Mohammad Dastbaz · Chris Gorse
Editors

Sustainable Ecological Engineering Design

Selected Proceedings from the International Conference of Sustainable Ecological Engineering Design for Society (SEEDS)

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Preface

The issue of sustainable development, using our planet's resources, and the current approach and policies we have adopted over the past decades have far-reaching impact not only on the current generation but also on many future generations to come. The debate about a measured and well-planned set of global policies in developing our societies is no longer just at the heart of the forums of interested academic institutions and researchers but at the forefront of decision and policy maker's agenda across the globe.

While it is ironic that we still have those voices around that deny our history of deliberate and destructive impact on our environment over the past centuries, it is also refreshing that the weight of public opinion has forced significant changes in government behaviours across the world. Three weeks after we held the SEED conference here in Leeds, more than 150 world leaders attended the "UN Sustainable Development Summit" during 25–27 September 2015 at UN headquarters in New York to discuss the challenges faced by our planet, the fast disappearing natural resources, the unchecked and unplanned urbanisations and also to formally adopt an ambitious new sustainable development agenda for 2030. Calling it: "Transforming our world: the 2030 Agenda for Sustainable Development", the UN general assembly meeting clearly stated that the "*agenda is a plan of action for people, planet and prosperity. It also seeks to strengthen universal peace in larger freedom. We recognize that eradicating poverty in all its forms and dimensions, including extreme poverty, is the greatest global challenge and an indispensable requirement for sustainable development.*"

It is generally accepted that the built environment has a greater impact on natural resources and produces more waste than any other industry. However, beyond the green rhetoric, research is being applied on the ground to address the balance between the built and natural environment.

Industrious endeavours mean that the capability to harness and shape resources for our needs has never been so great, but with this comes the capability to exert considerable change to the surroundings we inhabit and, importantly an increasing responsibility to ensure the ecosystem that supports us is sustained. As we increase in our requirements and impact on the planet extra care is required to ensure that the demands of today don't have a negative impact on the generations of tomorrow, and especially the aspect of the ecosystem that humans have come to enjoy. Through research and innovation, progress is balanced against the need to sustain the planet and key fundamental resources.

There is a growing concern with regard to how we balance the formed built environment against the natural environment, so that order in the ecosystem is sustained.

The SEEDS Conference

The aim of the International SEEDS Conference is to foster ideas, through research and proven practice, on how to reduce negative impacts on the environment while providing for the health of society. The professions and fields of research required to ensure buildings meet user demands and provide many diverse healthy enclosures are considered, endevouring towards a better understanding of the whole system. The SEEDS conference addresses the interdependence of people, the built and natural environments, and recognises the interdisciplinary and international themes required to assemble the knowledge required for positive change.

The conference brought together experts from all around the world to focus on the impact of the built environment, the changes that are taking place in the industry, and the benefits and consequences of change that are being predicted and measured. The focus of discussion and debate was on understanding how buildings and spaces are designed and nurtured to obtain the optimal outcome. Along with addressing technical issues, measuring energy efficiency and modelling energy performance, emphasis was placed on the health and well-being of the users of spaces occupied. This holistic approach has drawn together the research themes of energy, building performance and physics while placing health, well-being and ecology as the heart of the conference.

The SEEDS international conference brought together its members and partners to present work addressing some of the key topics. The conference had a necessarily wide agenda, considering all aspects of sustainability as they are presented and also had a considerable focus on the built environment. Selected papers are presented in this publication which covers some of the following key areas:

- Building and environment design
- Energy-efficient modelling, simulation and BIM
- Integrating urban and natural environment
- Building performance, analysis and evaluation
- Thermal comfort, air quality and overheating
- Green spaces, enclosures and buildings
- Green technologies and IT
- Renewable energy

- Energy flexible buildings
- Energy behaviour and lifestyle
- Dampness, water damage and flooding
- Building surveys, thermography, building pathology
- Water quality
- Air quality
- Planning and sculpturing positive change
- Reducing consumption and waste
- Sustainability, ethics and responsibility
- Occupant behavioural change
- Community building and master planning
- Health benefits of alternative and natural materials
- Urban heat island and mitigation
- Building resilience
- Sustainable cities
- Zero energy and energy plus buildings
- Local producers and urban environments, edible
- Trees and green city landscape
- Designing edible urban landscapes

Mohammad Dastbaz
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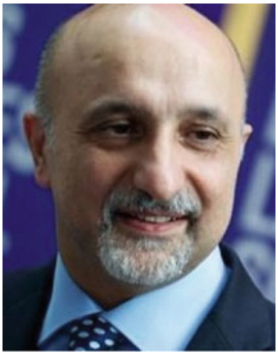

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Part I
Sustainability and the Policy Landscape

Chapter 1
The Meaning of Sustainability

John Sturges

Since the publication of the Brundtland Report (1987), the term 'sustainability' has passed into general usage. However, anyone reading into the subject quickly realises that not everyone who uses the term necessarily means the same thing. If we ask the question; 'What do you mean by sustainability?' we shall get a variety of answers. Since we are considering a collection of company annual and sustainability reports, it will be useful to examine the range of meanings attached to the word sustainability. The Brundtland Report actually uses the term 'sustainable development', which it defines as 'meeting our needs today without damaging the ability of future generations to meet their needs'. Implicit within this definition is the idea that sustainability has environmental, economic and social dimensions as well as inter-generational dimensions. Elkington (1999) has called this the 'triple bottom line' approach. It is argued that sustainability and sustainable development are not the same and cannot be the same. Indeed, there are those who say that the term sustainable development is an oxymoron.

Why is this? Why did Gro Harlem Brundtland use the term 'sustainable development'? The World Commission on Environment and Development was a very large assembly comprising representatives from all walks of life—government, industry, academia and the world of research, etc. Because of this those attending had widely differing agendas and areas of interest and concern. For the report *Our Common Future* to achieve credibility upon publication, everyone had to sign it. The insertion of the word 'development' and the Brundtland definition of it was inspired; it was this that ensured that everyone could sign up to it. Without the word 'development' the people from industry and commerce would probably not have signed

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up to it. The word ‘sustainable’ by itself would have implied limits to resource exploitation, energy use, economic development and so on. Besides, the Brundtland concept is easily grasped and it sounds very reasonable when read for the first time by most people.

There are good reasons for objecting to inclusion of the word ‘development’. Since the publication of the Brundtland report, the population of the Earth has increased by 2.5 billion people, the CO_2 content of the atmosphere has increased by over 50 parts per million, and the ecological footprint has now reached 1.5 Earths. Despite all the talk about sustainability, all the books and conferences and all the legislation enacted, it would appear that we have lived through a time of ‘business as usual’ since 1987. We must therefore ask ourselves—have we correctly understood what is meant by sustainability?

Dresner (2008) and Caradona (2014) have provided good insights into how our ideas about sustainability have first emerged and then developed over that past few centuries. It was concerns about timber supplies and their conservation that sparked the first thoughts on what has become the topic that we now call sustainability. At the end of the eighteenth century, Malthus (1798) first raised concerns about human population levels, and the feeding of more people in future, and gave a further impetus to our thinking about sustainability. During the nineteenth and twentieth centuries two developments ran alongside each other. Firstly, our understanding of how planet Earth works, expanded dramatically, and secondly, we became increasingly aware of the adverse effects our industrial and economic activities were having upon our world. Since the publication of the Brundtland report, sustainability has become an area of major concern and the subject of much research activity; as a result, it has become a much nuanced topic. The concept has also gone through a process of evolution as our understanding of the Earth has developed. This is not the place to discuss or describe this evolution in detail, but rather to explore a way of ranking the efforts that various organisations have made to achieve more sustainable ways of working. Washington (2015) has written a valuable critique of the various strands to our thinking about sustainability.

‘Strong’ and ‘Weak’ Sustainability

Since the publication of the Brundtland Report, the topic of sustainability has been the subject of a great deal of thinking, discussion and research. During the same time our understanding of how planet Earth functions has also deepened, and our thoughts about sustainability have changed in response to this deeper knowledge. Increased understanding of the Earth’s history has also had a bearing. There is now a huge bibliography on the subject, which has most recently been reviewed and discussed by Washington (2015). Such is the range of ideas developed since Brundtland, that some authors have adopted the terms ‘strong’ and ‘weak’ to help classify the different approaches (e.g. Helm 2015). Rather than reviewing the development of ideas on sustainability, it will be very useful to explore what might be defined as ‘strong’ sustainability and ‘weak’ sustainability and perhaps some intermediate positions.

Reference has been made above to our increased understanding of our planet. We have come to realise that our science is an anthropogenic construct, as is our understanding of economics. Over the past two centuries or so, we have come to regard the natural world as a resource to be used and exploited. We have lost our sense of wonder at the beauty of nature, and we have lost our reverence for the natural world. This did not happen overnight, but these attitudes developed as we acquired apparent mastery over the Earth’s resources of materials and energy. Somewhere around the year 1750, we moved from reliance upon renewable to non-renewable materials, and as the Industrial Revolution progressed, we slowly began to perceive the adverse effects that our development were having upon the Earth. This division of assets between renewable and non-renewable is very important, and it is very helpful to regard these assets as ‘natural capital’.

Items of natural capital include obvious things like deposits of oil and natural gas, forests of timber and also other less obvious things like heather moorland, peat bogs, wetlands and rare species of plants and flowers. Oil and gas can be exploited for economic gain, and turned into man-made or human capital. If we lost areas of heather moorland, peat bogs and wetlands we should notice increased flooding in other areas, because these areas control and slow up the rate at which rainfall enters the rivers and watercourses. So while such areas cannot be turned into tangible human capital, they nevertheless provide a valuable service. If they were lost many people would live to regret their loss. These items provide us with clean water supplies and many other valuable services and must be rated as natural capital. So we have two types of natural capital, that which can be exploited and converted into useable materials and sources of energy, and that which provides services such as clean air and water upon which we rely. We have already mentioned above that these two types can be further sub-divided into renewable and non-renewable types.

