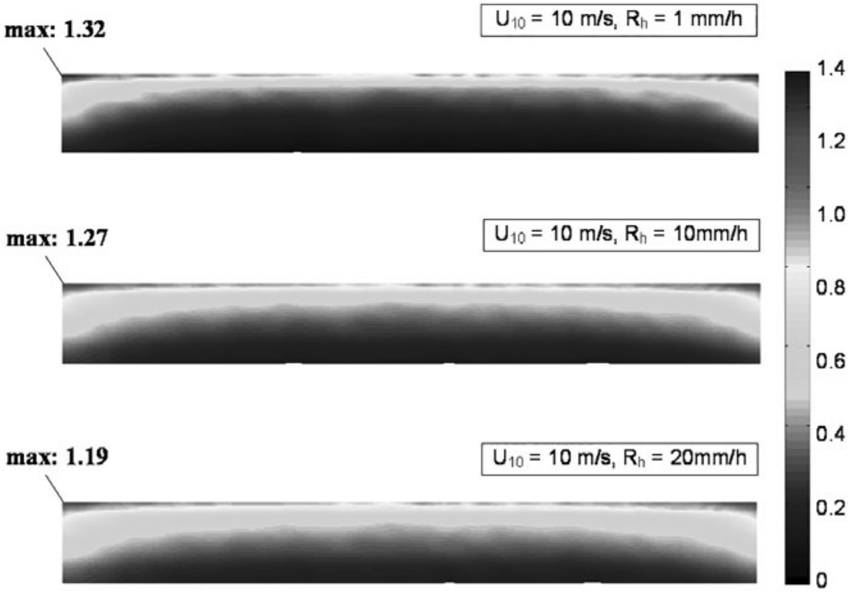

Figure 3.5.10 Wind driven rain, calculated catch ratio.

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3.6

DESIGNING NATURAL VENTILATION FOR URBAN BUILDINGS

Dejan Mumovic, Oliver Wilton and Sung-Min Hong

Introduction

Natural ventilation can serve a range of purposes in buildings, from delivering fresh air in order to maintain air quality to ventilative cooling to limit temperatures in summertime. It is also known as passive ventilation as no energy is used to drive airflow. Designs utilizing natural ventilation range in complexity from simple arrangements controlled by manually opened windows to complex automated BEMS-linked mixed-mode systems and those involving induced airflow via techniques such as passive downdraught evaporative cooling.

A major motive for the use of natural ventilation and ventilative cooling is the potential for low operational energy use and associated low CO_2 emissions and operational costs. The UK PROBE study (Bordass, Cohen, Standeven and Leaman, 2001) has revealed that nine out of the ten highest CO_2 emitters were air-conditioned and mixed-mode buildings. The study showed that in the air conditioned and mechanically ventilated buildings, the CO_2 emissions resulting from the fans and pumps required to move conditioned air accounted for up to 50% of the emissions associated with space heating and cooling. Furthermore, as the air-conditioned buildings tend to be a deep plan, the CO_2 emission associated with artificial lighting is substantial. These facts have caused a reappraisal of natural means of ventilation and a surge of interest in advanced natural ventilation technologies.

There are a range of further motives for utilizing natural ventilation techniques. A number of research projects have shown that naturally ventilated buildings tend to be more desirable to the occupants than mechanically ventilated or air-conditioned buildings. Usually, the occupants of the naturally ventilated buildings report lower sick building symptom prevalence in comparison to the mechanically and air-conditioned buildings. In addition to the health-related benefits, carefully designed naturally ventilated buildings can cost less to construct and maintain than more heavily mechanically serviced equivalents. Maintenance is generally required infrequently and is of a relatively simple and unspecialized nature when it is required.

This chapter gives an overview of natural ventilation in non-domestic buildings and describes more advanced natural ventilation strategies and technologies available to optimize the performance of naturally ventilated systems. A special attention is paid to urban areas as the lower wind speeds, the existence of heat islands and the potentially high ambient noise and air pollution levels represent a serious challenge to designers of naturally ventilated buildings.

It is important to note that in successful naturally ventilated buildings, natural ventilation strategy is integrated into the wider building environmental and architectural design strategy during a process of synthesis that occurs as the design develops.

Theoretical background

The magnitude and pattern of natural air movement through a building depends on the pressure difference acting across the ventilation path and the resistance of that flow path. The pressure difference driving the air flow is a function of two driving forces – wind and buoyancy.

Figure 3.6.1 shows the air flow around an isolated pitched roof building located in a low-density suburban environment with no built or natural elements which can obstruct the flow: plan view (top) side view (bottom). The wind induced pressure fluctuation on the building surfaces varies in time and space. The approaching flow separates in front of the cube (A) and forms the front stagnation point (B) at about three-fifths of the height of building. The flow goes down toward the ground, where it has more kinetic energy than the approaching flow, rolls up and forms a primary separation vortex (C). The main, so called 'horse-shoe vortex' (D) is formed around the base of the property forming the wake (E) and has a typical converging behaviour. A large separation region (F) develops behind the property ending with the reattachment point (G). The results of turbulence modelling suggest the existence of two strong three-dimensional coherent vortices (H). A region of very low pressure is generally observed on the roof surface (I). Note that flow at a certain distance from the roof should be unaffected by obstacles (J).

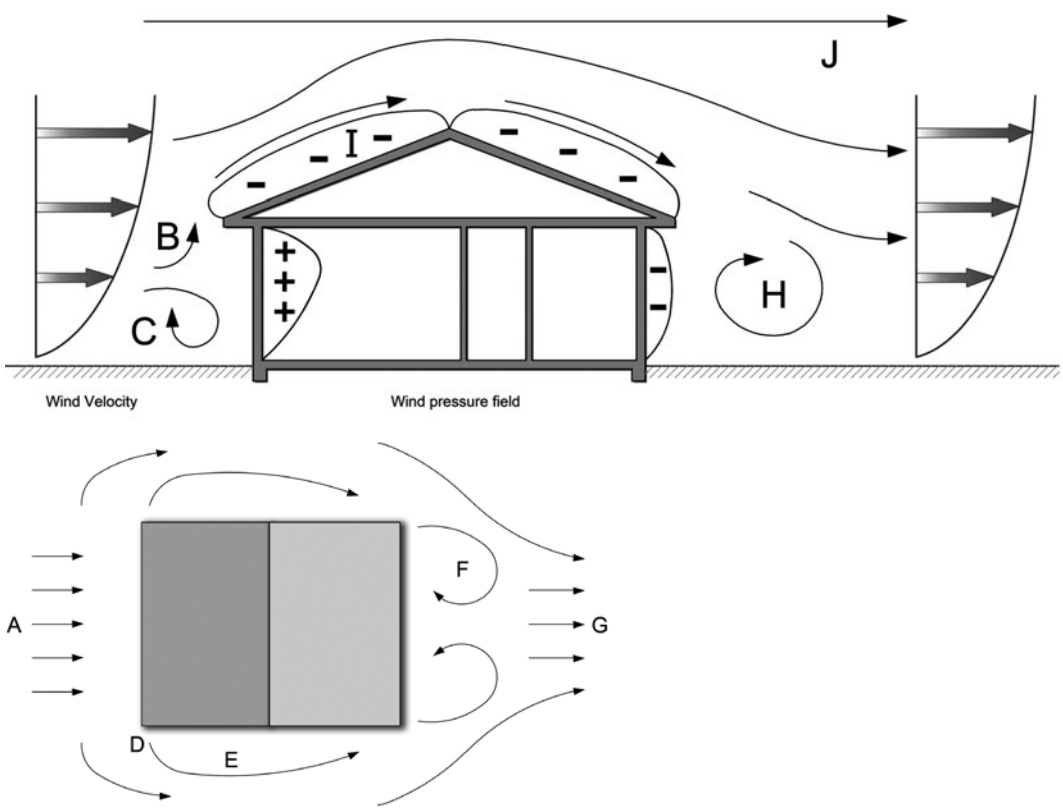


Figure 3.6.1 Wind pressures acting on an isolated building: (a) elevation (b) plan.

As can be seen, wind pressures are generally positive on the windward side of a building and negative on the leeward side. The occurrence and change of wind pressures on building surfaces depend on wind speed and wind direction relative to the building, the location and surrounding environment of the building and the shape of the building.

When air movement is due to temperature difference between the indoor and outdoor, the flow of air is in the vertical direction and is along the path of least resistance. The temperature difference causes density differentials, and therefore pressure differences, that drive the air to move. This is known as the stack effect. When buoyancy force is acting alone, a neutral pressure level (NPL) exists, where the interior and exterior pressures are equal (Figure 3.6.2a). At all other levels, the pressure difference between the interior and exterior depends on the distance from the neutral pressure level and the difference between the densities of inside and outside air. Note that the length of the horizontal arrows representing the magnitude of the resulting pressure difference across each opening. Figure 3.6.2b shows the variation in wind surface pressure with height.

However, even the lowest wind speeds will induce pressure distribution on the building envelope that will also act to drive airflow. Therefore, the pressure patterns for actual buildings will continually change with the relative magnitude of buoyancy and wind forces. Figure 3.6.2c shows the combined effect of buoyancy and wind forces. The pressures due to each effect are added together to determine the total pressure difference across the building envelope. To achieve the shown flow patterns in practice (inflow at the lower three openings and exhaust via the top) one has to adjust the internal pressure by judicious sizing of the ventilation openings. In this context, assuming that the same ventilation rate is required at each occupied level, the sum of all the inflows has to balance the single high-level outflow. Detailed analysis of driving forces for natural ventilation can be found elsewhere (CIBSE, 2005; Santamouris and Wouters, 2006).

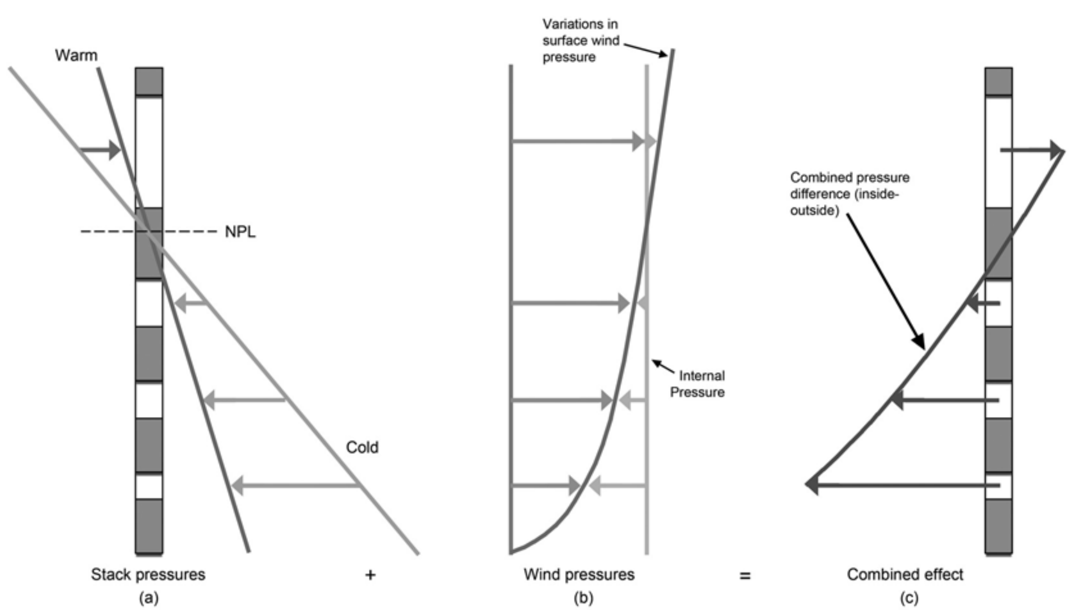


Figure 3.6.2 Combined buoyancy and wind driven ventilation.

Source: Reproduced from CIBSE AM10 (CIBSE, 2005) by permission of the Chartered Institution of Building Services Engineers

Design requirements and site analysis

Client brief and design requirements

Building designs are developed in response to the client brief, to site-specific conditions and constraints and to further statutory and technical requirements. These factors set out parameters within which designs develop, with some cases where there is significant delimitation to the range of viable design responses and others where there is less so.

The client brief will set out the basics of building type (residential, offices, educational, auditoriums, etc.) and specific accommodation requirements and will go on to deal with a range of further matters in a level of detail that can vary greatly. Environmental performance requirements (temperature targets, lighting levels, etc.) will generally be set out. The nature and structuring of these requirements are of key importance as they effectively determine the viability of natural ventilation as a response. For example, single figure summertime temperature targets are not deliverable via the use of pure natural ventilative cooling as this tends to deliver a temperature range relative to outside temperature rather than an absolute temperature regardless of the weather. Temperature targets set out as ranges with associated frequencies of occurrence are becoming increasingly common (for examples, those set out in BB101 for school design) and these can lead to the delivery of comfortable environments without precluding the use of natural ventilation.

Further briefing matters having a bearing on the application of natural ventilation include the level of compartmentation of internal spaces, acoustic compartmentation requirements between spaces, occupancy patterns and densities and internal heat gains.

It is of key importance that, wherever possible, the design team collaborate in the development of the final client brief. This is in order to assure that client needs and ambitions are reflected in performance requirements while also aiming not to preclude the development of the most elegant and efficient design response – which in many cases may involve a level of natural ventilation.

Further 'givens' when developing designs include the site-specific conditions and constraints. These include the physical nature of the site itself (be it land and/or existing buildings) and its surroundings (urban fabric or otherwise), local micro-climate and related factors and constraints exerted via the development control or planning system. The planning system exerts constraints on building form and fabric as does the use of natural ventilation and these can conflict. In most cases design solutions delivering natural ventilation will sit comfortably within planning parameters and may well be actively encouraged. However, in certain cases, such as projects involving Listed Buildings or sited within Conservation Areas, planning constraints may conflict with and so constrain natural ventilation solutions. A simple example of this would be the application of external shading on a Listed Building, which may be necessary to bring gains down within levels where natural ventilative cooling can be used but may well be of unacceptable appearance to gain planning (and listed building) approval.

The points addressed above together largely determine the design requirements for a project, these being the requirements against which the success of a building design can be measured. A design is then developed as a process of synthesis in response to these requirements. When considering the use of natural ventilation, it is important at an early stage of the design process to ascertain what it could achieve given the particular constraints and requirements. In particular, the technical viability of natural ventilation to deliver the following should be assessed:

- to provide an appropriate level of indoor air quality by removing and diluting airborne contaminants
- to reduce overheating in the building (particularly in summer months)
- to integrate with all other aspect of the building design such as the day lighting and acoustics design

Microclimate and weather data

The microclimate of a building site can have a strong influence on the effectiveness of natural ventilation systems. In the urban environment, the mean velocity of wind is reduced significantly and wind direction might be changed. As a consequence, the wind induced pressure on a building envelope is lower (Figure 3.6.3).

It is very difficult to offer a specific guidance on design of naturally ventilated buildings within urban street canyons. However, as a starting point one should take into account the following rules of thumb (Santamouris and Wouters, 2006):

- the potential for natural ventilation is greatly reduced if the height to width ratio of the street canyon is higher than unity;
- when the wind is perpendicular to the street canyon axis, the air flow inside of the canyon is nearly vertical and parallel to the window; as a consequence, the pressure coefficients inside a building are lower than the pressure coefficients calculated from the ambient wind speed directions; in this case the horizontal pivot, top hung or louvred windows should be used to direct flow toward occupants for daytime ventilation;
- when the wind is parallel to the street canyon axis, the flow inside of the canyon is nearly horizontal and parallel to the window; as a consequence, the pressure coefficients inside a building are lower than the pressure coefficients calculated from the ambient wind speed directions; in this case the vertical pivot and side hung (casement) windows should be used to provide either a positive or negative wing wall effect in response to the prevailing wind;
- when the wind is oblique to the street canyon axis the pressure coefficients inside a building are still lower than the pressure coefficients calculated from the ambient wind speed directions, but higher than the pressure coefficients calculated when the ambient flow is either parallel or perpendicular to the street canyon axis.

Solar radiation absorbed by urban surfaces results in a temperature increase that is important to take into account as it will limit the cooling potential of natural ventilation. In less dense urban areas this might be only a local phenomenon for intakes located on south facing walls, while in dense urban areas it might result in a general increase of outdoor temperatures compared to rural areas. This effect, known as the heat island effect, is addressed in the Chapter 1.3. A detailed analysis of the effect of the London urban heat island on building summer cooling demand and night ventilation strategies can be found elsewhere (Kolokotroni, Giannitsaris and Watkins, 2006).

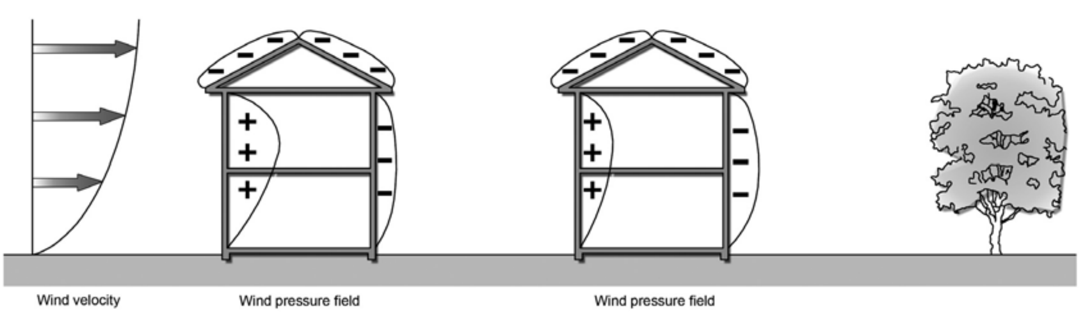


Figure 3.6.3 Wind pressures acting on an urban building.

To assess the internal temperatures likely to occur in naturally ventilated buildings and to establish the required ventilation rates CIBSE has produced two weather years for 14 UK locations:

- Design Summer Year (DSY)
- Test Reference Year (TRY)

The DSY is an actual year containing fairly extreme temperatures for the six months between April and September and should be used to assess whether or not there is an acceptably low risk of summertime overheating in the naturally ventilated buildings. For example, to create the DSY for London Heathrow, the average dry-bulb temperature was calculated for each year from 1976 to 1995. These were ranked in order of magnitude and the third ranked was selected as the DSY. This year, 1989, has 267 hours with a dry-bulb temperature in excess of 25.8°C and an absolute peak temperature of 33.7°C.

The TRY is a synthesized typical weather year and should be used to analyze energy use and overall environmental performance of buildings. The TRY for London Heathrow consists of successive typical months that have been extracted from the twenty different years. However, when assessing a building to be sited in the middle of London, the effects of both the heat island and the CIBSE design conditions must be considered. This is because Heathrow, the source of the CIBSE London data, is outside the heat island. Preliminary research has indicated that when these factors are considered, some form of cooling must be used to maintain comfort in the buildings sited in Central London. A detailed investigation of the impact of newly published CIBSE weather data on natural ventilation design is given elsewhere (Ren, Levermore and Doylend, 2003).

Air pollution

A second important issue in designing natural ventilated buildings in urban areas is the impact of outdoor air quality. While inadequate outdoor air quality affects both naturally and mechanically ventilated buildings, there are three reasons why the naturally ventilation designs are more sensitive to elevated levels of outdoor air pollution:

- a typical ventilation systems do not incorporate particle filtration;
- the natural ventilation systems may introduce far greater quantities of outdoor air into the building to reduce overheating particularly in summer months;
- due to low natural driving forces the positioning of the air inlets is more limited and inlets at high level (where levels of certain pollutants are generally lower) are often not a viable option.

Chapter 3.2 provides a detailed analysis of distribution of air pollutants in urban areas and their effect on air quality within buildings. In summary when designing natural ventilation systems for urban buildings one has to take into account the following rules of thumbs (Figure 3.6.4):

- lower concentrations at the windward side of street canyons which are almost perpendicular to the wind direction;
- higher concentrations at the leeward side of street canyons which are almost perpendicular to the wind direction;
- negative correlation between concentration and wind speed;
- wash-out and accumulation effects along those canyons whose axes are parallel to the wind direction.

Note that with different wind speed values, considerable differences would be observed in concentration values obtained (Mumovic, Crowther and Stevanovic, 2009). Generally, during low wind periods the

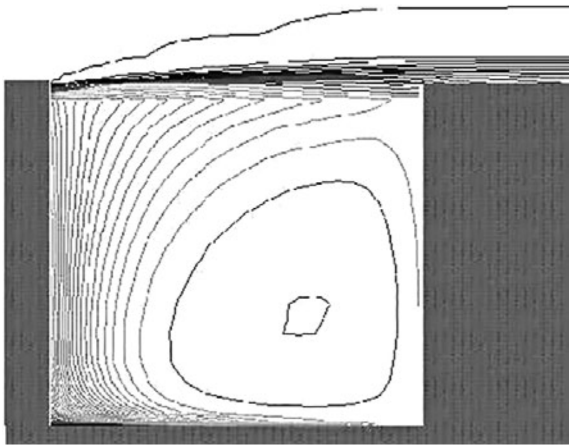


Figure 3.6.4 Air pollution distribution in an idealized street canyon.

convective transport of the pollutant would be greatly reduced, causing higher concentration at the very lower levels of street canyons. In contrast, during periods of very high wind speed, the washing out effect increases significantly, generally lowering the concentration levels within the city centre. As has been seen, the flow patterns that develop around buildings govern the pressure distribution and, consequently, concentration distribution, in a built environment. Although these rules of thumb are useful when designing natural ventilation for urban buildings, be aware that in a more complex built environment, the superimposition and interaction of flow patterns associated with adjacent buildings dominate the airflow and dispersion of air pollutants. Accordingly, the concentration distribution function becomes much more complex, taking into account the additional parameters (Mumovic, Crowther and Stevanovic, 2006):

> Concentration distribution = *f* (street width, height, length, orientation, wind speed, building geometry, upwind building configuration, intersection location and geometry)

Obviously, the local pollution concentration variation indicates that natural ventilation may still be viable option for buildings within urban air quality management areas. In this case, the designers should employ modelling tools such as CFD to predict indoor pollutant concentrations resulting from various case scenarios of different ventilation rates and outdoor air pollution concentration levels. A detailed analysis of local concentration gradients in complex-built environments is given elsewhere (Mumovic et al., 2009).

Noise

A third important issue in designing natural ventilation in buildings in urban areas is noise, whether it comes from outdoors or from other rooms in the same building. The noise is attenuated by the physical boundaries of the room such as building envelope, internal partitions, door and windows. Furthermore, the room acoustics (geometry and acoustic reflectivity of surfaces) controls whatever noise is transmitted in to the room. In urban areas the traffic noise can be of particular concern. There are two main solutions to this problem:

- positioning of the ventilation inlets on the sides of the building away from the noise source; and
- use of sound attenuating ventilation openings, for example those incorporating noise reducing baffles or acoustic labyrinths.

Note, the noise reducing mechanisms usually involve significant resistance to airflow and a careful balance between the two opposing effects must be sought. Absorbing internally generated noise in spaces with large areas of hard surface (usually associated with thermally massive buildings) is another important acoustic issue which can be resolved either by using absorbent partitions and hangings or use of carefully profiled ceilings. A detailed analysis of various noise control strategies for naturally ventilated buildings is given elsewhere (De Salis, Oldham and Sharples, 2002).

Developing a ventilation design strategy

The variety and diversity of purpose provided natural ventilation systems that have been proposed in recent years is staggering, especially in Europe. Often mechanical devices are added to enhance ventilation system performance and control adding to the complexity. Nevertheless, these systems are invariably conceived as variants of the basic forms of ventilation strategies. In this section, these basic forms of ventilation strategy are defined and related to the form and layout of the building for which they are typically best suited. General terms used are as follows: vents are ventilation openings through which air flows into or out of a space, an inlet is a vent through which air flows into a space and an outlet is a vent through which air flows out (these often reverse in naturally ventilated buildings).

Single sided ventilation

Single sided ventilation typically serves single rooms and relies on vents on one side only of the enclosure. It is closely approximated in many multi-room buildings with opening windows on one side of the room and a closed internal door on the other side. Figure 3.6.5 shows a schematic of two variants of this basic ventilation form:

1 Single sided ventilation with single opening (Figure 3.6.5a)

Relative to the other strategies, this one offers the least attractive natural ventilation solution and is characterized by lower ventilation rates and the ventilating air penetrating a smaller distance into the space. As a rule of thumb, the limiting depth for effective ventilation is about twice the floor to ceiling height, typically 4–6m in depth. In summer it relies upon wind turbulence to generate reversing flows in and out of the room. In the winter when greater temperature difference exists it is possible to get buoyancy driven exchanges if the single opening is reasonably tall.

2 Single sided ventilation with double opening (Figure 3.6.5b)

Driving forces in this case are enhanced by room-scale stack effects. The stack induced flow increases with the vertical separation of the openings and with the temperature difference between inside and outside. Furthermore, the wind induced ventilation is slightly improved due to the increased probability of pressure differences occurring between two openings. To prevent the cold draughts from the lower level openings in winter, special attention has to be paid to the positioning of the inlets within the room. As a rule of thumb, the limiting depth for effective ventilation is about 2.5 times the floor to ceiling height, typically 7–8m.

Cross-ventilation

Cross-ventilation is usually driven by wind generated pressure differences inducing positive (inward acting) pressures on windward surfaces and negative (outward acting) pressures on leeward surfaces. The floor depth in the direction of ventilation has to be limited to effectively prevent heat and pollutant build-up from the space during ventilation due to typical driving forces. As a rule of thumb, the limiting depth for effective ventilation is about five times the floor to ceiling height, typically up to 15m (Figure 3.6.6). This implies a relatively narrow plan depth for the building which is usually achieved by adopting either (a) a linear built form or (b) an open courtyard form. Note that in the latter case the significant

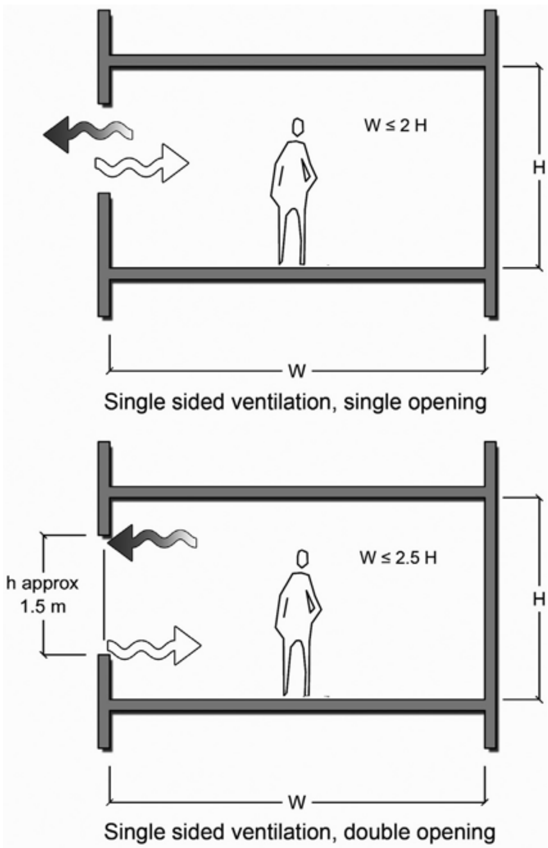


Figure 3.6.5
Single sided ventilation: (a) single opening (b) double opening.

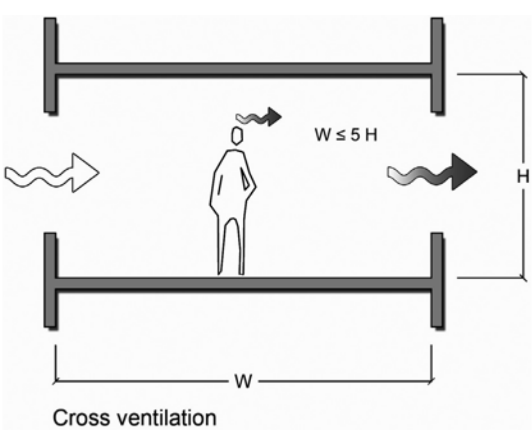


Figure 3.6.6
Cross-ventilation.

differences in wind pressure between the inlet and outlet opening will be more difficult to achieve because the courtyard and the leeward side of the building will be at similar pressures.

The ventilation principles of the wind-driven natural ventilation systems utilising roof mounted ventilators are illustrated in Figure 3.6.7. Using compartmentalized vertical vents, the pressure difference across the segment facing the wind drive the air into a space, while the suction created by the negative pressure on the leeward segments draws air out of the space. Combined inlet and outlet, static roof mounted natural ventilation systems are typically made up of a louvred terminal, a base, and damper assemblies that allow the user or an automated control system to adjust the ventilation.

Buildings that are particularly suited to roof mounted ventilation include educational buildings, libraries, health and community centres (all of which require low operational and maintenance costs). Figure 3.6.8 shows the temperature and air flow distribution within a space ventilated by means of two

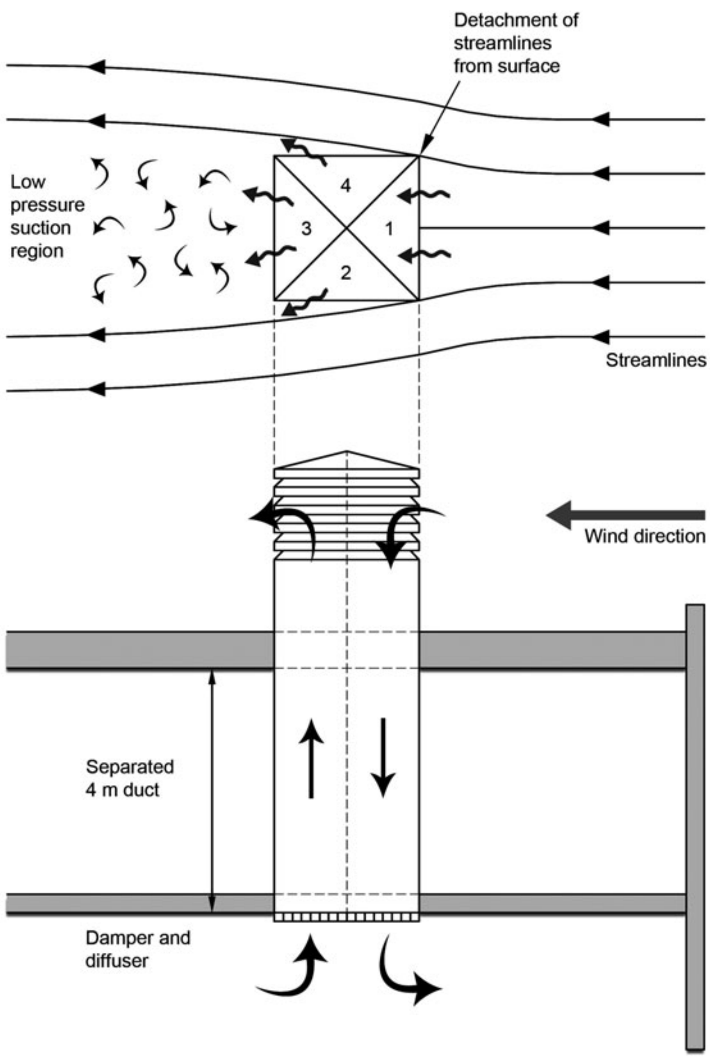


Figure 3.6.7 Flow around and inside of a squared roof mounted ventilator.

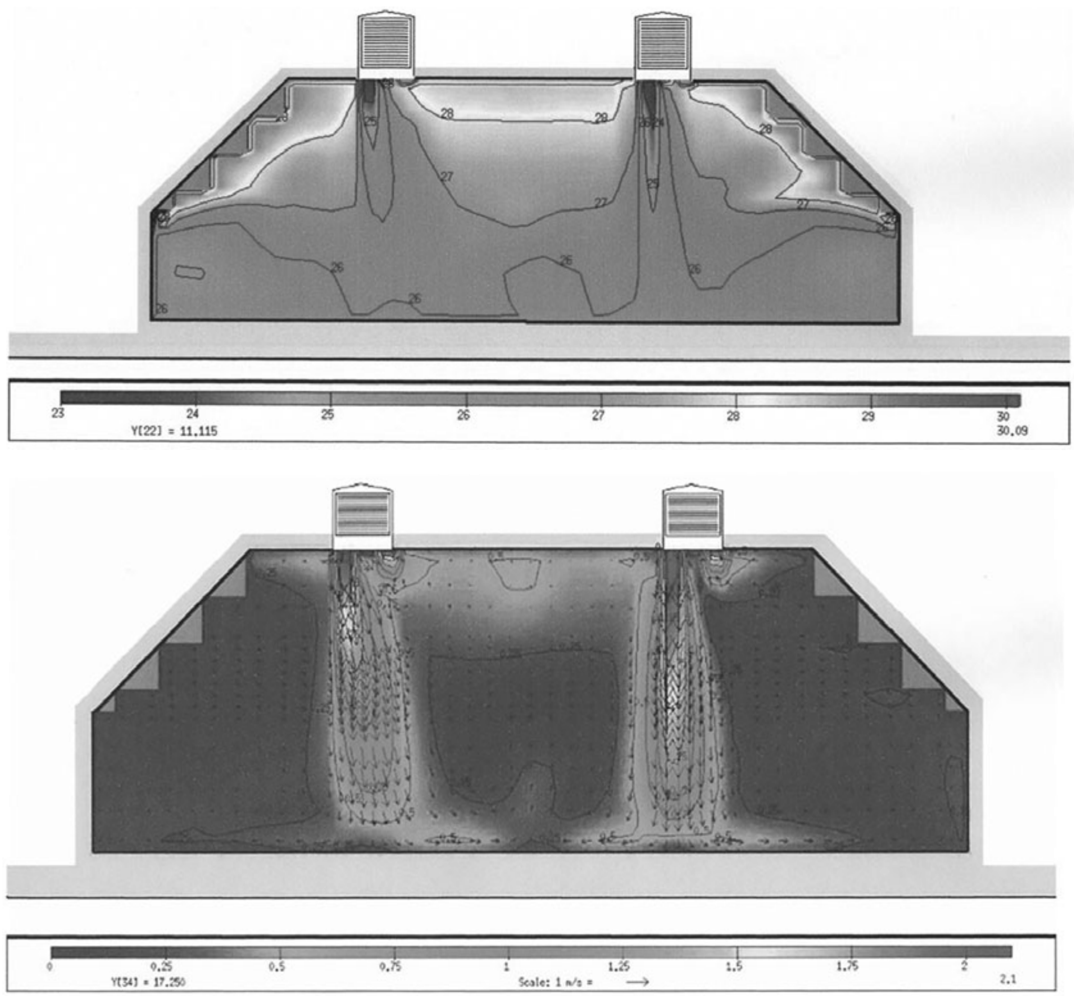


Figure 3.6.8 CFD simulation results: (a) temperature gradients (b) air velocity vectors.

Source: Monodraught

roof mounted ventilators manufactured by Monodraught. The optimum performance of this well-established system at a given speed and orientation is only possible if the ventilator is located in a free air stream, undisturbed by any obstructions. Other parameters affecting the performance include the shape of louvres, the resistance of dampers, the height of the louvres above roof level, the size of louvred area and the temperature difference between indoor and outdoor temperature. When installed in areas of heavy local traffic consideration should be given to providing acoustic internal lining which might affect the operational performance of the system. Detailed design, sizing and testing methodologies are given elsewhere.

Stack ventilation

A number of designers are achieving deeper floor plans than described above by providing stack ventilation within the building. This may be achieved via purpose built vertical ducts (also known as stacks or chimneys) or via an internal atrium or other type of vertical spatial continuity within the building. Stack ventilation is buoyancy driven and relies on density differences to draw cooler, denser outdoor air in to a building via low level vents and exhaust warmer, less dense indoor air via high level vents. Should the air inside of the building at any time be cooler than that outside, then the airflow direction will reverse. For any time where indoor air temperature is higher that outdoors (generally the case in the UK, other than for the hottest summer days in thermally massive buildings) the following stack effect occurs (Figure 3.6.9):

- the warmer air in the building rises up as the indoor air temperature is higher than that outdoors;
- the upward air movement produces a negative indoor pressure at the bottom and a positive indoor pressure on the top.

To promote natural ventilation, the elevated temperature should be maintained over a reasonable height within the atrium or solar chimney. However, if the atrium is open to surrounding spaces this may result in unacceptable temperatures at occupied levels. This could be prevented by absorbing solar gains at high levels using the elements of the structure or solar baffles. Note that the roof vents must be always positioned in a negative pressure zone with regard to wind induced pressure. This could be achieved by adopting one of the following design strategies (CIBSE, 2005):

- designing the roof profile so that the outlet is in a negative pressure zone for all wind directions (possibly utilizing the Venturi effect);

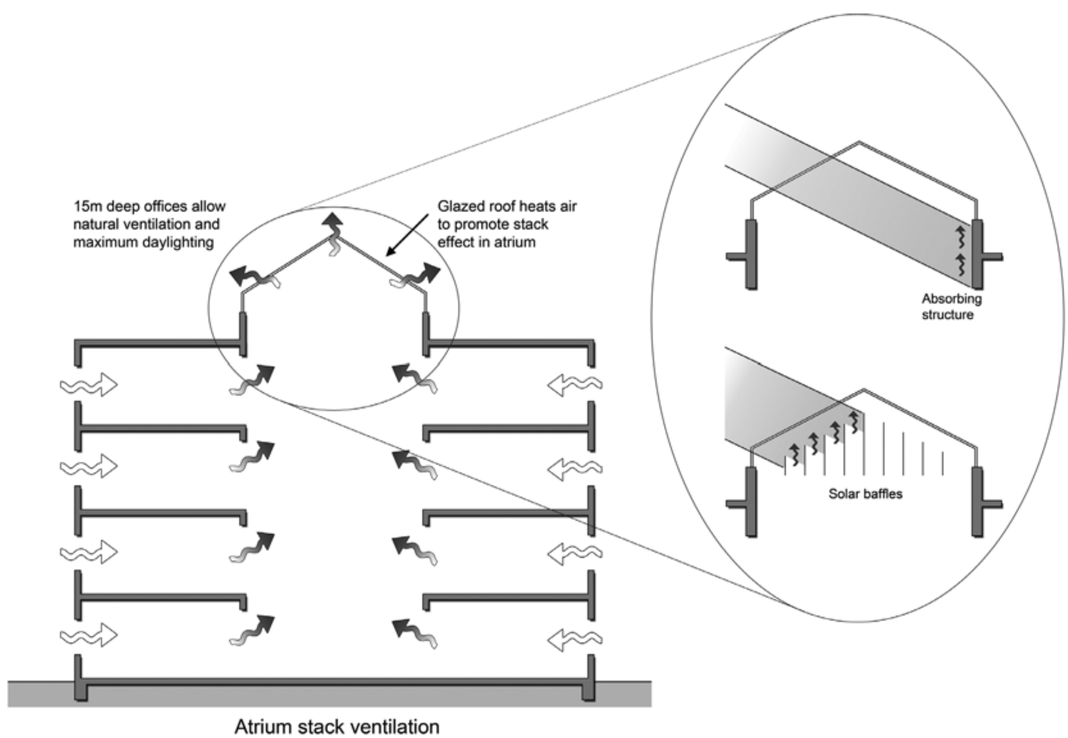


Figure 3.6.9 Atrium stack ventilation.

Source: Reproduced from CIBSE Guide B2 by permission of the Chartered Institution of Building Services Engineers

- installing an automatically controlled multi-vent system which would open and close outlets to ensure that the opened ones are always in a negative pressure zone (or using a single vent system which turns to face away from the wind).

Stack ventilated buildings can be divided in four main types according to implemented stack ventilation strategies (Lomas, 2007 – refer to Figure 3.6.10):

- the edge in, centre out (E-C);
- the edge in, edge out (E-E);
- the centre in, edge out (C-E);
- the centre in, centre out (C-C).

The edge-in strategies are susceptible to the noise, pollution and security concerns associated with natural ventilation design in urban areas. During the winter, perimeter heating elements could be used to preheat the outside air, while in the summer the operable windows could be used to enhance the air movement throughout the building without disrupting the basic air flow strategy. The edge in, centre out strategy (E-C) allows for a deep plan naturally ventilated building design and has been widely exploited in recent years.

The centre-in strategies enable the external façade to be sealed; therefore airflow is not susceptible to localized air pollution, noise and security concerns. Apart from being the air supply route, the central stack can introduce daylight into a deep-plan building. The exhaust stacks are located at the perimeter of

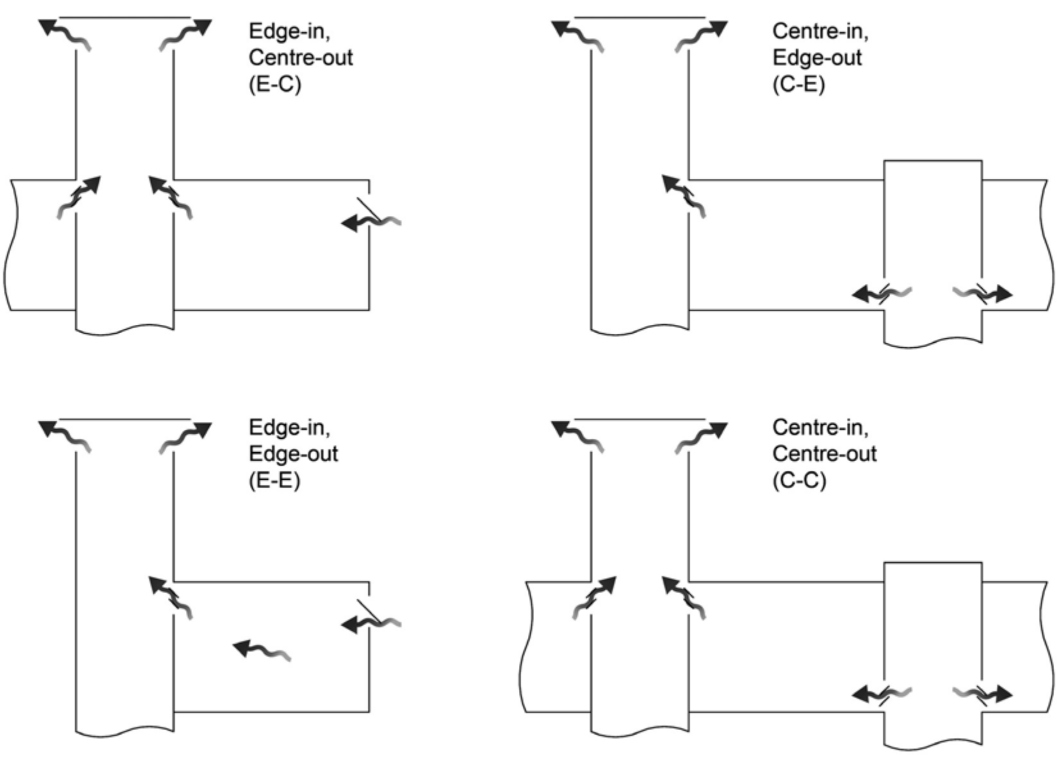


Figure 3.6.10 The stack ventilation strategies.

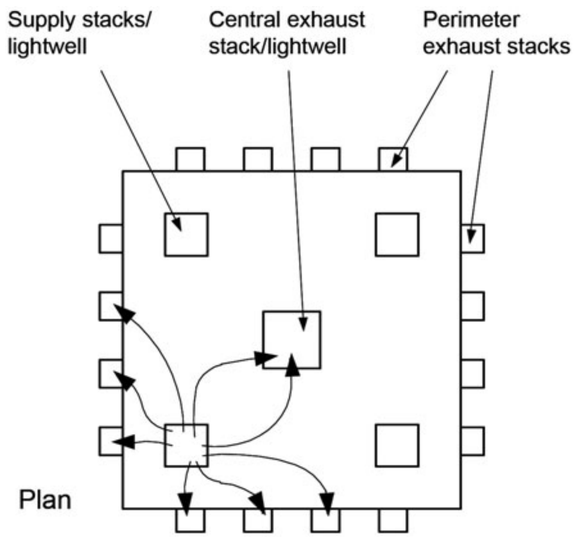


Figure 3.6.11 The centre-in, edge-out strategy (Lanchester Library).

the building allowing more flexible internal space planning. Figure 3.6.11 shows the simplified C-E strategy implemented in the Lanchester Library. Note that the centre-in natural ventilation strategies, if necessary, could be easily converted to the contingency or complementary mixed-mode ventilation design by adding mechanically assisted ventilation. Detailed discussion on the architectural design of an advanced naturally ventilated building form is given elsewhere (Lomas, 2007).

Mechanically assisted ventilation

As promising as these advanced natural ventilation systems are, the purely natural ventilation systems will fail when the natural driving forces are simply not available (no wind for wind-driven systems, no internal/external temperature difference for stack driven systems). As a consequence, recent trends have favoured mechanically assisted ventilation. For example, in stack driven systems extract fans are often installed in chimneys and/or high level in atriums and can pull air through the building as a means of providing adequate ventilation on very hot and still days. Note that in the natural ventilation mode the installed fan can provide a significant resistance to the air flow.

The inclusion of mechanical reinforcement of natural ventilation is the first step in the mixed-mode direction. The physical mixed-mode strategies are classified as (CIBSE, 2000):

- contingency design – usually naturally ventilated buildings in which the mechanical ventilation or cooling could be easily added or subtracted if necessary;
- complementary design – both natural and mechanical ventilation systems are present and designed to avoid clashes, wasteful and inefficient operation;
- zoned design – different ventilation strategies are servicing different parts of the building.

For complementary systems the operational strategies fall into two categories (CIBSE, 2000):

- Concurrent operation – an intrinsically efficient mechanical ventilation system (with or without cooling) operates in parallel with natural ventilation systems.

- Changeover operation – natural and mechanical ventilation systems are available and operate as alternatives according to need, but they do not necessarily operate at the same time; some examples include seasonal changeover (winter, summer and mid season modes), mechanically assisted night ventilation, top-up cooling (mechanical refrigeration provided when free cooling options are insufficient) and local changeover (if window is opened the mechanical cooling is switched off automatically).

CIBSE Application Manual 13 (CIBSE, 2000) identifies desirable features and discusses the issues involved throughout the process from inception and briefing to handover and operation of mixed-mode ventilation systems.

Mixed-mode systems tend to be inherently more complex than pure natural ventilation systems. They also tend to expend more energy during operation although there are exceptions to this. An example would be the use of natural ventilation in summer and mechanical ventilation with heat recovery in winter for a building located in Northern Europe, where energy used for mechanical ventilation in winter is more than offset by the heating energy saved via the heat recovery system. Mechanical ventilation with heat recovery for the winter season is becoming increasingly widespread in Northern Europe, particularly for high occupancy buildings such as schools where heat loss can be predominantly via ventilation.

Further refinements

The systems outlined in previous sections have the potential to work very well under a range of conditions (both external and operational). Outside of these conditions, the options are to develop a mechanically assisted or fully mixed-mode system and/or to exploit a number of further refinements in natural ventilation strategies. These further refinements are generally implemented when external temperatures and/or internal heat gains are too high to enable the limiting of internal air temperatures during occupied hours down within comfortable limits. They can be categorized as follows, those that:

- thermally temper the building fabric via airflow outside of occupied hours;
- thermally temper incoming air prior to introduction into the space.

The most commonly utilized refinement is that of night ventilation cooling which falls under the first category above. Here, the intention is to offset daytime internal gains by cooling the building's thermal mass with outdoor air during the previous night assuming that the outdoor temperature drops below the upper comfort limit temperatures (Figure 3.6.12). Depending on the technique used to transfer heat between the thermal mass and the conditioned space the night ventilation systems can be classified as either direct or indirect systems.

In direct systems the thermal mass of the building has to be exposed to the circulating cool air which could be driven either by natural or mechanical ventilation. In indirect systems cool air circulates through a thermal storage medium, which is usually a concrete slab covered either by false ceiling or raised floor. During the day, the incoming air, with a temperature generally higher than the corresponding temperature of the thermal storage medium, is circulated by means of mechanical ventilation. A further development here is the use of phase change materials. Although still in its infancy, this technology has the potential to improve the effectiveness of night ventilation cooling. The efficiency of these systems depends on the phase change temperature of the material, the night ambient air temperature and the airflow rate.

The night ventilation affects the indoor conditions during the next day by reducing peak air temperatures, reducing air temperatures in the morning and creating a time lag between the occurrence of external and internal maximum temperatures. The effectiveness of night cooling ventilation depends upon three main parameters (Santamouris and Wouters, 2006):

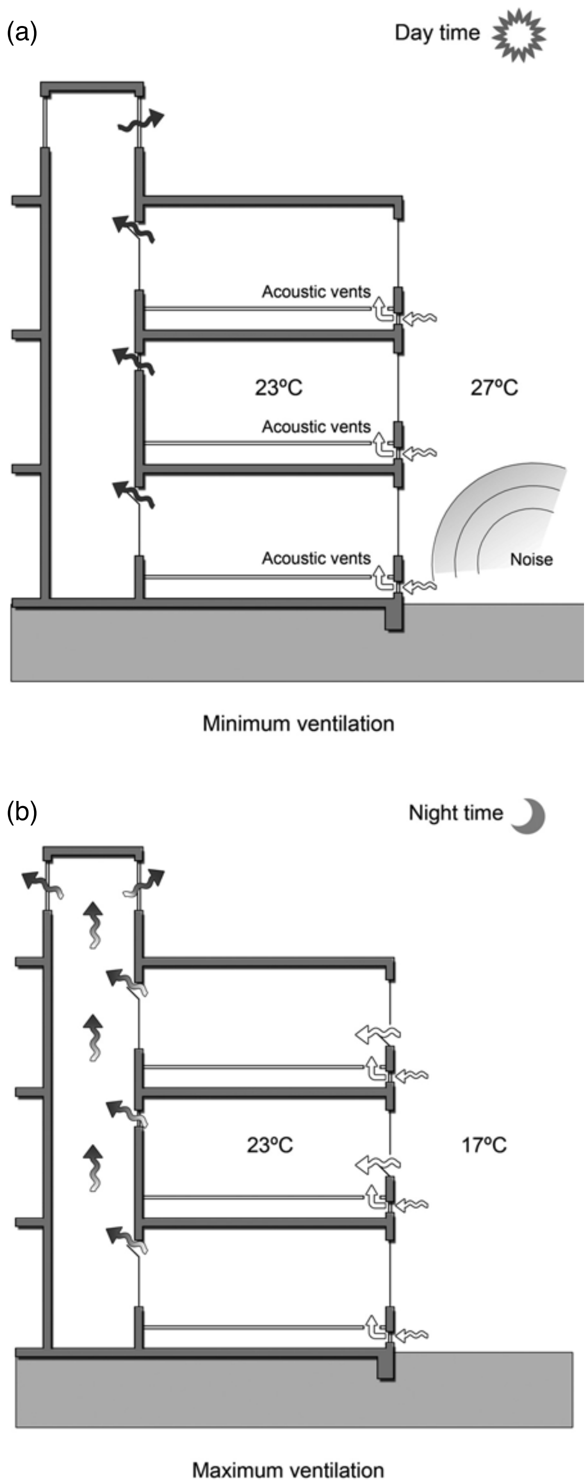


Figure 3.6.12 Night ventilation strategy: (a) day time, (b) night time.

- the temperature and the flux of the ambient air circulated in the building during the night period;
- the thermal capacity of the storage medium;
- the quality of the heat transfer between the circulated air and the thermal mass.

A number of other refinements are in use that fall within the second category at the start of this section, tempering external air prior to introduction into the space. These include the use of thermal labyrinths and ground pipes and also the use of passive downdraft evaporative cooling. Ground pipes involve the routing of air into a space via a duct under the ground in order to pre-cool the air prior to introduction into the space. This arrangement can be utilized with purely natural ventilation drivers. Thermal labyrinths are similar to ground pipes but involve airflow into a space being directed via a tortuous route through an area of high thermal mass in order to precipitate significant heat transfer. Resistance to airflow is typically high and mechanical assistance is usually required. Passive downdraught evaporative cooling can work where external air conditions are hotter and drier than target conditions inside. It involves introducing a water source (typically a fine water spray) into the incoming air at high level within a space. This then evaporates causing a rise in relative humidity and associated drop in air temperature and induces a downdraft through the space (functioning as a stack ventilation system with high level inlets and low-level outlets). This type of cooling can function as a part of a conventional stack driven system, operating only during the hottest summer months.

Integration of basic strategies

The previously described basic strategies are commonly used concurrently in a building to handle a variety of ventilation requirements (Figure 3.6.13). For example, single sided ventilation with double opening might be adopted for a number of cellular shallow spaces. However, a local stack ventilation system might be used to provide adequate ventilation in deeper spaces. Additionally, to temper the incoming air and to provide a greater control of air distribution across the building the use of in-slab fresh air distribution could be adopted. This type of fresh air distribution is similar to displacement ventilation, most commonly implemented mechanically, and similarly relies on thermal plumes generated by equipment and by occupants to assist airflow and improve air quality in the ventilated enclosure. Finally, for deeper high occupant density spaces the cooling potential of natural ventilation might not be sufficient to prevent overheating and an additional mechanically assisted strategy might be necessary.

An example of such an approach is Portcullis House (2000) in London designed by Michael Hopkins & Partners (Figure 3.6.14). Visually, the exterior of the building takes its references both from Charles Barry's 1860 Palace of Westminster and from Norman Shaw's neighboring 1890 New Scotland Yard building on Victoria Embankment. This seven-storey high building has a simple, rectangular, courtyard plan. The courtyard is covered by a glass roof at second floor level and surrounded by a two-storey cloister. The building is cellular in nature and the construction is thermally heavyweight with partitions and soffits being exposed concrete. Each office has a triple glazed window with an adjustable dark interpane blinds aimed at providing adequate thermal comfort in winter and summer. Fresh air is provided via the floor void and extracted via the window and directly from the room. The fresh air is drawn in via openings at the base of roof turrets and the vitiated air is exhausted via openings at the top of the turrets. Prior to discharge the air passes through a thermal wheel providing preheating to the incoming fresh air. The system operates at night to provide a night cooling mode. Additional cooling is provided through the use of the borehole ground water drawn at around 42°C from the chalk 150 m below and discharge to the river having been used in the grey water system. Heating is provided by a conventional gas fired condensing boiler operating on a 70/50°C temperature regime. A detailed description of this building can be found elsewhere (Dix, 2000).

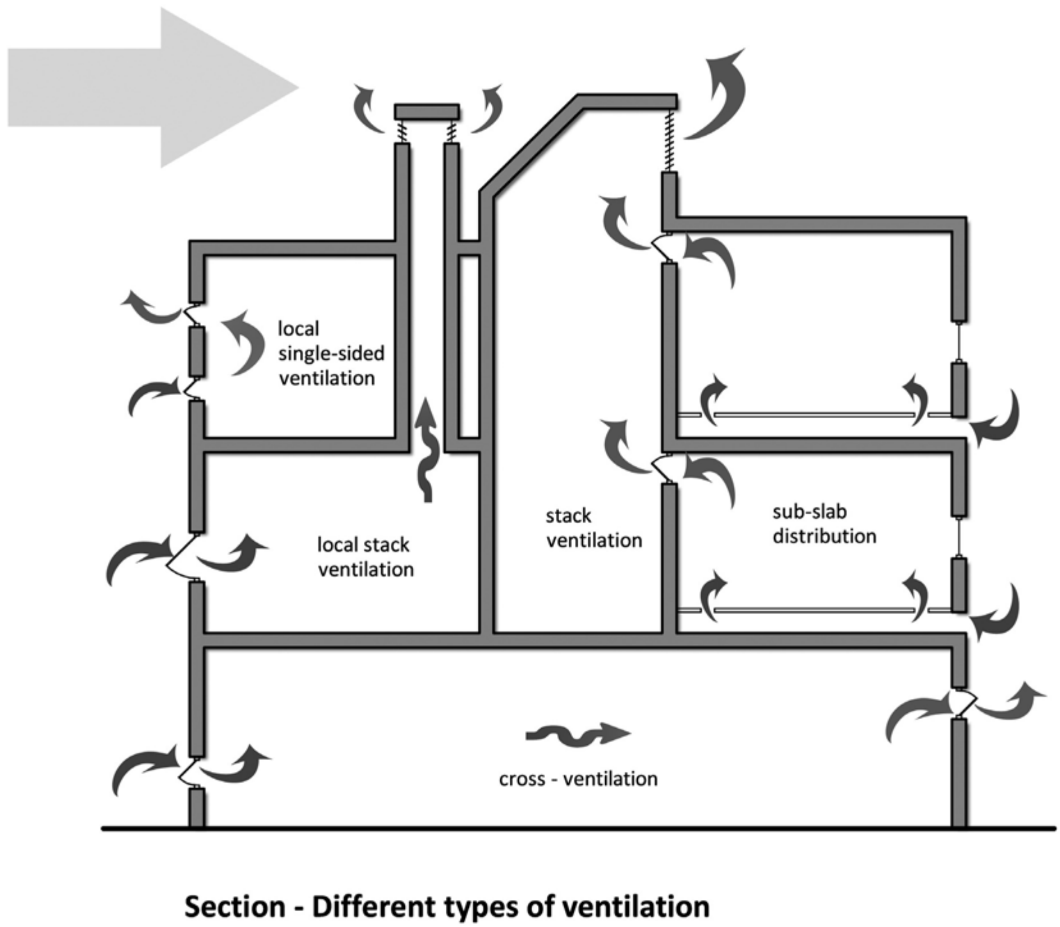


Figure 3.6.13 Integration of basic ventilation strategies.

Design performance evaluation

In order to ensure that the developed natural ventilation system performs adequately it is important that sound engineering-based methods are employed. This will include evaluating the design under various weather conditions and heat loads and determining potential situations where design goals might not be met. Depending on design requirements the analysis of the natural ventilation systems will require consideration of energy consumption (and associated CO_2 emission), airflow (due to wind, density differences and mechanical forces in the case of mixed-mode ventilation systems), and air pollutants distribution. The complex interaction between building envelopes and their indoor and outdoor environment make it difficult to address all these issues using one tool only. This has led to the development of a wide range of different analysis tools and they typically fall into two broad categories:

- mathematical models;
- physical models.

Figure 3.6.14 Portcullis House.

Mathematical models

Mathematical models used to design natural ventilation systems fall typically into three basic categories:

- single zone models;
- multizone models;
- computational fluid dynamics (CFD).

Single zone models consider the entire building to consist of a single volume of well mixed air with no internal partitions. Some methods also account for thermal characteristics of the building envelope. In general, they solve the equations that govern the flow of air through openings in the envelope of a building:

$$\sum q_i = 0 \qquad 3.6.1$$

$$q_i = C_{di} A_i S_i \sqrt{\frac{2|\Delta p_i|}{\rho_0}} \qquad 3.6.2$$

$$\Delta p_i = \Delta p_0 - \Delta \rho_0 g z_i + 0.5 \rho_0 U^2 C_{pi} \qquad 3.6.3$$

where i identifies the opening, q_i is the flow rate through the opening (m^3/s), C_{di} is the discharge coefficient (–), A is the are of opening (m^2), Δp is the pressure difference (Pa), $\Delta \rho_0$ is the air density difference (kg/m^3), g gravitational force (m/s^2), zi height of opening above ground level (m), sign of the pressure difference (+1 for flow entering the space; –1 for flow leaving the space), U wind speed (m/s), and C_{pi} wind pressure coefficient.

Equation 3.6.1 represents conservation of mass for the building envelope, i.e. the net mass flow into the building is equal to zero. Equation 3.6.2 defines the relationship between the flow rate through an opening and a pressure difference across it by means of the discharge coefficient and a specified geometric area. Finally, Equation 3.6.3 defines the pressure difference across an opening whose inlet or outlet is situated in the external flow. Note that the single zone models ignore internal resistances to airflow and are generally considered useful for the initial calculations only. A spreadsheet maybe downloaded for free from the CIBSE web-site (www.cibse.org/venttool).

Multizone models are based on an idealized physical representation of building systems and can be used to describe a building as a set of zones that are interconnected by airflow paths. It is assumed that the zones are typically well mixed, i.e. the pressure, temperature and pollutants concentration is the same throughout the zone. Nowadays, more advanced multizone design tools have been able to simulate airflow through openings in combination with the thermal response of a building. Using these features, one can perform simulations to investigate the differences in airflow rates obtained by varying different building features and weather conditions including the size and placement of ventilation openings in the building envelope, the orientation of the building in relation to the prevailing wind, the outdoor temperature and the size and location of ventilation stacks. Furthermore, some of the more advanced design tools can be used to determine the microscopic airflow and temperature fields within a given zone.

CFD modelling is the process of representing a fluid flow problem by mathematical equations based on the fundamental laws of physics and solving those equations to predict the variation of the calculated parameters within and around buildings. The applications of CFD to the design of naturally ventilated buildings include but are not limited to:

- calculation of velocity, temperature and air pollutants distributions in single- and multi-cell buildings;
- prediction of the external wind flow around a building and the resulting pressure field from which the pressure coefficient, *Cpi*[–], can be calculated;
- calculation of internal flow patterns through ventilation components.

Case Study 3C describes the main principles and concepts associated with CFD modelling. Furthermore, it highlights the fundamental problems of the microscale CFD models, which lie in the physical difficulties of modelling the effect of turbulence, and also the accuracy of the spatial discretization of complex building geometries, the numerical procedures applied, the boundary conditions and the physical property selected.

Physical models

Although the mathematical models are more cost-effective, the physical models are still used by both research and building design communities as they offer relatively high accuracy. These include:

- wind tunnel modelling;
- saltbath modelling.

The wind tunnel testing is usually used to determine wind pressure coefficients for individual building design. A physical model of a building and its surroundings can be constructed and placed in a wind tunnel where it is subject to a controlled wind flow. A boundary layer wind profile should be comparable to that appropriate for the site and can be induced in the wind tunnel by means of blockages. Determination of wind speed for evaluating wind pressure coefficients is carried out using the following formula:

$$U = U_{\text{met}} k z^{a} \qquad 3.6.4$$

where is the wind speed at height (m/s), is height above ground (m), and are coefficients determined by the terrain in which the building lies. Values for the terrain coefficients are given in Table 3.6.1. Most building application wind tunnels operate at scales of between 1:100 to 1:500. As long as the Reynolds number is kept high, through high wind tunnel air speeds, the turbulent regime is ensured and scaled and real flows will match. The results of measurements are available as design data for generic building forms.

The wind tunnels can also be used for flow visualization by introducing smoke or other tracers in the wind tunnel and observing the flow characteristics. For example, by introducing a fine grain in the wind tunnel one can observe airflow characteristics and assess the impact of a new development on pedestrian

Table 3.6.1 Terrain coefficients.

Terrain	*k*	*a*
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.2
Urban	0.35	0.25
City	0.21	0.33

Source: CIBSE, 2005

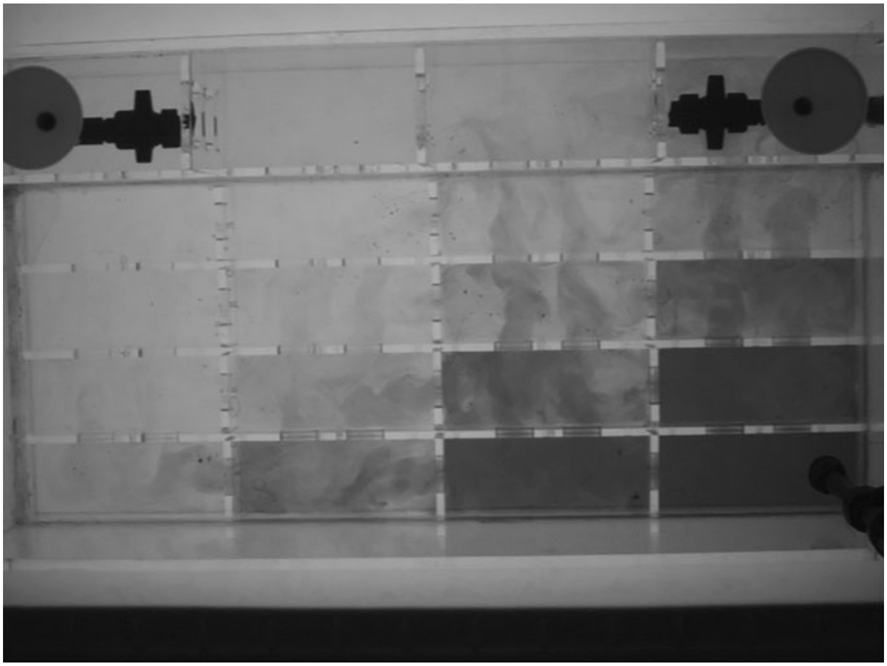


Figure 3.6.15 Saltbath test.

Source: Dr Liora Malki-Epshtein, UCL

comfort in urban areas (the grain will be cleared from more windy areas indicating wind exposure). Lately, the wind tunnels can also be used for measuring directly ventilation rate of a building providing that that the volume of the envelope at a model scales allows a tracer gas measurement inside the model. However, this is subject to certain limitations, i.e. the full scale ventilation openings have to be sufficiently large to be accurately modeled. Therefore, if possible the wind tunnel testing offers relatively high accuracy in the determination of ventilation rates due to wind because the effect of wind turbulence is inherent in measurements.

The saltbath method is relatively recent development and is primarily used for testing of buoyancy driven ventilation strategies. Figure 3.6.15 shows a small-scale model of a building envelope which is immersed in transparent bath containing saline solutions of different concentrations that simulate the density (temperature) differences. This is for airflow between rooms that are interconnected through several openings, enabling air to move between rooms through different paths. The water in the experiment is coloured with dye and it flows in at the bottom right and can flow out of the tank at the top right only. Note that using the saltbath method is not possible to realistically simulate boundary conditions, such as solar patching on the floor of an atrium.

Detailed design

Ventilation components

Primary vent sizing in natural ventilation systems tends to be determined by airflow rates needed to deliver ventilative summertime cooling. The issue of overheating in the summer is one of the main technical barriers related to the natural ventilation systems. To avoid overheating the airflow will commonly need to exceed that required solely to satisfy the minimum required for indoor air quality and health. As a result, sizes of openings are at least an order of magnitude larger than that used for winter ventilation.

Windows remain the most commonly used vents in natural ventilation systems. Different types of windows create different indoor air flow patterns and provide different options for controlling the direction and level of volumetric flow. The main windows types can be classified in four groups (Table 3.6.2).

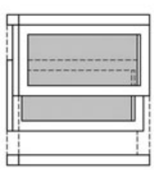
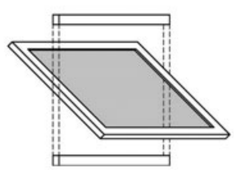
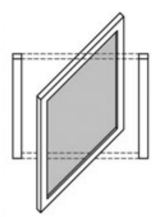
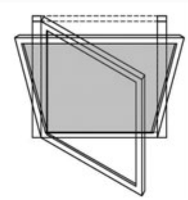
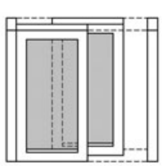
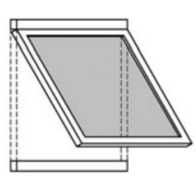
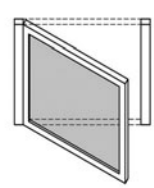
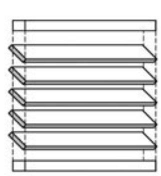
1 Sliding (sash) windows

This group of windows includes horizontal and vertical sash windows. This type of windows do not affect the air flow distribution around the opening to greater extend. Although the direction of the flow path cannot be influenced by projecting sashes, this design allows for control of the air flow path within the interior place by height (vertical sash windows) and width (horizontal sash windows). These windows have a fairly high ventilation capacity, and the effective area is maximum 50% of the structural opening.

2 Horizontal-vane opening windows

This group of windows includes horizontal pivot, top hung, bottom hung and louvred windows. This type of windows affect the air flow path mainly in vertical direction either upward (for example, a bottom

Table 3.6.2 Classification of windows.

Sliding (sash) windows	Horizontal-vane opening windows	Vertical-vane opening windows	Tilt and turn windows
 Vertical sash	 Horizontal pivot	 Vertical pivot	 Tilt and turn
 Horizontal sash	 Top/Bottom hung	 Side hung	
	 Louvered		

hung inward opening windows) or downward (for example, a top hung inward opening windows). The horizontal pivot and louvred windows can be designed to direct the airflow in either direction according to the position of sashes. The horizontal pivot windows have a high ventilation capacity and the geometry promotes a good air distribution. However, due to security and health and safety reasons the length of throw of stays is usually restricted which might affect the ventilation capability of these windows. Unlike the horizontal pivot windows, the louvred windows can be made secure and still having a high ventilation capacity. A less satisfactory seal and consequently the increased ventilation loss in winter is the major disadvantage for this particular design (Figure 3.6.16). If located adjacent to the ceiling the bottom hung inward opening windows are suitable for night ventilation cooling.

3 Vertical-vane opening windows

This group of windows includes vertical pivot and side hung (casement) windows. This type of windows affects the air flow path mainly in horizontal direction. The most common window of this type in Europe is the double side hinged inward opening casement window which has a great versatility with regard to air flow control. However, the ventilation characteristics are strongly influenced by wind speed and direction. The vertical pivot windows have a high ventilation capacity and will provide either a positive or negative wing wall effect. The vulnerability of the vertical vane opening windows to driving rain limits their popularity in the UK.

4 Tilt and turn windows

Note that these windows have been designed for manual operation and cannot be linked to actuator which limits their application in automatically controlled naturally ventilated buildings. If well designed and properly used by occupants, this type of windows can offer a great versatility with regard to air flow control as they offer two different opening geometries in a single unit.

Vents are controlled either manually or mechanically via actuators. An actuator responds to the output signal from a controller and provides the mechanical action to operate the vent (such as window or damper). The choice of vent type and its integration with different actuator options requires a special attention, particularly when using windows as these have generally been originally designed for manual operation. The windows used for automatic control may require adaptation to accommodate a motorized actuator and strengthening to take into account a number of forces imposed on an actuator such as the ventilator weight, external forces (wind, snow), actuator position and speed operation (high speed

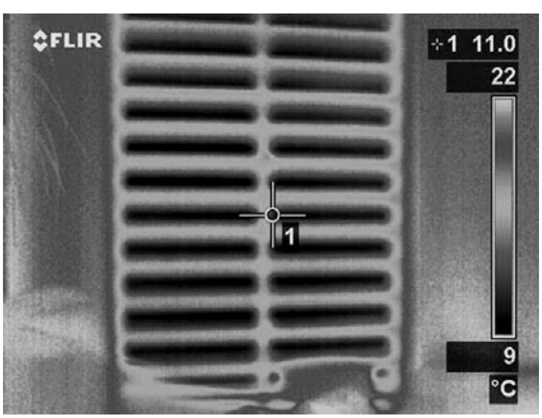


Figure 3.6.16 Louvred window: An IR image.

operation causes greater stresses and shock loadings at each end of its travel). If automatic control is required the horizontal pivot, top and bottom hung windows are usually used with linear and chain actuators. The louvred windows are usually coupled either with rotary or linear actuators. More detailed analysis of actuators suitable for natural ventilation could be found elsewhere (CIBSE, 2005).

For winter ventilation, trickle ventilators are commonly used and are generally able to provide the necessary background ventilation to satisfy the minimum ventilation requirements. To minimize cold draughts the trickle ventilators should be at the high level (typically 1.75m above floor level) and designed to promote rapid mixing within the room. The possible benefits of automatic ventilation control of trickle ventilators in dwellings has been investigated at the Bartlett (Ridley, Davies, Booth, Judd, Oreszczyn and Mumovic, 2007). Such ventilators could offer an improvement in performance over fixed ventilators, due to their ability to adjust to environmental conditions without occupant interaction, thus providing adequate indoor air quality while decreasing ventilative heat losses and so improving energy efficiency. Field tests in a highly instrumented test house were carried out on 3 types of trickle ventilator: fixed, pressure controlled and relative humidity controlled. A computer model of the performance of these types of trickle ventilators was developed and the results of the simulations set out the potential for pressure ventilators to reduce the occurrence of over ventilation in dwellings, and for humidity-controlled ventilators to reduce the incidence of excess humidity without significantly increasing ventilation heat loss.

Background ventilation can also be provided via more sophisticated methods which can deliver energy saving benefits. The most common example is mechanical ventilation with heat recovery. A less commonly utilized option is natural ventilation with heat recovery.

Whenever the air has to pass through more than one room on its way from the inlet opening to the outlet, it encounters additional resistance which depends on the size of interior openings. As well as providing a resistance to the air flow, changes in direction, contraction and expansion of air streams create turbulence and further reduce the air flow rate. Therefore, a special attention has to be taken to ensure that the ventilation path is not obstructed. For example, if cellular office space is required, transfer grilles will be needed to allow the air to move across the building.

Control systems

The need to maintain ventilation rates reliably using natural ventilation forces is a major challenge for the development of advanced natural ventilation systems. The wind and buoyancy forces are stochastic in their nature making control more difficult. As a result of poor controllability of the natural ventilation systems the ventilated enclosures may be:

- under-ventilated resulting in deterioration of air quality and overheating;
- over-ventilated resulting in higher heat ventilation losses;
- or may not provide acceptable air distribution resulting in local thermal discomfort (cold draughts or insufficient cooling) or local air quality problems (pockets of stagnant air).

An automatic control system for a naturally ventilated building is composed of one or more sensors measuring the parameters required for the implementation of any control strategy. In most cases one or more temperature sensors are normally positioned in the room to achieve an average reading. This is the simplest method of automatic control and is suitable for most applications. For example, the dampers are normally set to commence opening at 16°C during summer months and open 20% for every 1°C rise in internal room temperature. Seasonal switching enables the temperature set points to be increased in the winter setting to prevent heat loss during this period. In atria and other buffer spaces the coarse on/off method is most commonly used as the close control of comfort conditions is not essential. In the case of densely populated areas of a building, such as classrooms or conference theatres, CO_2 sensors may be used in conjunction with the temperature sensors. A key control problem is to provide sufficient but not excessive background ventilation while avoiding draughts. The preferred location for the CO_2 sensor may be around seated head height and away from direct draught. In addition to the temperature and CO_2 sensors, automatic control for a naturally ventilated building could be composed of room occupancy, humidity, rain detection, outside air temperature, wind speed and wind direction sensors. Generally, these parameters can be recorded, but are usually used for performance assessment purpose.

Sensible integration of user and automated controls is therefore critical to the success of natural ventilation. In the case of the user control, the resulting control strategy is based on purely subjective criteria, i.e. perceived indoor air quality and thermal comfort. If in the control of their indoor environment, the occupants are usually willing to accept wider comfort bands, even if they are not ideal. They will rarely act in anticipation of becoming uncomfortable. However, if uncomfortable, the occupants will take action to alleviate their discomfort and this case the rapid response is essential. Note that the automated control must not usurp control too rapidly after user intervention.

Installation, commissioning and post occupancy evaluation

Installation and commissioning is a four-stage process (CIBSE, 2005):

- Installation. Achieving successful automatically controlled natural ventilation system depends critically on the installation and integration of ventilation components. It is important that all involved take ownership of the agreed strategy including the quantity surveyors. Elements which are fundamental to the ventilation strategy cannot subsequently be regarded as insignificant in cost cutting exercises. The installer and commissioning specialist should establish systematic site control procedures to assist the progressive monitoring of the standard of the installation practices maintained on site.
- Static completion is a term which indicates that an installation is ready for commissioning. Briefly, it means that all components have been installed in accordance with the manufacturers' specifications, have been subject to final inspection, have been tested for air leakage, have been cleaned, made safe and ready to set to work.
- Practical completion should take into account all local conditions and consider the use and occupancy patterns within the space. To allow for adjustments in the controls to suit the range of different activities that may take place in the building the initial monitoring may be required.
- Fine-tuning after practical application should be carried out in the year following handover. It should focus on problems reported by the occupants and the analysis of operational performance of the installed ventilation system. This process should be repeated for each of the ventilation modes, i.e. winter, summer and mid-season ventilation modes.

Post occupancy evaluation of buildings is defined as 'an activity which originates out of an interest in how a building performs once it is built' (FFC, 2003). Post occupancy evaluation is increasingly being identified as an indispensable part of the building design, construction and occupation process. The key benefits include feedback of the success of hypothesis set out during design development process, with lessons learned fed into subsequent design work and also the opportunity to identify elements of the project which are operating way outside of their intended parameters – possibly to the detriment of the entire project – in order that these can be rectified post occupancy.

Acknowledgements

This chapter is partially based on a postgraduate dissertation entitled 'Advanced Natural Ventilation Strategies – State of the Art', which has been submitted by Sung Ming Hong in partial fulfilment of the requirements for the degree of MSc in Environmental Design and Engineering at the Bartlett, University College London.

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3.7

MECHANICAL AND MIXED-MODE VENTILATION IN CITY CENTRE BUILDINGS

Jarek Kurnitski and Olli Seppänen

Principles of mechanical and mixed-mode ventilation

Buildings with mechanical ventilation use fans to supply air to, and exhaust air from, the rooms. Depending on demand, the supply air may be heated, cooled, humidified, or dehumidified. The ventilation system may be equipped to recover heat from the exhaust air. The system may also re-circulate extract air. Windows may be sealed or operable.

Mixed-mode ventilation combines mechanical ventilation with the use of natural driving forces. When stack effect or wind pressure differences are available fans are no longer operated. Mixed-mode systems are either low pressure fan assisted mechanical systems or two mode ventilation systems operating mechanical ventilation or natural ventilation depending on conditions.

During the last decade, major developments have taken place or been further refined, such as various kinds of demand-controlled ventilation, systems with improved air flow characteristics at room level (e.g. displacement ventilation), heat recovery systems with efficiencies up to 90%, major developments in fan characteristics (e.g. direct current and inverter drive variable speed fans), low pressure air distribution systems, etc. In mechanically ventilated buildings, the ventilation air may also be conditioned before it is supplied to the rooms via duct systems. Because of supply and exhaust air fans the system is more flexible in respect to building design, and more energy efficient than other systems if heat recovery means are used. However, mechanical ventilation systems also may deteriorate indoor air quality if not properly operated and maintained as dirty air handling system may itself be a source of pollution and moisture in air handling system can cause mould growth. These issues have to be solved to achieve good indoor air quality.

The air flow in the ventilation system have different names depending which part of the building or the system the flows occur (Figure 3.7.1). The function of the air flows is described in the following numbered components in the figure:

1 Outdoor air is used for ventilation, usually the term ventilation rate refers to the outdoor air flow taken outside the building and therefore not previously circulated through the ventilation system (1.1 Single room outdoor air).
2 Supply air to the room can be conditioned (heated, cleaned, cooled, humidified or dehumidified). It can be 100% outdoor air or mixture of recirculation air (6) and outdoor air depending on the system. The supply air may not only be used for ventilation but also for temperature and humidity control of the room. Usually the air flow required for thermal control of the room is greater than that for ventilation (outdoor air flow) (2.1 Single room supply air).

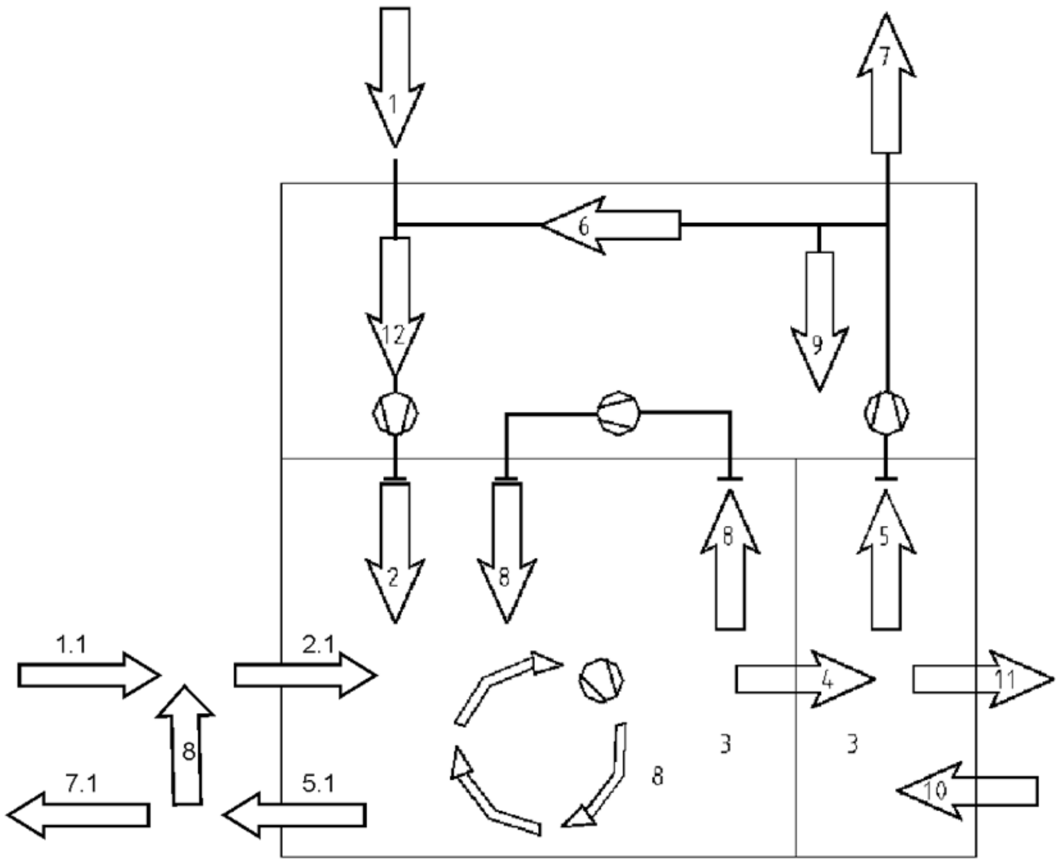

Figure 3.7.1 Various air flows in a ventilation system (EN 13779).

3 Indoor air is the air in the ventilated space. In mixing air distribution systems, the indoor air quality is uniform in the space. In displacement ventilation systems the gradients of concentrations and temperature are intentionally created.
4 Transfer air is the air moving between adjacent rooms in the building. This air flow can be used to prevent pollutants from spreading from rooms with low air quality to rooms with better air quality, like tobacco smoke from smoking areas to non-smoking areas.
5 Extract air is the air extracted from the room. Extract air should be taken from the location in the room where the air has the lowest quality (5.1 Single room extract air).
6 Recirculation air is a part of extract air (clean air) which is not exhausted from the building.
7 Exhaust air is extract air that is exhausted from the building and not recirculated (7.1 Single room exhaust air).
8 Secondary air is the air which is circulated within one space (extracted and supplied), usually it is treated during circulation – secondary air can be used for example for heating a room or be circulated through an air cleaner. Secondary air handling units can be located outside the room or in the room.
9 Leakage. If the duct and air handling system is not airtight, air will leak from, or into, the system depending on the pressure in the system, and reduce the air delivery efficiency of the system.

10 Infiltration is the air flowing through the building envelope into the building. The infiltration depends on pressure difference over the structure and the flow paths. This may bring harmful pollutants into the building.
11 Exfiltration is the air flowing through the building envelope from inside to outside due the pressure difference. In cold climates this may cause moisture damages in the constructions due to condensation of moist indoor air in the structure.
12 Mixed air is the mixture of outdoor air and recirculation air. The amount of outdoor air is based on ventilation requirements of the space. Total supply air rate flow is based on cooling or heating requirements of the space.

Ventilation systems for residential buildings

Why mechanical ventilation

The idea of mechanical ventilation system is that the required ventilation rate can be maintained in all weather conditions without influence of occupants of the building. When the ventilation is provided with mechanical system the building envelope can be made air tight, and by that way the energy losses due to infiltration and exfiltration reduced. Tight building envelope also improves sound insulation and reduces the transfer of external noise into the building. Energy efficiency of ventilation can be further improved with heat recovery from exhaust air and demand-controlled ventilation by occupancy, moisture or air quality. Ventilation air can be cleaned of outdoor air pollutants. Heating and cooling can easily be combined with mechanical ventilation systems. Mechanical ventilation systems may also control the pressure differences over the building envelope and prevent moisture damage in the building structures. Figure 3.7.2 illustrates some of the problems related to natural ventilation system. As natural ventilation is based on pressure differences created by temperature differences and wind in some conditions pressure difference will reverse the air flows, and the exhaust air stacks, which may be contaminated, become supply air routes, and spread the pollutant into the living rooms. Also, the use of cooker hood fan may overcome the pressure differences of natural forces and reverse the flows (Figure 3.7.3).

Mechanical exhaust ventilation

In mechanical exhaust ventilation systems air is exhausted from the rooms having higher pollutant generation and lower air quality. Air infiltration through building envelope or special air intakes brings outdoor air for ventilation to the building. In apartment buildings exhaust from the different floors can be connected to the same duct (Figure 3.7.4) if the pressure drop in the exhaust grille is high enough to prevent air flow from floor to floor. Central fan serves all apartments. Room air flows can be controlled with adjustable grilles by humidity or CO_2-concentration or other pollutants or by occupancy sensors.

The advantages of the mechanical exhaust are:

- constant ventilation rate;
- small negative pressure in building prevents moisture mitigation into the constructions of external walls and prevents condensation and consequently the mould growth.

Drawbacks of the mechanical exhaust system are:

- air infiltration through the building envelope creates easily draught in winter in cold climate;
- typical air intakes have low sound attenuation for outdoor noise;

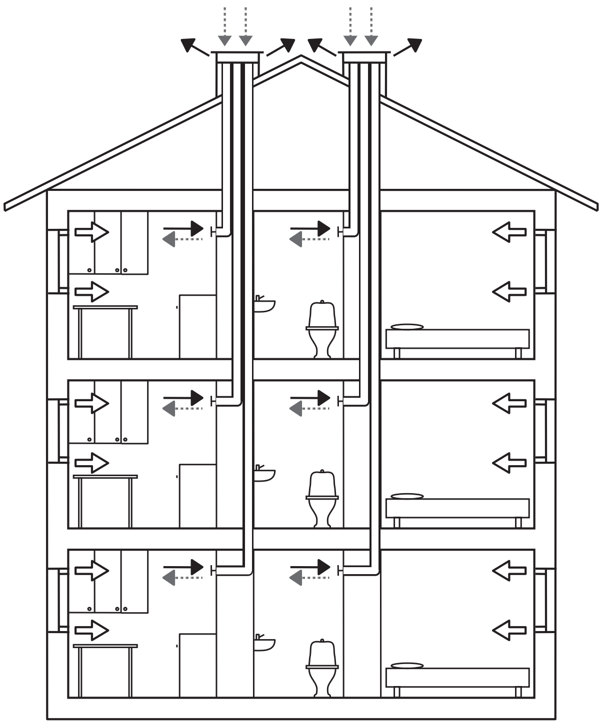

Figure 3.7.2 In some weather conditions the flow in the stack may be reversed (dotted arrows) in the natural ventilation systems which rely on temperature difference as a driving force for ventilation.

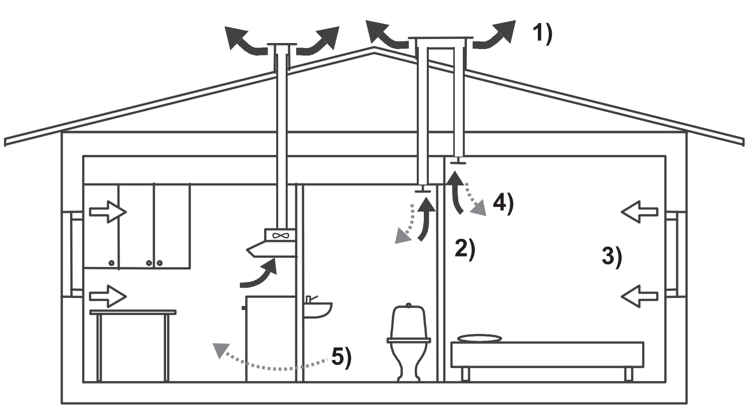

Figure 3.7.3 Use of the cooker hood fan may reverse the air flows (dotted arrows) in the shafts for natural ventilation. 1) Exhaust air in normal operation; 2) Extract air in normal operation; 3) Ventilation air in normal operation; 4) Reversed air flow; 5) Transfer air due to operation of cooker hood fan.

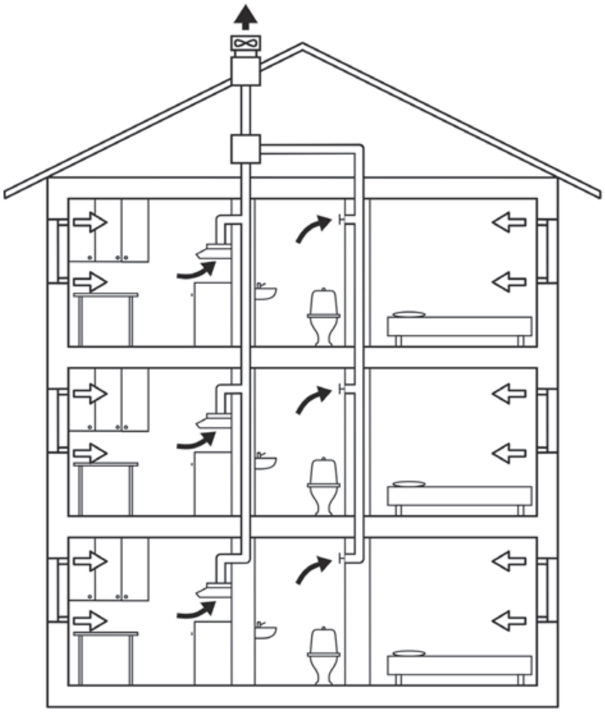

Figure 3.7.4 Mechanical exhaust ventilation system may serve one or several apartments.

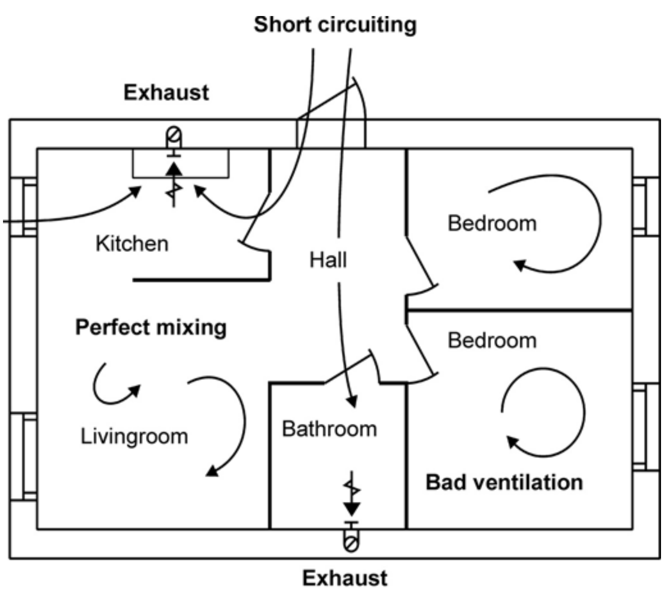

Figure 3.7.5 Example of the short-circuiting ventilation in an apartment with mechanical exhaust ventilation.

- heat recovery from the exhaust air is not easy to implement – recovered heat cannot be used to heat ventilation air – it can however be used to preheat the domestic hot water (using a heat pump);
- as the exhaust is usually from kitchens, bathrooms, and toilets ventilation supply air flow is not evenly distributed in the bedrooms and living rooms;
- distribution of outdoor air for ventilation depends on the leakage in the building envelope.