This natural capital is used by industry to produce the goods and services which we enjoy. Therefore when we attempt to assess how sustainable certain activities are, it is meaningful to rate them in terms of how much of this natural capital is consumed. If we use natural capital to build houses and transport infrastructure like rail and road systems, then we are creating useful man-made capital, which enhances our lives. If we convert iron ore into steel to produce warships and battle tanks in time of war, then we are producing man-made capital of an inferior (non-sustainable) kind. Such items are not life-enhancing; they are destructive and a waste of resources (natural capital). The rating of natural capital usage can range from ‘strong’ to ‘weak’ sustainability. In defining these terms, ‘Strong’ sustainability is at the extreme where we do not consume any natural capital, but conserve everything. This is obviously idealistic and impracticable. ‘Weak’ sustainability is at the other extreme where we assume that we can consume all our natural capital without limit. This is clearly not sustainable in the long term, and is equally impracticable. However, between these two extremes lies a useable scale with which we can rate how sustainable our industrial activities are.

We use a large area of land in total to grow food to feed the world's population. This land is part of our natural capital, and how we use it to feed a growing population presents us with huge problems. The land is irrigated by natural water resources, another part of our natural capital, and it can be used and reused, as long as we do not build permanent structures upon it. The footprint of any building erected upon the land takes that area out of photosynthetic activity, growing crops, etc. We will lose that area of re-useable natural capital. The building or structure that we put up will consume some non-renewable natural capital, but it may be worth doing if that building or structure brings great benefits to the people who live in that vicinity. The longer the building serves the community, the greater the benefit and the more worthwhile the investment. So in considering sustainability, this concept of natural capital is very useful, because it reminds us of exactly what we are doing when we utilise our stock of natural resources. More importantly, if we can assign meaningful values to our stocks of natural capital, we can make much better decisions about the future exploitation of our world's limited resources, and avoid the excesses of conventional bottom line financial accounting. We can do this because we will be putting values and prices on commodities that industrial accountants usually take as being "free".

In considering company and sustainability reports, one of the problems is that of 'greenwashing'. This is the use and misuse of the language of sustainability or imagery to disguise conventional, destructive practices. It includes the use of 'green' language to sell products that are not green to environmentally concerned people, for example. In their company reports, organisations are keen to place themselves in the best light by claiming to be greener than they really are. In the extreme, this behaviour can lead to campaigns of misinformation, as described by Monbiot (2007). Company reports should always be read in the knowledge that they may contain an element of greenwash.

To give some examples from the company reports reviewed, in the mining sector, Anglo Americans describe how they survey potential sites for mining operations. Historically, the mining sector has not had a good record from the environmental point of view. There are too many examples around the world of abandoned mine workings left in a dangerous and unsightly state. In contrast, Anglo American (Anon 2013) survey potential sites, accurately itemise the flora and fauna present, and if necessary, preserve samples of plants and vegetation for replanting when mining ceases, and when the site must be remediated and restored to its pristine state. This is a good example of 'strong' sustainability.

In the banking sector, Itaú Unibanco Holding S.A. (Anon 2012a) has an investment analysis and advisory section where investment proposals are examined before decisions on lending are taken. If the proposal is for some environmentally or socially damaging project, then investment is denied. This practice could be rated as strong sustainability within the banking sector.

On the face of it, Daimler AG (Anon 2012b) manufactures personal transportation systems, i.e. automobiles, an activity which might be regarded in some circles as non-sustainable in the long term. As a large automobile manufacturer, they will consume millions of tonnes of materials each year. However, with that caveat, Daimler does take its responsibilities to the environment very seriously. They have analysed the impact that their vehicles have in the manufacturing stage, during their service lives and finally, at end-of-life. Their policy is to use as much recycled material in the manufacture of their vehicles as possible. In use, the vehicles are designed to be as light as possible to minimise fuel consumption and to minimise emissions of CO_2 and particulates. Servicing requirements in terms of energy and materials are minimised, and when they reach the end of their service lives, they are designed to be at least 85 % recyclable. All these steps will reduce their environmental impact.

Manufacturers of mobile phones will use much less material, as these devices are very small and compact. Furthermore, these devices can enable better communication between users and in many cases obviate the need for some travel, for paper communications, etc. Notwithstanding the fact that such devices require relatively small quantities of materials, the fact that China Mobile Limited (Anon 2012c) report a saving of 18,000 tonnes of production materials usage in their 2011 Sustainability report is impressive, and could be regarded as an example of strong sustainability within this sector. They also report a cumulative avoidance of 6000 tonnes of plastic waste due to operating improvements. Since plastic waste is a major problem world-wide at the present time, this is a welcome development.

All of these large organisations make substantial contributions to the improvement of the lives of their employees, and the communities living near their operating facilities and factories. They contribute in various ways to health, education and housing, and in some cases to improving the local infrastructure by providing roads which are shared with the local communities. Some have helped fund the building of schools and clinics for the families of their employees. They all provide good employment opportunities and in these ways they all contribute to social, economic and environmental sustainability.

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Chapter 2
The Patchwork Politics of Sustainable Communities

Quintin Bradley

Abstract The aim of this paper is to review government strategies for sustainable communities in England and particularly the programme of neighbourhood planning introduced from 2011 in which responsibility for achieving sustainable development was devolved to local communities. It explores the definition of sustainability that emerged from these neighbourhood plans, one in which the priorities of environmental quality and the welfare needs of social reproduction were constrained through a choice of economic growth or self-reliance. The paper reports on research with urban and rural communities seeking sustainability through neighbourhood planning and it reveals the starkly unequal geography of sustainable development that is emerging. The paper concludes that hopes of sustainability in England are now heavily dependent on the geographical whims of the property market.

Keywords Sustainable communities · Neighbourhood planning · Inequality

Introduction

The pairing of community and sustainable development has dominated the international policy agenda for at least three decades with its assertion that the imperatives of capital accumulation can be balanced for the needs of social reproduction (Raco 2005). As a framework of state strategy, the concept of sustainable communities has come to define a particular mode of governance in which responsibility for ameliorating the impact of unfettered growth is devolved to place-based voluntary and community associations (Mayer 2000). The community provides a model of sustainability in which the economics of collective consumption and the politics of community action can be engaged in the planning and stewardship of local

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development. The strategies of sustainable communities that result combine the market zeal of spatial liberalism with themes of redistributive justice and equality, finding in the concept of community both a model of resilience and enterprise and conversely a dynamic of mutual aid and cooperation (Clarke and Cochrane 2013).

The aim of this paper is to identify these competing strands in government strategies for sustainable communities in England and particularly the programme of neighbourhood planning introduced from 2011. It is argued that neighbourhood planning relegated responsibility for achieving environmental and social sustainability to the domestic networks of the community and largely absolved the state and the market of their obligations. The paper explores the definition of sustainability that emerged from communities and their neighbourhood plans, one in which the priorities of environmental quality and the welfare needs of social reproduction were pursued through a Hobson's choice of economic growth or self-reliance. In this unequal geography of community initiatives, the paper charts the development of a new patchwork politics of sustainability.

Sustainable Communities and Neighbourhood Planning

The sustainable community has a noble pedigree in place-based projects of visionary design and the fusion of nature and nurture. Its antecedents are rooted in a renunciation of capitalism, in the collectivist communities of Charles Fourier, in Peter Kropotkin's (1912) celebration of mutual aid, and in William Morris' (1890) anarchist naturalism. In these radical visions of sustainable communities, economic life was to be localised and organically fused with the rhythms of social reproduction and an idealised natural world (Harvey 2000). State development strategies continue to present the neighbourhood and community as an organic entity in which a discrete sustainability can be achieved in apparent isolation from global connections. No return to nature is imagined, however, and sustainability is to be achieved without the renunciation of capitalism. The sustainable community is conceived as a coherent collective amid a global market (Rose 1999), and cast as an economic actor in charge of its own destiny and responsible for its own well-being (Hall and Massey 2010). This rendition of the sustainable community can be examined through a study of neighbourhood planning in England introduced under the Coalition government from 2011–2015.

The Localism Act 2011 handed responsibility to communities for the regulation of private market development through neighbourhood planning (Brownhill and Downing 2013). Neighbourhoods were invited to draw up sustainable development plans within growth targets set by the strategic authorities. Neighbourhood planning powers could not limit the amount of growth but could influence its location and design by establishing the local policies that development would be judged against. Subject to a light touch examination, and ratified by popular referendum, a neighbourhood plan could become a statutory development document, nested within and conforming to the strategic plan of the local authority and national planning policy. Despite its many limitations, neighbourhood planning appeared to offer local communities new political opportunities to develop a sustainable strategy of place. In areas across the country, therefore, communities saw in neighbourhood planning the potential to harness the practices of spatial liberalism to the requirements of social reproduction (Clarke and Cochrane 2013).

Table 2.1 Research sample of neighbourhood plans

Neighbourhood plan	City/Region	Parish/Town Council/Forum
Aberford	Leeds	Parish
Aireborough	Leeds	Forum
Allendale	Northumberland	Parish
Anfield	Liverpool	Forum
Balsall heath	Birmingham	Forum
Growing Together (Blackthorn and Goldings)	Northampton	Forum
Boston spa	Leeds	Parish
Caister	Lincolnshire	Town
Chatsworth Road	London Borough of Hackney	Forum
Clayton-le-Moors and Altham	Accrington, Lancashire	Forum
Coton Park	Rugby	Forum
Cringleford	Norfolk	Parish
Cuckfield	Mid Sussex	Parish
Dawlish	Devon	Parish
Daws Hill	Wycombe	Forum
Exeter St. James	Exeter	Forum
Heathfield Park	Wolverhampton	Forum
Highgate	London Borough of Highgate	Forum
Holbeck	Leeds	Forum
Hoylake	The Wirral	Town
Fishwick and St. Matthews	Preston	Forum
Lockleaze	Bristol	Forum
Marton West	Middlesborough	Forum
Northenden	Manchester	Forum
Slaugham	Mid Sussex	Parish
Thame	South Oxfordshire	Town
Thorner	Leeds	Parish
Upper Eden	Cumbria	Parish
Winsford	Cheshire	Town
Woburn sands	Milton Keynes	Town

The first neighbourhoods to produce their own plans were able to mitigate the impact of large new housing developments by parcelling it up into acceptable smaller sites (Thame 2012), and change planning policy to enable more affordable housing to be built in rural areas (Upper Eden 2012). By the beginning of 2015, over 1300 neighbourhood plans were under production and the paper now turns to primary research to explore the definitions of sustainability that emerged from some of these communities. This research was conducted with 30 rural and urban neighbourhood plans (see Table 2.1). It involved a preliminary review of online resources for each neighbourhood, including constitutions, applications for designation, council decision papers, minutes of meetings, consultation strategies, draft and final plans, followed by interviews with the chairs and secretaries of neighbourhood planning committees or forums, observation at meetings, and separate interviews with the relevant officers from the planning authority. Participants gave their informed consent to the identification of their localities on the understanding that they could be identified from their role descriptors. The national sample represents only a minority of neighbourhood plans and the findings from this research are not presented as representative, however, they contribute to an understanding of the new challenges facing sustainable development planning in communities. In the following pages, a discussion of three of these neighbourhood plans is used to illustrate the patchwork landscape of sustainable communities that has appeared.

The Uneven Geography of Sustainable Development

Neighbourhood planning was designed to 'create the conditions for communities to welcome growth' (Clark 2011) and its spatial planning powers are oriented towards private development not public infrastructure. The only source of investment available to town and parish councils, and urban neighbourhoods who produce a neighbourhood plan, is a levy on any private development that takes place. The amount received from this Community Infrastructure Levy is dependent on market demand for land in the area. Market towns and rural parishes that have land sites attractive to the large volume house builders will receive a quarter of the revenues accruing from the Levy while suburban neighbourhoods on the urban fringe may also benefit once they have agreed a neighbourhood plan. Public investment in schools, community facilities and infrastructure will, to a significant extent, be resourced through this Levy and the uneven geography of capitalist growth may increasingly be reflected in inequalities in public spending (Clarke and Cochrane 2013).

In the deprived east end of Preston, the community of Fishwick and St. Matthews thought neighbourhood planning was an opportunity to improve the quality of their inner city environment. The opportunities for changing Inner East Preston were, however, very limited without public investment. Development sites were few, there was little market interest, and the changes the community wanted to see required significant public funding. The Preston council planning officer working with the Fishwick and St. Matthews neighbourhood explained her concerns over the limit of what the plan could achieve:

> I have this worry that it's one thing to write a plan but how do you actually put it into action? It is the delivery which is the difficult part. I mean there's no harm in having a few aspirations, but the area won't be completely transformed. It will still be the same area.

The only source of investment for the neighbourhood plan in Preston comes from charitable donations, and the community have benefited from a Lottery grant, under the Big Local programme, which will enable them to carry out some environmental works. Patronage and donations aside, the expected course of action for communities marginalised by capital growth is to become economic actors and create their own development market. This approach has been adopted in the midlands city of Northampton, where a neighbourhood plan is being led by a voluntary association, under the project name, Growing Together. The lack of any development market and the restrictions on other sources of public investment limits the ambitions that can be planned for in this neighbourhood, as the Growing Together coordinator explained:

> To be honest I don't think there's any possibility of any sort of visionary vision for this area within the economic circumstances. It's a very difficult area to have a sort of bright, clear vision of the shining city in the sky in 20 to 30 years' time.

The solution for this community group is to be constituted as a charitable trading company that can bid to deliver local services for the Borough Council and generate income for the neighbourhood from public contracts. The neighbourhood plan will provide the community with the statutory framework through which this strategy of self-management can be envisaged. Growing Together plan to develop the capacity of residents for enterprise in the hope that sustainability can be achieved by market mechanisms. Their strategy appears to exemplify the self-reliance and resilience expected of communities under neighbourhood planning where sustainable development appears defined wholly in terms of economic self-sufficiency (Davoudi and Madanipour 2015). Without support from the local state, however, a social enterprise is unlikely to flourish in a deprived community (Trigilia 2001). The infrastructure for sustainable communities cannot be provided by neighbourhoods alone (Lowndes and Pratchett 2012).

In the east Pennine neighbourhood of Clayton-le-Moors, a neighbourhood planning forum is taking over public assets and running once-public services through local volunteer labour. The philosophy of this community company is that public services that are run by local volunteers become more truly public. The neighbourhood plan has become a blueprint for the social outcomes identified by the community while asset transfer passes the responsibility for achieving these outcomes to residents themselves. As the plan coordinator said:

> If the community can come up with a plan that addresses all these issues, and sets out what this township is going to be like in the next 10-15 years and that is all done by the community, that'll be great because it shows the community's in the driving seat, steering this and it's not something that's being imposed by the local authority.

This representation of community control disguises the continuing role played by the local authority in the management of this asset transfer strategy. The leadership of the community company remains in the hands of professionals and retired councillors, and the production of the neighbourhood plan depends on guidance and support from officers in the planning authority. Rather than a model of community resilience, the transfer of assets to a community interest company appears to be a council strategy to reduce costs by harnessing the community as unpaid labour. This is rationalised through the argument that volunteer participation in the delivery of public services and the running of public assets makes a community sustainable. Rather than provide a framework for sustainable development, the neighbourhood plan becomes a design for resilience in the face of service withdrawal. Sustainability is the ability to survive without economic growth or redistribution.

Conclusion: The Future of the Sustainable Community

Neighbourhood planning has unfurled a starkly unequal landscape in which a plurality of sustainable communities has appeared. This is a patchwork politics of place, structured by the demands of capital accumulation into winners and losers. Under neighbourhood planning, the task of communities is to attract development while seeking to mitigate its negative effects and render it sustainable. The community is imagined as a market place in which sustainability can be bought and development rights sold. The disputed concept of the sustainable community now inspires a plethora of projects attempting to regulate an unrestrained development market or fill a vacuum in state investment planning. Neighbourhoods may seek to acquire public goods through otherwise undesirable development, utilise their resource of social capital to stimulate enterprise, or rely on unpaid labour to meet their collective needs. The future of sustainability will be etched in these precarious attempts to piece together a new umbrella of environmental and social protection.

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Chapter 3
What has Posterity Ever Done for us? An Ethical Framework for UK Climate Change Policy

John Bradley

Abstract The Stern Review provides the rationale for UK climate change policy. The paper analyses the ethical basis of the Review and evaluates other ethical frameworks that challenge the Review's agent-neutral perspective. A rights-based approach to the interests of future generations is found wanting but an agent-relative approach is shown to provide a valid alternative to the orthodox approach exemplified by Stern. An agent-relative approach to fulfilling our obligations to future generations that recognizes the notion of empathic distance is proposed as a way of balancing the interests of those alive now with the interests of posterity.

Keywords Sustainability · Ethics · Climate change · Stern review

Introduction

'Climate change is a moral problem' (Broome 2014, p. 9). The costs of policies to stabilize concentrations of greenhouse gases (GHGs) to prevent damaging climate change will be borne by the current generation, largely by countries with relatively high GDP per capita. The benefit, as measured by prevention of damage to natural and productive capital, will be felt largely by future generations in countries that currently have relatively low levels of GDP per capita. Policies that aim to combat climate change pose especially difficult ethical questions because of conflicts of interest in both space and time, raising questions of both intra and inter-generational equity.

The issue of inter-generational equity is handled by economists by the use of a discount rate in the cost–benefit analysis of climate change policies. The discount rate reflects society's presumed trade-off between the consumption and welfare of current generations and of future generations. Whilst there is much academic debate as to the appropriate discount rate to use in evaluating climate change policies, it is

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often conducted at a technical level, and rarely involves discussion of the ethical basis of the rate assumed. Moreover, this academic debate remains largely hidden from public and policymakers' view.

The most influential example of this is the Stern Review (Stern 2007), commissioned by the UK Treasury, widely acknowledged to have provided the intellectual justification for UK climate change policy, that resulted in the Climate Change Act of 2008 (c.27, 2008). Indeed, as Lilley (2012, p. 5) points out: 'Ministers still rely almost entirely on the Stern Review of the Economics of Climate Change to justify their policies'. There has been a welter of criticism of the Review, in particular of its choice of discount rate, but this has largely been at a technical level. The Review does not hide its ethical assumptions, but different viewpoints are not evaluated. A careful reading of the debates on the UK Climate Change Bill, in both the Lords and the Commons, shows not a single reference to the ethical basis of the Stern conclusions, on which the Bill was based.