These problems are illustrated in Figure 3.7.5, which shows that air may flow directly from the locations of infiltration to the exhausts (air flow in where the building envelope is less air tight as in the kitchen window and entrance door). If the building envelope is air tight in bedrooms and living rooms the outdoor air does not ventilate those rooms but flows directly to extract air openings in kitchen and bathroom. This kind of short circuiting of air flow reduces the efficiency of ventilation and should be avoided. Specifically, at night when the bedroom doors are closed the ventilation may be very low and air quality unhealthy. This short circuiting can be avoided by arranging supply air grilles into each bedroom and living room as illustrated in Figure 3.7.6.

Mechanical supply and exhaust ventilation

In mechanical supply and exhaust systems the air is supplied via ducts and fans to bedrooms and living rooms, and typically exhausted from kitchen, bathroom and bedrooms (Figure 3.7.7). Usually the exhaust air flows through heat exchanger before it is discharged outdoors. In heat exchanger a major part of the heat content of the exhaust air is recovered and used to heat the outdoor air for ventilation. Thus, mechanical supply and exhaust systems are free of draught and outdoor noise problems typical to mechanical exhaust or natural ventilation. Use of the recovered heat for heating of the ventilation air is usually most economical as the need for heating is simultaneous with the available heat. Another alternative for the use of the heat is heating of domestic hot water.

Mechanical supply and exhaust ventilation provides effective filtering of outdoor air. This has great importance in urban areas with high traffic or industrial combustion loads. It is shown that mechanically ventilated buildings protect occupants from outdoor air pollutants. A probabilistic exposure modelling exercise has demonstrated that reducing the particulate matter ($PM_{2.5}$, e.g. particles smaller than

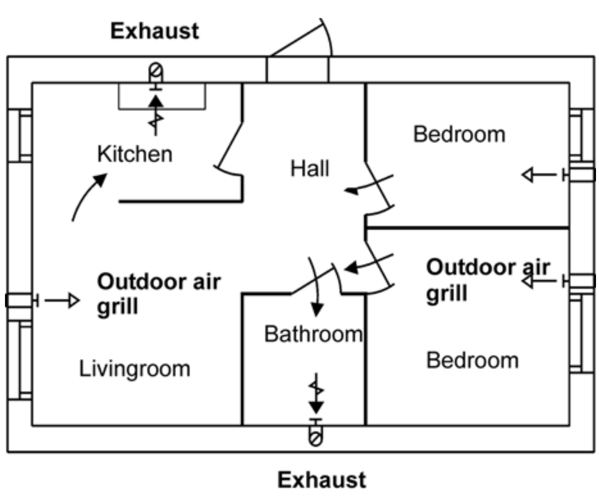

Figure 3.7.6 Outdoor air grilles in the bedrooms and living room guarantees that the ventilation air flows to bedrooms and living room before entering to exhausts.

2.5 micrometers) infiltration into all buildings in the city of Helsinki to the level of the office buildings built after 1990, would reduce the population exposure to $PM_{2.5}$ from ambient origin as well as its adverse health effects by 27%, in fact almost as much as total elimination of all traffic sources from within the metropolitan area limits (Hänninen et al., 2005). Effective way to reduce outdoor pollution entering indoors is tight building envelope and filtering the air intake.

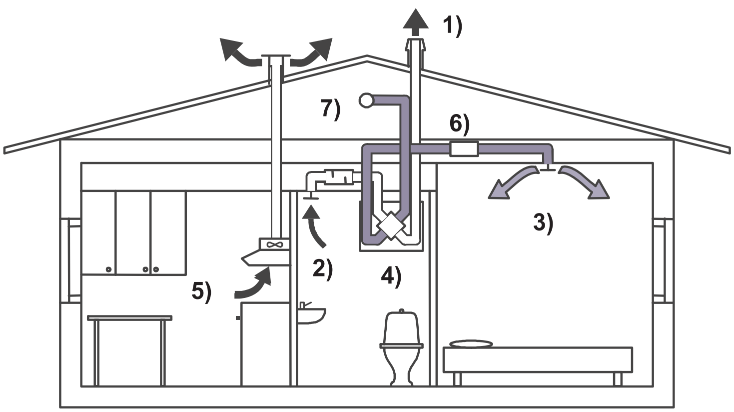

Figure 3.7.7 Principle of mechanical exhaust and supply system in a house: 1) Exhaust air; 2 Extract air; 3) Supply air to the bed room; 4) Heat recovery exchanger; 5) Kitchen exhaust; 6) Sound attenuator; 7) Outdoor air intake for ventilation.

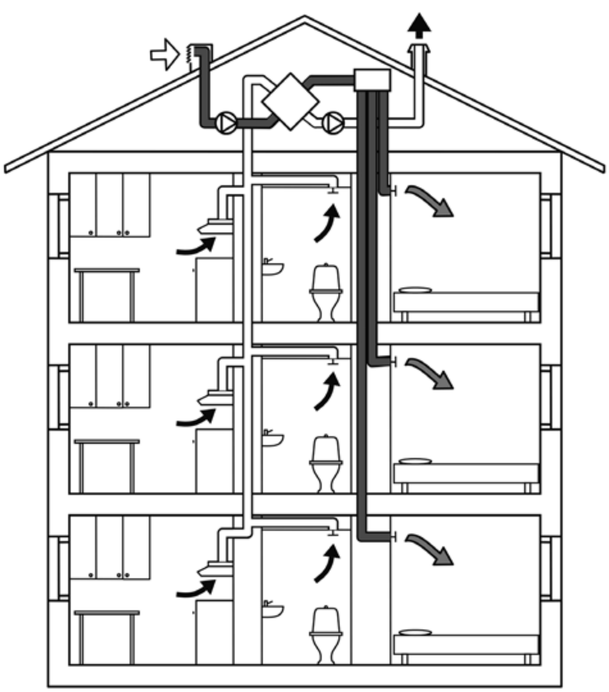

Figure 3.7.8 Centralized mechanical supply and exhaust system with heat recovery in an apartment building.

In an apartment building, the mechanical supply and exhaust system can be centralized (Figure 3.7.8) or decentralized (similar to Figure 3.7.7). Typically, the centralized systems have better heat recovery efficiency, but the control is more complex than in decentralized systems. For heat recovery to be beneficial the heat recovered has to exceed the additional energy expended by the fans. Where carbon is the base comparator and where the unit embodied carbon is higher for electricity than for the primary heating fuel source e.g. natural gas, it may be difficult to justify in moderate climate without careful design of the ductwork system, an efficient heat exchanger and energy efficient fans and motors. In decentralized systems the number of components requiring maintenance is higher and more spread out but on the other hand ventilation is easier to control by demand.

Ventilation systems for non-residential buildings

In commercial buildings the ventilation rates and requirements are usually higher than that in residential buildings. This is due to higher occupant density and generally higher expectations. Ventilation systems are often made more complex by floor plans that require provision of mechanical ventilation to all rooms. Usually outdoor air is treated in an air handling unit and supplied to the rooms via ductwork. Conditioning of the air may include cleaning, heating, cooling, humidification and dehumidification.

Constant air volume system (CAV)

Most common system for mechanical ventilation is illustrated in Figure 3.7.9 where outdoor air is filtered and heated in an air handling unit and supplied to rooms. Ventilation air is heated partly with heat recovered from extract air and district heating. Room is heated with hot water radiators. The water is

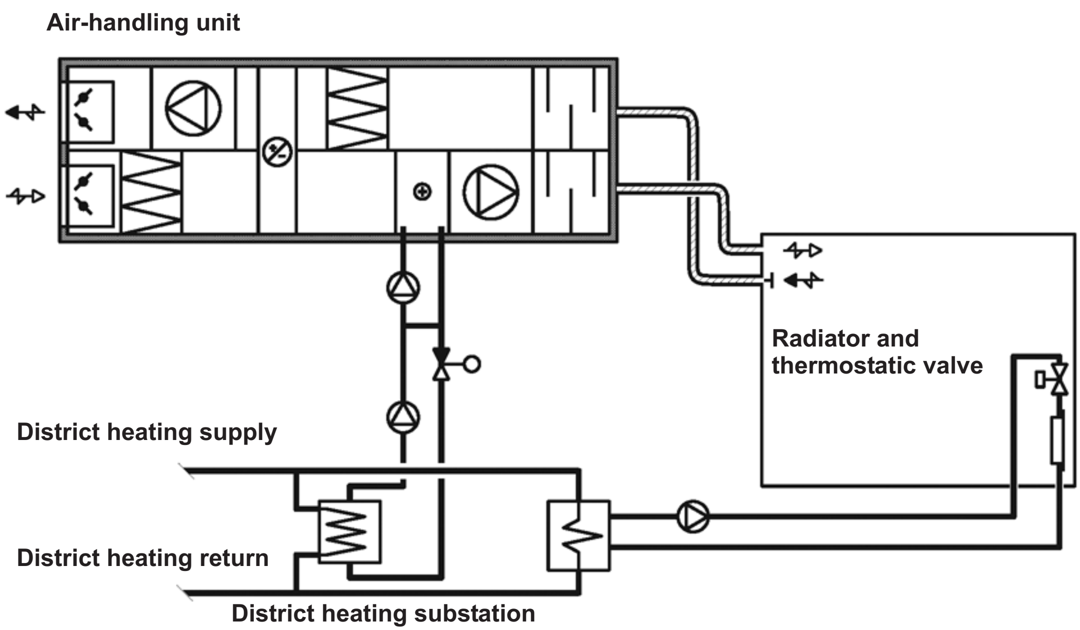

Figure 3.7.9 Air handling unit for heating only. Air is heated and filtered in an air handling unit before it is supplied via duct systems to the rooms. Air handling unit is equipped with filters and heat recovery heat exchanger. Heating of the rooms are with radiators. Heat supply can be district heating as in the figure, an individual fuel fired boiler or a heat pump.

heated with district heating, and flow controlled with thermostatic radiator valves. The air flow is constant to all rooms. The system in Figure 3.7.9 does not have air conditioning – only air cleaning and heating. The system illustrated in Figure 3.7.10 has also a cooling coil for air cooling and dehumidification if necessary. The purpose of supply air is now not only to ventilate for air quality but also to cool the rooms. Heating can be done also by supply air but in cold climate radiators are more common as illustrated in Figure 3.7.10. Cooling can be done with direct expansion cooling coils or with water chillers with storage capacity as in Figure 3.7.10. The system does not have any re-circulated air. Its energy saving function is replaced with heat recovery

CAV systems may be easily combined with natural ventilation through openings resulting as mixed-mode ventilation system. This allows to combine the best features of natural and mechanical ventilation at different times of the day or season of the year. In such systems mechanical and natural forces are combined in a two-mode system. The operating mode varies according to the season and within individual days, thus the current mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time. Mixed-mode systems will switch automatically between natural and mechanical mode in order to minimize energy consumption and maintain a satisfactory indoor environment. The aim of the strategy is to reduce energy, cost and the environmental side effects of

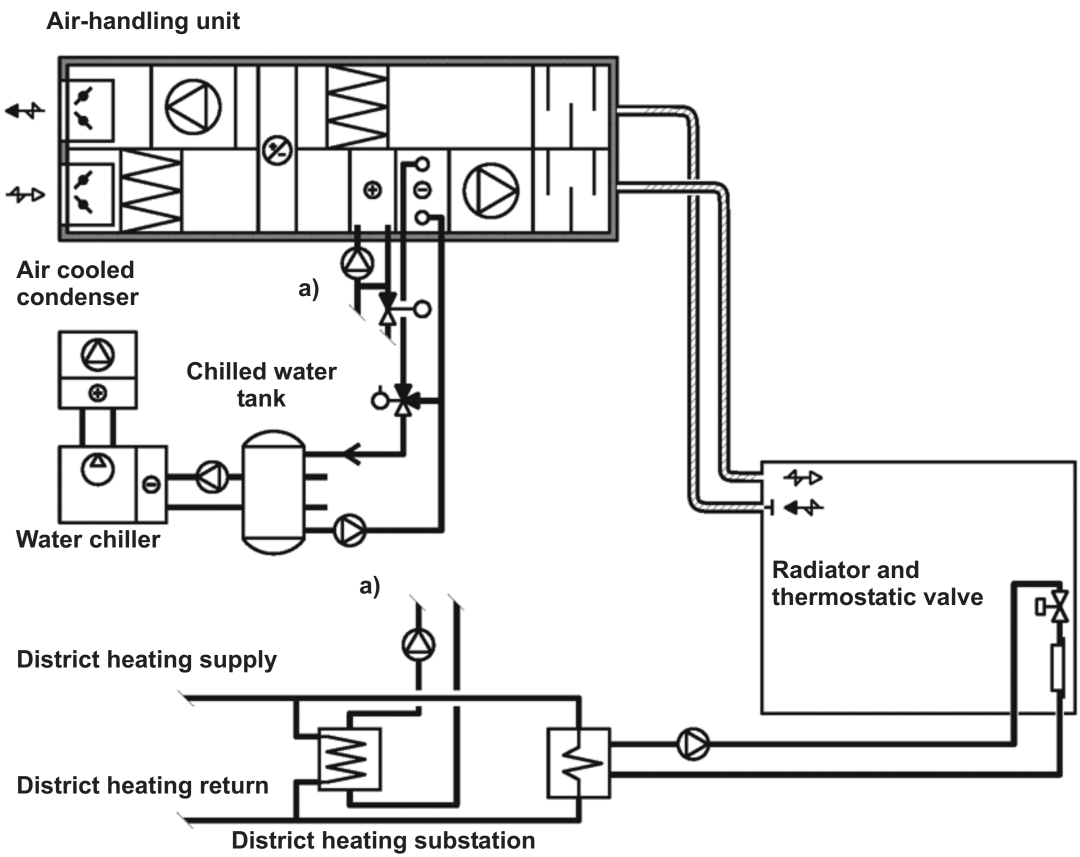

Figure 3.7.10 Air handling unit with air conditioning. Air is conditioned in an air-handling unit before it is supplied via duct systems to the rooms. Ventilation air can be heated or cooled. Air handling unit is equipped with filters and heat recovery heat exchanger. Heating of the rooms are with radiators. Heat supply can be district heating as in the figure, an individual fuel fired boiler or a heat pump.

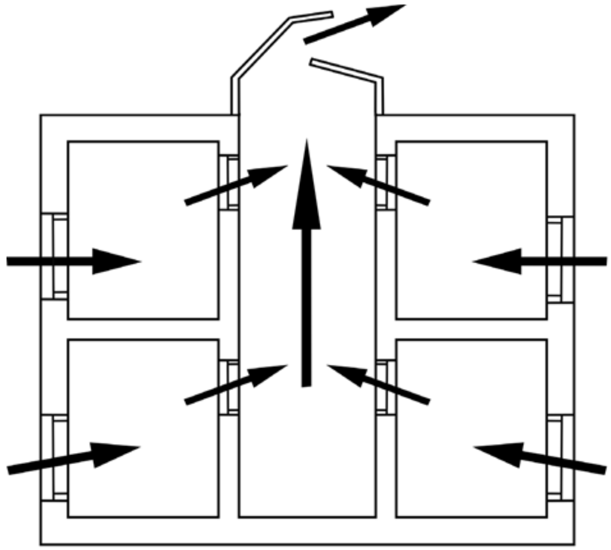

Figure 3.7.11 Utilization of mixed-mode ventilation in the building with atrium. Mechanical ventilation system (see Figure 3.7.9) is not shown in the Figure.

year-round air conditioning while optimizing indoor air quality and thermal comfort by combining the two modes of ventilation. The operating mode performs according to seasons and depends on external ambient conditions. Figure 3.7.11 shows the combination of a balanced ventilation system with natural ventilation. When the ambient conditions allow it, the atrium is naturally ventilated. Even the office rooms can be in principle naturally ventilated. In unfavourable weather conditions, natural ventilation is first shut down in offices with more strict requirements and in extreme conditions in the atrium and the mode is switched in two steps to mechanical ventilation.

Variable air volume system (VAV)

The flow of supply air to the rooms can be controlled by a room temperature sensor for heating or cooling purposes. The cooling demand of the room typically leads to higher design air flow in VAV systems than needed for ventilation. In the operation it is possible that the air flow is too low for ventilation if the control of the air flow is by room temperature only – the minimum supply air should be guaranteed to all rooms. Due to variable air flow, the energy for conditioning and transferring the air is lower than with CAV systems.

The pressure in the duct work is kept constant by controlling the fan speed and dampers. Pressure sensor in the duct work is used to control the fan speed, and consequently the supply air flow (Figure 3.7.12). In advanced systems the fan speed is minimized so that at least one damper is all the time completely opened. Since the average flow of air is smaller, and the fan has a speed control, the energy use of the system is lower than that of a constant flow system.

Ventilation in fan coil system

As the cooling or heating demand of room usually leads to higher design air flow than needed for ventilation, commercial buildings are often equipped with specific room units for cooling. This allows to avoid high design airflows and large size ductworks typical to VAV systems.

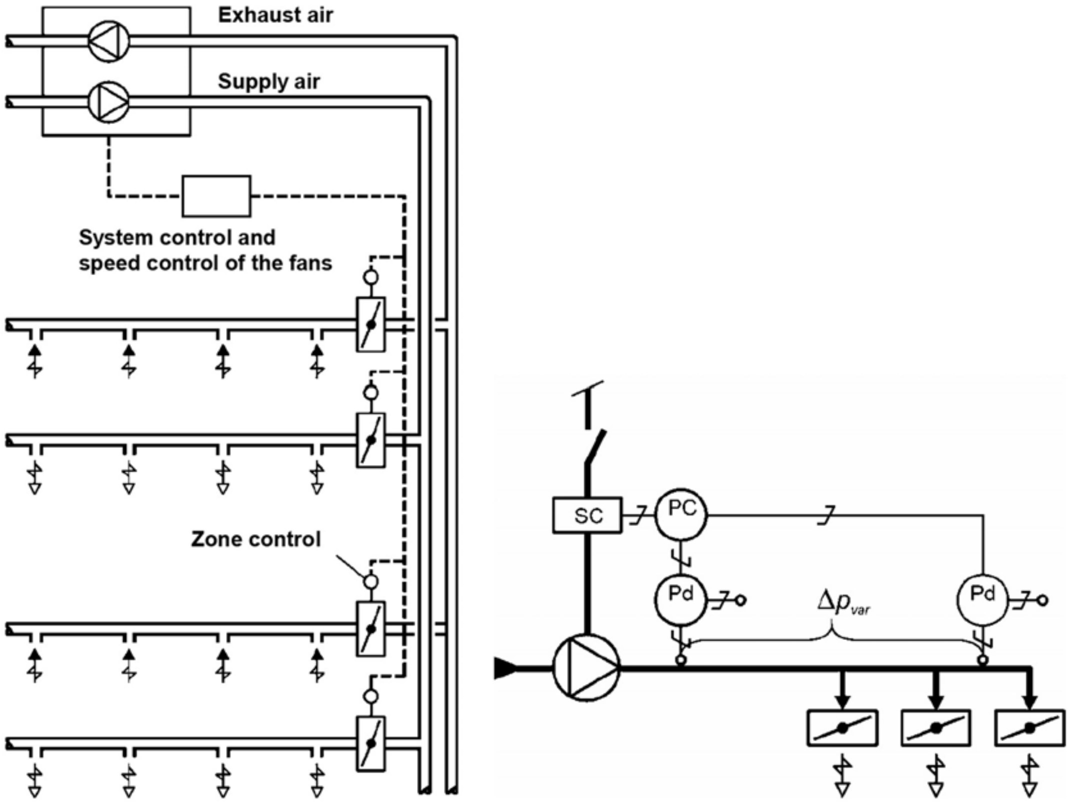

Figure 3.7.12 Control of duct pressure in VAV-systems reduces fan energy use.

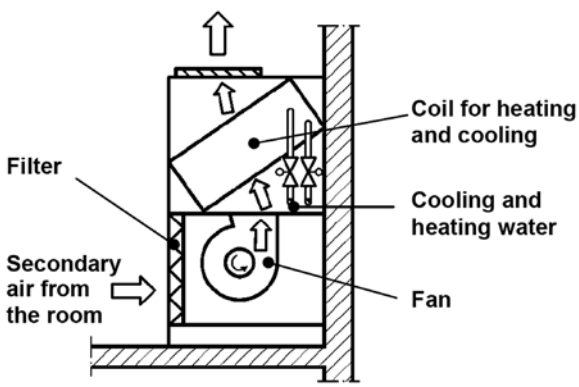

Figure 3.7.13 Cooling can be accomplished also with fan coils, where the room air is circulated via a coil which is heated or cooled with warm or chilled water.

In fan coil systems air is circulated via a coil which is heated or cooled with warm or chilled water (Figure 3.7.13). Fan coils can operate also as stand-alone units. In that case it may draw in the outdoor air for ventilation. Fan coils can be placed in the ceiling or below the window on the floor. Ventilation is usually separated from fan coils but may also be integrated in fan coils. These cases are illustrated in Figure 3.7.14.

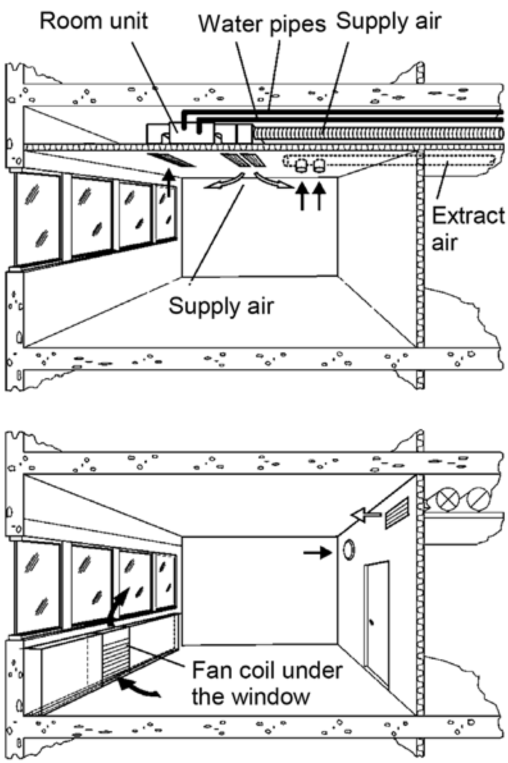

Figure 3.7.14 Fan coils can be placed in the suspended ceiling as in the top figure or under the window in the lower figure.

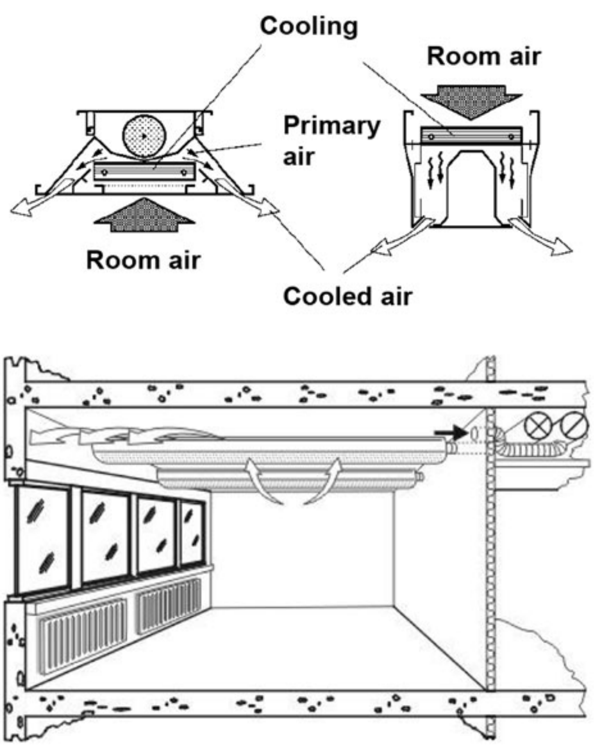

Figure 3.7.15 Chilled beams may be used in free installation in the ceiling as shown in the figure or in the suspended ceiling installation. Cross sections (on the top figure) on left illustrate active chilled beam where the supply air (ventilation air) is integrated in the beam to improve the heat transfer in the cooling coil, and on the right passive chilled beam.

Fan coils can provide effective dehumidification of supply and indoor air as well as very high cooling capacity if needed. Dehumidification is achieved by condensation of water vapour in the cooling coil, but when higher water temperatures are used non-condensing dimensioning with lower cooling capacity is also possible. For fan coil systems somewhat higher air velocities and noise levels compared to chilled beam systems are typical. Other drawbacks are the maintenance need (replacing the filter) and electricity use of fans.

Ventilation in chilled beam and cooled ceiling systems

Chilled beams are induction-type room conditioning units installed in the ceiling and controlled by room temperature sensors (Figures 3.7.15 and 3.7.16). There are no fans in chilled beams. In active chilled beams supply air ducted to the beam induces room airflow through the cooling coil. In passive chilled beams only, temperature differences cause the airflow through cooling coil and cooling capacity is therefore lower.

Chilled water system serves both air handling unit and chilled beams. Supply air flow is selected based on ventilation requirements but is heated or cooled depending on the requirements of the room. Major part of cooling and heating is still supplied by the water systems (beams and radiators respectively).

In passive chilled beam systems supply air is not connected to the beam but provided by supply air diffusers. This is similar to cooled ceiling systems where large water-cooled panels are installed in the ceiling and ventilation is provided by supply air diffusers. In these systems non-condensing dimensioning is always needed, and supply air can be dehumidified only in air handling unit.

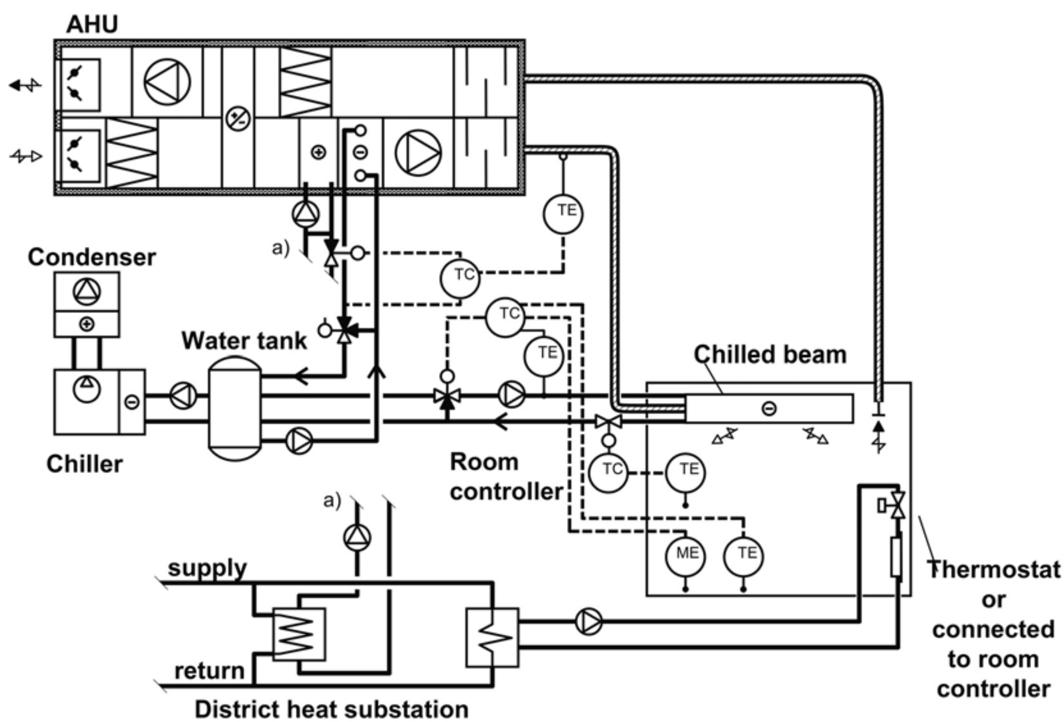

Figure 3.7.16 Ventilation and air conditioning system with active chilled beams. Chilled beams are installed in the ceiling and controlled by room temperature sensors. TE = temperature sensor; ME = moisture sensor; TC = temperature controller.

Chilled beam and cooled ceiling systems are most suitable for moderate cooling loads up to 80W per floor m^2. In such conditions high indoor climate standard with low air velocities not exceeding 0.2m/s and silent operation can be easily achieved (Virta, 2004). These systems have outstanding energy performance as room units do not include fans and relatively high cooling water temperatures are used due to non-condensing dimensioning and large heat transfer surface areas.

Control of ventilation by air quality (demand controlled ventilation)

Ventilation runs, typically, with constant out-door air flows through all operational hours, and the air flows are not changed with the change in the use of a room. Usually the ventilation loads of the interior spaces vary with time, and the ventilation rates should be adjusted to the loads. Air quality-controlled ventilation (AQCV) is a ventilation system where air flows in the rooms are controlled according to the contaminant loads or concentrations (Figure 3.7.17). The use of AQCV is based on temporarily varying contaminant sources, and actual needs of ventilation, when the system of constant airflow ventilation wastes energy, whereas a system with varying airflows saves energy but does not compromise indoor air quality.

The simplest way to do this is to adapt the ventilation according to demand. Contaminants originate from building and decoration materials, furniture, people and their activities, and intake air. For AQCV, proper air quality sensors are needed. A room sensor can be one of the following: carbon dioxide, mixed-gas, attendance, combined CO_2/mixed-gas, combined CO_2/temperature or combined CO_2/CO. At present mainly CO_2 and temperature sensors are used for AQCV in normal spaces due to cost and unreliability of other types of sensors. CO-sensors are used in special cases such as large garages.

Practical experience shows that adapting the ventilation to the actual requirement can very often substantially reduce the energy use of a ventilation system. Annual savings up to 50% have been reported.

Ventilation system components

Duct systems

The purpose of a duct system is to transfer the air to and from rooms with in an energy efficient and hygienic way. The energy losses in ducts should be kept reasonable with proper layout and selection of dimensions of ducts, good design and installation practice of the duct system and air tight construction.

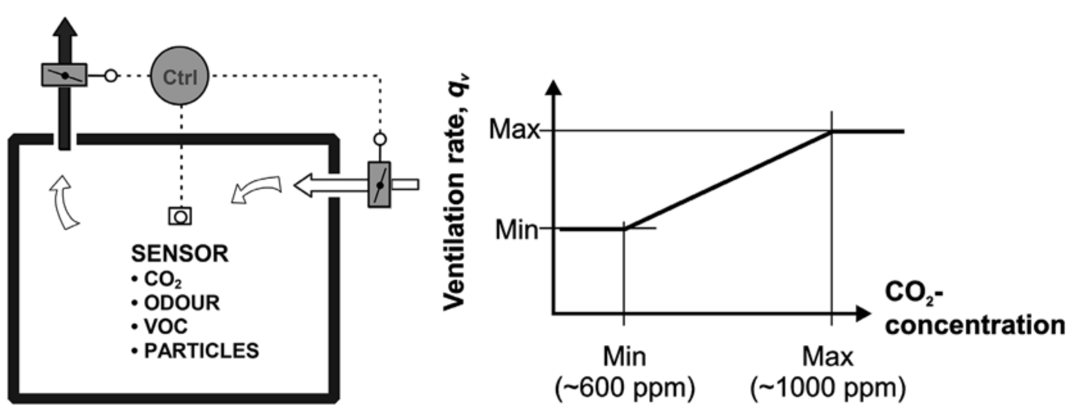

Figure 3.7.17 Principle of control of ventilation by air quality (air quality controlled ventilation – AQCV) and an example of the control curve of ventilation rate by CO_2 concentration.

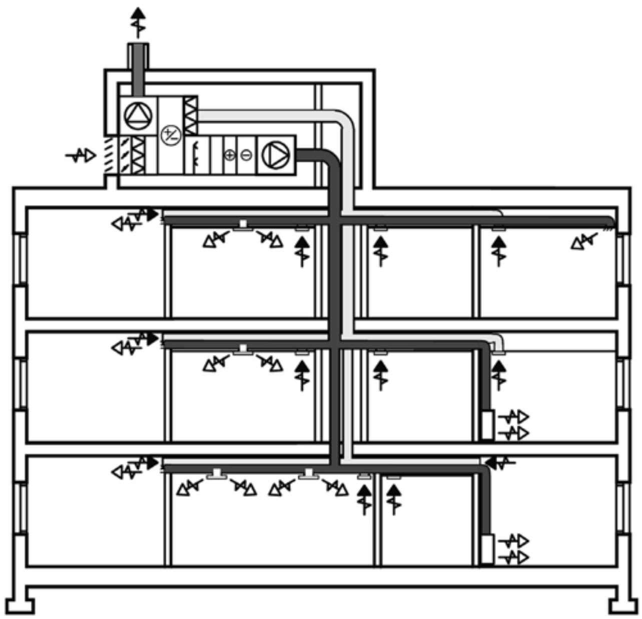

Figure 3.7.18 Air handling unit on the roof, ducts drop first in the vertical shafts and are then running horizontally through the building.

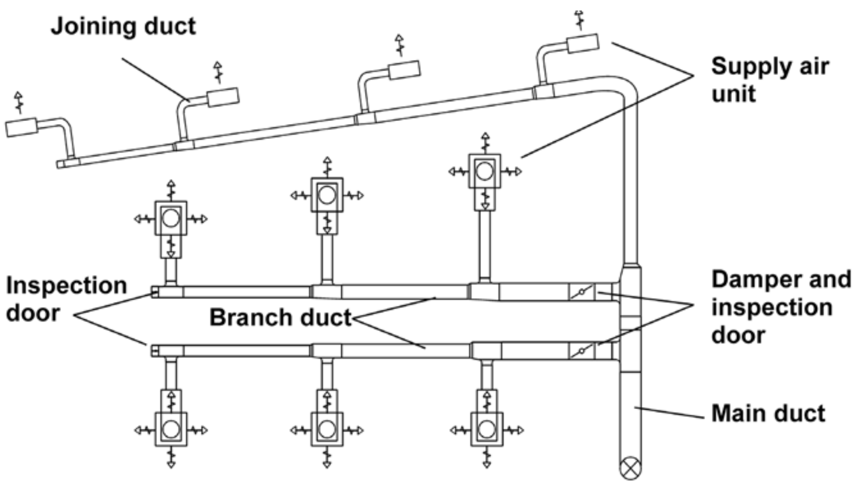

Figure 3.7.19 Duct work consists of ducts, fittings, air terminal devices, dampers and openings for inspection.

Figure 3.7.18 illustrates a duct system where an air handling unit on the roof is connected to room via ducts. The duct system is built of straight ducts (either round or rectangular), connection fittings (bends, T-pieces etc), dampers for flow control, terminal devices, inspection doors, measuring devices and sound attenuators (Figure 3.7.19).

The cross section of the ducts may be large in big buildings which often is a limiting factor for the free placement of the ducts. The horizontal ducts are often installed above a false ceiling of the corridor (Figure 3.7.20). The room supply and exhaust is connected to the main ducts. The open plan offices and other large spaces have usually suspended ceilings which form a plenum for air ducts and other installations.

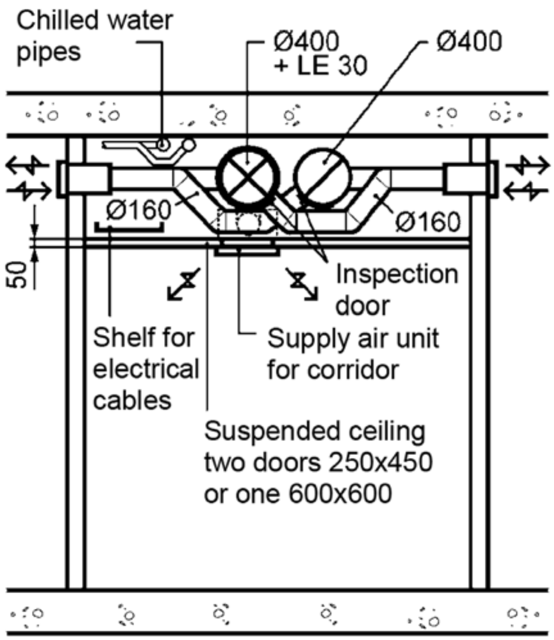

Figure 3.7.20 Ducts run often above the suspended ceiling of corridors in office buildings.

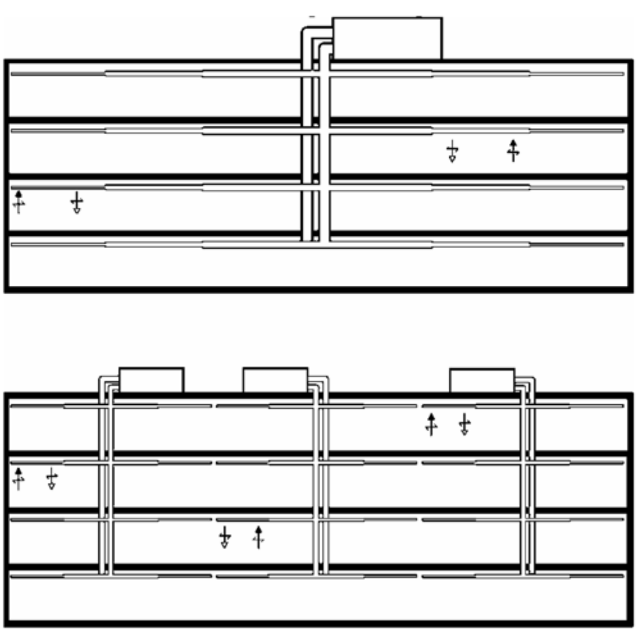

Figure 3.7.21 Two alternative principles of duct system. Above one air handling unit with large vertical and horizontal ducts, below three air handling units with smaller ducts.

Figure 3.7.21 illustrates two basic principles for layout of ducts in an office building. The advantage of the upper layout is having less vertical shafts but more space for the vertical ducts. Advantage of the lower layout is having less space for vertical ducts but more vertical shafts. The space required for the vertical shafts can be estimated with the help of Figure 3.7.22.

Air handling units

The air handling unit, AHU, consists of several components. The number and selection of components depends on the requirements for the treatment of the air. The cross section in the air handling unit is usually constant (Figure 3.7.23). As the pressure drop in the air handing unit is dependent on the average velocity it is important that the velocity is not too high – usually a unit with larger cross section is more economical in life cycle cost than a unit with smaller cross section area which may have lower first cost. The air handling unit may include also heat recovery as illustrated in Figure 3.7.24.

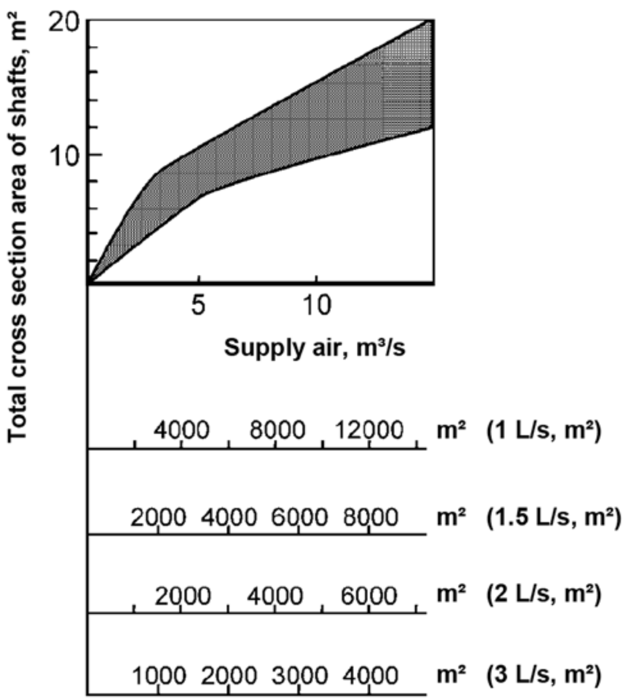

Figure 3.7.22 Space required for vertical shafts in office buildings depending on floor area and design supply air flow rate l/s, m^2.

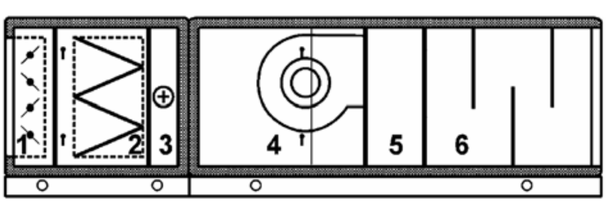

Figure 3.7.23 The components of a small air handing unit. Components included: 1) Air damper; 2) Filter; 3) Heating coil; 4) Fan; 5) Connection component; 6) Noise attenuator.

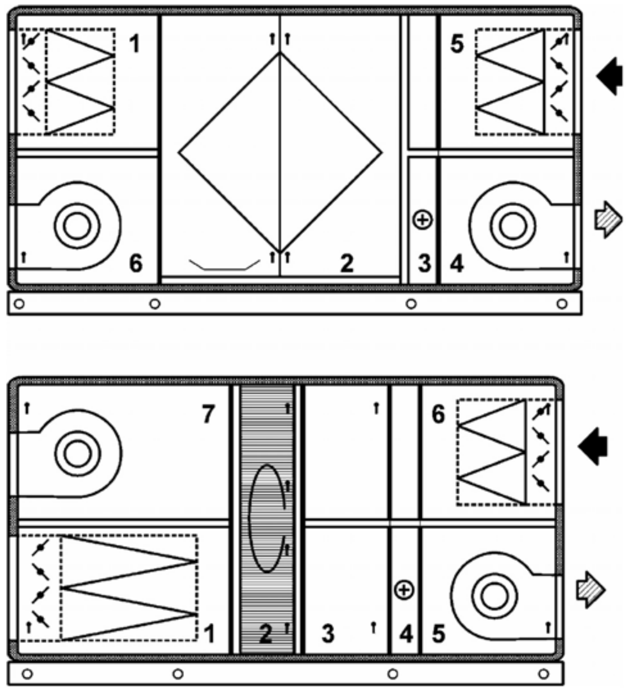

Figure 3.7.24 A heat recovery system can be an integrated part of an air handling unit. Above: AHU with plate-type heat exchanger comprising following parts: 1) Filter; 2) Cross flow plate-type heat exchanger; 3) Heating coil; 4) Supply air fan; 5) Filter; 6) Exhaust air fan. Below: AHU with wheel-type regenerative heat exchanger comprising following parts: 1) Filter; 2) Regenerative heat exchanger; 3) Space for future use; 4) Heating coil; 5) Supply air fan; 6) Filter; 7) Exhaust air fan.

Air handling units are often placed in a common mechanical plant room. The required floor area and height for such a room can be estimated from Figure 3.7.25. It is important that the plant room has enough spare floor area to perform the necessary maintenance operations such as change of the filters.

Filters

Most relevant urban air particles associated with adverse health effects are fine particulate matter $PM_{2.5}$ (particle mass smaller than 2.5μm). These particles originate mostly from traffic and combustion processes such as fireplaces and energy production plants. Particles in indoor air are described by indoor/outdoor ratio and size distribution both highly affected by filtration and air tightness of the building envelope.

Based on ambient air measurements and mortality records, epidemiologists have estimated that fine particulate matter ($PM_{2.5}$) exposures cause hundreds of thousands excess deaths in the developed world (Pope et al., 2002). It is shown that health effects are caused by the levels of PM of ambient origin and not by the exposures to indoor generated particles (Wilson, Mage and Grant, 2000).

The purpose of air filtration is to prevent harmful particles in the outdoor air to enter the building via the ventilation system. The benefits of the air cleaning are:

- Exposure of occupants to harmful particles from outdoor (traffic, energy production, combustion, industry, pollen, spores etc.) will be reduced.

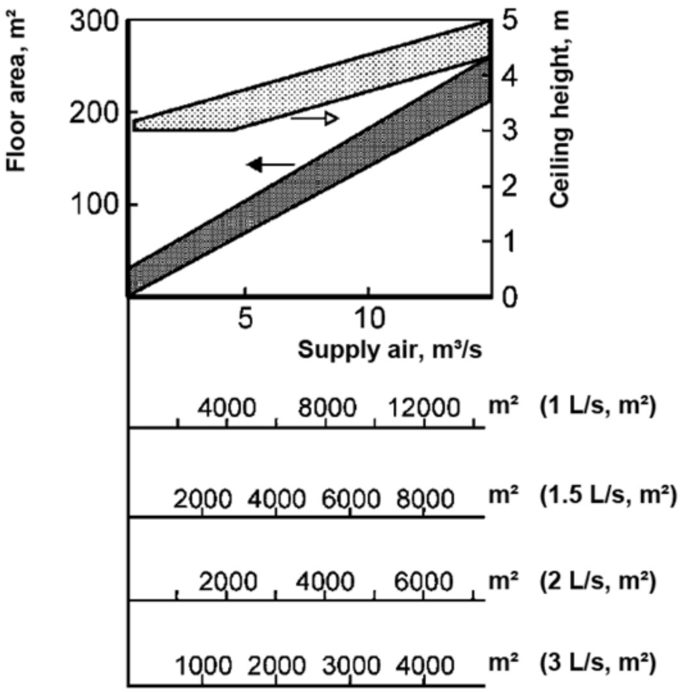

Figure 3.7.25 The floor area and required height for a mechanical room can be estimated from this graph depending on the conditioned floor area and supply air flow per floor area.

- The air handling equipment will stay clean and perform better (e.g. better performance of heat exchangers and fans, lower pressure drops in ducts).
- Cleaner supply air due to filtration also helps to keep the room surfaces clean and reduces the cleaning cost of the building.

Particles are usually removed from the outdoor air with fibre filters; the removal efficiency of those depends on filter media (fibre dimensions and type, type of filter media, pressure drop, velocity through the media etc.). Fine filters (filter class F8 or higher) remove most of fine particulate matter ($PM_{2.5}$) as shown in Figure 3.7.26.

As the pressure drop of a filter increases due to the accumulated dust in the filter; the air flow through the filter will decrease. The filters will have to be changed when the pressure drop has risen above the preset value. The filter media of fine filters cannot be cleaned but have to be replaced regularly depending the amount of accumulated dust in the filter and the dust holding capacity of the filter.

The filters described above are particle filters that only remove solid substances from the air. Gas filters, based on adsorption, can be used to remove odours and other gaseous pollutants from the air. This is necessary in highly polluted areas such as highly industrialized regions, near airports etc and in the case of special clean environments such as operation theatres or industrial clean rooms. A common type of these filters contains activated carbon made from crushed coconut shells.

For short time/peak gas concentrations particle filters covered with thin adsorptive media layer may be used. Such filters effectively remove odours of exhaust gases etc and have a low pressure drop similar to common particle filters.

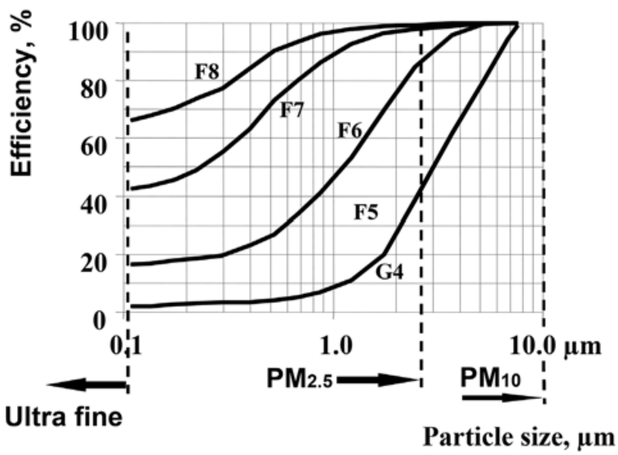

Figure 3.7.26 Typical efficiency of common fibre filters vs. particle size. Exact efficiencies show some variation within the filter class depending on the product. Filter class G4 refers to coarse filters capturing only large size particles and dust. The main filter of outdoor air should be a fine filter with filter class F7 or higher.

Basic design principles of ventilation

Air balance, direction of the air flows and air quality

The relative pressures of the building, different spaces and the ventilation system should be designed so that spreading of odors and impurities in harmful amounts or concentrations is prevented. No significant changes to the pressure conditions are allowed due to changes in weather conditions. The air tightness of the building envelope, floors and partition walls, which affect the pressure conditions, should be studied and defined in the design stage, taking account of both temperature and wind conditions.

Most important principle in the design for good indoor air quality is to try to avoid unnecessary pollutant generation and spread of pollutants in or between rooms. To achieve this:

- low pollution products and material should be used whenever possible;
- escape of pollutants from processes to the room air should be prevented by sealing the processes as much as possible;
- the processes causing pollution shall be equipped with local exhaust systems;
- pollution generating processes should be located in separate rooms whenever possible to minimize the spread of pollutants to other rooms;
- the air balance (difference between supply and exhaust air flows) of the rooms should be so that air flows from less polluted rooms to more polluted rooms;
- supply air jets should be directed so that they do not increase the spread of pollutants but decrease it.

The air balance principle of the ventilation means that air always flows from room with higher air quality to the rooms with lower air quality and higher pollution generation. This means that clean air is supplied in the cleaner rooms and exhausted from the polluted rooms, and air is transferred from "clean" to "dirty" rooms.

In residential building this means that outdoor air is supplied to bedrooms and living rooms and exhausted from kitchens, bathrooms and toilets, etc.

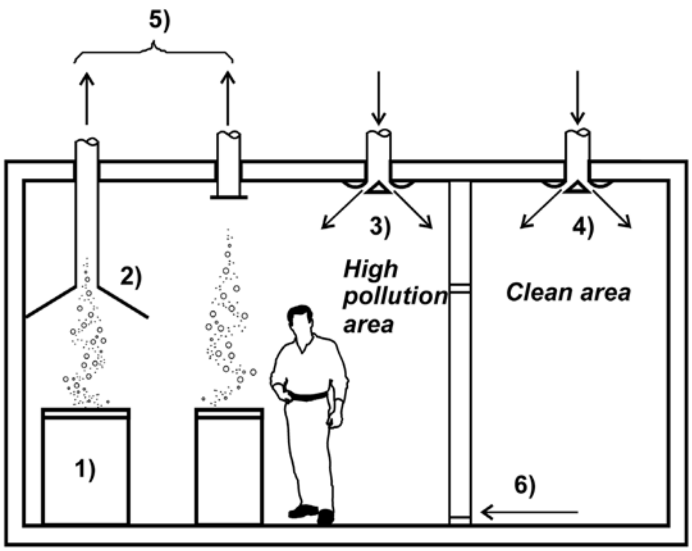

Figure 3.7.27 Principles to control air quality in mechanical ventilation system. 1) pollution generation processes are equipped with local exhaust; 2) exhaust air grilles and openings are located above the warm pollution generation sources; 3) air is supplied in the occupied zone in the rooms with high pollution generation to reduce exposure of the occupants to pollutants; 4) clean air is supplied to rooms with no specific pollution generation; 5) total exhaust air flow is larger than the supply air in the rooms with high pollution generation; 6) air is transferred from cleaner areas to more polluted areas through the openings in walls or doors.

In commercial buildings air is supplied to the occupied zones and exhausted from rooms with pollution generation so that air balance is positive in the occupied rooms and negative in rooms with higher pollution generation. The following principles should be applied. They are illustrated in Figure 3.7.27.

Air distribution

The airflow pattern in a ventilated room depends on the selection and location of supply air devices whereas extract air devices have only small effect on it. This is due to high momentum (air jet) of supply air compared to almost zero velocity near the suction point of extract air. There are two main types of airflow pattern:

- mixing (dilution) ventilation; and
- displacement ventilation.

Mixing ventilation is used in rooms with normal height (most homes and offices) and it can be provided with supply air diffusers, fan-coils or chilled beams (see Figures 3.7.18, 3.7.14 and 3.7.15). In mixing ventilation (Figure 3.7.28) the air is supplied in such a way that the room air is fully mixed and the pollutants concentration diluted with ventilation is equal in the whole room. If the supply air is not fully mixed with the room air, a part of it may flow directly to extract air opening. This short-circuiting reduces the efficiency of the ventilation (term ε in Equation 3.7.1) and should be avoided Mundt (2003).

Especially in high rooms such as concert halls, auditoriums etc. it is more efficient to bring fresh supply air directly to breathing zone. This can be done by displacement ventilation, where a stratified flow is created using a few degrees lower supply air temperature than room temperature. Displacement ventilation

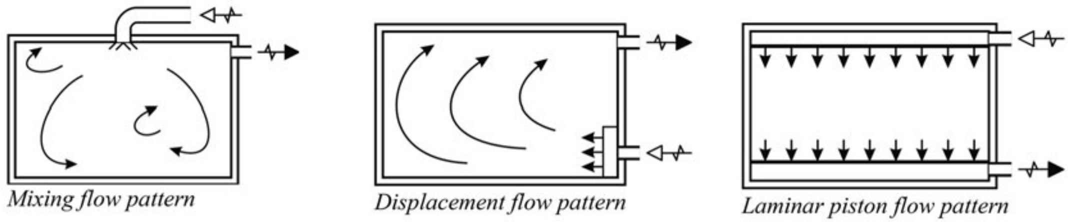

Figure 3.7.28 Mixing, displacement and laminar flow patterns. The upper diagram illustrates complete mixing with a uniform concentration of contaminants in the room.

creates a cleaner and cooler lower zone and more polluted and warmer upper zone (Skistad, 2002). The air quality in the occupied zone is then better than for mixing ventilation at the same ventilation rate due to higher ventilation effectiveness.

The opposite of the mixing flow pattern is the ideal piston flow in which the air flow is laminar and the room air is not mixed at all with the supply air. This flow pattern with maximum possible ventilation effectiveness is used in special cases such as operating theatres and other super clean rooms.

Performance criteria for ventilation

Ventilation (outdoor air flow) has to be adequate to remove and dilute the indoor generated pollutants and humidity and provide acceptable level of contaminants in the indoor air. Control of the pollutant sources, however, shall be considered as the first alternative to improve indoor air quality. Ventilation shall be energy efficient and arranged so that it does not deteriorate indoor air quality and climate and does not cause any harm to the occupants or to the building. Ventilation rates should be based on the pollution loads and use of the building.

The concentration of indoor air pollutants can be used to calculate the ventilation rate needed for dilution or removal of the pollutants. The source of the pollutants can come from a variety of internal sources, from the metabolic pollutants of the occupants (CO_2) to pollutants from processes taking place in the buildings. The dilution ventilation flow rate for a known emission rate and concentration level of a pollutant within the building can be calculated from pollutant mass balance (Figure 3.7.29) by Equation 3.7.1.

$$q_v = \frac{G}{C_{\text{in}} - C_o}\frac{1}{\varepsilon} \tag{3.7.1}$$

where

q_v = the volume flow rate of supply air in m^3/s
G = the net mass flow rate of emission to the room air in mg/s

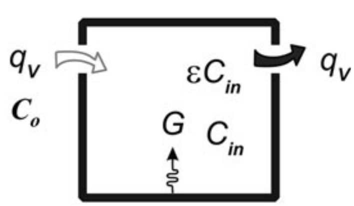

Figure 3.7.29 Air flow and pollutant emission in the room. Symbols are given in Equation 3.7.1.

C_{in} = the allowed concentration in the room in mg/m^3
C_o = the concentration in the supply air in mg/m^3
ε = the ventilation efficiency, (ε = 1 for complete mixing to ε = 2 for ideal piston flow)

Equation 3.7.1 does not take into account removal of the pollutant indoors by factors other than ventilation including deposition on surfaces, filtration of indoor air, chemical reactions etc which may reduce the emission term. In complete mixing of the air (typical for most common air distribution schemes as discussed above) ventilation efficiency ε = 1, i.e. the pollutant concentration in the occupied zone is equal to the pollutant concentration in the extract air. Short-circuiting of the supply air will decrease ventilation efficiency below 1 and higher airflow rate is needed for the same concentration. Displacement ventilation improves ventilation efficiency typically to ε = 1.2 . . . 1.5 and lower airflow rate is needed for the same concentration.

The same type mass balance equation applies also for humidity balance of air. Removal of indoor generated humidity can be calculated by Equation 3.7.2.

$$q_v = \frac{G_h}{v_{\mathrm{in}} - v_o} \tag{3.7.2}$$

where

q_v = the volume flow rate of supply air in m^3/s
G_h = the indoor humidity generation in the room in g/s
v_{in} = the humidity by volume of the indoor air in the room in g/m^3
v_o = the humidity by volume of the supply (outdoor) air in g/m^3

Ventilation removes humidity flow rate of $G_h(v_{in}-v_o)$. As the outdoor humidity is not constant, the humidity removal is higher (ventilation is more effective) at low outdoor air humidity. In hot climates the outdoor humidity may be higher than indoor humidity. In that case ventilation brings in humidity and humidity is usually removed by air conditioning (condensation on the cooling coil).

In case of different pollutants, it is necessary to check all relevant pollutants in order to determine the most critical one. As a rule, source control is preferable to ventilation. Equation 3.7.1, given above, is valid for a steady-state situation (default situation) with a long lasting constant emission. It also assumes that all pollution generated in room is carried out with the airflow - no other sinks are assumed to be in the room. When the emission-period is short, the stationary equilibrium-concentration may not be achieved or the airflow can be reduced for a given maximum concentration level. The time-dependence of the concentration level in the room is given by the following (supply air rate = extract air rate):

$$C_{in}(t) - C_o = C_{in}(0) + \frac{G}{q_v}\left(1 - \exp\left(-\frac{q_v}{V}\cdot t\right)\right) \tag{3.7.3}$$

where

$C_{in}(t)$ = the concentration in the room at time t in mg/m^3
C_o = the concentration in the supply air in mg/m^3
$C_{in}(0)$ = the concentration in the room at the beginning (t=0) in mg/m^3
q_v = the volume flow rate of supply air in m^3/s
G = the mass flow rate of emission in the room in mg/s
V = the volume of air in the room in m^3
t = the time in s

There do not exist a common standard index for the indoor air quality which will allow to use Equations 3.7.1–3.7.3 for determination of required ventilation rate. The indoor air quality may be expressed as the required level of ventilation or carbon dioxide (CO_2) concentration. CO_2 concentration can be used as a surrogate of ventilation rates, but its use to measure ventilation is uncertain as its concentration in buildings seldom reaches steady state due to variations in occupancy, ventilation rates and outdoor air concentration. Steady state values of carbon dioxide concentration can be calculated from CO_2 generation of 0.00567 l/s per occupant in office buildings.

It is generally accepted that the indoor air quality is influenced by emission from people and their activities (bio effluent, smoking), and from building, furnishing as well as from ventilation and air conditioning system itself (i.e. building components). The required ventilation is based on health and comfort criteria. In most cases the health criteria will also be met by the required ventilation for comfort. Health effects may be attributed to specific components of emission and if you reduce concentration of one source you also reduce concentration of others. Comfort is more related to the perceived air quality (odor, irritation). In this case different sources of emission may have an odor component that adds to the odor level. There is however no general agreement how different sources of emission should be added together. In the latest standards (EN 15251, ASHRAE 62.1 and 62.2) the criteria is expressed as addition of people (smoking, non-smoking) and building components. The total ventilation rate for a room is calculated from the following formula:

$$q_{\mathrm{tot}} = n \cdot q_p + A \cdot q_B \tag{3.7.4}$$

where

q_{tot} = total ventilation rate of the room, l/s
n = design value for the number of the persons in the room
q_p = ventilation rate for occupancy per person, l/s, pers
A = room floor area, m^2
q_B = ventilation rate for emissions from building, l/s, m^2

The ventilation rates for occupants (q_p) only (EN 15251) are depending on indoor climate category:

Category I (high): 10 l/s, pers
Category II (medium): 7 l/s, pers
Category III (basic): 4 l/s, pers

The ventilation rates (q_B) for the building emissions are shown in Table 3.7.1. An example how the ventilation rates is specified by pollution load with Equation 3.7.4 is given in the Table 3.7.2.

Table 3.7.1 The ventilation rates (*qB*) for the building emissions (EN 15251).

Category	*Very low polluting building, l/s, m²*	*Low polluting building, l/s, m²*	*Non low-polluting building, l/s, m²*
I (high)	0.5	1.0	2.0
II (medium)	0.35	0.7	1.4
III (basic)	0.3	0.4	0.8

Table 3.7.2 An example of ventilation rates for offices depending on the pollution load in three categories (EN 15251).

Category	*Occupants only, l/s, m²*	*Low-polluting Building, l/s, m²*	*Non low-polluting Building, l/s, m²*
I (high)	1.0	2.0	3.0
II (medium)	0.7	1.4	2.1
III (basic)	0.4	0.8	1.2

If ventilation rates are reduced, energy is saved but at the same time indoor air quality deteriorates. The minimum ventilation rate is 10–15 l/s per person, which is approximately 1 l/s per m^2 in office buildings with normal occupant density. For better IAQ and productivity a doubled airflow rate of 2 l/s per m^2 can be recommended for typical landscape and cellular offices. This is supported by latest reviews by Seppänen and Fisk (2004) and Fisk and Seppänen (2007) that summarize the effect of ventilation in respect of health and productivity as follows:

- ventilation rates below 10 l/s per person are associated with a significantly higher prevalence of health or perceived air quality outcomes;
- increases in ventilation rates above 10 l/s per person, up to approximately 20 l/s per person, are associated with a significant decrease in the prevalence of SBS (sick building syndrome) symptoms or with improvements in perceived air quality and task performance and productivity;
- relative to natural ventilation, air conditioning is often associated with a statistically significant increase in the prevalence of one or more SBS symptoms.

For the residential buildings it is summarized that the ventilation rates below 0.5 ach (air change per hour) are a health risk in Nordic residential buildings (Wargocki et al., 2002; Sundell and Levin, 2007) concerning dwellings in a cold climate.

Energy efficient equipment

Moving the air in and out in building requires energy in mechanically ventilated buildings, typically, this, however, is usually much smaller that the energy used to conditioning the air either in the air handling system or in the building. The use of electric energy of fans can be reduced by decreasing the pressure drop in the system and by selecting high efficiency equipment. The specific fan power (Equation 3.7.5) is used to define the overall air moving efficiency of each fan. When the specific fan power is defined for the air handling unit, the input power term *P* comprises the input powers of the supply and exhaust fans.

$$P_{SFP} = \frac{P}{q_v} = \frac{\Delta p}{\eta_{\mathrm{tot}}} \tag{3.7.5}$$

where

P_{SFP} = the specific fan power in W/m³/s
P = the input power of the motor for the fan, W
q_v = the nominal air flow through the fan in m³/s
Δp = the total pressure difference across the fan, Pa
η_{tot} = the total efficiency of fan, motor and drive in the built-in situation

The ventilation air can be used also for air conditioning. If air conditioning is used high efficiency equipment should be selected. For example, the selection of the best class A chiller instead of worst class F air cooled chiller will reduce the use of electricity by factor over 2.5 (Eurovent).

Heating energy of supply air can substantially decreased by the use of effective heat recovery equipment (heat exchanger transferring heat from extract air to supply air). Good heat recovery efficiency of 80% will decrease heating energy by a factor of 5, as only 20% of heating need should be covered by heating coil as the rest 80% is recovered from extract air.

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3.8
SUSTAINABLE COOLING STRATEGIES

Thomas Lakkas and Dejan Mumovic

Introduction

The aim of this chapter is to overview sustainable cooling strategy options, and to highlight the main design characteristics and requirements. The sustainable, low energy, cooling strategies have capability to minimise mechanical cooling loads in buildings while reducing the occurrence of summertime thermal discomfort and overheating. The increased interest in the sustainable cooling strategies has been underpinned by the fact that almost half of the global energy consumption originates from buildings and 16% of this energy represents the energy consumed by air conditioning. Furthermore, due to climate change, the growing internal heat loads in buildings and the inappropriateness of the building construction the cooling energy demand in Europe is continuously rising (Figure 3.8.1).

With changing climate, it is probable that average temperatures in the UK will increase by 4–6°C over the next 50–80 years resulting in a higher frequency of the summertime temperatures in the range

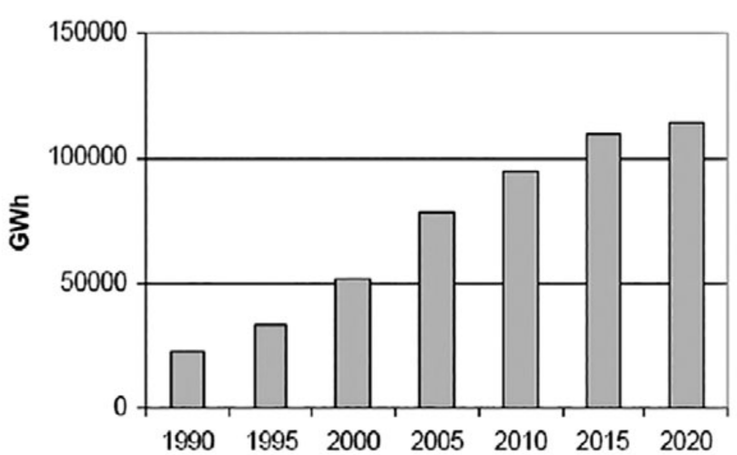

Figure 3.8.1 Annual cooling energy demand in the European Union.

Souce: Keep Cool Project, 2005

30–36°C (CIBSE, 2005). Temperatures within free running buildings are always closely linked to those outside meaning that the future will offer greater challenges to the designers of low-energy buildings. However, in line with adage that times are changing, and we are changing with them (*Tempora mutantur, nos et mutamur in illis*, in Latin), one has to take into account another variable – occupant behaviour. It has to be noted that in the future comfort expectations are likely to change and people will either adapt to accept higher temperatures or with increasing disposable income will have higher summertime thermal comfort expectations than are currently typically experienced in naturally ventilated buildings. In all cases, the integration of sustainable, low energy, cooling strategies in building design seems as a sound way forward.

Developing the sustainable cooling strategy

A sound sustainable cooling strategy should consider the following five steps (Figure 3.8.2):

- reduction and modulation of heat gains;
- use of direct and indirect ventilative cooling;
- cooling energy from renewable sources;
- analysis of free cooling options;
- implementation of sustainable distribution systems.

The key issues that need to be considered as part of developing a successful sustainable cooling design include:

- sustainable energy cooling must not be considered as an independent part of the building but need to be integrated into the building design;
- process of designing sustainable cooling systems is essentially iterative and progressive; this requires close collaboration between architects and building service engineers, and ideally should take into account views of number of stakeholders including end users (if known) and facility managers.

The following sections briefly summarise the main design requirements for each of five steps.

Reduction and modulation of heat gains

Reduction and modulation of heat gains is perhaps one of the critical steps in the development of sustainable cooling design. In most cases achieving acceptable summer conditions requires two main features in the design:

- **Effective solar control**
  The principal function of the advanced building envelope in summer is to control solar gain. The main objective of the effective solar control is to achieve a balance between controlling solar gain, admitting sufficient daylight, and providing occupant view while achieving an architectural appeal of the building envelope.
- **Control of internal heat gains**
  The parameters that should be taken into consideration concern the envelope's insulation, the façade's solar shading and the air infiltration (CIBSE TM29, 2005). Furthermore, energy efficient equipment and lighting can reduce significantly internal heat gains. However, heat gains from people are difficult to cope with, especially in spaces with high occupancy patterns. A good way of

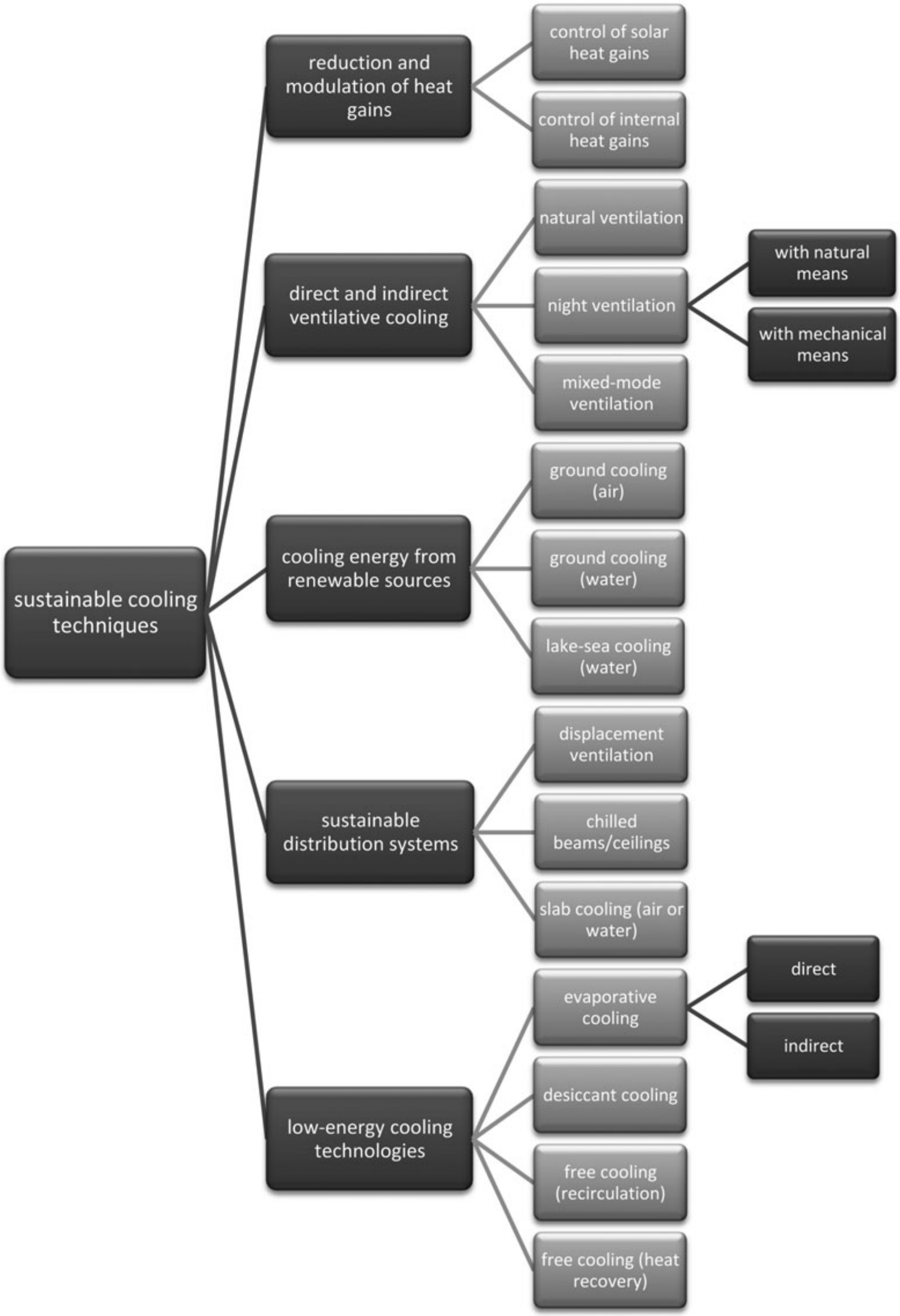

Figure 3.8.2 Sustainable cooling strategy – options.

modulating heat emitted by occupants is to spread the heat gains within the internal spaces, in order to avoid peaks. This can be achieved at the design stage, while designing the spaces and deciding the occupancy patterns together with the target temperatures for the different uses of the internal spaces.

Direct and indirect ventilative cooling

Ventilative cooling techniques contribute to reducing cooling related carbon emission by removing the higher indoor temperature and replacing it with fresh low temperature ambient air. The selection of a sustainable ventilative cooling strategy is affected by location, plan depth, heat gains, internal layout, internal and external sources of pollution, cost effectiveness and energy consumption. Figure 3.8.3 illustrates a typical decision-making process for selection of the ventilation strategy.

Natural ventilation

The cooling capacity of natural ventilation is not very high and depends mainly on the temperature of the outside air. Therefore, in most cases it cannot cope with the internal heat gains, especially in non-domestic buildings situated in the urban heat island, where outside temperatures are higher than in the rural areas. The most important key aspect in natural ventilation is the building layout which can enhance the air flow. The air flow path defines the different ventilation modes, which are illustrated in Figure 3.8.4 – single sided-ventilation, cross ventilation, stack ventilation and sub-slab distribution. More details concerning natural ventilation are given in Chapter 3.6.

Night Ventilation (natural or mechanical)

The night ventilation strategy takes advantage of the night temperatures which are lower than daytime ones and usually below thermal comfort in cool climates. The concept of this strategy is based on cooling the structure of the building with the use of either natural or mechanical ventilation during the night. Figure 3.8.5 illustrates how the strategy works – during daytime the exposed thermal mass, usually slab, provides radiant cooling by absorbing the internal heat gains. When night comes the absorbed heat gains are spread out of the building by cooling the exposed thermal mass using ventilation. The following day the thermal mass is able to absorb more heat than it would otherwise, reducing significantly the need for mechanical cooling. The key factor in night time ventilation is the thermal heat storage; thus, a good performance of the thermal mass is needed together with a good correlation between it and the ventilation air. However, there must be a careful control of night ventilation to avoid over cooling of the building structure.

Mixed-mode ventilation

Advanced mixed-mode ventilation is designed to achieve the high indoor environmental conditions while reducing the carbon emission associated with mechanical cooling. In the design of mixed-mode systems, it is often important to separate the design of ventilation system for indoor air quality and design of ventilation system for prevention of summer overheating. Of crucial importance is that the predicted performance of buildings with mixed-mode ventilation systems at design stage corresponds to the operational performance of the occupied buildings. Further research on the effect of occupant behaviour (i.e. user interaction with ventilation system controls), internal heat loads and wind effects is needed in order to obtain an expected range of building performance. More details concerning mixed-mode ventilation are given in Chapters 3.6 and 3.7.

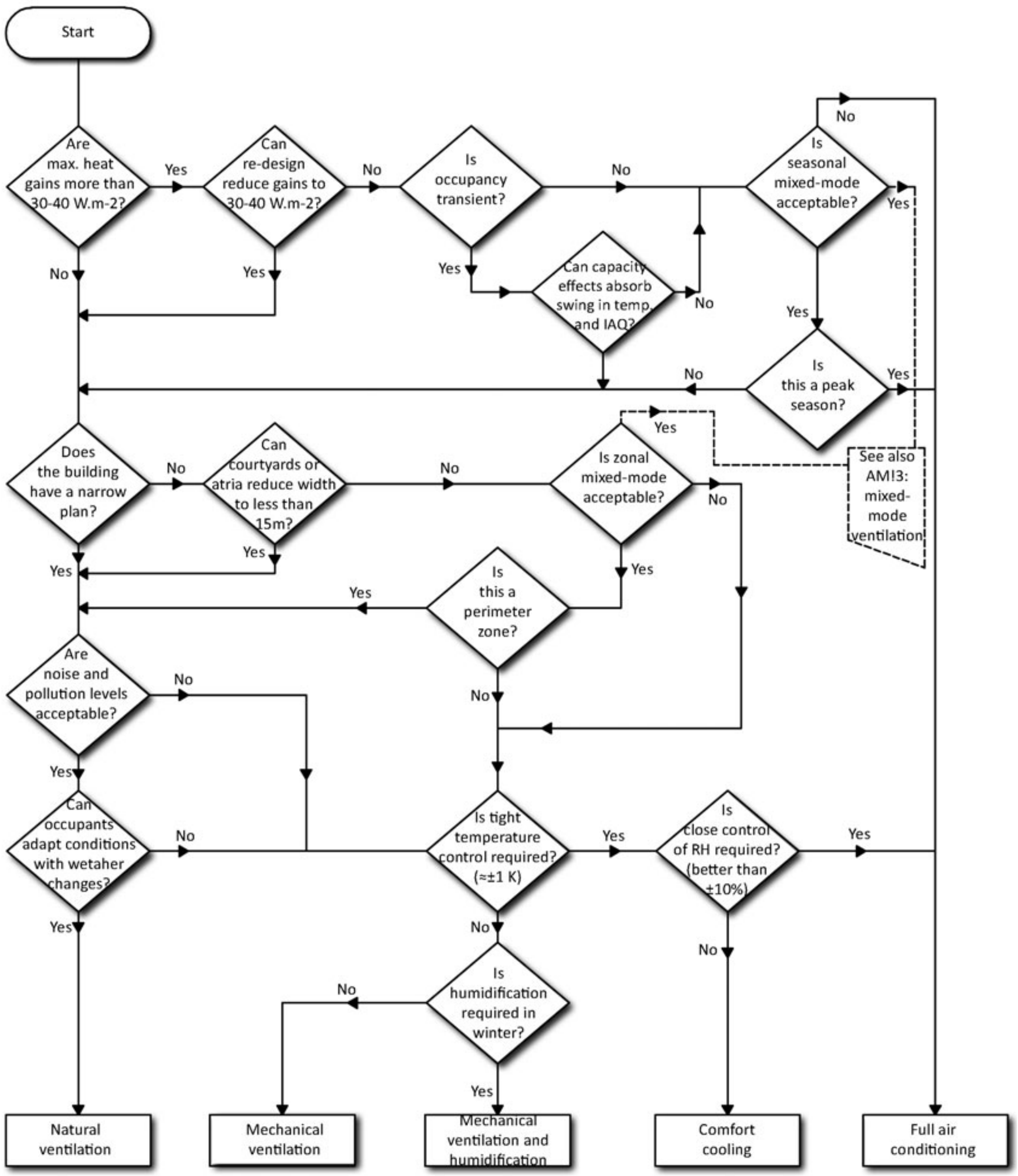

Figure 3.8.3 Selecting a ventilation strategy.

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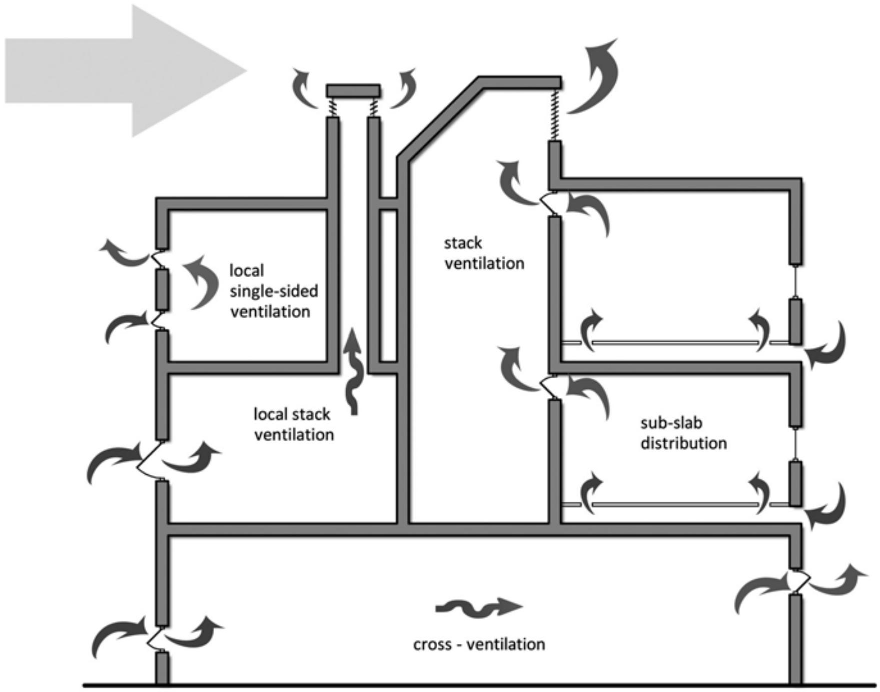

Figure 3.8.4 Cooling by different types of natural ventilation.

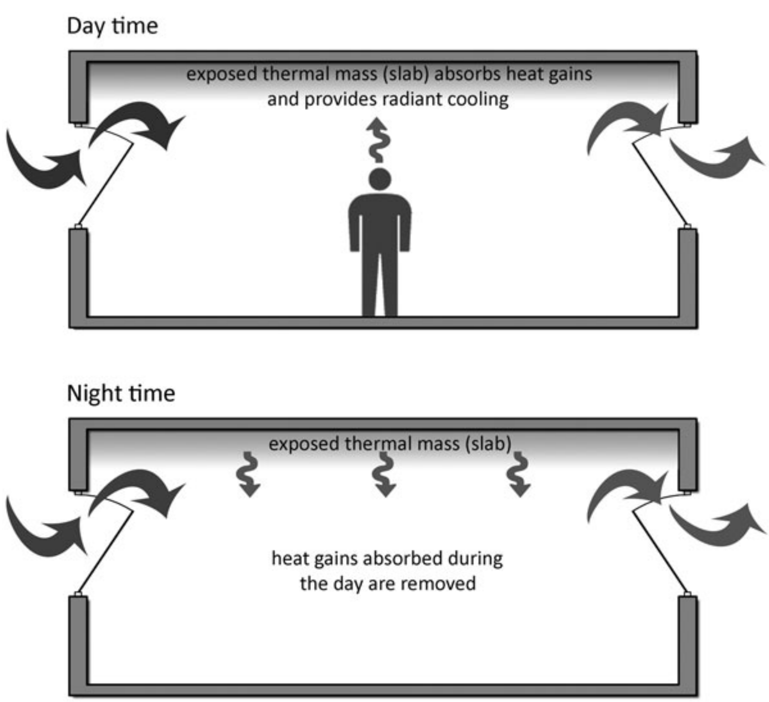

Figure 3.8.5 Night ventilation strategy.

Cooling energy from renewable sources

Another way of cooling buildings is with the use of renewable energy sources such as ground, lake, sea and river. These sources keep their ambient temperatures stable during the year and in this way can be used as a cooling or a heating source.

Ground cooling (air)

This system uses a network of underground ducts, buried into the ground approximately at 2–4m depth. The temperature of the ground at this depth is stable, usually around 10–14°C in the UK. Air is supplied as illustrated in Figure 3.8.6 and is being cooled through the thermal exchange with the ground. The cool air is then introduced to the building or used as pre-cooled air for the ventilation plant.

Ground cooling (water)

This system usually uses boreholes which are buried up to 150m deep into the ground. Heat transfer takes place either from the ground or from the aquifer. In this way water is cooled in the cold borehole and is used for cooling via a heat exchanger which is usually a ground source heat pump. After this process the warm water is re-injected back to the warm borehole and the procedure is resumed.

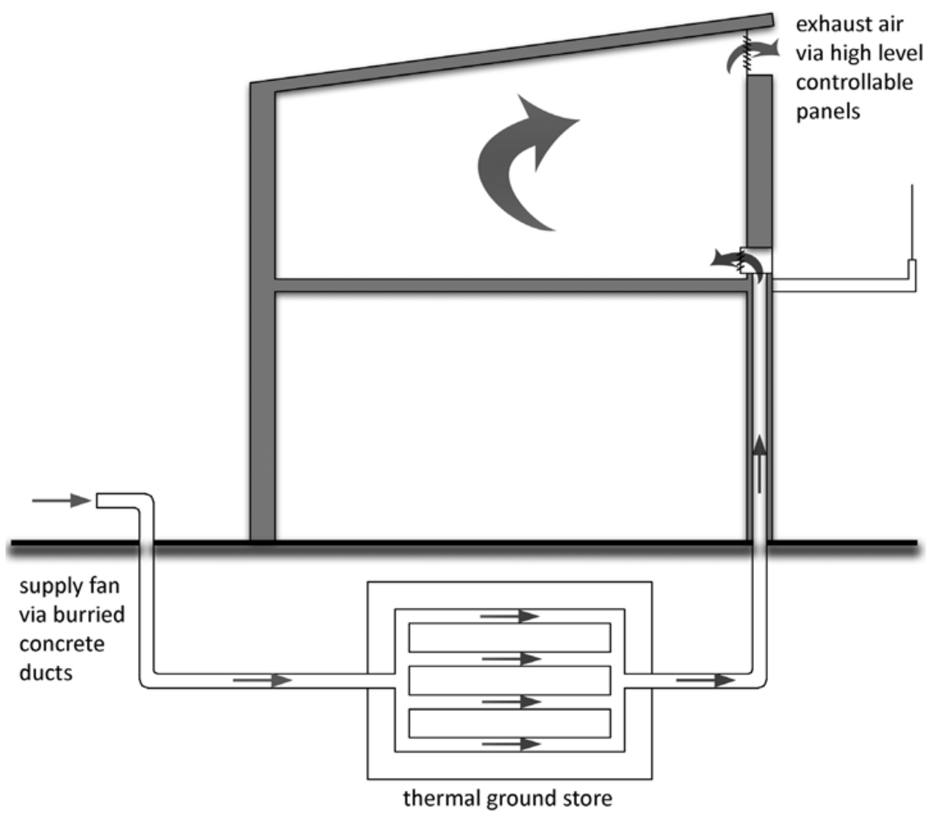

Figure 3.8.6 Ground cooling (air) system.

Lake/sea cooling (water)

This system comprises an alternative of a borehole system described in the previous section. The cold water of the lake or the sea is extracted and passed through the heat exchanger. In this system it is important that the depth from which water is extracted must be sufficient for the water to be cold enough and provide the appropriate cooling.

Sustainable distribution systems

The sustainable distribution systems take advantage of the high water temperatures (usually 14–18°C chilled water temperature) to provide the adequate cooling loads and more viable solutions to the low-energy cooling of buildings. There are four main systems:

- displacement ventilation;
- chilled beams and ceilings;
- slab cooling (air and water).

Displacement ventilation

Displacement ventilation is one of the most recent methods, used especially in office buildings. The basic principle of this technique is illustrated in Figure 3.8.7. The air is supplied at low velocities and at lower level, usually through raised floor and in this way creates a reservoir of cold air. This air is heated only when it gets into contact with an internal heat source, rises up and is extracted through upper level outlets, usually mounted at the ceiling. The movement of the air is enhanced from the heat emitted by the lighting fittings on the ceiling.

Chilled beams and chilled ceilings

Static cooling devices like long rectangular beams, called chilled beams, and rectangular panels, named chilled ceilings are used to provide cooling loads within occupied spaces – chilled water is passed through

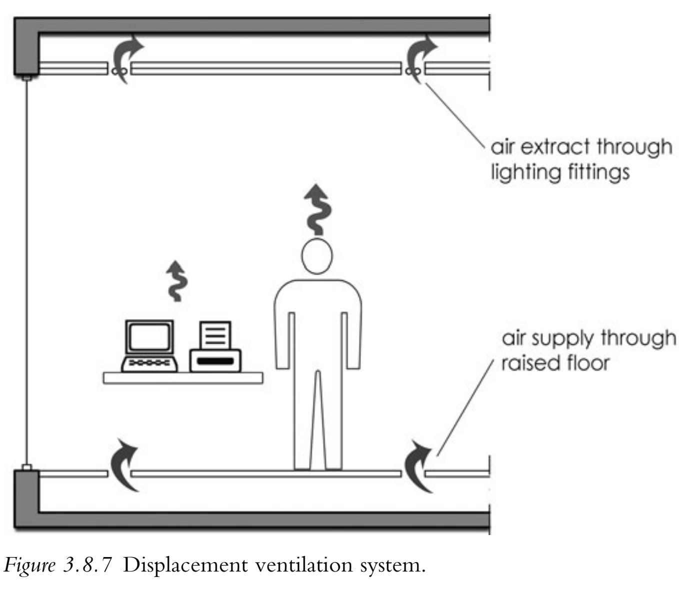

Figure 3.8.7 Displacement ventilation system.

these devices. They both commonly supplement other systems, like displacement ventilation. Figure 3.8.8 illustrates the combination of the three different systems. Chilled ceiling provides radiant cooling while chilled beam provides mainly convective cooling. One major advantage is that the temperatures of the used chilled water is high – between 15°C and 16°C – compared to conventional systems, like fan coils, which use temperature in the range of 6–8°C.

Slab cooling (air or water)

This technique is usually used with night ventilation to maximise the potential of cooling. The slab is constructed in a way that allows air to be passed in embedded channels. During the night (Figure 3.8.9) air is passed through the slab to enhance the cooling of the slab. Inversely, the day's time warm air is injected through the cool slab in order to be pre-cooled before being used to condition a space or send

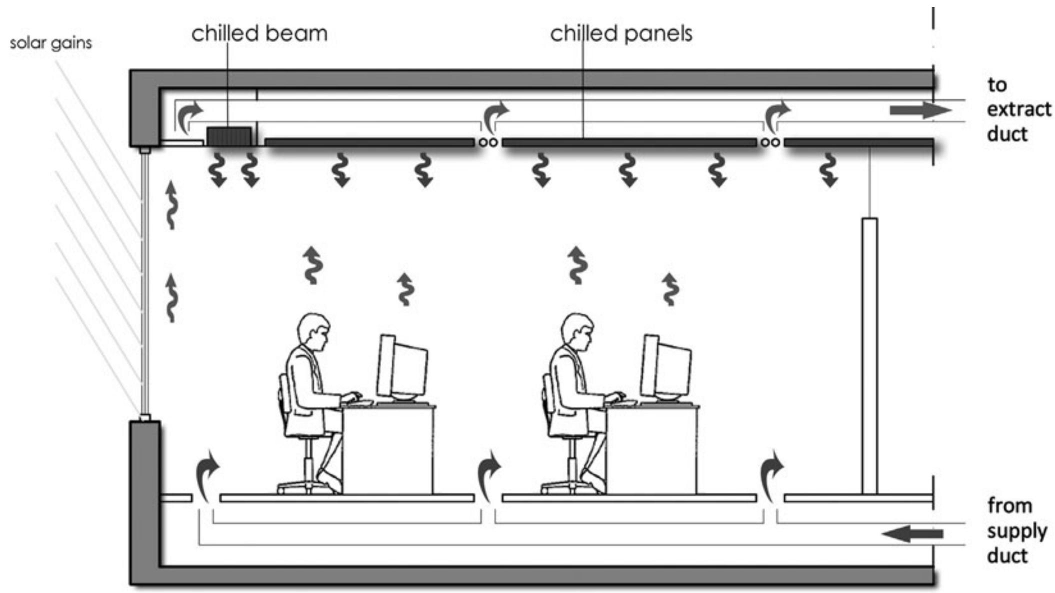

Figure 3.8.8 Chilled beam and chilled ceiling with displacement ventilation.

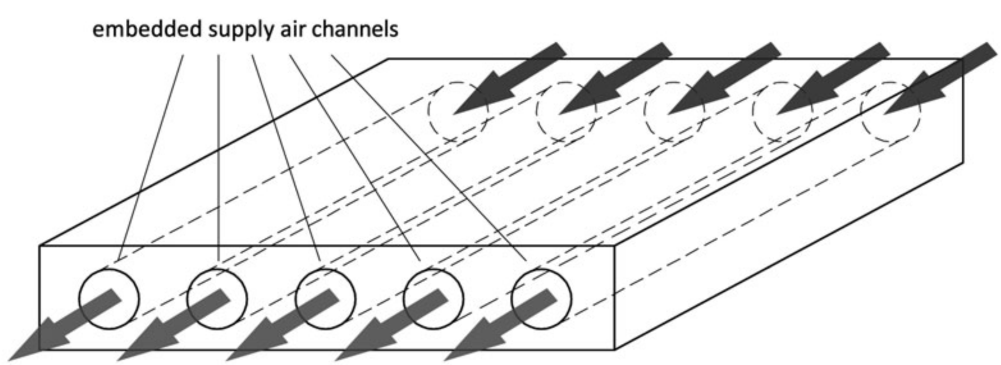

Figure 3.8.9 Slab cooling with the use of air.

to the ventilation plant. Slab cooling technique can also be implemented by using embedded water pipes. Chilled water circulates through the pipes at temperatures between 14°C and 20°C providing cooling. Attention is needed to avoid condensation of concrete surfaces – this happens usually with lower water temperatures.

Low-energy cooling technologies

Low-energy cooling technologies include the incorporation of free cooling to an air-conditioning system which can take advantage of the weather conditions to reduce the energy consumption by shutting down the cooling plant (CIBSE Knowledge Series, 2005).

Desiccant cooling

In this system the extract air is used to cool the fresh incoming air. The introduced air passes through a desiccant wheel, which uses specifically selected materials to achieve dehumidification, and this moisture is removed by the heated extract air (Figure 3.8.10). After the desiccant wheel the income air is cooled by a heat recovery device (thermal wheel); this cooling load stems from the extract air. The cooled supply air can be cooled again by passing through an evaporative humidifier. The degree of cooling can reach 8–9°C. This system works well in humid climates but not so efficiently in dry ones. Additionally, the desiccant material requires heat to dehumidify the air, which can be waste heat from another system or solar energy.

Free cooling (recirculation)

When the extract air is clean enough to be reused, recirculation of extract air can take place and save energy (see Figure 3.8.11). The fresh supply air is mixed with the extracted air, conditioned and introduced in the occupied space. This system is implemented in cases where the total volume of air needed to cool a space is greater than the amount of air needed to provide indoor air quality (minimum

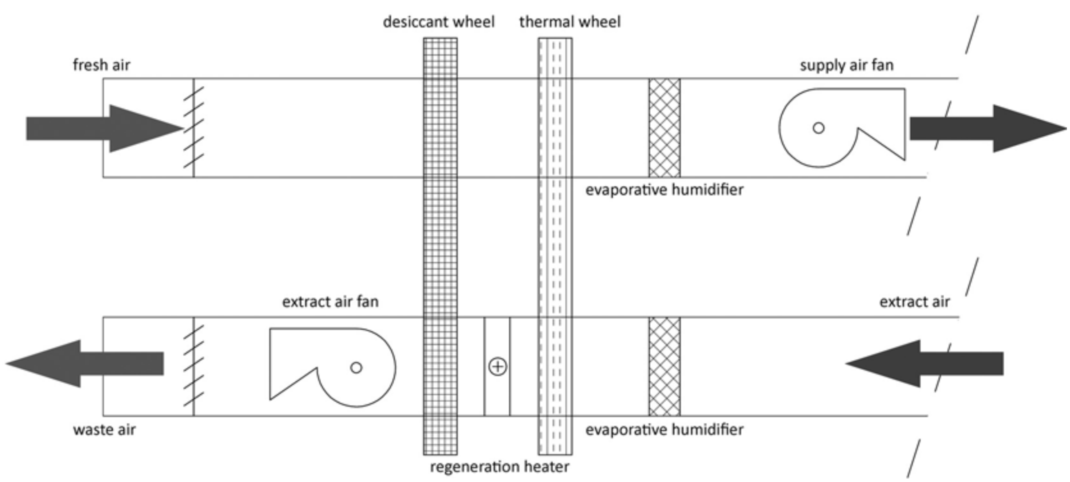

Figure 3.8.10 Desiccant cooling system.

Source: Reproduced from CIBSE Knowledge Series (2005) by permission of the Chartered Institution of Building Services Engineers

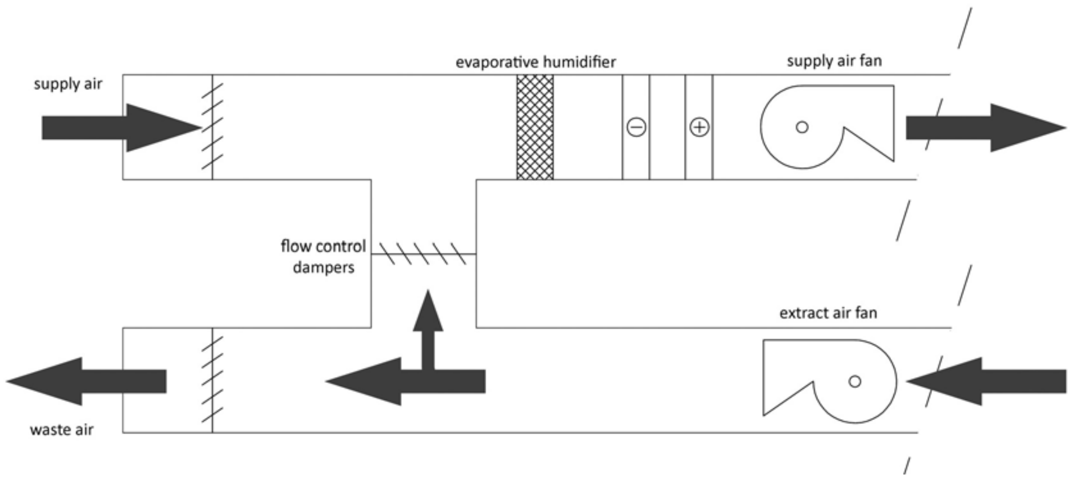

Figure 3.8.11 Recirculation of air system.

Source: Reproduced from CIBSE Knowledge Series (2005) by permission of the Chartered Institution of Building Services Engineers

ventilation). In this way, the system can use minimum amounts of supply air and extract waste air equal to the amounts of air needed to provide sufficient ventilation to the occupants.

Free cooling with heat recovery

In cases when the previous method cannot be used because of contamination in extracted air a heat recovery device can be used to transfer the heat from the fresh supply air to the extracted-waste air (Figure 3.8.12). This device can be fan coils, plate heat exchangers or thermal wheels. A requirement of this system is that the temperature of the introduced air must be greater than that of the waste air; for this reason, the extract air is usually cooled by an evaporative humidifier.

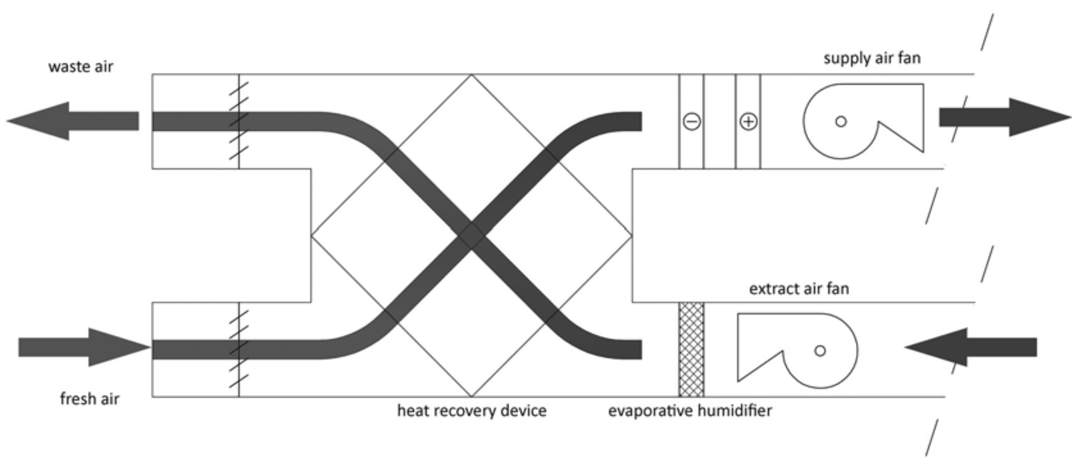

Figure 3.8.12 Heat recovery system.

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Evaporative cooling (direct and indirect)

Figure 3.8.13 illustrates that the evaporative cooling can be either directly, where the incoming air is blown along a spray of cold water which cools the air before it is being used to condition a space. However, the water content of the cooled air increases. To avoid this increase in moisture, indirect evaporative cooling can be utilised, where the cool air produced by the direct evaporative cooling process is passed through a heat exchanger, which cools the air supply. In practice, because of the limited cooling capacity of an indirect evaporative cycle, the primary air is often cooled again by direct evaporation or by a mechanical cooling system. This two-stage system is known as indirect–direct system. In the UK, this technique is used as the supplementary cooling technique only, or in combination with desiccant cooling.

Cooling potential of sustainable cooling techniques

The cooling potential of each of the sustainable cooling techniques (International Energy Agency, 2000) is presented in the Figure 3.8.14.

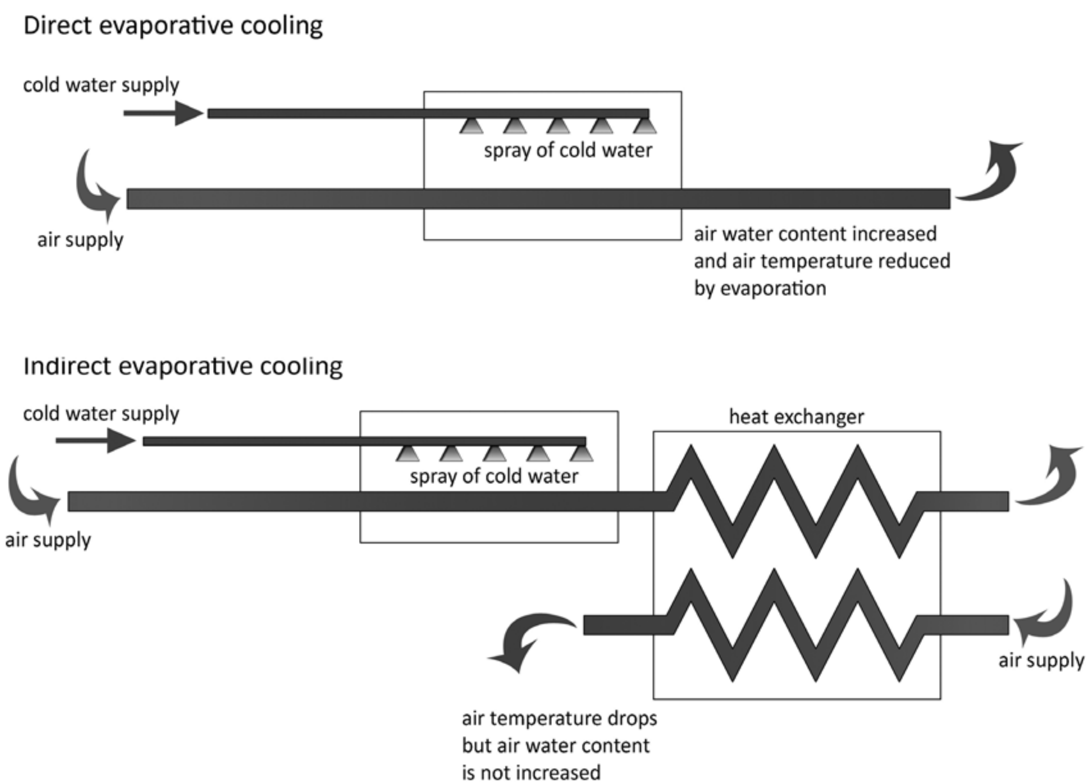

Figure 3.8.13 Direct and indirect evaporative cooling.

Source: International Energy Agency (2000)

	W/m²
direct and indirect ventilative cooling	
natural ventilation	30-40
night ventilation	20-30
mixed-mode	*
cooling energy from renewables	
ground (air)	~45
ground (water)	50-100
lake-sea (water)	-80
sustainable distribution systems	
displacement ventilation	30-65
chilled beams and ceilings	70-100
slab (water)	30-50
slab (air)	40-60

* depends on the energy consumed for generation and distribution

Figure 3.8.14 Cooling potential of the sustainable cooling techniques.

Case study: School of Slavonic and East European Studies Building (SSEES)

The building is located within a university campus at the heart of London (Figure 3.8.15). It is a five-storey construction, designed by Short and Associates, which accommodates the School of Slavonic and East European Studies at University College London (UCL). The programme of the building consists of a library with reading spaces and several offices. The general concept was to build a large naturally ventilated building, which is yet the first one within the urban heat island of London, which uses passive downdraught evaporative cooling. The key issue in the environmental strategy is the seasonal operation modes, which gives the opportunity to the building to acquire different ventilation modes dependent on the external weather profiles (Lomas, Short and Woods, 2004).

Ventilation strategy

There were a lot of restrictions for the ventilation strategy, which deal with the site and the adjacent buildings: traffic and pollution from a nearby street and propinquity with a chemistry building at the back of the site. There were also acoustic restrictions within the interior spaces because of the need for privacy of academic and research staff as well as security limits regarding the library stock. As a consequence, the building was sealed with no opening windows at the perimeter, and the central light well was placed at the centre of the building (Figure 3.8.16). The central well is the key feature for the ventilation strategy and is used to distribute the air within the building spaces (Figure 3.8.17). It is attached to a plenum which connects the basement with the ground floor, which is also used for ventilation reasons.

The front façade is a heavyweight brickwork wall which is used as thermal mass. A ventilation void is created behind it which isolates the internal spaces and also acts as a buffer to reduce noise and pollution from the street. It is also used as a stack for the first three storeys of the front internal spaces. At the same time roof mounted chimneys at the front façade act as exhaust stacks for the last two storeys, while perimeter stacks at the rear ventilate the spaces which are located at the back of the building. The lower ground floor is isolated with its own stack, placed outside the building.

Figure 3.8.15 Front façade of School of Slavonic and East European Studies.

Cooling strategy

A good low-energy solution for cooling was being sought: a way of distributing the air without mechanical support led to the passive downdraught evaporative cooling. Basically, the air is inserted at the head of the light well and passes through the cooling coils, where its temperature drops (Figure 3.8.17). This process creates a reservoir of fresh cool air which moves physically downwards and is being distributed within the spaces through bottom-hung windows (Figure 3.8.16). As the air is introduced at low level in the occupied spaces, it is warmed by the internal heat gains and rises to the ceiling before being exhausted through the stacks. The whole strategy relies on the driving force created by the temperature difference of air. This physical movement of air is enhanced by two design features, which are implemented to optimise the buoyancy of air during summer:

- opening windows at the base of each stack to exhaust cool air;
- injection of waste heat from the cooling coils below the head of each stack.

Figure 3.8.16 The central light well at the heart of the building with the bottom hung windows.

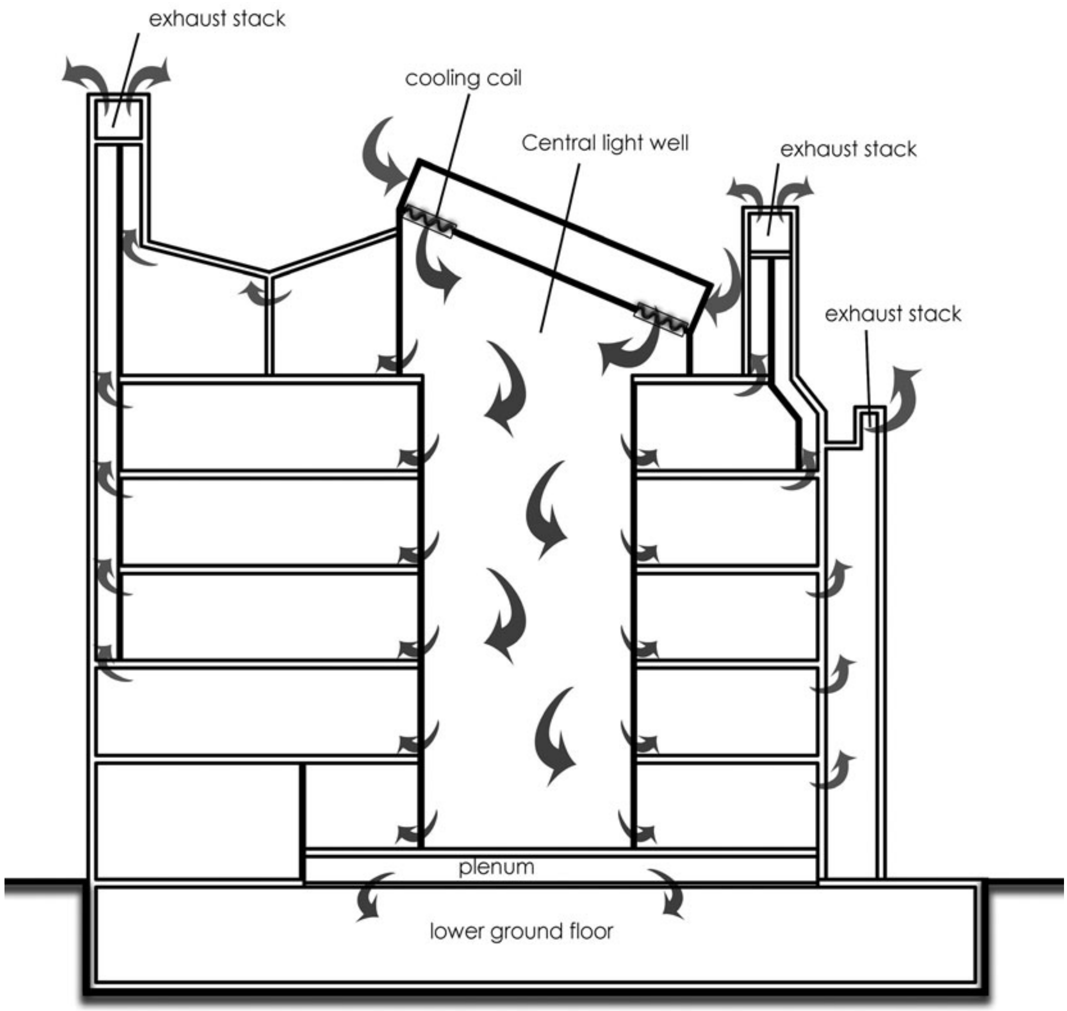

Figure 3.8.17 Ventilation strategy during summer period for SSEES building.

Case study: Portcullis House

Portcullis House is a parliamentary building, located opposite the Houses of Parliament and Big Ben in Westminster, London, designed by Sir Michael Hopkin's architects and partners (Figure 3.8.18). It is a seven-storey building that houses UK's 650 members of Parliament (MPs) in several offices, conference and committee rooms. The whole concept was to design a low-energy building which mostly takes advantage of the building fabric rather than the active mechanical and engineering services to provide good internal thermal comfort (Dix, 2000).

Building fabric and façade

Portcullis House relies on the integration of building services in the design of the building. The façade is a highly active construction which consists of triple plane glazing with argon filled and low emissivity

Figure 3.8.18 General aspect of Portcullis House, Westminster.

coating and also has a ventilative cavity, which serves for the distribution ducts (Figure 3.8.19). Louvres are used to block the lower sun angles during winter while higher sun angles during summer are blocked by a light shelf; glass prism surfaces on the self-act as a reflector of daylight upon the interior space. This results in doubling the daylight, especially in north facing offices, where adjacent buildings obstruct a sky view. The façade has a high U-value, which results in blocking the heat from outside to inside and vice versa; in this way, interior heat is kept indoors. Thermal mass materials with high thermal resistance are used at the interior finishes and also at the ceiling to absorb the heat.

Ventilation strategy

The building uses a low velocity state-of-the-art displacement ventilation system, instead of air-conditioning system, which saves energy because it is assisted by buoyancy. The plan is organised around a central courtyard. Along the building perimeter 14 chimney stacks ventilate the building; air is drawn at the base of the chimneys and is distributed through the sandwiched duct system, integrated at the façade (Figure 3.8.19). Each floor has a ventilation plenum at the floor level where air circulates before being introduced in the occupied spaces. Air is exhausted at ceiling level and distributed through the duct system at the façade to the chimneys. No recirculation of exhaust air takes place, but the system supports heat recovery, through a roof mounted rotary hygroscopic 'thermal wheel'; the recovered heat comprises solar heat captured at the façade, internal heat from occupants and electric devices and also heat emitted by the radiators.

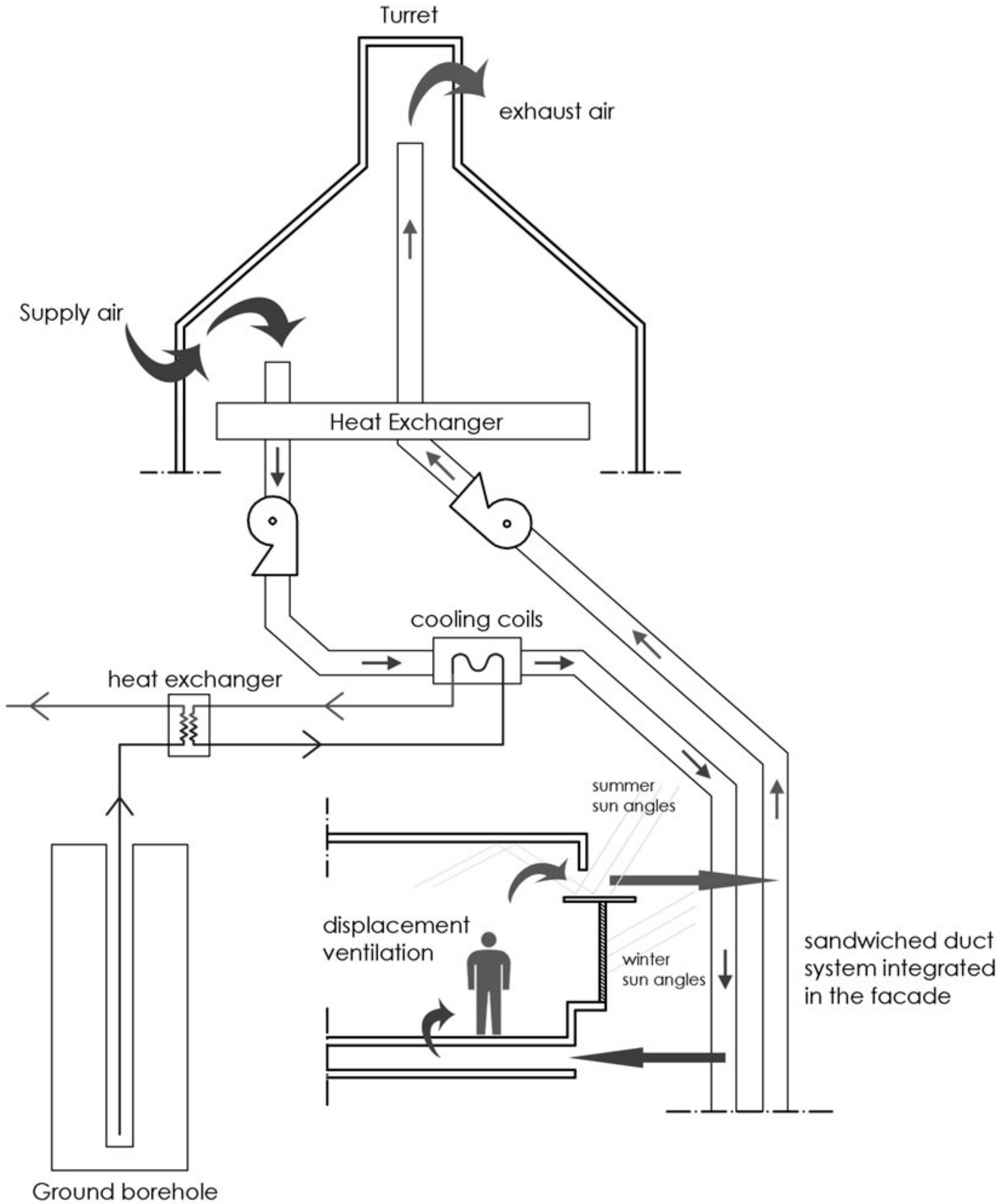

Figure 3.8.19 Cooling strategy during summer for Portcullis House.

Cooling strategy

Two main strategies are being used to cool the building. Ground cooling takes place with two boreholes used to pump water from a ground depth of 120–150m. When the outside temperature goes above 19°C, ground water of around 14°C is pumped and is used via a heat exchanger to cool the ventilation air (Figure 3.8.19). In this way, a 19°C temperature of fresh air is achieved; this air is used to ventilate and condition the occupied spaces through the displacement ventilation system. Additionally, night ventilation is used, when needed, to enhance the cooling strategy of the building and avoid overheating. In this way, internal heat gains absorbed by the thermal mass materials during the day are removed. The ventilation rate during night ventilation is half of that used during the day, reducing in this way the overall energy consumption of the building.

Case study: Swiss Re Tower

Swiss Re Tower is a 40-storey office, 180m tall building, designed by Foster and Partners (Figure 3.8.20). It is located at 30 St Mary Axe in the centre of London. It is the first environmental skyscraper in the heart of the city, whose cone like shape makes it a landmark. The concept was to design a building which takes the most advantage of the integration of structure and building services into the architectural design. In this way, the basic element in the environmental strategy was the façade of the Swiss Re Tower, which is an active ventilative one. The building is equipped with mixed-mode ventilation; natural ventilation assists the mechanical air-conditioning system and reduces the energy demand. Construction started in 2001 and first occupation took place in 2004 (Powell, 2006).

From building design to ventilation strategy

The tower's standing shape is aerodynamic due to the different diameters of each floor plate, with the 17th level having the biggest one. The plan is organised through a central core, where the staircases and elevators are located, while the offices are spread at the perimeter. Each floor plate has six triangular atriums at the perimeter, which develop a spiral stripe made of darker glass at the elevation (Figure 3.8.21); this is achieved because each floor plate is twisted 5 degrees relative to the floor below it. The atriums act as the lungs of the building used to naturally ventilate the building. The circular plan is the key feature for the ventilation strategy. This shape, because of its smaller surface, approximately 25% less than a rectangular one, copes with less heat losses and less solar gains. The most significant advantage of this shape is that it deals well with the wind, preventing turbulences. As the air flows around the building it creates positive pressure on the windward side and negative pressures on the sides of the building; this embraces the perfect driving force for cross flow ventilation. This pressure variation enhances the natural ventilation; air enters through monitored opening windows in the atria, which act also as buffers preventing draughts in the offices. However, the overall ventilation strategy of the building is mixed-mode, where air conditioning cannot be avoided because of the building height and the site location.

Façade design

The façade is the most important element of the environmental strategy of the building. It comprises a triple skin façade with a double glazed outer skin, followed by a 1.0–1.5m gap (Figure 3.8.22). The inner skin consists of a single glazing pane, a ventilative gap and a layer of aluminium louvres. The exhaust air circulates through the façade's gap and removes the heat coming from the inner glazed skin of the offices and also the heat absorbed by the blinds; in this way, the percentage of solar transmission is a mere 15%, while the U-value of the façade is reduced to 0.8W/m^2/K, when the air circulates through the gap. Therefore, the overall cooling load needed for the office space is reduced significantly.

Figure 3.8.20 Swiss Re Tower.

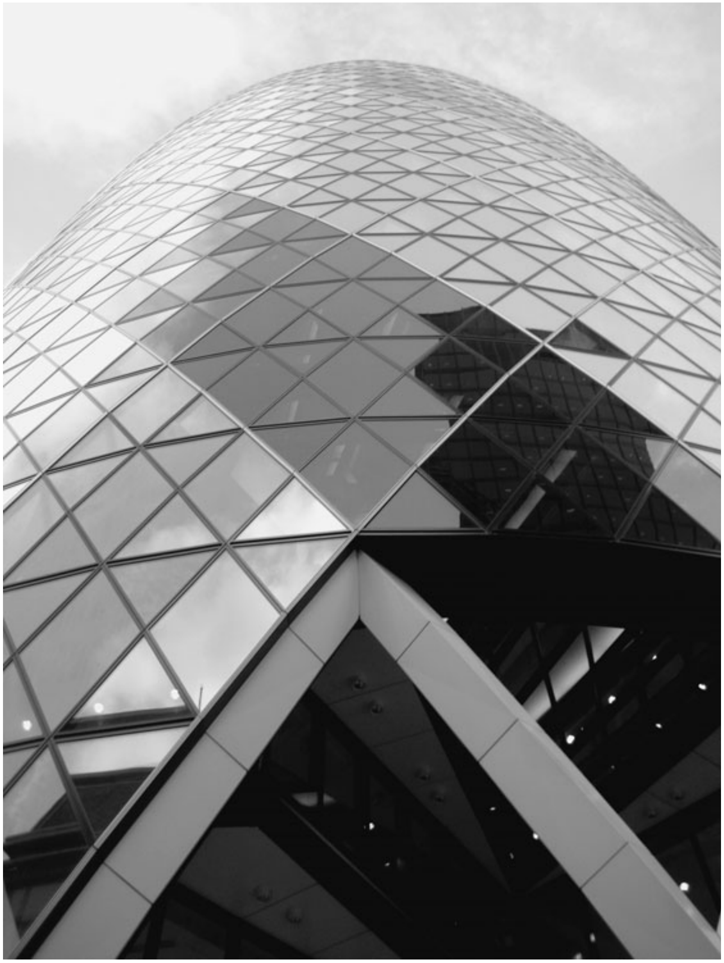

Figure 3.8.21 Atriums creating spirals of darker glass at the elevation.

Cooling strategy

Apart from the ventilative façade, which plays a major role in cooling the building, air conditioning is also installed. Mixed-mode system which also uses natural ventilation for cooling reasons is used for 40% of the year. The whole concept of the air conditioning installation is based on a decentralised system which serves each floor separately. Air is introduced through grilles at the façade at ceiling level (Figure 3.8.22), is passed through the air handling unit before being introduced in the occupied space at high-ceiling level; fan coil units are used to cool the air. Part of this cool air is then extracted through floor outlets and passes through the ventilative façade duct, cooling the glass and the blinds before being extracted outside. Most of the heavy plant, like chillers and tanks are located at the basement of the building while the cooling towers are located at 35th level. Energy efficiency is achieved by the use of the waste heat from condenser water. Waste heat is also used from the ventilated façade and is provided to the thermal wheels mounted at the AHU.

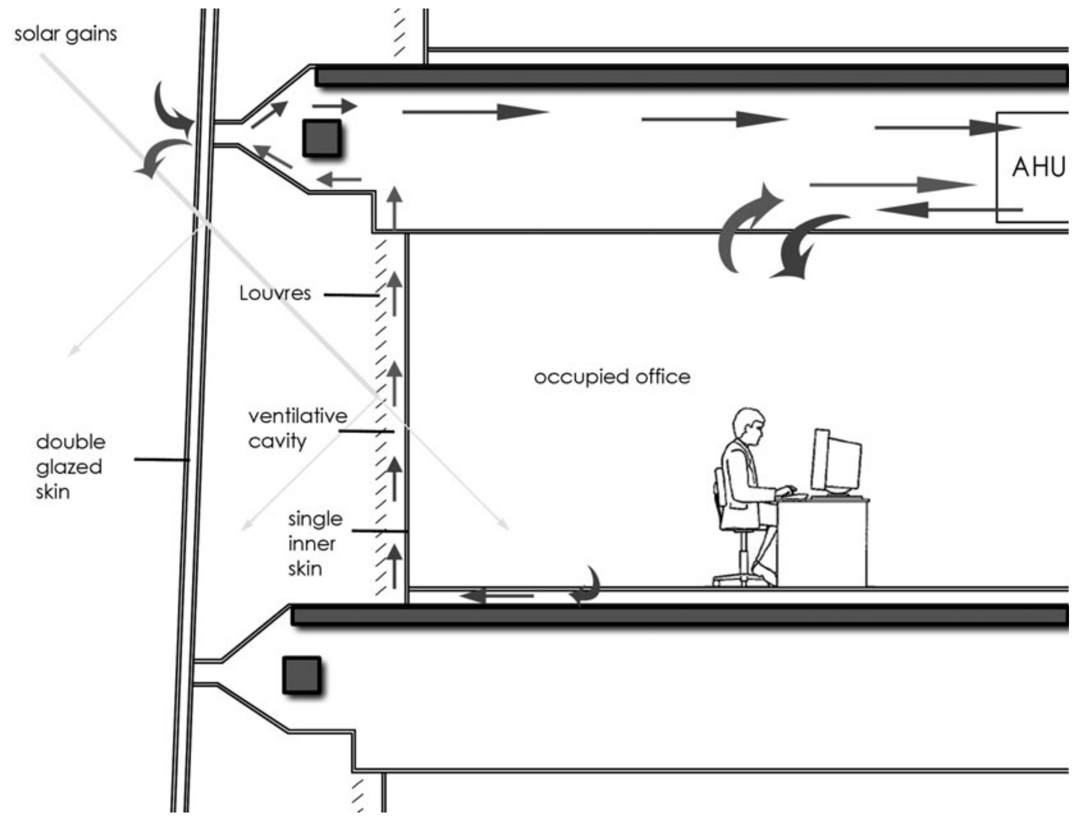

Figure 3.8.22 Cooling strategy (summer) for Swiss Re Tower.

Case study: National Assembly for Wales, the Senedd

The Senedd is a three-storey building, located on a prominent waterfront site in Cardiff Bay; it is designed by Richard Rogers and Partners. Architects and engineers were working together from the earliest stages of the building design. The design relies on the natural ventilation mode; the key environmental features are the roof cowl, which is used for ventilation purposes and for maximising daylight penetration within the building via the lantern. The main entrance area, the cafe and seating areas are open to the public while there are three committee rooms and also the debating chamber (Siambr) for the 60 Assembly members (Smith, 2001).

Natural ventilation

The predominant mode operating in the building is natural ventilation. Public spaces are entirely naturally ventilated with the use of windows on the glazed façades of the building. Important feature on the strategy comprise also the use of thermal mass materials such as concrete and slate, which help temper the internal conditions. The debating chamber and the committee rooms have an air conditioning back-up system, which is used when there are higher internal heat gains or when stricter internal conditions are needed. The air is inserted through inlets in the floor and is exhausted through windows in the committee rooms or through the roof funnel in the Siambr (Figures 3.8.24 and 3.8.25). The wind cowl located at the top

Figure 3.8.23 General aspect of the National Assembly for Wales, the Senedd.

Figure 3.8.24 The funnel acting as the stack effect for the Siambr viewed from the public space.

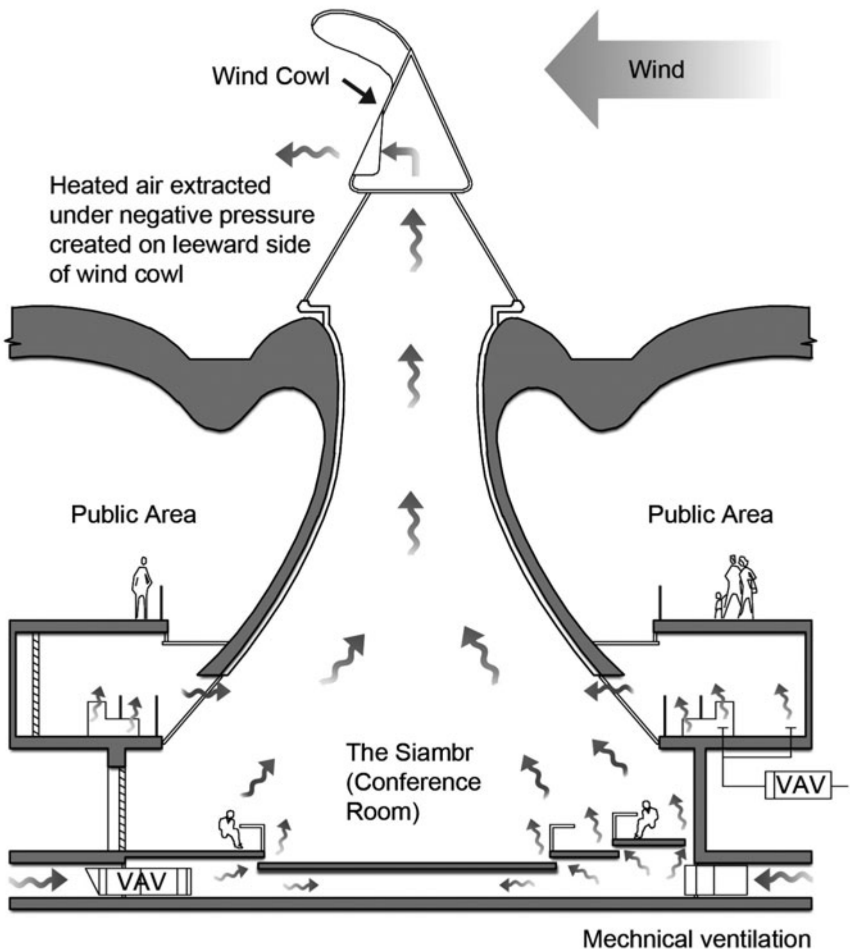

Figure 3.8.25 Summer ventilation strategy for the Senedd.

of the Siambr is 6m high and has the possibility to rotate according to the prevailing wind; in this way, a negative pressure is created at the leeward side of it, where outlets are located to exhaust the warm air from the building and thus reduce the energy requirements for air conditioning.

Daylight

One of the most important elements of sustainability is the daylight entering the Senedd. Extensive modelling of solar penetration and natural light was being held in the design stage to allow the maximum amounts for both low winter and high summer sun angles and also at different times a day. A combination of artificial and natural light takes place. Natural light enters the building through the lantern at the roof top funnel; this comprises a conical mirror which reflects the light within the building. Daylight penetration is also optimised by the glass façades on all four elevations of the building and also glazed roof light in the committee rooms.

Cooling strategy

The spaces in the Senedd have diversity in terms of environmental control; the minimum control is in the public spaces, while the committee rooms and the debating chamber at the heart of the building are highly controlled. The latter spaces, as mentioned before, have a backup air conditioning system. Ground earth heat exchangers are used for cooling; 27 boreholes are buried into the ground and supply with cool water via ground source heat pumps (GSHP). Water circulates through a matrix of small pipes underneath the slate floor and absorbs the heat from the building. Then, the heat is deposited to the ground and the process is resumed, resulting in reducing the cooling load demand. The system is also used as under floor heating during winter. The whole system reduces the size of conventional boilers and chillers; GSHP operate two to three times more efficiently than conventional systems. Therefore, significant energy savings are achieved. The engineers believe that the building will use no more than 50% of a conventional building operating in the same location.

Case study: National Trust Headquarters, Heelis Building

Heelis Building is the new building of National Trust Headquarters located on the site of Great Western Railway Works in Swindon. It is a two-storey construction of 7000m^2 which accommodates mainly offices together with a shop, a public cafe-restaurant and a membership recruitment area. The key feature on the design of the architects' Fielden Clegg Bradley was sustainability; to achieve this goal high quality benchmarks were essential. It is one of the fewest deep plan office buildings which uses almost entirely natural ventilation to keep it cool and also relies on natural daylight (Randall, 2006). The building has been operating for two years.

Figure 3.8.26 Main-south façade of Heelis Building.

Natural ventilation

The whole design of the building relies on the natural ventilation strategy. The plan is organised so that the main façade is due south and that the double-pitched roof faces south-north. In this way, an east-west axis organises the building plan with two main courtyards located in the middle; they act as lungs to provide natural ventilation even at the most central areas of the building. Air is introduced at the perimeter by high level automatically controlled windows and large door sized ventilation panels at the main-south

Figure 3.8.27 The snouts at the roof of Heelis Building.

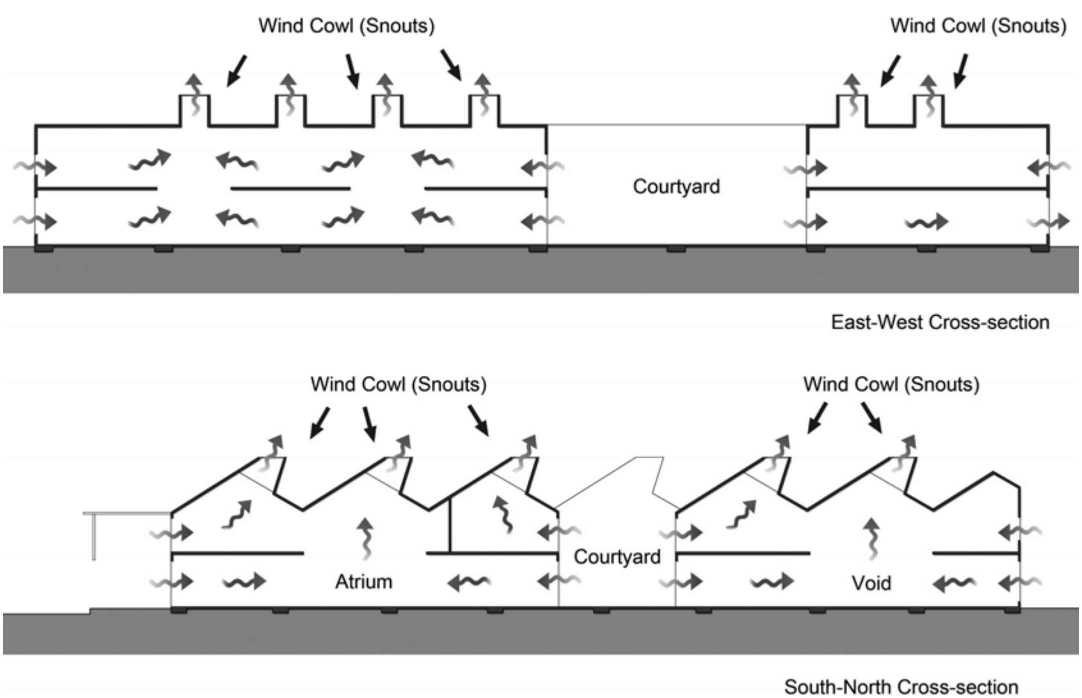

Figure 3.8.28 Ventilation strategy for Heelis Building.

façade (Figure 3.8.27). However, all windows have the facility to open manually; this gives the occupants the satisfaction of controlling the indoor conditions. Air is exhausted via roof ventilators called 'snouts' (Figure 3.8.28). Some of the exhaust outlets have mechanical support which is used in very hot, still internal conditions. The whole ventilation strategy is illustrated in two sections presented in Figure 3.8.28. Natural ventilation is achieved by stack effect but is also enhanced by external wind pressure.

Daylight

Almost two-thirds of the spaces rely on natural daylight. North facing slopes of the roof accommodate glazed units, from which daylight penetrates the building and reaches the ground floor. These are shaded by south facing photovoltaic installations, which provide nearly 15% of the total electricity consumption of the building. Voids on the first floor allow natural daylight to reach the ground floor. Daylight factors are more than 5% in a great percentage of the interior spaces; on the first-floor lights are rarely on while on the ground floor there are few 'dark' spaces below the mezzanines that usually have their lights on. Daylight penetration is also enhanced by the two courtyards.

Cooling strategy

The whole strategy for cooling relies in night ventilation. The 442mm thick walls, made of concrete blockwork and external brickwork, together with the roof which is made of 80mm thick exposed precast concrete panels have very high insulation values and high thermal resistances. In this way, they comprise the thermal mass of the building, which absorbs the internal heat gains during the day and purges them during the night. However, in spaces with high internal heat gains and stricter internal conditions like meeting and computer rooms mechanical cooling is needed. A mixed-mode system of local fan coils is being implemented; water is cooled by a zero-ozone depleting refrigerant.

Acknowledgements

This chapter is based on a postgraduate dissertation entitled 'Sustainable Cooling Strategies – State of the Art' which has been submitted by Thomas Lakkas in partial fulfilment of the requirements for the degree of MSc in Environmental Design and Engineering at the Bartlett, University College London.

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3.9

CLIMATE CHANGE AND BUILDING DESIGN

Steve Sharples

Introduction

Climate change is now seen as the key environmental challenge to the planet and its people for the remainder of the twenty-first century. Predicting both the form that climate change may take over the next 50–100 years, and the impacts that those changes may have on the natural and built environment, continues to be a complex and contentious area of research. The latest Intergovernmental Panel on Climate Change (IPCC) report states that warming of the climate system is now clearly identifiable, and that from the 1950s many of the observed changes are unequalled over previous millennia. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, sea levels have risen, and the concentrations of greenhouse gases have increased (IPCC, 2013). Envisaged future changes to weather patterns, based on various emission scenarios, have regional variations, but the major foreseen changes include warmer and drier summers and milder and wetter winters. There is a general scientific consensus that climate change arising from global warming is the result of increased greenhouse gas emissions from human activity, and the built environment, through the fossil fuel energy it uses to function, is a major contributor to those increased emissions. Historically, climate has shaped the built environment, but now the built environment is shaping the climate. In this chapter the potential impacts of climate change on buildings will be discussed and the options for changes to building design to make buildings more resilient to future climates will be considered (see de Wilde and Coley, 2012; Gething and Puckett, 2013; McGregor, Roberts and Cousins, 2013).

Climate change and temperature

Impacts

The average global surface (land + oceans) temperature increase by the end of the twenty-first century is *likely* to exceed 1.5°C relative to the 1850 to 1900 period for most emission scenarios and is *likely* to exceed 2.0°C for many scenarios (IPCC, 2013). As oceans generally warm less than land then temperature increases over land are expected to exceed these average values. In urban areas this warming will add to the already higher temperatures experienced in cities due to the urban heat island (UHI) effect (Watkins, Palmer and Kolokotroni, 2007). The impact of hotter summer days and much warmer summer nights will include thermal discomfort and difficulty with sleeping. There are suggestions that night time temperatures may be more significant then maximum day time temperatures in terms of health impacts upon people (PHE, 2013). Warmer temperatures are associated with several serious diseases, such as malaria, and an increase in food poisoning, air pollution and water contamination. However, the most serious thermal climate change impact upon people is the predicted increase in the frequency of heat waves. There is a direct relationship between very hot conditions and human illness and mortality. The European heat wave of August 2003 is estimated to have been responsible for around 35,000 excess deaths, with the elderly and the ill being most affected (Confalonieri et al., 2007). In France 91% of victims were over 61 years old (Salagnac, 2007). Studies in the UK suggest a possible 257% increase in heat-related deaths by the 2050s of compared to current mortality rates (Hajat, Vardoulakis, Heaviside and Eggen, 2014). Figure 3.9.1 shows the total daily deaths in London during 2003 for people aged over 75, with a marked peak occurring during the August heat wave. It is believed that the European temperatures experienced during the summer of 2003 heat wave will become ‘typical’ by the 2040s and could be considered ‘cool’ by the 2080s (Stott, Stone and Allen, 2004).

Responses

The first stage of managing higher future internal temperatures in buildings is to attempt to make the external air as cool as possible. Within the built environment this involves enhancing the green and blue infrastructure with parks, trees, open spaces, open water and water features. Parks and other open green spaces can be beneficial through their cooling effects in summer through shading and transpiration (Yu and Hien, 2006; Gill, Handley, Ennos and Pauleit, 2007) and improved access for natural wind-driven ventilation. In addition, the presence of water, plants and trees contribute to microclimate cooling and are an important source of moisture within the mostly arid urban environment (Robitu, Musy, Inard and Groleau, 2006). Urban surfaces should be cool or reflective to limit solar gain. Pavements, car parks and roads can be constructed with lighter finishes and have more porous structures. There is a growing interest in the use of rooftop gardens, green walls and green roofs for their cooling effect (Liu and Baskaran, 2003). Building surfaces, particularly roofs, should also have a high reflectance (or albedo)

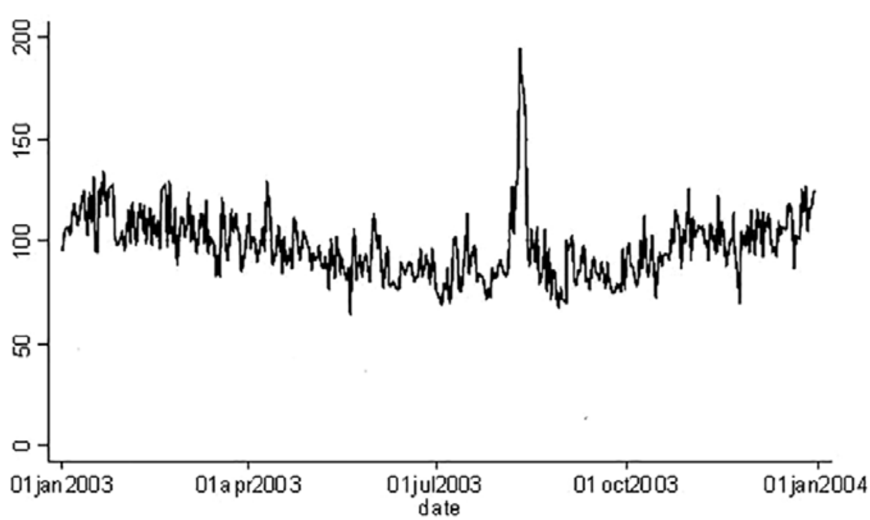

Figure 3.9.1 Total daily deaths of people over 75 in London in 2003.

Source: Greater London Authority, 2006

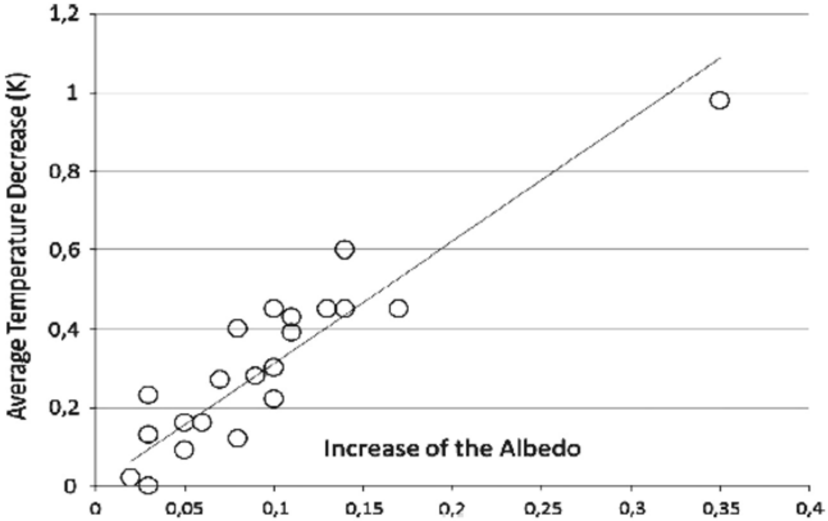

Figure 3.9.2 Relationship between albedo values and average ambient temperatures in urban areas.

Source: Santamouris, 2014

to solar radiation in order to minimise solar gain in the opaque fabric. This is a common practice in southern Europe but currently rare in cooler climates (Santamouris, 2014). Figure 3.9.2 shows typical roof albedos for different roof materials while Figure 3.9.3 shows the results from a number of studies of the impact of urban surface albedo on average ambient air temperatures in urban areas.

The key building fabric responses to climate change will involve solar shading, thermal mass, ventilation and insulation. The main building services considerations will include low energy heating and cooling systems.

Solar gain through windows and opaque elements will typically represent one of the largest heat gains in a building and so is one of the most important parameters to control in a warming climate. Shading devices can take several forms (louvres, blinds, shutters) but they should all, ideally, be light coloured, porous, external and moveable. Roofs should be shaded at latitudes where the sun reaches a high altitude in its path across the sky. In climates that are already hot building form and layout are also used to provide shade – for example, by placing building close together or by forming courtyards. A detailed discussion of solar shading control is given in the CIBSE publication TM37 (CIBSE, 2006).

Thermal mass is related to how much heat a material can absorb and how quickly that heat is transmitted through the material. Concrete and stone are high thermal mass materials and the interiors of caves and cathedrals demonstrate how effective mass can be in keeping spaces cool even on very hot days. This is obviously a very useful feature in a warming climate but has the disadvantage that the heat is still stored within the building fabric at night, when the UHI has its greatest impact. Night ventilation (by opening secure vents and windows) can be used to purge some of the heat out of the building mass, leaving the building a few degrees Celsius cooler by the start of the next day. Figure 3.9.4 shows a typical temperature profile for an office with and without night ventilation.

In addition to night cooling, ventilation is obviously also important in buildings for providing fresh air, removing stale air, controlling relative humidity and offering day time cooling in summer. Natural ventilation strategies involve wind driven forces (determined by wind speed and direction) and stack or buoyancy forces, which are driven by the height between inlet and outlet ventilation openings and the

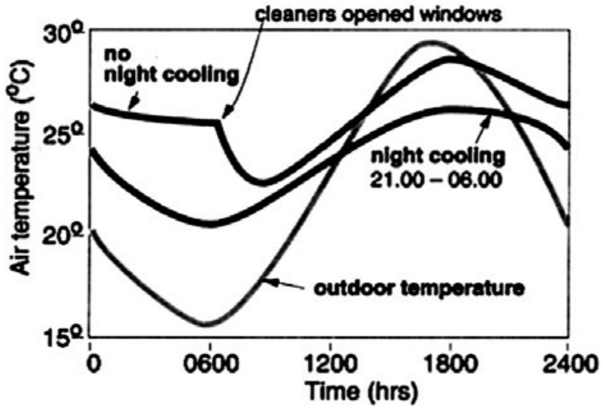

Figure 3.9.3 Impact of night ventilation on indoor air temperature.

Source: Rennie and Parand, 1998

indoor-outdoor temperature difference. Future wind speed and direction scenarios are currently poorly understood but it is clear that in a warming environment the potential of summer time natural ventilation to cool building interiors may be greatly diminished (Barclay, Sharples, Kang and Watkins, 2012). This implies that the demand for active or mechanical systems to cool buildings will increase, with consequences for energy demand and possible waste heat injection into an already warm urban environment.

Thermal insulation is used in building envelopes to reduce heat losses in winter, minimise energy use and maintain thermal comfort. In summer insulation can have two impacts – it can reduce and retard external solar heat gains being transmitted through the opaque building envelope to internal rooms, but insulation can also impede heat generated within a room (such as solar gains through windows or casual gains from activity) from leaving the space. In a warming climate it becomes less clear how conventional insulation should be used in a future building design. As an alternative, for example, green roofs offer reasonable winter insulation but also provide summer cooling, biodiversity and longer roof life.

Heating systems are likely to require much smaller capacities in the future to meet reduced winter heating loads. The efficiency of a boiler is highest when it is running close to full output and so the required maximum output of a boiler sized using historical weather data will need to be revised each time the boiler is replaced (say every ten years). For buildings constructed to a very high insulation and air tightness standard, such as the Passivhaus approach (Dequaire, 2012), a warming climate may remove the need for a central heating system altogether and enable a space to achieve thermal comfort using just passive solar gains and casual internal gains from people and equipment. Indeed, in some instances the key problem may become one of overheating rather than overcooling (McLeod, Hopfe and Kwan, 2013; NHBC, 2012).

It is very probable that the traditional passive means of cooling buildings (natural ventilation, thermal mass, evaporation) will not be able to ensure summer thermal comfort for future climate scenarios, especially in heat waves. Current active cooling systems are normally refrigerant-based air-conditioning units that have a high electrical energy consumption, and which use ambient air as a heat sink. There are alternative, more energy efficient cooling systems, which include the use of chilled beams, ground water, evaporative cooling and ground-coupled cooling (see GPG, 2001). Although there is little doubt that mechanical cooling systems will become more widely used to combat climate warming, they should always be the final step after all other passive cooling strategies have been designed into the building.

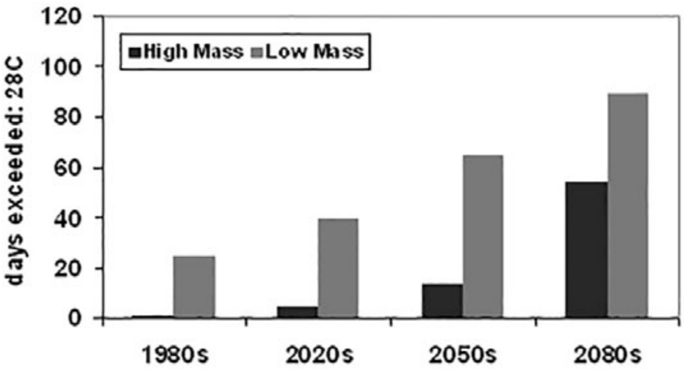

Figure 3.9.4 Impact of mass on living room air temperature.

Source: CIBSE, 2005

CIBSE (2005) have analysed how effective some of the above passive adaptive measures might be in combating climate change. They modelled the performance (space heating, risk of summer overheating, need for comfort cooling and performance of mechanical air conditioning systems) of a variety of building types for a current design hot weather year and future weather scenarios. For a new build detached house, the adaptive measures examined included mass, solar shading, a reduction of ventilation during the warm part of the day and an increase in ventilation at night. Discomfort temperature levels were taken as 28°C in the living room and 25°C in the bedroom. Figure 3.9.4 shows the impact of mass on overheating in a living room for an unadapted house in London for a period stretching from the 1980s to the 2080s, expressed as the number of days in a year when indoor temperatures exceeded 28°C. The high-mass house performs significantly better than the equivalent lightweight house. However, a similar analysis for an upstairs bedroom showed only a marginal difference in performance.

The adapted high mass is seen to perform significantly better and to provide a good level of thermal comfort in the living room up to the 2080s. The same is not true for the bedroom analysis, where even the high mass, adapted house displayed overheating problems by the 2020s. This type of finding is persuading some house designers to suggest that in future bedrooms should be located on ground floors with living areas at first floor level.

Climate change and precipitation

Impacts

The expected climate change patterns for precipitation are, typically, drier summers, wetter winters and a greater incidence of heavy rainstorms. More frequent and intense rainfall will lead to river flooding and the failure of urban drainage systems. Flooding is the most prevalent natural disaster globally, and worldwide economic losses from flooding have increased from around $0.5 billion in the 1980s to around $20 billion by 2010 (EM-DAT, 2012). Such flooding creates many problems, including building damage, disruption to transport, interference to water supplies and potential health risks (Ahern, Kovats, Wilkinson, Few and Matthies, 2005). Rising sea levels will add to flood risk for both coastal locations and low-level cities on or near rivers.

Responses

Urban development and pressure on land use have meant that more buildings have been, and continue to be, constructed on what were traditional sacrificial flood plains. This has had the effect of distorting and damaging natural drainage systems, and the consequences are increasingly evident, with large scale flooding becoming more common. The impact of climate change will probably be to make these flooding events more severe and more frequent. At the urban scale flood risk management can use Sustainable Urban Drainage Systems (SUDS), which attempt to control and slow down the run-off of surface water following heavy rain. This approach includes the use of vegetated, gently sloping landscape elements, soakaways to allow the rain to get directly back into the ground, permeable and porous pavements and car parks and sacrificial areas, such as fields and ponds, to store flood water. A detailed description of SUDS is given by Susdrain (2014). For an individual building the aims of flood risk management are to minimise the risk of flooding and reduce the damage caused by flooding. Apart from creating physical barriers between floodwater and the building, other risk-reduction approaches include reducing the run-off of rain through harvesting of rainwater, providing permeable and/or drained ground surfaces and the use of green roofs (these suggestions are also part of a SUDS strategy). Green roofs, in particular, are seen as a potentially very powerful tool in adapting buildings to reduce climate change urban flood risk (Carter, Jackson and Rhett, 2007). In order to minimise flood damage to buildings from present and future events there are a series of steps that can be implemented. Floodwater will penetrate not just through obvious openings in walls but also through cracks, defects, service penetrations and other openings, and so general maintenance and repair of the structural envelope is important, particularly for buildings in known flood risk areas. All utility services, such as supply meters, electrical fittings and boilers, should be at least one metre above ground floor level, with pipes and cables dropping from first floor level. Drainage and sewer pipes should have one-way valves fitted to prevent the backflow of contaminated floodwater entering the building. In the USA the Federal Emergency Management Agency (FEMA, 2014) provides very detailed guidance on protecting buildings and utilities from flood damage. Flood resistant finishes, such as plastics, vinyl, concrete, ceramic tiles and pressure-treated timber, should be used in place of carpets, chipboard, soft woods and fabric, and gypsum plaster should be replaced with a more water-resistant material, such as lime plaster or cement render. To reduce the amount of repair after flooding it is helpful to fix plasterboards horizontally on timber framed walls rather than vertically and to replace mineral insulation within internal partition walls with closed cell insulation. Several architectural practices are starting to specialise in the design of flood-resistant buildings (Baca, 2014), and some of the most advanced ideas for making buildings flood resilient can be found in Holland, a country that is, even before climate change, 6m below sea level. One architectural solution is floating buildings that rise and fall with water levels. Examples of this approach are described by H_2OLLAND (2013).

Climate change and wind

Impacts

The major interactions of the wind and buildings are in structural loading, wind speeds at pedestrian level and as a driving force for natural ventilation and cooling. There is a great deal of uncertainty about future patterns of wind speed and direction and climate models are not robust or consistent in their predictions. However, it is believed that there will be an increase in the number and severity of storms.

Responses

The most important wind feature is the once in 50-year design wind speed used in structural loading calculations. Given that buildings might stand for to 100 years then it could be argued that structural building codes will need to review the design wind speeds and frequency of events to factor in safety margins in response to future climate change. Roofs suffer the greatest amount of destruction in high winds, mainly due to a failure to tie the roof securely to its supporting walls or supports. Low pitch roofs are very susceptible to wind damage and a better choice might be a mansard roof, which has two slopes on each side, with the lower slope being almost vertical and the upper slope being almost horizontal. Other design features, such as buildings having a more aerodynamic form or minimum roof overhangs, may appear beneficial but would need to be tested to ensure that other problems are not created – for example, small overhangs might exacerbate flooding problems.

Climate change and subsidence

Impacts

Paradoxically, under predicted climate change scenarios some regions of the world may be concerned with increased flood risk while others will be suffering from very dry seasons, water shortages and the risk of soils drying out. Reduced soil moisture levels have impacts on agriculture, flood control and buildings, where subsidence damage will become an increasing problem. Over the past two decades, Europe has seen a marked increase in damage to buildings as a result of soil movements. A new loss model developed by Swiss Re and the Swiss Federal Institute of Technology (ETH Zurich) shows that in France alone, economic losses from soil subsidence have risen by over 50% since 1990 (Swiss Re, 2011).

Responses

Subsidence is already a significant cause of building damage and climate change is only likely to make things worse. Figure 3.9.5 shows the cost and scale of subsidence claims in the UK for a twenty-year period and the relationship with summer rainfall.

For existing buildings, it is not viable to underpin original foundations in a way that will make them climate change resilient, and so the incidence of subsidence damage to buildings will increase during the coming decades. To make new and future buildings climate change resilient it will be necessary to change the design of foundations to make them stronger, stiffer and deeper in order to resist movement. New

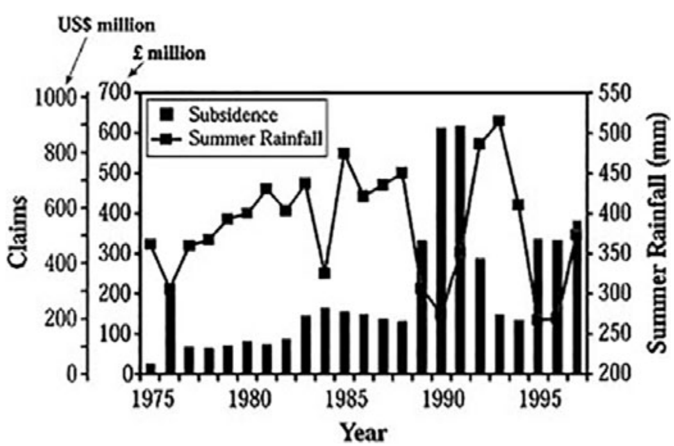

Figure 3.9.5 Relationship between rainfall and subsidence.

Source: IPCC, 2001

foundation technologies, such as pile-and-beam foundations, are described in an NHBC publication (NHBC, 2007), which also highlights the importance of careful tree planting management to avoid soil shrinkage and foundation damage by roots.

Conclusion

The mechanical servicing of buildings is a relatively recent phenomenon, with its origins only beginning at the start of the twentieth century. For thousands of years before then buildings had to modify the prevailing climate using only passive or low energy systems. It is not surprising that many of the building design issues relating to climate change resonate with elements found in the vernacular architecture and urban layouts of other countries. Features such as courtyards, wind catchers, narrow streets, green roofs, water features and houses raised on stilts all reflect a response to the contemporary local climate. It is too simplistic to say that since temperatures in London may one day resemble those already existing in, say, Lisbon then a linear design extrapolation can be implemented. The most obvious climatic difference is the different range of solar altitudes resulting from differences in latitude, but there are also cultural and historical traditions to respect. However, it is also true that there are lessons relevant to climate change to be learnt from vernacular architecture as it offers an historical perspective on how, globally, built environments evolved to deal with the challenges of changing climates.

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Case Study 3A

VENTILATION AND INDOOR AIR QUALITY IN NATURALLY, MECHANICALLY AND HYBRID VENTILATED BUILDINGS IN THE URBAN ENVIRONMENT

Katerina Niachou, Mat Santamouris and Iro Livada

Air flow in the urban environment

Oke (1987) characterized the wind variation with height over cities by defining two specific sublayers, the so-called 'obstructed sublayer', or urban canopy sublayer, which extends from the ground surface up to the height of the buildings and the so-called 'free surface layer' which exists above the roof tops. The obstructed or urban canopy sublayer has its own flow field, driven and determined by the interaction with the local features. The urban wind field is complicated. Small differences in topography may cause irregular airflows. A very detailed discussion of the problem in the urban canopy layer is given by Landsberg (1981). In general, the wind speed in the canopy layer is seriously decreased compared to the undisturbed wind speed and its direction may be altered (Santamouris, 2001).

Also, the air flow patterns in common urban structural forms such as urban canyons have received much attention during the last years. Different air flow regimes (Figure 3A.1) can be observed in urban canyons, determined by building (L/H) and canyon (H/W) geometry, as well as, by the prevailing wind direction with respect to canyon long axis, namely perpendicular, parallel and oblique flow (Oke, 1988).

The knowledge of airflow characteristics in the urban canopy layer is of high significance for pedestrian comfort, air quality, pollutant dispersion and ventilation studies.

Hybrid ventilation systems

Ventilation can be achieved through natural or mechanical forces or its combination, namely in a hybrid or mixed-mode and it is considered as one of the most important parameters for building design.

Hybrid ventilation is

> a new ventilation concept that combines the best features of natural and mechanical ventilation at different times of the day or season of the year. It is a ventilation system where mechanical

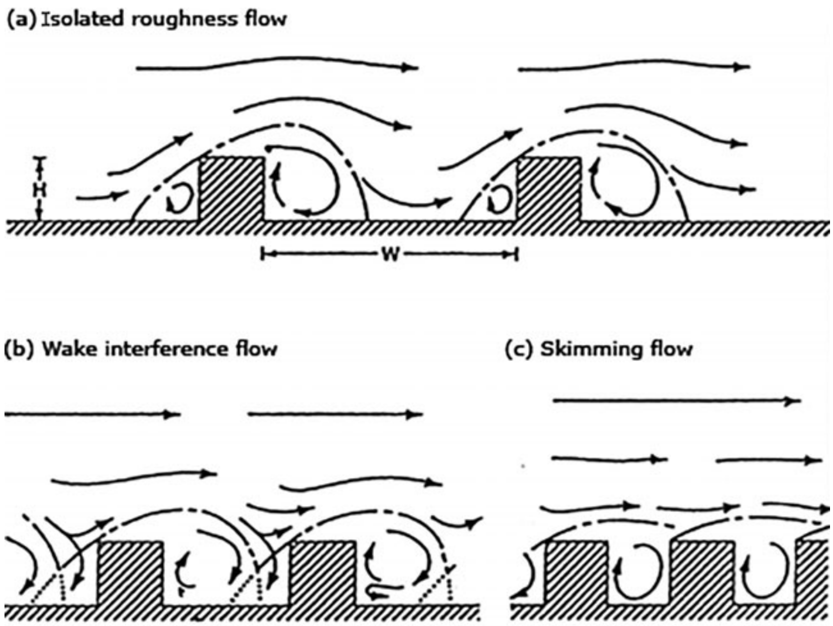

Figure 3A.1 The air flow regimes associated with perpendicular incident flow over buildings arrays of increasing H/W.

Source: Oke, 1987

> and natural forces are combined in a two-mode system. The operating mode varies according to the season and within individual days, thus the current mode reflects the external environment and takes maximum advantage of ambient conditions at any point in time.
>
> (Heiselberg, 2002)

Hybrid ventilation systems can be classified into three major categories: (i) Natural and mechanical ventilation, (ii) Mechanical assisted natural ventilation and (iii) Natural assisted mechanical ventilation.

The present chapter is emphasized on mechanical assisted natural ventilation where mechanical inlet/exhaust fans were used to enhance pressure differences when natural driving forces (wind effect and buoyancy forces) were insufficient.

Experimental indoor/outdoor air quality and ventilation studies in urban buildings

Despite the great number of experimental and theoretical studies on ventilation and indoor air quality, only a small number has been reported in real buildings in the urban environment. Measurements of indoor pollutants in urban buildings have been performed in offices (Bernhard, Kirshner, Knutti and Lagoudi, 1995; Lagoudi, Loizidou, Santamouris and Asimakopoulos, 1996a; Lagoudi, Loizidou and Asimakopoulos, 1996b), dwellings (Ilgen et al., 2001; Baya, Bakeas and Siskos, 2004; Edwards et al., 2005; Lai et al., 2006; Gadkari and Pervez, 2007), schools (Lee and Chang, 2000; Chaloulakou and Mavroidis, 2002), hospitals (Santamouris,Argiriou, Daskalaki, Balaras and Gaglia, 1994) and other public places (Lee, Chan and Chiu, 1999; Li, Lee and Chan, 2001). Furthermore, only a few experimental studies of indoor air quality have been conducted together with ventilation and outdoor air pollution measurements. The

Table 3A.1 Experimental indoor and outdoor air quality with simultaneous ventilation studies in urban buildings.

Type of buildings	*Region*	*Period*	*Pollutants*	*Ventilation system*	*References*
Three offices	London, UK	February and March 1990	CO_2, CO and NO_x	Natural	Phillips et al., 1993
Two offices	Birmingham, UK	February 1996 (one week)	CO_2, CO, SO_2 and NO_x	Natural, Mechanical	Kukadia and Palmer, 1998
Seven Residences	Birmingham, UK	August 1997 to July 1998	PM_1, $PM_{2.5}$ and PM_{10}	Natural	Jones, Thornton, Mark and Harrison, 2000
Ten offices and ten public places	Hong Kong	June 1998 to August of 2000	VOCs	Mechanical	Chao and Chan, 2001
Ten Residences	Hong Kong	Summer 1997	NO, NO_2, SO_2 and O_3	Natural, Mechanical	Chao, 2001
Office	Helsinki, Filand	January 1999	SO_2, NO_2, NO_x, O_3 and Particle size distribution	Mechanical	Koponen, Asmi, Keronen, Puhto and Kulmala, 2001
Residence	Paris, France	Winter and Summer 2000	CO, SO_2, NO, NO_2, O_3, VOCs, $PM_{2.5}$, black smoke	Natural, Mechanical	Collignan et al., 2001
Student office	Hong Kong	March to December 2001	RSP (Respirable Suspended Particulates) and NO_x	Mechanical	Chan, 2002
234 Residences	United States	1999 to 2001	Carbonyls (aldehydes and ketones)	Natural, Mechanical	Turpin et al., 2004; Weisel et al., 2005a, 2005b
Residence	Athens, Greece	24th and 30th June 2002 (2 days)	CO_2, NO_x, O_3, SO_2 and TVOC	Infiltration	Halios, Assimakopoulos, Helmis and Flocas, 2005
Eight schools	La Rochelle, France	Winter (one week) and spring or summer (one week)	NO, NO_2 and PM (0.3μm to 20μm)	Natural, Mechanical	Blondeau, Iordache, Poupard, Genin and Allard, 2005; Poupard, Blondeau, Iordache and Allard, 2005
Three offices One residence	Denmark, Sweden	2002 (2-6 days in each building)	UFP (Ultra Fine Particles)	Mechanical	Matson, 2005

latest experimental indoor and outdoor air quality with simultaneous ventilation studies in urban buildings are summarized in Table 3A.1.

The experimental procedures which will be described in this chapter were undertaken under the European research program RESHYVENT (2004) and consisted of field and indoor measurements in three residential apartments in Athens, Greece, during July–September 2002. Field experiments included air and surface temperature, wind speed and wind direction measurements which were carried out inside two street canyons and above building roofs. The understanding and interpretation of the complex mechanisms of airflow around buildings is determinant for the exact description of the boundary conditions which constitutes a prerequisite for further investigation of the performance of natural and hybrid ventilation systems in the urban environment. Thereupon, certain emphasis was given on the analysis of thermal and airflow characteristics inside the two urban canyons and very interesting observations have been resulted (Niachou, Livada and Santamouris, 2007a, 2007b). At the same time, air temperature, ventilation and indoor air quality measurements were measured in the interior of buildings.

A full comparison analysis will be presented taking into account ventilation and indoor air quality measurements in naturally, mechanically and hybrid ventilation systems. Indoor air quality is examined in relation with a number of decisive parameters such as: (i) air exchange rates, (ii) outdoor pollutant concentrations and (iii) indoor pollutant sources mainly as a result of human activities.

Measurements and instrumentation

The indoor experimental procedures were carried out on a 24-hour basis during three measurement periods, consisting of five consecutive days in each apartment. The two street canyons were characterized by different geometry and orientation and they were adjacent to high circulation roads. The major characteristics of the studied apartments and street canyons are summarized in Table 3A.2.

The first apartment (A_1) was placed on the south façade of the first canyon, while the other two apartments (A_2 and A_3) were on the opposite building façades of the second canyon. Natural ventilation was provided through open windows from canyon or rear canyon façades. The main difference between the third apartment (A_3) and the other two (A_1 and A_2) is that external openings were on the same side of the street and there was practically no natural cross ventilation. Besides, windless conditions or calms were measured during the third experimental period outside A_3 apartment. During the measurements periods, all apartments were occupied and the total number of occupants ranged from two to six, including also smokers.

A total number of 114 ventilation – consisting of infiltration, natural, mechanical and hybrid ventilation – and indoor air quality experiments were conducted. The single tracer gas (N2O) decay method was applied at the first apartment (A_1) and the multi-tracer gas decay method with two tracer gases, N_2O and SF6 was performed in other two apartments (A_2 and A_3). The multi-tracer gas acquisition system of Bruel and Kjaer was used consisting of a photoacoustic multi-gas monitor, a multipoint sampler and doser unit and a controlling computer. The multi-gas monitor measurement principle is based on the photo acoustic infrared detection method. Except for the two tracer gases (N_2O and SF_6), the multi-tracer gas acquisition system measured also carbon dioxide (CO_2) and total volatile organic compounds [TVOC (ref. toluene)] concentrations inside and outside the ventilated spaces adjacent to external openings. Mixing fans were used to establish a uniform tracer gas concentration during the injection phase within the ventilated spaces. In all experiments the minimum sampling period from one channel to the next one was one minute, while a total number of five measuring nozzles were appended inside each building apartment and one

Table 3A.2 Characteristics of studied apartments and street canyons.

Apartment	*Area (m^2)*	*Effective Volume (m^3)*	*Canyon*	*Orientation from North*	*H/W*	*L/W*
A_1	65	112	Ragavi	100°	1.7	3.8
A_2	78	130	Ag. Fanouriou	137°	2.6	9.5
A_3	50	120				

outside adjacent to external openings. Besides, the ventilation instrumentation consisted of two T-series window fans appended vertically on wooden patents attached at the position of external openings adjacent to canyon façades. The mechanical fans were reversible operating either in inlet or exhaust mode and they were characterized by a maximum performance of 730m^3/h with a reduction of 15.8m^3/h for 1Pa pressure loss.

Natural ventilation consisted of single-sided and cross ventilation experiments. In single-sided ventilation, one or two external openings were considered from the same building façade. Cross ventilation experiments were performed within two or more external openings placed on canyon and rear canyon walls. Mechanical ventilation was studied with one or two inlet/exhaust fans. In case of hybrid ventilation, a number of sixteen fan-assisted natural ventilation configurations (Figure 3A.2) were investigated, where mechanical fan assistance was applied to enhance pressure differences across building façades.

Results and discussion

Ventilation experiments

The theoretical analysis was focused on the estimation of air-exchange rates based on multizone methods with one and two tracer gases (Niachou, Hassid, Santamouris and Livada, 2005). The estimated air-exchange rates under different ambient weather conditions are illustrated with the form of boxplots in Figure 3A.3. Besides, the mean air-exchange rates for each ventilation system in the three studied apartments are summarized in Table 3A.3.

Natural cross ventilation was proven very effective even for low wind speeds inside the two urban canyons. It was found that the 95% of the total measured wind speeds adjacent to external openings were lower than 1.5m/s and the corresponding air temperature differences inside and outside buildings were lower than 6°C. In case of natural cross ventilation with two or more windows, then the estimated air-exchange rates have a mean value ranging from 11h^{-1} to 15h^{-1} (Table 3A.3). Even under calms (wind speed lower than 0.2m/s) natural cross or single sided ventilation was not eliminated, since

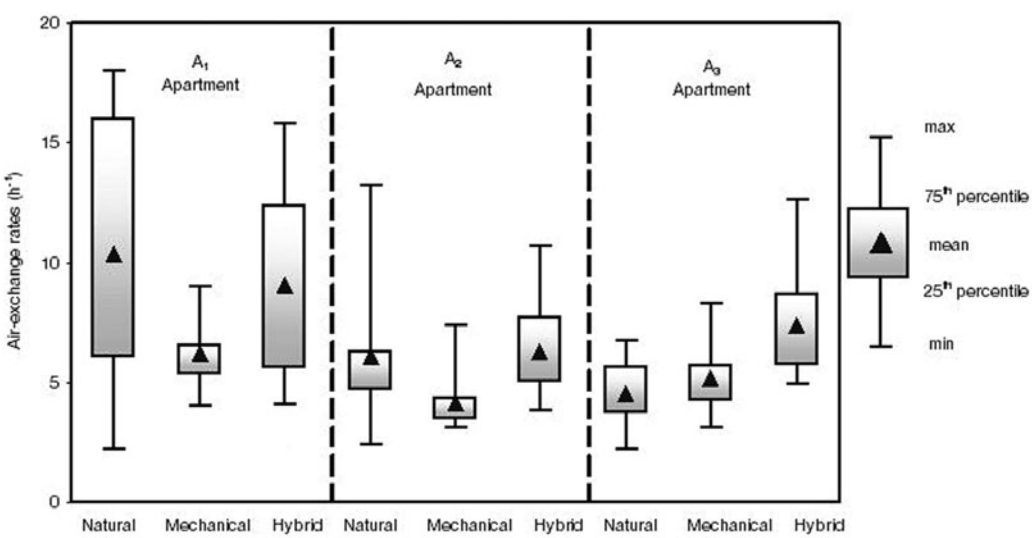

Figure 3A.2 Estimated air-exchange rates (h^{-1}) for natural, mechanical and hybrid ventilation systems in the three residential apartments (A_1, A_2 and A_3) under different ambient conditions.

Table 3A.3 Estimated mean air-exchange rates [N1(h^{-1}), N2(h^{-1}) and N3(h^{-1})] for the total number of ventilation experiments (No) in the three residential apartments (A_1, A_2 and A_3).

Ventilation	*Description*	*No*	*N1 (h^{-1})*	*N2 (h^{-1})*	*N3 (h^{-1})*
Natural	Infiltration	3	0.3	0.3	0.5
	Single-sided with one window	14	3.1	4.5	4.2
	Single-sided with two windows	5	–	–	5.2
	Cross ventilation with two windows	7	15.2	9.8	–
	Cross ventilation with more than two windows	4	11.0	–	–
Mechanical	One supply/exhaust fan	15	5.7	3.8	4.9
	Two supply/exhaust fans	19	6.6	4.5	5.4
Hybrid	One supply/exhaust fan and natural ventilation with one window	31	7.4	5.6	7.4
	One supply/exhaust fan and natural ventilation with more than one windows	8	13.2	5.9	–
	Two supply/exhaust fans and natural ventilation with one window	6	–	6.3	–
	Two supply/exhaust fans and natural ventilation with more than one windows	2	15.4	–	–

the air temperature differences between inside and outside the ventilated spaces compensated for the reduced wind effect.

In natural ventilation a wider range of airflow rates exist because of the variability of natural driving forces. However, the existing variability of natural ventilation rates is greater in A_1 experiment (Figure 3A.3) in comparison with the other two (A_2 and A_3), due to the variation of outdoor conditions and the implementation of cross ventilation experiments between more than two windows.

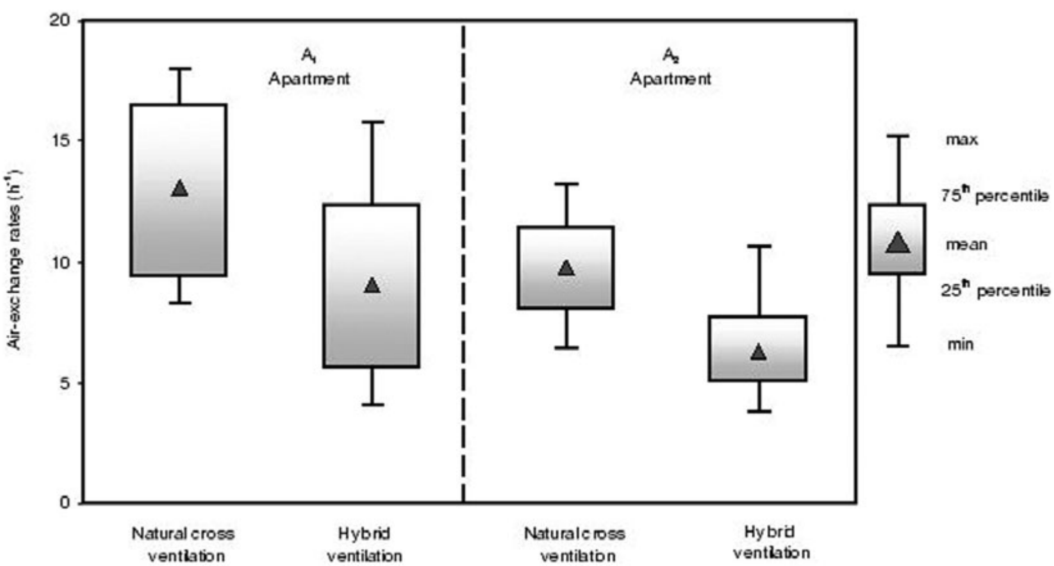

Figure 3A.3 Estimated air-exchange rates (h^{-1}) for natural cross and hybrid ventilation systems in A_1 and A_2 apartments.

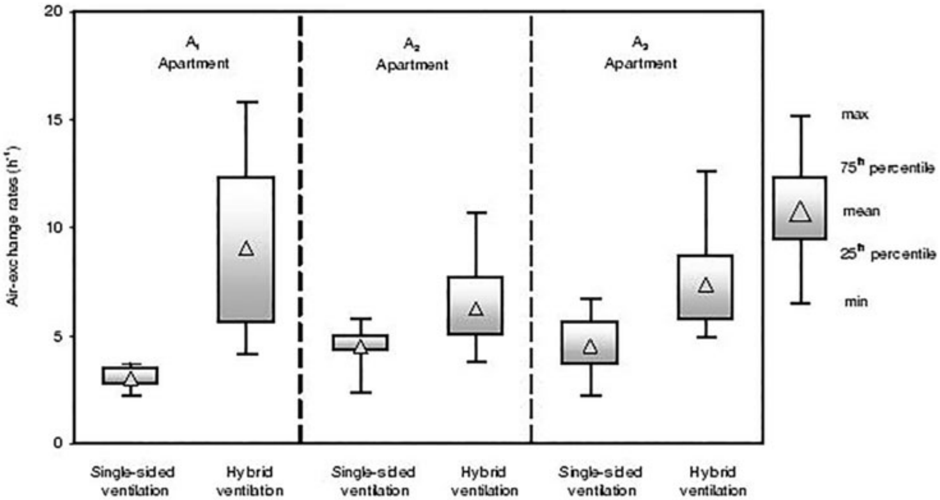

Figure 3A.4 Estimated air-exchange rates (h^{-1}) for single-sided and hybrid ventilation systems in the three apartments (A_1, A_2 and A_3).

Contrary to natural ventilation, mechanical ventilation was characterized by almost constant airflow rates, irrespectively of ambient weather conditions. Higher ventilation rates were measured in A_1 experiment probably, because the volume of the apartment was smaller. The observed variability in mechanical ventilation experiments (Figure 3A.3) is mainly attributed to different combinations of one or two inlet/exhaust fans.

Hybrid ventilation has been shown to be associated with rather lower air-exchange rates than natural cross-ventilation (Figure 3A.4), but relatively higher values in comparison with single-sided ventilation (Figure 3A.5), especially under calms. In general, air-exchanges in hybrid ventilation presented a smaller variability than in natural but greater than in mechanical. The mean air-exchange rates range from $6h^{-1}$ to $15h^{-1}$ according to the position of inlet/exhaust fans and external openings (Table 3A.3).

The main result is that under conditions ventilation experiments were performed, where all internal doors were open, there is little advantage to be gained in those apartments by using hybrid in place of natural ventilation.

It should also be stated that apart from the comparison of the estimated air-exchange rates, there was a qualitative difference between natural and hybrid ventilation. The thermal comfort was completely different and the feel when someone was exposed to airflow during natural ventilation was much better than those in rooms where airflow was assisted by mechanical fans.

Of course, this is not to assert that hybrid ventilation has little use. There is definitely an advantage of hybrid ventilation when one is forced to have doors closed in an apartment and thus, making natural ventilation much less effective. Besides, there is also an advantage when one needs hybrid ventilation to vent a closed space (kitchen or bathroom) where natural ventilation may be insufficient or when there are flows in the wrong direction.

Indoor air quality experiments

For the study of indoor air quality, the mean weighted average pollutant concentrations $C_{in}(t)$ were estimated inside the ventilated spaces based on the mean zone concentrations, $C_i(t)$, where weighting functions are determined by the effective volume of each zone:

$$C_{\text{in}}(t) = \frac{\sum_{i=1}^{K} V_i C_i(t)}{V_{\text{tot}}} \qquad 3A.1$$

where

$C_i(t)$ = mean pollutant concentration in zone i (ppm),
V_i = effective volume of zone i (m^3),
V_{tot} = total effective volume of each ventilated space (m^3), and
K = number of zones in each ventilated space.

Then, the mean instant concentrations $C_{\text{in}}(t)$ were averaged for the time period from $t_0 = 0$ to $t_1 = e$, which corresponds to the tracer gas decay period during the ventilation experiments:

$$C_{\text{in}} = \frac{\int_0^e C_{\text{in}}(t)\, dt}{e - 0} \qquad 3A.2$$

Besides, for the same time period the mean outdoor concentrations, C_{out}, were estimated outside the ventilated spaces:

$$C_{\text{out}} = \frac{\int_0^e C_{\text{out}}(t)\, dt}{e - 0} \qquad 3A.3$$

where

$C_{\text{out}}(t)$ = pollutant concentration (ppm) outside each ventilated space at time t.

CO_2 measurements

CO_2 can be considered as a surrogate for other occupant-generated pollutants, particularly bioeffluents and for ventilation rate per occupant, but not as a causal factor in human health responses (Apte and Erdmann, 2002). The primary source of CO_2 in buildings is respiration of building occupants. The threshold limit value for 8-hour time-weighted-average exposure to CO_2 is 5000ppm (ACGIH, 1991). In ANSI/ASHRAE Standard 62.1–2004, it is stated that CO_2 monitoring is a method of determining occupant variability. In case no national regulation is available, the European Standard prENrev 15251:2006 (CEN, 2006) indicates recommended CO_2 concentrations for different categories of indoor environments in residential and non-residential buildings. These values vary from 350ppm up to 800ppm above outdoor concentrations accordingly for high and acceptable or moderate level of expectation in new and existing buildings.

Figure 3A.6 depicts the cumulative frequency distributions of the absolute maximum indoor CO_2 concentrations in the three residential apartments (A_1, A_2 and A_3) during the ventilation experiments.

As shown the absolute maximum CO_2 concentrations didn't exceed 1600ppm, while the existence of concentrations above 800ppm was observed locally in rooms with more than two occupants including also smokers and where fresh air was not efficiently distributed. The threshold value of 800ppm was defined as an indicator of high level of expectation indoors since it is 350ppm above maximum ambient CO_2 concentrations which were always lower than 450ppm.

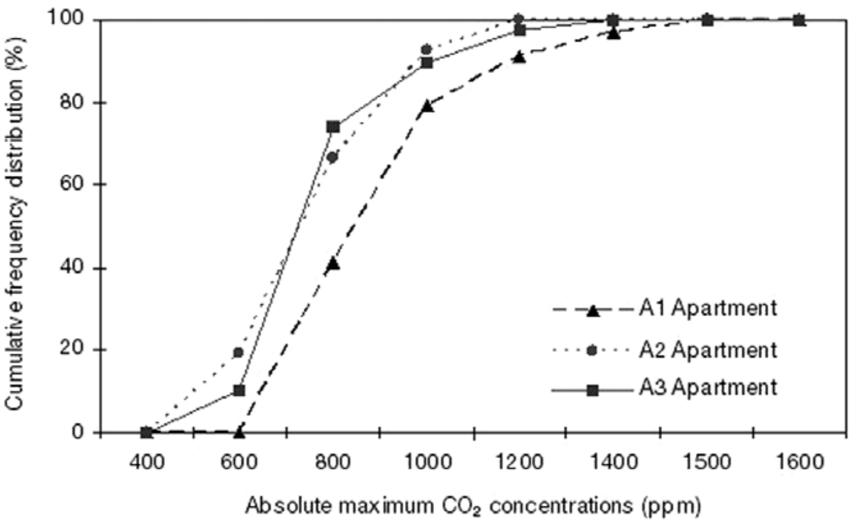

Figure 3A.5 Cumulative frequency distribution of the absolute maximum indoor CO_2 concentrations in the three residential apartments.

TVOC measurements

TVOC may be used for a number of applications, namely testing of materials, indication of insufficient or poorly designed ventilation in a building and identification of high polluting activities (ECA-IAQ, 1997b). Although there are not standards for indoor TVOC upper limits, Molhave (1990) has suggested four exposure ranges of TVOC (ref. toluene): a comfort range (< 0.2mg/m^3), a multifactorial exposure range (0.2–3mg/m^3), a discomfort range (3–25mg/m^3) and a toxic range (> 25mg/m^3).

Figure 3A.7 shows the cumulative frequency distributions of the absolute maximum indoor TVOC concentrations measured during ventilation experiments inside the ventilated spaces.

Maximum indoor TVOC concentrations exceeding 0.8ppm (or 3mg/m^3), where discomfort may be induced, resulted from human activities related with tobacco smoking and the use of paints, since the corresponding outdoor TVOC concentrations did not exceed 0.3ppm. In particular in A_2 apartment during some hybrid ventilation experiments where an areaway was open, the maximum TVOC indoor concentrations were higher up to 12 times in comparison with ambient concentrations due to renovation of an apartment inside the building (paints, glues, coatings).

With regard to TVOC emission rates, the mass balance equation was applied considering a steady-state analysis for periods of relatively constant TVOC concentrations when the only active sources were those associated with building materials and furnishings, based on the methodology described by Persily et al. (2003). The estimated mean emission rates in the three ventilated spaces ranged from 1.7 to 3.8mgm^{-2}h^{-1}, as a result of different furniture and environmental conditions. These values are in agreement with emission rates reported by Gustafsson and Jonsson (1993) and ECA-IAQ (1997a). However, a statistically significant variation of TVOC emission rates with air temperature was observed in each ventilated space. The extended analysis and the corresponding results were presented in detail by Niachou (2007).

Indoor–outdoor air quality relationships

In order to investigate the effect of outdoor pollutant levels on indoor air quality, the correlation between the mean indoor and outdoor CO^2 and TVOC concentrations was studied in the three apartments (A_1, A_2 and A_3).