The purpose of this paper then is to evaluate the ethical framework of the Stern Review, and thereby evaluate the ethical basis of UK climate change policy, in which the Review has been so influential. Section 3.2 analyses the method by which ethical considerations are handled in the Review, which we call the Orthodoxy. Section 3.3 offers a critique of the Orthodoxy. Section 3.4 discusses the implications of this critique of the Orthodoxy. Section 3.5 concludes.

The Orthodoxy: The Stern Review

Stern adopts the economist's standard inter-temporal welfare-maximising model for determining the rate of discount to be used in economic analysis of climate change policy, formulated by Ramsey (1928) and subsequently developed by Koopmans (1965), shown in Eq. (3.1):

$$W = \int_{t=0}^{\infty} U(c_t)\mathrm{e}^{-\delta}\mathrm{d}t \tag{3.1}$$

Welfare (W) is a utilitarian Social Welfare Function (SWF). (c_t) is per capita consumption at time t. δ is the time discount rate applied to future generations. Optimizing this SWF gives Eq. (3.2):

$$r(c_t) = \delta + \eta(c_t)[\mathrm{d}(c_t)/\mathrm{d}t]/c_t \tag{3.2}$$

where r is the social rate of time preference (SRTP) and η is the elasticity of marginal utility of consumption. Assuming that η does not vary with the level of consumption and simplifying, gives the famous Ramsey rule, Eq. (3.3):

$$r = \delta + \eta g \tag{3.3}$$

This states that the discount rate (r) to be used to discount inter-temporal consumption is equal to the rate of pure time preference (δ), also known as the utility rate of discount, plus the product of the elasticity of marginal utility of consumption (η) and the rate of growth of per capita consumption (g).

The Review makes the assumption that the welfare of future generations (of people living 100, 200, a thousand years hence), should be given the same weight or importance as the welfare of the current generation. In Eq. (3.3), this means that $\delta = 0$. Stern allowed for the remote possibility of the extinction of mankind by increasing δ to 0.1.

The Review also assumed an elasticity of marginal utility of consumption $\eta = 1$. The parameter η summarizes our preference for equality. It determines how fast marginal utility falls as income rises; the higher the value of η, the higher society's aversion to inequality.

It is likely that future generations will enjoy higher levels of consumption per capita than the current generation. The rate of growth of per capita consumption g, is assumed to be 1.3 % per annum. As $\eta = 1$, future consumption is therefore discounted at 1.3 % per year. This means that the consumption of future generations is valued less than the consumption of the current generation, because future generations are expected to enjoy substantially higher levels of per capita income.

From Eq. (3.3), SRTP (r), which is the rate that ought to be used for discounting public projects, is 1.4 % per year. Applied to the problem of climate change, this means that the benefits to future generations of actions by the current generation to reduce GHG emissions are discounted by 1.4 % per year. The advocacy of what is an extremely low discount rate by the standards of mainstream economic analysis has provoked controversy. The most prominent critic of the Stern approach is Nordhaus (2007) who advocates using a discount rate of 6 % per year.

The Review estimates that if we do not act, the overall costs and risks of climate change will be equivalent to losing at least 5 % of global GDP each year. If a broader range of risks and impacts is included, damage could rise to 20 % of global GDP. The costs of action—reducing GHG emissions to avoid the worst impacts of climate change—can be limited to around 1 % of global GDP each year. The second conclusion is that, using the low discount rate of 1.4 %, the discounted benefits of avoiding damaging climate change are greater than the cost of mitigation, and therefore urgent, substantial action is justified. That urgent action, in the case of the UK, is the Climate Change Act which requires an almost complete decarbonisation of the UK economy by 2050. The justification for this action is crucially dependent on this controversial assumption of a low discount rate. This in turn is dependent on the assumption of zero pure time preference; that the welfare of all future generations has the same importance as the welfare of the current generation.

The conclusions of the Review were regarded, outside the academic community, as a statement of fact, rather than the normative claim that it is. The claim relies on the assumption of a specific ethical framework, namely an impersonal, utilitarian SWF, and on a set of ethical assumptions, namely the relative valuation of the welfare of current generations in relation to posterity (δ), and aversion to inter-generational inequality (η).

This paper is concerned with one of those ethical parameters, δ, which expresses the valuation placed on the welfare, or utility, of the current generation in relation to posterity. In choosing $\delta = 0$, Stern adopts a classical utilitarian position that is indifferent between the welfare of individuals or generations. In this impersonal consequentialist approach, the goodness of any outcome is measured by the total utility resulting from the actions in question, irrespective of who gets the utility. Thus, the recipients of utility are regarded 'simply as vessels into which one puts a certain amount of utility' (Beckerman 2007).

For utilitarians, the principle of forming ethical judgments from the recommendations of what Rawls (1972) calls the Ideally Rational and Impartial Spectator trumps all other considerations. The Rawlsian impartial spectator operates behind a 'veil of ignorance' in assessing the weight to be attached to each generation's welfare. The Review is explicit about this assumption, although it is regarded as axiomatic. Thus: 'It is, of course, possible that people actually do place less value on the welfare of future generations, simply on the grounds that they are more distant in time. But it is hard to see any ethical justification for this' (Stern 2007, p. 31). There is an appeal to a list of distinguished economists who espouse a similar view, notably: Ramsey (1928), Pigou (1932), Koopmans (1965) and Solow (1974): '[Our] argument… and that of many other economists and philosophers who have examined these long-run, ethical issues, is that [a positive time discount rate] is relevant only to account for the exogenous possibility of extinction' (Stern 2007, p. 60). Many philosophers agree with this point of view. For example, Parfit (1984, p. 357) claims that: 'The social discount rate is indefensible. Remoteness in time has no more significance than remoteness in space'.

The ethical framework, the value of the ethical parameters, and the policy prescriptions derived from this, are given the label the 'Orthodoxy', both for ease of exposition and to convey the unanimity with which this view is held by policy-makers in the UK and elsewhere.

Critique of the Orthodoxy

Introduction

The utilitarian, impersonal consequentialist approach, at first blush, does seem an eminently rational and indeed virtuous standpoint: maximization of the common good, respect for the rights of future generations, non-discrimination between people because of when they happen to be born, and so on. Yet it conflicts with many people's moral convictions and there are other ethical standpoints that have support amongst economists and philosophers. This section examines some of the weaknesses of the Orthodoxy and sets out other views.

	Deontological	Teleological	
Philosophical tradition	Kant	JS Mill	
Ethical criterion	Duty/rights	Consequences of actions	
Concerned with	Means	Ends	
Variants		Agent-relative	Agent-neutral
Characterisation	Challenge 1	Challenge 2	The Orthodoxy

Fig. 3.1 A taxonomy of ethical positions

At the risk of a gross oversimplification of hundreds of years of moral philosophical thought, Fig. 3.1 suggests a taxonomy of ethical perspectives pertaining to inter-generational equity.

For the purposes of this paper, the prime organizing concept for the Orthodoxy is taken to be its *agent-neutrality*, its impersonality, which Nagel (1986) calls 'The view from nowhere'. It is central to all consequentialist theories that value is determined impersonally; that the real value of any state of affairs does not depend on the point of view of the agent. The challenges to the Orthodoxy come from *agent-relative* ethical standpoints. Challenge 1 is that deontological constraints restrict what we are permitted to do in the service of impersonal reasons. These constraints stem from the claims of other people not to be maltreated; they are demands arising from our relations with others and are therefore agent-relative. This is a challenge to the formulation of the social welfare function of Eq. (3.1). Challenge 2 is that agent-relative obligations demand the rejection of the requirement to give equal weight to the welfare of generations. Formally, this is a challenge to the specification of the ethical parameter δ in Eq. (3.3). These challenges are now examined in turn.

Challenge 1: Deontology

Stern (2007, p. 29) sets out the limitations of the Review's ethical framework which 'looks first only at the consequences of actions (… 'consequentialism') and then assesses consequences in terms of impacts on 'utility' (… 'welfarism'). It has no room for ethical dimensions concerning the processes by which outcomes are reached. Some different notions of ethics, including those based on concepts of rights, justice and freedoms, do consider process'.

Rawls (1972) interprets this classical utilitarianism as a teleological theory, as it defines the 'good' independently of the 'right', and then defines the right as that which maximizes the good. Deontology, on the other hand, is an approach to ethics that judges the morality of actions by reference to the value of actions themselves, rather than the value of the consequences of actions. In this view, acts are intrinsically right or wrong, regardless of their consequences. Deontological constraints restrict what we are permitted to do in the interests of both impersonal and agent-relative goals. For example, Sen (1982) argues that the utilitarian, welfarist framework is insufficiently robust to deal with questions of inter-generational equity, because it fails to incorporate concepts of liberty, rights and entitlements as ends in themselves. As Beckerman and Pasek (2002, p. 4) tartly remarks: ‘it is quite likely that a cost-benefit analysis in ancient Rome of the spectacle of throwing Christians to the lions in the Colosseum would have come up with a positive result’. Bias, bigotry or discrimination can be justified from a utilitarian perspective as long as they promote greater welfare. The needs/desires of the many can suppress or negate the needs of the few, resulting in the potential for a tyranny of the majority. Thus, from a deontological perspective, in the interests of justice, there must be restrictions on what we do, to protect people’s rights. Moreover, there are obligations to act that arise from basic duties.

The predicted impacts of climate raise questions of rights and corresponding duties. A deontological viewpoint would argue that future generations have *rights* (to a minimum quality of life; a right to environmental amenity, and so on), and the current generation has correlative obligations or duties to future generations; for example, fiduciary duties (acting as trustees for the unborn), or duty of care (avoiding reasonably foreseeable harm).