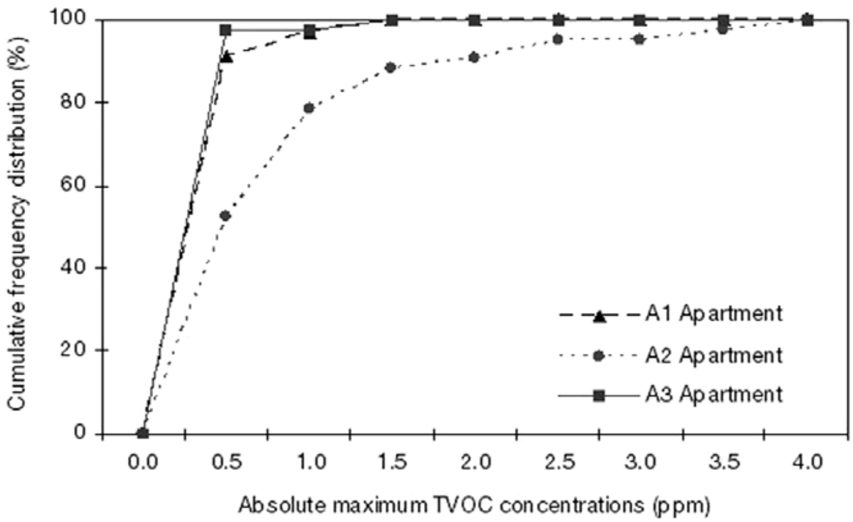

Figure 3A.6 Cumulative frequency distribution of the absolute maximum indoor TVOC concentrations in the three residential apartments.

As shown in Figure 3A.8, a statistical significant correlation described by an exponential formula was observed between the mean indoor and outdoor TVOC concentrations. However, the lowest correlation coefficient R was observed in A_2 apartment due to the strong impact of indoor emission sources related with human activities. TVOC concentrations above 0.3ppm were observed during tobacco smoking, while concentrations exceeding 0.8ppm were associated with the use of paints.

As expected, no correlation was found between the mean CO_2 concentrations inside and outside the ventilated spaces, since indoor CO_2 levels are substantially affected by human presence.

Influence of ventilation on indoor/outdoor pollutant ratios

From the study of the impact of the measured air-exchange rates on indoor–outdoor mean CO_2 concentration ratios, it was found that when air-exchange rates increased then the mean values of CO_2 ratios decreased. This is depicted in Figure 3A.9 where the measured CO_2 concentration ratios (C_{in}/C_{out}) are illustrated with the form of boxplots. The total number of air-exchange rates in natural, hybrid and mechanical experiments under different outdoor conditions have been classified in three categories (0–4h^{-1}, 4–8h^{-1}, >8h^{-1}). Outliers are extreme values out of the confidence interval of 95% (Zar, 1999).

However, when the impact of indoor emission sources on pollutant concentrations became significant, then the influence of ventilation was weaker. This was mainly observed with TVOC and as it is shown in Figure 3A.10 the increase of air-exchange rates did not always result in lower indoor-outdoor concentration ratios (C_{in}/C_{out}). As mentioned above, maximum indoor TVOC concentrations were, up to twelve times, higher than the outdoor concentrations but they are not depicted in order not to reduce the distinctness of the illustrated boxplots.

Thus, the control and minimization of indoor sources is essential in order to achieve the optimum indoor air quality conditions with the minimum design airflow rates.

Table 3A.4 presents the mean indoor/outdoor CO_2 and TVOC concentration ratios (C_{in}/C_{out}) in the three studied apartments for each ventilation system. In general, when human activities related with smoking and the use of paints were absent (unlike those values marked with bold in Table 3A.4), then

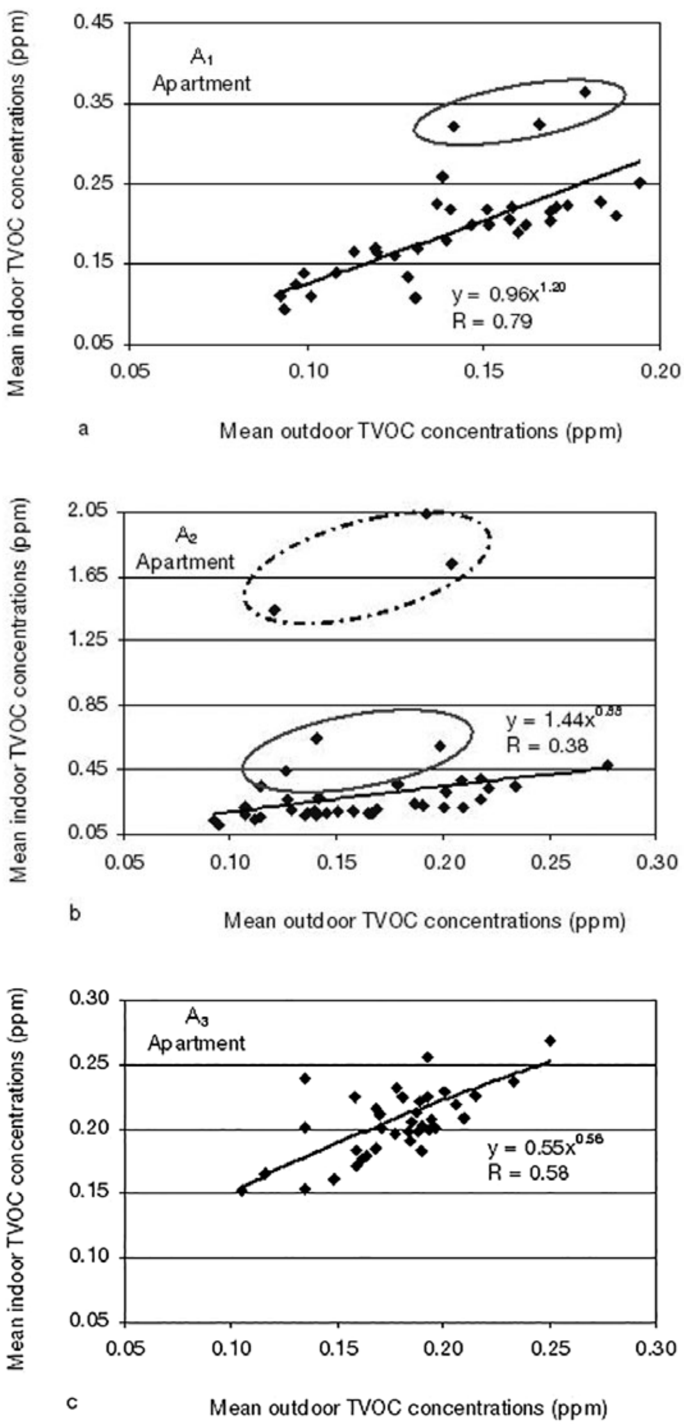

Figure 3A.7 Correlation between the mean indoor and outdoor TVOC concentrations during ventilation experiments in the three studied apartments (A_1, A_2 and A_3).

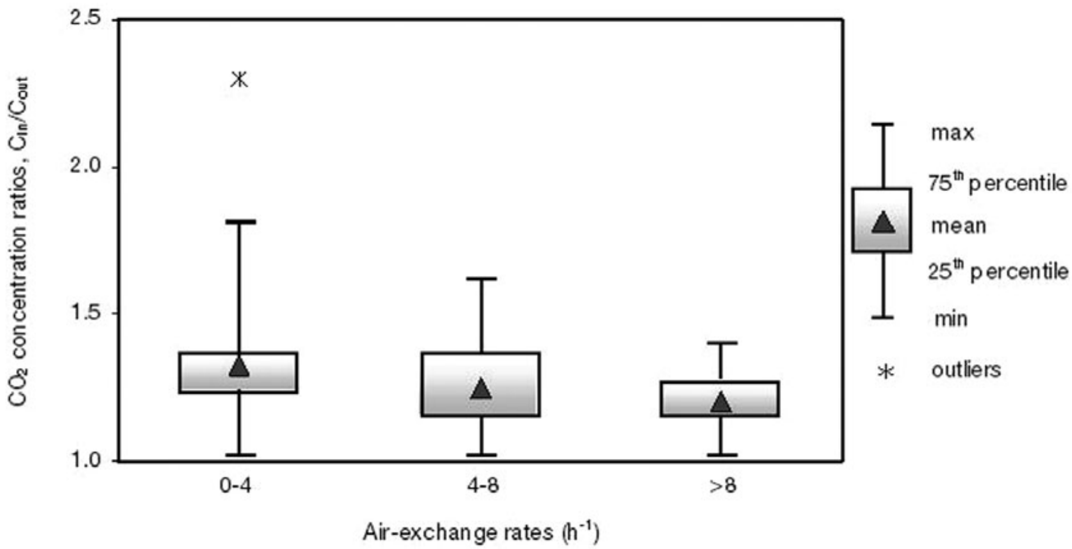

Figure 3A.8 Impact of air-exchange rates (h^{-1}) on indoor/outdoor CO_2 concentration ratios (C_{in}/C_{out}) during ventilation experiments in the three residential apartments.

the highest concentration ratios were observed during infiltration and single-sided ventilation and the lowest in hybrid and cross ventilation experiments. This is attributed on one hand to the higher measured air-exchange rates during cross ventilation and hybrid ventilation experiments and on the other hand to the better mixing of air between the different zones inside the ventilated spaces (Niachou, Hassid, Santamouris and Livada, 2007d).

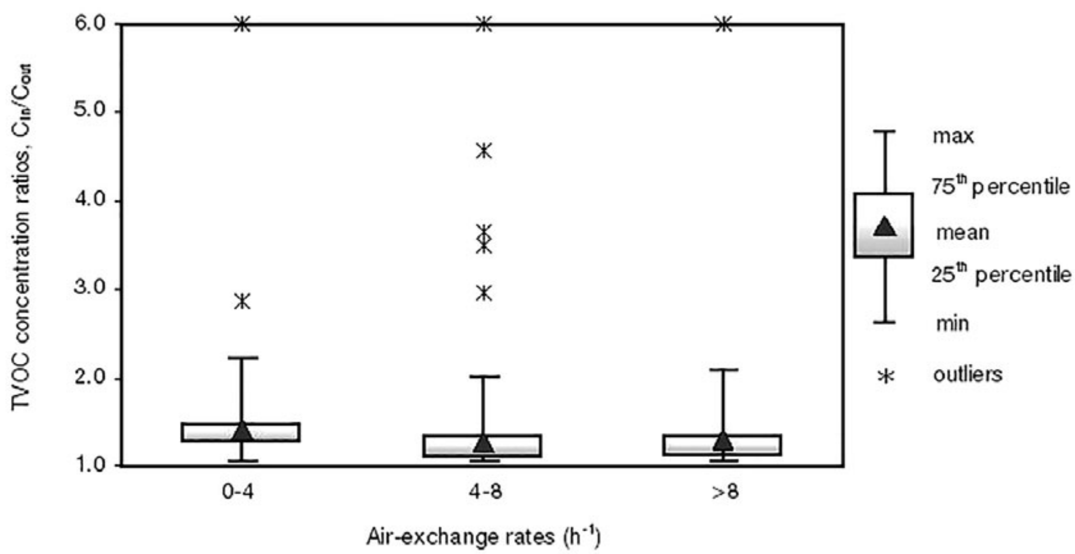

Figure 3A.9 Impact of air-exchange rates (h^{-1}) on indoor/outdoor TVOC concentration ratios (C_{in}/C_{out}) during ventilation experiments in the three residential apartments.

Table 3A.4 Estimated mean indoor/outdoor CO_2 and TVOC concentration ratios $[(C_{in}/C_{out})_1$, $(C_{in}/C_{out})_2$ and $(C_{in}/C_{out})_3]$ during ventilation experiments (No) in the three studied apartments (A_1, A_2 and A_3).

Ventilation	*Description*	*No*	*CO_2*			*TVOC*		
			$(C_{in}/C_{out})_1$	$(C_{in}/C_{out})_2$	$C_{in}/C_{out})_3$	$(C_{in}/C_{out})_1$	$(C_{in}/C_{out})_2$	$C_{in}/C_{out})_3$
Natural	Infiltration	3	2.3	1.3	1.2	2.0	1.5	1.5
	Single-sided with one window	14	1.8	1.3	1.4	1.6	1.5	1.1
	Single-sided with two windows	5	–	–	1.3	–	–	1.2
	Cross ventilation with two windows	7	1.3	1.2	–	1.3	1.1	–
	Cross ventilation with more than two windows	4	1.2	–	–	1.3	–	–
Mechanical	One supply/exhaust fan	15	1.5	1.5	1.2	1.5	1.4	1.2
	Two supply/exhaust fans	19	1.3	1.1	1.1	1.3	**4.8**	1.2
Hybrid	One supply/exhaust fan and natural ventilation with one window	31	1.4	1.3	1.1	1.4	1.5	1.2
	One supply/exhaust fan and natural ventilation with more than one windows	8	1.2	1.1	–	1.0	**2.5**	–
	Two supply/exhaust fans and natural ventilation with one window	6	1.4	1.2	–	1.5	**5.6**	–
	Two supply/exhaust fans and natural ventilation with more than one windows	2	1.2	–	–	1.3	–	–

Conclusions

A comparative monitoring analysis of different ventilation systems was carried out in three residential building apartments located in two urban street canyons. The ventilation performance of natural, mechanical and hybrid or fan-assisted natural ventilation systems was investigated together with indoor air quality under different ambient weather conditions.

The ventilation experiments pointed out that, in spite of the reduced wind speeds in urban canyons, appreciable ventilation rates can be obtained with natural cross ventilation. Even under low wind speeds or calms, natural cross or single-sided ventilation was not eliminated since the temperature differences inside and outside the ventilated spaces compensated for the reduced wind effect. This could be an advantage for night ventilation during summer period or for natural ventilation during transient periods. Hybrid ventilation has been shown to be associated with rather lower air-exchange rates than natural cross-ventilation but higher air-exchange rates than single-sided ventilation especially in windless conditions.

Indoor air quality has been studied as a result of air-exchange rates, outdoor pollutant concentrations and indoor pollutant emissions mainly due to the human activities. A statistically significant correlation was found between the mean indoor and outdoor TVOC concentrations. However, the maximum indoor TVOC concentrations (greater than 0.8ppm) were associated with tobacco smoking and the use of paints. Besides, the presence of maximum CO_2 values (more than 800ppm) was related with increased occupancy and smoking.

As a result, source control to diminish pollution load in indoor environments will improve health and comfort. Besides, since indoor pollution constitutes unambiguously a major problem, before thinking of increasing ventilation rates, it is prerequisite to reduce indoor emission sources and thus improving energy efficiency.

The knowledge and comprehension of mass transfer mechanisms in urban buildings is of great importance for the appropriate design of natural and hybrid ventilation systems so as to accomplish the optimum indoor air quality and thermal comfort conditions and besides to succeed in energy savings mainly for cooling reasons.

Acknowledgements

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Case Study 3B
INDOOR AIR QUALITY AND HEALTH

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Introduction: House dust mites, housing and health

House dust mites can be found in beds, carpets and soft furnishings. They primarily feed on human skin scales and are normally invisible to the naked eye due to their size (less than 1mm) and their translucency. Since HDM thrive in warm and humid environments, their infestations are linked to climatic characteristics and indoor conditions. Exposure to HDM allergens can lead to allergic sensitization and to exacerbation of rhinitis, eczema and asthma symptoms. Noticeable differences have been found in the prevalences of allergic sensitization and asthma symptoms worldwide, with the UK having some of the highest values (ISAAC Steering Committee, 1998). Several epidemiological studies have reported an increase in the occurrence of allergies and asthma over the past 30–40 years, particularly in affluent countries. Some authors even refer to an "epidemic" of allergy and asthma (Holgate, 2004), although there is some evidence that this "epidemic" may have reached a plateau in certain countries, including the UK (Anderson et al., 2004). Some authors have also stated that the rise in asthma levels in Westernized countries may be due to recent changes in the building stock, whereby energy efficiency concerns may have contributed to excessively low ventilation rates in housing, resulting in favourable conditions for HDM infestations because of high moisture levels (Howieson, Lawson, McSharry, Morris, McKenzie and Jackson, 2003). However, most existing data is inadequate for definitive conclusions to be drawn on whether low ventilation rates directly cause ill-health (Davies et al., 2004). Although it is unlikely that increased exposure to perennial allergens (such as dust mite allergens) is the sole cause of the allergy and asthma "epidemic", these allergens do play a role in explaining, for example, the worldwide variations in allergies and asthma – which partly reflect differences in exposure to HDM allergens due to geographic variations in climatic conditions.

The term house dust mite (HDM) refers to the mite family *Pyroglyphidae*, of which the 3 species most commonly found in house dust are: *Dermatophagoides pteronyssinus* (DP), *Dermatophagoides farinae* (DF) and *Euroglyphus maynei* (EM). Two major groups of HDM allergens from the genus *Dermatophagoides* have been identified, referred to as group I allergens (called Der p1 for the species DP, Der f1 for the species DF), and group II allergens (called Der p2 for the species DP, Der f2 for the species DF). Both allergens are digestive enzymes excreted in mite faecal pellets which easily become airborne and are the right size to be inhaled deep into the lungs.

House dust mites rarely encounter water in liquid form but are able to absorb moisture from the air. If the ambient RH is too low, mites dehydrate and eventually die. The critical RH low below which mites die is often referred to as the *Critical Equilibrium Humidity* (CEH). For DF, the most common species in the USA, CEH is temperature-dependent (Arlian and Veselica, 1981). Some evidence exists that a similar temperature-dependence of CEH also occurs for DP, the most common species in the UK (Crowther, Wilkinson, Biddulph, Oreszczyn, Pretlove and Ridley, 2006). Temperature also affects HDM egg-to-adult development times (i.e. lower temperatures giving rise to longer development times). Thus, by adequately controlling the hygrothermal conditions of mite microclimates, it should be possible to reduce mite populations (i.e. psychrometric control). Because of the dependency of mite populations on hygrothermal conditions, their growth in temperate climates is usually greater in late summer/early autumn, and winter months are crucial for reducing mite populations (Crowther et al., 2006). If outdoor winter air – with its low moisture content – is sufficiently heated in housing, the resultant indoor RH will be too low for mite population growth, which will thus decline. If these dry conditions can be maintained over winter, the mite population will be reduced to such an extent that it will not recover significantly during the more favourable late summer to autumn months.

HDM can survive when exposed to brief spells of high RH, even when the daily average RH is below critical levels. Nonetheless, the reduction of indoor RH is still a viable control method, as mite development rates are much slower when HDM are only exposed briefly to favourable RHs (Arlian, Neal and Vyszenski-Moher, 1999). For typical indoor temperatures, maintaining the average daily indoor RH below 50% is often recommended to reduce mite levels and their allergens. However, feasible threshold levels for temperature and RH in housing are still being discussed. Taking into account the temperature dependency of CEH, Cunningham suggested that relative humidity should be kept under 40% at 16°C, 45% at 21°C and 50% at 26°C (Cunningham, 1996). Using Cunningham's figures, Lowe pointed out the important role of ventilation rates and also demonstrated that in UK dwellings – which are often under-heated – HDM psychrometric control can only be achieved if internal temperatures are raised significantly (Lowe, 2000).

Most studies on the psychrometric control of house dust mites in housing have focused on mechanical ventilation. However, there is some scope for modifying residential hygrothermal conditions by changing the occupants' heating and ventilation habits. For example, a well-designed extractor fan can remove up to 70% of moisture generated during cooking (Liddament, 2001). Also, a UK study found that the presence of an extractor fan in the kitchen was associated with lower HDM allergen concentrations (Luczynska, Sterne, Bond, Azima and Burney, 1998). Furthermore, a large-scale study concluded that mite allergen exposure may be reduced by increasing the ventilation of the bedroom, particularly in winter (Zock et al., 2006). Nevertheless, very few intervention studies have been carried out attempting to reduce HDM levels through the modification of occupant behaviour alone. Compared with methods acting on the building fabric or on heating and ventilation systems, behavioural changes can be inexpensive and implemented in shorter time-scales.

Many strategies other than the psychrometric method are available for the control of HDM populations and/or allergens, including: high-efficiency vacuuming, steam cleaning, mite-proof barriers and acaricides. However, most of these strategies can be time-consuming, while the psychrometric approach could be "built-into" housing design or refurbishment, potentially reducing asthma symptoms and even preventing allergic sensitization. But it should be emphasized that psychrometric measures for the control of house dust mites do not remove any existing allergen reservoirs, which can be long-lasting. Therefore, in any study aiming to reduce adverse health impacts, any pre-existing HDM allergens have to be removed. On the other hand, most allergen removal strategies (e.g. steam-cleaning) are time-consuming, cannot be applied to all possible dust reservoirs and they need to be repeated over time. This is because if hygrothermal conditions continue to be favourable to mite growth, allergen levels will be replenished after some time. Psychrometric control methods should therefore accompany allergen removal measures (and vice-versa), since they potentially strengthen and extend their effects.

There is still conflicting evidence as to whether any mite control strategies can permanently reduce mite infestation to a level sufficient for health benefits (Gøtzsche, Johansen, Schmidt and Burr, 2006).

However, many studies on the clinical efficacy of HDM allergen avoidance measures have focused on the impact of one intervention type at a time, but there is growing consensus that a combination of strategies is probably the most effective approach.

This chapter describes a pilot intervention study on house dust mite allergen avoidance for twelve asthmatic children (two being controls). The study adopted a holistic approach, with a number of measures for allergen (pet and mite) removal and avoidance, including tailored advice aimed at reducing mite population growth via changes in moisture production, heating and ventilation habits. The study addressed four issues:

1 the effect of allergen removal on the children's health;
2 the effect of tailored advice on occupant behaviour and the resultant hygrothermal conditions;
3 the effect of the hygrothermal changes on mite populations;
4 the efficacy of monitoring/modelling techniques.

The study was filmed by *Twenty Twenty Television* and resulted in two 50-minute episodes of the UK TV series 'Dispatches' on Channel 4 (April 2006). Due to its short time-scale and small sample size, the study did not aim to establish the clinical efficacy of allergen avoidance, but to illustrate its potential benefits and to give researchers the opportunity to test a protocol for a larger future study. In this chapter, the study is described with a view to demonstrate the complexities associated with housing, indoor air quality and health.

Study design and methodology

In October 2005 twelve asthmatic mite-sensitive children aged 6 to 14 were selected in the London area; eleven dwellings were examined overall, since two of the children were siblings living in one dwelling (here termed bedroom/child 12a and 12b). The properties included: 4 flats, 1 detached house and 6 terrace houses. A pre-intervention analysis was carried out, where baseline measurements were taken of:

- the children's health status;
- HDM numbers and allergen levels in each dwelling (child bedroom: mattress, pillow, one soft toy and floor; living room: sofa and floor – all using a standard protocol);
- hygrothermal conditions (monitored for 2 weeks, logging every 15 minutes);
- building characteristics (including airtightness via a fan-pressurization test);
- heating and ventilation habits.

The fan-pressurization results at 50 Pa were converted to an estimated air-infiltration rate in air changes per hour under average external conditions. Prior to the interventions, the children's health status including history of asthma, eczema and rhinitis, skin prick testing and airway measurements was assessed by Dr Glenis Scadding, consultant physician at the Royal National Throat Nose & Ear Hospital. After the pre-intervention study, a number of interventions were carried out, followed by a post-intervention study, where the children's health and the dwellings' hygrothermal conditions were monitored for 6 weeks. The interventions carried out after the baseline measurements were:

- professional steam-cleaning of the child's bedroom and thorough cleaning of the dwelling (followed by further dust sampling);
- replacement of carpets in the child's bedroom with laminate flooring;
- covering mattresses, pillows and duvets with micro-porous mite-proof barriers;

- removing pets and cuddly toys; and
- avoiding exposure to environmental tobacco smoke.
- The participants were also advised to implement a thorough cleaning regime throughout the post-intervention period.

Following the analysis of the pre-intervention study results, tailored advice was also provided on moisture production, heating and ventilation. Outdoor hygrothermal conditions were also monitored throughout the study. For the two households acting as controls, the interventions were carried out at the end of the post-intervention period, but their dwelling's hygrothermal conditions were monitored throughout the study. At the end of the study, further dust samples were taken, and a final medical examination was carried out.

Study results

Table 3B.1 shows the baseline results from the pre-intervention study, including the dust sampling findings. Since little dust was found in toys and pillows, the allergen results were not only expressed as allergen concentrations, but also as 'allergen loads', i.e. total allergen weight collected for a given vacuumed area, corresponding to μg Der p1/m^2 (μg Der p1/total object area, for pillows and toys). The pre-intervention results included baseline indoor and outdoor hygrothermal conditions, from which the Vapour Pressure Excess (VPX) (kPa) was calculated as the difference between indoor and outdoor vapour pressures. A dwelling's VPX is the result of the combination of ventilation rates and of the moisture

Table 3B.1 Baseline measurements for building characteristics, hygrothermal conditions and mite infestation levels.

Dwelling	*$^{\theta}$Moisture Product. (kg/day)*	*Volume (m^3)*	*$^{\Delta}$Air Infiltr. (ach^{-1})*	**Mites (mites/ m^2)*	**Der p1 Conc. (μg/g)*	**Der p1 Load (μg/m_2)*	*#Pre, VPX (kPa)*	*#Pre, % Time CEH> RH (%)*	*#Pre, Temp (°C)*	*#Pre, RH (%)*
1	7.2	163.1	0.2	20.3	23.0	1.16	0.6	92.1	20.9	68.7
2	4.2	198.6	0.4	0.0	1.7	0.10	0.2	18.1	20.7	52.3
3	3.4	127.2	0.5	0.0	0.3	0.13	0.4	66.8	20.8	57.3
5	6.5	484.5	0.9	0.0	0.4	0.01	0.2	0.0	20.9	40.4
6c	11.9	286.2	1.1	21.7	0.3	0.11	0.3	36.3	20.6	54.1
7	13.7	189.8	0.6	17.7	21.4	2.30	0.2	73.4	18.7	57.5
8c	6.4	137.4	0.5	0.0	3.3	0.24	0.4	37.4	22.3	55.8
9	7.9	215.9	1.4	0.0	(–)	0.02	0.2	47.2	20.2	54.5
10	6.3	141.3	0.6	0.0	0.9	0.11	0.4	20.2	22.1	54.6
11	10.1	396.1	1.3	5.3	1.8	0.31	0.2	99.2	17.4	61.8
12a	5.3	263.0	0.6	1.3	2.2	0.26	0.3	90.3	(17.6)	57.4
12b	5.3	263.0	0.6	0.0	0.8	0.12	0.3	100.0	(17.4)	60.5
Average	7.7	227.3	0.7	5.1	1.4α	0.16α	0.3	56.8	20.5	55.8
Outdoor Conditions									11.4	76.8

[c]Control Dwelling; *Bedroom, Average of: Mattress, Floor, Pillow; #Child Bedroom; $^{\theta}$Whole dwelling, estimated; $^{\alpha}$Geometric Mean; $^{\Delta}$(Air-infiltration measured at 50 Pa)/20; (–) Missing data. Note: central heating in Dwelling 12 was malfunctioning in the pre-intervention study.

produced by the occupants. The baseline hygrothermal conditions were also utilized to calculate the percentage of time the bedroom RH was above the Critical Equilibrium Humidity, with the latter being a function taking account of the effect of temperature (Arlian and Veselica, 1981).

The pre-intervention study results were analysed so that tailored advice could be provided to each household on the most appropriate heating, ventilation and moisture-production patterns, which could reduce HDM population growth. For example, in a leaky (and thus well-ventilated) dwelling inhabited by a household with average moisture production, it is not advisable to increase ventilation rates further, since this might excessively reduce temperature levels. Although low indoor temperatures increase mite egg-to-adult development times, they also result in higher relative humidities which are favourable for mite growth. The tailored advice was formulated by considering the baseline hygrothermal results as well as the dwelling's measured infiltration rates and the household's predicted moisture production rates. The predicted daily moisture production (kg/day) was estimated by the moisture algorithm of Condensation Targeter II (Oreszczyn and Pretlove, 1999), which requires information on moisture-production items, such as number of occupants, frequency of cooking, bathing, etc.

Based on the pre-intervention results and depending on the dwelling and occupant behaviour characteristics, each household was advised to implement one, or a combination of, the following measures: a) reducing moisture production; b) increasing ventilation levels; and c) increasing temperature levels. For example, Household 1 – with low air infiltration rates, and highest RH and VPX levels – was advised to: a) only dry clothes indoors in a well-ventilated room, which is closed to the rest of the home; b) use the extract fans in the kitchen and the bathroom during use, and for at least 15 minutes afterwards; c) keep the trickle vents always open and d) leave the windows slightly open, for as long as possible. On the other hand, Household 11 – with low temperatures and high infiltration rates – was advised to increase indoor temperatures. Control households (6 and 8) did not receive the advice until the end of the study.

Table 3B.2 Post-intervention hygrothermal results, and difference with pre-intervention conditions, for the child's bedroom.

Bedroom Number	*Post: VPX (kPa)*	*Pre-Post# VPX (kPa)*	*Post: Temp. (°C)*	*Pre-Post# Temp. (°C)*	*Post: RH (%)*	*Pre-Post # RH (%)*	*Post: % Time CEH> RH*	*Pre-Post# % Time CEH> RH (%)*
1	0.6	0.0	19.4	1.5	59.8	8.9	76.3	15.8
2	0.1	0.1	19.5	1.2	40.7	11.6	0.0	18.1
3	0.2	0.2	19.6	1.2	41.9	15.4	0.0	66.8
5	0.0	0.2	19.2	1.7	37.6	2.8	0.0	0.0
6	0.1	0.2	18.0	2.6	41.6	12.5	1.8	34.5
7	0.2	0.0	17.4	1.3	47.4	10.1	9.5	63.8
8	0.5	–0.1	21.9	0.4	48.4	7.4	0.1	37.3
9	0.2	0	21.3	–1.1	38.4	16.1	0.0	47.2
10	0.3	0.1	20.4	1.7	43.5	11.1	1.2	19.0
11	0.2	0	17.8	–0.4	47.8	14.0	12.1	87.1
12a	0.0	0.3	17.3	0.3	40.3	17.1	5.6	84.7
12b	0.2	0.1	17.2	0.2	47.1	13.4	2.8	97.2
Average⋆	0.2	0.1	18.9	0.8	44.5	12.1	10.8	50.0
Outdoor	(n.a.)	(n.a.)	6.6	4.8	80.2	–3.4	(n.a.)	(n.a.)

#Pre-Post Difference; ⋆Excluding controls (bedroom 6 and 8)

After the tailored advice was provided and implemented for 6–8 weeks (post-intervention), the monitored hygrothermal conditions were analysed in order to assess whether a change had occurred in indoor conditions, as a result of such advice. It was found that in all dwellings, the bedroom RH decreased from pre- to post-intervention periods, and the percentage of time the bedroom RH was greater than CEH ('% time RH>CEH') also decreased (Table 3B.2). In some dwellings the monitored post-intervention bedroom RH was never above CEH.

It should be highlighted that the measured reduction in indoor RH levels was partly due to changes in outdoor conditions: although the average outdoor RH increased during the post-intervention period, it was colder, and the outdoor absolute humidity was lower. In order to disentangle the weather effect from the implementation of advice, the pre- and post-intervention RHs were adjusted for each bedroom following a procedure described in another paper (Ucci et al., 2007), so as to be theoretically equivalent to a situation where outdoor conditions stayed the same throughout the whole study. Once the impact of changes in outdoor conditions were taken into account, it was found that the reduction in bedroom RHs was smaller than suggested by the measured results (Figure 3B.1) – particularly for some bedrooms (12.1% measured pre-post average RH difference vs. 5.1% adjusted pre-post average RH difference, excluding control bedrooms).

A paired t-test showed that there was a statistically significant difference (p<0.01) between pre and post bedroom RHs, for both the *measured* and the *adjusted* RH results. The importance of the adjustment procedure is illustrated by the case of the control Dwelling 8, where the measured bedroom RH decreased from the pre- to the post-intervention period. However, its adjusted RH *increased* (by a small amount, Figure 3B.1). This was due to an increase in the measured post-intervention vapour pressure excess (Table 3B.2), probably because of a reduction in window opening for the colder outdoor temperatures. It should also be pointed out that the other control dwelling (Dwelling 6) experienced an above average reduction in adjusted RH levels. However, it is possible that Household 6 learnt about the advice provided to other families. It is also possible that the RH adjustment method utilized in this study may underestimate reductions in relative humidity (see Ucci et al., 2007).

At the end of the intervention study, tailored interviews were carried out in order to establish further the extent to which households had implemented the advice. Based on the interview results, each household was given an 'implementation score'. No correlation was found between the measured pre/post RH reduction and the 'implementation score'. Therefore, for those dwellings which experienced small reductions in RH, it is difficult to establish whether this was due to: a) lack of participants' action, b) adverse building characteristics hindering changes, c) limitations of the advice itself. However, during the interviews it also became apparent that participants experienced some difficulties in reporting their ventilation habits coherently.

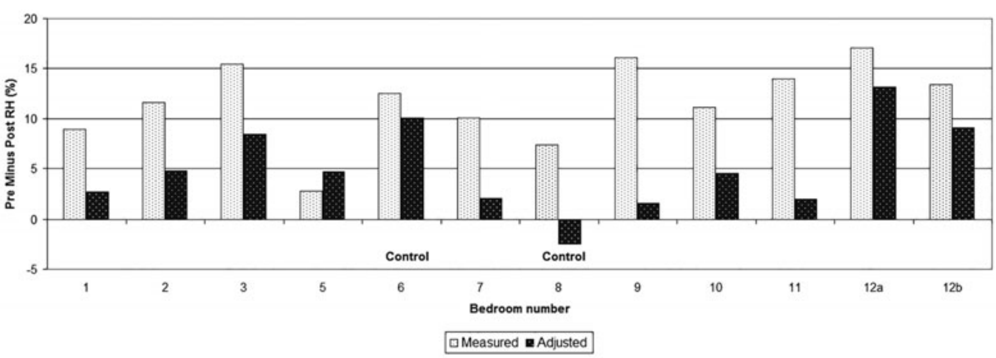

Figure 3B.1 Measured and adjusted reduction in bedroom RHs.

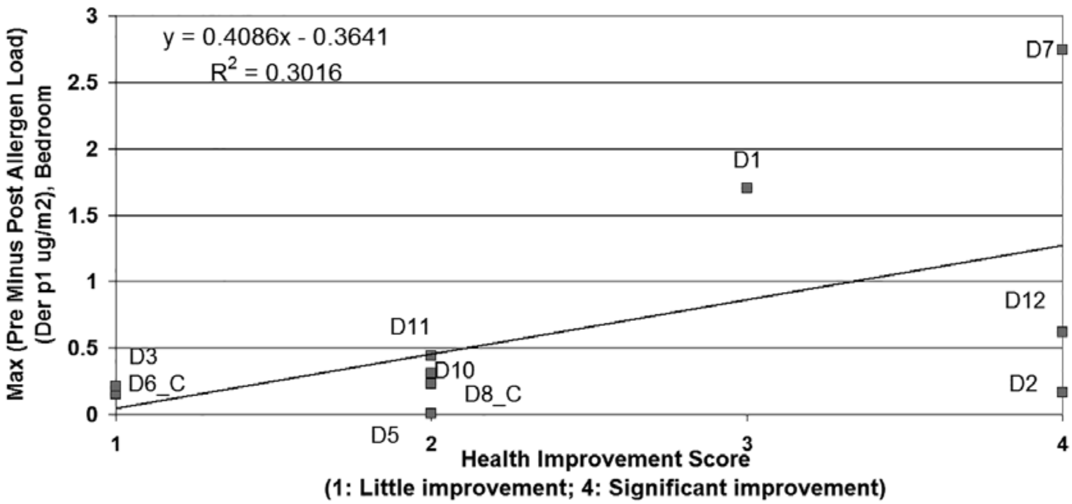

Figure 3B.2 Respiratory symptoms 'improvement score' and reduction* of Der p1 levels in child's bedroom. (*difference in average Der p1 levels between pre and post intervention)

At the beginning of the intervention period, all soft furnishings were steam-cleaned. As a result, a statistically significant reduction was found for Der p1 load levels ($p<0.01$). At the end of the post-intervention period, the initial medical examination was repeated, and an improvement score involving symptoms, medication use and airway measurements was determined for each child by GS who was blinded as to the HDM data. Figure 3B.2 shows the child's improvement score plotted against the reduction in bedroom allergen load. The graph suggests that a (weak) correlation exists between health improvement and allergen reduction (r=0.55; R^2=0.30). Some children experienced an improvement which did not correspond to a dramatic reduction in Der p1 levels. This may be due to confounding variables, such as concomitant allergies to pets which were removed from the homes or the placebo effect.

Modelling techniques

The HDM population model Mite Population Index (MPI) (Crowther et al, 2006) was utilized in this study in order to: (1) help identify those dwellings most at risk from mite growth; (2) assess the effect of changes in hygrothermal conditions on mite populations. The MPI model predicts the likely effect of steady-state average hygrothermal conditions on HDM population growth. The output is the MPI index, where, for example, 1.1 indicates 10% population growth and 0.9 indicates 10% population decline. The results obtained by utilizing measured pre-intervention average conditions indicated that the mite populations were rather stable at an average MPI value of ≅1. This suggests that even small hygrothermal changes could determine whether the population grows or declines (threshold effect). Dwelling 1 had the highest predicted pre-intervention population growth for both bedroom and bed (MPI=1.03).

Since the interventions included the removal of mites and their allergens, it was not possible to assess the *direct* effect of RH reductions on mite levels in the dwelling. Modelling was therefore utilized in order to assess the likely impact of hygrothermal changes on mite populations. In order to exclude the effect of changes in outdoor conditions, the monitored post-intervention temperatures and the adjusted post-intervention bedroom RHs were used as inputs in the MPI model. As indicated earlier, the use of adjusted hygrothermal conditions makes it easier to assess the likely impact of advice implementation on mite populations. Figure 3B.3 shows a plot of the adjusted average hygrothermal conditions, with the pre- and

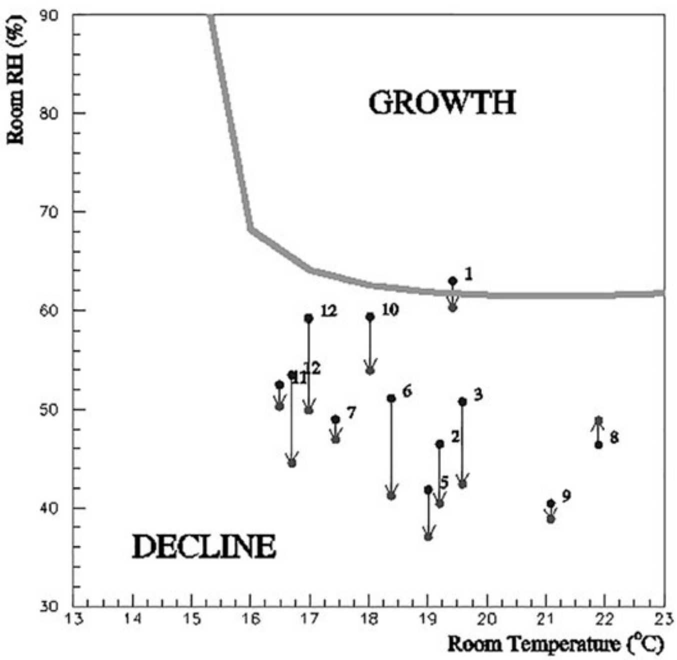

Figure 3B.3 Predicted bedroom mite growth risk, using adjusted hygrothermal conditions: pre versus post intervention. The solid curve represents conditions where HDM populations are stable (MPI=1).

post-conditions joined by an arrow for each bedroom (numbers near data points correspond to the bedrooms' code). The plot includes a curve – corresponding to an MPI value of 1 – above which mite populations grow, and below which they decline.

The results show that in all but Dwelling 8 conditions improved – independently from weather changes. Because of a threshold effect (linked to the CEH), even small reductions in RHs can lead to a reduction in mite populations (e.g. Bedroom 1 in Figure 3B.3). Therefore, although the RH reductions obtained via changes in occupant behaviour may appear small, they could be sufficient to reduce mite infestations – particularly in winter times.

Discussion

This chapter describes the methods and findings of a pilot intervention study on HDM allergen avoidance for asthmatic children, with a view to highlighting the complexities of such studies due to a number of confounding factors. Firstly, the study shows that, depending on the time of the year, changes in outdoor conditions may result in short-term improved hygrothermal conditions (i.e. less favourable for mite growth), thus confounding the effect of hygrothermal changes due to long-term interventions such as implementation of tailored hygrothermal advice. Furthermore, occupant behaviour can change in relation to outdoor conditions. It is therefore important to adjust for changes in outdoor conditions in any similar future study. Secondly, the study shows that changes in occupant behaviour can be difficult to assess – particularly with regard to ventilation habits. It is therefore vital that ventilation rates – not only air leakage – are measured in future studies, and a closer monitoring is carried out of occupant habits (for example through the use of participants diaries). As demonstrated in this study, it is vital that *tailored* advice is provided, ensuring that the most effective intervention is carried out - since greater ventilation rates are not always desirable (e.g. in a leaky building). Changes in occupant behaviours can also be hindered by adverse dwelling characteristics. For example, in this study Household 1 was advised to increase ventilation rates, but their VPX did not decrease, most probably because of a combination of existing habits and their very airtight dwelling.

A further difficulty highlighted by this study was assessing the impact of changes in hygrothermal conditions on mite populations (and, indirectly, on health). This is because psychrometric control does not immediately affect HDM allergen reservoirs, which have to be removed in order to obtain any health improvement. However, allergen removal also results in killing the existing mite population, which therefore cannot be monitored for subsequent reductions due to hygrothermal changes. In any case, live mites are notoriously difficult to sample, and mite populations would also be affected by changes in outdoor conditions. On the other hand, high allergen levels cannot be taken as a marker of favourable hygrothermal conditions, since a reservoir effect can be observed, for example due to the age of the substrate (e.g. mattress) and to the ineffectiveness of some cleaning regimes. Therefore, the use of population modelling techniques such as those utilized in this pilot are recommended as a useful tool for assessing the likely impact of hygrothermal changes on mite populations. Although the current models are based on steady-state data, transient models for mite microclimates are being developed by the authors, which will allow for more accurate predictions of mite populations. Furthermore, the authors have also developed an innovative technique for monitoring the impact of a dwelling's hygrothermal conditions on mite populations – using encapsulated populations of mites as described in a future paper. The development of models predicting the effect of hygrothermal conditions on allergen levels (as opposed to mite population only) is also recommended, since this would allow for a better understanding of the impacts of hygrothermal changes on respiratory health.

The study in this chapter shows some promising results with regard to its health impact. However, it should also be highlighted that due to practical constraints it was not possible to adequately control for the placebo effect and for the role of other confounding health variables (e.g. sensitivity to other allergens) in this study. Above all, this study demonstrates the complexities associated with attempting to establish a direct link between changes in hygrothermal conditions in housing (e.g. due to changes in ventilation) and health (e.g. asthma). This is because any study attempting to do so is faced with a large number of variables, whose direct measurement is often very expensive (e.g. ventilation rates) and/or challenging (e.g. meaningful mite levels). Furthermore, a number of the mechanisms involved in the links between housing and atopic asthma are not yet fully understood. For example, although much is known about asthma, there is still some uncertainty on the causes of asthma onset, and even on the definition of asthma itself. Similarly, the mechanisms which determine HDM sensitization following exposure to HDM allergens are not fully understood, nor are there clear threshold levels of exposure above which sensitization occurs. Another source of complexity of any such study is linked to the mechanisms which determine indoor hygrothermal conditions, on which house dust mites are dependent. Building characteristics, occupant behaviour and climatic conditions all affect indoor conditions. However, these variables are not independent: for example, climatic conditions can affect occupant behaviour (e.g. less window opening in cold weather). Furthermore, it should be emphasized that although HDM microclimates (e.g. beds) are strongly influenced by room conditions, they nevertheless can differ from them, as a result of, for example, the hygrothermal properties of the mattress, the amount of time the bed is occupied, etc. Figure 3B.4 highlights the main variables which should be taken into account when considering the links between the building stock, house dust mite infestations (e.g. in a mattress) and health outcomes – with a focus on psychrometric control.

Despite the complexities discussed above, this study showed that there was a statistically significant ($p<0.01$) decrease of measured bedroom RHs, which remained statistically significant, although smaller, once the effect of changes in outdoor conditions were taken into account. The population modelling results indicated that during the pre-intervention period the mite populations were rather stable at an

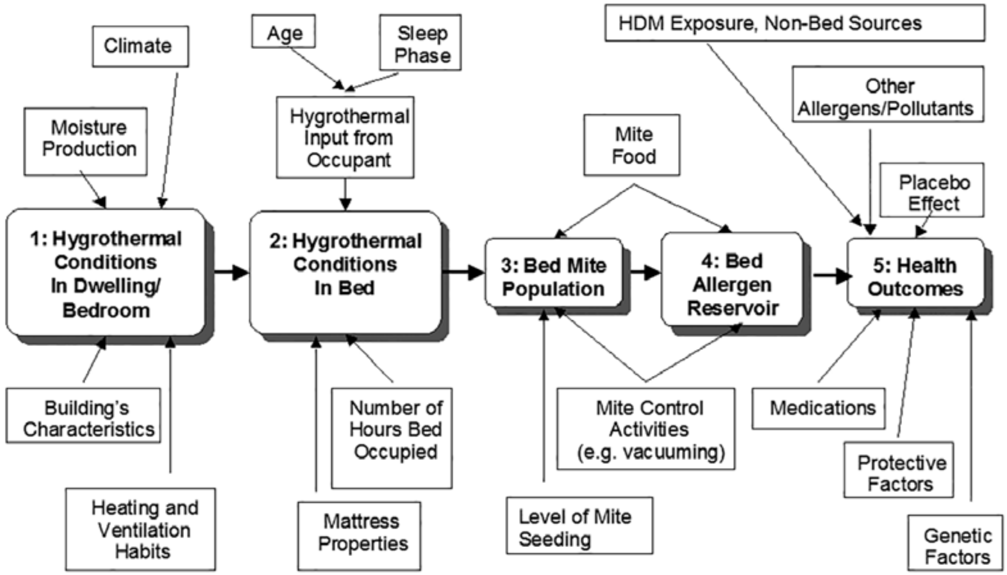

Figure 3B.4 Complexity of the links between hygrothermal conditions in dwellings, HDM levels in beds and adverse health outcomes.

average MPI value of ≅1, suggesting that even *small* hygrothermal changes could determine whether mite populations grow or decline.

Conclusions

This study suggests that in temperate climates even small changes in hygrothermal conditions can be crucial for the reduction of house dust mite infestations, particularly in winter. Tailored advice on heating and ventilation habits can lead to valuable changes in hygrothermal conditions. In some cases, however, these improvements may be hindered by occupants' reluctance to change and/or by pre-existing adverse building conditions. Due to the complexities associated with these types of studies, formulaic interventions should be avoided, while careful consideration should be given to the study design and to appropriate monitoring and modelling techniques.

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Case Study 3C

VENTILATION AND AIR QUALITY MODELLING

Zarko Stevanovic, Dejan Mumovic and Miroslava Kavgic

Introduction

Modelling is a very important activity in built environment engineering. The need for modelling arises from the complex systems and processes that must be addressed, and we cannot afford to measure (monitor) on many locations and throughout time. We are frequently challenged to explain why an environmental system behaves as it does, to predict how it will evolve if left undisturbed, or to discern how a system will respond to a change (to predict the effects of the future scenarios).

In practice, there are two classes of frequently used models based on material balance:

- reactor (box) models; and
- general heat, mass and momentum balance models.

Despite the simplicity power of reactor models, in many cases more detailed aspects of pollution phenomena must be considered to accurately model an environmental issue or process. General heat, mass and momentum balance models can be used to study more complex problems. Analytical solutions for these models are possible for only a small fraction of the cases of interest. Usually, one must either make major simplifying approximations about the system, as in reactor models, or use numerical methods to solve the governing differential equations of heat, mass and momentum conservation as well as introduced turbulence model. The general heat, mass and momentum balance models that are numerically solved is known as computational fluid dynamics (CFD) technique.

CFD is now widely used for assessing thermal comfort and air quality in and around buildings. CFD can simulate airflow, the dispersion characteristics of air pollutants and their temporal and spatial variations. When used carefully, optimising input and output requirements, it can offer useful insights into the physical processes that govern the dispersion of atmospheric pollutants. This chapter provides a general guide to the use of CFD for assessing thermal comfort and air quality in and around buildings. Within this framework, relevant experimental and theoretical problems are also briefly discussed.

Air flow and pollution distribution around buildings

This section provides a step by step guide to the use of CFD for assessing pedestrian comfort and air quality around buildings. Furthermore, it highlights the fundamental problems of the micro-scale CFD models, which lie in the physical difficulties of modelling the effect of turbulence, and also the accuracy of the spatial discretization of complex urban geometries, the numerical procedures applied, the boundary conditions and the physical property selected. In this section the authors presented the results of two case studies aimed to:

- assess suitability of a general CFD code for use in the integrated urban air quality modelling for regulatory purposes in Glasgow (Scotland); and
- assess the impact of a new building on air flow and pollution distribution in a district of Copenhagen (Denmark).

Although, at this stage, the accuracy of developed urban air quality models highly depend on experience of its users, it is believed that use of a CFD in urban air quality modelling could be to the benefit of urban planners, architects, HVAC engineers and all other professionals interested in public health.

Defining the geometry

Domain size3

The choice of size of computational domain strongly depends on at least two factors: (a) the size of modelled built environment area and (b) the wind direction. No definitive studies have been conducted to identify the specific limits to which a computational domain of a built environment should be extended. However, the basic guideline of computational domain size is connected to the nature of conservation partial differential equations of heat, mass and momentum transport. These equations are elliptic ones, therefore, in order to obtain uniquely solution, we have to specify boundary conditions at all domain faces. There is no problem to specify boundary conditions at the inlet faces and the walls since they are known, however, the problem arises at the outlets and open surfaces where the boundary conditions are unknown. The common practice to overcome this problem is to extend the domain size to the level where we expect no change of fluid flow parameters, e.g. assuming zero gradients. Therefore, this depends on the modeller's experiences. There are no general guidelines, but an analysis of the published literature suggests that the computational domain for buildings of height H should be extended upstream, downstream and vertically by H to 6H, 5H to 16H and 0.5H to 16H, respectively.

For a single building, or a simple group of buildings, where size of each building in lateral direction is comparable with their heights, the upstream, the cross stream, and the top boundary conditions should be extended to 5H, where H is height of the tallest building (Hall, 1997). Downstream the computational domain has to be extended to include the reattachment point beyond the latest building column, meaning that the outlet should be positioned at 15H behind the building.

However, in the case of a complex configuration of buildings, such as that already mentioned in the Glasgow case study, the situation is more complex. Knowing that one is constrained by present day computer power, as a starting point, the upstream, cross-stream and downstream boundaries should be positioned at least at 5H, 7H, and 12H respectively. Assuming the same heights of buildings the top boundary could be extended to 3H.

Object geometry

As can be seen in Figure 3C.1, much of central Glasgow is divided into rectangular blocks by orthogonal streets. A block surrounded by streets usually consists of several almost regularly positioned buildings with small courtyards, or one large building. The older, Victorian building style and height restrictions of approximately 20 metres have given rise to an almost regular array of streets with buildings all of a very similar height. This is very convenient for the application of the following refinements:

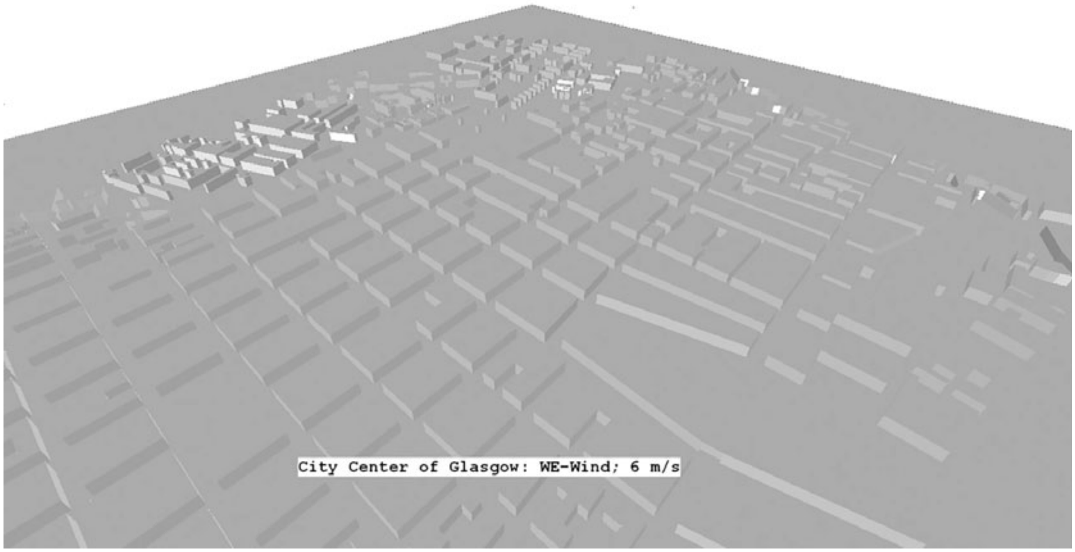

Figure 3C.1 Object geometry of central Glasgow area.

- Linearization of minor irregularities in street direction (as a consequence of this minor geometrical simplification, a significant reduction in the number of the cut cells may be achieved).
- Rotation of the supportive plate of the solid model. This simple technical solution enables the alignment of the solid model of an urban area with the direction of the non-uniform Cartesian grid and hence allows the use of very limited computer power without causing numerical diffusion (i.e. an artefact).

On the contrary, object geometry of Copenhagen district area is characterized by highly irregular street network that is shown on Figure 3C.2.

Generally speaking, the level of detail required for each building is determined by both (a) its distance from the point of interest, such as an air quality monitoring station in an urban area, and (b) the application of the CFD model. While the general wind flow pattern characteristics are determined by the distribution of buildings in the modelled built environment as a whole, the micro-environment is critical when assessing surface pressure on the façade of specific buildings or, for example, dispersion of air pollutants from large boiler flues.

Numerical grid

Arguably the most important step in CFD is the generation of a grid, which defines cells at which flow variables are calculated throughout the computational domain. As a general rule, if configuration of buildings is not suitable for alignment of the grid with the local flow direction, body-fitted coordinates (hexahedral shapes) should be used. However, in the case of Glasgow and probably other Victorian cities across the United Kingdom, where cities are divided into rectangular blocks, a non-uniform orthogonal coordinate system may be used. In that case at least 10 cells should be used between two buildings for rapid and accurate convergence. However, in the Copenhagen study the authors opted for a dense

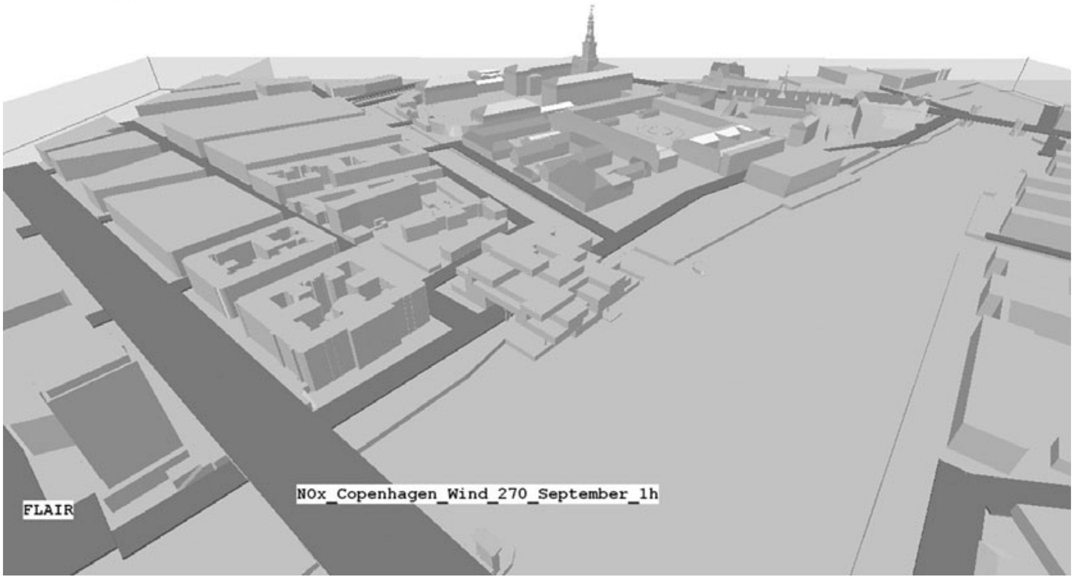

Figure 3C.2 Details of object geometry of Copenhagen district area.

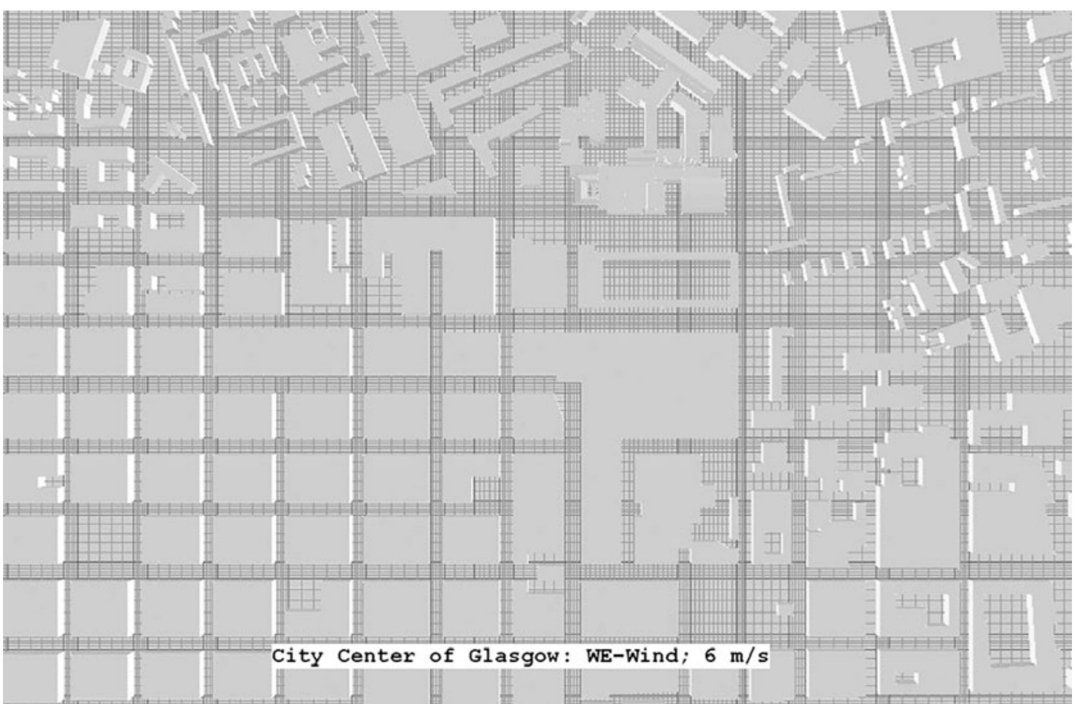

Figure 3C.3 Details of horizontal numerical grid of central Glasgow case study.

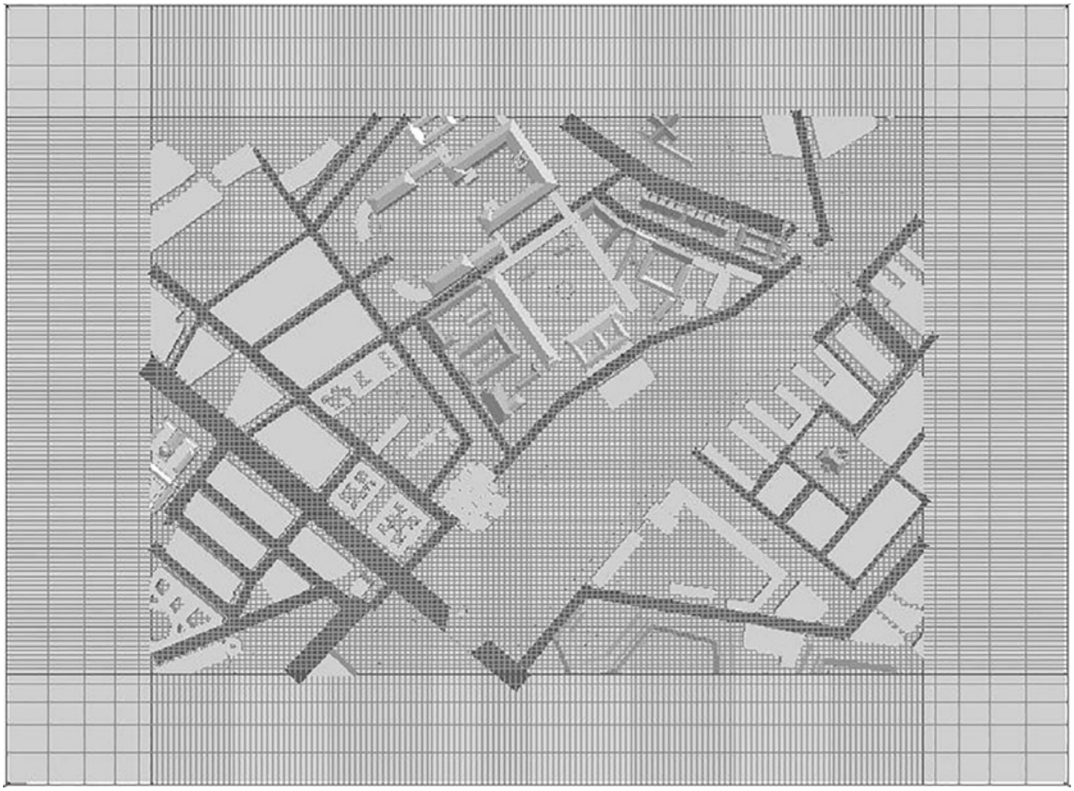

Figure 3C.4 Horizontal numerical grid of Copenhagen district case study.

uniform horizontal grid resolution as the highly irregular street network did not allow for the grid refinement.

A well-designed grid is critical to an accurate CFD solution of airflow in a built environment and time spent generating the grid is usually time well spent. The numerical grids of central Glasgow and Copenhagen district area are shown on Figures 3C.3 and 3C.4 respectively.

Defining the physical model

Governing equations

In urban air quality modelling, a computational domain is set up within the atmospheric boundary layer assuming incompressibility of the air. Generally, the airflow governing equations represent the conservation of mass (continuity), momentum (Navier-Stokes equations), heat (energy equation) and species concentration (CO_2, CO, NO_x, SO_x, H_2O, etc.). All these equations can be presented by means of the general conservation equation for property Φ:

$$\frac{\partial}{\partial \tau}\left(\rho\Phi\right)+\frac{\partial}{\partial x_j}\left(\rho U_j\Phi\right)=\frac{\partial}{\partial x_j}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial x_j}\right)+S_\Phi \tag{3C.1}$$

where Φ denotes the general airflow physical property (velocity, temperature, concentration, etc.), ρ denotes the air density, U_j denotes the component of time averaged velocity vector (j = 1,2,3), and Γ_Φ and S_Φ denote transport coefficient and source term aligned to the general variable Φ, respectively. It is common practice to represent the governing equations as in Table 3C.1.

Table 3C.1 Summarized governing equations of urban pollution model.

Governing equation:	Φ	Γ_Φ	S_Φ
Continuity	1	0	0
Momentum	U_j	ν_{ef}	$-\partial P/\partial x_i$
Energy	T	a_{ef}	0
Species concentration	C	D_{ef}	0

where P denotes averaged atmospheric pressure, T denotes averaged atmospheric temperature, C averaged species concentration, νe_f denotes effective molecular viscosity, and ae_f, De_f denote effective thermal and mass diffusivity, respectively. In the case of isothermal airflow, the energy equation is omitted. However, as the airflow is turbulent, additional equations representing a turbulence model must be solved as well.

Turbulence modelling

In recent years modelling of micro and meso scales of atmospheric boundary layer phenomena has received growing interest. One of the basic phenomena associated to air motion is its turbulence nature; therefore, many attempts have been made to produce sufficiently accurate turbulence models.

When asked about the applicability of individual turbulence models to specific situations, Professor Spalding, one of the founders of CFD, once replied: "NObody Knows FOr Sure". This answer has become the well-known 'NOKFOS' principle. Therefore, the suggestions made in this section on the use of CFD for similar built environment applications should be understood as a good starting point only, and the reader is strongly advised to keep up-to-date with progress in this rapidly developing research area.

In the engineering practice, the most popular and frequently used two-equation turbulence model is well known k-ε model. However, the popularity of the k-ε turbulence model in engineering applications raises the question of whether it could be used for micro and meso scales modelling in the atmospheric boundary layer. Applying the standard k-ε turbulence model, used in engineering applications to atmospheric boundary layer flows, yields unrealistic results, since it is unable to reproduce the right level of turbulence in the weak shear layer away from the ground, where the turbulent viscosity is over predicted (Detering and Etling, 1985). In order to overcome these misleading, some modifications of standard k-ε turbulence model have been proposed, almost modifying the set of model's coefficients based on experimental evidence of urban boundary layer (Rotach, 1995).

As noted previously, the additional modelled transport equations of turbulence model have to be added to set of governing equations. Fortunately, the structure of these equations has the same form as the general conservation equation (3C.1), therefore the general variable Φ can be assigned to turbulence kinetic energy (k) and its dissipation rate (ε). Using these turbulence properties, it is possible to calculate turbulent parts of effective viscosity and diffusivity. Details of modified two-equation turbulence model of urban boundary layer is presented in Table 3C.2:

Table 3C.2 Summarized two-equation k-ε turbulence model.

Turbulence model equations:	Φ	Γ_Φ	S_Φ
Turbulence kinetic energy	k	$\nu+\nu_t/\sigma_k$	$2\,\nu_t\,S_{ij}S_{ij}-\varepsilon$
Turbulence dissipation rate	ε	$\nu+\nu_t/\sigma_\varepsilon$	$(\varepsilon/k)\,(C_{\varepsilon 1}\,2\,\nu_t\,S_{ij}S_{ij}-C_{\varepsilon 2}\varepsilon)$
$\nu_t = C_\mu k^2/\varepsilon$; $S_{ij} = ½\,(\partial U_i/\partial x_j + \partial U_j/\partial x_i)$			
$C_\mu = 0.0324$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.85$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$			
$\nu_{ef} = \nu+\nu_t$; $D_{ef} = D + D_t$; $D_t = \nu_t/\sigma_Y$; $\sigma_\gamma = 0.9$			

Boundary conditions

In order to solve the system of partial differential equations given above, the boundary conditions have to be applied to solid walls, inlets, outlets and open surfaces:

1 Solid walls. In urban areas, the airflow is highly turbulent, dominated by modifications of the atmospheric flow caused by the buildings, and the velocity of the airflow varies very rapidly near walls. To solve this problem, avoiding the introduction of extremely fine grids, the conditions at building walls have to be connected to the dependent variables at the near-wall grid cell. Therefore, the near wall integration is bridged by empirical logarithmic wall functions. This technique is applied only to the first cell slab on the wall; therefore, the question is how heights of the first cells on the wall should be. The recommendation can be connected with near wall turbulence Reynolds number ($y^+ = C_\mu^{1/4}k^{1/2}\delta/\nu)$), that should be less than 150. Here, δ is normal distance of the central node of the first cell to the wall. If the suggested equilibrium logarithmic law wall function for smooth walls in the region of interest is selected, the numerical probe should not be placed in the first two cells (minimum) next to the wall, due to the inherent inaccuracy of wall functions.

2 Inlets. At the inlet, the airflow entering the computational domain is usually defined as:

$$U(z_1) = U(z_2)\left(\frac{z_1}{z_2}\right)^a \tag{3C.2}$$

where $U(z_1)$ is the wind speed calculated at height z_1, and $U(z_2)$ is the wind speed measured at height z_2. The power law exponent, α, depends on the roughness of surrounding built environment, but in general a value of 0.22 may be used for an urban area when the atmosphere is neutrally stratified. The turbulence intensity should be set to between 10 and 15 %.

3 Outlets and open surfaces. The outflow, zero gradients boundary conditions should be set up for all other boundaries of the computational domain (top, two side boundaries and the boundary behind the obstacles) to allow more natural outflow at all boundaries (all three components of velocity are calculated).

Defining the numerics

Discretization scheme

As we have seen, the equations governing the motion of airflow and concentration distribution in a built environment are partial differential equations. These equations have to be transformed into their algebraic analogues in the process called numerical discretization. There are three common discrete approximations, namely: finite difference, finite element, and finite volume. The finite volume method is well established and used by major commercially available CFD codes (PHOENICS, Fluent, STAR-CD, etc.) and will be discussed in this section.

The most attractive feature of the control volume formulation is that it ensures global conservation of mass, momentum, heat and concentration independent of the grid size. This method divides the physical domain into discrete three-dimensional control volumes, so called cells, and then formally integrates the governing equations over them. While the diffusion process affects the distribution of a transported quantity, Φ, along its gradients in all directions, convection influences the transported property, Φ, only in the flow direction. This suggests that the same numerical solutions cannot be applied to solving both diffusion and convection problems. As the airflow in a complex built environment is convection-dominated, care must be taken when discretising the convection terms of the governing equations (3C.1).

Different linear and non-linear numerical schemes could be used for the discretization of convection terms. Linear methods, like the upwind method, tend to be highly diffusive, whereas, non-linear methods tend to produce numerical oscillations near sharp gradients. Despite the diffusive behaviour of linear methods, some of them, such as the hybrid discretization scheme (Rosten and Spalding, 1987) can be still used in large-scale urban airflow calculations due to their boundedness, stability and feasible convergence rates. However, this scheme (or any other first order scheme) is recommended for initial calculations only. The modelling results would then be refined (if possible) using the higher order discretization schemes.

Convergence criteria

The solution algorithm of the algebraic equations derived from the partial differential equations is iterative in its nature, meaning that successful progress toward a converged solution has to be measured using residual errors. As the solution progresses the residuals should reduce. In urban airflow/quality applications a limit on the residual error of 10^{-5} is recommended. Once all the residuals fall below this limiting value the calculations will be stopped.

Progress toward a converged solution can be additionally assessed by monitoring different variables, such as wind velocity and/or pollutant concentration, at specified locations within a computational domain. These so-called 'numerical probes' should be positioned in the area of interest (e.g. corresponding to the position of a monitoring probe in a real built environment). If values recorded by the numerical probe are constant for a number of consecutive iterations, and in agreement with experimental results, then the obtained solution has converged.

However, this might not always be the case, i.e. the solution shows poor convergence or no convergence at all. Progress toward a converged solution in this case could be assisted using various relaxation factors. As this step depends on the experience of user, it is very difficult to give specific recommendations and the user must learn by experience.

Grid independence

Flow calculations can be carried out using either a non-uniform orthogonal grid or body-fitted coordinates. In both cases routine refinement tests have to confirm satisfactory grid independence. A grid has to provide the highest possible resolution near the ground and the roofs, and in the regions next to the windward and leeward sides of the street canyons. The grid spacing has to be varied gradually in order to avoid an increase in the truncation error and is limited by the maximum processing power of the available hardware. The change in any successive cell dimension should be kept at less than 30%.

Visualizing air flow and pollutant dispersion

The two standard means of depicting air flow are velocity vectors and streamlines. Velocity vectors are arrows that point in the direction of air flow. They are also scaled and collared that the length and colour of the vector is proportional to the magnitude of the velocity. The vectors are usually drowned at each node. However, they can be thinned if needed or extra vectors interpolated if the nodes are too far apart to achieve good visualization, or opposite, they can be restricted to every second or third node. Streamlines are essentially a form of contour plot. They show lines of air flow; a fluid particle that is flowing through the computational domain will follow one of the streamlines. Generally speaking, streamlines are better than velocity vectors at representing the direction of fluid flow, but they tell little about how fast the fluid is moving. Details of air flow visualizing in the both case studies are presented in Figures 3C.5 and 3C.6 for Glasgow and Copenhagen, respectively.

Also, the two-standard means of depicting air pollutant concentration are contour lines and filled sub-areas within a specified range of values. The complexity of visualizing by this technique is arising in the three-dimensional computational domain. One of the ways to overcome this problem is to present air pollutant concentration distribution separately by one specified plane, as it is shown in Figures 3C.7 and 3C.8 for Glasgow and Copenhagen, respectively.

Model validation

As we have seen, CFD must be used cautiously to set up the model of airflow and/or pollutant (gaseous, passive) dispersion in a more complex built environment. When analysing the results of a simulation, the obtained airflow/pollutant distribution patterns have to look qualitatively correct, and the paramount criterion is that the mass of fluid entering the domain should equal the mass leaving the domain (this is often calculated by software itself). If the airflow patterns obtained seem to be satisfactory, the next step is to compare modelling results against reduced-scale (wind tunnel, water channel) or full-scale (field) experimental measurements. It is not always appropriate to simply compare CFD results with the measured

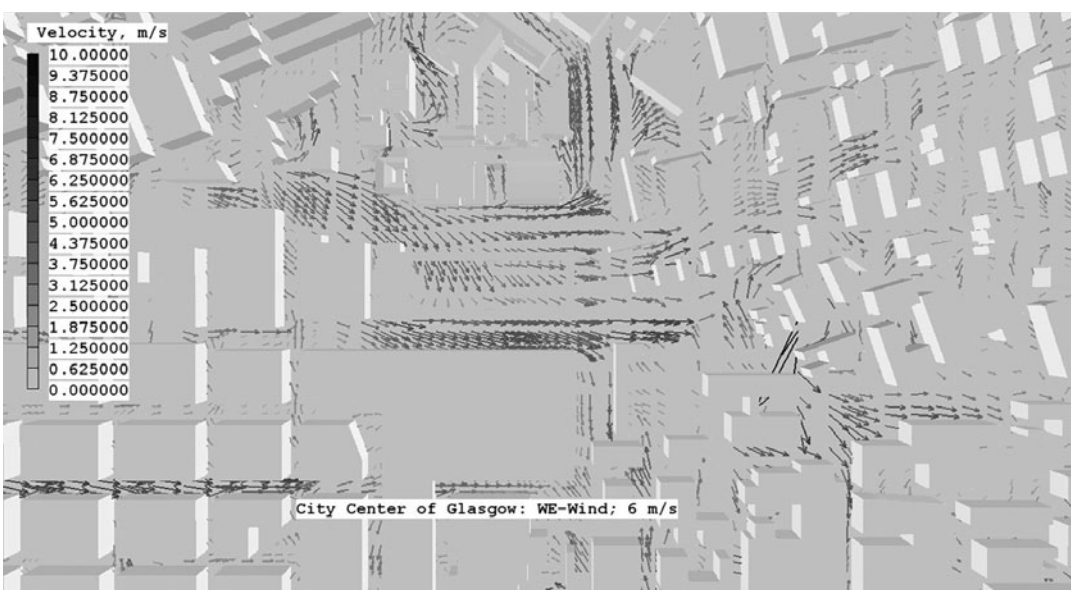

Figure 3C.5 Glasgow case study – air flow visualizing.

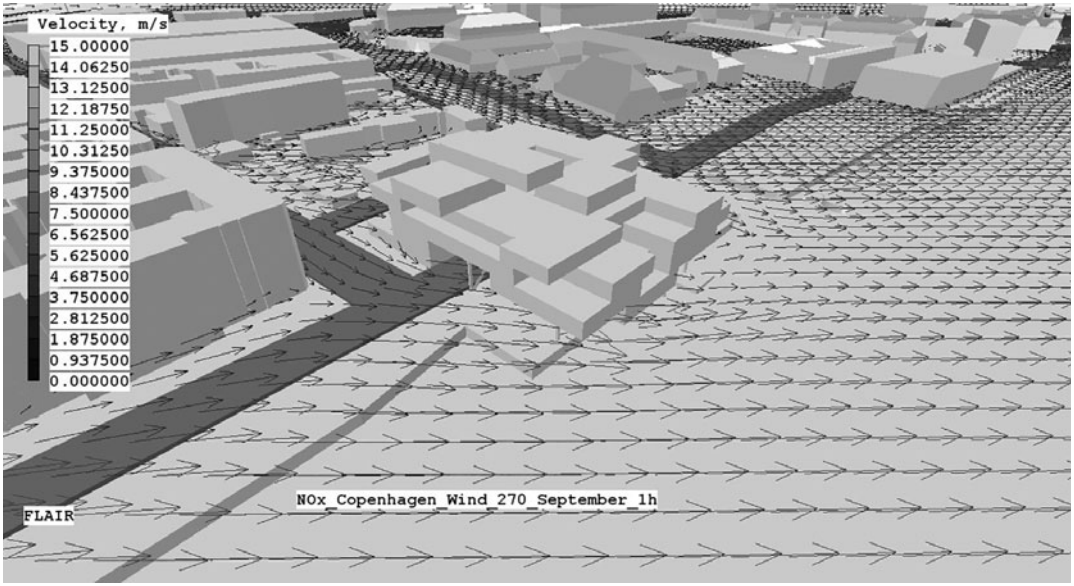

Figure 3C.6 Copenhagen district case study – air flow visualizing.

Figure 3C.7 Details of CO concentration distribution of central Glasgow case study.

data, obtained either from a wind tunnel or a real built environment (MacDonald, Griffiths and Hall, 1998; Liedtke, Leitl and Schatzmann, 1999; Schatzmann and Leitl, 2002), because they are physically different. Generally speaking, if all major similarity parameters were properly determined in the wind tunnel experiments, the measured results should be similar to that of the field test. However, they are not. The wind tunnel data are usually less intermittent because low-frequency wind direction variations present

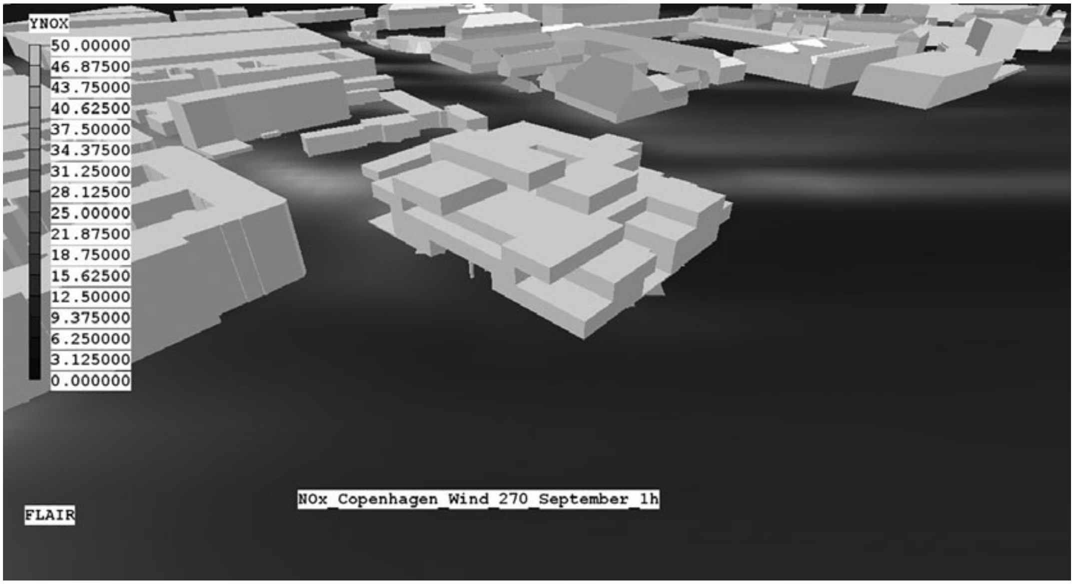

Figure 3C.8 Details of NO_x concentration distribution of Copenhagen district case study.

in the field are usually reduced in a ducted (wind tunnel) flow of finite width (Leitl and Schatzmann, 1998). As a consequence, the maximum averaged concentrations determined in the wind tunnel may be larger than those obtained in the field. Note, however, that other factors may also influence the degree of overestimation, such as the turbulence structure of the ambient flow or the source/receptor distance. As a result of the high intermittency, long averaging times are required in order to produce a meaningful mean value, and a most favourable averaging time of measurement periods is very difficult to determine, since the atmospheric boundary conditions change frequently during a day. Usually, averaging times of 10, 15, 30 or 60 minutes are used. It is strongly recommended that the standard deviations should be attached to time-averaged concentrations determined in field situations, as this would be very valuable in validation of the CFD model. Finally, the CFD model delivers a constant concentration value if stationary boundary conditions (wind speed, wind direction, wind profile and turbulence intensity) are used. Note that this value is not just time-averaged, but also spatially averaged over the whole volume of a grid cell. Thus, model validation is certainly not straightforward and it is essential that the fundamental differences be properly taken into account.

In conclusion, the physical nature of all wind tunnel experiments, field measurements, and CFD modelling is significantly different and certain discrepancies in results may be expected. Further, it is more important for a CFD model to be consistently accurate, to certain level, across the whole of computational domain rather than to fit the measured data for certain specific locations only.

Air flow and pollution in buildings

The air-flow pattern in a ventilated enclosure space such as rooms, offices, halls, theatres, etc., is mainly divided into two different concepts: mixing (dilution) ventilation and displacement one. Mixing ventilation is characterized by the heating, ventilation and cooling (HVAC) system which provides fully mixed air in the whole enclosure space. In displacement ventilation, a stratified flow is occurred by buoyancy-driven-flow. It can be regarded that displacement ventilation concept is an opportunity to improve both the temperature and ventilation effectiveness. A typical displacement ventilation system for cooling supplies conditioned air from a low side (or floor) diffusers to the occupant's zone. The supply air temperature is lower than operating one causing the vertical air movement by buoyancy force as the air is heated by the different heat sources (e.g. persons, lightning, electrical machines, etc.). Heat sources create upward convective flows as thermal plums. These plums bring heat and contaminants from the surrounding occupied zone to the upper space of the enclosure space. Diffusers of return air are manly located at the ceiling. A stratification level exists where the airflow rate in the plumes equals to the supply air flow rate. However, it is very difficult to obtain ideal air flow pattern of displacement ventilation concept when the interior geometry of different objects became complex.

Indoor air quality (IAQ) and thermal comfort (TC) are important factors in the design of high quality buildings. Although innovations in air-conditioning and other forms of cooling or ventilation, which can be viewed as technological solutions to the problem of producing and maintaining energy efficient environmental conditions that are beneficial for human health, comfort and productivity, there is often a conflict between reducing energy consumption and creating comfortable and healthy buildings.

Theatres are the most complex of all auditorium structures environmentally. They usually have high heat loads, which are of a transient nature as audiences come and go, and from lighting which changes from scene to scene, and they generally have full or nearly full occupancy. All these factors place constraints on the ventilation design, and if this is poor, it can lead to the deterioration of indoor air quality and thermal comfort. To analyze the level of indoor air quality and thermal comfort, as well as to identify where improvements could typically be made, a comprehensive post-occupancy evaluation study was carried out on a typical medium-sized mechanically ventilated theatre.

In this case study, the issues concerning the numerical aspects of the governing equations are the same as ones given in the previous section, and therefore have been omitted. The following sections highlight specifics related to CFD modelling in buildings.

Defining the geometry

Domain size

The theatre is roughly a rectangular box with a gallery over the rear and sides of the ground floor (or stalls), bounded by theatre hall external walls. Therefore, the domain size is constrained by dimensions of theatre hall. Around half of the ground floor area is given over to the stage. The auditorium is served by a displacement-type ventilation system. Fresh air is introduced via vortex diffusers, mounted at ground and gallery floor level directly under the seats, boosted by a few circular diffusers in the ceiling of the gallery. Air is also supplied at low level from the side walls of the stage. Extract air is removed by rectangular outlet grilles set into the ceiling over the stalls and gallery level.

Object geometry

Basically, the geometric model of building interior consists of three groups of objects: (1) the building interior objects; (2) the HVAC objects; and (3) the internal source objects.

Building interior objects

The building interior objects include internal walls, perforated plates, furniture, utility equipment, etc. Most of these objects are already defined in the building orientated CFD codes. Apart of geometry specifications of these objects, frequently there are options to specify object materials (metal, bricks, concrete, wood, plastics, etc.), plate roughness, heat release rate, etc. However, if there are highly irregular

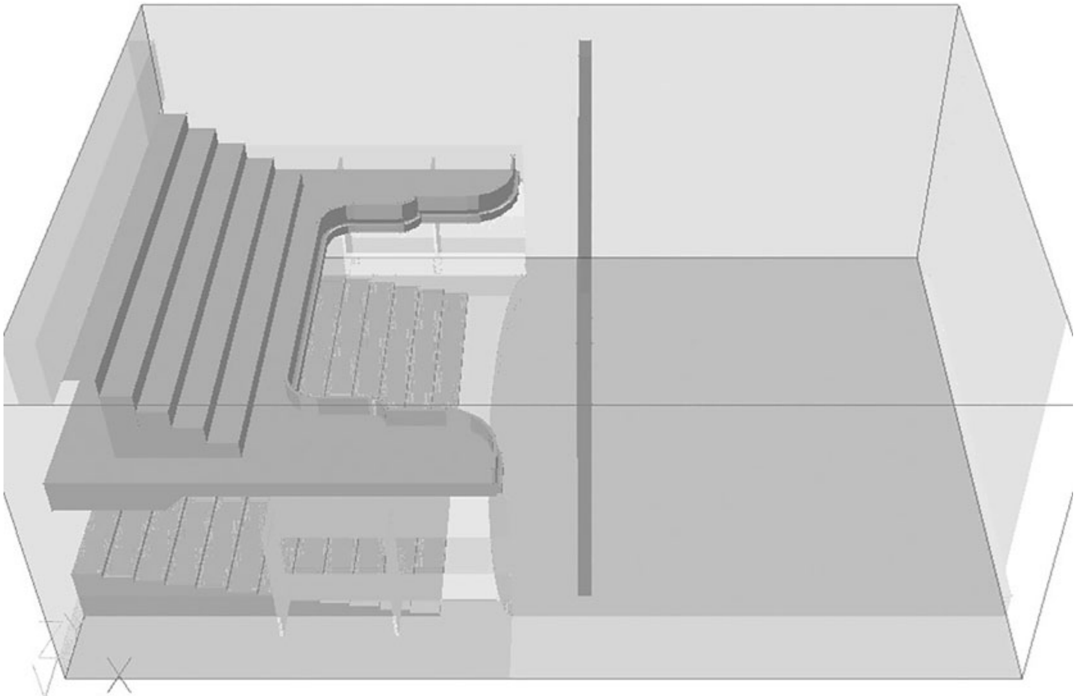

Figure 3C.9 Building interior objects of theatre case study.

objects, such as the shape of theatre gallery in this case study, a solid model of such object can be created in any CAD software and imported into CFD codes. As the example, these types of objects are shown in Figure 3C.9.

HVAC objects

Generally speaking, there are two groups of HVAC objects: (a) these which belong to HVAC system, such as HVAC casing assembly, rack-units, jet fans, etc., and (b) HVAC air supplying and exhausting units, such as different types of diffusers (round, vortex, quadric-rectangular, quadric-directional, displacement, etc.), grills and nozzles. Beside the shape and size of these objects, the air supply pressure, density, temperature, humidity, pollutant concentration, as well as supplying volume flow rate have to be specified. Also, in the case of exhausting units, effective flow-area and pressure drops have to be defined. The values of these parameters can be specified in two ways: (a) using the design values or (b) using the measured ones.

Actually, the HVAC objects are specific inlet and outlet boundary conditions. In the case of the theatre, these specific boundary conditions are summarized in Tables 3C.3 and 3C.4, respectively, and shown in Figure 3C.10.

Internal source objects

Internal heat and mass sources are related to occupants and equipment. Regarding the occupants, they can be specified as shaped single seating or standing persons or by rectangular box of group of persons.

Table 3C.3 HVAC inlet boundary conditions of theatre.

HVAC air supply system					
Supply diffusers	*Number of units*	*Air temperature (°C)*	*Air humidity (kg/kg)*	*Volume air flow rate (m^3/h)*	*CO_2 volume fraction (ppm)*
Ground level					
Vortex	312	20	0.008654	15650	350
Round	8	20	0.008654	1600	350
Gallery level					
Vortex	120	20	0.008654	6450	350
Mean stage level					
Grille	6	20	0.008654	6000	350

Table 3C.4 HVAC outlet boundary conditions of theatre.

HVAC return air system				
Return diffusers	*Dimension (mm)*	*Number of elements*	*Effective area (m^2)*	*Pressure drop (Pa)*
Gallery ceiling				
Grille	1025 × 525	10	0.269	2
Mean stage ceiling				
Grille	825 × 425	4	0.175	2

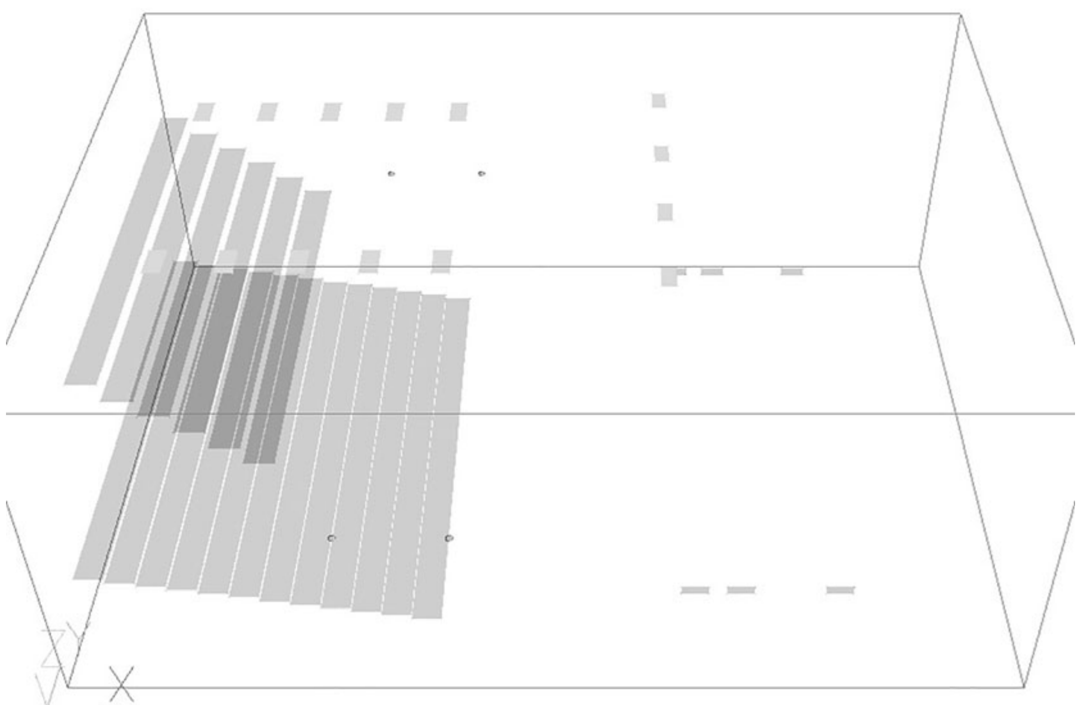

Figure 3C.10 HVAC objects of theatre case study.

Table 3C.5 Internal sources of theatre.

Occupants					*Equipment*
Sensitive heat (W/person)	*Latent heat (W/person)*	*Total number of persons*	*Water vapour source (g/h/person)*	*CO_2 source above outdoor air (ppmv)*	*Lighting (W)*
Ground occupants					
60.5	55	332	55	450	0
Gallery occupants					
60.5	55	132	55	450	0
Mean stage					
60.5	55	4	55	450	19,600

The persons are source of heat (sensitive and latent) and mass (water vapour and CO_2 emissions). These parameters depend on metabolic rates, external work-activities, clothing, age, sex, etc., which can be found in various thermal comfort and indoor air quality standards and guides (Tennekes and Lumley, 1972; CEN, 1998; ASHRAE, 2002). The equipment is basically source of heat (lighting, computers, domestic utilities, etc.). These internal sources can be specified as fixed values or time and space dependent prescribed by manufacturers. In the case of the theatre, the internal sources are summarized in Table 3C.5 and shown in Figure 3C.11.

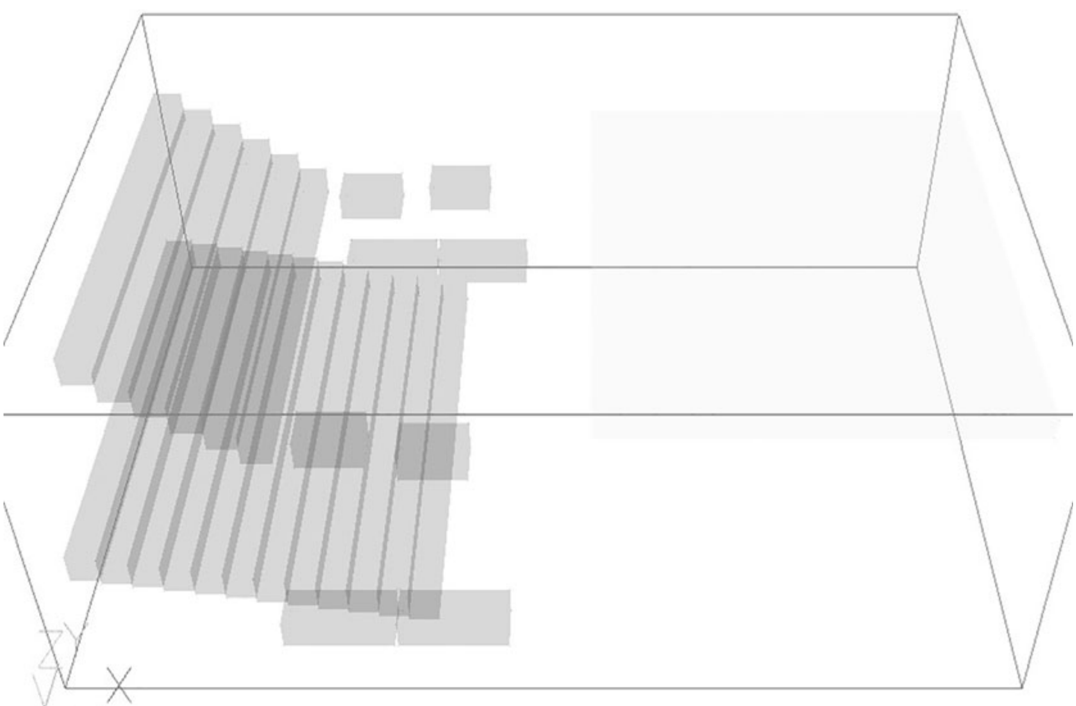

Figure 3C.11 Internal source objects of theatre case study.

Numerical grid

The main dilemma of grid generators selection is between structured or unstructured grids, and orthogonal or non-orthogonal grids. Each of these grids has its advantages and disadvantages related to grid complexity, solution convergence and computer time consuming. Non-orthogonal and unstructured grids are very complex and sensitive to solution convergence; however, the complex shapes of internal objects as well as complex building envelope walls can be introduced without significant geometry approximation. On the other hand, orthogonal and structured grids are simpler; however, there are needs for some geometry approximation. In any case, the accuracy of final solution should not be depended on selected grid generator.

The computer resources should be utilized in a balanced manner, care being taken not to squander time by the use of excessively fine computational grids when the models of the physical processes are comparatively crude.

The opposite extreme should be equally avoided. Some turbulence models are rather elaborate and time-consuming; and these are sometimes (ill-advisedly) employed in circumstances in which, because many small solid objects are immersed within the fluid, the number of grid nodes between two adjacent solids is far too small for the velocity gradients to be computed with adequate accuracy. Therefore, there is a need for a 'balanced-accuracy' models and grid resolution, which, by avoiding extremes, make optimal use of limited computer resources. For example, one possible way would be to generate an effective and simple grid using an orthogonal structured grid with option to increase grid resolution in specific parcels by technique of fine-grid-embedding, because this provides sufficient ability to fit small-scale flow features without the computational overhead of fully unstructured grids.

Based on the previous discussion and a need for 'balanced-accuracy' models, in the theatre case study, 140 × 153 × 75 cells were set-up in the x, y and z directions, respectively.

Defining the physical model

Governing equations

A three-dimensional flow model should be set-up using the incompressible steady state Navier-Stokes equations coupled with continuity equation, energy, mass fraction of water vapour and mass fraction of carbon dioxide conservation equations, as it is summarized in Table 3C.6. It should be noted that additional source term of buoyancy forces is added in momentum equations. Also, the production of heat and mass of water vapour and carbon dioxide are specified as the boundary conditions.

Table 3C.6 Summarized TC and IAQ model of theatre.

Governing equation:	Φ	Γ_Φ	S_Φ
Continuity	1	0	0
Momentum	U_i	ν_{ef}	$-\partial P/\partial x_i + \beta\,\rho\,g_i\,(T - T_{ref})$
Turbulence dissipation rate	ε	$\nu+\nu_t/\sigma_\varepsilon$	$(\varepsilon/k)\,(C_{\varepsilon 1}\,2\,\nu_t\,S_{ij}S_{ij} - C_{\varepsilon 2}\varepsilon)$
Energy	T	a_{ef}	0
Mass fraction of water vapor	X_{H2O}	$D_{ef,\,H2O}$	0
Mass fraction of carbon dioxide	X_{CO2}	$D_{ef,\,CO2}$	0

Turbulence modelling

Apart the geometry complexity, the central physical phenomena responsible for mixing processes is turbulence. Air motion and heat and mass transfer of related species such as water vapour and pollutant (e.g. CO_2) are turbulent in nature. The turbulence diffusivity, which causes rapid mixing and increased rates of momentum, heat, and mass transfer is the single most important feature as far as HVAC applications are concerned. Actually, the outstanding characteristic of turbulent motion is its ability to transport or mix momentum, kinetic energy, and contaminants such as heat, moisture, pollutants and particles. The rates of transfer and mixing are several orders of magnitude greater than the rates due to molecular diffusion.

In this case, it is much better to apply one of appropriate modification of k-ε model since the extra sources due to buoyancy forces fluctuations have to be added into k and ε equations. For example, Chen-Kim modification of standard two-equation k-ε turbulence model is frequently recommended. The modified k-ε model is summarized in Table 3C.7.

Table 3C.7 Summarized turbulence model TC and IAQ model of theatre.

Turbulence model equations:	Φ	Γ_Φ	S_Φ
Turbulence kinetic energy	k	$\nu+\nu_t/\sigma_k$	$2\,\nu_t\,S_{ij}S_{ij} + B - \varepsilon$
Turbulence dissipation rate	ε	$\nu+\nu_t/\sigma_\varepsilon$	$(\varepsilon/k)\,(C_{\varepsilon 1}\,G - C_{\varepsilon 2}\varepsilon + C_{\varepsilon 3}B) + C_{\varepsilon 4}G^2/k$
$\nu_t = C_\mu k^2/\varepsilon$; $G = 2\nu_t\,S_{ij}\,S_{ij}$; $B = (\nu_t\beta g_i/\sigma_T)(\partial T_i/\partial x_i)$; $S_{ij} = 1/2\,(\partial U_i/\partial x_j + \partial U_j/\partial x_i)$			
$C_\mu = 0.09$, $\sigma_k = 0.75$, $\sigma_\varepsilon = 1.15$, $C_{\varepsilon 1} = 1.15$, $C_{\varepsilon 2} = 1.9$, $C_{\varepsilon 3} = 1.44$, $C_{\varepsilon 4} = 0.25$			
$\nu_{ef} = \nu+\nu_t$; $a_{ef} = a + a_T$; $D_{ef} = D + D_t$; $D_{tH2O} = \nu_t/\sigma_{H2O}$; $D_{tCO2} = \nu_t/\sigma_{CO2}$			
$\sigma_T = \sigma_{H2O} = \sigma_{CO2} = 0.9$; $\beta = 1/T_{ref}$			

Thermal comfort indices

Important purpose of every environment is to provide sensation of thermal environment for the occupants. Sensation of thermal comfort is related to environmental parameters, such as air temperature, mean radiant temperature, air velocity and humidity, as well as personal factors, such as metabolic heat production, clothing, etc. Balancing the heat production by the body to the heat loss from the body at a comfortable skin and body core temperature defines a set of environmental and personal parameters that result in a neutral thermal sensation.

In practice, the indoor environmental indices are rarely optimal for achievement of thermal neutrality. In such case the thermal environment puts a strain on the thermoregulatory mechanisms of the body. The measure of this strain is provided by the PMV index, which is the Predicted Mean Vote of a large group of people subjected to certain combination of environmental parameters. The vote is represented on the seven-point thermal sensation scale, which ranges from –3 (cold) to +3 (hot). The dissatisfaction with the thermal sensation is estimated using the PPD index (Predicted Percentage of Dissatisfied), which is calculated as a function of the PMV index. This is known as PMV-PPD approach of thermal comfort quantification (ISO, 1994; ASHRAE, 2004; CIBSE, 2005) commended criteria for the thermal environment can be found in EN (2007). Examples of recommended categories for design of mechanical heated and cooled buildings are presented in Table 3C.8.

Table 3C.8 Recommended categories for design of mechanical heated and cooled buildings.

Category	*Thermal state of the body as a whole*	
	PPD (%)	*PMV*
I	< 6	– 0.2 < PMV < + 0.2
II	< 10	– 0.5 < PMV < + 0.5
III	< 15	– 0.7 < PMV < + 0.7
IV	> 15	PMV < – 0.7, or PMV > +0.7

Indoor air quality and ventilation rates

The most clearly defined area of indoor environmental health is occupational health, particularly as it pertains to workplace air contaminants. In general, in non-industrial environments, there are many more contaminants that may contribute to problems, they are more difficult to identify, and they are usually present in much smaller concentrations. There are different categories of indoor air quality, which will influence the required ventilation rates. These categories can be expressed in different approaches:

- combination of ventilation for people and building components;
- ventilation per m^2 floor area; and
- ventilation per person or according to required CO_2 level.

By CFD simulations, it is possible to obtain local distribution as well as averaged indoor level of CO_2. Therefore, the third approach is the most appropriate to quantify level indoor air quality. For example, recommended CO_2 concentrations for energy performance of buildings calculations and demand control are summarized in Table 3C.9, whereas the basic required ventilation rates diluting emissions of bio effluents from people are summarized in Table 3C.10.

Table 3C.9 Recommended CO_2 concentrations above outdoor concentration.

Category	*Corresponding CO_2 concentration above outdoor concentration (ppm)*
I	350
II	500
III	800
IV	> 800

Table 3C.10 Basic required ventilation rates.

Category	*Basic required ventilation rates*	
	Expected percentage dissatisfied	*Air flow per person (l/s/person)*
I	15	10
II	20	7
III	30	
IV	> 30	< 4

The local air diluting by achieved local ventilation rate can be assessed by simple formula:

$$\dot{V} = \frac{\dot{m}_{PROD}}{C_{IDA} - C_{SUP}} \tag{3C.3}$$

where:

$\dot{V}$ = local volume flow rate of supply air (m^3/s)
$\dot{m}_{PROD}$ = local mass flow rate of bio effluents production (mg/s)
C_{IDA} = the allowed CO_2 mass concentration in the occupied space (mg/m^3)
C_{SUP} = the local CO_2 mass concentration in the occupied space (mg/m^3)

Additionally, for local indoor air quality assessment is very useful parameter knowing as mean age of air (τMAA). This quantity represents the time since air particle entry (e.g. related diffuser) at each point in the domain; therefore, it provides a measure of air freshness, lower values being more favourable. It can be derived from its own transport equation which is numerically solved, simultaneously with the set of governing equations (Table 3C.6) and turbulence transport equations (Table 3C.7).

$$U_j \frac{\partial \tau_{MAA}}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\Gamma_{MAA} \frac{\partial \tau_{MAA}}{\partial x_j}\right) = 0 = 1 \tag{3C.4}$$

where Γ_{MAA} (m^2/s) is the transport coefficient of τ_{MAA}.

In 'dead' zones, such as in recirculation areas, the time since entry will tend to be a large value as the air will be trapped there. These values should be treated as indicative rather than the exact ones. In regions where there is a reasonable exchange of air, the values will be correct.

Boundary conditions

The unique solution of the coupled partial differential equations of the set of governing equations (Table 3C.6) and turbulence transport equations (Table 3C.7) and equation (3C.4) can be obtain by specifying boundary conditions and related sources. There are some different classes of boundary conditions and related sources:

- inlet and outlet boundary conditions;
- internal heat and mass sources; and
- wall boundary conditions.

Inlet and outlet boundary conditions as well as internal heat and mass sources are related to the HVAC and internal objects. Details of this kind boundary conditions specification are presented in the previous section.

Wall boundary conditions are specified by well-known logarithmic wall functions. However, the internal wall temperature has to be specified. Basically, there are two possibilities to determine these temperatures, by calculations or by direct measurements. Calculations can be based on indoor and outdoor heat fluxes balance. It should be noted that radiation heat transfer has to be taken into account.

Specifically, for the theatre case study, the surface temperatures of the ceiling, floor and internal walls, were measured: 23.8°C, 22.8°C and 24.8°C, respectively, at the beginning of the monitoring period, staying almost constant during the performance.

Model validation

Rigorous CFD simulation requires implementing a sequence of stages: an object – a model – a discrete model and computational algorithm – computation – an analysis of results and comparison with practice. Conditionally speaking, two phases may be distinguished in the mathematical modelling: a choice and validation of a model, therefore, any model which pretend to be used in future scenarios has to be validated by existing well tested experimental or numerical cases. Obviously, validation phase raises the question of which level of CFD accuracy has to be achieved. The CFD accuracy is strongly dependent on the designer's skill, experience, and knowledge. Accordingly, the increasing number and increasing quality of numerical calculations of flow fields require more adequate and reliable data for examining the CFD validation in order to decide whether the physics of the problem has been modelled correctly.

Generally speaking, there are no specific recommendations on acceptable CFD accuracy for built environment CFD applications, however, the previously mentioned Professor Spalding commented once that: "it is much better to be approximately right than absolutely wrong." Having this principle in mind, the Figures 3C.12–3C.15 give the distribution of a few parameters (air flow, air temperature, PMV and AGE) in the central vertical cross-section plane clearly showing the basic principles of displacement ventilation.

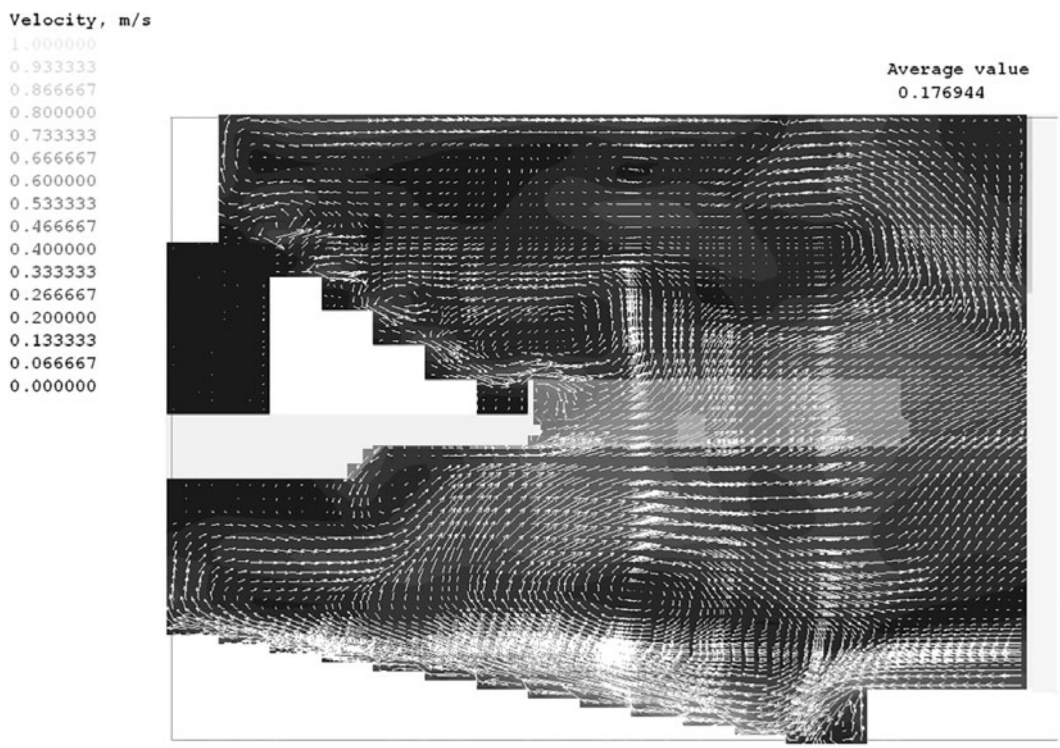

Figure 3C.12 Air flow pattern of theatre case study.

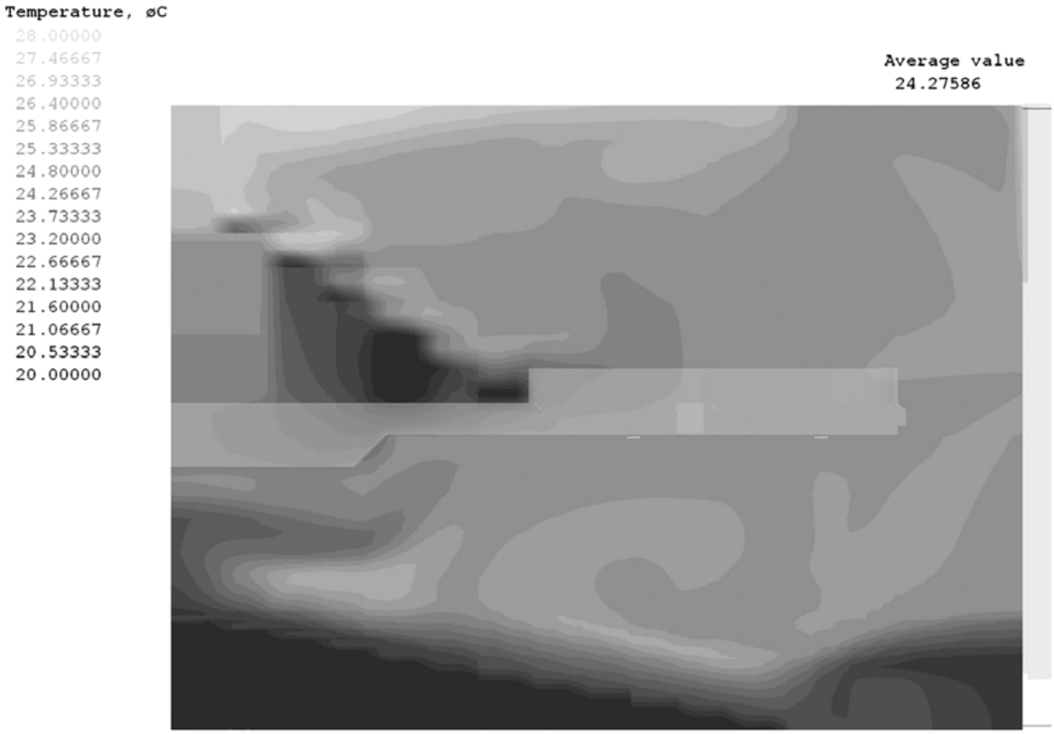

Figure 3C.13 Air temperature distribution of theatre case study.

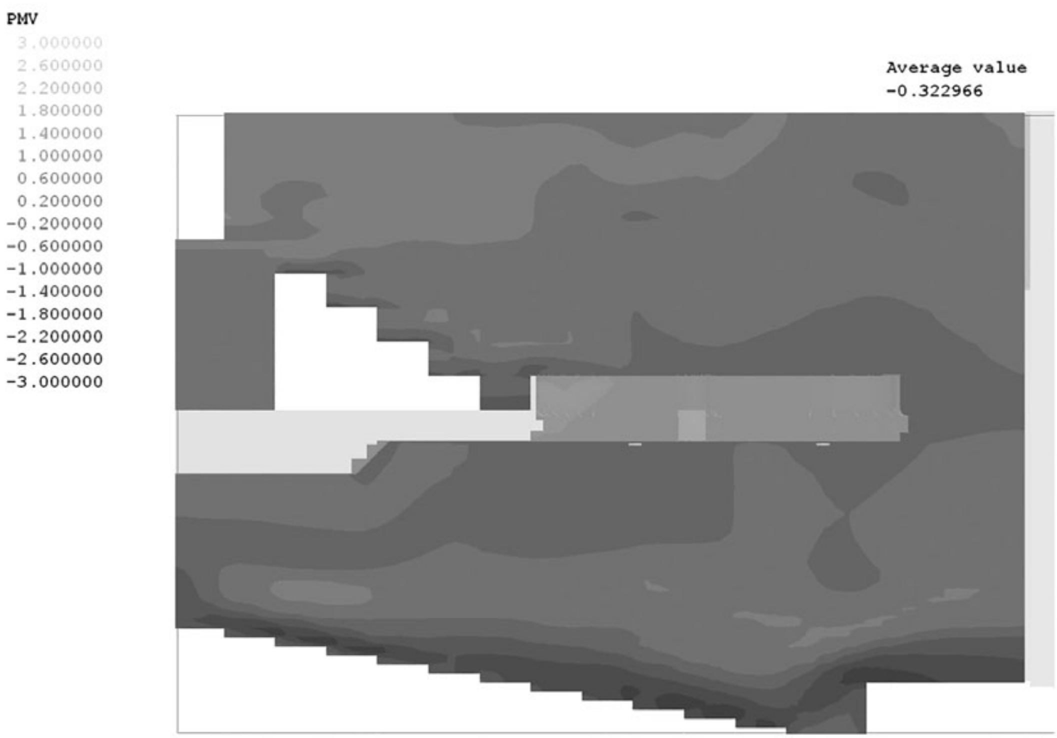

Figure 3C.14 PMV indices distribution of theatre case study.

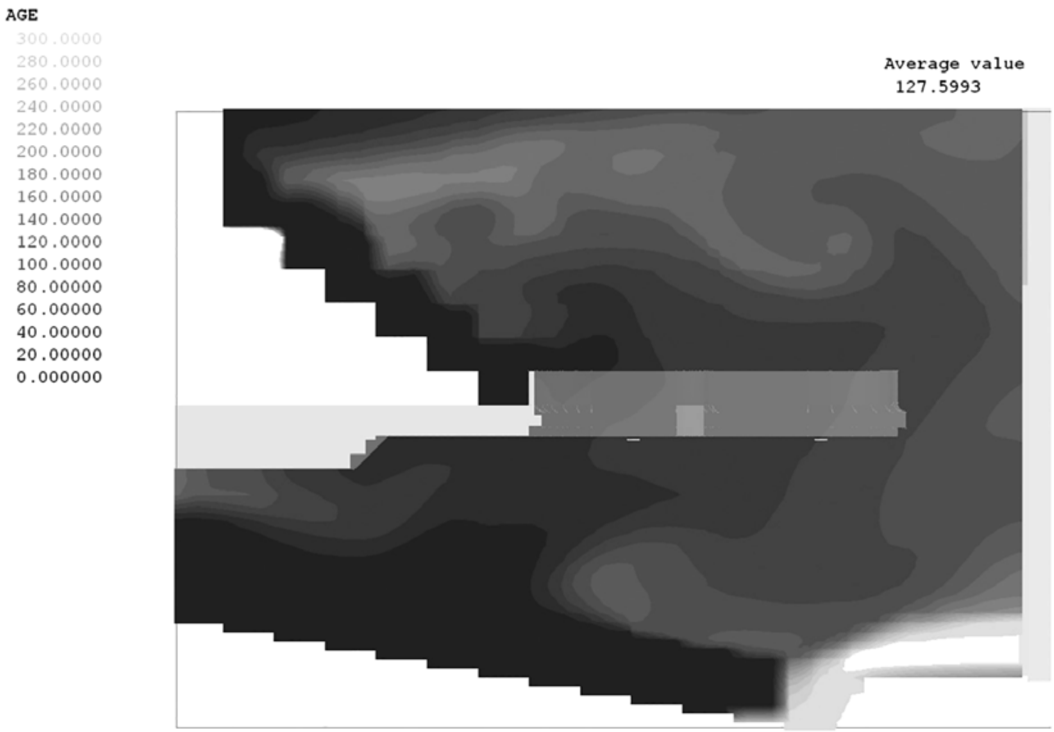

Figure 3C.15 AGE distribution of theatre case study.

In the theatre case study, the monitoring of indoor physical parameters was performed before, during and after performance. These measured data have been used to validate CFD predictions. Numerical probe is located approximately at the same position as location of measurement. It is the centre of the first exhaust diffuser located at the theatre hall ceiling. The proper view to compare the experimental and numerical results is the distribution of related variables in horizontal plane located near the theatre ceiling. For example, the air temperature, CO_2 volume fraction and relative humidity distribution in horizontal cross-section plane where measurement has been performed are shown in Figures 3C.16–3C.18 respectively. At the right-upper part of figures, the probe value of related variable is specified as well as the average value in the shown plane. Comparison of measured and numerical data is summarised in Table 3C.11.

Table 3C.11 Comparison of measured and numerical data.

Probe location (first exhaust diffuser)	*Air temperature (°C)*	*CO_2 volume fraction (ppm)*	*Relative humidity (%)*
Measured data	25.40	795.0	61.0
Numerical data	25.65	738.8	45.4
Relative error	1.0 % over predicted	7.0 % under predicted	25.6 % under predicted

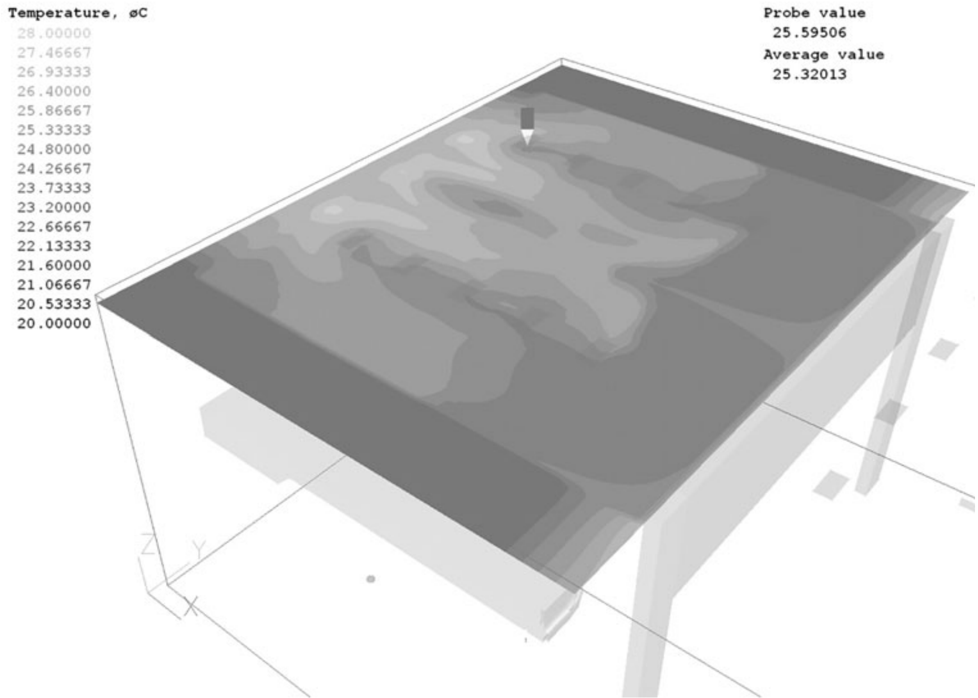

Figure 3C.16 Air temperature distribution in horizontal cross-section plane.

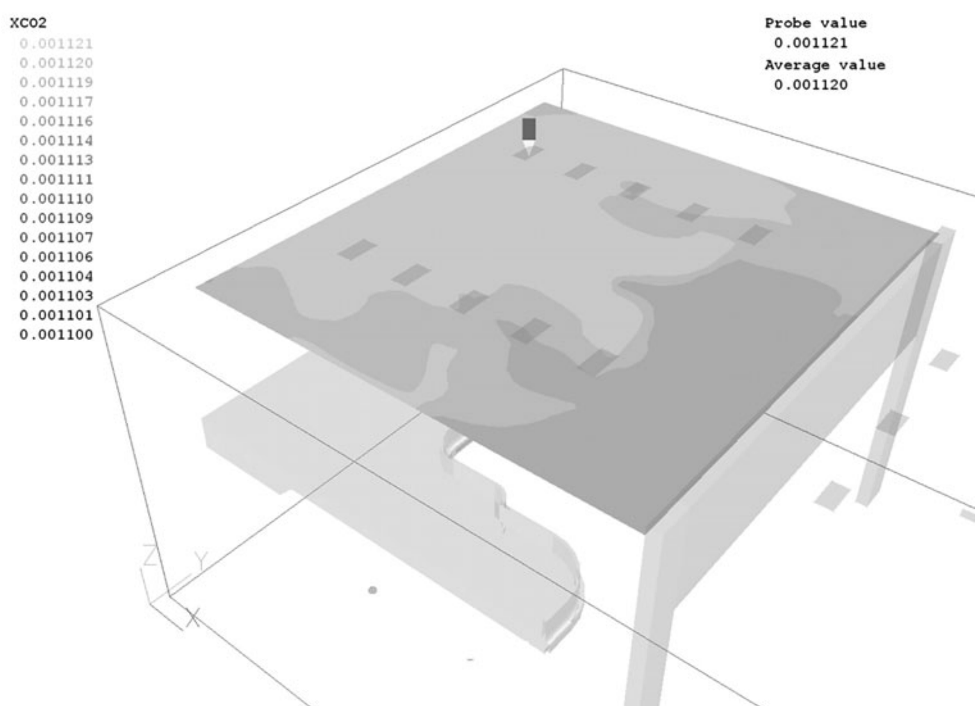

Figure 3C.17 CO_2 volume fraction distribution in horizontal cross-section plane.

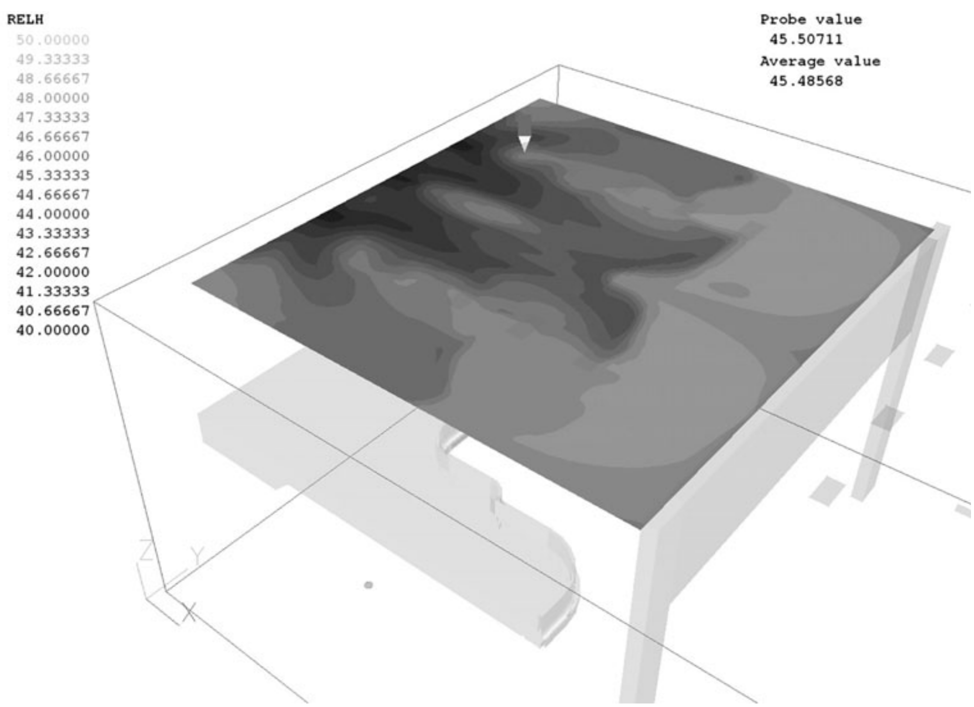

Figure 3C.18 Air relative humidity distribution in horizontal cross-section plane.

Based on relative errors, it can be concluded that the air temperature and volume fraction of carbon dioxide are at the acceptable predicted level, however the under predicted level of relative humidity is too high. It should be expected since the partial pressure of water vapour and saturation pressure as well as mass fraction of water vapour are very sensitive to air pressure and density. Since the mixture of air, water vapour and carbon dioxide are assumed to be an ideal gas related by the air ideal gas law, it is reasonable to conclude that is the mean reason of high level of under predicted relative humidity.

Acknowledgements

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PART 4

Operational performance of buildings

Introduction

Dejan Mumovic and Mat Sanatmouris

The post occupancy evaluation (POE) of buildings is a vital component in the construction of complex built environments. Chapter 4.1 states that it is only from a sound understanding, based on robust evidence, of how a building works in use that the design process can be developed to produce the built environment that satisfies the needs of the occupants, owners and the larger environment in terms of reduced carbon emissions. Use of POE in benchmarking, appraising a building design approach and investigation of a problem is discussed. In addition to the energy use, the sound technical methodologies for the assessment of the internal environmental performance, such as thermal comfort, ventilation, lighting and noise are proposed. Building on Chapter 4.1, Chapter 4.2 explores the impact that the contextual pressures (the framework of legislation, guidance and other influences) may have on building energy consumption and discusses how feedback information could be used to facilitate better decisions in the design, construction and management of buildings to improve resultant building energy consumption.

Chapters 4.3 and 4.4 are focusing on two essential aspects of the energy performance of buildings: energy benchmarking and energy performance gap. Chapter 4.3 introduces benefits of energy benchmarking: (a) it raises the awareness of how efficiently energy is being used in a building, which is often identified as a key barrier to improving the energy efficiency of buildings, and (b) feedback from the exercise can put the operational efficiency into perspective, therefore encouraging building operators to take actions to identify problematic areas and operate their buildings more efficiently. Chapter 4.4 describes on-going efforts to understand the energy performance gap which utilises calibration techniques to fine-tune a building energy model to actual operating conditions and energy use, ideally over a longer period of time. This chapter also gives insights into the operational inefficiencies of a building and pinpoints underlying reasons for differences between design estimations and actual use. Chapter 4.5 explains more specifically that unexpected behaviour by occupants can degrade whole system performance and potentially overturn the savings expected by designers or policymakers. Therefore, the aim of the chapter is to explore the socio-technical factors that operate in the built environment, specifically the relationship of occupant behaviour to energy use in the domestic sector, using three examples from the UK.

Last but not least, at the end of Part 4 of the book we have included four case studies:

- Case Study 4A: Natural ventilation of auditoria – three case studies. This chapter presents guidance distilled from the POE and experiences gained by the design teams involved to provide architects and engineers with some insight into the design of naturally ventilated auditoria. The selected case studies include the Queens Building at De Montfort University, the Contact Theatre in Manchester, which comprises two auditoria, and the Lichfield Garrick, also incorporating two auditoria.

- Case Study 4B: Naturally ventilated building in a city centre. The Frederick Lanchester Library at Coventry University is a deep plan, naturally ventilated building close to the city centre of Coventry. This chapter describes the design and operating strategies that are employed in the building and presents user comments as well as results from monitoring studies, which include assessments of the building's thermal and energy use performance. The building's likely performance in other UK cities is also discussed.
- Case Study 4C: Low carbon, high performance, large retail premises. A team from Faithful+Gould and UCL evaluated the performance of the Marks and Spencer's (M&S) flagship sustainable learning store (built in 2012) after a year of operation. The store was designed to be their most sustainable to date and incorporated several key features to help in this. The design target for the store was to be 30% more energy efficient, and have 35% less carbon emissions than a benchmark M&S store.
- Case Study 4D: Impact of an energy refurbishment programme in Chile: more than energy savings. The analysis of housing energy performance in Chile has revealed how poorly designed dwellings could negatively feed the poverty cycle and how vulnerable to energy dependence such dwellings could be. This complex study highlights a number of issues of importance to the success of an energy refurbishment programme including: (1) the characterisation of type, form, materials and heating systems of the housing stock, (2) estimation of the current energy intensity of the housing stock, (3) proposal of refurbishment goals, (4) regional adjustment and optimised priorities, (5) expected energy intensity improvement, cost analysis and payback, (6) expected social and private benefits, (7) institutional requirements, human resources and financing schemes. This overarching chapter clearly highlights that sustainable building design and engineering requires an integrated approach to energy, health and the operational performance of buildings.

4.1
POST-OCCUPANCY EVALUATION OF BUILDINGS

John Palmer

Introduction

The post occupancy evaluation (POE) of buildings is a vital component in the construction of complex built environments. It is only from a sound understanding, based on robust evidence, of how a building works in use that the design process can be developed to produce the built environment that satisfies the needs of the occupants, owners and the larger environment in terms of reduced carbon emissions. The history of POE goes back to the 1960s in the UK and was even designated as Part M of the RIBA Plan of Work (Cooper, 2001).

A strict interpretation of POE requires that the building has been completed and occupied for a significant period – usually more than one year – and the evaluation relates directly to performance aspects of the building. However, a wider definition to include the design and construction process has been used (HEFCE, 2006).

Given that modern buildings are asked to respond to a wide range of performance demands, for example optimised space provision, productivity, costs and energy, the designs become more challenging for the architect. Hence for more advanced and complex buildings it is important to return to the building, as constructed and used, as only by doing this can we assess the success or failure of the design.

POEs can vary from a simple 'walk round' of the building through to detailed monitoring of minute by minute performance of a specific feature over a year of operation. This chapter will outline some of the issues that POE must address and measurement and monitoring techniques that have been developed. It provides guidance on methods to adopt for the variety of issues that POEs can be used to appraise and shows the breadth of methods available. Pointers are given on how they can be used rather than the fine detail of any particular POE method, as these can be found elsewhere in the referenced material.

Post occupancy evaluation tends to be used in the following situations:

- benchmarking;
- appraising a building design approach;
- investigation of a problem.

The focus of a POE can be either on the physical aspects of the building and its performance, such as the energy or internal environmental conditions, or the responses of the occupants in relation to matters of productivity, health or amenity.

It is not particularly important which of these two possible motives is responsible for conducting the POE. The first question to be asked when considering a POE is 'why is this investigation being made?' Answering this question will set the scene for the choice and development of the appropriate approach. The methods used may be similar in these two cases but the aims may be quite different. It is necessary to bear in mind that the occupant's satisfaction can be appraised as a result of some physical design feature of the building which is either working correctly or not; and the physical performance of the building may be a result of occupant usage. POEs have been used in all these permutations. The following considers the main range of interests for POEs.

Benchmarking

Placing the performance of the building in the context of other similar buildings provides a useful pointer as to how it is performing. This has been widely used in assessing energy performance and a range of 'key performance indicators' (KPIs) can be used to judge the performance. These may be absolute values of energy consumption, but, most often, they are based on a normalisation procedure which makes for more reliable comparisons. For example the energy use of a school may be expressed as the energy use per unit area of the school (kWh/m^2) or based on the number of pupils (kWh/pupil).

The KPIs tend to be based on the global performance of the building using the type of information which would be available from the utility meters used for billing. In some cases it may be desirable to disaggregate the energy by end use. In the UK, Part L of the Building Regulations now require that this is possible in larger, non-domestic buildings (BRECSU). This benchmarking exercise is becoming more prevalent with the introduction of the 'energy performance of buildings directive' (EPBD) (European Parliament and Council, 2002). This requires the energy performance of buildings to be measured and compared with benchmark figures.

Benchmarking can also be used for other aspects of the building such as the space allocation, productivity and costs of construction, which may be expressed as m^2 per occupant of £/m^2, for example. For the more subjective parameters such as the occupant satisfaction and amenity it is more difficult to benchmark unless a consistent methodology and technique has been used.

Design approach

If the POE is being carried out to investigate the extent to which a design solution has been successful, it is necessary to have a clear definition of the design intention. There can be a range of design intentions and each of these can be expressed at different levels of design. The normal overarching design intentions relate to one or more of the following:

- low carbon/energy use;
- sustainability;
- high productivity;
- healthy occupants;
- low cost.

These over-arching design intentions are typical of the aspirations of modern designs. However, which of these (and how these design intentions have been realised) needs to be specified before the POE begins.

Low energy or sustainable designs may incorporate passive design features such as night time cooling by natural ventilation or daylighting to displace electric lighting. It may be the purpose of the POE to evaluate the benefit of this design solution, precisely commission it, or remedy a malfunctioning system.

This is largely an exercise in building physics and as such will require a systematic measurement approach based on firm physical properties.

However, it is not only the energy performance that may be the driving force behind the design. For example, a building may have been designed to produce a highly productive office facility. The actual design may have intended for this to come about by any number of design solutions. It may be attention to layout of the internal space in line with current ideas about working styles or it may be by narrow plan design giving good daylight and occupant control over natural ventilation. In this context we may use the term 'human factors' to address all the variables that have an impact on the occupants and their experience of, and interaction with, the building – including 'occupant satisfaction'.

The term 'occupant satisfaction' as used here is taken to represent, in the broadest sense, the satisfaction of the people who inhabit the building. It can be the response of the day-to-day users of the building to how it affects their working experience and health but it may also be the owner's expectation of productivity, cost, or the facility manager's ability to control the building performance. Many of the recent approaches to POE have been directed toward the productivity and occupant satisfaction aspects of the building performance (Jaunzens et al., 2002; British Council for Offices, 2007).

The productivity can be a function of a wide range of factors in the building. The physical aspects of the internal environment such as thermal comfort, lighting and ventilation can all have an impact on the energy performance, as discussed above, but the occupant satisfaction is also highly dependent on these parameters. In addition to this there are many other factors in the building that can affect productivity and occupant satisfaction.

It is the POE on the design aspect of the building that serves to provide the feedback to the design profession as to the success or failure of specific design solutions. As POEs are not required as part of the normal duties of constructing a building it is rare that they are carried out. Typically in the UK, the POEs that have been conducted to establish the performance of a building, based on an interest in the design solution, have been funded as research projects such as the Energy Performance Assessment of 1987–1993, sponsored by the Energy Technology Support Unit on the behalf of the UK Department of Energy.

Investigating a problem

Most common is the POE that is carried out to determine why a building is not performing to the standard required. This can be either from the energy or environmental requirements – too much energy or occupant dissatisfaction with internal conditions – or low productivity.

When productivity is the focus of the POE the benefits to an organisation can be great if the solution means less absence due to sickness or lower turn-over of staff. The costs of a POE can be small compared with the long term benefits of reducing these staff related problems. The British Council for Offices Guide to POE (BCO, 2007) gives a number of case studies of the benefits of POEs in offices.

Key issues that influence productivity, but are not related directly to the environmental conditions, include personal control, responsiveness, building depth and work groups. But factors such as layout of the space, aesthetics and privacy can also have both an influence and confounding effect. Simply measuring the 'productivity' of the occupants of the office may not necessarily provide the answer to the underlying causes of the problem.

Physical performance evaluation

Providing the optimum internal environment for the occupants is one of the main purposes of the design of the building and its services. The combination of the building and its services should also do this using the least amount of energy. This is a key area for POE as failure to achieve the design conditions will most likely have impacts on the overall performance of the building and its occupants. For example, a novel daylighting scheme may well cause a problem for the occupants with glare or gloom and also have consequences for the energy consumption.

The key physical parameters of the internal environmental performance that require study are normally:

- thermal comfort;
- ventilation;
- lighting;
- noise.

Thermal comfort

The thermal comfort of an occupant is dependent on many variables (BSEN 7730: 1995). The most important parameters of the environment – other than the level of dress of the occupant – are the temperature and the air movement. For most POEs the key parameters to measure are either the dry air temperature or the mean radiant temperature and some aspect of air movement.

The most precise measure of thermal comfort is to use a 'thermal mannequin' (Tsuzuki et al., 1999). This simulates the human form and takes account of its own internal heat source and clothing levels. It is also fitted with the full range of sensors to determine the thermal comfort. This is more of a specialist research method and is therefore not used in routine POE assessments.

Most commonly, the temperature of the environment is measured by a temperature sensor (platinum resistance) covered by a small (approximately 2.5cm diameter) black sphere. This will give a reasonable measure of the thermal experience of an occupant, if the environment is reasonably uniform. If large radiant surfaces are near to the occupants then this asymmetric radiant field will distort the perception of thermal comfort. Placed in direct sunlight this will give a very high reading.

The time interval for recording the temperature measured by this method does not need to be very short, a time interval of 15 minutes is quite adequate. Any requirement for a shorter interval probably implies that the issue is to do with draughts or transient radiation rather than normal environmental temperature control.

Draughts are the second most important aspect of thermal comfort and this can be measured by a suitable anemometer. Air velocities over the range 0.05m/s to 5m/s may be of interest but these are at the lower end of the resolution for many anemometers as used in dealing with ventilation systems. The variability of draughts can also be an issue and therefore in some cases the 'turbulent intensity' of the air stream is also measured.

Ventilation

Measuring the ventilation rate in buildings is challenging. Unlike energy or occupant satisfaction, the rate of air exchange is difficult to measure directly. Even in mechanically ventilated buildings where the air flowing in the ventilation system can be measured directly, the actual supply of external air will still depend on other factors such as the air leakage of the building envelope and the ventilation system ductwork.

The most accurate methods of measuring fresh air rates involve some means of measuring a constituent of the internal air and noting its change with time. Ventilation studies in the past have used a range of tracer gases that are introduced into the building in a known way and their concentration measured over time to provide the ventilation rate of external air not containing the tracer gas. AIVC (1988) describes, in detail, the alternative methods that may be used.

Unfortunately, many of the methods use gases such as sulphur hexafluoride or perfluorocarbons that may be unacceptable to occupants and are now less acceptable as they have a high global warming potential. The simplest method is to use the carbon dioxide which is emitted into the building by the occupants. Using carbon dioxide from the occupants is safe and non-intrusive. If the building is empty it can easily and safely be dosed with carbon dioxide which provides even more control over the determination of the ventilation rate.

A study in secondary schools in England used this technique extensively (Mumovic et al., 2008) and in doing so also carried out intervention studies to determine how changes in window use would influence the ventilation rate in the classrooms. Under normal circumstances in buildings a carbon dioxide analyser measuring over the range of 0–5000ppm is required. Preferably, the analyser should have a sampling interval of approximately 5 minutes and internal memory to store the results for later analysis.

The normal analysis is to determine the decay of the carbon dioxide under the ventilation conditions of interest. The rate of decay is then a function of the rate at which external air enters the space. It is possible to infer ventilation rates of occupied spaces by the concentration of carbon dioxide measured directly but this requires stable occupancy over a longer period of time to ensure that steady state conditions have been reached.

Lighting

The way in which a building is lit can have significance for both the energy use and the occupant satisfaction and productivity. Large, deep plan offices must rely on electric lighting and this has implications for energy use (not only for the lighting but potentially for the air-conditioning required to remove the heat it generates) and the visual comfort of the occupants. Providing daylight to the space can replace the electric lighting energy use but in doing so it must not produce glare or excessive solar gains.

A simple measure of the daylighting potential is to determine the 'daylight factor' in the building. The daylight factor is the ratio between the external global illuminance and the internal illuminance under a particular type of sky condition known as 'standard overcast'. Making a measurement of this is not difficult but does require the simultaneous measurement of internal and external illuminance under a completely overcast sky – a condition which is less common than imagined. Measurements of illuminance over the range 100 to 20,000 lux would normally be adequate for determining the daylight factor. The measurement of the performance of a daylighting strategy is given in Heap et al. (1988).

The most likely issues with a POE of lighting will either be glare from incorrect provision of daylight or electric light or excessive energy consumption of lights which are not sufficiently well controlled – either by the occupants or a lighting control system. Although glare is a subjective experience, measurements of the luminance environment may show if this is a likely cause.

Noise

The acoustic environment in a building can be a crucial factor in its success or failure. At the extreme end of the spectrum of performance requirements are spaces such as concert halls and recording studios which both have exacting standards. However, noise (simply defined here as an unwanted level of sound) is important in all building types. Schools are a particularly interesting case as they incorporate a wide range of activities within a single building. Teaching spaces, that have strict requirements of acoustic performance, can be in close proximity to gymnasia occupied with noisy activities. In the UK this has led to the publication of Building Bulletin 93 'Acoustic Design of Schools' (DES, 2003) which deals with the prevention and control of noise. It also deals with the fundamentals of acoustics and how it is measured in buildings and provides a series of case studies.

If noise is considered a problem it may be a consequence of a number of factors, but, most likely, it will be too much sound or a problem with reverberation time. The intensity of the noise is a function of the sound pressure level, most commonly expressed as dBA, which is used to indicate the human response to a noise. The instruments for measuring sound are normally able to report a range of measures of the noise source, including the minimum and maximum and on a time averaged basis.

The reverberation time in the space has an effect on the auditory experience but is not easily measured without specialist equipment. In general it may be that for acoustic problems it is advisable to take advice from an expert acoustician.

Energy performance

The energy performance of buildings is increasingly important as measures are taken to reduce their carbon footprint. The determination of the energy use of buildings has a long history and is of course used in billing for the energy utility. However, in terms of the POE of the performance there are still a large number of variables to consider if a low energy design intention is to be accurately assessed. The PROBE series of studies (Bordass and Leaman, 1995), adopted the Energy Analysis and Reporting Method (CIBSE, 1999).

Whichever method is used it is clear that, at the least, the occupancy of the building and the weather need to be taken into account. These are the two major determinants of the energy use of a building. The occupants need the building to be heated, ventilated and lit for their needs and if these are not fully measured then the energy performance will not be fully appreciated. Likewise, if the weather prevailing at the time of the monitoring is not monitored in parallel then the energy data may not reveal the answers that are required.

Simple analysis by means of degree-days can go some way to describe the building performance but it needs to be decided at the outset of the POE if this level of accuracy is adequate, or if some specific design intention is being investigated. Measurement of energy use on a daily basis is a reasonable recording interval as it can be used to distinguish between weekdays and weekends. Some aspects of performance that change during a day or night would require at least hourly measurements. In general, it is probably better to measure at an interval shorter than that which has been determined as the minimum for analysis.

Disaggregating the energy into the end uses is often required so that the performance of the mechanical and electrical services can be determined. This can also be important to take account of incidental heat gains from lights and appliances, as ignoring these can provide a significant under-estimate of the heating energy required.

In larger buildings there is usually a building or energy management system. It may be possible to use this for the monitoring but it is best to carry out a pilot study prior to committing to this for data collection to establish that it can collect, store and allow retrieval of the data that is required.

In some cases, a very detailed evaluation of the energy performance can be used to understand some of the underlying physical processes that are taking place. An example of this is the passive solar heating of dwellings in which a complex set of interactions exists between the available solar radiation and the way in which it replaces the need for heating energy. The Energy Performance Assessment Project (Hildon, 1986) and the 'Pstar: short term energy monitoring methodology' (Palmer et al., 1994) are examples of the techniques developed to investigate this aspect of building performance.

Human factors

Taking the term human factors to deal with all the occupant related issues, there are many aspects of a POE that can be investigated. POEs of the human factors can establish the performance of the building's productivity, health and amenity. It can tease out factors of occupant perception of the buildings performance, their understanding of control and the social interaction aspects of the building.

In response to this a wide range of techniques have been developed to provide the correct level of information. The key to this is that the study should be rigorous and evidence based. Simple anecdotal information can be misleading and dangerous if not dealt with due regard to subjectivity or bias.

The BCO guide (BCO, 2007) gives a very good account of how to carry out a POE of the occupant issues. It identifies the various techniques such as questionnaires, structured interviews and focus groups and how to deal with sampling and analysis.

Monitoring plan

Before beginning the POE it is always advisable to have a clear and written aim for the POE so that it can be focussed and effective. If there is no known and well defined purpose to the POE then it can become overly complex, ill-defined and finally inconclusive. Each data point collected costs time, resources and money to acquire and if it is not needed it is useless baggage to carry throughout the investigation. It will result in an excessive amount of data to process and analyse and may not provide the correct answer.

The ideal approach is to prepare a monitoring plan which defines the purpose of the POE, i.e. what question do we want to answer and what data will provide the answer. The monitoring plan that comes from this direct question will make the investigator consider how to answer this question and what data are needed to provide a robust answer.

For example, if a new building has been designed to avoid overheating by the use of phase-change materials to provide thermal mass, the obvious question to answer would be 'does the thermal mass of the phase change material reduce the level of overheating?' In asking this question a POE can be developed in the form of a testable hypothesis, but, it can be seen that even this simple question raises key methodological issues. For example, is the building to be compared with an identical building without the thermal mass or, in the case of a single building, is the overheating to be measured before and after installing the material. If is it only possible to make measurements with the material already in place then how do we determine the effect of the phase change material on the overheating in isolation from other influences within the building? Detailed consideration of the analysis route will also help with deciding what factors should be measured.

An issue allied to this is to the state that the building is in for the period of the POE. For example,is the POE carried out on the building 'as found' which is possibly malfunctioning, or is it to be re-commissioned to ensure that it is working at the optimum 'as designed' condition. This is a key decision if the POE is studying the success of a design solution which may be condemned on the basis of a malfunctioning system. For very complex situations this may warrant some modelling of the design to establish what factors are significant. The monitoring plan should also deal with the need for intervention studies.

Decisions will need to be made on the type of data-collection method to be used and if it is to be locally based or remotely accessible by interrogation over the web. The cost and scale of the project will determine some of these options but data integrity and security are issues and the danger of data loss is important. Regular checking of data is required to ensure that the full data set needed for analysis is available at the end of the project. To this end, it is worthwhile retaining, and frequently updating, a 'data map' showing data availability over the monitoring period.

This applies to the occupant issues as well as the physical parameters. Changes in occupancy during a monitoring period can have a major effect on the performance that is being evaluated and if this is not monitored during the project the conclusions may be in error.

Energy Performance Assessment project

The Energy Performance Assessment Project was a POE project that developed a rigorous methodology for monitoring and evaluating the performance of passive solar buildings taking account of all the physical aspects of building performance: the energy consumption, solar performance, daylighting, natural ventilation, occupancy issues, thermal comfort, amenity, satisfaction, control and building cost (Hildon, 1986). For houses, pilot trials of possible methods of determining the solar performance were backed up with dynamic thermal modelling of proposed methods.

The EPA project used the standardised methodological approach in both domestic and non-domestic buildings to assess more than 30 buildings in the UK. The starting point was interviews with the designers to learn the design intent and, from this, the production of the monitoring plan to test the efficacy of the design.

In houses the main aim was to determine the 'passive solar displaced space-heating', a term defined during the development of the project to judge the solar performance of the house. The analysis route for this can be seen in Figures 4.4.1 and 4.1.2, which show the need to measure some variables at hourly intervals to provide the resolution required for the analysis and how these were taken forward to provide an annual estimate of performance. Monitoring for a full year was seen as the minimum required in this case because of the whole year response of a passive solar design, in terms of displaced space heating in the heating season and overheating in the summer and shoulder seasons.

For non-domestic buildings the design intention was less to do with solar displaced space heating and often to do with a combination of daylighting and natural ventilation, with some element of solar heating. For these buildings it was even more important to learn how the designer intended the building to operate.

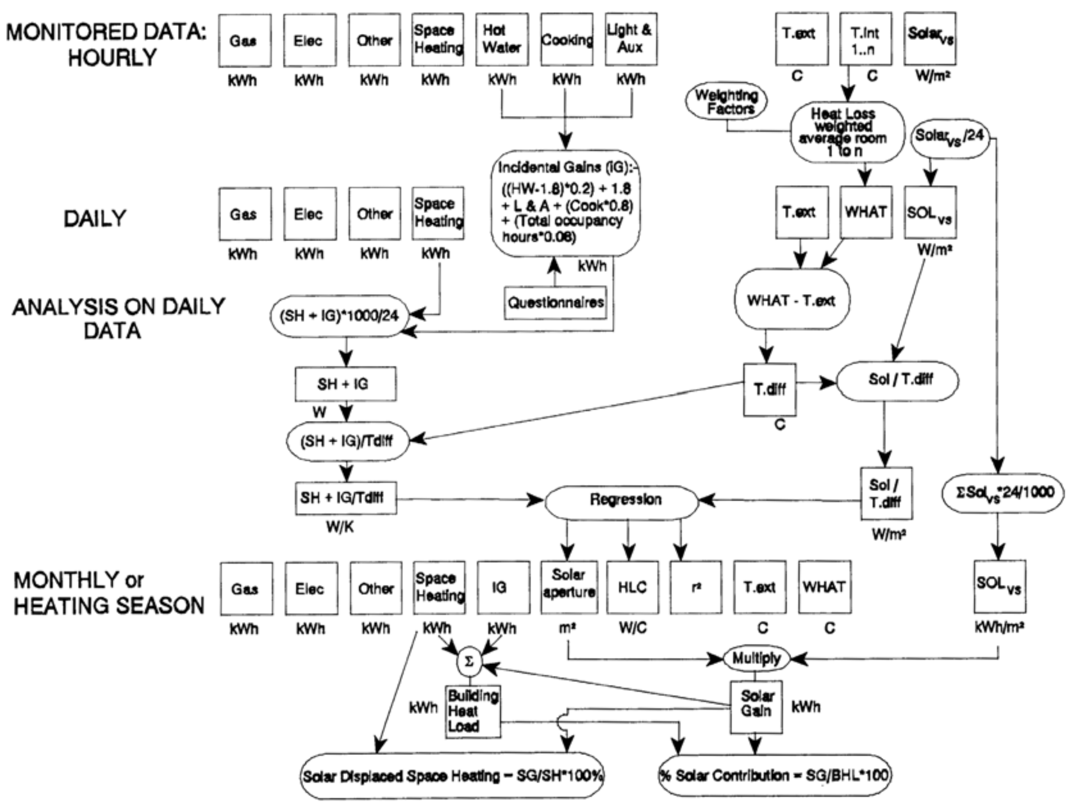

Figure 4.1.1 EPA analysis of hourly data.

However, it was acknowledged that passive solar design may cost more and possibly provide less thermal comfort (due to overheating) than a conventional house. Therefore, the POE evaluation also developed a series of questionnaires and occupant interviews to determine the occupants' satisfaction with the environment and their ability to control it.

Questionnaires were devised for both housing and the non-domestic buildings to be administered on a monthly basis to understand the dynamics of the occupants' response to the solar radiation and internal conditions. At least one interview was carried out with the occupants'. The information from these questionnaires and interviews was collated with the physical measurements to establish a high level of understanding of the occupants' satisfaction and the conditions provided by the design.

For the dwellings, the costing of the house was carried out by consultant QSs who also worked out the over costs due to the solar design. For the non-domestic buildings the costs were based on tender costs but normalised for location and time.

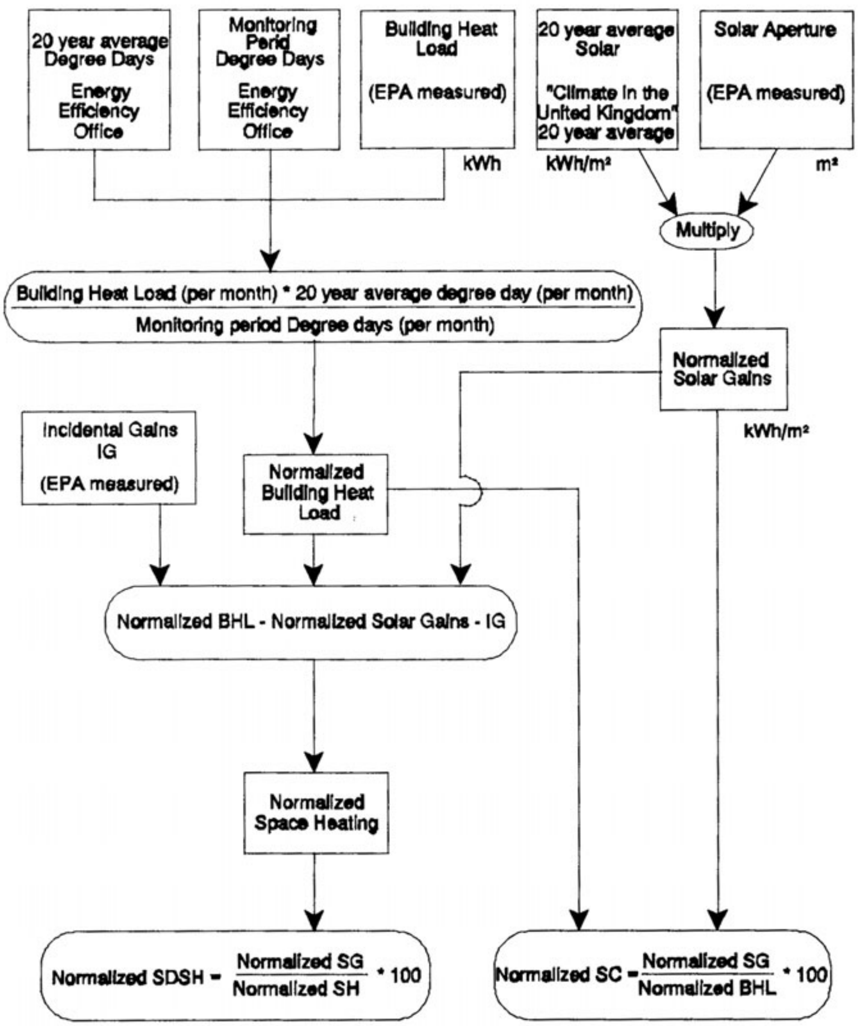

Figure 4.1.2 EPA normalisation of monthly data.

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4.2

THE ROLE OF FEEDBACK IN LOW CARBON BUILDING DESIGN, CONSTRUCTION AND MANAGEMENT

Craig Robertson and Dejan Mumovic

The contextual pressures

There is currently no tradition of integrating feedback into briefing, design and management of buildings and no meaningful connection between Post Occupancy Evaluation (POE) and the design process (Vischer 2009). There are many theoretical models of the design process and practical models used to organise the building procurement process, for which this chapter uses the RIBA Plan of Work. The RIBA Plan of Work is the main model for organising the procurement of buildings in the UK. The plan of work integrates the design process into the broader legislative and procurement process.

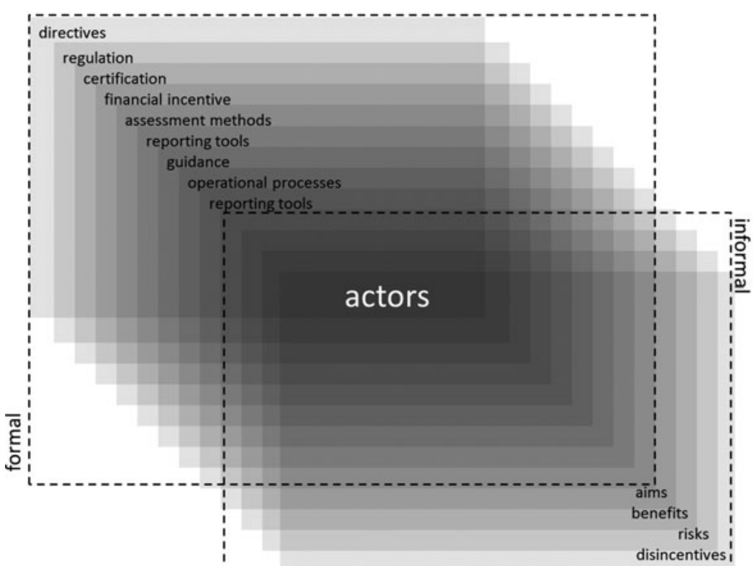

Figure 4.2.1 Actors work within a network of formal and informal pressures.

The contextual pressures describe the legislative and other frameworks through which this plan of work navigates, it includes, but is not limited to, the following mechanisms and principles.

Formal framework

The 'formal framework' describes mandatory regulations and voluntary guidance, incentives and certification schemes that are formalised and recognised throughout the industry.

Regulation and policy

In the UK, proposals for new or refurbished buildings are regulated by the Building Regulations.

Approved Document Part L (NBS 2014) regulates building fabric and fixed buildings services' energy consumption. Compliance is measured as per the calculation methodology developed to comply with the EU Energy Performance of Buildings Directive (EPBD). The CO_2 emissions of a proposed building are calculated as $kgCO_2/m^2$; the proposed Building Emission Rate (BER). The BER must better a Target Emission Rate (TER), calculated as the emissions from a notional building, geometrically identical to the proposed building but using default specifications from the 2010 edition of Part L, with an improvement factor applied. Other statutory approval required for new (or substantially altered) buildings in the UK is permission from local authority development control planning departments. As of March 2015, local authorities cannot stipulate energy targets but must refer to the National Planning Policy Framework which replaces both operational targets and renewable requirements.

Certification

Mandatory certification schemes implemented following the introduction of the EPBD in the UK include Display Energy Certificates (DECs) and Energy Performance Certificates (EPCs). The EPC uses the same calculation methodology as the building regulations and presents a benchmarked 'Asset Rating'. DECs use actual energy consumption records, benchmarked as a 'Operational Rating' and compared to the Asset Rating if available. Voluntary certification schemes like the Building Research Establishment Environmental Assessment Method (BREEAM) have become quasi-legislative; planning approval is often dependent on commitment to achieving a certain BREEAM level. BREEAM uses indicators of environmental 'sustainability' including transport, biodiversity, water use and energy consumption to calculate an overall sustainability award. (NB the Code for Sustainable Homes has been discontinued as a measure for domestic buildings.)

Financial incentives

Financial incentives are aimed at both the commercial and domestic sectors, some are currently under review but the principles remain. The Carbon Reduction Commitment (CRC) scheme was designed to target buildings and organisations that do not already fall under CO_2 emissions legislation covered in the Climate Change Act and the EU Emissions Trading Scheme. This used tax rebates to encourage management-based, year-on-year carbon reductions. Enhanced Capital Allowances (ECAs) are similarly aimed at commercial organisations and are a tax incentive for the purchase of efficient servicing equipment. In the domestic sector, domestic energy suppliers have a duty to reduce the carbon emissions associated with their customers (Department for Energy and Climate Change, 2012). The Carbon Emissions Reduction Target (CERT) obliged suppliers to achieve 68% of this reduction through home insulation measures. The Energy Company Obligation (ECO) replaced CERT in January 2013 and continues the principle of corporate responsibility for carbon reductions, with additional emphasis on customers in low income households and measures that cannot be met through other policies (such as the Green Deal) (Rosenow 2012). Feed in Tariffs (FITs) and the Renewable Heat Incentive (RHI) allow households to sell or be paid for renewably generated electricity and heat (Department for Energy and Climate Change 2013a). The Green Deal is a government run scheme to fund energy efficiency improvements through long term payments linked to energy bills but has been considered a failure due to poor uptake (Department for Energy and Climate Change 2013b).

Assessment methods and reporting tools

The Chartered Institute of Building Service Engineers (CIBSE) Technical Memorandum (TM) 22 'Energy Assessment and Reporting Methodology' sets out a means of quantifying a buildings' energy use (CIBSE 2006). It has three aims: to identify poorly performing buildings and systems, to indicate the cause(s) of poor performance and to benchmark operating procedures. It can also be used to assess building designs or occupied buildings in use. The Building Use Survey (BUS) developed by the Usable Buildings Trust (UBT) is a qualitative assessment methodology of building users' opinions of facilities (www.usablebuildings.co.uk). The survey takes into account levels of user satisfaction through rating aspects of the design such as air quality, lighting, noise, overall comfort, design, needs, perceived health, image to visitors and perceived productivity and benchmark this against similar buildings.

Benchmarks and guidance

CIBSE TM46 benchmarks are the basis for DEC benchmarking. One of the stated purposes of TM46 is to provide designers and managers with a yardstick against which designs and records can be measured: it is 'all about tracking performance and identifying opportunities for improvement' (CIBSE 2008). Current benchmarks, as described by CIBSE TM 46, provide total electricity and fossil fuel consumption figures categorised by building use type (CIBSE 2008).

Operational processes and POE

The Royal Institute of British Architects (RIBA) has said that of all of the interaction between clients, building users and architects, the greatest improvement in the service that architects could offer would come from the provision of systemised feedback and instituting Post Occupancy Evaluation (POE). The updated Plan of Work reflects this. Other schemes have been developed to deal with the handover of new buildings and to encourage learning from the performance of finished buildings. The Soft Landings framework is designed to be a 'golden thread' running through a project, linking the design and procurement process with initial and long term; a lead member of the design team moves into a building with the first occupants and is on hand to witness the way people use a building, answer questions and assess how the building is working (BSRIA 2009).

The formal framework represents a series of obligations, incentives and guides. The informal, a set of aims, expectations and fears.

Informal framework

The informal framework of pressures was developed through the literature review and supplemented with participation in the development of a feedback tool. The development of the tool centred on what industry actors would like to be able to do with a web-based building energy consumption database.

Aims and benefits

Industry aims of engaging with energy data include meeting the requirements of directives and carbon targets, meeting legislative and regulatory targets, achieving certification, meeting briefing targets, meeting client's needs and achieving organisation-wide or personal ambitions. The benefits perceived in achieving these aims include raising awareness of corporate activity in 'sustainability', increasing knowledge transfer between actors, developing innovation, using the opportunity to reduce or monitor costs, develop publicity material, develop markets and raise awareness of the typical difference between design predicted and actual recorded energy consumption. A significant potential benefit is that perceived technical risks, such as using untested or unfamiliar solutions could be overcome through the transfer of knowledge and greater insight gained by assessing buildings in use.

Disincentives and risks

Risks associated with engaging with energy data and POE (and potentially finding out that a building has poor performance) were found in the existing formal contextual pressures and included financial risks via penalties, reduced fees, lost work; 'extra' or unpaid work associated with not achieving regulatory or other compliance, reputational risks – personal and corporate – and other contractual liabilities.

These risks feed into other, mainly financial and practical, disincentives to carrying out POE studies: a simple reluctance to pay for the evaluation to be carried out, clients' general inability to see the benefit to themselves as their building is 'finished', a lack of engagement with the building occupiers on the part of commercial clients; uncertainty about how to carry out an evaluation, clients' inability to see an immediate financial benefit (Way and Bordass 2005) and a perception that gathering 'evidence' of a building not functioning as intended might expose practitioners to extra work beyond the scope of an initial appointment or even litigation (Jaunzens et al. 2003). There is an overriding perceived lack of value in the information gathered through feedback with the commercial benefits not perceived to match the outlay in gathering information (Andreu and Oreszczyn 2004). There is also a practical issue: POE information is often published in places that are not often accessed by industry (such as academic journals) and practitioners are often left to use previous ideas again or reinvent things blindly (Vischer 2009).

The above risks and disincentives can be summarised as the cost of carrying out building assessments, with the lack of obligation and the fear of litigation the main barriers associated with their own organisations engagement with POE.

Current interplay of actors and energy feedback

Currently, building occupants' knowledge is not being exploited and the tacit knowledge of design teams is not being integrated into improvements to buildings' performance (Leaman and Bordass 2004). When information is collected, it is most often informally and is not used analytically. Most actors gain tacit knowledge throughout a design or management process and applied this informally to future projects.

Industry actor interest is largely driven by their role: developers are interested in carbon and designers are more often interested in energy. Current policy is arguably not focussing the correct metrics on the right people. Costs, whether fees and profits, capital investment or running costs, are all important factors to individuals, organisations and projects. Carbon (the primary metric of the formal framework) does not seem to be a natural part of the conversation. Legislation is pushing against the natural interest of actors and policy makers are beginning to identify a need for a change of focus from carbon to the less abstract notion of energy.

Setting design and operational energy targets

The formal aspects of the contextual pressures are the main determinants of energy targets. Figure 4.2.2 illustrates the results of the industry survey. Mandatory targets such as building regulations are the main aims, with client goals also considered important. Designers with ambition to deliver low energy buildings beyond these targets still regard aspects of the contextual pressures of value, in particular the more stringent targets set by planning dependent BREEAM standards means that clients are forced to engage with higher energy targets.

The problem of the performance gap is illustrated by Figure 4.2.3, a scatter plot of design versus actual energy data. Pearson's r regressions show a strong positive linear correlation between design and actual electricity and heat consumption values. The positive correlation is stronger in electricity than in fossil fuel consumption, reflecting the apparently random relationship between design and actual values.

The relationship between electricity predictions, generally under-predicted, and actual records is more consistent than in heat data. The contextual pressures and building regulations in particular focus on building fabric performance and fixed building services for environmental control. In contrast, electricity use is much more influenced by unregulated end uses – the consistent increase is likely due to unaccounted for equipment loads. The inconsistency of fossil fuel consumption predictions is an indictment of the contextual pressures and the calculation methods used.

The iterative process of designing a building, service strategy or management regime is dependent on information flow; good decisions are made with good information. Understanding how building designs and operations are currently assessed and reported could inform how future provision of feedback information is presented.

'Part L Design Calculations' are used more often than any other design stage energy assessment method. Assessment methods are often used as exploratory mechanisms for identifying optimum performance or erroneously as 'value engineering' tools. Proving compliance is just one use of energy assessment methods, the calculation tools are also used as part of the broader design discussion to explore design options and assess costs.

POE and data collection

The data most often collected in POE that is carried out is 'Physical information about the building' (room dimensions, construction, U-Values, windows sizes etc.). The next most often collected information is headline energy information; 'Total kWh Gas', 'Total kWh Electricity'. This information is often supplemented by circumstantial and anecdotal evidence and often about aspects of buildings other than energy; most actors only get information back from a building when something goes wrong. The process of

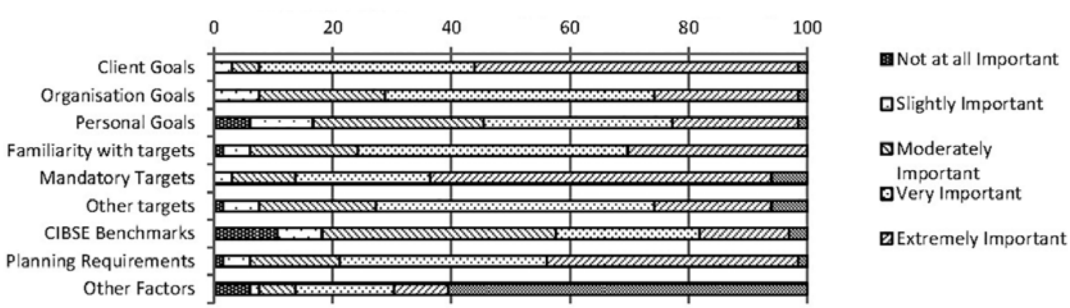

Figure 4.2.2 Factors driving project energy targets.

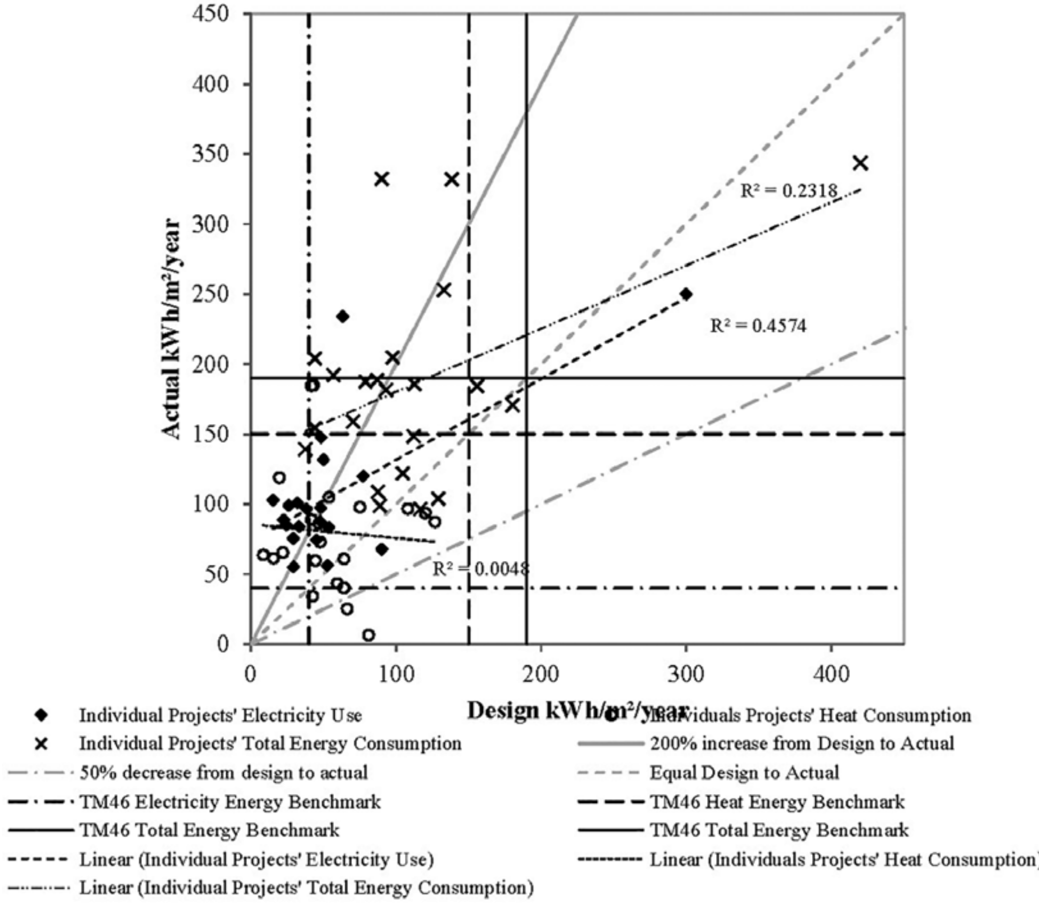

Figure 4.2.3 Design versus actual energy consumption.

disseminating this data can also be haphazard, with no formalised database and often relying on word of mouth within their organisations. However, this does mean there is a tacit feedback loop in a number of design practices, the process of iterating a design to compliance on one project filters through to the starting point for the next, but often this information is not recorded and the process not formalised. There is a disconnect between the aims of assessment of buildings at design stage and the aims or expected outcomes of post occupancy evaluation.

Perceived barriers identified in the contextual pressures influence designers. Barriers to data collection are diverse, ranging from the cost of carrying out POE, 'cost to clients', 'concern over liability', 'inexperience in POE' and reputational concerns. Survey results are illustrated in Figure 4.2.4.

> . . . it's kind of a double edged sword, it could be brilliant or the client could turn round and say well hang on you haven't given us the building we paid for!

While some recognise the potential benefits to POE, the lack of contractual necessity, monetary incentive or access to buildings all mean that designers do not often carry out formal evaluations. Those that could overcome these barriers tended to be those working on the client side as they have a financial incentive and ongoing access to their own buildings.

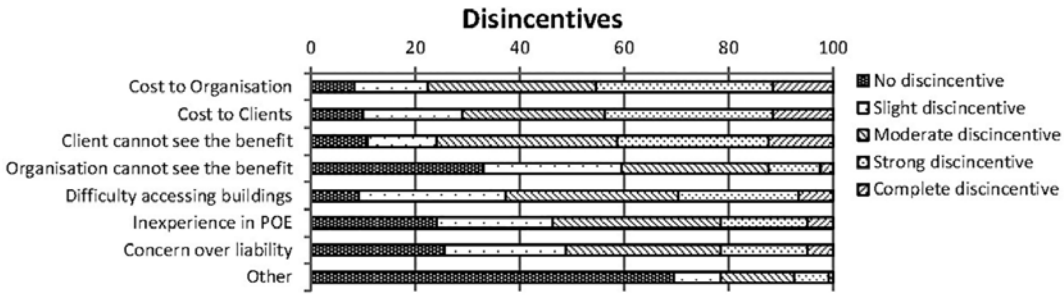

Figure 4.2.4 Barriers: survey results.

The contextual pressures deal in carbon emission targets. The common language of the design and procurement of buildings is costs: fees, capital expenditure and running costs. Carbon is seen by some as abstract and does not address the fundamental issues of management, efficiency and building physics. Relating legislation and targets more directly to costs may be a way of engaging more of the industry with the issue of energy and carbon emissions.

Crowd-sourced data

Crowd-sourcing – gathering and interrogating the subsequent collective experience and expertise – is a relatively new phenomenon facilitated by internet-based communication. This chapter has shown a top down approach to the development of energy legislation to which individuals, or groups of individuals working on individual projects, are required to respond. Crowd-sourcing could help solve the problem of the performance gap, decrease building energy consumption and advance a low energy built environment. Crowd-sourcing is a strategic model used to 'attract an interested, motivated crowd of individuals capable of providing solutions superior in quality to those that even traditional forms of business can' (Brabham 2008).

Analysis of the DEC schools data and CarbonBuzz database has illustrated the legislative and behavioural changes in building energy consumption. This headline data and current benchmarks may not offer either sufficient insights or realistic motivational goals to be able to diagnose operational problems and improve performance.

Figure 4.2.5 shows the breakdown of design and actual energy consumption by end use in eight school projects to illustrate the compensatory impacts of variations in design to actual relationships that can create the appearance of an accurate design prediction. For example, Project 4, which has the closest relationship between design and actual total figures – an increase from 135kWh/m^2 to 142, representing a 5% increase – shows changes in end use that are quite different. Heating fossil goes from a design figure of 75kWh/m^2 to a recorded figure of 33kWh/m^2 while electricity used by equipment and appliances goes from 20kWh/m^2 at design stage to 38.7 in actual records. This confirms that the TM46 assumption that 55% of fossil fuel is degree-day-dependent while the other 45% is not reflective of actual use patterns. The ratio in some projects is as high as 98:2. The mean values for heat and hot-water energy consumption represent an 81%:19% split in heat consumption.

Feedback derived from crowd-sourced data could highlight these discrepancies and may be able to offer insights to designers to improve design and management decisions and offer greater encouragement to investigate and improve performance. The potential for crowd-sourced data to offer this insight is large, however, a key weakness of a crowd-sourced platform is that it is dependent on the 'crowd' supplying data; low participation, data entry error or falsification can lead to a weakness in the benchmarks.

There are a number of existing web-hosted databases and data collation methods in existence that aim to address many of the issues raised in this review. Some examples are described below.

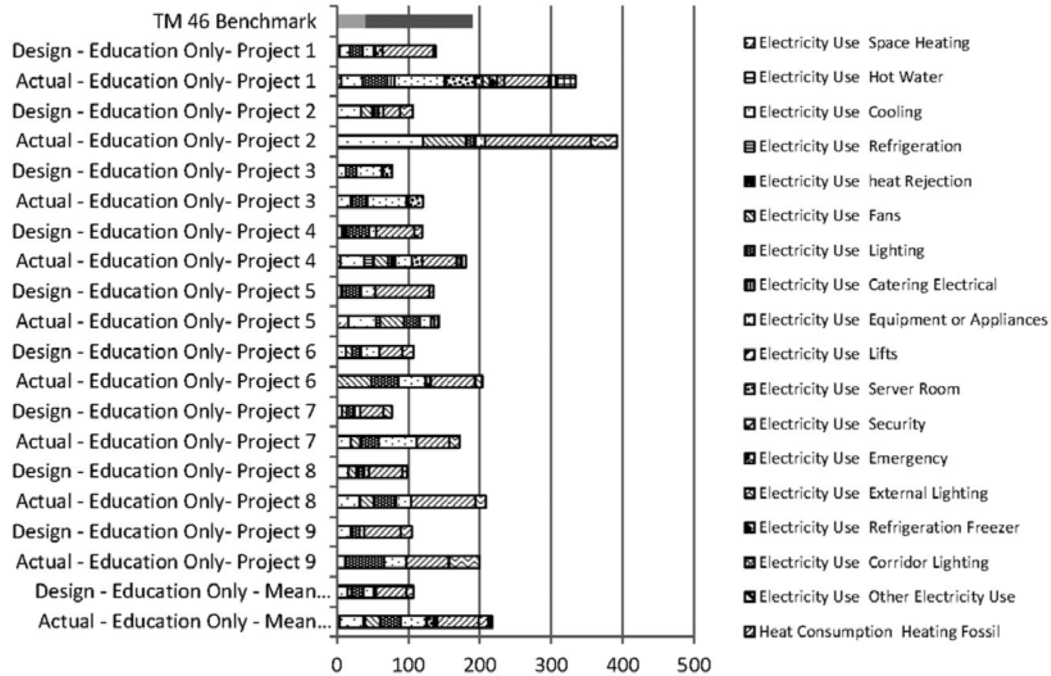

Figure 4.2.5 Crowd-sourced data/disaggregated information.

Future role of feedback information

This section discusses how feedback information itself could help to overcome the barriers currently in industry and improve collection and dissemination of information and future decision making.

Creating value and reputational benefits

The value of post occupancy evaluation data will only be realised when actors can see what kind of impact it can have on changing a building's design or operation. Feedback should put forward the case for energy efficiency, show the opportunities to implement efficiency measures and quantify the benefits by using metrics that are motivating to actors. To do this, the default metric should be costs: a metric that is universally used across industry. Whether capital expenditure, profitability, savings or fee generation, framing the impact of feedback on a project and the potential impact of any changes generated in these terms will create more interest in the topic and overcome one of the principal barriers. The costs or savings associated with this information will encourage commercially driven organisations to engage with energy consumption and, more importantly, engage with designers who can produce cost effective buildings. This could simultaneously overcome some of the problems with a disconnected project team and ascribe successes to actors who can use them to publicise their work.

Overcoming risks and other barriers

The mechanism for overcoming the barriers inherent in the contextual pressures is feedback data itself. Existing standard project set-ups, the need to pass risks down the chain of the project team and the complexity of building energy systems requires effective coordination of expertise. Feedback could not only provide effective coordination of expertise but also encourage actors to assume responsibility for the impact of their decisions. Understanding the likely impact of decisions before they are committed to them financially could help create a blame-free environment in which building performance can be explored for the benefit of future performance.

The interconnectivity of the elements of building performance is not reflected in contextual pressures or the way that decisions are made. Feedback could provoke change in the way the industry operates through an understanding of the faults in the current contextual pressures by collating building performance data in order to challenge the status quo of the formal framework, and to demonstrate to policy makers where future legislation and guidance should be aimed.

The atomised nature of project teams mean that information flow is often not good enough to help project teams make good decisions. Feedback has a role to play in bridging the unfamiliarity of new project relationships through the communication of clear project goals and performance targets, furnishing actors with knowledge and understanding of the in-use functioning of low energy buildings and what characterises successful buildings.

The existing contractual relationships established by the contextual pressures mean that information flow is often very informal and anecdotal, or limited to very specific aspects of compliance calculations or finished buildings. A feedback platform could build on these existing flow paths and embellish the information with the kind of in-depth, scientifically robust data that will offer actors the necessary insights to improve building performance.

Motivating actors

Actors can be classified in three groups: those uninterested in energy or carbon but obliged to make some effort to reduce the energy consumption associated with their buildings or projects; those for whom energy and carbon is of interest to them personally, or to their organisation, but who feel they are hampered in implementing meaningful changes; and those who are interested in energy and have found a means of implementing what they feel are meaningful energy reduction measures. These groups are discussed below.

The engaged actors tend to have developed their own organisation-specific feedback mechanisms, however this insular system can result in the repetition of similar ideas. Engaging with a broader, industry-wide, feedback platform could highlight other successful designs and management strategies and promote innovative thinking to drive industry forward. There is however a boundary between sharing data and retaining a competitive advantage. A wider feedback platform could allow engaged actors to push forward a low energy agenda to wider industry by demonstrating where the value in energy efficiency lies with respect to other motivations and metrics.

The contextual pressures, while requiring actors to engage with energy, do not support the development of innovative low energy buildings. Feedback must provide aspirant actors with supporting data to show other members of the project team that their aims are achievable, that the barriers currently preventing action are surmountable and ensure alignment of ambition with technological feasibility and costs by providing a robust evidence base for decision making. They need to be able to convince others that feedback is worth using and that a low energy building is a valuable asset.

Uninterested actors need to be engaged by the advocacy of engaged actors, using feedback that presents information in a format that appeals to their motivations. Feedback is most used in industry when it is causal, anecdotal and informal. This feedback loop relies on individuals passing on information that they deem important without a comprehensive set of information that can render insights more actionable. A feedback platform could enable this to happen by providing a natural forum to embellish existing discussions with greater understanding of the issues.

What needs to change to make this happen?

Many of the financial benefits that can be realised through engaging with POE and utilising feedback already exist, but most are not taken up by industry. There are weaknesses in the current pressures that have a bearing on both the quantum and quality of available feedback data and the formal parts of the contextual pressures is currently undergoing some political led change. However, a few key points could be adjusted to address these weaknesses. The formal portion of the contextual pressures has a role to play in shaping the informal, therefore this section only addresses the formal in the expectation that the informal – which is created from actors' perception – will follow suit.

The commercial nature of construction needs to be taken into account in the contextual pressures and the chain of responsibility needs to be maintained throughout commercial transactions. The balance of the contextual pressures should be shifted away from risk and liability to financial benefit (whether reduced expenditure or increased profits) and reputational gain.

The major role of feedback in a proposed revision of the contextual pressures is to provide the underlying benchmarks for all policy and targets. Using actual energy consumption records as the basis for energy targets, legislation and policy, and subsequent performance, will allow for a constant comparable metric across all industry activity which can be monitored against CCA commitments. This requires a dataset that includes the full range of energy end-uses.

Legislation and regulation

The legislative framework has been shown to form the basis of the majority of actors' target setting. Due to the limited nature of calculation methodologies, there is no guarantee that designed performance will be achieved in finished and occupied buildings.

The regulatory framework therefore should be adjusted to use feedback derived targets presented in a metric that meets actors' motivations (via a conversion rate from energy consumed per unit of area), encourage calculation of total energy consumption at design stage by reference to actual disaggregated records, track potential changes to this throughout the procurement process and, finally, mandate and regulate POE.

Certification

Certification should become a genuine reputation maker (or breaker). Organisations who achieve low energy buildings should be rewarded by positive publicity and marketing opportunities. The use of a feedback-derived benchmark as a certification guide will allow for easy comparison across all policy and buildings. Using a metric that appeals to potential clients will help turn good performance into reputation and market advantage. The use of certification as a means of generating reputation relies on other aspects of the contextual pressures and good building performance itself becoming a valuable commodity. This will only happen by changing the metrics to meaningful figures.

Procurement process

Adjusting the formal framework of contextual pressures, through the mandated parts, will create the necessity for greater actor involvement across the procurement process. When the benefits of using feedback are made explicit, developers, clients, owners and managers may realise the need to employ expertise throughout the process. Incentivising the project team by tying them to the reputational benefits of good energy performance of finished buildings may provoke change in how the team is set up, how they operate and how responsibility is attributed.

Summary

This chapter has reviewed current pressures on design, construction and management actors and how these pressures can influence design and operational energy consumption. A number of ways that feedback information could better inform industry actors' decision making have been discussed. The main areas of opportunity, linking cost and profit, benefits directly to energy targets and stimulating a reputational benefit associated with well performing buildings.

These changes are reliant on engaged actors taking the initiative and collecting and sharing data – as the formal framework of contextual pressures is weakened for political reasons, the onus on enlightened and progressive practitioners becomes stronger. The different roles an actor plays in the procurement process influences their attitude to energy and is an important factor in targeting policy. This work begins to build a picture of how a suite of legislation might better relate to the actual interactions and discussions that happen in the procurement of buildings in the UK and further work aims to refine this.