The subject of inter-generational rights and distributive justice is one of the most tortuous areas in moral philosophy. As Rawls (1972, p. 284) remarked ‘the question of justice between generations… subjects any ethical theory to severe if not impossible tests’. Yet there are many who take it as ‘intuitively obvious’ (Dunn 1999, p. 77) that future generations do have rights.

There are two main problems with the notion that future generations have rights. First, that it is meaningless to grant rights to individuals who do not exist. This is the *non-existence* problem. Second, that since our actions that are allegedly harmful towards the future will also influence who will end up being born or not, future people could not meaningfully be said to be harmed, and even less wronged. If people cannot be harmed, what would rights protect them against? This is the *non-identity* problem.

Taking first the non-existence problem, that future generations cannot have rights to anything, simply because they do not yet exist (Steiner 1983; Beckerman and Pasek 2002; de-Shalit 1995). Properties (such as being tall, being poor, or having rights) can be predicated only on some subjects that exist: ‘Unborn people simply cannot have anything, including rights’ (Beckerman and Pasek 2002, p. 16). Furthermore, because justice requires some type of reciprocity between people, the whole idea of having reciprocal relations with persons who do not yet exist is tendentious (Ball 1985). As Rawls (1972) remarked: ‘We can do something for posterity but posterity can do nothing for us… and so the question of justice does not arise’. A second condition must also be fulfilled if those putative rights are to a specific asset, such as a certain level of environmental amenity; namely, that it must be possible in principle to provide it. Thus, Steiner (1983, p. 159) is led to conclude: ‘it seems mistaken to think of future persons as being already out there, anxiously awaiting either victimization by our self-indulgent prodigality or salvation through present self-denial’.

The second problem is Parfit's (1984) non-identity problem which is relevant when adopting one policy or another will also affect the identity of those who will be born. Parfit compares a 'risky policy' (for example, taking no action to mitigate GHG emissions), with a 'safe policy' (taking action to curb GHG emissions). The risky policy will cause many future people to be killed, at some stage in their life. Parfit argues that if we had chosen the safe policy the people who were killed would never have been born. If these people's lives are worth living, our choices will not be worse for them. 'If what we are doing will not be worse for some other person, we are not, in a morally relevant sense, harming this person' (Parfit 1984, p. 374). The import of this uncomfortable problem is that as decisions today not only determine the welfare but also the identities of future humans, and, if a life is worth living, every person born, whether wealthy or impoverished, should simply be grateful that, by our actions, we have chosen them from the set of potential persons.

These problems are fundamental weaknesses in the deontological critique of the welfarism of the Orthodoxy. The deontological position accordingly is not a sound or useful basis for policy. This conclusion means only that the 'rights' of future generations cannot trump the interests of the current generation. It does not imply that we have no obligations to future generations. In Sect. 3.3 the nature of those obligations is examined.

Challenge 2: Agent-Relative Ethics: Problems with δ

The first challenge to the welfarism of the Orthodoxy was to the formulation of the social welfare function itself. This challenge was found wanting. The second challenge is to the impersonal nature of the welfare evaluation; a challenge to the assumption that the welfare of future generations should count the same as the welfare of the current generation. In other words, a challenge to the rate of pure time preference, $\delta = 0$.

The acceptance of zero pure time preference derives its intellectual justification from eminent economists such as Ramsey and Pigou, who regarded the failure to see that a future unit of satisfaction will be just as good when it arrives as an equal present unit as representing some form of impatience or myopia, or even the conquest of reason by passion. However, as Schelling (1995) pointed out, while the references of Ramsey and Pigou to 'impatience' or 'myopia' might accurately describe time preference for consumption during one's lifetime by oneself; it is absurd to apply these adjectives to the consumption of somebody in 200 years' time that one will never know. So, in the context of individuals' decisions within their own lifetime, this is a valid criticism of pure time preference discounting. However, in the context of inter-generational decision-making, myopia and impatience have no bearing: $\delta = 0$ cannot be justified on this basis.

Nor does the assertion, Dietz et al. (2007), that $\delta > 0$ would represent 'ethical discrimination by date of birth', stand up to scrutiny. The idea of discrimination by birth date is misleading as it confuses a cross sectional with a time series view point.

The population at any time includes those born over a range of birth dates spanning a century or so. Most people regard discrimination by birth date as wrong. Thus, throughout their lives, those born in, say, 2010 will suffer no material discrimination relative to those born in, say, 1970. Pure time preference, δ, with respect to increasingly distant future populations, is a quite different ethical issue.

The justifications for $\delta = 0$ are weak and furthermore there are good reasons for $\delta > 0$. Whilst high rates of discount produce seemingly unreasonably small present values, the converse is true if $\delta = 0$. For example, Harvey (1994) rejects zero utility discounting, on the basis that it is so obviously incompatible with the time preference of most people that its use in public policy would be illegitimate. He states that the notion that events occurring in ten thousand years are as important as those occurring now (which is implicit in the infinite time horizon of the Stern model) simply does not pass 'the laugh test'.

Nordhaus (2008) has estimated that, applying Stern's methodology, half of all benefits of preventing climate change will accrue to generations living after 2800. Nordhaus further considers the following scenario: Suppose that we knew for certain that one consequence of climate change, which would not happen until the year 2200, would reduce the welfare of generations thereafter by 0.001 %. Discounted at 0.1 % pa the present value would be £20 trillion, equivalent to over half the world's annual GDP or 300 times the current world spending on overseas aid. He then asks the question: would it really be worth this generation foregoing that sum to make our remote descendants imperceptibly better off?

A related feature of zero discounting is that it puts present decisions on a 'hair-trigger' (Nordhaus 2007, p. 696) in response to far-future possibilities. Under conventional discounting, contingencies many centuries ahead have a tiny weight in today's decisions. With the Review's discounting procedure, by contrast, present decisions become extremely sensitive to uncertain events in the distant future.

A further consequence of the Review's near-zero time discount rate is that it also demands excessively high savings rates. Arrow (1999, p. 16) concludes: 'the strong ethical requirement that all generations be treated alike, itself reasonable, contradicts a very strong intuition that it is not morally acceptable to demand excessively high savings rates of any one generation'.

No more justified is the lofty assertion of the Review that placing less value on the welfare of future generations ($\delta > 0$) '…is not a position which has much foundation in ethics and which many would find acceptable'. This statement is questionable on both counts: a positive δ *has* a foundation in ethics and *would* be found acceptable by many people.

Agent-relative ethics is the ethical foundation for people not valuing the welfare of all other people equally. This is a respectable and traditional ethical structure going back to David Hume that contrasts with the Review's impersonal consequentialism. Hume's 'Treatise of Human Nature' (Hume 1969) locates the foundations of morality in 'sympathy'; eloquently expressing the notion of what has come to be known as 'empathic distance'.

Hume regards sympathy as the cement of the moral universe that affectively binds others to oneself and, by implication, binds a community of ethical individuals.

Experience shows that sympathy is diminished by distance of time and proximity and relatedness. We are much less affected by the pleasures and pains of those at a great distance than by those in our immediate physical vicinity or (say) close family relations. In his chapter ‘Of contiguity and distance in space and time’ Hume writes ‘in common life… men are principally concerned about those objects, which are not much removed either in space or time, enjoying the present, and leaving what is afar off to the care of chance or fortune’ (Hume 1969, p. 180). As sympathy is extended beyond the narrow scope of one’s family and friends, it gives way to benevolence, an interest in the well-being of all mankind, as the basis of morality.

This agent-relative objection to setting the ethical parameter δ to zero then is that people tend not to value the welfare of others equally. As Schelling (1995) observed, ‘we may prefer beneficiaries who are closer in time, in geographical distance, in culture, surely in kinship’. Furthermore, this agent-relativity has an instrumental benefit. The ties of trust, sentiment and obligation within units that have developed within society foster the cohesion of that society. Agent-relative ethics does not exclude concern for those people outside the particular groups with which one identifies oneself. It is simply that our moral intuitions have evolved in a manner that leads us to have special obligations to our own group; family, friends, community, nation or generation. The condition for intensity of feeling for a certain group is a reduced intensity of feeling for other groups. If everyone is special, no-one is special. From this agent-relative philosophical view point then, time imparts some empathic distance, that in an inter-generational welfare context, should be reflected in a positive value for δ.

Discussion

The preceding section has argued that the notion of the rights of future generations cannot be used as a justification for climate change policy. Rejection of a rights-based approach to policy, though, does not leave a moral vacuum. Rights do not exhaust the whole of morality. Although future generations do not have rights that we are obliged to respect, we do have *obligations* to take account of the impact of our actions on future generations. It is possible to have obligations without counterpart rights; in other words, obligations are non-correlative. We may not act to protect future generations’ supposed rights, but that does not mean that we should ignore the impact on future generations of what we do. Behaviour can be influenced by some idea of what our moral obligations are, without necessarily believing that somebody or other must have some corresponding rights.

What obligations, then, might we have to future generations? The answer proposed here is that, following Hume, our obligations should reflect the empathy that people feel towards others. The degree of empathy that people exhibit may be a declining function of distance in space and time; it may not be the degree of empathy that some elite may deem to be appropriate, but it is surely the case that in a democracy, policy should be a reflection of the empathy that those who are being called upon to sacrifice feel for those who are the beneficiaries of that sacrifice.

A nation's resources available for consumption or investment are the product of the efforts of the current generation and its inherited capital and each generation is usually content to maintain and develop this capital for its successors. The decisions on climate change policy are about the allocation of the current generation's resources. Allocation of these resources by a government to spending on other people, in ways that are inconsistent with the informed preferences of the current population is elitist, and has no clear ethical justification.