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4.3

BENCHMARKING THE OPERATIONAL ENERGY EFFICIENCY OF BUILDINGS

Sung-Min Hong and Dejan Mumovic

Introduction

Words 'benchmark' and 'benchmarking' are defined as "a standard or point of reference against which things may be compared" and an action taken to "evaluate (something) by comparison with a standard", respectively (Oxford Dictionaries n.d.). It is a technique that is widely used in various sectors of the economy, such as businesses, to evaluate and improve the operational performance of an organisation (Camp 1989).

In the built environment, benchmarking is often employed as part of an energy management practice in existing buildings to improve the level of efficiency at which energy is used during the operation (CIBSE 2012). This often involves monitoring the energy performance of a building over time to improve the understanding of how much energy is being used. The operational performance is then compared to reference points such as established energy benchmarks that represent energy performance of similar buildings to gauge the operational energy efficiency of the building.

Benchmarking can be beneficial for several reasons. First, it raises the awareness of how efficiently energy is being used in a building, which is often identified as a key barrier to improving the energy efficiency of buildings (Carbon Trust 2009). Second, feedback from the exercise can put the operational efficiency into a perspective, therefore encouraging building operators to take actions to identify problematic areas and operate their buildings more efficiently. For these reasons, benchmarking has been selected as the key method underpinning various energy certification schemes, such as the UK's Display Energy Certificate (DEC) scheme under the European Energy Performance of Buildings Directive (EPBD) and voluntary energy certification schemes around the world, such as the US ENERGY STAR or Australia's National Australian Built Environment Rating System (NABERS), which are all aimed at improving the operational energy efficiency of the building stock.

Despite the benefits, there are various elements that can influence the robustness of benchmarking processes, hence the relevance of feedback. This chapter therefore defines key aspects of benchmarking methodology and factors that should be taken into consideration in order to obtain useful feedback on the operational energy efficiency of buildings.

Indicators of energy performance

Energy performance indicator (EPI) or Energy Use Index (EUI) are terms widely used to express the energy performance of a building, enabling its performance to be compared against another, as in benchmarking processes. In general, the indicators are commonly expressed in kWh/m^2/year or MJ/m^2/year in countries that use the SI units. In countries which use imperial units on the other hand, kWh/sqft/year or Btu/sqft/year are used instead.

Types of benchmarks

As with buildings, energy benchmarks are presented in a similar format. There are three different types of benchmarks:

- Overall building benchmarks: In general, most benchmarking systems provide benchmarks that represent the energy performance of the overall building. Such benchmarks are inclusive of all forms of energy use in a building from fixed building services such as artificial lighting or ventilation systems to plug loads from equipment such as personal computers or printers.
- End-use benchmarks: Although seldom used, there are also benchmarks that are presented at finer levels of granularity. The end-use energy benchmarks presented in CIBSE *Guide F*, for example, express the intensity of energy use for each end use in a building (CIBSE 2012).
- Component benchmarks: There are also benchmarks for components of systems such as fan efficiency. These are, however, more specific to the design specifications but not necessarily for evaluating the operational energy efficiency.

In addition, electrical and fossil-thermal EUIs are often benchmarked separately to take into account the differences in carbon intensities between types of fuels. Taking the UK's Display Energy Certificates (DEC) scheme for example, the CO_2 emissions factors used for electricity and fossil-thermal fuel are 0.550 $kgCO_2$/kWh and 0.190 $kgCO_2$/kWh respectively (CIBSE 2008). Moreover, separate benchmarks are sometimes provided for buildings heated mainly using electricity rather than fossil-thermal energy, which is a more common form of heating (CIBSE 2012).

Denominators

The EPI is created generally by normalising the delivered energy consumption of a building relative to a determinant of energy use, which is usually the floor area of a building for the majority of building types in the UK and other countries. By normalising various determinants of energy use, the index can be used to compare energy performance between buildings to highlight the inefficiency of a building or building services. Although floor area is the most widely used denominator, there are other types of denominator used in certain types of buildings in which other characteristics of buildings or businesses are considered to represent energy use better than the floor area. For example, these might be the number of prisoners in prison (kWh/prisoner), number of meals served in catering buildings of the Ministry of Defence (kWh/meal), or the number of covers (place settings) in a restaurant (kWh/cover) (CIBSE 2012).

Approaches to benchmarking

In engineering disciplines, there are two fundamentally different approaches that are used to analyse or design systems: top-down and bottom-up. A top-down approach refers to the way in which a system is designed by first formulating an overview without details of the sub-systems. The system would then be refined further, subject to the availability of more detailed information. A bottom-up approach on the other hand would involve specification of lower-level system information that would then be used to build up a more precise overview. In much the same way, the methods that are used to derive energy benchmarks for buildings can be grouped into two different approaches based on the granularity of the information involved.

Top-down approaches

In the built environment, a top-down approach can refer to ways in which energy benchmarks are derived based on building-level energy performance figures collected over a year. These benchmarks are usually expressed in the form of overall building benchmarks and indicate how buildings with similar demand use energy. There are a range of methods with varying levels of complexity that are top-down in their nature which form the bases of numerous benchmarking schemes around the world.

In general, top-down methods involve deriving energy benchmarks from a distribution of energy performances of a sample of buildings. As shown in Figure 4.3.1, descriptive statistics such as 50th and 25th percentiles of a sample are often used to represent 'typical' and 'good practice' energy performances of similar buildings in the wider stock. This approach has been predominantly used in the UK where examples of historical benchmarks can be seen in the CIBSE *Guide F* or, more recently developed benchmarks, in CIBSE *TM46* that underpin the DEC scheme (Action Energy 2003; CIBSE 2012; Hernandez et al. 2008; Jones et al. 2000). A similar method was also used to assess the energy performance of schools in Argentina and Greece (Filippin 2000; Santamouris et al. 2007).

The benefit of using the simple top-down approach is that it is an effective way to describe the actual energy performance of the population. Such characterisation of the stock present opportunities for building operators or managers to put their buildings' performance into a broader context. Comparing the performance of modern secondary schools to whole building energy benchmarks that represent the distribution of the school population, for example, can be an effective way for assessing how efficient a given group of buildings is in relation to similar buildings in the stock. With regard to schools, such feedback would be beneficial for local authorities or county councils who have energy efficiency as part of their agenda. Moreover, such feedback would provide motives for improving the energy efficiency of buildings based on peer pressure rather than absolute levels of energy efficiency. For other building types, such as commercial offices, where reputation is of crucial value, such peer-driven feedback may generate stronger motives to improve energy efficiency.

The simplicity of the method is also beneficial in that there is minimal requirement for information both to derive the benchmarks and to evaluate the performance of buildings. Taking the UK's DEC

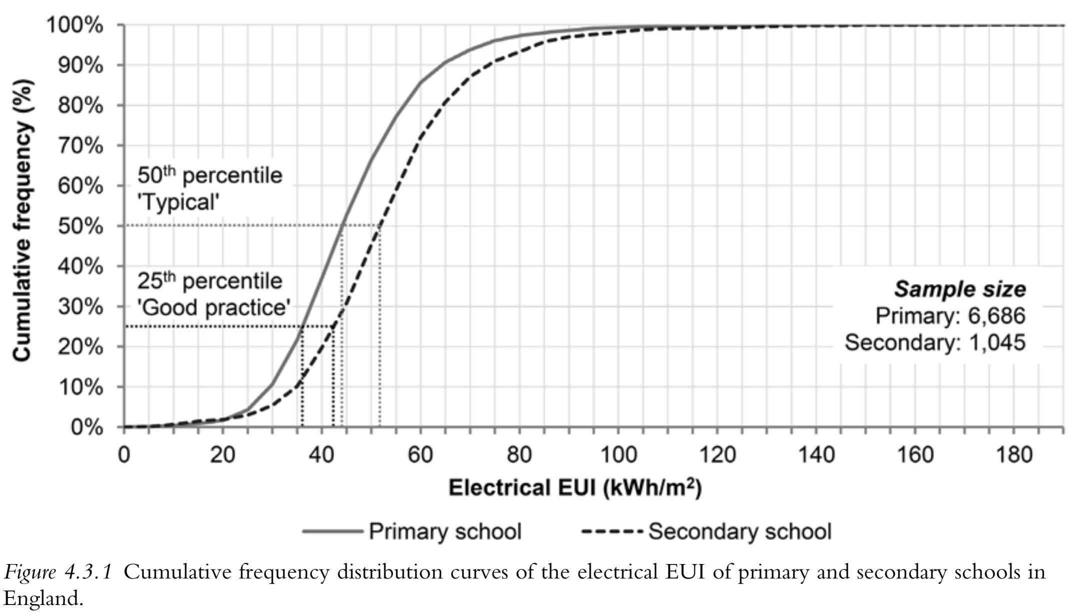

Figure 4.3.1 Cumulative frequency distribution curves of the electrical EUI of primary and secondary schools in England.

scheme for example, information that is required is annual metered energy consumption, floor areas, occupancy levels, location of a building (to take into account the regional and seasonal variation in weather) and knowledge of any separable energy uses, if they exist. Such low granularity data is more likely to be obtainable through utility bills, regular meter readings, or through various stakeholders associated to a building such as architects or facilities managers, although this may not apply for the separable energy uses. It is therefore relatively less intensive in resources than the bottom-up approaches, which often require activities such as post-occupancy evaluation (Hong et al. 2014).

A key drawback of the approach however is that feedback from using these simple top-down benchmarks is not likely to indicate precisely whether a building is being operated efficiently or not. This is largely due to the low granularity of the data that were used to derive these benchmarks, which are usually based on minimal information about buildings such as the annual energy performance, floor area and regional weather conditions. This means that varying implications of intrinsic features of buildings such as the built form or age on the pattern of energy demand are not accounted for (Hong et al. 2013). A comparison without a way of incorporating these characteristics, therefore, is more likely to indicate buildings that are more or less intensive in energy use but not necessarily with regard to their efficiency. A newly built school whose EUI is close to the 10th percentile, for example, would suggest that it is likely to be very energy-efficient based on the fact that the EUI is lower than 90% of the buildings in the stock. Such a comparison would, however, ignore the fact that the building had been built to much higher thermal performance standards, therefore would have intrinsically less demand for energy use than Victorian buildings that were put up more than a hundred years ago and are less airtight (Chatzidiakou et al. 2014).

The empirical nature of the top-down approaches also means that building operators acquire relative levels of energy efficiency that are defined by buildings in a sample. Although peer pressure can be a strong motive, such a reference point may not be aspirational for those building operators that aim to achieve absolute levels of energy efficiency. A primary school building whose electrical EUI is less than the 25th percentile, for example, would indicate that the building is likely to be more energy-efficient than the majority of school buildings in the sample, or more broadly the school stock. As highlighted by Federspiel et al. (2002) however, the level of energy efficiency represented by these benchmarks are dependent on buildings in the underlying sample which may all be hypothetically inefficient. In such instances, operators of the building would acquire a feedback which presents a false sense of efficiency even when it is inefficient in the absolute sense.

Bottom-up approaches

The bottom-up approach refers to ways in which overall building energy benchmarks are built up by aggregating system level information. For example, benchmarks for a building could be derived by first estimating the energy performance of individual systems, such as the ventilation or lighting systems. These system-level consumption figures would then be aggregated together into a single EUI representing the hypothetical performance of a building.

There are a few examples of bottom-up approaches being used for benchmarking the energy performance of existing buildings. Federspiel et al. (2002) proposed using a simulation model to derive whole building benchmarks for laboratories in the US, citing limitations of using top-down approaches for benchmarking the operational energy efficiency of complex buildings such as laboratories. In the study, energy used by various systems and equipment in laboratories were calculated based on theory and aggregated to an overall-building benchmark, with an intention for deriving benchmarks that represent energy consumption achieved at the maximum level of operational energy efficiency. There was, however, a series of assumptions that were made to simplify the calculation process of the model. It was, for example, assumed that there are no conductive heat transfers or transmissions of solar energy through the

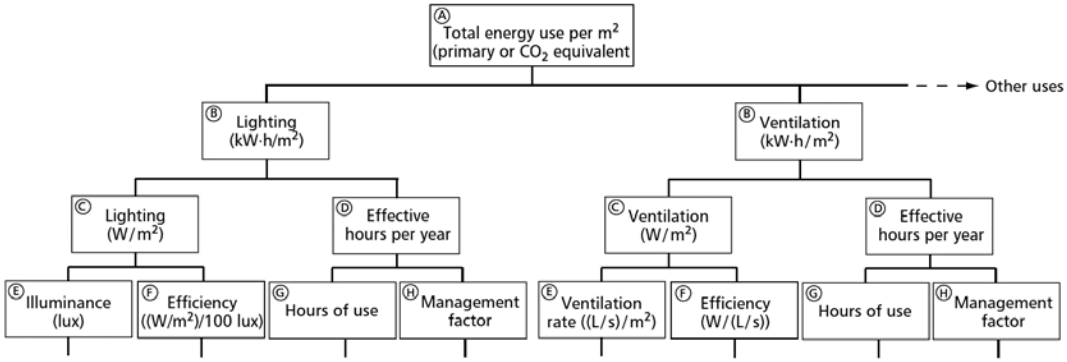

Figure 4.3.2 Tree diagram method in CIBSE TM22.

Source: CIBSE 2006

building fabric, which are crucial parts of building physics that determine the demand for space, heating and lighting. Similarly, default values were specified for a range of variables including those that describe the occupant density and schedule. Similar approach was also explored by Mathew et al. (2004) and Mathew et al. (2010).

In the UK, Simplified Building Energy Modelling (SBEM) or dynamic thermal modelling software are also used to estimate the energy performance of new buildings for producing EPCs or for demonstrating compliance with the Building Regulations (DCLG 2012; HM Government 2010). Due to limitations in assumptions made for occupancy and exclusion of plug loads such as computers, printers or kettles, these methods are not suitable for benchmarking the operational energy efficiency of existing buildings.

Other bottom-up methods include the CIBSE *TM22* method which has the potential to be used to benchmark the energy consumptions of major building systems or end uses (CIBSE 2006). Unlike the simulation-based approach, a tree diagram approach is used to derive energy benchmarks (see Figure 4.3.2).

As shown in Figure 4.3.2, energy consumption of each end-use is derived based on parameters that describe specifications of equipment and the usage. Taking the end use lighting for example, the end-use energy consumption is derived based on the designed lighting level, efficiency of lighting, and parameters that describe the occupancy and maintenance. Similar to the simulation-based approaches, these benchmarks have potentials to portray absolute levels of efficiency in finer detail. Recently, Bordass et al. (2014) explored possibilities of estimating the whole building benchmarks that are inspirational by aggregating the end-use consumptions using the CIBSE TM22 method and prescribed specifications of building services and their use. The limitation of the method is, however, that the implications of variations in building design on the energy uses are not taken in to consideration. The variances in glazing area or shading design, and climate conditions such as cloud coverage for example, would all have different implications on the demand for artificial lighting in different buildings. Similarly, the method currently does not provide means to estimate energy consumption for space heating for cooling, as these end uses are dependent on the thermal performance of buildings as well as features of building fabric, such as thermal mass, that are not account for by this method (Hong et al. 2014).

The bottom-up approaches provide a fresh perspective on producing benchmarks apart from top-down approaches that can act as baseline performances, which could be suitable for deriving aspirational targets (Federspiel et al. 2002). Until the limitations and uncertainties are explored and developed further however, top-down approaches are likely to be more appropriate for benchmarking the operational energy efficiency of the non-domestic stock.

Representativeness of energy benchmarks

Deriving energy benchmarks that are representative of the stock is a key factor in developing a robust benchmarking system. Benchmarks that are representative of how buildings in the stock use energy can provide an opportunity to gauge ones performance to its peers and establish how intensive they are in comparison to the stock. This is due to the fact that benchmarking currently plays a passive role in that the motive to improve the energy efficiency is purely based on the feedback from the exercise. The discussions in this section focus on the factors that affect the reliability of the benchmarks, their implications on the DEC scheme and future development of benchmarking systems.

Reliability

Energy benchmarks derived using top-down approaches are presented in the form of statistics, such as medians that represent the patterns of energy use in the stock. These benchmarks are commonly derived by making inferences about the wider population from a smaller sample, due to difficulties in acquiring data for the entire population. The limitations in generalising the observations from a sample to the population however, means that there are uncertainties associated with how accurate the estimated parameter of the population is likely to be. It is therefore important to assess the uncertainties associated with these reference points to ensure that benchmarking can provide meaningful feedback to building operators.

Historically, 50 or 100 samples are often quoted as a sample size that is sufficient to derive energy benchmarks that are reliable representations of the energy performance of buildings (CIBSE 2012; Jones et al. 2000; Jones 2014; Bruhns et al. 2011). Although limited to primary and secondary schools in England, an analysis of the changes in uncertainties associated estimated statistics (Figure 4.3.3) showed that benchmarks derived based on sample sizes of 50 or 100 were not likely to be as reliable as previously believed. Conversely, it was found that the confidence interval was found to reduce down to approximately 10% of the estimated parameter when the sample size increased to approximately 200 (Figure 4.3.3).

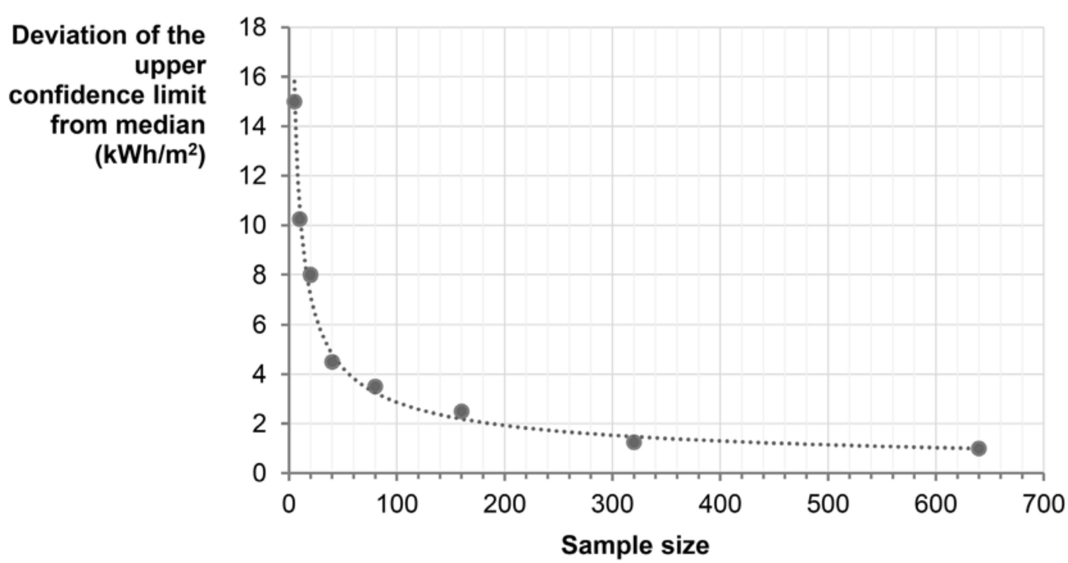

Figure 4.3.3 Differences between the upper confidence limit of the electrical EUI of primary schools from median with varying sample sizes.

Changes in the pattern of energy use over time

Time is an important factor that determines how representative benchmarks are of the latest patterns of energy use in the building stock. This is due to various factors such as developments in technologies, introduction of more stringent building standards, and warming climate which can change the patterns of energy use in buildings over time.

Changing patterns of energy use in buildings over the long-term can be seen in Table 4.3.1, which shows the latest statistics on the electrical EUI of English schools as well as various electricity benchmarks published over the past two decades. The comparison of the sample median to the existing benchmarks shows that what was perceived as a typical performance of schools has gradually changed over the years. The benchmarks in the energy consumption guide (ECG), for example, were derived from a survey conducted in the late 1990s. The differences in the sample median and the ECG figures show that schools were considerably less intensive then in terms of electricity use. The continued increases in electricity consumption is likely to have occurred due to growing integration of ICT equipment such as personal computers, laptops or electric whiteboards for teaching. Comparing energy performances of schools against the benchmarks that do not reflect these trends are therefore likely to provide inaccurate feedback to building operators, which can hinder the effectiveness of a benchmarking exercise and the potential to improve the energy efficiency of a building.

In the general sense, keeping the benchmarks up-to-date with the latest trends in patterns of energy use is vital for acquiring a fair and relevant assessment of the operational energy efficiency of buildings.

Classification of buildings

Grouping buildings into appropriate classifications plays an important role in ensuring that the energy performance of various types of non-domestic buildings are compared against the energy benchmarks that are representative of buildings with similar demands for energy.

The difficulty in classifying buildings correctly with their peers with similar patterns of energy use comes from the complexity and heterogeneous nature of buildings in the non-domestic stock. Unlike the

Table 4.3.1 Statistics of the electrical EUI of primary and secondary schools in England.

Phase of education	*N*	*Electricity EUI (kWh/m²)*					
		Min	*25th %*	*Median*	*75th %*	*Max*	*IQR**
Primary	6,686	1	36	44	53	191	17
Secondary	1,045	1	42	51	61	174	19
All	7,731	1	36	45	55	191	19
Existing benchmarks							
CIBSE TM46			-	40			
CIBSE Guide F							
– Primary			22	32			
– Secondary			25	33			
ECG 73**							
– Primary			20	28			
– Secondary			24	30			

* Inter-quartile range (IQR)
** Energy consumption guide (ECG) (BRECSU 1996)

domestic stock, there is a large variation in the way buildings are used, hence the varying patterns of energy use (Mortimer et al. 2000). The types of activities engaged by occupants, including their use of machinery, vary widely between buildings where, for example, in the retail sector there are general stores, lighting and electrical goods shops and food stores, each with distinctive sets of requirement for use, environment and equipment. In addition to the diversity of activities there is a diverse range of characteristics of buildings and their quality within the building stock such as built form, size, services and age, which can have varying influences on energy consumption. For example, there are, at one extreme, small buildings such as information kiosks with less than 30m^2 in floor area and with a minimum level of building services, and, at the other extreme, heavily serviced high-rise buildings which are tall and slender with floor areas greater than 5,000m^2, such as hospitals or commercial offices, or low-rise buildings with deep plans such as supermarkets or warehouses. The complexity of the stock due to variation in activities and physical properties of buildings is further exacerbated by a very loose relationship of built form to function. Taking the function 'office' as an example, office businesses can operate in various types of building from converted Victorian houses or purpose-built low-rise buildings with courtyards in an office park to temporary huts on a construction site.

Basis of grouping

In the UK, buildings are commonly grouped based on the type of activity that takes place in a building. Taking the UK's CIBSE *TM46*, for example, which categorises buildings under the philosophy that activities in the same category are expected to have similar requirements for use, environmental conditioning and installed appliance loads, hence the pattern of energy use (Bruhns et al. 2011).

There are also classifications which base the grouping on the physical properties of buildings. Adopting physical parameters of buildings as a basis for grouping to improve the relevance of benchmarking can be seen in a number of categories in CIBSE Guide F (CIBSE 2012). An example of this can be seen in the categories 'Education (higher and further)', 'Industrial buildings' and 'Offices', in which buildings are further grouped into sub-categories based on different physical and technical parameters. In the 'Education' category for example, a distinction is made between buildings which are naturally ventilated and those that are air-conditioned. Using the ventilation system as a basis for grouping can also be seen in the 'Offices' category where a distinction is made between offices of different sizes with different ventilation systems (Action Energy 2003). Due to the similarities between intrinsic features of the buildings, such a grouping would allow the comparison to show more accurate evidence of the efficiency of the building.

Levels of classifications

The level of detail that the classification in a benchmarking scheme provides is also an element that has influence over the relevance of the comparison. In general, the level of detail can be observed from the variation in the number of categories. Simply comparing the number of benchmarks provided in UK's CIBSE *TM46* and *Guide F* for example, shows how widely the levels of complexity in existing classification systems vary (CIBSE 2008, 2012). There is, on one hand, classification of buildings in *TM46* which provides just 29 benchmarks, with only a single category for offices and schools. This means that the energy performance of a diverse range of buildings is compared to a shared benchmark value, which may compromise relevance. Analyses of the energy performance of English schools based on the latest DEC data, for example, showed that secondary schools are significantly more intensive in electricity use (Hong et al. 2013). This therefore suggested that the ways that electricity is used in primary and secondary schools are distinctively different, which is likely due to greater uses of electrically intensive equipment in secondary schools such as computers, laptops, and also the presence of teaching facilities that require greater use of electrical equipment such as laboratories (Global Action Plan 2006; Carbon Trust 2012).

In this instance, the classification of schools would have been aggregated too much leading to a comparison that is likely to produce feedback which may suggest primary schools are more energy efficient.

There are on the other hand classifications of buildings that provide categories in excess of 100, acknowledging differences in activities and their implications on the pattern of energy use in great detail. In general, such refined classification would be beneficial in benchmarking the energy performance of buildings with greater relevance. In the cases of schools, historical benchmarks such as those presented in *Energy Consumption Guide 73* and CIBSE *Guide F* had previously separated primary and secondary schools, which was perhaps more appropriate for schools (BRECSU 1996; CIBSE 2012). The challenge in disaggregating the classifications into finer categories may however lie with the fact that there will be less buildings under each category as the classifications become increasingly more detailed, hence compromising their reliability.

Comparability of benchmarking

There are various factors that determine the energy demand of non-domestic buildings. There are factors that are intrinsic to buildings such as the type of activity, the shape of buildings or occupancy hours that influence the basic demand for energy in providing a healthy and comfortable indoor environment to occupants (CIBSE 2012). There are also factors such as how equipment is used by occupants and building services are operated that can lead to inefficient use of energy (Bordass et al. 2001). The extent to which the intrinsic features of a building that determine the demand for energy is comparable to buildings that form the basis of energy benchmarks is therefore important in acquiring an accurate indication of how well a building is being operated.

In various benchmarking schemes, adjustments, also known as normalisation, are made to energy benchmarks or actual energy used in buildings to take into account the influences from variations in individual circumstances on energy demands of buildings, which in turn allows fairer comparison. Among a range of parameters that are taken into account in various countries, adjustments for variations in weather and occupancy are the most common. Adjustments for weather involves normalising the heating or cooling consumptions according to seasonal and regional variation in weather conditions, typically using degree-days (CIBSE 2008; Cohen et al. 2008; Environmental Protection Agency 2011; Office of Environment and Heritage (OEH) 2011). This procedure takes into account the weather-dependent characteristics of the space heating or cooling systems of buildings to external temperatures so that performance of buildings in regions with different weather conditions can be compared with greater relevance.

There were also adjustments for occupancy hours or intensity of use which were intended to acknowledge the differences in energy demand of buildings due to variations in how long buildings are occupied for. Taking a supermarket, for example, a store may be occupied throughout the day and close in the evening while the other store could be open for 24 hours. The differences in hours of occupancy means that the 24 hour store would intrinsically require more energy to operate the equipment and building services. It would therefore be sensible to take into account the impact of different occupied hours on energy use when comparing the energy performance of these stores.

The allowance for separable energy uses is, on the other hand, a unique method that is used in the UK's DEC scheme. Separable energy uses are end-uses in a building such as server rooms and catering facilities that generally consume considerable amounts of energy but which are uncommon among the majority of buildings in the category (CIBSE 2009). By allowing these separable energy uses to be excluded from the comparison, a more relevant comparison is made with energy benchmarks.

Beyond these parameters, the review of relevant literature also showed studies that have integrated additional factors that determine the energy use of non-domestic buildings.

In the US, Sharp (1998) assessed the impacts of various building and operational characteristics on the energy use of offices and schools as part of a benchmarking process. Through analyses of schools for example, Sharp (1998) identified that year of construction and presence of walk-in-coolers were the most common characteristics in schools that were correlated with the electricity consumption. These factors were then used as a basis for normalising the energy performance of buildings to raise the comparability. The approach now forms the basis of the US Environment Protection Agency's (EPA) Energy Star scheme (EPA 2011). Similar approaches have been used elsewhere for benchmarking the energy performance of supermarkets and government office buildings respectively.

In Australia, the National Australian Built Environment Rating System (NABERS) takes a similar approach in normalising for a particular set of factors that affect the energy demand of each activity type (NSW Government 2011). Taking offices for example, the scheme allows for divisions in energy use between the landlords and tenants (Office of Environment and Heritage (OEH) 2011). Moreover, the methodology allows adjustments for variation in the number of computers and occupancy hours. The rating of hotels on the other hand, considers a completely different set of parameters that are specific to the activity type such as number of guest rooms, hotel AAA rating and climate (Office of Environment and Heritage (OEH) 2011).

Conclusions

Benchmarking is a technique that can play a key role in assessing and improving the operational energy efficiency of a building or the building stock. Without a robust methodology however, there are a plethora of elements that can hinder the effectiveness of the exercise and render the feedback irrelevant. It is therefore important to acknowledge what type of feedback one is acquiring from an exercise, ensure that the benchmarks are representative and reliable, comparisons are made with benchmarks that groups buildings with similar energy demand and a method is used that improves the comparability.

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4.4
ENERGY PERFORMANCE GAP

Chris van Dronkelaar, Dejan Mumovic, Esfand Burman, Mark Dowson and Catalina Spataru

Introduction

Although building energy modelling is an integral part of today's design process, research has shown that buildings can use twice the amount of their predicted regulatory energy performance (Pegg, Cripps & Kolokotroni 2007). One of the first major post-occupancy evaluation studies were the PROBE studies, which found little connection between values assumed in design estimations and actual values found in existing buildings (Bordass et al. 2001). This makes it unlikely that the building industry achieves model-based targets (UKGBC 2007). In the UK, and most other countries, regulatory performance is determined through compliance modelling, which is the implementation of thermal modelling to calculate the energy performance of a building under standardised operating conditions (occupant density, set-points, operating schedules, etc.), set out in national calculation methodologies. Compliance modelling is useful to assess the energy efficiency of buildings under standardised conditions to determine if minimum performance requirements are met. However, such calculations should not be used as baselines for actual performance (Burman, Mumovic & Kimpian 2014). Using the outcomes of compliance modelling to evaluate actual energy performance creates a significant risk for energy-related issues to go unnoticed, as the discrepancy between measured and modelled energy may be understood as the result of expected differences in operating conditions and exclusion of non-regulated loads from compliance modelling. This type of comparison has often been used to define the term 'the performance gap' (Menezes et al. 2012; Carbon Trust 2012; Cohen & Bordass 2015). This was to some extent inevitable, due to the dominance of compliance modelling in the context of the current regulatory framework in the UK and European Union. However, comparing compliance modelling with measured energy use may lead to a distorted view of the energy performance gap. Theoretically, a gap could significantly be reduced if a building is simulated with actual operating conditions, in other words, when attention is paid to the building context, defined here as performance modelling. The term performance modelling, in this context, includes all energy quantification methods which aim to accurately predict the performance of a building. The difference between compliance modelling and performance modelling is further illustrated in Figure 4.4.1.

On-going efforts to understand the energy performance gap have utilised calibration techniques to fine-tune a building energy model to actual operating conditions and energy use, ideally over a longer period of time. This method gives insights into the operational inefficiencies of a building and can pinpoint underlying reasons for differences between design estimations and actual use. Subsequently, a calibrated model could reintroduce design assumptions to quantify impacts of any underlying causes and their effect on energy performance. As such, a distinction can be made between three types of modelling

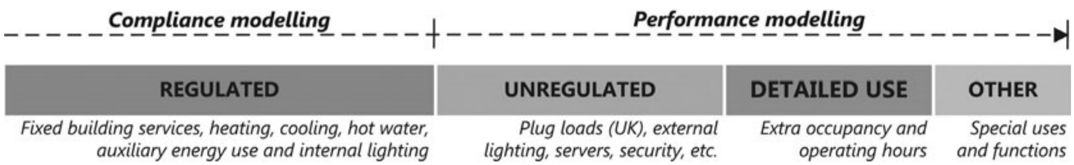

Figure 4.4.1 Compliance modelling versus performance modelling.

efforts, which can be classified in three different ways to interpret the energy performance gap. These are the gap between compliance modelling and measured energy use, performance modelling and measured energy use and calibration and energy use with a longitudinal perspective:

- Regulatory performance gap – comparing predictions from compliance modelling to measured energy use.
- Static performance gap – comparing predictions from performance modelling to measured energy use.
- Dynamic performance gap – utilising calibrated predictions from performance modelling with measured energy use taking a longitudinal perspective to diagnose underlying issues and their impact on the performance gap.

Underlying causes of the energy performance gap

There is a need for design stage calculation methodologies to address all aspects of building energy consumption for whole building simulation, including regulated and unregulated uses and predictions of actual operation (Norford et al. 1994; Torcellini et al. 2006; Diamond et al. 2006; Turner & Frankel 2008). Building energy simulation models need to closely represent the actual behaviour of the building under study for them to be used with any degree of confidence (Coakley et al. 2011). In terms of performance modelling, such models contain the design goals and should, therefore, be the basis for an assessment to determine whether the completed product complies with the design goals (Maile, Bazjanac & Fischer 2012). Although a margin of error between predicted and measured energy use is inevitable, due to uncertainties in design and operation as well as limitations of measurements systems, explaining its magnitude and underlying causes are necessary to more confidently forecast and understand energy use in buildings.

In Figure 4.4.2 an overview is given of the underlying causes of the performance gap in the different stages of a building's life cycle, projected along the Royal Institute of British Architects' (RIBA) plan of work (RIBA 2013), and drawn in relation to an S-curve visualisation of building performance proposed by Bunn & Burman (2015). The S-curve model allows for the transient and unstable nature of building performance during design stages and early stages of operation, before the building reaches steady operation, and can help visualise performance issues. These performance issues are identified as underlying causes of the energy performance gap, some directly related to the regulatory performance gap, whereas others are more applicable to the static performance gap, such as the simplification of system design in modelling. These issues are discussed and qualitatively analysed to understand their importance.

Investigation of predicted and measured energy use is necessary in order to understand the underlying causes of the performance gap. Furthermore, feedback helps with improving the quality of future design stage models by identifying common mistaken assumptions and by developing best-practice modelling approaches (Raftery, Keane & O'Donnell 2011). In operation, methodologies that analyse a discrepancy and related issues can help in understanding how a specific building is operating, highlighting poor-performing and well-performing buildings and identifying areas where action is required.

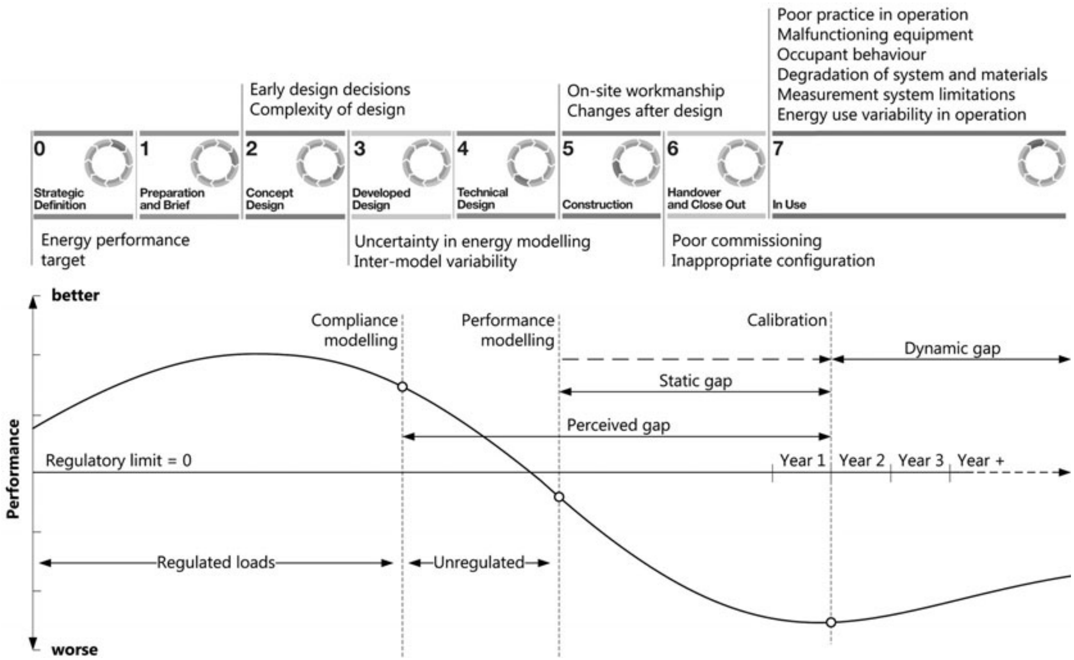

Figure 4.4.2 Underlying causes of the performance gap in a building's life cycle.

Limited understanding of impact of early design decisions

During the early design stage there is a lack of focus and understanding on the energy implications of design decisions (ZCH 2014a, 2014b). Choices such as form, orientation, materials, use of renewables, passive strategies, innovative solutions and others should be critically addressed during the concept design. Uncertainty and sensitivity analysis that determine the impact of design parameters can guide the design process through identifying and preventing costly design mistakes before they occur (Bucking, Zmeureanu & Athienitis 2014). The impact of such an issue can be highly dependent on the project team and is likely to influence various aspects of the energy performance of the building.

Complexity of design

Complexity of design can introduce problems during building construction, affecting building performance. For example, mistakes in construction become more frequent and complex systems are less well understood (Bunn & Burman 2015). Simplicity should be the aim of the design as many of the underlying issues are related to the complexity of the building (Williamson 2012).

Uncertainty in building energy modelling

In the detailed design stage, building energy modelling requires a high level of detail in order to predict energy use of a building. Myriad parameters with a certain level of uncertainty can have a large effect on the final performance due to the aggregated effect of uncertainties. Among uncertainties in design, those related to natural variability, such as material properties, are relatively well covered (de Wit & Augenbroe 2002). Other uncertainties are less well understood and need a strong basis for research to be established in modelling procedures. Investigation toward well-defined assumptions can assist in more accurately and confidently predicting performance of a building (Heidarinejad et al. 2013). Different sources of uncertainty exist in the use of building simulations. de Wit (2001) classified specification, modelling, numerical and scenario uncertainty, where heuristic uncertainty has been added to describe human-introduced errors as reported by Kim & Augenbroe (2013):

- Specification uncertainty: Arise from incomplete or inaccurate specification of the building or systems modelled. This refers to the lack of information on the exact properties and may include model parameters such as geometry, material properties, HVAC specifications, plant and system schedules, casual gains, etc. Parameters related to specification uncertainty are often 'highly unknown' during the early design stage, and can have a large effect on the predicted energy use. Assumptions for such parameters are often not representative of actual values in operation, for example, Burman et al. (2012) identified that the values assumed for specific fan powers were often much lower than in operation. Similarly, Salehi et al. (2013) identified that underlying design assumptions for plug loads and lighting were significantly underestimated.
- Modelling uncertainty: Arise from simplifications introduced in the development of the model. These include system simplification, zoning, stochastic process scheduling, but also calculation algorithms. Wetter (2011) asserts that mechanical systems and their control systems are often so simplified that they do not capture dynamic behaviour and part-load operation of the mechanical system or the response of feedback control systems. This is further supported by Salehi et al. (2013) who were unable to model the unconventional heating system of a building in utilised modelling software, which may lead to wrong performance prediction. The software was not able to model a water-to-water heat pump, so the system was therefore represented by a water-to-air heat pump with an electric boiler for perimeter radiators. Heat load of the boiler was then converted using the coefficient of performance of water-to-air heat pumps. Burman et al. (2012) found that pumps' auxiliary power consumption is not modelled for compliance purposes in England, default values based on HVAC system type are used instead. Such tool limitations are extensively reported and contrasted. This also highlights that certain systems and their configurations are not supported by building simulation software (Crawley, Hand & Kummert 2005).
- Numerical uncertainty: Errors introduced in the discretisation and simulation of the model. Neymark et al. (2002) performed a comparative analysis of whole-building simulation programs and found that prominent bugs and faulty algorithms caused errors of up to 20–45% in predicting energy consumption or COP values.
- Scenario uncertainty: Uncertainty related to the external environment of a system and its effects on the system. The specification of weather, building operation and occupant behaviour in the design model. Accuracy of design weather data can have a large effect on the predicted energy performance of a building. The predicted annual building energy consumption can vary up to 7% as a function of the provided location's weather data. While Wang, Mathew & Pang (2012) showed that the impact of year-to-year weather fluctuation on the energy use of a building ranges from −4% to 6%. Knowing the uncertainty of related microclimate variables is necessary to understand its impact on energy prediction (Sun et al. 2014). Similarly, occupants are an uncertainty external to the system and play a major role in the operation of a building. Occupants operate the building through adjusting lighting levels, operate electrical devices, open windows and possibly control HVAC operations. In design calculations occupancy is normally accounted for through a fraction profile, which determines their presence in the model and separately determine when they can operate building equipment. This profile is simplified by taking the average behaviour of the occupants, and therefore neglects temporal variations and atypical behaviour (Kim & Augenbroe 2013). Furthermore, occupant effects are related to specification uncertainty through assumed base loads (e.g. lighting and equipment), which make

it difficult to determine how occupant profiles or wrong base load assumptions impact the energy performance. Murphy and Castleton (2014) identified lower lighting energy use than predicted in their case study building due to unanticipated unoccupied hours.

- Heuristic uncertainty: Human-introduced error in the form of modeller's bias or mistakes. User errors are inevitably quite common due to the complexity of building energy simulation and its tools. These errors range from modellers setting up building systems in different ways, forgetting to correctly apply operation or occupancy profiles to the correct zones or can be related to geometry creation. Some of these errors can have a negligible effect on the predicted energy use, while others can significantly change the final outcome. Guyon (1997) investigated the influence of 12 energy modellers on the prediction of energy consumption of a residential house and found a 40% variability in their final predictions. A similar observation was made by the Building Research Establishment (BRE) where 25 users predicted the energy consumption of a large complex building and found that their results varied from −46% to +106% (Bloomfied 1988). Although these studies show significant differences, not much evidence is available to further support these results.

Inter-model variability

Ultimately, energy use prediction is performed using different tools, developed in different countries and for different reasons, and as such introduce variability in the results when modelling the same building, i.e. inter-model variability. This is directly related to uncertainties in building energy simulation; model simplification, user error and numerical uncertainties will drive the variability between different tools. These tools are utilised for the purpose of building performance prediction and thus have to give credible and relatively accurate results. Raslan & Davies (2010) compared 13 different accredited software tools and highlight a large degree of variability in the results produced by each of the tools and the consistency in achieving compliance with the building regulations for the same building. In a more recent study, Schwartz & Raslan (2013) performed an inter-model comparative analysis of three different dynamic simulation tools using a single case study and found a 35% variability in the total energy consumption. Similarly, Neymark et al. (2002) compared 7 different tools and indicated a 4–40% disagreement in energy consumption.

On-site workmanship

As building regulations become more stringent and new technologies are introduced, the quality of construction has to be improved. On-site workmanship needs to adapt and be trained to these increasing levels of complexity in building construction. New skills, such as extreme air tightness for limiting air infiltration, give rise to performance issues as airtightness is compromised during construction by discontinuous insulation or punctured airtight barriers (Williamson 2012), whereas Olivier (2001) reports that UK figures for construction U-values are optimistic. Installation of services, such as drainage, air ducts and electrical pipe work can often leave gaps which also reduce airtightness and induce thermal loss (Morant 2012). Other common issues related to on-site workmanship are eaves to wall junction insulation, incorrect positioning of windows and doors which reduce the actual performance of the thermal envelope (ZCH 2014a, 2014b). These issues are more prone to affect the energy performance in domestic buildings, where usually the performance of the thermal envelope is more significant.

Changes after design

After the building is designed, products or changes are often value engineered, which can affect building performance while not being fed back to the design team for evaluation against the required performance standard (ZCH 2014a, 2014b). These changes can occur during design due to site constraints, not well thought of integration of design modules and problems with detailing and budget. Morant (2012) reported inconsistencies between design specified and installed lighting loads in an office, which had a considerable impact on the discrepancy between predicted and measured electricity use. Good communication and coordination by the contractor is essential to prevent changes in design that may influence the energy performance.

Poor commissioning

When a building is constructed it is handed over: a separate stage that includes the installation and commissioning of building services. Done poorly, this results in problems such as reduced system efficiency and compromising the air tightness and ventilation strategies. Piette et al. (1994) reported poor commissioning of control measures, which were not set-up for proper control, and operation. Kimpian et al. (2014) identified that inverters for supply and extract fans were provided to AHUs, but were not enabled during commissioning, resulting in the fans operating at maximum speed at all times. In operation, such issues persist and require frequent commissioning.

Poor practice and malfunctioning equipment

The actual operation of a building is idealised during design by making assumptions for temperature set-points, control schedules and general performance of HVAC systems. However, in practice it is often the case that many of these assumptions deviate and directly influence a building's energy use. Kleber & Wagner (2007) monitored an office building and found that failures in operating the building's facilities caused higher energy consumption; they underline the importance of continuous monitoring of a building. Wang et al. (2012) showed that poor practice in building operations across multiple parameters results in an increase in energy use of 49–79%, while good practice reduces energy consumption by 15–29%. Piette et al. (1994) suggest that building operators do not necessarily possess the appropriate data, information and tools needed to provide optimal results. As such, operational assumptions made in the design stage may not be met by building operators (Moezzi et al. 2013).

Occupant behaviour

Another dynamic factor for a building in use are occupants. They have substantial influence on the energy performance of a building by handling controls, such as those for lighting, sun-shading, windows, set-points and office equipment, but also through their presence, which may deviate from assumed schedules. People are very different in their behaviour through culture, upbringing and education, making their influence on energy consumption highly variable. One of the major factors that has been reported to have a large influence on the discrepancy between predicted and measured energy use is the issue of night-time energy use related to leaving office equipment on (Masoso & Grobler 2010; Zhang, Siebers & Aickelin 2011; Mulville, Jones & Heubner 2014; Kawamoto, Shimoda & Mizuno 2004). This can be both related to occupant behaviour (not turning off equipment) and assumptions for operational schedules, extended working hours not taken into account in the design model. In an uncontrolled environment (not extensively monitored) it is impossible to determine how one or the other is influencing the discrepancy. Azar & Menassa (2012) investigated 30 typical office buildings and found that occupancy behavioural parameters significantly influence energy use. Parys, Saelens & Hens (2010) reported a standard deviation of up to 10% on energy use to be related to occupant behaviour. A more significant value is reported by Martani et al. (2012) who studied two buildings and found 63% and 69% variation in electricity consumption due to occupant behaviour. Using modelling, Hong and Lin (2013) investigated different work styles in an office space and found that an austere work style consumes up to 50% less energy while a wasteful work style consumes 90% more energy. Similarly, Clevenger and Haymaker (2006) studied an elementary school with varying types of occupant behaviour, whereas high-end values affected energy use by up to 150%.

Measurement system limitations

Similar to predicting energy use using building energy models, metered energy use obtained from measurement systems needs to be validated to ensure accuracy of the data. Limitations of measurement systems make adequate assessment of energy use inaccurate (Maile, Fischer & Bazjanac 2010). For energy measurement systems the accuracy is the sum of all its components and has an error percentage of up to about 1% (IEC 2003). For monitoring environmental variables, typical sensor accuracies lie within 1–5% for normal operating conditions, whereas incorrectly placed sensors will have increased levels of error (Maile, Fischer & Bazjanac 2010). Most common sources are calibration errors or the absence of calibration (Palmer & Armitage 2014). Fedoruk et al. (2015) identified that system measurements were not accurately representing its performance due to mislabelling, incorrect installation and not being calibrated. They report that simply having access to large amounts of data may actually result in more confusion and operational problems.

Longitudinal variability in operation

Finally, commonly the energy performance gap is generally assessed for a year of measured data. However, longitudinal performance is affected by factors such as building occupancy, deterioration of physical elements, climatic conditions and building maintenance processes and policies (de Wilde, Tian & Augenbroe 2011). Brown et al. (2010) present a longitudinal analysis of 25 buildings in the UK and found an increase of 9% in energy use on average per year over 7 years, with a standard deviation of 18%. Similarly, Piette et al. (1994) analysed 28 buildings in the US and found an average increase of 6% between the third and fourth year, with no average increase during the fifth year. Thus, a longitudinal variability in operational energy use has to be taken into account when investigating the energy performance gap. It should be noted here that longitudinal variability can be related to many of the previous factors mentioned, also sometimes such increase in energy use is related to an expected increase of equipment loads or changes in building function.

Assessing the underlying causes

All of these causes combined can have a large influence on the final energy performance of a building. Table 4.4.1 shows a risk matrix that defines the potential associated risks of the discussed underlying causes based on general consensus in literature. Important underlying causes identified in literature are those that have high impact and high evidence rating. These are specifically related to specification uncertainty in building modelling, occupant behaviour and poor practice in operation, with an estimated effect of 20–60%, 10–80% and 15–80% on energy use respectively. Other important factors that are likely to have high rated impact are the energy performance target, impact of early design decisions and heuristic uncertainty in modelling. It is important to note here that results are mainly based on studies that compare compliance modelling with measured energy use, theoretically many of these factors have a lower quantitative impact on energy use when performance modelling is used to predict energy use.

Table 4.4.1 Potential risk on energy use from reported underlying causes assessed, based on general consensus in literature.

	Underlying cause	*Evidence from literature*	*Rated impact on energy use*	*Estimated quantitative effect on energy use*
Context	Impact of early design decisions	Medium	High	
	Complexity of design	Low	Medium	
Model	Specification (geometry, material, equipment)	High	High	20–60%
	Modelling (simplification)	Medium	Medium	<10%
	Numerical (discretisation)	Low	Low	<5%
	Scenario (weather, schedule, operation)	High	Medium	10–30%
	Heuristic (user)	Low	High	<70%
	Inter-model variability	Medium	Medium	5–40%
Construction	On-site workmanship	Medium	Low	
	Changes after design	Low	Low	
Commissioning	Poor commissioning	Medium	Medium	<20%
Operation	Poor practice in operation	High	High	15–80%
	Occupant behaviour	High	High	10–80%
	Degradation of system and materials	Low	Low	<10%
	Measurement system limitation	Low	Low	<10%
	Energy use variability in operation	Low	Medium	5–15%

Reducing the energy performance gap

A major concern in the built environment is the segmentation of disciplines involved in the building life cycle stages. Traditionally, designers, engineers and contractors are all involved in the building development process, but leave once the building is physically complete, leaving the end-users with a building they are unlikely to fully understand. The design community rarely goes back to see how buildings perform after they have been constructed (Torcellini et al. 2006). Feedback mechanisms on energy performance are not well developed and it is generally assumed that buildings perform as designed. Consequently, there is little understanding of what works and what does not, which makes it difficult to continuously improve performance (ZCH & NHBC Foundation 2010). Gathering more evidence on both the performance gap and its underlying issues can support feedback mechanisms and prioritise principle issues. For this, the primary requirement is the collection of operational performance data, which can be fed back to design teams to ensure lessons are learnt and issues are avoided in future designs. It can help policy makers understand the trend of energy use and support the development of regulations. Finally, operational data is valuable to facilities management in order to efficiently operate the building. This feedback process is illustrated in Figure 4.4.3.

Legislative frameworks

Recently, the UK department of Energy & Climate Change introduced the Energy Savings Opportunity Scheme (ESOS) in order to promote operational management in buildings. A mandatory energy assessment to identify energy savings in corporate undertakings that either employ more than 250 or have an annual turnover in excess of ~38 million pounds (50 million euros). An assessor should calculate how much can

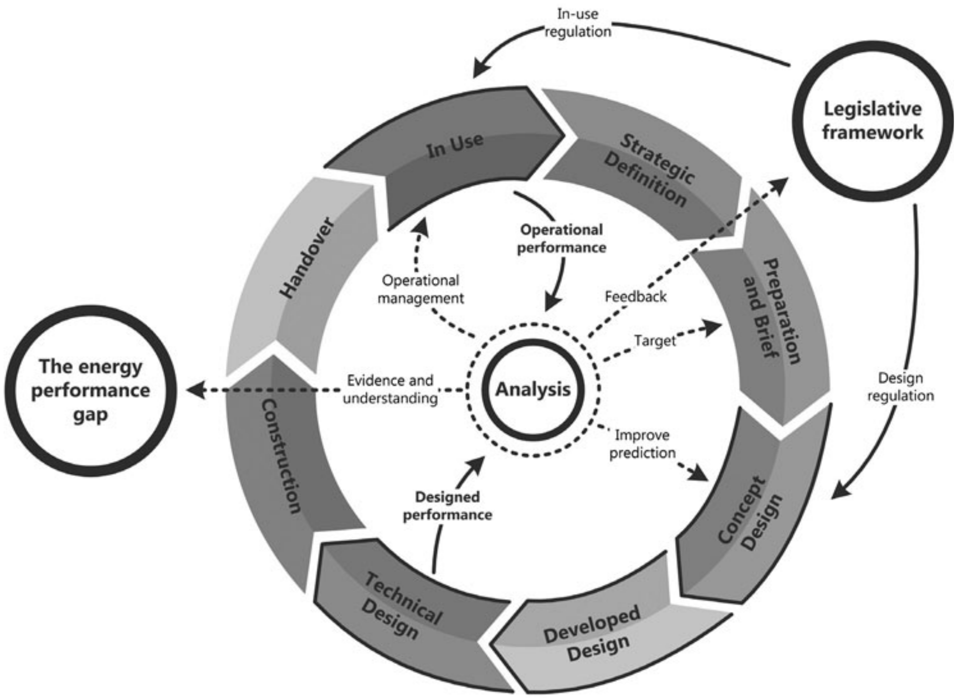

Figure 4.4.3 Operational performance feedback process.

be saved from improved efficiency. How these savings are predicted is, however, left open and could entail simple hand calculations instead of the more detailed dynamic thermal simulations. Furthermore, implementing proposed energy savings are voluntary. In the same context, Energy Performance Contracts are legally binding a third party for predicted savings to be realised, otherwise equivalent compensation needs to be provided. It thus becomes important to make accurate predictions of energy saving measures as their reliability directly influences the profit of the businesses providing these contracts. Therefore, building energy modelling is normally applied in order to take into account all aspects of energy use. Typically, performance modelling is supported by measured data to make such predictions. The EU Energy Efficiency Directive calls for a need to remove regulatory and non-regulatory barriers to the use of energy performance contracting to stimulate its use as an effective measure to improve efficiency of the existing building stock (European Parliament and Council 2012).

For new buildings, regulatory limits become ever more stringent in order to mitigate climate change. Achieving these regulatory limits requires new energy efficient technologies and higher quality construction materials to be proposed. Although such limits are theoretically engineered, evidently these regulatory limits are not achieved in practice. This can foster a lack of confidence in simulation in the building industry and may soon be met by legal and financial implications (Daly, Cooper & Ma 2014). Burman, Mumovic & Kimpian (2014) propose a framework that would enable effective measurement of any excess in energy use over the regulatory limit set out for a building. This excess in energy use could cause disproportionate environmental damage and it could be argued that it should be charged at a different rate or be subject to an environmental tax. Kimpian et al. (2014) suggest mandating the disclosure of design stage calculations and assumptions as well as operational energy use outcomes in building regulations; such data would significantly support the understanding of the energy performance gap. Furthermore, addressing all aspects of energy use beyond regulated energy use for compliance purposes would resolve the regulatory performance gap. However, such changes would make it difficult for regulators to assess energy efficiency of buildings under standardised conditions. Governments continue to face the difficult task of balancing the principal of not interfering in the affairs of businesses with the recognition of serious consequences of energy waste and climate change (Jonlin 2014).

Data collection

Accessible meter data is mandatory to confirm that buildings really do achieve their designed and approved goals (UKGBC 2007). A continued lack of such data is likely to lead to a progressive widening of the gap between predicted and measured energy use (Oreszczyn & Lowe 2009). Energy performance data can be used by: design teams to enable them to deliver better designs, clients to enable benchmarking and develop a lower carbon building brief, building users to drive change and management in operation, policy makers to target plans and incentives and monitor the trend of energy use (HM Government 2010). To this end, sub-metering is now mandatory in the UK for new builds. It is common however to find meters installed, but not properly commissioned and validated, which can make data futile (Austin 2013). Without data collection there would be no feedback loop to inform future policy and regulation (ZCH 2010).

Data itself does not solve any of the underlying issues of the energy performance gap as it is not directly visible how a building is working. It needs to be clear what this data represents. The issue of determining where errors exist between measured and simulated performance is simple when using monthly or diurnal plots. At hourly levels, many of the traditional graphical techniques become overwhelmed with too many data points, making it difficult to determine the tendency of black clouds of data points (Coakley et al. 2011; Haberl & Bou-Saada 1998). Tools to support intuitive visualisation are needed to disaggregate and display energy uses at detailed levels (building, sub-zone, system) and for different time granularity (yearly, monthly, weekly and sub-hourly) comparing predicted and measured energy use taking a longitudinal approach.

Design improvements

Negating the performance gap starts at the beginning of a project. At this point it is important to set a stringent energy performance in-use target, which can assist in a more rigorous review of system specifications and operational risks (Kimpian et al. 2014). With such in-use expectations, it becomes necessary to carry out performance modelling, validate assumptions made in the building model, make sure that building fabric is constructed to a high standard, systems are properly commissioned and that the building is operated as efficiently and effectively as possible. Making an accurate prediction of building energy performance then becomes an integral part of the design process. A building design, however, is based on thousands of input parameters, often obtained from guidelines or building regulations, some of which have extensive background research while others are only best-guess values. In particular during the early design stage, these values have a major influence on the design and its final performance. Pegg, Cripps & Kolokotroni (2007) argue for the use of feedback to inform design and the need for realistic and relevant benchmarks. Mahdavi & Pröglhöf (2009) suggest the collection of occupancy behaviour information to derive generalised (aggregate models) and utilise such models in building energy simulation. Capturing user-based control actions and generalising these as simulation inputs can provide more accuracy in performance modelling predictions, and ideally such results are fed back to improve compliance modelling processes as well. Menezes et al. (2012) used basic monitoring results to feed into energy models in order to gain a more accurate prediction of a building's actual performance (within 3% of actual consumption for a specific study). Similarly, Daly, Cooper & Ma (2014) showed the importance of using accurate assumption in building performance simulation, and identified the risks associated with such assumptions. They examined the sensitivity of assumptions on predicted energy use by using high and low assumptions and found that payback periods of simple retrofits could vary by several years depending on the simulation assumptions used.

Continuous feedback can improve the design process and more accurately predict actual in-use performance. Such predictions can be further supported by introducing well-defined uncertainties in design, improving the robustness of the building design, the reliability of energy simulation and enable design decision support, in particular when supported by sensitivity analysis (Hopfe & Hensen 2011)

Training and education

Often, the real performance of building elements are underestimated, as they are taken from lab-tests and omit, for example, the occurrence of thermal bridge mistakes during construction, which are more common with a higher design complexity. During construction, robust checking and testing is necessary to ensure that the quality of construction is maintained (Morant 2012). Clear guidance on thermal bridging should therefore be provided to the construction industry (ZCH 2014a, 2014b). Training and education is needed to increase skills in the construction industry and ensure better communication and quality of construction. Similarly, training and education should be enhanced for facility managers, to more strictly perform maintenance and operation of buildings. In the design stage it is important to create awareness to energy modellers of the energy performance discrepancy, while promoting skills, innovation and technological development in order to deal more appropriately with creating a robust design.

Operational management

After construction of a building, its systems are commissioned in order to ensure they perform as expected. However, post occupancy evaluation has shown that this is often poorly done and that there is a lack of fine-tuning during operation (Kimpian et al. 2014). Frequent re-commissioning exercises can help maximise the efficiency of building services, avoiding unnecessary energy use (Morant 2012). For guidance in this process, the Soft Landings framework was developed in order to provide extended aftercare, through monitoring, performance reviews and feedback. Aftercare and professional assistance are required as technologies and solutions made during the design often prove too complicated to be manageable (Way et al. 2014). Continual monitoring of the performance during operation is thus important in order to ensure that design goals are met under normal operating conditions (Torcellini et al. 2006). It is essential that facilities managers take ownership of energy consumption in buildings as they have detailed information of operational issues (CIBSE 2015).

When a building is in use, a discrepancy between predicted and measured energy use can be identified by representing the operation using advanced and well-documented simulation tools. A calibrated energy model can pinpoint differences between how a building was designed to perform and how it is actually functioning (Norford et al. 1994), this can then allow operational issues to be identified and solved, assisting facilities managers in the operation of their building. Furthermore, it can be used to assess the feasibility of Energy Conservation Measures (ECMs) through forecasting energy savings (Raftery, Keane & O'Donnell 2011). However, model calibration intends to compensate errors that can mask modelling inaccuracies at the whole building level (Clarke 2001). A well set-up methodology should therefore be established. Maile, Bazjanac & Fischer (2012) developed such a method using a formal representation of building objects to capture relationships between predicted and measured energy use on a detailed level, and were able to identify and solve operational issues. Raftery, Keane & O'Donnell (2011) argue that these calibration methods improve the quality of future models by identifying common mistaken assumptions and by developing best-practice modelling approaches. Reliability and accuracy of calibrated models depend on the quality of measured data used to create the model as well as the accuracy and limitation of the tools used to simulate the building and its systems (Coakley, Raftery & Molloy 2012).

In addition, there are often many constraints to going back to the building in order to make it more efficient, such as cost, reputational concerns and liability (Robertson & Mumovic 2013). A review of, and methodology for, calibration techniques are presented by Coakley, Raftery & Keane (2014) and Raftery, Keane & O'Donnell (2011) respectively.

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4.5
OCCUPANT BEHAVIOUR AND ENERGY USE

Alex Summerfield, Tadj Oreszczyn, Ayub Pathan and Sung-Min Hong

Introduction

Over recent years governments have refocused on energy efficiency in the built environment as having an important role in meeting their commitments to avoid serious climate change, with the UK aiming to reduce its overall carbon emissions by 60% from their 1990 levels by 2050 (DTI 2007). So there is also a heightened interest both in ensuring that such policy measures work and that the predictions of resultant energy savings are accurate. It implicitly assumes that improved efficiency, such as in appliances or heating systems, will lead to lower overall energy consumption. However it has also long been recognised that a ‘rebound effect’ occurs, whereby some of the expected energy savings do not eventuate due to benefits being mitigated by changes in occupant behaviour. It may even lead to an overall increase in energy consumption by stimulating new demands (Saunders 1992). However, the extent and full implications of this phenomenon remain a matter of on-going debate (Herring and Roy 2007).

The rebound effect has been delineated in terms of three categories (Dimitropoulos and Sorrell 2006), normally framed in economic terms, but here interpreted in terms of occupant behaviour:

- Direct effects: occupants take the savings from energy efficiency improvements as an opportunity to use the system more. In dwellings this can occur when occupants ‘take-back’ the benefits of energy savings in a home due to a more efficient heating system as improved thermal comfort (say, higher room temperatures), rather than as lower heating costs.
- Indirect effects: if occupants find that energy costs associated with operating their home are lower, then more income is available for them to spend on other products and services, each of which involves energy in their production and delivery, such as new appliances or overseas holidays.
- Economy wide effects: these reflect broad technological innovations or social changes which lead to long-term changes in the economy, for instance broadband communications that enable occupants to work from home (and imply reduced energy required for commuting) but alter dwelling occupancy patterns and heating demands, or where innovation and efficiency leads to greater affordability of appliances that substitute energy for occupant labour, such as washing machines and dish washers.

From a historical perspective, one of the best illustrations is given in the study by Fouquet and Pearson (2006) that examined the per capita usage of lighting in the UK, spanning several centuries. Each shift in lighting technology from candles, to oil and gas lamps and then to modern electrical lighting, represents a significant improvement in efficiency. But each has also been accompanied by a dramatic rise in lighting usage. So that while the lighting efficacy – that is the lumens per watt – of modern lighting is more than 700 times that of eighteenth-century oil lamps, consumption in lumens per capita has increased more than 6000-fold. Such demand is driven not only by the reduced cost of lighting as the efficiency improves and our relative increase in wealth over that time, but highlights the great value humans place on the amenity and aesthetics that lighting provides.

These effects are embodied in what has been termed the Khazzoom-Brookes postulate (Saunders 1992), which takes a top-down approach (and the opposite of the conventional 'bottom-up' approach of researchers in the built environment) to suggest that while energy efficiency improvements might be justified at the micro-level, they lead to higher levels of energy consumption at the macro-level than in the absence of such improvements. While this is discussed elsewhere there is ongoing debate as to the extent that this holds and its implications, in spite of manifold efficiency improvements nations generally have struggled to reduce in absolute terms their overall energy usage alongside economic growth (Herring & Roy, 2007). Moreover, it has been argued that people have an apparently innate ability of finding new ways to consume energy (Oreszczyn 2004).

Yet, this does not undermine the worthwhile objective of greater energy efficiency, since it is also important to be mindful of the motivation behind all this is not energy per se, but the environmental costs and carbon emissions associated with energy generation and distribution. Occupants can choose to use the benefits of lower heating costs to further consumption in carbon intensive activities, such as a flight for a weekend holiday overseas, or they may use it as an opportunity to shift to activities that have low or even negative carbon emissions, such as by being able to afford renewable or low-carbon energy supplies. Such choices by households are in turn framed by wider government policies and priorities, and efficient dwellings allow such policies, when they ultimately occur, to be effective. The main point is that energy efficiency in buildings and energy use by occupants is not an isolated relationship, but is set in a much broader social and economic context.

The issues are highlighted for building researchers and designers when using technical models to predict energy consumption for an individual building, or at the level of how the entire domestic building stock performs. These types of analysis have become an everyday part of professional activity, particularly with sophisticated computer simulations that provide a convenient and efficient tool for a comparison of the alternatives. These generate abundant quantitative data on building performance and even seductive graphics that convey confidence, whereas outcomes are uncertain and predictions seldom, if ever, verified over the long term. Indeed, the closer one examines how energy performance of the built environment is predicted, the more it seems entirely contingent on occupant behaviour being as expected.

The key lies in the way models are used to account for these socio-technical factors, that is the interactions between the occupants and building and its services. In the process of evaluating various options, often it is the case that occupant behaviour is assumed to remain essentially constant, i.e. independent of the scenarios being tested. Alternatively, it may be implicitly understood that occupants will automatically shift from their existing patterns to a new behaviour appropriate to the proposed building specifications, such as ventilating buildings at the 'suitable' times. For instance, with installation of a new central heating system, it might reasonably be expected that occupants will operate this rather than the less efficient heating methods that they used previously. It will be seen that just such unexpected behaviour by occupants can degrade whole system performance and potentially overturn the savings expected by designers or policymakers.

The aim of this chapter is to explore the socio-technical factors that operate in the built environment, specifically the relationship of occupant behaviour to energy use in the domestic sector, using three examples from the UK. The first is the Warm Front project, a government funded energy efficiency scheme for vulnerable households that involved building improvements, such as cavity wall and loft insulation and in some cases gas central heating systems. Second, we examine the impact of conservatories

– this typically prefabricated and highly glazed addition to existing homes – that was originally conceived of as a passive solar design retrofit. Last, we return to the 'low-energy' homes of Milton Keynes, previously described in Part II Case Study A on environmental monitoring, to examine the impact of some of the many social and technological changes in the domestic setting that have occurred over time. This by no means provides an exhaustive list of behavioural effects, but aims to create an appreciation of the range of complex interactions that can occur in the real built environment, and beyond the often optimistic and overly simplified assumptions that underlie simulation models. The discussion section encapsulates the socio-technical factors at work in a schematic form to assist designers and researchers with their analysis and prediction of energy performance.

Examples from the UK domestic sector

Warm Front

The main aim of the Warm Front scheme is to alleviate fuel poverty by providing grants for the installation of cavity wall insulation, loft insulation, draught proofing and, for some particularly vulnerable households, the option of gas wall convector heaters or a gas central heating system (Wilkinson et al. 2006; Hong et al. 2006). In the UK a household is deemed to be 'fuel poor' if more than 10% of total household income needs to be spent on fuel use to heat the home to an adequate standard of warmth, defined as 21°C in the main living room and 18°C in other occupied rooms during daytime hours (DTI 2001). This is not the same as the amount the household spends on fuel, since many will reduce heating costs to a lower fraction by keeping their homes at a temperature much lower than is typical in the UK. This is precisely the behaviour the scheme aims to address, since occupants are at increased risks of mortality and morbidity in dwellings with inadequate heating (Wilkinson et al. 2001).

Analysis of more than 1300 dwellings in the Warm Front scheme indicated that energy efficiency improvements lead to an increase of both living room and bedroom temperatures which are likely to have substantial benefits for the occupants in terms of thermal comfort and well-being. Under standardised external conditions of 5°C, the daytime living room temperatures 1.6°C higher (19.1°C) and night time bedroom temperatures were 2.8°C higher (17.1°C) in dwellings that received both heating and insulation measures, compared with temperatures in dwellings prior to this intervention. Using the benefit of efficiency measures for improved comfort rather than lower fuel costs is known as the 'take-back' factor (Wilkinson et al. 2006). Temperatures were influenced by property characteristics, including its age, construction and thermal efficiency and also by the number of occupants and the age of the head of the household. An improved thermal performance of the dwelling due to insulation and draught stripping will itself reduce the decline in temperature when the heating system is off, which will tend to produce higher average temperatures. So the choice of a warmer home is far easier for occupants in such dwellings, especially if the capacity of the heating system and its control also facilitate this, and hence is likely to lead to a significant increase in average temperatures. For Warm Front, the 'take-back' factor was both an expected and desired outcome, with subsequent results also showing a 'take-off' factor in some cases, whereby occupants were wearing less clothing in response to the higher internal temperatures (Hong et al. submitted). This is an example of the interaction, or bi-directional relationship, between internal conditions and occupant behaviour.

In terms of energy savings, the findings indicated that cavity wall and loft insulation reduced space heating fuel consumption by 10% in centrally heated properties and 17% in non-centrally heated properties. So occupants were taking a combination of energy savings and comfort benefits. The gas central heating system, although theoretically more efficient than the systems it replaced, was not found to reduce fuel consumption even after adjusting for increased internal temperature. Again, there are a number of possible mechanisms at work to explain this. Analysis of pressure testing data showed that the installation of the

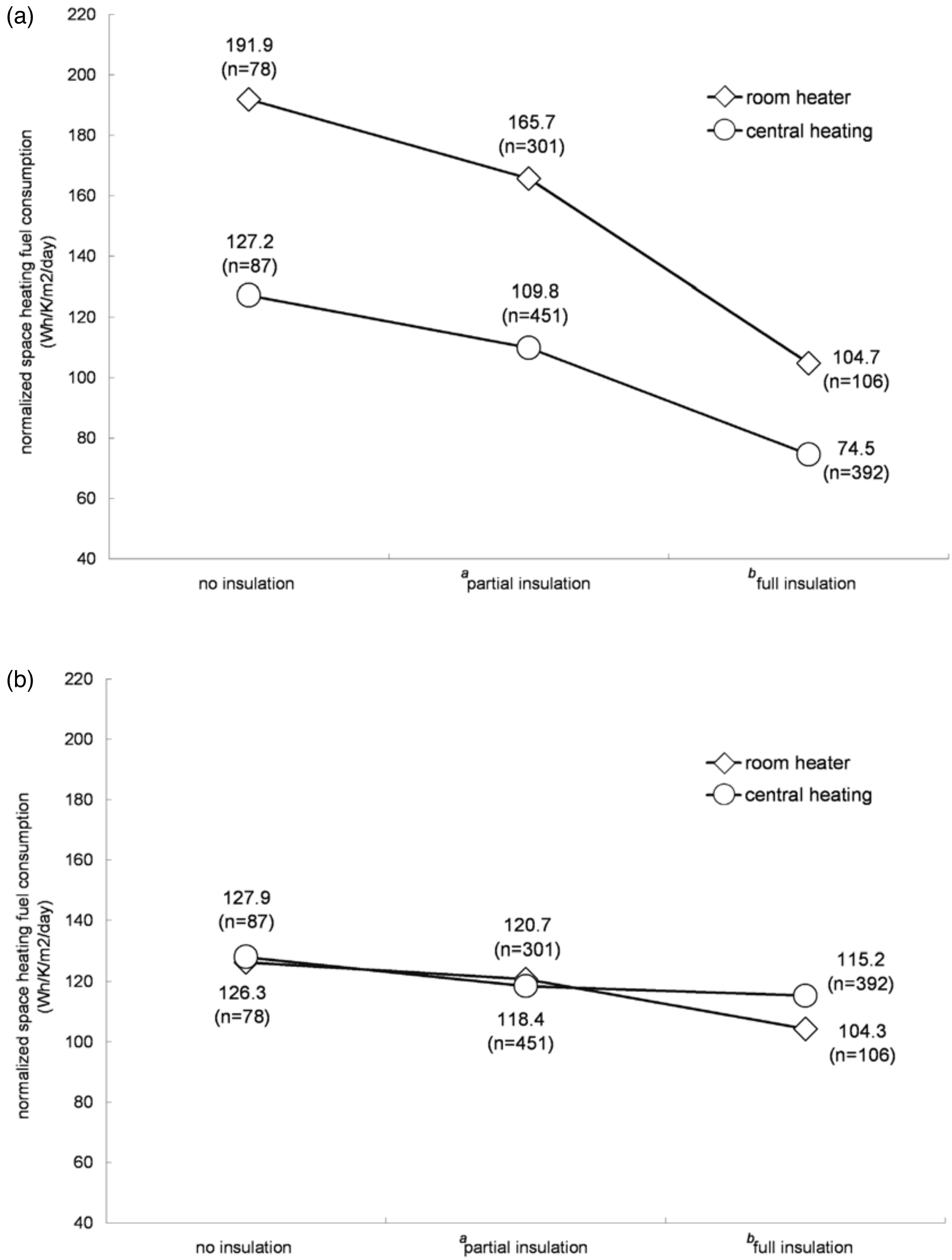

Figure 4.5.1 Normalised space heating fuel consumption (Wh/K/m^2/day) in Warm Front dwellings disaggregated by primary heating system and insulation level, according to (a) modelled results and (b) results from monitoring.

central heating system increased air infiltration rates, probably due to pipe work penetrating the building fabric (Hong et al. 2004). But from a socio-technical perspective, having central heating was also associated with higher rates of window opening by occupants (3.3 days/wk compared with 2.9 days/wk for those without central heating). Thus, overheating or stuffiness that resulted from the central heating operation may have prompted occupants to increase the ventilation rate (Hong et al. 2006). Once a window is open in one room, it may easily be forgotten and left open while the occupant is in another, and the central heating – according to how the controls are set – will continue to heat the whole dwelling.

Another issue is when the expected behavioural change does not occur. Figures 4.5.1a and 4.5.1b compare performance based on predictions from technical modelling with monitored fuel consumption, and show that the combination of insulation and central heating should have produced a decline of more the 60%, whereas no significant difference due to central heating was identified in the data. One of the reasons there may not have been the expected efficiency gains from central heating (for instance via the use of condensing boilers) is possible continued use of fixed gas fires that remained in some dwellings after the central heating refurbishment. In other words, although there is no direct data, some occupants, perhaps the more elderly, may have preferred to carry on heating their home in the way they were accustomed. Results from another study illustrate how the interaction between this behaviour and a central heating system may lead to a greater decline in overall system performance than might be anticipated (Bell & Lowe 2000). By operating the gas fire in the same room as the thermostat control, the high temperatures would prevent the central heating system from operating. Thus, the much lower efficiencies from operation of the gas fire will tend to prevail in the overall system performance, compared with the contribution from the more efficient gas boiler of the central heating system. This serves to illustrate how large variations in behaviour may occur in specific types of occupants, possibly according to their sociodemographic background (age, income, health, family structure) and lifestyle factors.

Trends in conservatory use

Historically, conservatories in the UK were the preserve of wealthy households and used as a highly glazed space to protect plants over the winter months, but by the 1920s they had become unpopular. Interest was reawakened in the 1970–80s, when conservatories were considered from the perspective of being buffer spaces and one of the main options for passive solar retrofit. For the UK, research at that time estimated that each installation would provide 900–1000kWh/year of annual energy savings, with an additional 150kWh/year if the conservatories were double glazed (NBA Tectonics 1992; ETSU 1998). The identified potential energy savings were initially seen as due to the conservatory having the effect of additional insulation for the enclosed walls and windows and also by supplying pre-heated ventilation air to the house via a fanned or natural convective loop (though subsequent analysis indicated that there were few occasions when this was worthwhile).

Although it was recognised that these savings would be heavily influenced by occupant behaviour, little research was conducted on exactly how conservatories were being utilised until a questionnaire survey of more than 1800 conservatory owners was conducted in 1991 (Oreszczyn 1993). This revealed that two out of three conservatories were heated directly, and of the remainder, 72% heated indirectly by not having a door (open plan) or leaving the door open to the rest of the house. Thus, over 90% of conservatories were heated by some means, with over a third of these heated regularly. Over half (51%) of the directly heated conservatories had thermostats, with a quarter (27%) of these set at 10°C or below – probably for frost protection of plants. Although there was uncertainty about the timing in which doors were left open relative to timing for heating, it was clear that most conservatories were regarded as either an extension (by leaving the doors open) or integral (by not having doors) to the house.

Over the intervening years this comparatively easy way use a prefabricated unit to add floor area to a dwelling has proven to be immensely popular. By 2003 more then 200,000 new conservatories were

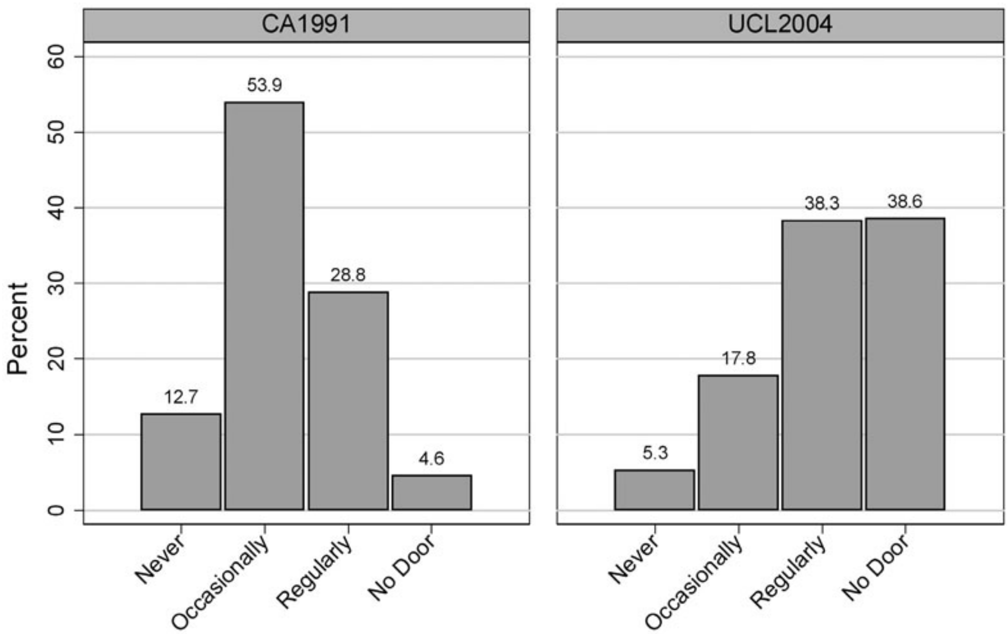

Figure 4.5.2 A comparison of door opening (and the prevalence of conservatories without a door) across the two surveys.

being built annually in the UK, with an estimated 15% of dwellings having a conservatory (Economist 2004). So in 2004–5, parts of the 1991 survey were repeated for more than 300 conservatory owners in London, to see what changes in occupant usage had occurred (Pathan et al. 2007).

It was found that more than 90% of respondents now reported using their conservatory all year (up by almost 20% on the 1991 figure). More than a third (38%, up from 5% in 1991) now have no door between the conservatory and the rest of the house. Nearly three out of four occupants heated their conservatory on a daily basis, with the majority of respondents heating it more than 7 hours a day in winter (Figure 4.5.3) and there has been a related shift to the use of central heating (69% in 2004). When the analysis was repeated and the 1991 survey limited to those from a comparable region (Southern England), these results remained essentially the same.

The issue lies in the potential impact this occupant behaviour has on overall energy performance of the dwelling, by, for instance, using central heating to heat conservatories. This is due to the relative poor thermal performance of the conservatory compared to other external walls, hence greatly increasing the proportion of exposed area with relatively high U-values. The policy fix, as suggested by technical models, might be to require conservatories to be double glazed with about a 30% lower specific heat loss. Unfortunately, this again does not allow for adaptations in occupant behaviour, as further results from the 1991 survey show, double glazed conservatories were heated for almost double the length of time compared to the single glazed counterparts. It may be that while single glazed conservatories tended to be too cold to heat in winter, the double glazed conservatories provided the considerable amenity value of a habitable space all through the heating season that justified the increase in heating costs. By 2004 almost all conservatories were double glazed and used in winter. As conservatories are perceived as integral to the rest of the house, so their function changed and shifted from being a passive solar space – even in the initial survey almost two thirds (64%) used it after dark.

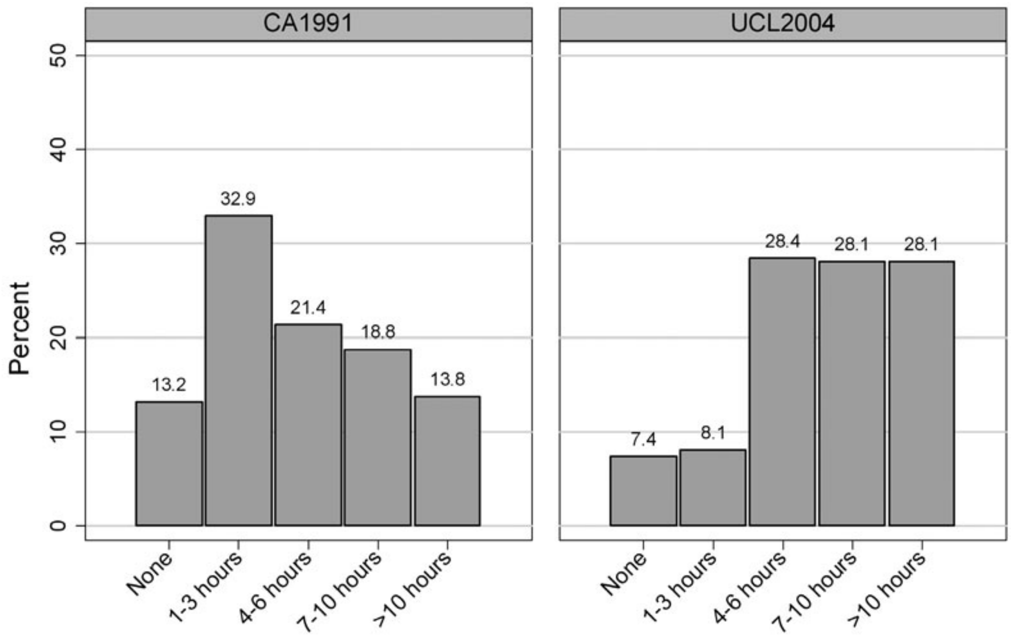

Figure 4.5.3 A comparison of winter heating duration across the two surveys.

While building regulations in the UK have been amended so that open plan conservatories must meet the general thermal performance standards that apply to normal building extensions, it was still the case in 2008 that conservatories with doors to the house and floor area of less than 30m^2 are exempt. Doors may simply be left open or even removed after the final inspection. In the end, this must be taken as a cautionary tale of how an initial intention of improving the energy performance of the domestic sector with passive solar design, has not only failed to provide the expected benefits from passive solar retrofit, but, for many dwellings, may have proven to be completely counter-productive in terms of energy efficiency.

Milton Keynes low-energy homes

A key objective with energy efficient design is not just the performance obtained at construction, but the enduring gains in efficiency that last over the life of the building. As was described in Part II Case Study A, the MK0 study of 'low-energy' dwellings in Milton Keynes has provided an invaluable opportunity to investigate changes in energy usage over 16 years. Out of a project that involved more than 120 dwellings, a sub-sample of 29 dwellings were monitored for both hourly energy and temperature from 1989–91. By current standards, these homes may not be considered as being particularly efficient, but they are referred to as being 'low-energy' since they were constructed to higher standards of energy performance than required by building regulations at that time. They incorporated features such as increased floor and wall insulation, double-glazing and condensing boilers, to the extent that they broadly complied with building standards of a decade later (Edwards 1990). In the follow-up study of 2005–06, referred to as MK1, temperature monitoring and energy meter readings were undertaken in 14 of the gas centrally heated homes from the original sub-sample (Summerfield et al. 2007).

Table 4.5.1 Household characteristics of the MK0 (1990) and MK1 (2005).

Household Characteristics (per dwelling)	*MK0 (SD)*	*MK1 (SD)*
Number of occupants	2.7 (0.1)	2.5 (0.1)
Number of children (<16yrs)	1.0 (0.1)	0.30 (0.05)
Annual hhld. income ('000s GBP)	-	53 (25)
Floor area (m^2)	104 (3)	109 (4)
Bedrooms	3.1	3.2
Tumble dryers	0.1	0.5
Dishwashers	0.1	0.5
Televisions	1.2	1.5
Computers (incl. laptops).	-	1.6

The socio-demographic changes that have occurred over the fifteen years are shown in Table 4.5.1. One of the most striking changes has been the decline in the number of children (reflective of broader changes that have taken place in the demographics of the UK population) which is likely to have resulted in large differences in the lifestyle of the occupants. Secondly, there has been a marked increase in the number of appliances (of which we have only limited information from 1990), particularly labour saving devices of dishwashers and tumble dryers which have increased fourfold. Although not included in the 1990 list, it is likely that computer ownership has also greatly increased and some appliances that are now relatively commonplace, such as game consoles or large flat screen TVs, would have been non-existent in 1990.

However from Figures 2A.3–2A.4 in Case Study 2A, it was seen that the overall increase in daily gas consumption of 10% to 71kWh/day (under standardised external conditions of 5°C) was primarily due to the increase in high energy usage households, and this corresponded to the 9% increase in floor area that occurred in these dwellings (Summerfield et al. 2007). The increase in electricity consumption of 30% at 15kWh/day was even more skewed toward increases in high energy using households, which also – as expected – were the larger dwellings. Some caution is required since the numbers in this sample are too small to ascribe changes to energy usage to specific household characteristics in a statistically significant way. However, research currently being undertaken with a total sample size of more than forty dwellings confirms a similar pattern of results whereby changes are skewed toward higher energy users.

Underlying this phenomenon is the inherent asymmetry in the potential for occupants to alter energy usage, since there is a certain limit for a given building's construction and external conditions below which energy usage cannot fall and still maintain thermal comfort and air quality inside. While even in a highly insulated building, no such inherent limit exists in the potential for increased energy usage as a result of occupant behaviour – except in the capacity of systems to supply energy and the occupant to pay for it! Moreover, conventional design can facilitate disadvantageous behaviours, for instance simply in the consequences of forgetting to close a window or door. In MK1, 9 of the 14 households reported leaving their bedroom window open on winter mornings, usually to help ventilate the adjoining bathroom. If energy efficiency measures are in place, it is difficult to ensure the system maintains optimal operation. A few of the Milton Keynes dwellings had relatively sophisticated heat recovery systems, which the original owners may have been proficient in operating, but in the transfer of dwelling ownership over time, this knowledge had not been passed on so that the new owners were unaware even of its existence.

Based on some of the general observations during field work on the follow-up study, it was also clear that major changes had occurred in the way some occupants lived, and these were likely to be substantially different to the original design intentions. One was the number of occupants working from home. In many cases, spare bedrooms or extensions were used as studies and had large amounts of office and related computer equipment that were more typical of non-domestic environments. Since they are located in part of the dwelling that would have had minimal heating previously, indirect gains from this additional equipment may not contribute to reducing the usage of central heating. These indirect gains may even lead to greater energy usage, as in one case where the bedroom/office had five computers and suffered from localised overheating even in winter, with the result that windows were kept open in that room and hence suggesting increased ventilation rates for the whole house.

So part of this asymmetry in energy demand may also be related to the greater scope that larger dwellings provide for occupant lifestyle changes to have an impact. For instance, by having the outdoor space to enable an extension to be added to the dwelling, which then requires more heating and provides space to accommodate more appliances. If it is highly glazed then it will also increase heat losses. By contrast, occupants on smaller dwellings that do not have the land to provide this opportunity and accommodate such lifestyle choices may simply choose to move away instead. Hence there is potentially a differential impact of occupant behaviour increasing energy usage both at the level of day to day operation and in terms of more fundamental changes to lifestyle and building design.

Discussion

The three case studies have illustrated not only the important role of occupant behaviour in energy usage, but the diverse ways this influence can be manifested and disrupt predictions of energy savings from technical models. They may be summarised as follows:

- In some cases the issue is that occupant behaviour does not change, precisely when some modification in behaviour would be expected.
- Occupant behaviours are likely to vary across distinct occupant groups, such as the use of heating systems by the elderly, the poor, the wealthy, and those with ill health.
- Occupant behaviour is an ongoing factor, not just an issue concerning initial occupation, hence such issues as ensuring control systems are supported by information.
- Broader social changes over time, such as in lifestyle or technological innovation may introduce entire, unanticipated occupant behaviour, such as changes in different social groups, different designs.
- Occupant behaviour may result in the energy efficiency measures performing less than expected, and even to being counter productive.

In the face of so many potential options for occupant behaviour to influence energy performance of the dwelling, it is worthwhile reframing the issues into a schematic diagram that can delineate the various inter-relationships at work. While Figure 4.5.4 uses generic descriptions, for instance there are more aspects to building design than those listed, it delineates the various pathways leading to resultant energy usage and carbon emissions. First, there are the intrinsic properties of the building, such as the infiltration rates, which impact on the internal conditions, such as temperature and ventilations rates. These are also affected by the external conditions. An additional pathway may be traced from the building (and any extensions) to the occupant behaviour and their actions to influence the internal conditions, for instance by setting the thermostat temperature or by opening windows. Thus the relationship between the building and final energy use is also mediated by occupant behaviour.

External environmental conditions, primarily weather conditions but also pollution and noise, affect the internal conditions and thereby can also prompt a change in occupant behaviour (for instance to shut a window). Thus, relationship between occupant and the internal conditions is bi-directional as each influences the other. The sociodemographic and lifestyle characteristics of the household, such as family size, education and income, have an influence of a range of factors, including the scope of any building alterations, occupant behaviour and appliance ownership and usage. This last factor can impact energy

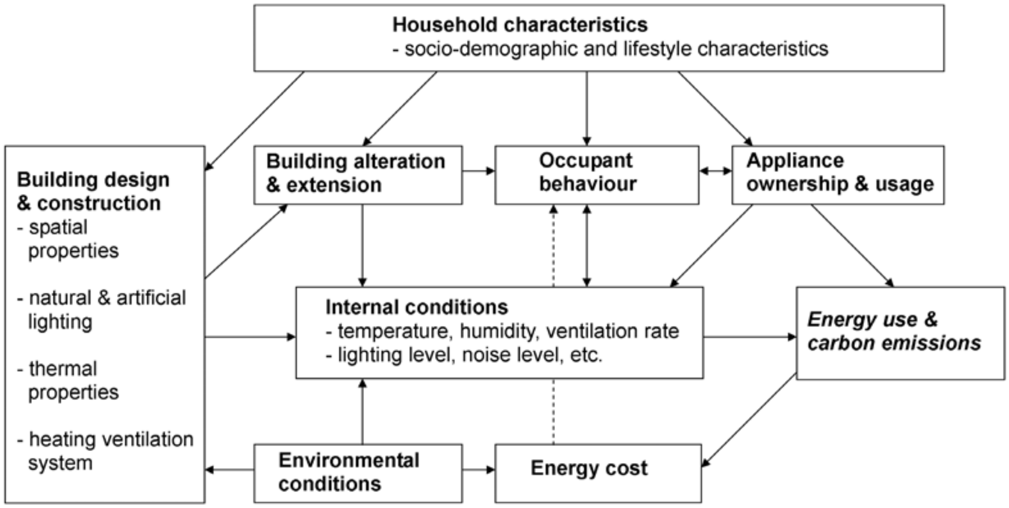

Figure 4.5.4 A schematic representation of the inter-relationships between occupant behaviour and other factors in influencing energy use in domestic buildings.

usage both directly and via indirect effect to the internal conditions, for instance, consider a tumble-dryer that both consumes energy and contributes to moisture production in the house. As this may lead occupants to open windows, It also has a bi-directional connection with occupant behaviour, for instance ownership of a smart energy meter may lead to occupants altering their thermostat setting.