The type of elitist, paternalistic approach exemplified by the Orthodoxy has been termed 'Government House utilitarianism'. Sen and Williams (1982, p. 16) define it as: 'social arrangements under which a utilitarian elite controls a society in which the majority may not itself share those beliefs'. Dasgupta (2008, p. 147) comments that 'it is all very well for the ethicist to assume the high moral ground and issue instructions like a philosopher king or a Whitehall Mandarin, but social ethics commands an irremediably democratic element'. Rawls' advocacy of the impartial sympathetic observer as the arbiter of policy decisions, may well be relevant in an intra-generational setting, but simply cannot function in an inter-generational context.

Of course the amount of empathy that people exhibit is not fixed. Empathy is aroused, or diminished, by various things, including information. Rawls' 'reflective equilibrium', is an expression of the interplay between facts and values that gives rise to informed values that guide us in what we should do. Ethical perspectives adapt and change when exposed to evidence and the process of discussion and scrutiny of policies and values.

This stance then has implications for the approach to inter-generational discounting. If the driver for our obligations to future generations is the empathy that the current generation feels for posterity, then this precludes making the assumption, that from an objective moral standpoint, δ should be set to zero.

This, then, is to advocate a moral contextualism, rather than a moral absolutism; a concern for the preferences and interests of individuals alive today rather than the pursuit of some distant social goal that an elite has claimed is their duty to promote; a moral absolutism that as Berlin (1997) observed 'has been a common cause of misery for millions of people throughout the ages'. Contextualism says that no act or practice can be seen to be right or wrong, good or bad, without the full specification of circumstances and context, including the identity of agents.

This paper argues for an agent-relative stance, if only to show that the Orthodoxy is not the only approach to climate change policy. We do not presume here to adjudicate between various ethical viewpoints. The point is that climate policy cannot properly be conducted without considering a range of ethical perspectives, including those that attach a lower value to a unit of welfare accruing to a distant generation as to one accruing today.

As Lind warned back in 1995, the problem is not that the impersonal, agent-neutral utilitarian framework is in some absolute sense wrong. It is that it is neither well understood nor accepted by elected decision-makers, and it implies that we should take actions that are inconsistent with the choices society actually makes. For economists to introduce such an ethical system as a basis for discounting and then for the results to be presented as science without setting out the ethical system embodied in these results is not a sound basis for policy making.

There is an uncomfortable parallel here between the way in which climate change policy decisions have been arrived at in the UK and the way in which five years earlier the same protagonists justified the Iraq war. At the unveiling of the Stern Review Mr. Blair stated, in a message reminiscent of the supposed threat posed by Saddam Hussein's weapons of mass destruction: 'It is not in doubt that if the science is right, the consequences for our planet are literally disastrous… [W]ithout radical international measures to reduce carbon emissions within the next 10–15 years, there is compelling evidence to suggest we might lose the chance to control temperature rises' (Blair 2006, p. 1).

Conclusion

This paper has evaluated the ethical basis of the UK's climate change policy. The Orthodoxy represented by the Stern Review and reflected in the Climate Change Act, is that urgent and substantial action must be taken to combat the damaging effects of climate change. The ethical framework assumed by the Review is a utilitarian social welfare function, embodying an agent-neutral assumption of a zero rate of pure time preference. Two criticisms of its agent-neutrality are considered.

First, that deontological constraints should be placed on the agent-neutrality of the social welfare function itself, to confer rights to future generations restricting what may be done, and dictating what must be done, by the current generation to ensure these putative rights are satisfied. This rights-based approach to the ethics of climate change policy is found to be neither intellectually robust, nor useful in an inter-generational context.

The second criticism is found to have significantly more force. The agent-neutral assumption that the welfare of the current generation and of posterity should be given equal weight, as reflected in the assumption of a zero rate of pure time preference, is found to be wanting. The a priori justification for it is weak and the consequences of assuming it do not chime with commonly held moral intuitions.

It is further argued that, although there is no intellectually justifiable or useful role for a rights-driven approach to climate change policy, and no justification for assuming that the welfare of future generations should be accorded the same weight as the current generation, the current generation nonetheless does have moral obligations to future generations. These obligations arise out of empathy, of compassion for others. The extent of our obligations is determined by the extent of our empathy. Empathy is a declining function of time. The level of empathy for as yet unborn people may not be sufficient to satisfy either the supposed rights of posterity, or the preferences of an impartial elite. Yet in a democracy people can only be persuaded to be altruistic.

It follows from what has been said, that:

- In the same way that there is a range of plausible relationships between concentrations of GHGs in the atmosphere and global mean temperature, there is a range of valid policy responses to address the problem of climate change.
- These policy responses depend on the ethical framework chosen and the ethical assumptions made in the model chosen to derive the policy recommendations.
- The role of economists and philosophers should be to assess the implications of normative assumptions and to populate the ethical landscape.
- The ethical basis of policy must reflect the informed willingness, however, arrived at, of the people being asked to make sacrifices in the interests of future generations.

Further areas of research suggest themselves if this agent-relative viewpoint is accepted. First, it can no longer be taken for granted that the conclusions of the Stern Review provide a sound basis for the development of UK climate change policy. The economics and the ethics of the UK Climate Change Act need to be revisited. Second, the relationship between intra-generational and inter-generational equity must be evaluated in the context of UK climate change policy. This paper examined only the latter. The type of question that needs to be answered here is: is it ethical for the UK government to incur costs of £18 billion per year for the next 35 years, to implement the changes needed to decarbonise the UK economy to avoid damages to immeasurably richer future generations (inter-generational equity), when there are so many people living now leading miserable lives in disease and poverty (intra-generational equity)?

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Chapter 4
The Rocky Road of Post-Capitalist Grassroots Experimentation

Paul Chatterton

Abstract This paper explores more radical notions of social and ecological transitions beyond life as currently conceived under capitalism. It forms an inquiry into the everyday practices of what is called post-capitalist grassroots experimentation. It explores what these practices mean through an empirical case study of a community-led housing project in the North of England. Drawing on six themes which were derived from in-depth interviews with residents, this paper explores how everyday practices in this project give shape to post-capitalist grassroots experimentation: taking risks, transformational change, a fine-grained approach to placemaking, deepening deliberative democracy, embedding security in insecure times and learning. By drawing on the concept of the urban commons, the paper concludes by sketching out some future issues along the rocky road to post-capitalism. First, exploring these practices as part of a minoritarian politics focused on qualitative development rather than mere quantitative growth offers different perspectives on scaling up. This kind of prototype niche experiment is more interested in breakout from, rather than breakthrough to, the dominant regime. Second, these practices represent hybrid bottom-up and middle-out forms of experimentation, which can help to form novel meso-level institutions to deepen a post-capitalist urban commons. Finally, this kind of grassroots experimentation acts as a reminder of the need for deeper critiques of global capitalist urbanisation, and that the broader struggle remains resisting the further embedding of capital accumulation and commodification rather than mere environmental or climate change issues. Drawing on Holloway's (Crack capitalism. Pluto Press, London 2010) concept of cracks, we can see that the daily practices of niche experiments represent a complex spatial politics of being simultaneously in, against and beyond life under capitalism.

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Introduction

Debates on the nature and form of socio-technical and ecological transitions have flourished in activist and academic circles (Trapese Collective 2008; Shove and Walker 2007; Mason and Whitehead 2012; Hawkins et al. 2008; Smith and Stirling 2010). Different visions of the future as well as roadmaps to get there are pitched, often against each other, ranging from the prospect of future conflict and collapse, liberatory, and some would argue utopian, transformation, business as usual as well as technological and technocratic-led modernisation and renewal (see for example, Holmgren 2009). Contained within these debates are assumptions and struggles over very different forms of social relations, institutions, values and forms of governance. This paper is situated squarely in these debates, and in an attempt to offer further empirical depth, draws upon the daily experiences, motives and values of residents in a community-led, co-operative cohousing project in the North of England. The project is a cohousing community of 20 straw-bale homes with a common house which is home to 35 adults and 10 children. It is a co-operative society that uses a novel mutual home ownership model to deliver permanently affordable intermediate housing. The particular empirical context for this paper, then, is the long tradition of self-managed and community housing encompassing ecovillages, low impact dwellings, intentional communities as well as cohousing (see Bunker et al. 2011; Durrett and McCamant 2011; Jarvis 2011; Pickerill and Maxey 2009; Sargisson 2007; Scotthanson and Scotthanson 2005; Williams 2005). All of these have long and diverse traditions and contain more or less radical elements. For example, Sanguinetti (2014) stresses cohousing contexts can be deeply transformatory; as the kinds of interpersonal connections they are based on promoting pro-social and pro-environmental behaviour. However, at the same time, some recent tendencies towards eco-focused community projects reinforce elements of the contemporary market-based neoliberal paradigm through gated and segregated residential 'lifeboat' communities (Hodson and Marvin 2009).

This is a paper about much more than daily community practices in this project. It is about a deeper philosophical and practical enquiry about the prospect of life after capitalism—or what has been referred to as post-capitalism (Gibson-Graham 2006). The aim here is to open up new areas of conceptual and practical enquiry based on a rather different political and intellectual project. One of the motivations of this paper is a sensitive critique towards the explanatory power and intent of these various fields to really capture the practices and motives of grassroots experiments that are committed to life after capitalism. There is a growing interest in exploring the meanings and practicalities of transition debates through more radical political motifs such as social justice, a broader ethics of care, networked politics and critique of parochial forms of localism (Mason and Whitehead 2012; North 2011; Bailey et al. 2009). Moreover, it is now recognised that provocative and disruptive interventions are usefully needed and can lead to some dramatic transformations within the urban system (Radywyl and Biggs 2013). My aim here, then, is to bring these diverse sets of the literatures into further conversation to extend nuances and insights into the daily practices of those attempting to implement socio-ecological-technical transitions beyond life under capitalism.