In practice, when considering a specific scenario or energy efficiency measure, these pathways can be specified more precisely as mechanisms that alter the strength of the connections between each factor. Thus it might be hypothesised that buildings constructed with lower infiltration rates will mean that external environmental conditions will have a reduced influence on internal conditions and hence energy usage. But it can also be seen that the same measure may result in a greater likelihood of occupants increasing ventilation rates by opening windows.

It is not feasible to eliminate pathways, particularly in the domestic sector where the occupants have control over their home environment. Rather, both researchers and designers should undertake sensitivity analysis, by varying the level of interactions, to find the most robust, energy efficient measures available. While energy costs are relatively low and occupants have poor feedback regarding their energy usage there are limits to what designers can do but, generally, it is worthwhile to aim for simplicity and minimise the need for occupants to be specifically aware of the building operation. In other words, we should design so that the 'default' mode of building operation is one of the most efficient, and make the choice the easiest for occupants to attain. As Oreszczyn, one of the authors, is fond of reminding colleagues: 'it is not buildings that use energy, it's people in buildings!'

Acknowledgements

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Case Study 4A
NATURAL VENTILATION OF AUDITORIA
Three case studies

Malcolm Cook and Alan Short

Introduction

The recovery of natural ventilation as a viable means of cooling and ventilation for large, non-domestic buildings in temperate climates is now well established. More recently the use of natural ventilation has been extended to the design of auditoria. The successful natural ventilation of auditoria is particularly challenging. Some of these challenges are highlighted here.

In natural displacement ventilation, layers of warm air at high level drive a flow of air out through high-level ventilation openings. This flow draws in fresh air at a low level. Large inlet and outlet areas are required to ensure that the horizontal interface separating the fresh cooler air from the warmer stale air above remains above the breathing zone. For this reason, in an auditorium with raked seating, the height difference between the lowest and the highest audience seat, as a proportion of the overall internal height, is critical. The decision to introduce galleries or balconies in performing arts venues to increase capacity, or reduce furthest distance to the stage, has profound consequences for the design of the natural ventilation scheme.

Air inlets and damper control need to be carefully considered to avoid wind-induced pressure imbalances whereby negative pressures at the inlet location prevent ambient air from being drawn into the building. Even when air is successfully drawn into a plenum below raked seating, care is needed in the design to prevent air being driven directly through the plenum and out of the building without being drawn into the occupied space.

Auditoria, whether for the performing arts or lectures, are occupied intermittently. The BMS must be able to respond to these dynamics and have an operating resolution able to cater for a wide range of occupancy density, from full houses down to just a few people during rehearsals.

This chapter looks at how these, and other technical challenges, have been tackled in the design of three auditoria: the Queens Building at De Montfort University; the Contact Theatre in Manchester, which comprises two auditoria; and the Lichfield Garrick, also incorporating two auditoria. The chapter presents guidance distilled from the experiences gained by the design teams involved to provide architects and engineers with some insight into the design of naturally ventilated auditoria.

The Queens Building, De Montfort University

The Queens Building at De Montfort University in Leicester was completed in 1993 and contains two wholly naturally ventilated, 180 seat wide-fan, lecture theatres (Figures 4A.1 and 4A.2). It represents the

Figure 4A.1 View from the south of the Queens Building at De Montfort University.

Source: MJ Cook, De Montfort University

first attempt by architects Short and Associates to make a naturally ventilated auditorium. The natural ventilation strategy is buoyancy-driven displacement ventilation assisted by tall stacks (two per auditorium). Fresh air is drawn in at low level beneath the seating rake. The orientations of the two theatres lie at 180° to one another which reverses the sense of the seating rake and the inlet and outlet positions. In terms of buoyancy-driven displacement ventilation this should be irrelevant, but, in practice, anecdotal evidence suggests that the 'reversed' auditorium is less successful than the other in terms of acoustic performance and draught risk. This is thought to be because the air entering the 'reversed' auditorium air can bypass the plenum below the raked seating and enter directly into the space via 2.5m high heating elements. This results in less opportunity for acoustic attenuation and higher air speeds over the heating elements.

For the more successful auditorium, air is introduced from the north side via dampers behind belfry louvres 4m above street level (Figure 4A.3), into triangular plena, subdivided by acoustic splitters, before entering a full plenum above a 300mm in situ concrete slab, below a timber and steel framed seating rake. Air enters the occupied space through continuous grilles in the risers to the stepped rakes, passing through finned tube heat exchanges. Warm, stratified air then passes through large rectangular openings in the vertical plane below soffit level into the parallelogram-shaped stacks. The stack terminations comprise four top-hung conventional steel-framed windows opening out, achieving an effective stack height of 17.6m. The envelope of each auditorium is in very heavy construction using concrete and calcium silicate brick masonry.

Being one of the first of the new generation of large scale, naturally ventilated buildings in the UK, the design team was keen to test the likely performance of the system. Both physical and numerical techniques were used by the design team in developing the natural ventilation strategy. Dynamic thermal simulations were carried out to investigate the likely thermal performance of the auditoria over a typical year. This modelling work included looking at the effects on thermal performance of adding acoustic lining (i.e. reducing the exposed thermal mass), reducing internal heat gains and increasing ventilation opening sizes (Eppel and Lomas 1991). For the cases investigated, the number of occupied hours for which the dry resultant temperature was above 27°C was in the range 3–9, using 1967 weather data for Kew, London; none of these hours fell in the term-time period.

Figure 4A.2 150-seat auditorium at the Queens Building.
Source: MJ Cook, De Montfort University

While dynamic thermal simulation models are ideal for predicting thermal performance over an entire year, they are not well suited for investigating detailed temperature and air flow distributions in individual spaces. This meant that for analysing the thermal stratification expected in the auditoria, a different technique was needed. Perspex scale models using brine in water to represent the flows driven by heat in air were used for this purpose (Lane Serff et al. 1991). The models gave confidence that the basic design principles were sound in terms of whether adequate ventilation flow rates could be generated and whether warm air stratified above head height. Under some operating conditions, the models showed that over-ventilation could occur. Experiments with and without ventilation stacks were undertaken and the decision made to use two stacks for each of the auditoria in order to ensure stratification above head height.

Post occupancy monitoring has been carried out by Clancy and Howarth (2000). More recently, researchers at the Institute of Energy and Sustainable Development, De Montfort University, have monitored temperature and CO_2 levels in the auditorium. Temperature and CO_2 readings are measured at the base of each ventilation stack. The intention is that the readings at these locations represent the conditions of the air leaving the space and are thus worst case. The occupied period is clearly identifiable by the CO_2 readings which rise to a peak of 1682ppm. Guidance on air quality standards for teaching spaces given in Building Bulletin 101 (DfES 2006) recommends that the average and maximum CO_2 concentrations should not exceed 1500ppm and 5000ppm respectively. The temperatures do not rise

Figure 4A.3 Inlet louvres leading to plenum below seating rake.

Source: MJ Cook, De Montfort University

significantly above their night-time set point temperatures of 20°C, illustrating the damping effect of the thermal mass exposed around the walls and ceiling of the auditorium. More interesting is the capacity of the thermal mass effect to hold internal temperatures below the external (ambient) temperature throughout the occupied period.

The design process and post-occupancy monitoring of the Queens Building led the design team to the following important findings, which were used in the development of subsequent projects incorporating natural ventilation.

- The minimum required ventilation rate of 5ac/h (air changes per hour) for fresh air was almost always achieved with ease in both summer and winter (Howarth 1997).
- In heating mode, with a high buoyancy force, the stack effect was found to be too great (Clancy and Howarth 2000) and finer control was required to provide smaller opening sizes to prevent cold draughts. Damper settings were designed to vary in 25% increments, giving only five positions.
- The single stage pre-heat strategy was too crude and air could bypass the finned tube units, particularly directly above the inlet openings into the base of the plenum. The conventional proprietary dampers appeared to leak in their fully closed mode (Asbridge and Cohen 1996). These findings influenced the designers' approach to the natural ventilation strategy for the later Coventry University Library (Field 2000), incorporating two-stage pre-heating and high performance dampers, developed by the manufacturers specifically for the project.
- The beneficial effect of the thermal mass is noticeable, especially when coupled with night-time ventilation, achieving a one-degree fabric temperature rise (ceiling) over 5 days during daytime periods of 26°C ambient temperature and high occupancy. Typically, five-degree internal fluctuations in temperatures are recorded against 13–14 degree external fluctuations. Howarth (1997) has suggested that the concrete-lined plenum is effective in damping the temperature of incoming air during the day, particularly after it has been subjected to night time ventilation.

The Contact Theatre, Manchester

The original Contact Theatre was built in 1963 for the University of Manchester's drama department. In 1993, work began on consolidating the Company's activities onto one site by adding new foyers and a 120-seat, flexible studio performance space to the side of the original brick masonry auditorium, which remains within the enlarged building. The rebuilding and adaptation was completed in 1999.

Main Auditorium

Air is introduced from an enclosed courtyard to the west, through a bank of acoustic splitters and directly into a plenum below the raked seating. This is the only orientation available for locating inlets because the new foyers are arranged along the west side of the auditorium, blocking potential intake routes. Air flow paths of the cross sectional area required, acoustically protected from foyer noise, would have necessitated so many separate high-level ducts to maintain workable head room, as to be uneconomical and intrusive.

Incoming air enters into four compartments of the plenum below the raked seating in the auditorium. Each compartment is individually controlled by dampers operated by the building management system (BMS) in order to balance the distribution of air entering the auditorium. Thermal mass inside a concrete-lined labyrinth with blockwork sub-divisions helps to cool the air during peak summer conditions. Before entering the auditorium the air path turns through 90°. This helps to diminish the effect of sudden gusts of wind and helps to reduce external noise ingress. Heating elements are hung below each seating platform in the air flow paths. Air then enters the auditorium beneath each seating row through continuous openings in the risers providing a free area of about 20m^2 (equivalent to 3.2% of the gross floor area).

Computational fluid dynamics (CFD) modelling revealed the possibility of warm air stagnating below the cantilevered control room, such that the occupants of the three rows of seats at the top of the rake below could penetrate the warm displaced layer. This was addressed in the design by adding extra air intake grilles in the floor of the rear gangway providing 1.25m^2 of free area fed from a dedicated plenum (Figure 4A.4). In addition, the control room is detached from the rear wall to allow warm buoyant air to flow upwards into the roof cavity.

Air is exhausted through a new 5m high chamber cut into the existing roof profile (Figure 4A.4). Five stacks, each with a free area of 4m^2, sit above the void, with dampers and low speed fans located at the junction between the void and the auditorium. The large zone above the theatre lighting grid holds warm, stale air before it flows into the roof void. The stacks contain arrays of vertically mounted splitters which help to minimise noise ingress from the nearby roadway and adjacent student's union concert venue. The stack terminations comprise two integrated orthogonal H-pots which minimise flow reversal induced by wind pressures and generate negative pressure for all wind directions. Trays are suspended below the stack openings to intercept rain drops should they breach the geometry of the termination.

During commissioning, a heat load test was carried out in which 60kW of theatre lighting and 40kW of simulated occupants were used. During the test, no pre-cooling by the thermal mass in the intake ducts

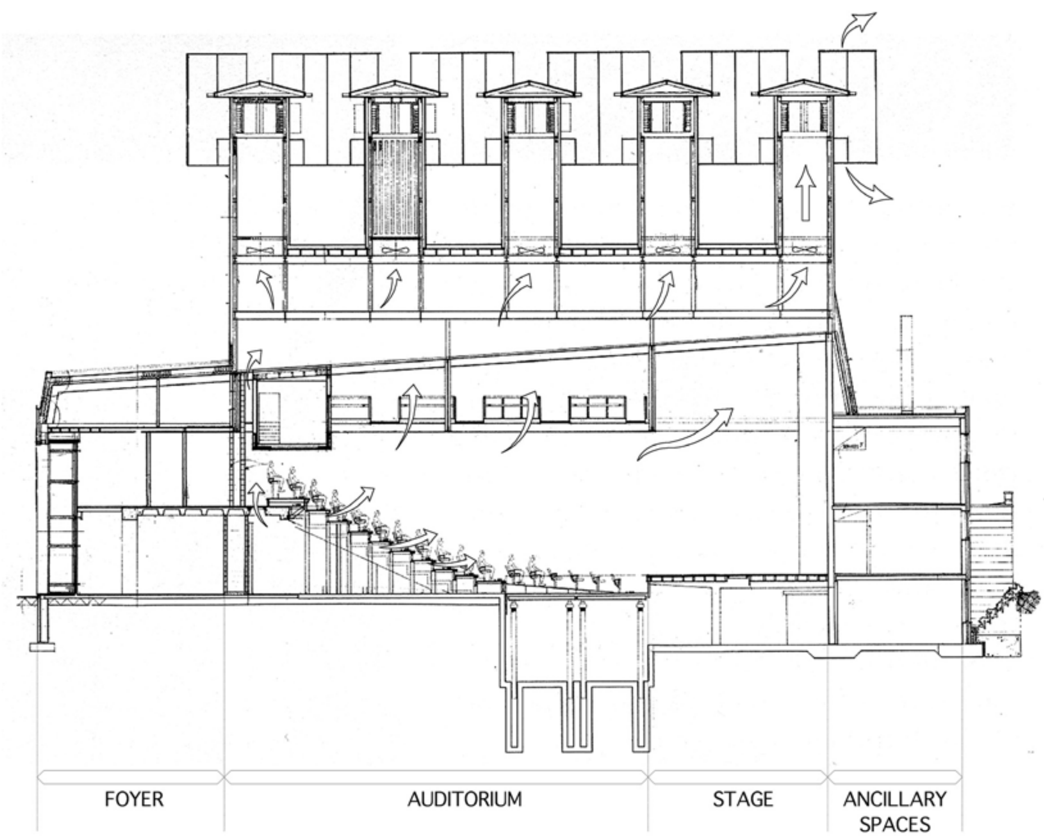

Figure 4A.4 Section showing ventilation strategy for the Contact Theatre, Manchester.

Source: Short and Associates Architects

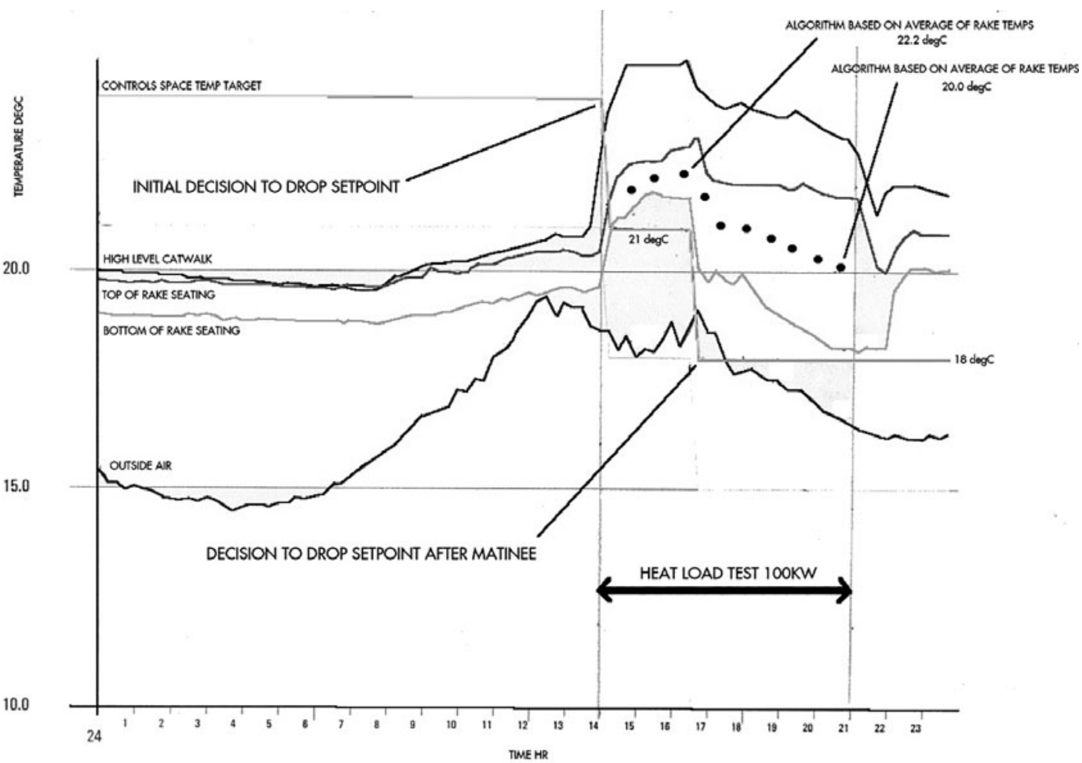

Figure 4A.5 Results of heat load test conducted at the Contact Theatre.

Source: Internal project report by Richard Quincey, formerly of Max Fordham and Associates

was available and about 50% of the design air flow was achieved. The test operated for longer and with higher heat gains than were expected to be the case in reality. The results (Figure 4A.5) showed that the design temperature differential of about 3-degrees was achieved in most of the seating locations, except in the top seating rows which were slightly warmer; a revision to the controls has been implemented to improve this. Lowering the set point after the matinée simulation caused the fans to operate in the exhaust stacks; prior to this time, the fans were not needed for maintaining environmental conditions.

Studio theatre

The studio is a flat-floored space elevated two storeys above the main auditorium scene assembly area and workshop. Air is introduced from the north side only at a height of 6m above street level. This flows into a 600mm high plenum below the entire floor. The plenum comprises a high thermal mass labyrinth and splits symmetrically into two paths via banks of acoustic splitters, before dividing again into chambers beneath the studio floor. Air passes through heating elements suspended below grilles in the plane of the floor on all four sides of the studio. It is intended that open frame bleacher seating can be located over the grilles. The studio theatre is 6m high with acoustic absorbent panels partially covering all four walls.

Air is exhausted via four vertical openings at soffit level connecting to an exhaust plenum above the perimeter corridor on all four sides. A shelf is formed to intercept rainwater drops. Four tapering splitter chambers connect to masonry stacks above, terminating in cross H-pots at the same level as those venting the main auditorium. Three small, half bladed, short-cased axial fans are placed at the base of each stack above the attenuators. This is more desirable, acoustically, than the position of the auditorium fans which are located below the acoustic splitters for ease of maintenance. The studio stacks have accessible inspection panels at roof level. The fans have aerofoil blades, and bellmouths, with speed controllers that enable slow speed quiet start up.

A simple wall-mounted dial in the studio enables staff to input the expected level of occupancy. Their prognosis informs the BMS which makes a decision regarding the opening extent of the dampers in the inlet and outlet stacks. Anecdotally, the studio is a very successful and heavily used space.

Post occupancy monitoring work (Woods and Fitzgerald 2007) has suggested that, under certain conditions, inflow can occur through some of the high-level openings intended for outflow. It may be possible to avoid this by close control of inlet and outlet dampers to ensure high-level openings remain similar, or smaller, in size to low-level openings. Small scale water bath models can be used to investigate such flow scenarios with multiple steady state solutions (Chenvidyakarn and Woods 2005).

The Lichfield Garrick

The Lichfield Garrick is a performing and static arts centre. This building was a rebuild project, albeit with significant reconstruction. It is exposed on three sides and butts up against a shopping centre along the north-east side (Figure 4A.6). In addition to the foyer and bar areas along two sides, the building comprises two key spaces: a 500-seat auditorium and a more flexible 180-seat studio space. Full details about the building are described by Gorst (2003).

Both auditoria employ buoyancy-driven displacement ventilation in which naturally occurring heat gains drive air flow out of the spaces through high-level openings, making way for cooler, fresher air to enter at low-level. This was reasonably straight forward to develop for the studio space, which is rectangular in plan with moveable seating positioned to suit the performance style. In this zone, low-level

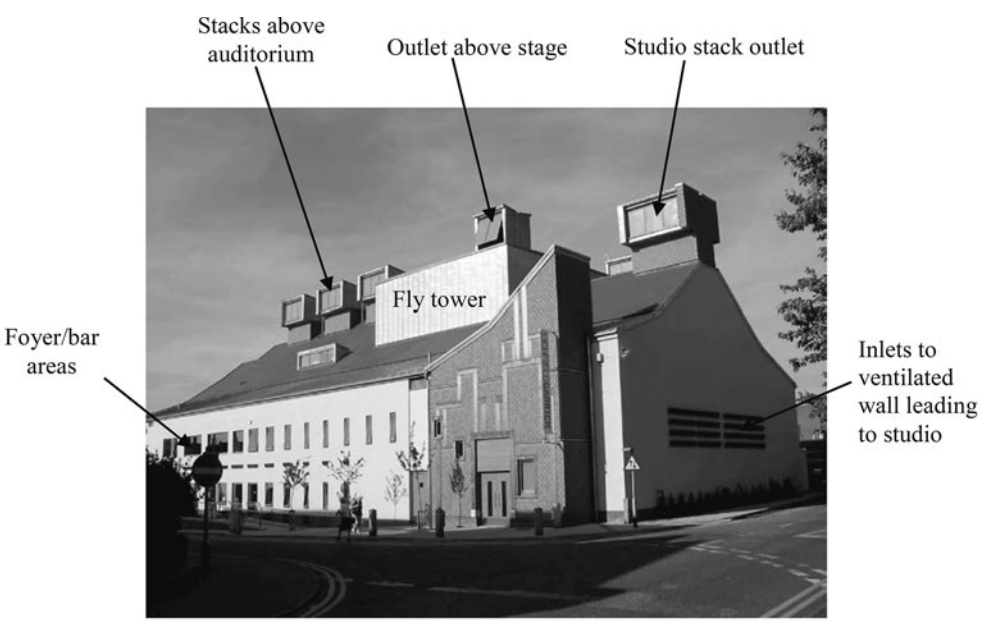

Figure 4A.6 Lichfield Garrick viewed from the south.

Source: MJ Cook, De Montfort University

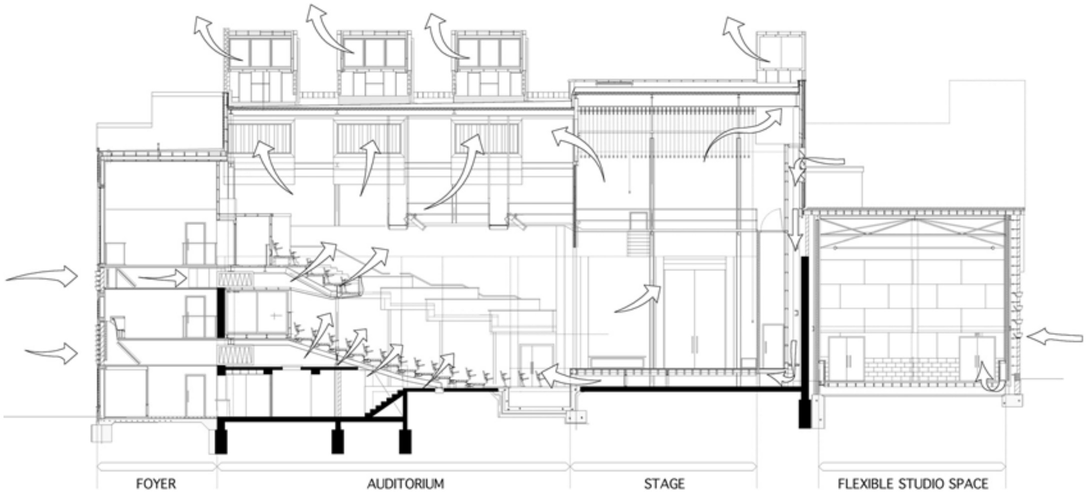

Figure 4A.7 Section showing ventilation strategy for the Lichfield Garrick.

Source: Short and Associates Architects

air inlets were located along each of the long sides of the space. These are fed by a 'ventilated wall' on the south-east side of the building which leads into a plenum below the floor. The inlets to the ventilated wall are shown in Figure 4A.7. These provide a high-level intake position 3m above street level which reduce the ingress of pollutants and street noise. The outlet path is provided by a single stack. The stack contains a low power fan, positioned above acoustic splitters, for use during peak load conditions. Above the fan the air flows through BMS-controlled dampers and out of the stacks through top-hung opaque panels. CFD simulations verified that warm air stratified safely above the occupants' breathing zone and drove a sufficient flow through the space.

The main auditorium, with its raked seating and high heat gains, posed greater design challenges. Seating is provided in two zones: stalls extending from the stage to the rear of the auditorium and a circle located above the rear stalls (Figure 4A.7). Heat gains from occupants and lighting could be as high as 110kW. The main challenge was how to provide the required 36m^2 of free opening area for incoming fresh air necessary to ensure warm air stratified above the occupied zone.

The final design uses a plenum below each of the seating rakes, supplied along sheet metal ducts from three sides of the building. On the north-east side, where the building abuts a shopping centre, openings below the eaves of the sloping roof lead into an acoustically lined vertical duct which guides air downwards and into the plenum below the rear stalls. This is supplemented by a duct passing through the lower ground floor from the south-west side and by ducts from the north-west passing at high-level through the foyers on the ground and first floors. A duct, leading from above the rear stalls up to the ceiling above the circle, mitigates the build-up of warm air below the circle. Outflow paths for the main auditorium are provided by six stacks mounted along two ridge lines on the roof.

Fresh air supply to the stage is via a second ventilated wall at the rear of the stage which is fed by openings in the south-east façade of the fly tower. The ducts lead to heating elements below the stage from where the air is drawn into the space through horizontal openings in the floor at both sides of the stage. Two stacks, located above the stage, provide the exhaust path.

Computational fluid dynamics (CFD) simulations were undertaken to predict the position of the interface between the fresh air and the stale, warmer air above (Figure 4A.8). This led to recommendations

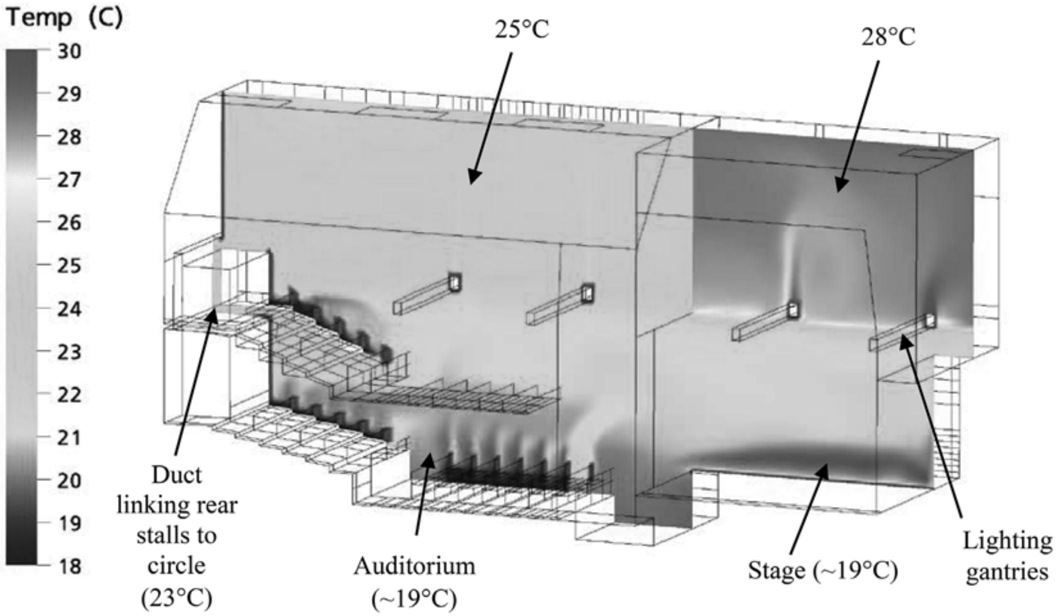

Figure 4A.8 CFD simulation of main auditorium showing stratification and duct linking rear stalls with circle (ambient temperature = 18°C).

Source: MJ Cook, De Montfort University

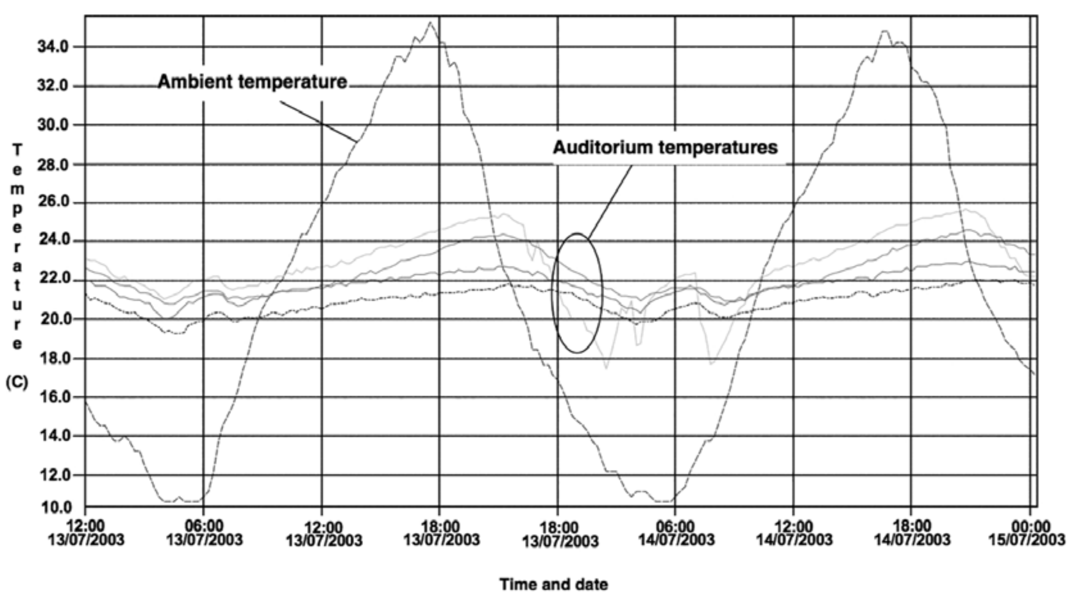

Figure 4A.9 BMS data for the main auditorium at the Lichfield Garrick.

Source: Lincoln Green Control

for larger effective opening areas which were realised through a combination of larger structural openings and lower pressure drops. Also, due to the light-weight nature of the internal surface finishes and the close proximity of the warm air stratification to the upper-most seating, low power fans were installed in all of the outlet stacks for use under peak conditions.

During the July 2003 heat wave when external temperatures exceeded design conditions, internal temperatures remained comfortable for most of the time, and for longer periods than anticipated. This illustrates the ability of the thermal mass in the intake ducts and plena, albeit modest, and the BMS-controlled dampers, to prevent internal temperatures rising to unacceptable levels (Figure 4A.9). In a similar way to the Contact Theatre, post occupancy monitoring has suggested that, under certain conditions, inflow through the high-level outlet stacks can occur (Woods and Fitzgerald 2007).

Design guidance

Experience gained during the design, commissioning and post-occupancy periods of the buildings described in this chapter has led to a substantial body of knowledge regarding the technical design issues surrounding naturally ventilated auditoria. A summary of this knowledge is given here; further details can be found in Short and Cook (2005).

Air inlets and supply ducts

Low level air inlets need to provide large, secure free areas configured to exclude birds, rodents and large insects. Typically, open areas which total 1–2% of floor area are required, but these should be calculated accurately based on the required air change rates and anticipated internal heat gains. Fly screens, grilles, dampers, acoustic attenuators and insulation will induce pressure losses along inlet paths. Cross sectional areas need to be checked on construction drawings to ensure the total effective area equates to what was identified as being required at the design stage. Computer simulations or analytical techniques are useful for investigating the effect of pressure drops due to devices such as grilles, dampers, etc.

Ideally, inlets should be located away from obvious sources of noise. This may not always be possible in dense city centres and a design strategy needs to be evolved to reduce particularly low frequency noise ingress at the building envelope, or as close to it as possible. Inlet locations should avoid obvious localised sources of pollution, such as traffic junctions, car parks and loading bay areas. The performance of inlets should be robust to changing wind direction and the potential occurrence of negative wind pressures. Ideally, air should be drawn from several orientations, but the particular circulation requirements within the building may prevent this. Multiple inlet locations also helps with the challenge of realising the large free inlet area required.

Well-sealed dampers are essential to prevent cold draughts and air leakage in winter (building regulations now require all new buildings to adhere to stringent pressure testing DCLG 2006). It is also necessary that such dampers have full modulatory control. This is to enable control of a wide range of air flow rates, from winter fresh air requirements (typically 10 l/s per person) to summer-time cooling requirements (possibly up to 10ac/h).

Acoustic attenuation is required in the supply path to exclude urban background noise. The splitters will need to be accessible for maintenance and will reduce the effective duct area (typically by about 50%). Care is needed to preserve the effective free area by increasing the overall duct size. Inlet ducts should be regarded as external spaces until the first dampers and heating elements are encountered. Therefore they must be insulated from internal (heated) spaces, for example, the supply ducts traversing the foyer spaces at the Lichfield Garrick.

Plena

Heating elements behind grilles leading into the auditorium need to be configured to ensure winter air at ambient temperature cannot by-pass the elements. Plena should be compartmented as necessary to provide even distribution of supply air across the whole auditorium and to avoid incoming air flowing straight through the plenum without being drawn into the occupied space. Care is needed to ensure that adequate flow paths are maintained after compartmentalisation, i.e. that plenum compartments are large enough to accommodate the air flowing into them from the ducts. Where possible, plena also need to be configured (and compartmentalised if necessary) so that differential pressures at the inlet locations can be equalised by feeding chambers from different orientations.

The opportunity of using plena for locating thermal mass should be used where possible to assist the thermal performance of the occupied space as acoustic requirements are likely to limit the use of exposed mass in the occupied space. The mass should be exposed to the air flow and be regenerated (cooled) by night-time ventilation.

High-level intakes

In certain circumstances it is necessary or advisable to provide high level air intakes on the outside of the building, for example, where adjacency to other buildings prevents intakes on the building façade, and to diminish noise and pollution levels. These must be designed and controlled so that they do not behave as air outlet routes under particular wind conditions. This risk can be minimised by positioning such intakes away from zones where there is known to be negative wind pressure (normally identifiable through wind tunnel testing) and positioning heating elements such that they encourage air to rise into the occupied space rather than upwards through the stack.

Auditorium

The vertical distance between the lowest and highest members of the audience and between the head height of the highest audience members and the ceiling is critical. Numerical modelling, such as computational fluid dynamics modelling, is recommended to ensure that the interface between the warm, stale air which collects in a layer beneath the ceiling, and the cooler, fresher air below, remains above head height. The position of this interface depends on the effective inlet and outlet areas and the height of the auditorium. The height required to ensure that the displaced warm layer remains above head height will impact on the overall height of the building. Local planning officials and planning consultees will need to understand the natural ventilation strategy in determining their overall recommendations. The infrastructure related to ventilation cannot be considered in purely formal terms, the natural physics embodied in the proposal must be acknowledged.

The auditorium volume required for natural ventilation purposes may be in excess of the ideal volume to give the required reverberation time. Additional acoustic attenuation material is therefore likely to be needed, but its performance should be traded off against the usefulness of exposing adequate thermal mass to the occupants. Dynamic thermal simulation models can be used to assess the performance of exposed thermal mass.

Outflow paths

Ventilation outlets should be configured to achieve similar levels of acoustic attenuation as intakes. They are likely to be large (same order of size as air intakes), and will need to be accessible for maintenance, possibly from lighting gantries in performing arts venues. In some cases, such as the Lichfield Garrick, the exhaust structures present an opportunity for incorporating acoustic absorption on surfaces facing into the auditorium.

Low power fan assistance provides a means of increasing flow rates in cases where it has proved difficult to realise the total opening areas required. It should be noted that fan assistance is intended for use under peak load conditions, rather than continuous use, i.e. the success of the natural ventilation strategy ought not to rely on such assistance during a typical day. If included, fans should be incorporated beyond acoustic splitters to attenuate any noise generated being discernible in the auditorium.

Outlets should remove air at the highest soffit level to prevent pockets of trapped warm air developing which could jeopardise the thermal performance of the space by increasing the temperature of any exposed thermal mass.

Outlet terminations

Termination design should be robust to changing wind direction and avoid the development of a positive pressure with respect to the inlet. This is possible using devices such as H-pots, as exemplified at the Contact Theatre, and/or a BMS algorithm which closes windward outlets. In many cases it is beneficial to undertake wind tunnel tests to investigate the pressure distribution around the proposed termination device and differentials between inlet and outlet locations. Raising the terminations above the roof line using stacks is beneficial for increasing the buoyancy driving force. However, issues of wind control and maintenance become more critical.

Wind effects

Various points have been made in this section regarding the effects of wind on natural ventilation design. Indeed, it is often useful to commission wind tunnel tests to avoid placing intakes in low pressure regions or air recirculation zones which could fight against the upward buoyancy force inside the building. The urban context may also impact on the performance of terminations leading to a need for localised design solutions or, potentially, a fundamental reconfiguration. Note that the natural ventilation strategies described in this paper use buoyancy-driven displacement ventilation and are designed to be independent of wind direction and speed. Although the authors do not deprecate the use of wind assisted systems, they envisage such solutions to be less robust and more complex.

Summary

These three case studies illustrate many of the design constraints of naturally ventilated auditoria and demonstrate how natural ventilation and cooling can be achieved without the need for conventional air conditioning or mechanical ventilation. Each case study has built on the experiences of the preceding studies.

Much of the environmental design has been based on the use of physical modelling and computer simulation. These design tools proved to be very useful in predicting thermal performance and ventilation effectiveness, and are widely used today, especially in more complex or innovative design proposals.

Anecdotal evidence and monitoring data suggest that the case studies presented perform well, but do point to the need for good controls, high quality components (e.g. dampers with air-tight seals) and an understanding on the part of the building owners of how the building management system should be implemented, operated and maintained through the full life of the building. In parallel, the understanding of the control strategy should enter the long term culture of the building occupants.

Acknowledgements

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Case Study 4B
NATURALLY VENTILATED BUILDING IN A CITY CENTRE

Birgit Painter and Malcolm Cook

Introduction

The Frederick Lanchester Library at Coventry University (Figure 4B.1) opened in September 2000 and is one of the largest naturally ventilated buildings in the world. The deep-plan layout and its urban location, close to the city centre of Coventry, made the design of a low energy building without air conditioning and with maximum daylight provision particularly challenging. Computer simulation techniques were used to assess the likely performance of the proposed design in order to ensure that the passive methods employed would be adequate to meet the cooling demands of such a large scale building. The final design has proven to be very successful, both in terms of its thermal and energy use performance as well as its user satisfaction.

This case study describes the design and operating strategies that are employed in the building and presents user comments as well as results from monitoring studies, which include assessments of the building's thermal and energy use performance. The building's likely performance in other UK cities is also discussed.

Description of the building

Much has been written about the design and operating strategies of the building by members of the design team (Cook et al. 1999a; Cook et al. 1999b; Short et al. 2004; Cook and Short 2005; Lomas and Cook 2005; Lomas 2007; Krausse et al. 2007) and others (Field 2000; Pidwell 2001; McDonald 2002). This section provides an overview of the design process, the environmental features and the intended ventilation strategy for the building.

Client brief

Coventry University required a large building (net floor area ~ 12,000m^2) to accommodate the university library. In order to provide the required floor area and meet the local authority height restriction of four storeys, a deep plan floor layout became unavoidable. It was important that the layout should be simple and thus easy to understand by its users. In order to allow for changes in study methods, the building was required to be able to accommodate the anticipated increase in the use of computers by the library users.

The client requested a sealed façade for security reasons. It was further specified that the new building should be environmentally friendly and as energy efficient as possible. For that reason the potential for

Figure 4B.1 View of Lanchester Library from the west.

the use of sustainable building features such as day-lighting, natural ventilation and the use of combined heat and power was to be investigated by the design team. The client was also particularly interested to assess the likely environmental conditions prevailing in the building and the anticipated energy running costs. Computer models were therefore used to evaluate design options in the initial stages of the development.

The University also wanted the new library to be a distinctive building with an innovative design, which would receive national and international acclaim, and could be used as a teaching vehicle by its School of the Built Environment.

Site constraints

A number of further constraints were imposed by the location of the site. As the aerial view in Figure 4B.2 shows, surrounding buildings, including a Grade 2 listed hospital, limited the area available for the new building. Due to its city centre position and close proximity to a raised ring road, there were potential noise and air quality issues to be considered. Although located in the UK midlands, with its temperate summer and winter conditions, the site suffers from gusty and unpredictable wind conditions, which are typical for built up city centre locations. Furthermore, the site is surrounded by a number of buildings of different height, which could affect air flows around the new building.

Environmental design features

The final design (Figures 4B.3 and 4B.4) has a gross floor area of 9103m^2 and includes three deep-plan library floors, a smaller, cruciform-shape top floor, and a basement, which comprises the book archive and 24 hour computing lab. Apart from the basement, the building is fully naturally ventilated.

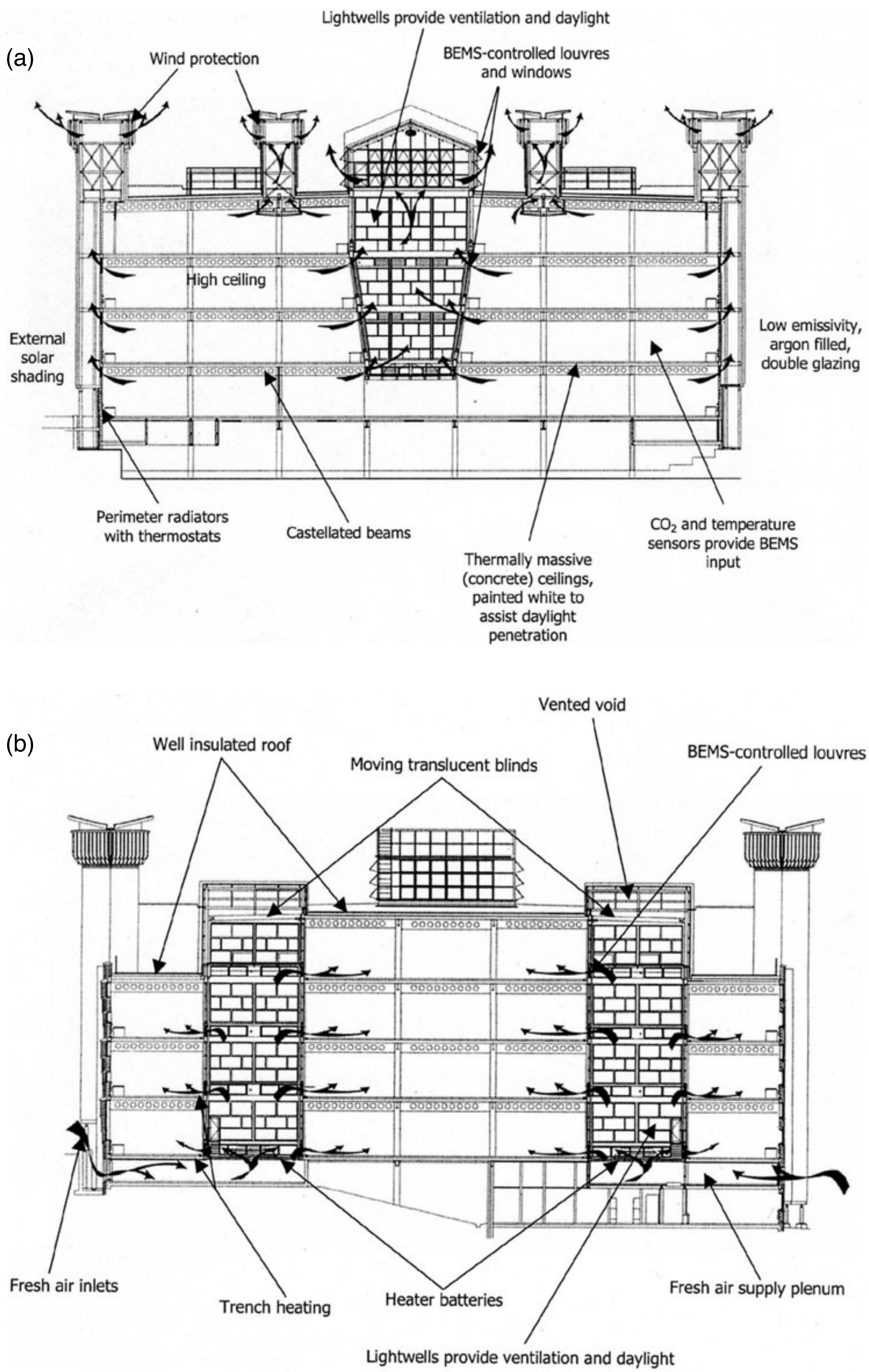
Figure 4B.2 Aerial view of the site, showing the proximity of the ring road and surrounding buildings.

The four deep plan library floors are penetrated by four 6m square corner lightwells and a central lightwell, which is tapered (6m square at ground level to 9m square at third floor level) and only partly penetrates the ground floor (Figures 4B.5 and 4B.8). Together with the large floor-to-ceiling height (3.9m), an under-floor plenum and twenty 1.8m square perimeter stacks, these lightwells form an integral part of the natural ventilation strategy, as described below. The cross-sectional area of the stacks and the central lightwell increase with height in order to compensate for the reduced stack effect and to accommodate the larger volumes of exhausted air. The perimeter stacks, which extend 6m above roof level in order to achieve the required driving force for the stack ventilation, give the building its characteristic look (Figures 4B.1 and 4B.6).

Another distinctive feature is the exposed thermal mass of the walls and ceilings (Figures 4B.5 and 4B.7) which is fundamental to the passive cooling strategy. When required, air is allowed to enter the building at night, where it cools down the exposed building fabric. During the following day, the cool surfaces provide a radiant heat sink which offsets high air temperatures and helps to maintain the indoor environment at a comfortable resultant temperature.

To reduce the heating demands, the building is very well insulated and comprises double glazing with an argon-fill cavity to all external windows. The U-values of the materials used are significantly lower than the guideline values in force at the time and even exceed current guidelines (see Table 4B.1).

The library has been designed to maximise daylight provision while keeping solar heat gains to a minimum. Small windows around the perimeter are enclosed by deep reveals and overhangs, and shading



Figures 4B.3 Sections through the building showing (a) the central exhaust lightwell and stacks and (b) the supply lightwells.

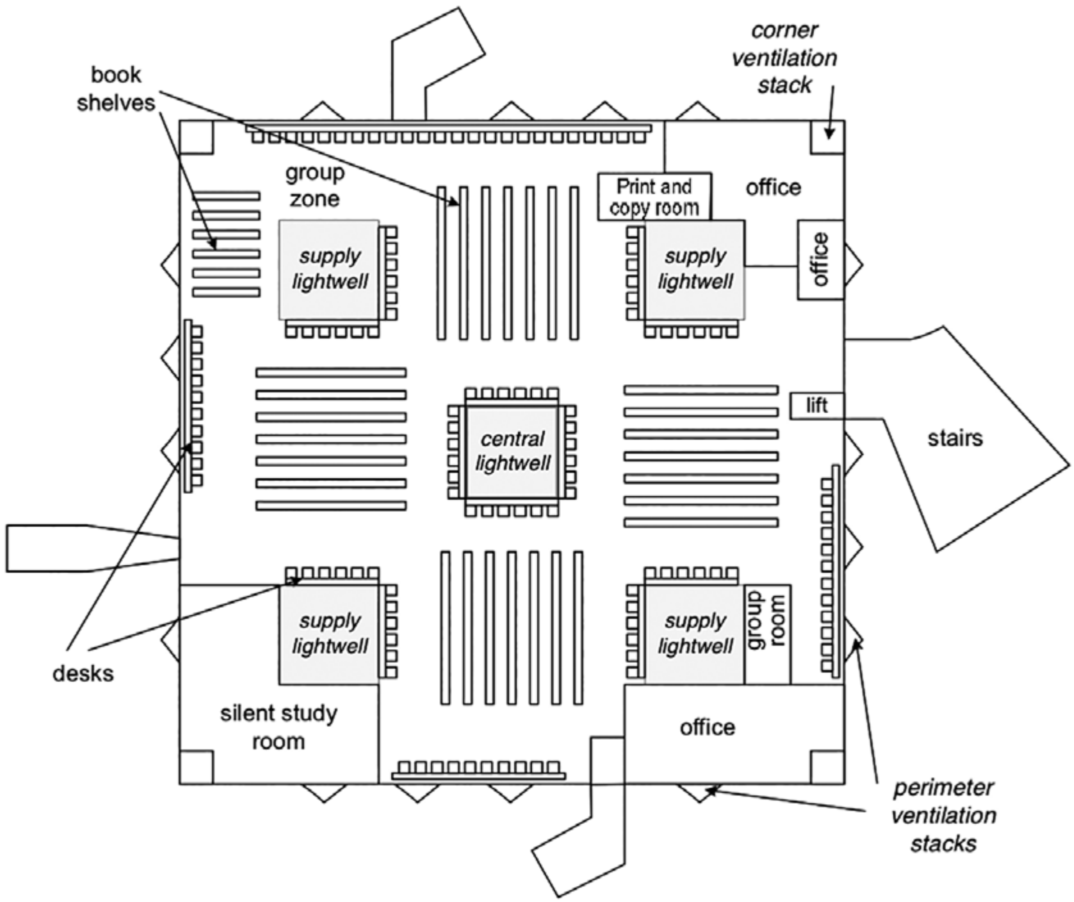


Figure 4B.4 Floor layout – showing the location of architectural features (italics) and usage zones on the 2nd floor.

Table 4B.1 Comparison of the U-values [W/m²/K] of the building construction (Cook et al. 1999b) with old and current building regulation guidelines (DoE 1995; ODPM 2006).

	Library (completed 2000)	*Building regulations 1995*	*Building regulations 2006 (area-weighted average)*
Wall	0.26	0.45	0.35
Roof	0.18	0.25	0.25
Windows	2.0	3.3	2.2

fins were placed on the façade in order to reduce direct sunlight entering the space (Figure 4B.6). However, the library is still perceived to have a bright feel due to the five lightwells that penetrate the space. The central lightwell is tapered, which assists daylight penetration. Workspaces are clustered around the lightwells while the book stacks occupy the deeper parts of the building. At the top of each lightwell, an automatically controlled translucent blind can be closed to prevent direct solar gain during the summer months.

Figure 4B.5 Central lightwell, tapered to account for increased airflows higher up the building and to maximise daylight provision across the deep plan floors.

Since the library is used for a variety of purposes, from book storage to study areas for PC users and group work, the basic square open plan floor layout has been adapted on each floor to provide a range of suitable spaces (Figure 4B.4). Offices and seminar rooms are located adjacent to lightwells and ventilation stacks in order to provide dedicated ventilation and daylight control.

Design study

During the design process the architects, Short and Associates, carried out a concept study which resulted in an initial design proposal (RIBA stage D design). Based on this proposal, detailed dynamic thermal and computational fluid dynamics (CFD) simulations were conducted in order to develop a design which would meet all heating and cooling requirements while at the same time provide a comfortable indoor environment for the building users and remain energy efficient. The simulation studies are described in Cook et al. (1999a) and only a summary is given here.

In order to model the time-varying interaction of internal temperatures and airflows as closely as possible, a combined air flow and thermal simulation study was carried out. For this purpose an air flow network and a thermal network of the proposed building were generated.

CFD simulations were carried out for a typical warm summer day using an ambient temperature of 24.5°C. Two occupancy scenarios were investigated, one for the expected occupancy (heat gains of 28W/m^2 core and 48W/m^2 perimeter, which included solar gain) and one for heavier use (42W/m^2 core

Figure 4B.6 View of South façade showing perimeter stacks, shading fins, deep window reveals and overhangs.

and 60W/m^2 perimeter). The CFD simulations did not take into account the effects of night cooling and exposed thermal mass, and assumed calm ambient conditions, i.e. no wind.

Dynamic thermal simulations were carried out to predict the building's internal temperatures throughout the year, taking into account solar shading, thermal mass and anticipated heat gains. Heating set-points of 18°C (occupied) and 14°C (unoccupied) were imposed and a climate file for Kew 1967 was used (Holmes and Hitchin 1978).

The results of the CFD simulations showed that air change rates for the lower three floors were fairly well balanced, resulting in uniform temperatures across the floor plates. However, it was observed that under some conditions warm air rising up the central lightwell, which had been exhausted from the lower floors, could flow out into the top floor rather than continue upwards to the outlet due to the lack of stack height. This resulted in reduced fresh air intake and a rise in temperatures on the third floor. To prevent this, the design was modified by sealing the central lightwell and the perimeter stacks at the top floor level and providing dedicated exhaust stacks solely for this floor (Figure 4B.7).

The internal air temperatures predicted by the CFD simulations for the expected occupancy were 2.5–3.5°C above ambient, increasing only by 1°C for the heavy occupancy scenario. Taking into account that the effects of night time cooling and exposed thermal mass were not considered in the simulations and that dry resultant temperatures can be expected to be lower than the CFD-predicted air temperatures, these simulation results indicated that the library should easily be able to maintain comfortable internal conditions on warm summer days.

This was supported by the results of the dynamic thermal simulations, which indicated that the building would be able to maintain internal dry-resultant temperatures below 28°C at all times and only exceed 27°C for 11 hours of the year. It was further expected that with refined air flow control, using a sophisticated Building Energy Management System (BEMS), the building would perform better than these results indicated, i.e. lower maximum temperatures were expected.

Natural ventilation strategy

The building relies fully on buoyancy driven displacement ventilation. Heat gains from the occupants and equipment cause the air in the spaces to warm up and rise. The large floor-to-ceiling height allows stale air to collect above head height and castellated beams (Figures 4B.5 and 4B.7) enable it to flow across the ceiling toward the air exhaust openings around the central lightwell and the perimeter stacks (Figures 4B.3a and 4B.5) from where it can flow up and out of the building. This stack effect causes fresh air to be drawn into the building at low level through a plenum beneath the ground floor, which supplies the four corner lightwells. From these lightwells the fresh air enters each floor at low level (Figures 4B.3b, 4B.8).

Air flow rates are controlled by dampers located at the entry level to the under-floor plenum and in the exhaust outlet in each perimeter stack. Air flow control to the individual zones on each floor is

Figure 4B.7 View of the third floor, showing the central lightwell, exposed thermal mass, castellated beams and dedicated ventilation stacks.

Figure 4B.8 Supply lightwell with low-level air inlet dampers and trench heating.

provided by low-level dampers in each corner lightwell and high-level dampers in the central exhaust lightwell.

Heating is provided by pre-heating coils at the base of each supply lightwell and by trench heating at the point where the air enters onto each floor. Cooling occurs entirely by passive means using a combination of controlled natural ventilation and night-cooled thermal mass.

Building control

On each floor a number of zones with different occupancy and usage characteristics can be identified. For example, on the second floor (Figure 4B.4) these include: open plan area with book shelves; a silent study room; two differently sized group study rooms; study desks with PCs (open plan); study desks without PCs (open plan); a print and photocopy room and two offices.

Conditions in each of the zones, both temperature and air quality (CO_2), are constantly monitored by the Building Energy Management System (BEMS) which controls air inlet and outlet dampers as well as heating settings in order to provide a comfortable environment. To control these processes, the BEMS relies on data from a large number of sensors, which are distributed throughout the building. In the open plan areas the sensors are positioned near the perimeter stacks, typically four pairs of temperature and CO_2 sensors along each wall. Additional sensor pairs are located in the enclosed study spaces and offices. Based on readings from these sensors, individually controllable dampers are adjusted to provide ventilation for thermal comfort and air quality in each of the zones.

The BEMS also regulates the night venting behaviour of the building. The BEMS uses a self-learning algorithm to predict the likely ambient temperature for the following day and can thus initiate night-time cooling appropriately.

The following gives a brief overview of the intended operation in summer and in winter mode.

Summer operation

To ensure daytime thermal comfort, night venting is used to cool the exposed thermal mass of the building at night-time. Based on prevailing weather conditions and estimated temperatures for the following day, the BEMS controls the air inlet dampers to the plenum and the outlets on the top of the central lightwell. If appropriate, they are opened to allow cool night air to enter the space. Over-cooling is prevented by fully closing all dampers to any floor on which the slab temperature falls below a set-point of 18°C.

At the beginning of the occupied period, all dampers open in response to fresh air demand. As occupancy of the individual zones increases, heat gains from occupants and equipment result in buoyancy-driven air flow. The BEMS controls these flows by adjusting opening sizes based on both the air temperature and CO_2 measured in each zone. During the day, the translucent blinds at the top of the lightwells may be closed to reduce solar gain and thus unnecessary heat gain to occupied spaces. The voids at the top of the supply lightwells can be cross-ventilated to avoid unnecessary heating of the supply air.

In order to prevent over-heating of the building by ventilation air when the supply air temperature is above the internal space temperature, the inlet dampers are set to their minimum for fresh air provision. Comfortable conditions are then maintained by means of the pre-cooled building fabric and the reservoir of air inside the large building volume. When the supply air temperature falls below this set-point and internal temperature readings dictate, the air inlets are opened again to maximise ventilation cooling.

Winter operation

In order to avoid heat loss during unoccupied periods, and particularly at night time, all ventilation openings are closed. The translucent blinds at the top of the lightwells are closed to prevent heat loss by radiation to the night sky. At about two hours prior to occupancy, the heating coils in the plena warm the air in the supply lightwells in order to avoid cold draughts when the supply dampers open into the occupied zones, and to reduce heat loss from the main library into a cold lightwell. When occupancy begins, readings from CO_2 sensors determine when the dampers need to be opened to supply fresh air. When supply air then begins to move from the lightwells onto the main library floors, it can be heated by the trench heaters at the point where it enters at low level onto each floor, if necessary.

Daylight provision is maximised by opening the blinds at the top of the lightwells during daytime.

Performance evaluation

Operation and use of the building

The Lanchester Library opened in September 2000 and now provides a range of library and computing facilities. Coventry University view the building as a landmark building and use it as a prestigious feature for advertising their campus. The building has received national and international acclaim and won a number of awards, including: Brick Award 'Building of the Year' 2001; the SCONUL Library Design Award 2002; Coventry City Council Design Award 2001 and The Institution of Civil Engineers Environmental Award 2001.

The library offers 1100 study places, 350 of which are equipped with PCs. With a daily average of 4500 visitors and average seat occupancy of 65% the library is significantly more popular than initially anticipated; it was designed for 2500 entries a day. The opening hours have been extended significantly from the originally anticipated period of occupancy of 08.00–20.00. The library is now open 08.30–24.00 during term time and 08.45–21.00 during vacation time.

Since the building opened, some changes were made to the layout and operation of the building. During the first few months of operation users and library staff found that strong draughts occurred on the ground floor as a result of air entering through the main entrance (a covered walkway between the library and the adjacent bookshop). An entrance lobby was added to overcome this problem. The number of PC workstations was increased according to requirements for more computer based course work, as anticipated in the client brief.

Both the library and the estates staff are well aware that naturally ventilated buildings require different maintenance procedures to traditional, mechanically ventilated buildings. They are dedicated to making the building work in order to maximise its energy efficiency potential while maintaining occupant comfort, and therefore pay particular attention to addressing any concerns, e.g. local discomfort reported by staff in certain zones, and keep in mind the intended passive ventilation and cooling strategies.

For example, it was realised that the potential risk of cold air draughts around the supply lightwells in winter could be avoided by simply modifying the damper operating parameters. Rather than changing heating set-points or blocking individual air inlets, which would have compromised the intended air flow paths, the risk of draughts was prevented by reducing the maximum opening range of the dampers to 20% during winter operation; for summer operation the setting is changed back to the default (100%).

According to anecdotal feedback (Rock 2007), the building has become a popular study location, partly due to its bright and airy feel, which is unusual for such a deep plan building. The high number of library users and visitors indicates that the building is well liked, and it has been reported that it functions as an informal meeting place, with the ground floor serving as a focal point for this.

In a world of increasing awareness of the implications of excessive energy consumption, the staff value the building's 'green' credentials and its pleasant working environment, which results from the provision of daylight and fresh air, avoiding all the draw-backs of air conditioning.

The building's distinctive look makes it a feature of the campus and helps it to be a truly 'landmark' building.

Thermal performance

Using temperature and energy data for the years 2004 and 2005, the performance of the building has been evaluated in terms of its ability to maintain comfortable internal conditions throughout the year. Since overheating in summer is one of the potential problems associated with naturally ventilated buildings, particular attention was given to the effect of the night time cooling on internal temperatures during periods with high ambient temperatures. The results from the 2004–05 monitoring period were presented by Krausse et al. (2007) and are summarised below.

Internal temperatures

Average temperatures inside the building remained relatively stable throughout the year (Figure 4B.9). During the heating season, the daytime indoor temperature remained below 24°C and decreased to approximately 21°C during the night, as set by the heating schedule and heating set points. Temperatures below the 21°C set point can be observed for non-occupied periods during weekends and the Christmas

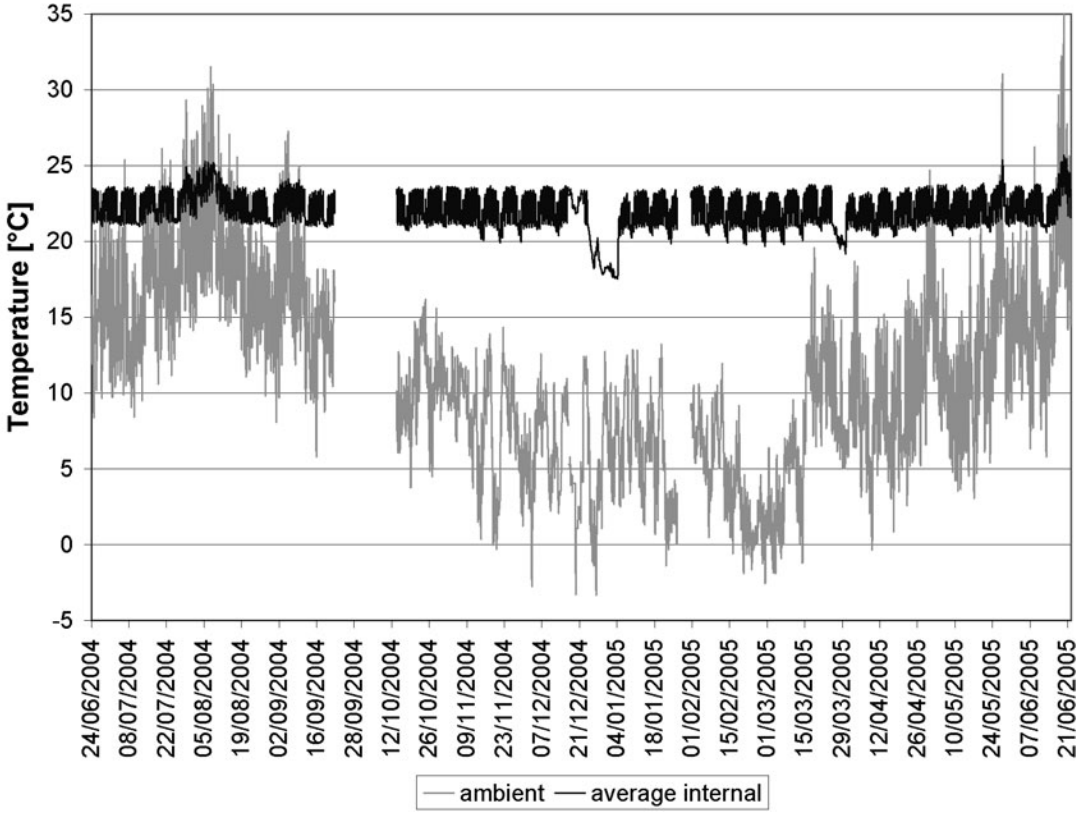


Figure 4B.9 Internal and external temperatures during the monitoring period (June 2004–June 2005).

and Easter breaks when the building was not heated. Apart from the daily variability, the temperatures during the heating season also follow a regular weekly pattern, with lowest temperatures recorded on Sunday nights and peak daily temperatures rising throughout the week.

During the warmer periods of the year, internal temperatures are strongly influenced by ambient conditions but remain relatively stable due to the high thermal mass of the building and the night venting strategy. Even during the two periods of prolonged high ambient temperatures during the monitoring period, internal temperatures only occasionally exceeded 25°C while ambient temperatures of up to 35°C were recorded.

During a prolonged hot spell in August 2004, a diurnal temperature swing in excess of 9°C was observed, indicating a substantial night-time cooling potential (Figure 4B.10). The data show that this potential was utilised well: temperatures generally remained in the range 21–22.5°C during the first four days of the hot spell and then gradually increased, with peak temperatures, however, remaining below 26°C at all times. This represents a temperature depression of over 5°C.

Although temperatures during this hot spell generally stayed within the desired parameters, there was some variation in the behaviour of the individual floors. The ground floor, which has the greatest stack height available, and thus the greatest potential buoyancy driving force, had the highest night-time temperature reductions. The third floor tended to be warmer than the second, which was warmer than the first. Considering the relative stack heights on each of these floors, and their similar occupancy

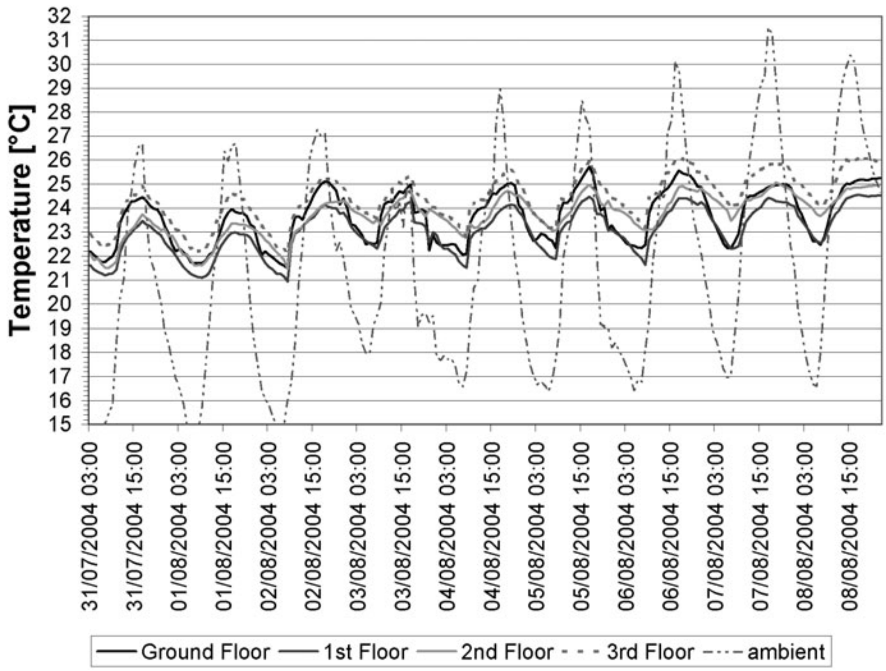


Figure 4B.10 Average temperatures on each floor and the ambient temperature during a 'hot spell'.

characteristics, this is to be expected. It reinforces the notion that it is the top floors of naturally ventilated buildings that are the most susceptible to overheating.

Comparison with overheating criteria and simulation predictions

As outlined above, the computer simulations carried out during the design phase indicated that the building should be able to maintain comfortable internal temperatures throughout the year. In order to assess the building's actual performance, internal temperature data from the monitoring study were compared with predictions from the simulation stage as well as commonly used overheating criteria, published by the Chartered Institution of Building Services Engineers (CIBSE). The two criteria were:

- CIBSE Guide A (CIBSE 2006): 'dry resultant temperature should not exceed 28°C for more than 1% of the occupied hours'; and
- CIBSE Guide J (CIBSE 2002): 'dry resultant temperature should not exceed 25°C for more than 5% of the occupied year'.

As shown in Table 4B.2, temperatures remained below 25°C on the first floor throughout the monitoring period and only occasionally exceeded 25°C on the other floors. However, all floors of the building met the CIBSE Guide A thermal comfort criterion, as well as the stricter criterion of the CIBSE Guide J. The building's performance also exceeded design stage expectations since internal temperatures never exceeded 27°C, which is better than the 11 hours predicted by the original simulations (Cook et al. 1999a).

Table 4B.2 Number of hours during which various temperature thresholds were exceeded between 26 June 2004 and 24 June 2005 during the occupied period.

Guideline temperature	*Number of hours over stated temperature (h) / Percentage of occupied hours over stated temperature (%)*				
	Ambient	*Ground floor*	*1st floor*	*2nd floor*	*3rd floor*
25°C	149h / 4.1%	78h / 1.95%	0 / 0	32h / 0.8%	152h / 3.8%
27°C	73h / 2.0%	0 / 0	0 / 0	0 / 0	0 / 0
28°C	48h / 1.3%	0 / 0	0 / 0	0 / 0	0 / 0

Estimated performance in other UK cities

By comparing weather data recorded in Coventry during the monitoring period with that for other UK locations, it is possible to infer how the building would perform at these other locations.

An analysis was presented by Krausse et al. (2007), who used CIBSE weather data from 14 UK cities (CIBSE 2003), ranging in latitude from Plymouth and Southampton in the South to Edinburgh and Glasgow in the North, to assess whether comfortable conditions would be maintained in the building if it was located in these cities (Figures 4B.11 and 4B.12). For each city both the Test Reference Year (TRY),

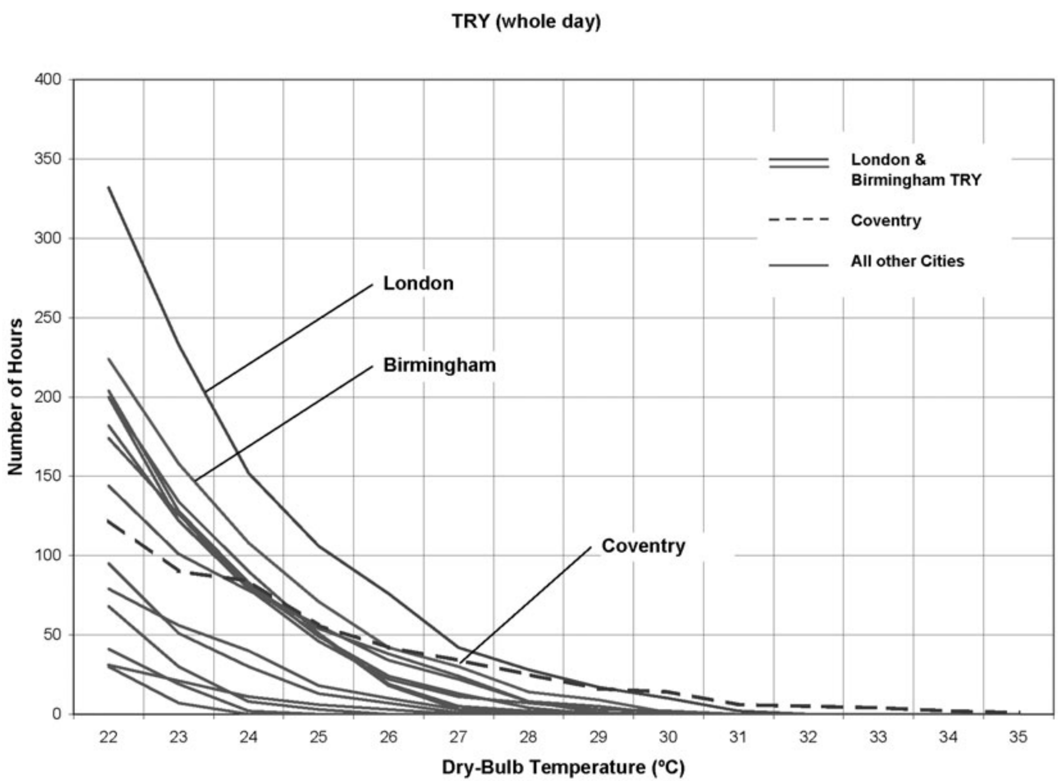


Figure 4B.11 Comparison of recorded exceedance hours from Coventry with CIBSE's Test Reference Year data (TRY) from 14 UK cities.

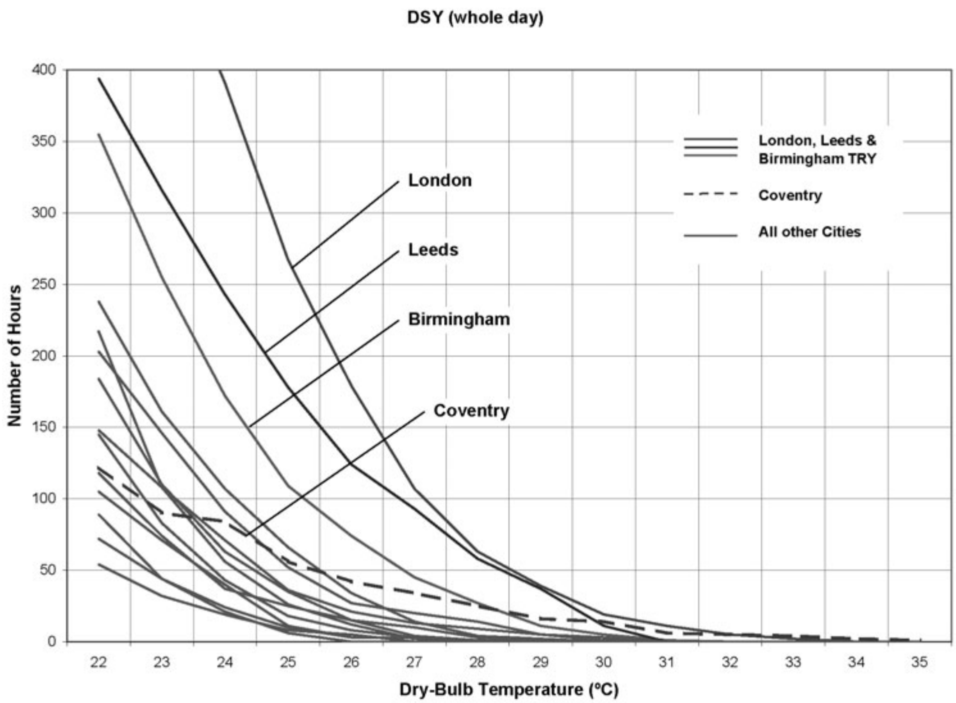


Figure 4B.12 Comparison of recorded exceedance hours from Coventry with CIBSE's Design Summer Year data (DSY) from 14 UK cities.

which typifies conditions experienced at the site, and the Design Summer Year (DSY), which is intended for use in analyses to assess the risk of summertime overheating in naturally ventilated buildings, were used. The TRY is composed of 12 individual months chained together, where each month is the most typical of that experienced during a 20-year period, and the DSY is the third hottest year in the 20–year period, i.e. there is only 1 year in 10 that is likely to be hotter.

The total number of hours for which the ambient temperatures recorded in Coventry exceed certain values is compared with the corresponding values for the TRY and DSY data from 14 other UK locations. As Figure 4B.11 shows, the Coventry data show a similar trend to the TRY data of the other cities but the number of hours with temperatures over 30°C is greater than in any other of the 14 cities. The comparison with DSY data in Figure 4B.12 shows that the Coventry temperatures exceeded 26–29°C more frequently than all but three of the other cities, indicating that the monitored year was a comparatively hot year.

Considering that the building met all three of the overheating criteria considered (Table 4B.2), it is reasonable to expect that the building would have met the CIBSE Guide J criterion (CIBSE 2002), i.e. less than 5% of hours over 25°C, in 12 out of the 14 cities in a typical year (Figure 4B.11). It may also have remained comfortable, as defined by hours over 28°C, in the London environs. However, in the middle of the city comfort may have been compromised due to the substantial urban heat island effect. The results further indicate that the building could be expected to have remained comfortable during hot years (i.e. those that are only exceeded in 1 year in 10) at all locations, except perhaps Birmingham, Leeds and London (Figure 4B.12).

Energy consumption

The building consumed 0.049kWh/(m^{2}h) of gas and electricity in 2004 (Table 4B.3). This includes the heating, lighting and power consumption of the 24hr computer suite in the basement (air conditioned) as well as the four naturally ventilated library floors. Since the library's energy consumption cannot be disaggregated from the total, a comparison can only be made by including the computer suite's consumption, leading to a rather conservative estimate.

However, even with this included, the building performs significantly better than the ECON19 typical benchmark for office buildings (BRECSU 2000). As shown in Figure 4B.13, the building uses 51% less energy than the typical air-conditioned building and 35% less than the typical, naturally ventilated, open plan building. In fact, the Lanchester Library also performs better than an office building built to the good practice standard for naturally ventilated open plan office buildings.

Table 4B.3 Energy consumption of library in 2004.

	End use		
	Heating	*Electricity*	*Cooling*
Total annual consumption [MWh]	1117	1012	205
Consumption per m^2 [kWh/m^2]	95	86	17
Consumption per m^2 and per occupied hour [kWh/m^2/h]	0.024	0.021	0.004

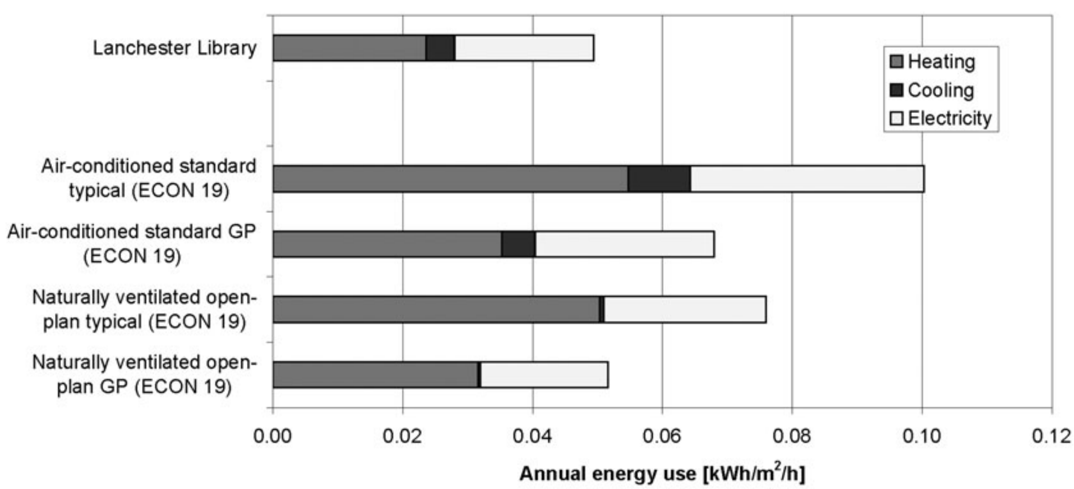


Figure 4B.13 Comparison of the library's annual energy consumption during 2004 with ECON19 benchmark values for typical and good practice offices (BRECSU 2000).

Conclusions

The Lanchester Library at Coventry University uses a number of features which are typical for low energy naturally ventilated buildings: exposed thermal mass; night-time ventilation; solar shading; high levels of insulation; good glazing specification; and daylight provision. By using these features, the design team were able to create a deep-plan city centre building which remains comfortable throughout the year without having the high energy demands associated with air conditioning and artificial lighting.

Performance monitoring has shown that temperatures within the library remain relatively stable and meet the overheating criteria recommended by CIBSE. The building would be expected to perform equally well in a range of other urban locations in the UK. Data has further shown that in terms of its energy use statistics, the library compares favourably with good practice guidelines for similar buildings.

The successful measured performance is supplemented by positive perception. The library is considered a comfortable and stimulating place to work and study and is also used as a popular meeting place.

The success of the Lanchester Library shows that the perceived barriers to natural ventilation techniques, such as the need for deep-plan built forms, sealed façades to maintain indoor air quality and low noise levels and high internal heat gains due to computers, with long periods of occupancy, can be overcome by applying an intelligently designed, advanced natural ventilation approach.

It is, however, important that such innovative design is supported by the client, who needs to be actively involved throughout the design process in order to ensure that the building fulfils all their needs and to appreciate how the building is intended to function. This knowledge transfer ensures that after commissioning the building is operated in a way that fully utilises its low energy use potential.

In the case of the Lanchester Library, the close involvement of the energy manager has revealed that adapting the operating strategy to seasonal variations in ambient conditions can result in improved performance. For example, summer time performance can be improved by closing the air inlet dampers when external temperatures rise above internal temperatures (controlling ventilation based on fresh-air demand only), and the risk of over-ventilation in winter can be reduced by limiting the ventilation openings compared to summer operation, resulting in reduced heating energy consumption and draught risk.

Client involvement is also likely to result in a stronger feeling of ownership, which in turn helps to promote the building as a desirable space in which to work and as an asset that is cared for. It may also help users to view unusual characteristics of such a building as positive features ('it has character') rather than negative.

The library has also demonstrated that it is possible to co-locate areas which are to be occupied for longer periods of time, especially into the evenings and night, within a naturally ventilated building by keeping them separately accessed and controlled. This approach ensures comfortable working conditions for night-time occupants without compromising the night-time cooling procedures and thus thermal performance of naturally ventilated areas of the building.

Acknowledgements

The building was designed by Short and Associates Architects with staff in the Institute of Energy and Sustainable Development at De Montfort University serving as the Environmental Design Consultants. The mechanical and electrical services consultants were Environmental Design Partnership. We gratefully acknowledge the continuing support from Pat Noon (head librarian), Caroline Rock (deputy librarian) and their colleagues, and from the Estates Department at Coventry University, particularly Jim Skelhon.

Acronyms/Abbreviations

CIBSE	Chartered Institute of Building Services Engineers
DSY	Design Summer Year
TRY	Test Reference Year
BEMS	Building Energy Management System
CFD	Computational Fluid Dynamics

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Case Study 4C

LOW CARBON, HIGH PERFORMANCE, LARGE RETAIL PREMISES

Ben Croxford, Keeran Jugdoyal and Sean Lockie

Introduction

The UK retailer, Marks and Spencer (M&S), completed their flagship, sustainable learning store in 2012. A team from Faithful+Gould and UCL evaluated the performance of the building after a year of operation.

The store was designed to be their most sustainable to date and incorporated several key features to help in this. The design target for the store was to be 30% more energy efficient, and have 35% less carbon emissions than a benchmark M&S store.

This fits with M&S aims of being a sustainable retailer and their hope to associate their brand with sustainability in the eyes of the consumer.

The UK Technology Strategy Board's Building Performance Evaluation programme provided the funds to assess whether the buildings aims had been achieved. Additional funds were also provided by M&S to determine how local community, customers and staff appreciated the building.

Energy monitoring was carried out by Faithful+Gould with UCL carrying out questionnaire surveys and focus group studies of different groups of building users.

This case study describes the building but its main focus is on the post occupancy evaluation and, in particular, on the soft analysis. Conclusions are drawn about the design of the building based on the results of the study.

Building description

This is a very large store (~15,000m^2 of sales area) located in a retail park 20km south of Liverpool, in the north of England, with easy access to the UK motorway network.

It is a two storey, steel framed building with a ground floor and an upper floor, both including retail space and public catering areas. Ancillary spaces for loading and storage are on the ground floor, and offices and a staff cafeteria are found on the upper floor.

Key features visible to visitors are relatively highly glazed walls, natural wood cladding, a spectacular, glulam beam ceiling, an external green wall, and extensive external landscaping; overall the design of the building feels spacious and light.

The building uses construction materials with low embodied energy, including wood, (glulam beams and timber cladding), and Hemcrete panels for the walls. The landscaping is designed as sustainable drainage, including a swale and a pond. The building also has a large rainwater harvesting system of 80,000 litres.

The building has a range of low carbon building services, with a biomass boiler (300kW wood pellet) supplementing a gas fired boiler, and a displacement ventilation system with six independently controllable zones delivering free cooling. An automatic daylight compensation system is used for the lighting system throughout the store. Heat is reclaimed from refrigerators, and used in the store, the refrigeration fluid used is CO_2 which has the lowest climate change potential of all current refrigerants.

As part of the development improvements to transport to and from the store were made with contributions toward; improved bus services, traffic light changes and roadway changes. Cycling is encouraged by various measures including covered bike storage areas and staff showers.

Design issues

The main design issues were to achieve the aims of low carbon in construction and in operation. In addition, aims were to maximise retail space and minimise cost. As a consequence of these aims, it was very important to adhere to the following principles:

- Reduce air infiltration to a minimum.
- Clear vision for the building expressed through Plan A and the Sustainable Construction Manual.
- Close collaboration with designers and contractors throughout the construction and commissioning process.
- Detailed hand-over process with clear operation and maintenance manuals.
- Post occupancy workshops which bring together designers, contractors and facilities staff to examine the building's performance in use.
- Good insulation.
- Reduce thermal bridging as far as possible.
- Maximise natural light.
- Control solar gains.
- Keep HVAC systems simple as then they are easier to control and monitor.

Problems encountered:

- Difficult to assess the performance of certain sustainable features due to lack of consideration to monitoring at the design stage.
- Initial resistance from some stakeholders not used to sharing information with third parties.
- Challenging to interpret some of the data received without knowing the day to day activities in the building.
- Using relatively new building materials such as Hemcrete and glulam supports meant it was challenging for the design team to accurately model the in use performance of the building at the design stage.

Performance

Marks and Spencer have extensive experience of building new stores. Their processes are well rehearsed and they are used to working at speed. However this store was not a typical store and had senior management oversight ensuring the project was kept to time and budget.

The post occupancy evaluation (POE) team began meeting before the project was completed and met regularly with M&S head office staff, and visited the store quarterly post-completion. The POE team had access to monthly meter readings and also reports from the site maintenance and snagging team. These were reviewed monthly and anomalies found both by the normal processes used by M&S and the POE team, were quickly addressed by either in-store maintenance staff or the outsourced building management services company that are routinely used by M&S.

This regular checking uncovered issues that in some buildings would go undiscovered for very long periods. Typical issues would include heaters left on, lights not operating to schedule and sensors malfunctioning. All of these would be detrimental to building performance if left unchecked. However, the opposite is also true, and constant attention to the detailed building performance helped lead to the excellent performance seen by the project team as detailed in Figure 4C.1. Note that M&S Cheshire Oaks emitted 39% less CO_2 per m^2 of retail area than a peer store, Warrington Gemini, with 34% less electricity and 71% less heating energy required. In addition to this the figures for Westfield White City were 40% lower CO_2 emissions, 36% less electricity and 80% less heating energy.

In addition to the physical measurements of meter readings and of temperatures, the team carried out questionnaire surveys of community groups, frontline retail staff, back of house retail staff and of customers. Collectively these are referred to here as soft analysis.

The soft analysis programme was planned for execution after one year of occupancy. It included the surveying of a peer store (Warrington Gemini), as well as Cheshire Oaks. In each store the team would carry out a Building Use Survey (BUS) using the protocol as required by the TSB Building Performance Evaluation programme over a period of two days and within those two days carry out a series of focus groups. The peer store was selected as having a similar size, similar footfall and a similar socio-economic demographic. Table 4C.1 shows a comparison between the two stores including performance data.

Table 4C.1 Comparison data.

Variable	*Cheshire Oaks (CO)*	*Warrington Gemini (WG)*	*% reduction of CO compared with WG (negative is increase)*
Nearest major town	Chester/Ellesmere Port	Warrington	
Net sales area	14,915m^2	10,519m^2	–42%
First floor area as % of total	41%	17%	n/a
Food hall as % of total	10% (~1500m^2)	18% (~1900m^2)	44%
Footfall (May, June, July 2013)	671,713	663,704	–1%
Electricity consumption (1st September 2012 to 31st August 2013)	3,818,532kWh	3,781,030kWh	–1%
Gas consumption (1st September 2012 to 31st August 2013)	338,875kWh (gas) 197,202kWh (biomass)	1,493,449kWh (gas)	64%
Total electricity consumption per m^2 of sales area	275kWh/m^2/yr	414kWh/m^2/yr	34%
Total gas and biomass consumption per m^2 of sales area		38kWh/m^2/yr^2	130kWh/m^2/yr 71%
Total CO_2 emissions per m^2 of sales area	127kgCO_2/m^2/yr	208kgCO_2/m^2/yr	39%
Total energy consumption per m^2 of sales area	313kWh/m^2/yr	544kWh/m^2/yr	42%

Sources: M&S, Faithful and Gould

BUS survey process

In both stores staff surveys were carried out using the BUS questionnaire as specified by the TSB. For details of BUS methodology see www.busmethodology.org.uk.

In both stores the teams were based in the staff canteen as almost all staff passed through the canteen at some point during the day. M&S stores have a large number of part time staff and also have staff present outside of the 9 to 5 period that the team were in attendance.

The team handed out questionnaires personally to all staff found in the staff canteen and those in nearby offices. In both stores the team visited the staff canteen multiple times during each day to encourage responses. Staff returned completed questionnaires to a box in the canteen. Overnight, questionnaires were left in the canteen, with notices encouraging out of hours staff to fill them in during their shift.

In CO the staff had been specifically requested by management during their morning meetings to help fill in the questionnaires.

The completed questionnaires were coded into a spreadsheet for each store, and checked. The CO spreadsheet for the BUS survey was sent to Arup for processing.

Focus group process

Four focus groups were planned for each store to cover; community, customers, shop floor staff, and 'back of house' staff. The same procedure was followed at both stores but additional questions on sustainability features were asked at CO.

In advance of our visit, both stores were given detailed requests to recruit participants for the focus groups, with M&S head office liaising with local store staff. The incentive for customers and community participants was a £20 M&S voucher; staff received no incentive to participate.

A pre-prepared list of topics with suggested wording, and timings for each topic was used by the focus group leader to guide each group discussion. Each focus group had a leader, a note taker, and a scribe using the flipchart. The focus group leader took no notes, the other two took notes and added additional points where necessary. All groups were recorded using both the Livescribe recording pen see www.livescribe/com/uk and a dictaphone.

A brief preparation discussion between the team occurred before each focus group and a summarising discussion was held at the end of each day to identify key points raised.

At the start of each focus group, a warm up task was conducted where all members were asked to introduce themselves, explain about their journey to the store and mark their home location on a map. The discussion was then led and encouraged by the focus group leader, occasionally prompting and moving the discussion along to ensure all topics were covered.

Level of participation

Overall numbers of participants for each focus group in each store are given in Tables 4C.2 and 4C.3.

At WG, the POE team directly recruited customers for the two customer focus group slots and the focus group agenda designed to gather community responses was modified to allow customers to reflect on the impacts of the store on community life.

At CO, note that all members of all focus groups were recruited by M&S staff. It was clear to the POE team following both sets of store surveys that CO focus groups had not been selected for their opinions but for their availability.

In both WG and CO, staff allocation to focus groups was made on the same morning in most cases.

Table 4C.2 Focus group participants at Cheshire Oaks.