This paper is structured in three main sections. In the first section, detail is given on the meanings of the terms used, specifically post-capitalism grassroots and experimentation. By doing this, the innovation in bringing these terms together is stressed and how they add to and extend existing debates which cover this terrain. The second section presents some empirical material drawn from interviews with residents of a cohousing co-operative project. Drawn from interview analysis, five different aspects are highlighted which together outline how the everyday practices of post-capitalist grassroots experimentation unfold: taking risks, transformational change, a fine-grained approach to placemaking, deepening deliberative democracy, embedding security in insecure times and learning. The final section provides conceptual reflections on the meaning and significance of this daily practice. In particular, it is highlighted that this kind of post-capitalist grassroots experimentation helps us to give further texture to what an urban commons means in practice—those already existing disruptive and subaltern practices that are simultaneously in, against and beyond life under capitalism.

Post-Capitalist Grassroots Experimentation

This paper is grounded in the idea of post-capitalist grassroots civic experimentation. First, it is worth stressing that we are dealing with a term that encompasses those who envision more clear ruptures against capitalism, and those exploring a myriad of possibilities of what might come after, as well as building competences and skills in the here and now to facilitate transitions. Specifically, what is explored are the meanings and significance of those transformations that are anti-paradigmatic and in myriad ways pitch themselves beyond the status quo. Second, there is a focus on the idea of the grassroots. What is meant by this term are projects that are self-initiated and self-motivated and removed from the direct influence and values of centralised governments, large institutions or business. Many grassroots groups might be more agitational towards the central state and market capitalism, acting more like social movements seeking paradigmatic change to overturn the status quo and usher in a radically different social deal. The third term is experimentation. This term traditionally refers to the more commonly understood act of experimenting, which is undertaken to verify or falsify a hypothesis or to explore causal relationships between phenomena in controlled environments. However, the largely socially constructed nature of laboratory conditions is now well established. Experiments are in fact highly contingent, open and negotiated spaces, far from immune to external pressures and indelibly mixed up with the outside world. Urban community settings present particular challenges for experimentation. What we are dealing with in terms of transformatory grassroots projects is something more akin to open field experiments.

The paper focuses on activities which address or indeed attempt to solve perceived societal crises but in a way that first addresses equality, openness and social justice rather than the needs of the (neoliberal) market. Therefore, the idea of experimentation is used to valorize practices and processes at the grassroots that are counter-hegemonic and embedded in a commitment to envision and develop a post-capitalist politics. What is discussed below is the ways in which post-capitalist grassroots experimentation is strung between being simultaneously in, against and beyond the pressent capitalist moment.

Exploring the Contours of Post-Capitalist Grassroots Experimentation

This paper is based on in-depth research with members of a cohousing project in the UK throughout the early period of moving and settling in, during 2013. The aim of this work was to get a sense of how residents' lives were changing as a result of moving, and to explore the broader meanings of this novel and disruptive approach to community life. With the help of two students at the time, members of the project designed and implemented in-depth qualitative interviews with eight households using a standard set of questions which focused on motives for joining the project, aspirations for living there, the relative importance of key aspects, and wider concerns. What the paper does in this section is to build an understanding of the motives and intent underpinning everyday practice in the project by drawing on the resident interviews. The paper draws on a number of subthemes from interviews, which taken together help to flesh out post-capitalist grassroots experimentation in practice.

Taking Risks

The first theme that emerged was the sheer riskiness of participation in the project. This is a significant starting point given that we are dealing with housing, an aspect of daily life that people usually regard as central to their sense of stability and identity. To experiment with one's own housing situation in a context of uncertainty requires courage and clarity. The following quote expressed this:

> actually it's going to be a huge leap of faith… a weird leap into the unknown. It's going to be a real shift. And I haven't really got a yardstick about what my life's going to be like in six months' time.

What the above stresses is the assumption that initial risk is worthwhile as it is likely to give way to increased stability. There seems to be a recognition that this early and risky experimentation will pay dividends, given the future potential societal challenges. Coupled with this is a clear statement that risk can be overcome through determination. As one resident stated: '*I think, with dogged determination, it's possible to do anything*'. In a context of increased perceived uncertainty, this level of determination legitimises or normalises experimentation, which can then challenge or disrupt what people perceive to be the current status quo. This kind of risk-taking can help to normalise what is previously considered to be deviant, or foolhardy, action.

Transformational Change

The second theme that emerged from the resident interviews is that living in the project offers the opportunity for changing the world in broader ways beyond one's individual life(style), and beyond mere environmental change. Overall, there was a sense that members were keen to commit to a 'step change' in terms of their environmental impact, and also in terms of the kinds of relations they have with other people and the wider community. This would entail more structural rather than incremental changes in group and individual behaviour. One resident expressed that this kind of bigger change could be a catalyst for further change:

> I'm sort of hoping XXX will allow me to make a step change. I'm definitely making moves in the right direction but I'm hoping that living there will enable some of the other stuff to happen.

One resident expressed explicitly how a low impact co-operative cohousing project encourages a group or community level response to the various social, ecological and economic challenges, and therefore contains a critique of the individualisation of responses: *our input is acting together and supporting each other and creating a model that can spread.*

There was also a sense from some residents of an enthusiasm to embark upon broader changes in their lives, but the way their lives were hitherto structured prohibited this. As one resident commented, moving to the project foregrounded and supported changes in group and individual behaviour. A similar sentiment was expressed in the following quote where the project itself acts as a supportive platform for enabling individuals to make the changes they want to make:

> I think living in xxx will make it kind of easier, because it's just built into the actual structure of living itself, living there, there will be certain ways in which you don't need to make the effort it does it for you, you know, like it should be very low energy consumption

in those buildings etc. We won't have to worry about trying to keep that down, it'll just be that way, which is good.

What is important in the above is that the actual physicality of the community takes on agency, acting as an enabling device to facilitate broader more structural changes, or as one resident commented, '*it offers a path of least resistance*'.

Focusing on the Fine Grain

Interestingly, especially alongside a clear intent towards broader, structural change is a preoccupation with the fine-grained aspects of placemaking. There is a long established body of work which pays attention to the very localised and small-scale aspects of constructing everyday life and how they allow individuals to flourish and intervene in the world. While these tendencies of transformational along with fine-grained change may seem contradictory at first, they are actually highly interrelated and codependent. The transformational step change that many communities can represent are built from the myriad of small practices that are embedded into the rhythms of everyday life over extended periods of time. It is the small, fine-grained changes that can be implemented piece by piece in a way that makes sense to participants and can be expressed in a meaningful way externally.

A recurring theme was that the project offers a village feel within a large city context. This was one of the design intentions of the project as a cohousing approach to design specifically attempts to engineer and design as much natural surveillance and face-to-face neighbourly interaction as possible. When asked what residents would see as some of the most rewarding aspects of living in the project one resident commented: *The village like situation when you get to interact with people*.

What is of interest here is the recognition that such relations are based upon a novel form of permission beyond regular public encounters in the street. The intimate and interactive nature of the site offers a unique basis for social interaction. This manifests itself in myriad opportunities for micro-interactions, such as collecting post or laundry, waving to neighbours at windows and doorways, conversations from balconies, passing people as they leave the site, or indeed asking for permission to talk more formally about business matters.

These kinds of micro-interactions and small details may seem trivial but they are incredibly important to everyday well-being. A cohousing context has the potential to build forms of hesitant, modest but affirmative neighbourliness that Painter (2012) talks about. It is the sum of these encounters rather than grand gestures of techno-fixes that have the ability to accumulate larger scale and longer lasting pro-environmental pro-social change.

The knitting together of community facilities within the overall design both offers a greater sense of connection with the place, opportunities for meaningful interactions and a greater sense of well-being and security. This is mainly achieved through a centrally placed common house at the heart of the site, which contains shared laundry, postal facilities, dining facilities, meeting room, office and shared toolshed, as well as homes that are designed to face towards each other around shared landscaped areas. These are the kinds of additions that could easily be made in existing communities with very little effort. In fact, there is increasing interest in retrofit cohousing where these kinds of communal facilities could be peppered throughout existing streets through, for example, merging back gardens, closing roads or adapting empty buildings into communal facilities such as dining, kitchen and communal areas.

Deepening Democracy

Much of the experimentation highlighted in this paper emerges from a renewed desire for democratic engagement and a horizontal and collective approach to governance. Elements of this approach include a focus on process as much as content, attention to difference and conflict resolution, as well as building strong interpersonal relations based on trust and solidarity. The approach to cooperative and community self-governance in the project is embedded within these broader shifts. The formal co-operative structure is the democratic heart of the project where every member has an equal voice. In particular, a deeper sense of democracy is explored through a commitment amongst members to the use of both non-violent communication (NVC) and consensus decision-making. This commitment to deeper democracy works well with a considerable amount of ground work to instil a common purpose. While it needs considerable effort, it does pay dividends in the longer term as it allows a shift in mindset from a highly individualised owner-occupier to resident-member with an equal stake in a self-managed, and member-led organisation. What the following quote reflects is that this commitment to democracy is not just built up through processes and procedures but a commitment to friendship, trust and respect:

> I think it's that we like each other. Does that sound silly? I've met a lot of good friends through xxx and I think there's generally a feeling of common purpose. A feeling of like and respect for each other.