Group	*Number*	*Males*	*Females*
Community (~1 hour)	11	3	8
Customers (~1 hour)	12	0	12
Shopfloor staff 1 (~30 mins)	3	0	3
Shopfloor staff 2 (~30 mins)	2	0	2
Shopfloor staff 3 (~30 mins)	4	2	2
Operations and maintenance staff (~30 mins)	6	6	0
Total	35	11	27

Table 4C.3 Focus group participants at Warrington Gemini.

Group	*Number*	*Males*	*Females*
Customers 1 (~1 hour)	6	1	5
Customers 2 (~1 hour)	11	3	8
Shopfloor staff 1 (~30 mins)	4	0	4
Shopfloor staff 2 (~30 mins)	4	0	4
Shopfloor staff 3 (~30 mins)	5	1	4
Operations and maintenance staff (~30 mins)	4	4	0
Total	34	9	25

M&S Cheshire Oaks (CO)

The following sections present the results from the BUS survey and then from the focus groups with key points and a summary, followed by more detailed analysis under a series of headings. The BUS questionnaire respondents were all staff, focus groups also included customers and community.

BUS survey results

From a pool of around 200 possible respondents (staff count of 169 on day 1, 181 on day 2), 81 completed questionnaires were received. The summary results from these are presented below with more detailed analysis in later sub-sections.

The BUS has results for 48 individual variables and from these, 4 overall index variables are created. The scores for CO are as follows:

- overall summary index: top 5% of all buildings surveyed
- comfort index: top 11%,
- satisfaction index: top 2%
- forgiveness index: top 26%

As seen in later sections, the highest individual ratings for CO are for 'image to visitors' and 'design', with most other variables comfortably above benchmark, 'temperature winter overall' and 'needs meet occupants' are both far better than benchmark.

In the following figures, we use 'traffic light' terminology to categorize the variables: the 'green zone' (here shown as squares) indicates better than benchmark, the 'amber zone' (circles) means within or very near to the benchmark and 'red zone' (diamonds) means outside of the benchmark. Overall, of the 48 variables surveyed, 20 were in the green zone, 14 were in the amber zone, and 14 were in the red zone. These variables are grouped into several different categories, and are reported as below.

Overall variables

The results from the "overall" variables considered during the BUS survey were very positive, with no response values appearing in the red zone (see Figure 4C.1). Of the overall variables all were within or better than the benchmark, none were in the red zone.

Temperature

The staff surveyed included not just those who worked in air conditioned areas (offices and retail areas) but also in the unconditioned 'back of house' areas of the store. The temperatures were found to be stable all year round, with slightly too hot in summer and near benchmark in winter.

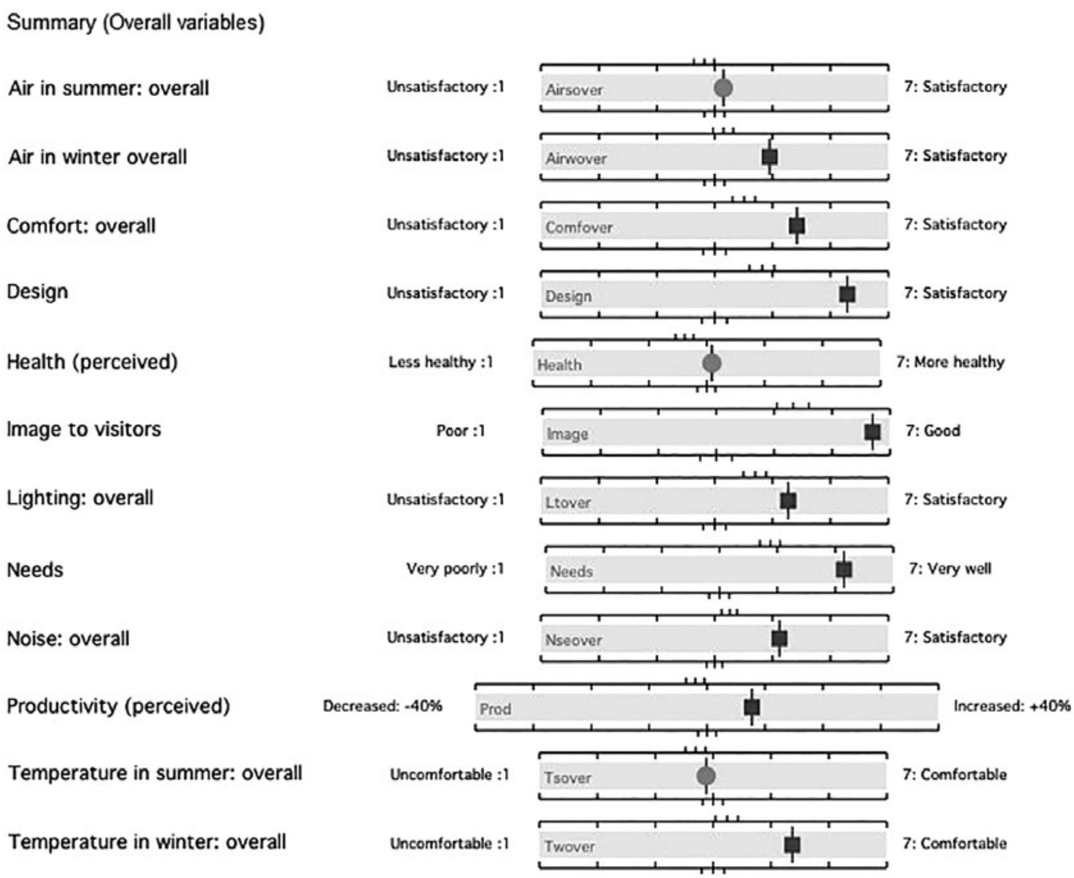

Figure 4C.1 BUS survey overall summary results.

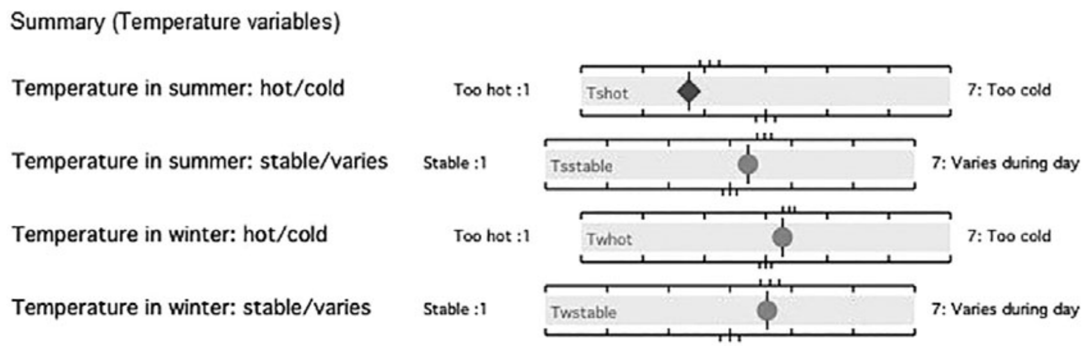

Figure 4C.2 Temperature results from the BUS survey.

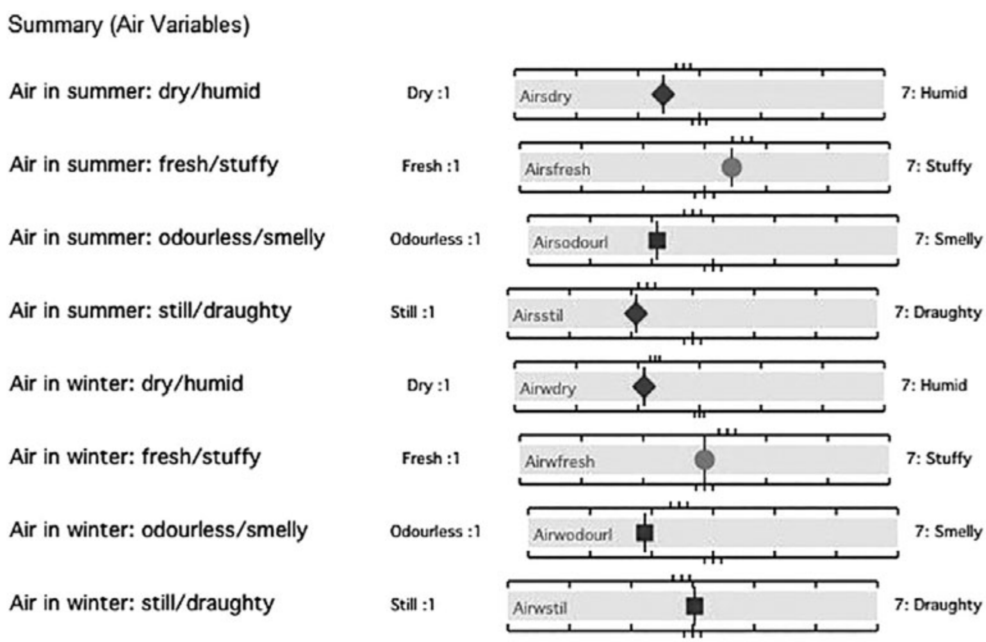

Figure 4C.3 Air results from the BUS survey.

Air

The air in both summer and winter was perceived to be odourless and dryer than the benchmark. In summer, air was perceived as being a little stiller and a little stuffier than the benchmark.

Lighting

In the CO store, natural light was rated within benchmarks and little glare from sun and sky was reported. But two of the four lighting variables are in the red zone (see Figure 4C.4). CO was rated by staff as having slightly too much artificial light, and slightly too much glare from artificial lights. Note that in focus groups, glare was found to be an issue for staff in a small part of the sales area on the ground floor in the mornings and in the upstairs cafe at certain times when the sun was low.

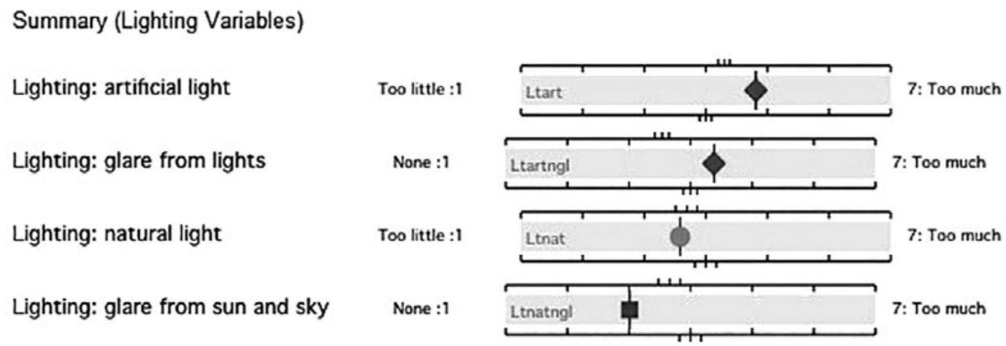

Figure 4C.4 Lighting variables from the BUS survey.

Noise

One of the five noise variables was in the red zone (Figure 4C.5), with CO perceived as having too little noise from outside, the remaining variables are within benchmark values. This can be a negative factor for offices.

Control

All control variables were well below benchmark, CO is mechanically ventilated with a remotely managed building management system so most staff have no direct control at all over their environment (Figure 4C.6).

Design and needs

All design and needs variables were rated to be well above benchmark values (Figure 4C.7).

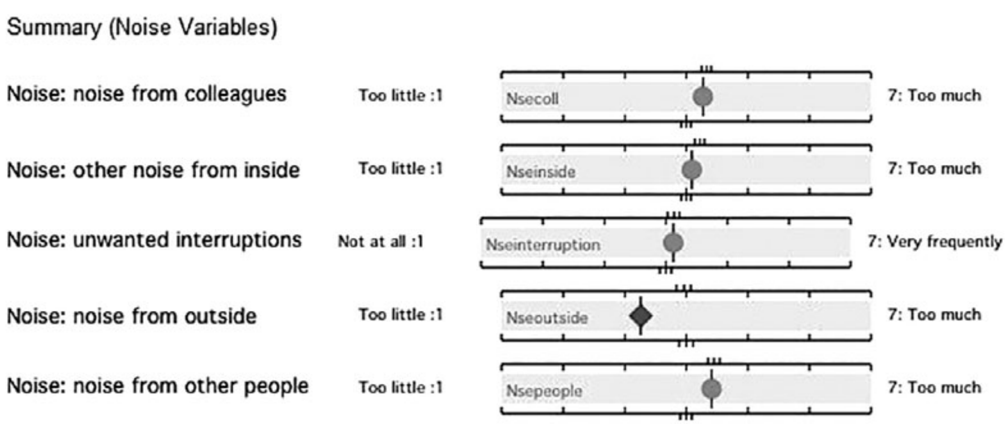

Figure 4C.5 Noise variables from the BUS survey.

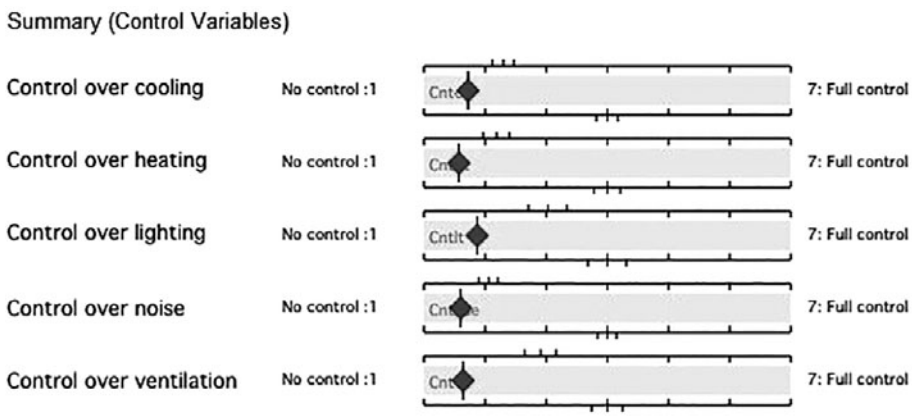

Figure 4C.6 Control results from the BUS survey.

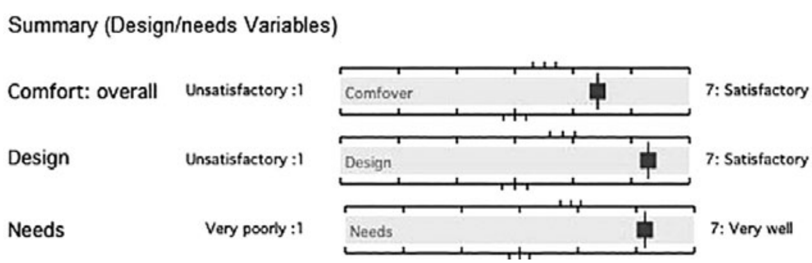

Figure 4C.7 Design/needs results from the BUS survey.

Facilities management

Most of the facilities managment (FM) variables were rated as being well above the benchmark with 'image to visitors' particularly high. The only 'red zone' variable in this section was 'space at desk' which was actually a little higher than benchmark, toward too much space (Figure 4C.8).

The 'perceived health' variable, tended toward the more healthy and is slightly above the benchmark but not significantly higher than the mean of all buildings surveyed using the BUS methodology.

Focus group results

In this section key points are drawn out from the focus groups (see Tables 4C.2 and 4C.3 for numbers) and interpreted with some representative quotes. Following that, some more general themes are also presented with quotes.

Customers

The overriding outcome from the customers focus group was that they love the store, thinking it impressive, light and airy, spacious, and with no problems with temperature, lighting or air quality. Some typical quotes were:

> 'I think it's fantastic.'

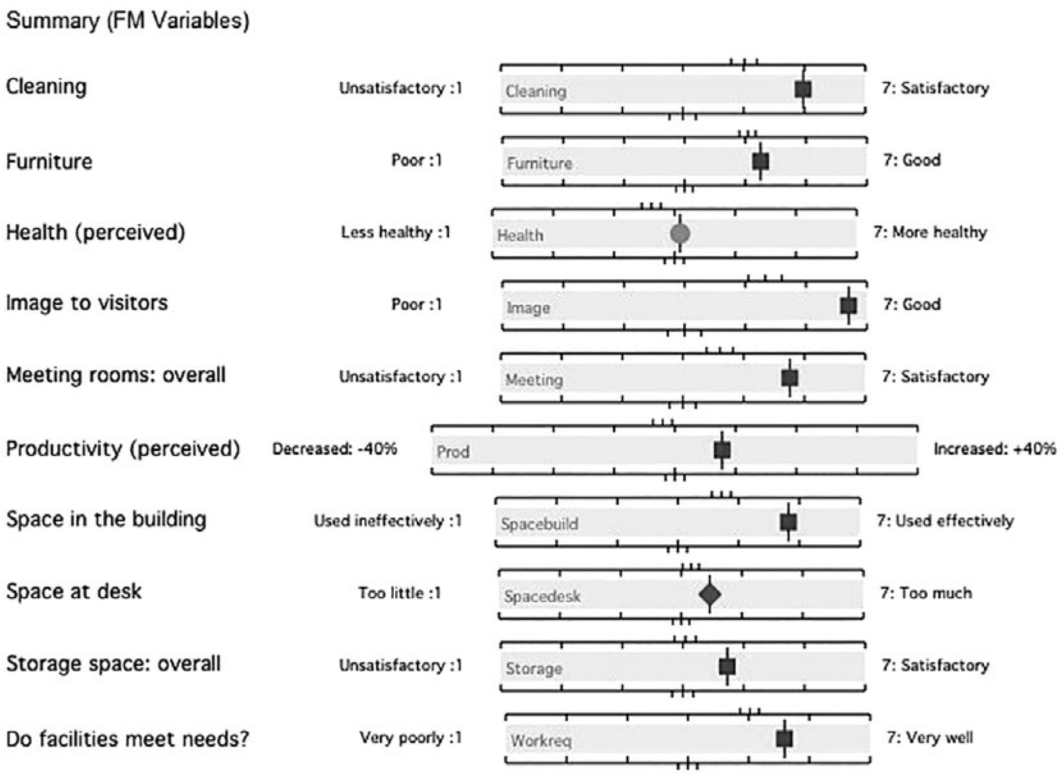

Figure 4C.8 FM results from the BUS survey.

> 'When I first came here I was in awe of it – I just couldn't work my way round it at all. However, I persevered and I absolutely love this store now.'

> 'It takes three or four hours to walk round and have a look at everything . . . and then you have something to eat.'

Local community

Representatives were very positive; all of them liked the store and the sustainable landscaping around it and have moved from a position of resenting the arrival of the store to treating it as their local corner shop.

> 'It's my local store; it takes me five minutes – I just think the whole experience is really positive.'

> 'It looks better than I thought it would . . . The exterior isn't as intrusive as I thought it might have been . . . It has blended in quite well.'

> 'Because we're local we're here two, three times a week.'

> 'I think the changes to the traffic have improved the situation.'

Shop floor staff

Staff love working there, in general there are no problems. They mention the design of the store, the daylight and the greenery outside in particular. The store is big and the distances staff walk are significant; an unusual benefit for some is weight loss. Working there does seem to have changed the attitudes of some staff toward being more environmentally friendly.

> 'I've found it very privileged to work here. I think it's one of the most incredible stores I've ever seen.'
>
> 'I like it because there's lots of windows everywhere so it's light and airy. I came from a place where there were no windows, where you didn't see daylight at all [Chester store]. Unless I went out at lunchtime I never saw daylight. Whereas I can just walk along this corridor and just look up and it's light.'
>
> 'I've definitely lost weight since I started working here. I like the fact that I'm always on the go, it's good exercise – in my previous job I just sat.'
>
> 'I think the structure of the building is absolutely incredible – you go outside and you see the natural wall. There's no other store I think in the country that have got any concept of what this is like where you see the living wall and all the natural flowers.'
>
> 'If I find things on standby I have been known to confiscate them and lock them in the boot of my car until he learns his lesson. At the moment I've got his PlayStation and Xbox in the boot.'

'Back of house' staff

Overall there were no particular or unusual problems and they felt they were still settling into the building. The back of house area was not seen to be particularly special, though the eco-friendly features throughout the store were appreciated.

> 'Generally good place to work.'
>
> 'The big thing I've noticed is natural light. . . . I'd say the natural light in this store is better than in every store I've ever worked in and I think it's a noticeable difference.'
>
> Backstage has changed a lot over the past 12 months trying different things . . . it's getting better but it's still a way off – it's not perfect.'
>
> 'It's a bog standard backstage area.'
>
> 'Freezing in winter, far too warm in summer.'
>
> 'You're still going to get a draught from the bottom of the vehicle – you can't avoid that.'

About sitting by the pond:

> 'It's nice. It's like a bit of escapism – just a couple of members of the public I've seen sat there.'

Themes from all groups

Some themes were mentioned by several groups and are picked out in the sections below. There were far more positive comments than negative ones.

Store size

The size of the store impressed all with positive comments about being spacious and airy but the size also had some drawbacks for some customers and some staff. The long distances between entrances, stock, fitting rooms and toilets being mentioned by several.

> 'Looking up at that roof it's like a cathedral: St Marks it should be called.'

> 'I think anybody coming here for the first time is like "wow" but when you get to know where everything is – the layout and everything – I just think it's great.'

> 'Really nice big gaps between everything – you can look properly without having to get in anybody's way.'

> 'Could they provide a seat in the store? Not everybody who walks in the store is fifteen or twenty. I had both my knees operated on. . . . The only place I can sit down is one of the plinths where the mannequin sits.'

> 'It doesn't make you feel comfortable – it's like standing in a barn.'

The food hall was considered a little small:

> 'Food hall isn't big enough for the size of the store.'

Sustainability features

The various sustainability and biodiversity features were commented on by many, with the only negative comments relating to the cost. No negative comments were raised about the rainwater harvesting. Many were impressed with the visual impact of the store, mentioning the sustainable features as part of that impact.

> 'The air is so fresh here that you can walk around and you don't get tired as quickly.'

> 'I like the fact they've got all these plants and I like the fact they've got stuff on the roof.'

> 'The lavender outside it's lovely.'

> 'I come out on my bike and sit and watch the dragonflies.'

> 'The eco aspects are probably less important than the visual impact.'

Travel and access related issues

Customers appreciated the free parking, and being able to park outside. Some people travelled from quite long distances away, eg from Wigan, others, such as the local community can walk and visit more often. Improved public transport was appreciated by the local community. Some noted that the bend in the ramp to the upper floor of the car park was not safe.

> 'The car park itself is very easy . . . the spaces are good, they've got a walkway which is very safe for pedestrians.'

> 'For me one of the biggest things is that you can park outside.'

> 'It's free parking, it's easy to get here – Chester isn't.'

> 'It gave us a bus route – that was very positive for me.'

> 'Absolute nightmare. When you meet a car on the bend.'

Social and relational purposes of shopping

Plenty of customers went shopping with members of their family, M&S has capitalised on this very well indeed.

> 'I liked it the first time I came here – the idea that you've got food and shopping. Shopping takes time so if they get hungry (indicates toward her young child) go get something – you know – continue shopping.'

> 'My daughter and I sometimes come in the evening.'

Cafe

The upstairs cafe was very well liked, with views and daylight mentioned in particular. There were some issues with waiting to be seated and some queues. Some questioned why there was a downstairs cafe.

> 'It's lovely sitting having a coffee watching the snow.'

> 'I like to sit where Joanna Lumley sat when she opened the store.'

Negative comments

There were very few negative comments regarding the store. Of those, most were related to its size, there were some glare issues in certain parts of the store but only at certain times.

> 'Too big, barn like, clinical with pipes and lighting conduits visible.'

> 'If you need to go to the loo and you're on the shop floor – for example if we're in the fitting rooms – it's a heck of a hike up to the staff loos. There are customer toilets right beside the fitting rooms but we're not allowed to use them and it just seems a bit of a waste – bad time management if you like – The time it can take to get from the fitting rooms up to the loo.'

'On limited downstairs the sun comes in dreadful – that's blinding down there as well – by the front door . . . it's really unpleasant trying to see in this area in early morning.'

Remote building management

The building management system is remotely managed by Matrix, based in Scotland. Their role is chiefly concerned with managing energy and water use, and ensuring that sales floor lighting and environmental conditions are maintained within limits according to appropriate time schedules.

Their chief aims are to save money, energy and carbon in that order, with some provisos.

Notably they don't find Cheshire Oaks any more difficult to manage than any other store, despite the unusual systems present.

They are particularly impressed by the displacement ventilation system that provides good environmental conditions with low energy consumption.

Operations and maintenance staff for both stores request environmental control changes from Matrix. A typical comment was 'Matrix deal with the control side of it. When something goes down we have to basically ring Matrix up and say "can you sort this out for us?"'

Summary

The M&S Cheshire Oaks is very well liked by all groups of people questioned whether by questionnaire or by focus group. It is clear that after the first year the store is working very well. It presents an excellent image to customers, the design is well liked by all those asked and the environmental conditions in the store are highly praised.

The Cheshire Oaks store has performed ahead of expectations in terms of its energy performance in the first year of operation when compared to both the traditional benchmark store and against the predictions made by the building's designers. The results for heating and hot water fuel savings are all the more impressive when seen in the context that the electricity use is lower than expected, hence the internal heat gains from electricity use are lower and therefore displace less fuel used for heating. Also, the cafe is more popular than expected and so the hot water demand is higher than anticipated. The savings can be attributed to a number of factors including more efficient lighting with better controls, along with a more efficient HVAC system.

In terms of the heating fuel use, it is felt that the building's excellent thermal performance is a factor in why the heating and hot water energy fuel consumption is 66% less than the benchmark store. The heat recovered from the CO_2 refrigeration system is also felt to be making a significant contribution to this, however there is currently no system in place to measure the amount of heat being recovered.

The shopping environment in CO was widely praised and actively encouraged customers to stay longer, with many mentioning fresh air, impressive design and comfortable temperatures. Customers in WG complained strongly about the temperatures in that store but those questioned were the ones that still shopped there.

Customers at CO thought the merchandise to be good quality and good value. Interestingly, customers at WG thought M&S merchandise was dated, needed refreshing and that CO had better ranges than WG, this is a suggestion that the store itself improves customers' perception of merchandise.

The sustainable and biodiversity features at CO were widely appreciated by customers, local community and staff and were considered to have improved the surrounding environment significantly. It is clear that they have had an impact in encouraging customers to visit the store and to spend longer in the store, but it is not clear yet if this has had an impact on sales per customer, although it does encourage customers to return. It is clear that staff are very positive about working in the store so absenteeism is likely to remain low and staff retention is likely to be high. Staff at CO perceive that the environmental conditions improve their productivity. Both staff and local community enjoy the environmentally friendly landscaping surrounding the store.

In comparison with the peer store M&S Warrington Gemini, M&S Cheshire Oaks was by far the better store on almost every count important to customers and staff.

The design of the CO store and the frequent posters and notices mentioning the sustainable features were not disliked and many found them educational, particularly the local community. Staff reported being more environmentally aware at home.

Both CO and WG are very large stores, this meant that customers were impressed with the store itself and also the range of items on offer but disappointed if their size was not in stock. Customers thought however that the food hall in CO was too small.

A consequence of an aging demographic and large floor areas meant that many mentioned a lack of customer seating in the sales areas of both stores. Store layout in WG was a problem with no ground floor toilets and poor access by lift to the first floor.

Traffic and car parking were key issues for many at both stores. The ease of out of town shopping was apparent with free parking being popular. Public transport to CO was far better than to WG, but could be better still. Aging customers would still want to shop even if they were not able to drive any more.

Internet shopping was not commonplace, with a few customers looking at the internet first then coming to see the products. Very few ordered online at home. One customer had ordered items from the in-store 'browse and order' points on their own. However several had been guided to use them when an item they wanted was not available in their size and they needed to order it online.

Overall, the Cheshire Oaks store should be heralded as a great success, both in terms of its performance and its user satisfaction, and be marked out as an exemplar retail building.

Case Study 4D

IMPACT OF AN ENERGY REFURBISHMENT PROGRAMME IN CHILE

More than energy savings

Eugenio Collados and Gabriela Armijo

Introduction

The energy crisis derived from increasing oil prices is striking low-income housing in Chile by aggravating the chronic problems of the poverty circle that links income, housing and health. The prevalent model of urban and architectural design reliant on plentiful energy, long distance transportation and access to global markets is showing its weakness and vulnerability. Primary energy sources in Chile are increasingly dependent upon imported fuels, precisely when natural gas availability has plummeted and oil prices keep climbing. Inexpensive local wood fuel could be an alternative for domestic heating; but current technology is not environmentally compatible with urban population density. Thus, an urgent strategic change is required at all decision-making levels, recognizing the need to become energy independent. This change points to energy efficiency, less foreign dependence and major improvements in construction and heating technologies.

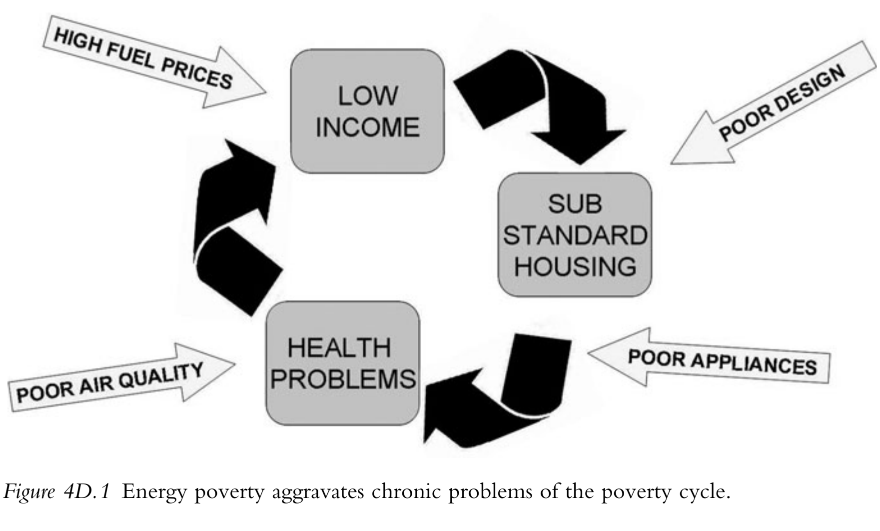

Figure 4D.1 Energy poverty aggravates chronic problems of the poverty cycle.

Box 4D.1 Fuel poverty concept

A first definition of the 'fuel poverty' concept was given by Lewis (1982) as 'the inability to afford adequate warmth in the home', in the National Right to Fuel Campaign in Bradford, UK. It refers to households that would need to spend more than 10 per cent of their annual income on fuels in order to achieve satisfactory indoor heating. The concept is what people would need to spend, not what they actually spend. In other terms, a fuel-poor household spends too much and/or suffers poor heating.

A definition more closely related to housing design is given by Healy (2004): 'The inability to heat one's home to an adequate (safe and comfortable) temperature owing to low income and poor (energy inefficient) housing'.

The British definition assumes satisfactory heating as where the main living area is at 21°C, with 18°C in other occupied rooms. It is assumed that heating is available for 16 hours per day for households likely to have occupants home all day, and nine hours per day for households in work or full-time education (Defra, 2003).

The lack of reaction in Chile after the 1970s world energy crisis, mostly due to the local availability of inexpensive fuels and a policy in favour of unregulated markets, has revealed a costly outcome in economic, social and environmental terms. In addition, the effects of a technological gap of two decades are such that fewer solutions are currently being offered, little knowledge has been integrated within architectural training and few engineering firms are prepared to take up the coming task.

To face these problems, several initiatives are in place. The housing ministry started to enforce an energy building code in 2000 for all new housing. However, the replacement of the stock is very slow, given the lifetime of buildings. Widespread awareness of the profits of energy efficiency has not been enough to encourage investment mechanisms due to market failure (see Box 4D.2). Since it is becoming more difficult to keep the existing stock operating at a sustainable level, the government advocates a policy aimed at improving the energy performance of this stock by attempting to break these market barriers. Consequently, a study was commissioned during 2006 to:

- identify and assess the potential measures and resources required for an energy refurbishment of residential buildings;
- estimate the impacts on energy demand from such measures;
- propose management models in order to channel private investment and promote private investment; and
- estimate the expected benefits, both private and social (Ambiente Consultores, 2007).

On the other hand, the National Commission of the Environment (CONAMA – the future ministry of the environment) promotes several programmes to control emissions from wood combustion appliances for heating and cooking. Since wood is by far the least expensive energy source for these purposes, just restricting its use as fuel is not practicable since it would necessarily increase health and inequality problems. As a result, the method of reducing emissions aims to lessen heating demand by means of improving the thermal performance of buildings and appliances, as well as encouraging the use of low moisture firewood.

This chapter presents some results of these and other related studies and presents a pilot case study.

Box 4D.2 Market failure: A barrier to improvements in energy efficiency

Energy-saving opportunities are immense with current technology; but new product standard mandates will be needed. Electricity consumption in residential buildings in the US in 2020 could be reduced by more than one third. The energy saving would result in a significant reduction in the amounts of fossil fuel burned and carbon dioxide, the main greenhouse gas, spewed into the atmosphere. Yet, market forces alone (even considerably higher energy prices) will not be enough to cause wholesale adoption of the most energy-efficient technology.

This study emphasizes the need for correcting market distortions. Such distortions result from individuals lacking adequate information to make the best decisions or the market's failure to encourage individuals to make energy-efficient investments. Everyone would be better off if the capital investments were made; but the individual parties do not have the incentives to make the needed investments.

Source: McKinsey Global Institute (2007)

Background information

Energy and residential sector

The residential sector has not played a relevant role in the making of strategic decisions about energy-secure supply and efficient use in Chile. Access to electricity has been the only aspect of concern in national energy policies. A single fact clarifies the irrelevance of residential energy use: new buildings receive the approval certificate with no need to have a heating system or even a design of a heating system. Most buyers or tenants have to manage by themselves in order to provide some form of heating, choosing from the retail market without much technical or financial support.

Heating represents about 11 per cent of the country's energy consumption, although typical warmth and health conditions in residential buildings are far from being considered satisfactory. This historical failure to achieve effective, efficient and clean heating operation in residential buildings represents an enormous opportunity for energy efficient initiatives. For this reason, this sector has been included in the recently initiated series of Energy Efficiency Programmes.

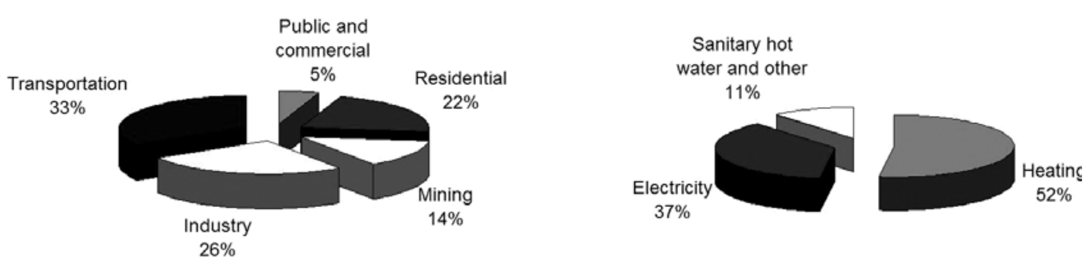

Figure 4D.2 Energy share by sector (left) and by final use (right) for the residential sector in Chile.

Source: CNE (2007)

Social housing and energy policy

A social housing policy aimed at building the highest possible number of dwellings has prevailed in Chile for a long time, in spite of compromising quality standards. The model has been based on the state financing low-cost dwellings (under 10,000 euros per unit, including land value). This model involves large building companies producing vast housing developments settled on low priced suburban areas. Little care for urban design, architectural quality or technological innovation has resulted (Rodríguez and Sugranyes, 2005). The recent emphasis on the energy factor has dramatically exposed the unsustainability of such models. Programmes for enhancing the design standards of social housing have recently begun to provide a better living environment, acceptable size of dwellings and basic habitability. The poor quality of the existing stock and urban decay are also matters of growing concern.

The housing stock in Chile comprises approximately 4.4 million dwellings, of which only 0.8 million were built after the year 2000, when basic thermal insulation goals began to be enforced.

From those 3.6 million earlier dwellings, very few could be considered adequately insulated or sited in places that require little heating, meaning that there is an urgent need and significant opportunity for energy refurbishing. Otherwise, the burden of energy expenses on households would exacerbate low income, health problems, fabric decay and environmental problems. Finally, it could end in a depreciation of scarce family assets, averting any hope of breaking the poverty cycle.

Facing the question of where to start in implementing an energy refurbishment programme, the first approach should be to arrange priorities simply according to climatic loads, starting from colder regions. However, heating deficiencies and energy poverty are not concentrated in higher latitudes since they are dependent and biased by other social factors, particularly the source of available energy. In the far south regions (latitude 53° S), natural gas is still available, meaning low cost supply in urban areas and energy poverty in rural areas. Population density is also scarce. Farther north (between latitudes 36° S and 45° S), climate is rainy, forests abundant and firewood is readily available in the countryside. In towns, however, fuel demand and prices have been rising continuously, becoming a heavy load for most families since the heating season may be nine to ten months long.

For many years there had been a shift from traditional solid fuels (coal, firewood and charcoal) to bottled propane and, in large cities, piped natural gas. A rise in propane price has meant that some families have had to return to their old firewood cookers, putting even more pressure on increasing fuel demand

Box 4D.3 Climates in Chile

Extreme latitudes in Chile are 18° S and 54° S, with urban areas at altitudes from sea level up to 2400m, involving all sort of climates except hot humid.

Biomes in Chile range from arid deserts in the north to cold steppes to the far south, with a strong contrast between coastal and inland valleys. Excluding high mountains, the lowest temperatures are found at latitudes 50° S and more than 100 km away from the sea.

This diversity of climates is both a challenge and an opportunity for smart design. In particular, in any location of the country, overheating control in summer can be achieved exclusively by passive means, either through solar control, roof reflectance, night ventilation, radiation cooling, evaporative cooling or other design options. Thus, there is no reason at all for air conditioning in residential buildings in Chile.

In most inland regions, wide day–night temperature fluctuations and moderate average temperatures allow for passive strategies based on thermal mass in order to reduce energy loads.

and atmospheric emissions. Northern towns, with milder winter seasons, are still relying on propane as a main source of heating, but gradually have started to shift to firewood stoves for heating.

In some southern urban areas, over 80 per cent of households rely on firewood while remaining energy poor; worst of all, air pollutants have deteriorated air quality to such an extent that health problems have become a major threat, in addition to diseases related to cold exposure and unflued heating. This fact has made it imperative to seek improvements in the energy performance of the housing stock in order to reduce the incidence of burning wood.

Current strategies to face the energy crisis in buildings

The current thermal quality regulations for new residential construction began to be enforced in 2000 for all new dwellings in Chile, according to seven thermal zones depending upon location and altitude. At its first stage, it covered only loft insulation. Since 2007, regulations were extended to windows, external walls and exposed floors, but only considered the main fabric of each envelope element, with no correction for thermal bridges. This regulation specifies mandatory maximum U values in W/m^2K. No requirements are set yet for ground heat transfer, air infiltration, ventilation or heating. Table 4D.1 shows a summary of requirements.

This regulation states the bottom line for design; but in most cases a much higher standard would be justified by a simple cost-benefit analysis, even with current fuel prices. However, both the lack of information by new owners in making their choice and the neglectful cover-up by the construction industry put pressure against reaching higher standards.

Regarding existing dwellings, the recent governmental response to face the fuel price increase was to subsidize the demand by compensating for its impact on low-income household budgets during winter. In reality, this policy would only sustain wastefulness and dependency upon imported fossil fuels. In contrast, a subsidy aimed at reducing energy demand would result in permanent relief for household budgets, while also stimulating local markets with emerging insulation technologies and skilled labour. Ironically, running inefficient buildings with no refurbishment is the most expensive alternative by far.

Recent trends and energy crisis

Energy supply at the national level appeared to be secure and cost-effective after gas pipes were built in the 1990s to bring natural gas from Argentina. Improvements in air pollution, wider access to utility gas

Table 4D.1 Minimum requirements for new residential buildings according to thermal zones.

Thermal zone	*Degree days (reference: 15°C*	*Minimum U value for loft insulation*	*Minimum U value for walls*	*Minimum U value for exposed floors*
		W/m^2 K	*W/m^2 K*	*W/m^2 K*
1	< 500	0.84	4.0	3.60
2	500–750	0.60	3.0	0.87
3	750–1000	0.47	1.9	0.70
4	1000–1250	0.38	1.7	0.60
5	1250 to 1500	0.33	1.6	0.50
6	1500–2000	0.28	1.1	0.39
7	>2000	0.25	0.9	0.32

and less expensive electricity were all positive results for over a decade. During this period, most new developments in energy technology were based on natural gas creating a lock-in. At the same time, renewable energies and biomass fuels were neglected as ‘non-competitive’ technologies, despite social awareness and interest. However, imported gas shortages began in 2003 and prices have since kept increasing.

Heavy pressure is now being put on firewood, raising air pollution to unacceptable levels. Old firewood cookers are becoming valuable appliances for winter heating and many central heating gas boilers have been left redundant (Collados and Cifuentes, 2007). The effect of using wood combustion appliances for heating and cooking is directly related to PM10 concentrations – as is the case, for example, in the city of Temuco (see Figure 4D.4).

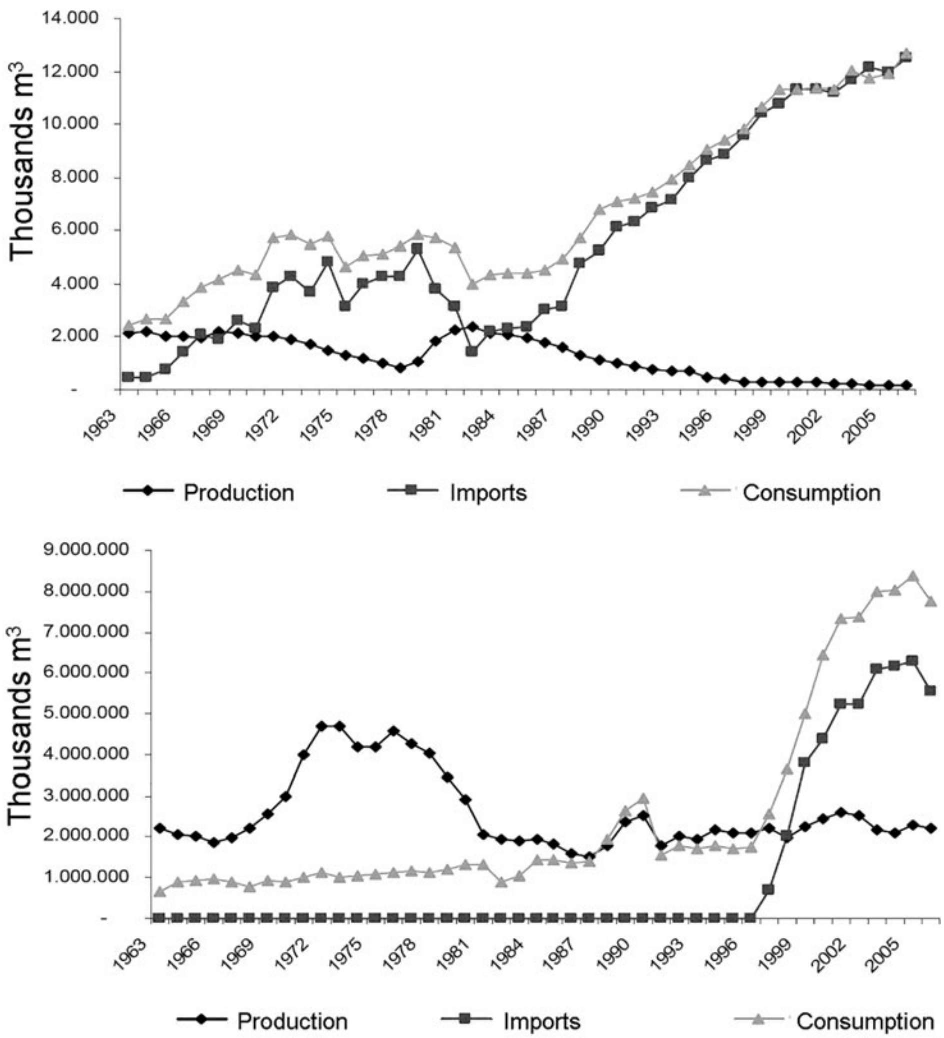

Figure 4D.3 Historic evolution of dependence upon foreign fuels and the short-lived conversion to natural gas during the 1990s: Oil (top) and natural gas (bottom).

Source: adapted from CNE (2007)

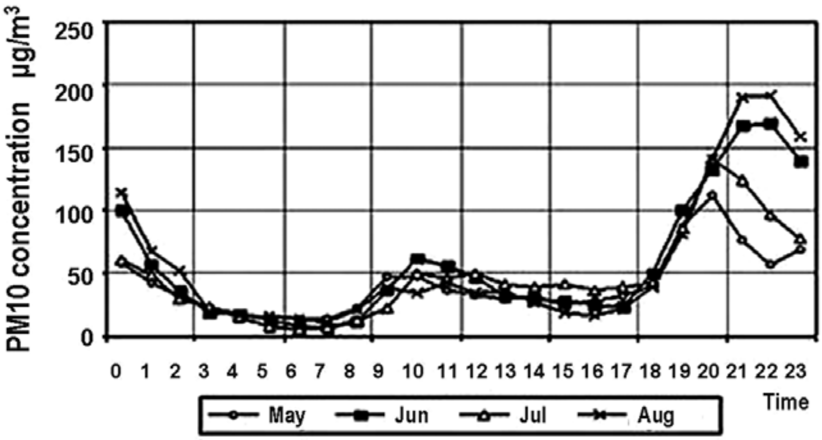

Figure 4D.4 Hourly PM10 concentrations in Temuco.

Source: Sanhueza et al. (2006)

On the other hand, architectural design is not prepared for changing to other heating systems such as solar thermal or geothermal, either centralized or individual, so propane portable heaters are the only alternative left to many urban households, particularly in blocks of apartments. Again, rising prices reveal how poor design could make a huge stock of buildings unsustainable under future conditions.

Box 4D.4 Barriers in technology uptake

In the residential sector, where energy makes up only a relatively small portion of total expenditure, the gap between the optimal and current level of energy efficiency is particularly large as a result of numerous market barriers. These barriers include lack of information and technical understanding, lack of disposable income for upfront capital investment, and split incentives between purchasers of equipment and consumers of energy.

Technology lock-in arises when a competitive advantage results in the mass uptake of a particular technology or fuel upon which the economy becomes reliant. Technological lock-in can prevent new technologies from entering the market given the significant costs associated with developing new supporting infrastructure and industries.

Source: Ford et al. (2007)

Box 4D.5 Health impacts from air pollution

Some of the main parameters to measure the impacts of air pollution on health are the daily number of healthcare deliveries under acute respiratory diseases (ARD) and the infant mortality form of ARD.

A strong correlation between the time series of deliveries has been found with the following variables (Barrios et al., 2004):

- environmental: particulate matter under 2.5 micrometres in size (PM2.5);
- meteorological: seasonal cycles and cold waves;
- epidemiological: outbreaks of contagious diseases;
- demographic groups: children under the age of five, pregnant women, older people; and
- social vulnerability: overcrowding, substandard housing and poor combustion heating.

A study by Sanhueza et al. (2006) has identified the group of adults over the age of 65 as a high risk in Temuco. Several of these factors are directly related to the poor quality and/or the poor design of dwellings and their heating systems.

Figure 4D.5 Winter atmosphere in Temuco.

Fuel costs for heating

The cost of energy for heating may represent up to 20 per cent of household income for the lowest quintile. The most vulnerable population groups include those with less access to energy sources, the socially excluded and indigenous segments, mostly in southern regions (Márquez and Miranda, 2007). Even with such an impact on household budgets, heating needs cannot be fully afforded and average effective temperatures of around 13°C are far from satisfactory.

The distribution of household income and energy expenditures is shown in Table 4D.2.

Table 4D.2 Energy expenses per household per income quintile, excluding firewood.

	Quintile 1	*Quintile 2*	*Quintile 3*	*Quintile 4*	*Quintile 5*
Per capita annual income	477 euros	928 euros	1429 euros	2208 euros	7678 euros
Percentage of household budget spent on energy, 1996	7.9%	5.8%	5.2%	4.2%	2.9%
Percentage of household budget spent on energy, 2006	10.8%	8.1%	7.3%	5.8%	3.9%
The above percentages could rise by 2% to 8% when firewood is included.					

Source: Moreno and Rosenblüth (2006) and Márquez and Miranda (2007)

Box 4D.6 Population in Chile, income distribution and housing quality

The population in Chile is 14.4 million urban and 2.2 million rural individuals (2002), growing at 1.3 per cent per year. Mortality rate is 5.4 per 1000 inhabitants, with an average life expectancy of 74.8 years. The average number of residents per dwelling is 4.2.

The quality assessment of dwellings shows a strong inequality, measured by the percentage of units with some deficit disaggregated by income quintile.

Table 4D.3 Percentage of dwellings with deficit per income quintile.

Type of deficit	*Quintile 1*	*Quintile 2*	*Quintile 3*	*Quintile 4*	*Quintile 5*
Overcrowding	27.9	15.5	8.5	4.7	1.4
Poor fabric quality	37.7	23.7	18.6	11.6	5.7
Poor access to utilities	31.8	19.0	12.7	6.5	3.7
Any type of deficit	61.8	42.2	31.0	18.9	9.4

Source: Moreno and Rosenblüth (2006)

About 79 per cent of dwellings have a quality mark ‘acceptable’; 17 per cent are ‘unacceptable but recoverable’; about 4 per cent are qualified ‘unrecoverable’; and 11 per cent need enlargement to become ‘acceptable’.

Appliances

The share of residential energy consumption by source is 14 per cent electricity; 8 per cent natural gas; 19 per cent liquefied propane gas (LPG), kerosene and oil derivatives; and 59 per cent wood and wood derivatives (Márquez and Miranda, 2007). The vast majority of kerosene and LPG heaters have open-flame, unflued burners, generating significant amounts of water vapour and indoor pollution. A high percentage of wood consumption is concentrated in southern regions between 36° S and 45° S, and the wood is mostly used in burners that have efficiencies typically below 50 per cent.

If rural areas are included, only 63.2 per cent of households in Chile have a hot water heater or boiler – that is, about 1.6 million have no access to hot water. However, installed solar heaters reach only 6000m^2, or about 3000 dwellings in Chile, despite plentiful solar radiation availability reaching annual insolation values of between 1500 and 2000kWh/m^2 for most cities.

Field assessment

A survey study carried out during winter 2007 (July and August) (IC, 2007) showed the actual temperatures in 392 households located in four cities at different latitudes. All dwellings were built after 2002, meaning

Table 4D.4 Percentage of urban households using appliances by energy source.

	Cooking	*Heating*	*Hot water*
Electricity	3%	11%	1%
LPG	88%	36%	70%
Natural gas	13%	3%	14%
Kerosene	0%	22%	0%
Wood	24%	67%	0%
(May include more than one source per household and use.)			

Source: Baytelman (2005)

Table 4D.5 Results from a survey on a sample of 400 dwellings built after 2002.

Town, latitude	*Heating hours per day*	*Time of the day*	*Outdoor temperature (°C)*	*Indoor dry bulb temperature (DBT) temperature (°C)*	*Walls radiant temperature (°C)*	*Effective temperature (°C)*
La Serena 29.9° S	1.18	Morning	15.4	15.6	10.7	13.1
		Afternoon	17.8	17.9	15.6	16.8
		Evening	15.8	18.0	16.9	17.4
Santiago 33.4° S	7.18	Morning	11.4	13.0	5.8	9.4
		Afternoon	15.5	15.6	11.3	13.4
		Evening	13.0	14.9	10.8	12.8
Concepción 36.5° S	7.02	Morning	11.1	11.8	2.7	7.2
		Evening	15.7	15.7	6.6	11.2
		Evening	12.9	14.7	7.6	11.2
Puerto Montt 41.5° S	13.88	Morning	9.3	13.6	10.8	12.2
		Afternoon	14.3	16.6	16.1	16.7
		Evening	12.5	16.1	16.9	17.2

Source: IC (2007)

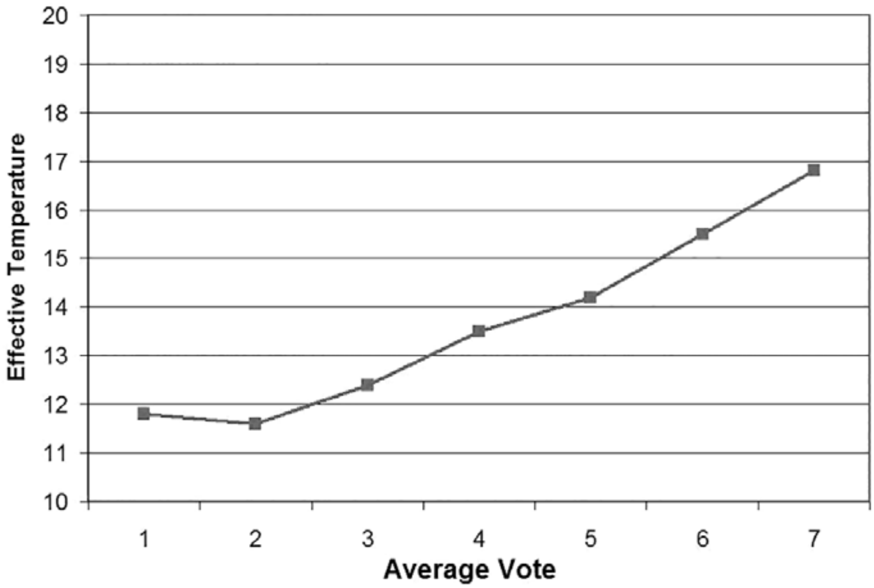

Figure 4D.6 Vote on subjective thermal perception in relation to effective indoor temperature.

Source: IC (2007)

that they included loft insulation according to regulations. Some results of the survey are summarized in Table 4D.5.

The survey also asked about the thermal perception of the residents, assessing it through a 7-point scale: 1 being 'fully unsatisfactory' and 7 'fully satisfactory'. The curve in Figure 4D.6 shows that the population sample voted 'fully satisfied' when heating provided was, on average, 16.8°C.

It can be concluded that despite the growing incidence of energy expenses on household budgets, satisfactory levels of comfort and healthiness are not achieved. Again, reckless design and market failure are to blame.

Box 4D.7 Effective temperature

The energy balance between the human body and its environment involves exchanges, through contact, with the surrounding air and non-contact infrared radiation with surrounding surfaces. About 75 per cent of the subjectively perceived temperature is explained by air dry bulb temperature (DBT) and surfaces temperature. Other factors include air speed and humidity. Since radiation from different surfaces may vary, uneven radiation may also affect thermal comfort. In addition, body activity has a strong influence on comfort, given that all other variables are fixed.

Some definitions of effective temperature consider all factors; but in the cited field study, only DBT and radiant temperature were measured, assuming negligible air movement and calculating the effective temperature as the average between radiant and DBT values. Radiant temperature is measured with a non-contact infrared thermometer, with adjustment of the emissivity coefficient.

Design of a prioritized refurbishment programme

How to assess priorities

The method that was used for devising the energy refurbishment programme is presented here (Ambiente Consultores, 2007). It includes the following stages:

- characterization of type, form, materials and heating systems of the housing stock;
- estimation of the current energy intensity of the housing stock;
- proposal of refurbishment goals, regional adjustment and optimized priorities;
- expected energy intensity improvement, cost analysis and payback;
- expected social and private benefits; and
- institutional requirements, human resources and financing schemes.

The output of the method is a prioritized programme that put a figure on costs and benefits for different refurbishing options applied to different building types and different locations.

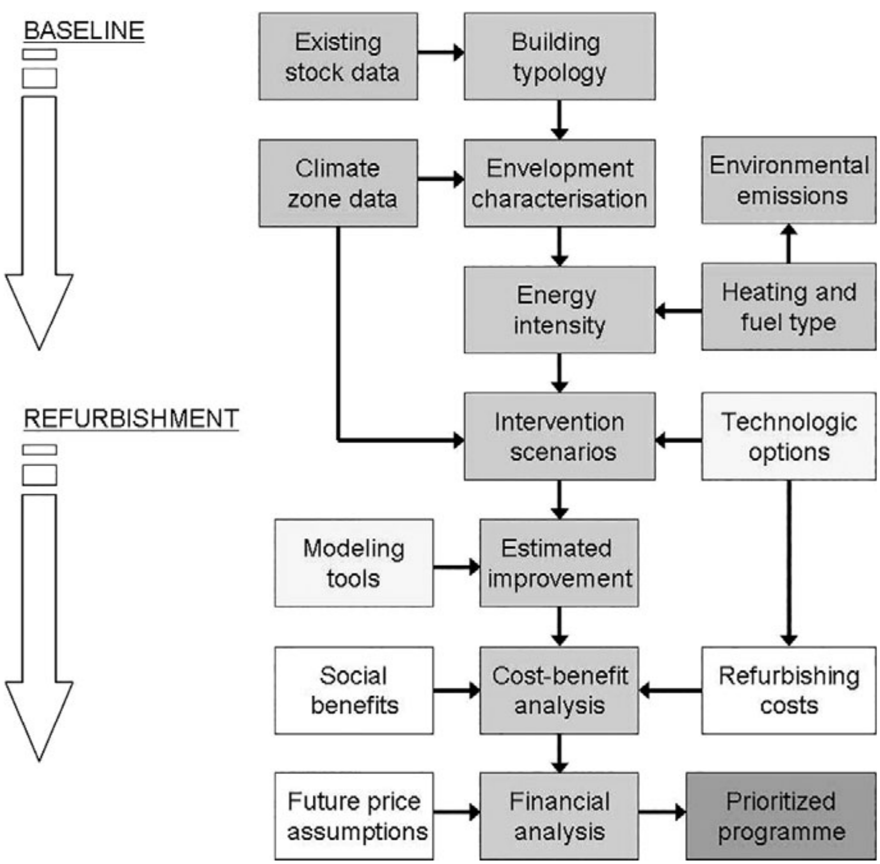

Figure 4D.7 Method of design of the prioritized refurbishment programme.

Existing residential building types

In order to define the baseline (i.e. to estimate the thermal performance of existing housing stock), assumptions should be made about the building types that best represent the diversity of designs. Fifteen types had already been identified in an earlier study by DECON (2003). From those 15, the 10 most widespread types have been considered representative of all the existing stock built before 2000 for the purpose of this simulation, as detailed in Table 4D.6.

Table 4D.6 Characteristics of dwellings for ten representative types used in the baseline study.

	Prevalence (percentage)	*Stories*	*Size (m^2)*	*Main material*	*Attachment*
Type 1	13.9	1	32.5	Hand-made brick	Semi-detached
Type 2	12.3	2	40.0	Concrete reinforced brick	Semi-detached
Type 3	8.8	1	39.8	Wood	Detached, above ground
Type 4	7.8	4	42.8	Concrete reinforced brick	Apartments
Type 5	7.4	1	72.0	Hand-made brick	Detached
Type 6	5.7	2	81.1	Concrete reinforced brick	Semi-detached
Type 7	3.4	2	39.9	Wood	Semi-detached
Type 8	3.1	1	74.3	Brick ground floor Wooden first floor	Detached
Type 9	2.1	10	67.7	Concrete	Apartments
Type 10	2.0	6	68.3	Concrete	Apartments

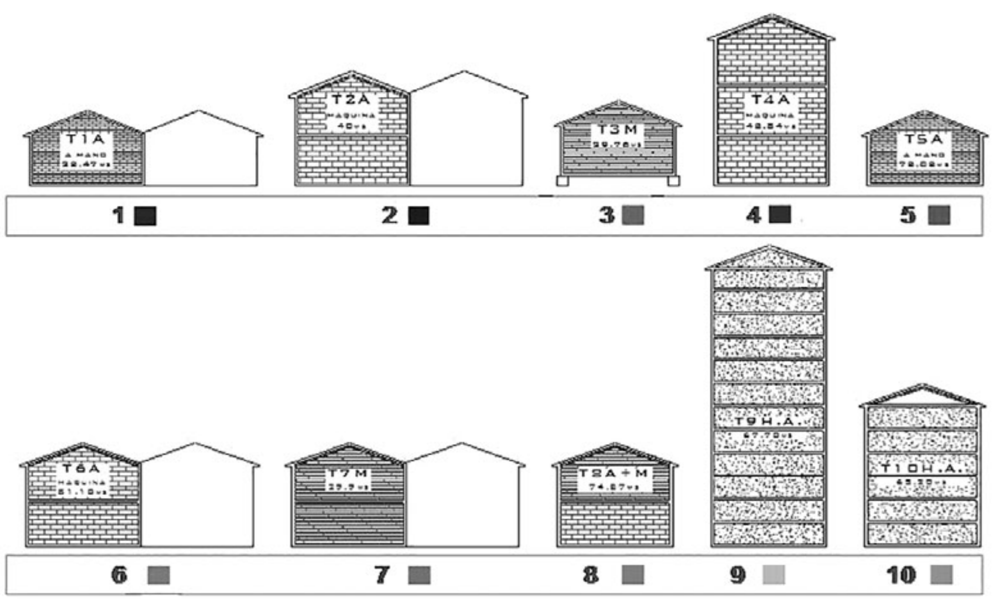

Figure 4D.8 Building types (schematic) used in the baseline study.

Source: Adapted from DECON (2003)

Eight of the ten types have no insulation at all. Two types have loft insulation but no wall insulation. Most houses rely on a single heating appliance, and a small fraction of apartment buildings have central heating systems. Usually, hot water is provided by an independent gas heater (a tank-less type).

An example of a semi-detached type 2 house in La Pintana (thermal zone 3) is shown in Figure 4D.9. The brick is exposed, with no insulation. Lofts are insulated with 80mm of glass wool.

An example of type 4 three-storey apartments in La Florida (thermal zone 3) is shown in Figure 4D.10.

Examples of detached type 3 houses in Coyhaique (thermal zone 7) and type 6 and 8 houses in Valparaíso (thermal zone 2) are shown in Figure 4D.11. Full cladding and insulation is standard in zone 7. There is no insulation in the walls, although 60mm of glass wool is required in lofts in zone 2.

Table 4D.7 Combinations of building type and geographic location for the 56 cases of the baseline that were existing dwellings built before 2000.

City	*Calama*	*Valparaíso*	*Santiago*	*Concepción*	*Temuco*	*Pto. Montt*	*Pta. Arenas*
Latitude	22.5° S	32.5° S	33.4° S	36.5° S	38.7° S	41.5° S	53.0° S
Altitude (m)	2320	9	475	12	114	85	37
Thermal zone	2	2	3	4	5	6	7
Degree hours	40,810	10,442	17,393	18,186	33,789	30,648	76,900
Type 1	x	x	x	x	x		
Type 2	x	x	x	x	x		x
Type 3		x		x	x	x	x
Type 4	x	x	x	x	x	x	
Type 5	x	x	x	x	x	x	x
Type 6		x	x	x	x	x	
Type 7		x	x	x	x	x	x
Type 8	x	x	x	x	x	x	x
Type 9		x	x	x	x		
Type 10		x	x	x	x	x	
Total	5	10	9	10	10	7	5

Source: Ambiente Consultores (2007)

Figure 4D.9 Example of social housing project under construction in La Pintana.

Source: Oficina de Vivienda

Figure 4D.10 Example of social housing in La Florida.

Source: G. Armijo

Figure 4D.11 Examples of house type 3 in thermal zone 7 and types 6 and 8 in thermal zone 2.

Source: JAVE

Baseline energy intensity

Once defining the 'universe' of existing dwellings, it is necessary to estimate their thermal performance. Energy intensity measures the annual amount in $kWh/m^2/yr$ of effective thermal energy to be supplemented in order to ensure a 15°C minimum temperature throughout the winter, not including other gains from occupation, cooking or lighting.

Firstly, for each type of dwelling, a detailed analysis was carried out to calculate the rate of heat loss according to a temperature difference of 1°C as follows:

$$\text{Rate of heat loss} = \text{envelope heat loss} + \text{air change heat loss}$$

$$\text{Rate of heat loss (W/h)} = \sum U_i A_i \times 3600 + A_{CH} V_h \rho_o c_p$$

where:

ρ_o = air density = 1.225kg/m^3, at po = 101325Pa and To = 15°C;
c_p = air heat capacity = 1.006kJ/kg K = 2.79 10–4 kWh/kg K;
V_h (m^3) = heated indoor volume;
A_{CH} (h^{-1}) = air change rate in air changes per hour;
U_i (W/m^2 K) = air to air transmittance (U value) of envelope element i;
A_i (m^2) = exposed area of envelope element i.

Air changes were estimated as 2 (h^{-1}).

Then, for each combination of type and climate, the heating demand was estimated by:

$$\text{Annual heating demand (kWh)} = \text{rate of heat loss} \times \text{annual degree hours}$$

$$\text{Annual heating demand (kWh)} = \left(\sum U_i A_i \times 3600 + A_{CH} V_h \rho_o c_p\right) \times \text{degree hours} \tag{7}$$

The degree hours were obtained from the monthly average data. A rather low reference temperature of 15°C was measured, considering that neither solar nor internal gains were taken into account. Values range from 10,000 to 77,000 heating degree hours. Solar gains could represent a significant gain in some locations, even in winter; but these calculations were not considered since orientation of type buildings is not a defined variable.

The resulting average energy intensity for the existing stock is 208kWh/m^2/yr, spread in a wide range from 60 to 600kWh/m^2/yr.

Potential scenarios of refurbishment

The best possible allocation of financial resources requires defining the number, type and place of dwellings to be refurbished, as well as the amount of investment in each one. Even assuming that any improvement of the thermal performance would be profitable in the long term, it is essential to make clear the priorities in assigning the right type of intervention and the right degree of improvement. The optimization process should consider the dwelling baseline, local climate, local fuel type and fuel price, as well as environmental, social or other factors, in order to allow fair comparisons between the simulated scenarios.

The first step was to define four scenarios for gradual steps of intervention:

- Scenario 1, or the baseline, involves only the maintenance of the existing stock with no improvement of energy performance.
- Scenario 2 involves reaching the energy standard according to mandatory regulation for new housing, including loft and wall insulation.
- Scenario 3 involves the same goals as scenario 2, but with extra wall insulation to match loft insulation.
- Scenario 4 involves the same goals as scenario 3, but with higher-quality windows of U value $2.4W/m^2K$.

For all interventions, the air change rate was assumed to be reduced to 1 air change per hour (ACH); as a result, no mechanical ventilation is required to satisfy indoor air quality standards. Scenarios with higher airtightness would be desirable, but were beyond the scope of this simulation.

The baseline simulation model was then modified for each scenario, replacing the calculation parameters in order to assess the changes in energy performance. Each refurbishment scenario is then assessed by the energy intensity per square metre for any particular combination of dwelling type and climate. Results are expressed as a frequency distribution of dwellings according to its energy intensity value. Figure 4D.12 show the light grey) curve for the baseline (no intervention) and for scenarios 2, 3 and 4, which represent growing degrees of intervention. The majority of the current stock of dwellings exhibit intensities above $100kWh/m^2/yr$, even some above $500kWh/m^2/yr$. For scenario 4, almost all intensities fall below $120kWh/m^2/yr$.

Average intensities for intervention scenarios 2, 3 and 4 would be 96, 75 and $66kWh/m^2/yr$, respectively, implying savings from 54 up to 68 per cent relative to current intensities.

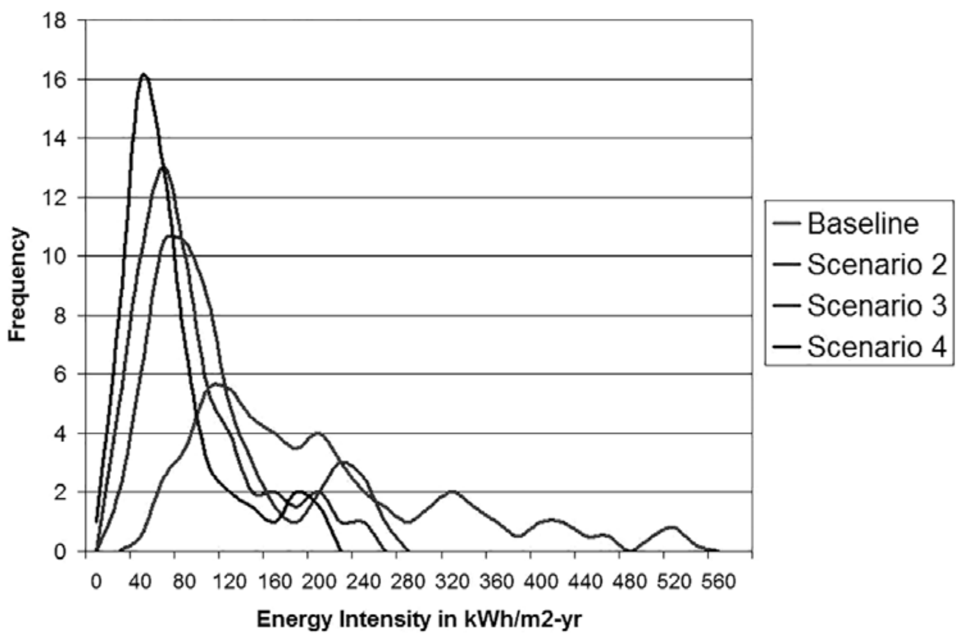

Figure 4D.12 Histogram distribution of energy intensity for different scenarios versus the baseline.

Costs per refurbished dwelling

An inventory analysis was carried out in order to quantify materials usage and labour for each one of the 280 possible interventions. From a market analysis of the existing options to comply with transmittance values, the less expensive options were selected. Unit cost calculations included locally adjusted transportation and installation labour costs.

Interventions to reach scenario 2 (compliance with new construction regulation) would cost up to 52 euros per square metre. In some cases, the only cost would be sealing air infiltrations.

Interventions under scenarios 3 and 4 would cost between 27 euros to 90 euros per square metre (floor area of the dwelling). Compared to new building costs of around 250 euros per square metre, refurbishment costs represent 11 to 36 per cent of the cost of new construction of social housing.

As expected, energy intensity reductions for the more substantial interventions are less significant in relation to additional cost. Considering all cases, the reduction in energy intensity could be up to 400kWh/m^2/yr with an investment of 61 euros per square metre. However, for some cases, a reduction of 230kWh/m^2/yr could be achieved with an investment of only 10 euros per square metre.

The total costs of refurbishment per dwelling range from 1000 euros to 4800 euros, including all types described in Table 4D.6, all locations described in Table 4D.7 and all scenarios of intervention.

Cost-benefit analysis

Having simulated the reduction of energy intensities after refurbishment, the monetary return of such improvement during a lifetime could be estimated. The method applied by Ambiente Consultores (2007)

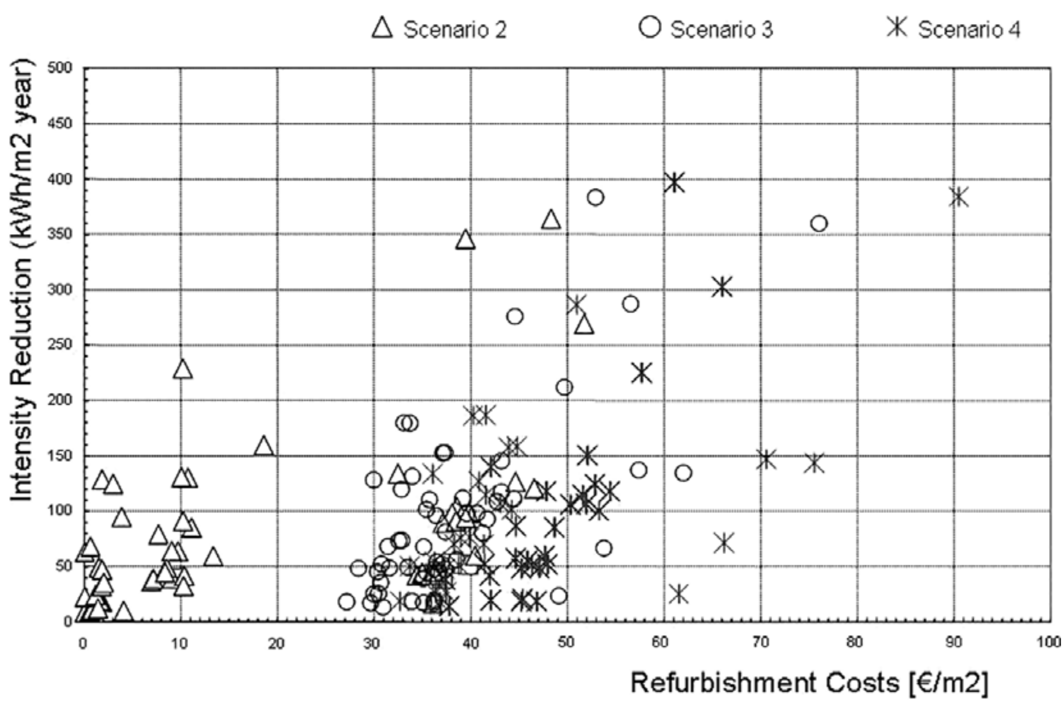

Figure 4D.13 Energy intensity reduction versus refurbishment costs for all cases.

is aimed at estimating the net present value (NPV) of all future costs and benefits for each single refurbishment alternative. For the costs calculation, the following input data were considered:

- initial investment in materials, transportation and installation of all refurbishment elements;
- energy consumption costs at current prices, considering that for each location a different mix of fuels is used, from which the equivalent cost of 1kWh was estimated;
- maintenance costs, estimating cost of labour and parts, including repairs from moisture damage; and
- initial value, useful lifetime and residual value (the evaluation was made assuming a 20-year horizon).

The following assumptions were also considered:

- *Escalation rate of future prices of oil-derivative fuels*. Two rates were considered: a conservative one at 4 per cent increase per year, equivalent to the average from 1995 to 2005, and a realistic one, estimated at a 10 per cent yearly increase.

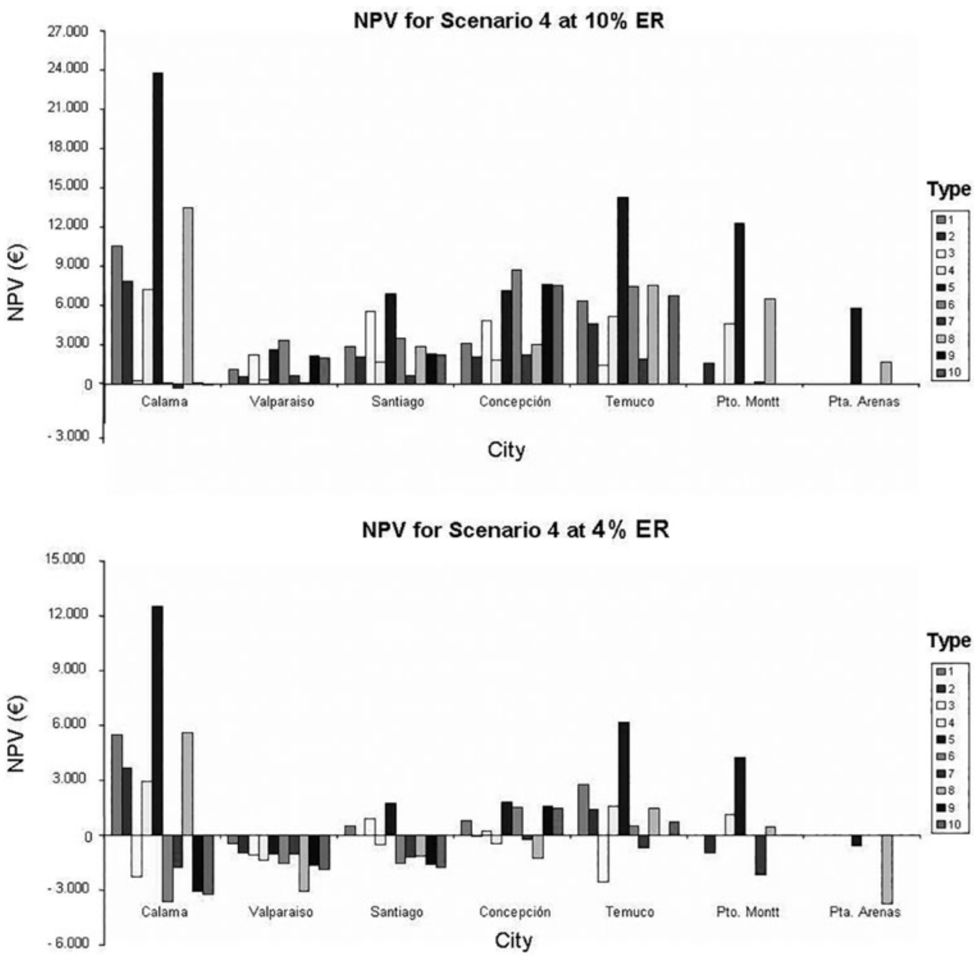

Figure 4D.14 Net present value after ten years of maximum refurbishment (scenario 4) for all types and cities at oil price escalation rates of 10 per cent (top) and 4 per cent (bottom).

- *Discount rate*. Two options were considered: a social rate at 8 per cent for public investments and a private rate at 12 per cent for the private sector.

For estimating benefits, the following factors were considered:

- *Avoided costs in health services*. Only the costs for the health system related to a reduction in environmental pollution (and not including patient valuation or labour time loss) were included.
- *Avoided costs in fuel*. These costs were obtained from the energy intensity differences with the baseline and the estimated fuel prices.
- *Reduction in maintenance frequency*.
- *Increase in residual value*. A growing residual value was assigned to progressive intervention scenarios.

Results were that for the highest degree of intervention (scenario 4), all cases but one showed positive NPV at an oil price ER of 10 per cent per year, evaluated at ten years. At the same scenario 4, but with an ER of 4 per cent, only 24 cases showed positive NPV, pointing to those types and cities where refurbishment is still profitable in less than ten years. NPVs are very sensitive to price escalation rate. Differences between building types are significant. Regional differences are mainly due to climate, with some exceptional results:

- Punta Arenas has the coldest climate, but an inexpensive natural gas supply; and
- Calama has cold nights every day of the year, but daily maximum temperatures above 20°C, which would allow for passive energy savings by means of thermal mass (not included in this simulation).

For scenario 3, results were similar to those of scenario 4.

For scenario 2, in all cases, NPVs at ten years were positive for both high and low ER. This result confirms that a goal at least equivalent to the thermal regulation is justified under any future price condition.

Higher goals such as those of scenarios 3 and 4 are fully justified in certain places and with certain types.

Other expected benefits

A number of expected benefits were also identified, both social and private.

Expected social impacts include:

- *Energy security*. Less dependence upon imported fossil fuels would partially alleviate the impact of price increase. Lower demand would allow a shift toward local renewable sources based on biomass without exhausting natural resources.
- *Higher efficiency*. Lower burdens on budget would release financial resources after payback of investment is completed. Private savings could be redirected toward other investment sectors, improving capital mobility.
- *Higher comfort levels*. Higher and more uniform temperatures would be achieved. There would be less discomfort from cold walls, draughts and excess humidity.
- *Improved air quality*. Less fuel combustion in heating appliances would reduce emissions and lower concentrations of air pollutants, both indoors and outdoors, particularly in urban neighbourhoods.
- *Avoided health costs*. Reduction in diseases related to cold, mould and air pollution would mitigate loads on health services, particularly those for children, old people, people with chronic respiratory diseases and other sensitive population groups.

- *Lower carbon emissions*. Lowering the demand for heating would necessarily reduce the aggregated greenhouse gas emissions from fuels or electricity.
- *Employment*. Qualified staff would be required for proper installation of windows, wall cladding or loft insulation. Suppliers of parts and materials would also increase local employment requests.
- *Research, development and innovation*. Technology transfer, new solutions and optimization tools would increase research and development (R&D) activity. Experimental research and certification results would provide valuable information on successful solutions.
- *Native forest conservation*. Unlawful extraction of wood from native forests would be reduced because of the lower demand for heating.
- *Improved visibility*. Reduced atmospheric turbidity would improve visibility and mitigate the negative effects on safety.
- *Resilience against natural disasters*. Self-sustainment, local energy supply and less vulnerability to extreme weather, would mitigate the effect of hazards, particularly in a country with high seismic recurrence.

Expected private impacts include:

- *Energy savings*. Reduction in fuel and electricity expenses would directly benefit household budget. The cost of fuel storage and seasonal stock financing would also be reduced.
- *Lower depreciation*. The commercial value of properties would rise due to better performance, particularly if an energy performance certificate is provided. The market value of such certificates could immediately compensate for refurbishment costs.
- *Investment security*. The life cycle is extended. Capital assets are less vulnerable to future energy price fluctuations or energy shortage. The risk of vacancy due to high running costs is reduced.
- *Maintenance savings*. Maintenance frequency would be reduced, particularly on paints and wooden parts. Damage from condensation and freezing would also be diminished. Extended life would result in less frequent replacement of parts.
- *Comfort improvement*. More uniform temperatures throughout the house or flat, particularly for direct heating appliances, results in a larger useful area. Better windows would reduce cold spots and draughts. Higher temperatures of inner surfaces would improve the balance between radiant temperature and air temperature.
- *Health*. Better control of temperature and moisture would reduce the impacts on health due to damp walls, insufficient heating or cold waves.

Box 4D.8 Energy and sustainability

Chile has an immeasurable opportunity for progress towards a more sustainable energy policy. Even if more than 30 years have been lost in this subject because of inaction and ideological biasing, we are prepared to take advantage of the international experience, avoiding the mistakes made in the past and taking in the successful achievements in institutional and technical issues, as well as regulatory and promotion mechanisms.

The essential bases of energetic sustainability are:

- safe and timely supply, with reasonable quality and cost;
- energy and equality in terms of access to energy use, including local and economic issues;
- energy and environmental sustainability (most large energy projects have cast doubt about their environmental impacts not being fairly assessed or mitigated);

- energetic dependence (this topic has long been mentioned, but only recently has awareness been raised in Chile after gas shortages began in 2004); and
- energy, community involvement and democracy (strengthening democracy is no doubt a foundation of sustainable development and this means creating channels for active citizenship to discuss issues such as the setting and technology of energy projects or property concentration in the energy sector).

Source: Adapted from Maldonado (2006)

Potential programmes

Proposed refurbishment programme

A progressive investment programme is structured by three objectives:

1 investment in substandard housing and low-income households located in polluted urban areas, maximizing social benefits;
2 investment in medium-income households, promoting massive refurbishment and maximizing both social and private benefits; and
3 investment in promoting private investment and breaking market failures, maximizing private benefits and reducing the country's energy dependence.

Financing schemes

A programme for refurbishment of 20 per cent of dwellings built before 2000, to be implemented in 18 years, was proposed. This involves an average of 50,000 refurbishments per year, and a total public investment of about 1000 million euros. Private investment would follow according to oil price evolution; but it is expected to be at least a similar amount. Some barriers limiting the feasibility of this programme are the lack of human resources to implement it and the uncertainty about the remaining lifetime of buildings.

The proposed programme includes three basic financing schemes. The first one, oriented toward low-income residents, is a full subsidy for refurbishment of up to 1400 euros, provided the household is already registered as belonging to one of the two lower-income quintiles, the dwelling is located in a polluted area and the dwelling qualifies as 'unacceptable but recoverable'. This is a very favourable alternative to cash compensations for fuel price increase and also an alternative to extending health services.

The second proposed scheme is a matching grant for households that refurbish their dwelling to achieve the thermal standard of a new construction. The matching grant would benefit individual households or communities with non-returnable help of up to 1400 euros per unit, not exceeding 50 per cent of total refurbishment cost.

The third proposed scheme would benefit larger energy consumers and only provides a mechanism for access to low-interest loans. The mechanism could be based on the existing mortgage loans which security exceeds the capital debt, that is, with a homeowner's equity enough to allow an additional loan to finance the refurbishment. This could result in an increase in payments, which is typically less than the savings in energy expenses. The advantage of this scheme is that due to the low interest of mortgage loans, there would be no extra cash flow compared to previous loans if the remaining loan period is long enough. In case the debtor has not enough income to afford the increase in payments, the number of payments could be extended.

This scheme could break the barrier of initial investment without affecting the household budget. In addition, it is likely that the property would increase its commercial value, particularly if it achieves some certification, with benefit for both the owner and the lender.

Box 4D.9 Energy efficiency – 'low-hanging fruit'

Energy efficiency (EE) is about minimizing the input of energy resources per unit produced and, at the same time, optimizing consumer utility. Improvements in energy efficiency can be made at various stages of a product or service's life cycle. Typically, improvements in EE are made in building construction, lighting, cooling, heating and insulation. Various studies have found that, empirically, it is cheaper to improve energy efficiency than to use more energy, and that relatively small adjustments can greatly improve overall efficiency. For example, a small adjustment, such as replacing an ordinary incandescent bulb with an energy-saving compact fluorescent light bulb (CFL), provides the same amount of light while using 80 per cent less energy and, therefore, emitting 80 per cent less carbon dioxide. For this reason, the policy community has often called implementing EE measures as picking the 'low-hanging fruit' of reducing energy use and mitigating environmental pollution.

In early 2005, the Chilean government established the Programa País Eficiencia Energética (PPEE), a nationwide energy efficiency programme involving experts from the private and public sector. In 2007, the PPEE announced its ambitious aims of bringing about a 1.5 per cent reduction in annual energy consumption. In other words, if Chilean energy demand is projected to increase an average of 6.5 per cent per year until 2020, as it is, the PPEE works on measures to ensure that annual growth in consumption does not grow beyond 5 per cent.

Source: Speiser (2008)

A pilot programme

A more detailed analysis is focused on two districts of the Araucanía region: Temuco and Padre Las Casas, an example of the critical role of past housing design on users' welfare and long-term sustainability. The Araucanía region has 930,000 inhabitants, of which 350,000 are in the main conurbation that includes the districts of Temuco and Padre Las Casas, with about 90,000 dwellings. Fast urbanization has meant more dependence upon energy supply and, thus, a higher number of pollution sources that eventually exceeded the natural capacity of atmospheric ventilation.

These two districts were declared 'environmentally saturated' in 2005 due to particulate matter (PM) concentrations exceeding 150μg/m^3. About 87 per cent of PM pollution comes from residential wood burners for heating and cooking (PDA, 2007) (see Table 4D.8).

A mitigation plan is under implementation and expects to reduce 31 per cent of current concentrations levels by 2018. It includes improvements in fuel quality, combustion appliance quality and housing envelope quality. The total investment would be 18.7 million euros and total benefits would amount to 55.3 million euros (PDA, 2007).

A pilot project aimed at social housing was implemented. At least 1000 dwellings were refurbished during 2008, with up to 1400 euros in subsidy, financed by the Housing and Urban Planning Ministry. Basic insulation treatments aimed at achieving compliance with the thermal regulations for new construction are being considered.

Table 4D.8 Probability of use appliances by income group.

Appliance	*Low income*	*Medium income*	*High income*
Cooker	0.59	0.28	0.08
Foundry stove	0.10	0.04	0.03
Single-stage stove	0.11	0.39	0.30
Two-stage stove	0.00	0.08	0.09
Fireplace	0.00	0.04	0.07

Source: CENMA (2007)

The effect of adding insulation to 1000 dwellings will be a reduction of 19 tonnes per year of particulate matter emitted by firewood heaters. The impact of such a measure may seem a small improvement of only 1.1 per cent of dwellings avoiding 0.5 per cent of emissions, adding up to 3737 tonnes per year of PM from all sources. However, since the programme has proven profitable in economic terms, it should be replicated as long as there are inefficient households willing to undertake it and capital resources are available. All estimations for pilot programmes have been made under extremely conservative assumptions.

The annual benefits per dwelling are estimated at 119 euros in terms of avoided costs in health services (i.e. 142 euros in terms of fuel and 16 euros in terms of maintenance).

The cost of refurbishment will be 1332 euros per dwelling (CENMA, 2007). At a discount rate of 8 per cent, the NPV of the avoided costs would amount to 1859 euros for the first ten years and 2720 euros for the first 20 years (authors' own calculation assuming fixed price for firewood). These last values would be the amount spent if nothing is done. In addition, enhanced quality of living would be a free benefit for households, as well as all other social benefits for the community.

Other subsidy programmes

Other potential subsidy programmes include the following:

- Subsidizing households that are currently using LPG for heating in order to compensate for price increases relative to 2007 prices, assuming an annual escalation rate of 4 per cent. No private or environmental impact is expected.
- Refurbishing households that are currently using LPG for heating. In this case there is a benefit for the household in terms of lower fuel consumption and higher levels of comfort. Assuming zero emissions from gas heaters, there is no environmental impact. In case the current heater has no flue, a flue type should be installed to compensate for less air infiltration in order to keep a healthy air quality.
- Refurbishing households that are currently using firewood for heating and adapting to LPG. In this case there is a public benefit for eliminating a pollution source. A negative impact on the household is expected in terms of fuel budget and a positive impact in terms of higher levels of comfort.
- Refurbishing households that are currently using firewood for heating. Here there is a benefit for the household in terms of less fuel consumption and higher levels of comfort. In addition, there should be a positive impact on PM emissions because of less fuel burned.
- Appliance exchange in households that are currently using firewood for heating. In this case there is a benefit for the household in terms of lower fuel consumption and a public benefit for fewer emissions. An improvement of 50 to 75 per cent in thermal efficiency is expected, as well as emission reductions of 70 per cent.

Table 4D.9 Summary of costs and benefits of different subsidy programmes per household (own estimate).

	Current LPG user		*Current firewood user*		
	Subsidy to LPG users	*Housing refurbishment only*	*Housing refurbishment shift to LPG*	*Housing refurbishment only*	*Appliance exchange only*
Cost of fuel price rise compensation (10 years)	−€1121	0	0	0	0
Cost of refurbishment (20-year lifetime)	0	−€1332	−€1332	−€1332	0
Cost of appliance exchange (10-year lifetime)	0	0	−€150	0	−€578
Annual savings in health services (public)	0	0	€170	€119	€131
Annual savings in fuel (private)	0	€855	−€150	€142	€27
Annual maintenance savings (private)	0	0	€32	€16	€16
NPV of public costs and benefits in 10 years	−€1121	−€1332	−€341	−€534	€301
NPV of private costs and benefits in 10 years	0	€5629	−€991	€1061	€288
NPV of all future benefits in the first 10 years	0	€5629	€349	€1859	€1167
NPV of costs and benefits after 10 years	−€1121	€4297	−€1133	€527	€589
NPV of costs and benefits over the next 10 years	−€4248	€2607	€1471	€861	€550
NPV of the costs and benefits after 20 years	−€5369	€6904	€2604	€1388	€1139

Note: € = Euros.

Table 4D.9 shows, in monetary terms, the impacts expected from different subsidy programmes for firewood users and LPG users, as well as firewood appliance exchange, all simulated for the current Temuco scenario under conservative assumptions.

It can be concluded from the values in Table 4D.9 that:

- The highest public return would be for a refurbishment and shift to LPG, but with a high private cost.
- The highest private return would be refurbishing a gas-user household, but with no public (environmental) benefits.
- Both refurbishment only and exchange only options would produce positive benefits in less than ten years.
- The worst option would be subsidizing the increase in fuel price (calculated at 4 per cent price escalation rate).

Conclusions

This analysis of housing energy performance in Chile has revealed how poorly designed dwellings can negatively feed the poverty cycle and how vulnerable to energy dependence such dwellings are. It has also demonstrated that there is no economical reason for not correcting the current deficiencies, thus avoiding future aggravation of energy supply or pricing. Responsible design, careful planning, interdisciplinary knowledge and accurate information are the tools needed to reach energy independence.

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