One of the notable features of the approach to democratic governance in the project community is a processual, in contrast to the merely procedural approach to democratic engagement. In this sense, rather than simply working out policies and procedures in advance which and implemented, clear processes are supported by trust, friendship and dialogue. As one resident commented: '*When things go wrong if all you do is open a rule book that's a really poor community*'.

Reinforcing this point, another resident suggested that it generated a commitment from everyone to making life in the society function that allows unanticipated issues to be dealt with effectively: '*So really you can't say what things will arise but* *what you can say is that everyone who signed up to xxx is motivated to want it to work*'. Clearly, this approach to governance can be quite a departure from what many people use to in their daily lives. Foregrounding values within a community setting means accepting conflict and difference within everyday settings.

A further key element is an approach to success judged as both means and ends. The project is not seen as an endpoint, but an opportunity for debate, reflection and improvements in action. Moreover, one of the strengths is that there is an attempt to see problems and failures as learning points rather than times which might break the community. As one resident commented: '*so I don't think we've got to where we want to go, but it's not a failure*'.

Embedding Security in Insecure Times

One of the repeated motivations for moving into the project was balancing the desire for broader structural changes with that of greater security. While this does seem paradoxical, it is the stability and security that the project offers that gives confidence to participants to experiment more radically with change, and to deal with the perceived insecurity of the world around them. The context of greater global financial instability since 2008 was a catalyst for many residents. One of the perceptions of greater security came from the collective context of a co-operative society. As one resident commented:

> on a basic level we've more security 'cos we kind of stand an fall together, so we're kind've we're all collectively responsible for making sure we're all secure.

The particular mutual home ownership society (MHOS) model which this project uses is perceived to lock in further security. In MHOS, residents pay a monthly member charge which is set at 35 % of their net income. These payments accrue equity for the member which, after additions and deductions, they can take with them when they leave. The value of equity is indexed to earnings rather than house prices which therefore radically deflates speculation and ensures permanent affordability for future generations. The mutual home ownership society in particular was seen to be a source of greater stability. Setting monthly payments for housing at 35 % of net income gives members greater stability and longer term management over household financial planning. Moreover, the commitment to member support within a co-operative society ensured that several mechanisms are in place to support members in times of financial hardship. An important point to note is that before moving to the project, the average proportion of income spent on rent/mortgage was around one fifth of earned net income. In the project, given the proportion of income required to be spent on rent through a monthly member charge is 35 %, this shows a conscious financial assessment made on more than cost of housing. These other factors include greater perceived security, as well as lower costs of living through formal and informal patterns of sharing. Moreover, the greater level of interaction that is designed into the project offers a greater sense of security. This kind of sentiment which links a community context to greater security was particularly noted by older age groups in the project, which is a notable feature in many cohousing communities. While it is important that cohousing does not retreat into generational ghettos and that the principle of intergenerationality is preserved, there are really clear benefits derived from collective housing situations for more senior age groups.

Learning

A final feature that emerged was that of learning. This manifests itself in different ways. There is both group learning between members and a wider commitment to acting as a learning exemplar for the outside world. Internal learning helps people to focus on learning from each other, especially in terms of working through differences. The following illuminates this:

> That behaviour change stuff might get accentuated as we live there and start to feed off each other. Learning tricks around people about how to do things differently that stuff will really start to kick in.

The process of learning can be a path fraught with problems and tensions. However, it was regarded that the journey of community formation created strong bonds of trust and solidarity which allowed the project to learn collectively and flourish. The kinds of learning that emerge in this context speak less to social learning but are more akin to the longer traditions of popular education where learning is aimed at a commitment to social and personal transformation. This latter tradition stresses the anti-paradigmatic nature of education, where the process of learning is focused on recovering some of the lost skills and practices of (re) building community.

Conclusion. Deepening the Urban Commons

In this concluding section, this paper sketches out some of the broader implications of what this kind of post-capitalist grassroots experimentation might mean for our understanding of spatial politics and strategies. If we embed a deep commitment to social and environmental justice as well as undermining and reversing capital accumulation and surplus value, what does this add to our understanding of grassroots experiments? Strategically, it means that any socio-ecological transition that fails to address the mechanisms that reproduce capitalism at a daily level is not a transition worth making. It is likely to lead to 'lock-in' to weak carbon gains and perverse rebound effects, deference to technological solutions and opportunities for extending value production, and all the attendant problems of exploitation, alienation, competition, depression, powerlessness and status anxiety into more areas of our lives.

So what are the alternatives? This paper proposes the concept of the commons to extend our understanding, a concept around which there is growing debate and interest (De Angelis 2007; Linebaugh 2008; Radywyl and Biggs 2013). The commons, and in particular the urban commons, has become a well-used conceptual and practical devise for thinking through and enacting social and spatial political forms beyond the status quo. The commons at its most basic level is a widely understood spatial motif, evoking bounded entities, which exist to nurture and sustain particular groups. In this simple historical form, the common (the fields, the village greens and the forests) are geographical entities governed by those who depend upon them—the commoners. It is also important to look beyond these basic physical attributes and see a common as a complex organism and web of connections which combine to articulate particular spatial practices, social relationships and forms of governance that produce and reproduce them. The common then is made real through the practice commoning, which reflects, not so much a set of bounded, defensive or highly localised spatial practices, but dynamic ones.

So what does an urban commons approach offer for deepening our understanding of the future potential of the kind of grassroots experimentation outlined in the project? The ‘so what?’ question is so prevalent, and so pernicious, that it must be addressed, if only partly. In particular, debates in transition management are concerned with the scalability and impacts of niche innovations and these are actually issues of political strategy. Micro-level niche experiments still need to be committed to contributing to more widespread change. But when we move onto the terrain of post-capitalist change, the specific characteristics of this scaling process needs interrogating.

First, Tormey (2004) makes the useful distinguishes between minoritarian and majoritarian politics, the former more focused on the qualitative nature of development, with the latter more on quantitative growth. What we see in the commons are experimental forms of association that can begin to act as a bulwark against the centralization and hierarchy, and obsession with growth, embedded in majoritarian political strategies. We depart from the idea of actually scaling up, and shift emphasis towards a networked micropolitics that can spread mimetically and virally through decentralised swarming, networking and infiltrating, countering and corroding the dominant regime as they connect (Scott-Cato and Hillier 2011). Their effects, then, can be discerned far beyond the quantitative number of projects, and this is where innovation and transition studies may encounter an ontological blind spot. To use the language of the multi-level perspective, prototype experimental niches like the one in this paper are less interested in breakthrough, but more in breakout. These are not daily practices interested in simply looking to scale-up and influence the mainstream. Usefully, Radywyl and Biggs (2013: p. 168) call this tactical urbanism which facilities disruptive innovation in the urban system. Moreover, what needs to be recognised are the highly uneven outcomes for those trying to put down markers against the status quo. We need to recognise that more sinister tendencies can indeed thwart grassroots experimentation. These can take many forms such as infiltration by police, informers or political opponents, or direct oppression.

Second, this is not merely micro-level, bottom-up innovation. The connections forged through these counter-topographies have the potential to form novel meso-level institutions to deepen the institutional forms of a post-capitalist urban commons (see Albert 2004). These kinds of experiments do not just represent a potential for diffusion, but also the corrosion of the dominant regime attempts to weave together cracks that will eventually lead to the undermining of the status quo. This is not just a bottom-up process, therefore, but a middle-out one through the formation of community-led and owned institutions (Parag and Janda 2014; Hamann and Kurt 2013). Here, statutory agencies take on a role as enablers and facilitators of innovation that can further embed the urban commons.

Third, there are points of departure around value and intent. One of the surprising elements of contemporary debates on transitions is the marginalisation of longstanding and formative critiques of industrial society, especially in the context of a rapidly globalised and urban world. Since the Limits to Growth report and the foundational work of Schumacher (1973), a whole body of thought and action has emerged across the globe (see Jackson 2009; Bookchin 1992) which has presented not just a sustained argument against recent neoliberal casino-capitalism, but a post-growth critique of the whole development project of modernity, and even further the deep schism that has emerged between humans and the natural world with which they are intertwined and codependent. What we can take from these debates is a commitment to experimentation as an attempt to sow the seeds of what places might be beyond capitalist urbanisation.

So what can we take from the snapshot of post-capitalist grassroots experimentation in action? There is novel and disruptive innovation geared towards transformation, risk-taking, deep democracy, learning and a search for security—and this is framed by the complexities of real world processes. To conclude, this paper returns to Holloway's (2010) concept of cracks which is useful in helping to understand that niche experiments represent a spatial politics of being simultaneously in, against and beyond life under capitalism, or as Wright (2013) articulates it, transformation that is ruptural, interstitial and symbiotic. It is these complexities that give texture to our understandings of this post-political urban commons. Experiments like the one explored in this paper exist in the daily quagmire of the status quo, but are keenly aware of the need to breakout from it, as they embark upon the rocky road of building post-capitalist grassroots commons.

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Part II
Sustainability and Technology

Chapter 5
An Evaluation of Thermal and Lighting Performance Within an ETFE Structure

Benjamin A.J. Martin, Dawa Masih, Benson Lau, Paolo Beccarelli and John Chilton

Abstract This paper reports on a study into the thermal and lighting environment of an enclosed ethylene tetrafluoroethylene (ETFE) foil-covered structure. This is based on the on-site monitoring over set periods of time in summer 2014 and winter 2015. ETFE foil is a relatively new highly-translucent construction material that has been used in some high profile projects around the world. In a unique development, this project looked at a new building product that makes use of ETFE film and tensioned it over aluminium frames to create a modular ETFE-covered panel that can look similar to and can be installed as a replacement for glazing. This opens up new markets for the use of ETFE film, such as agriculture and horticulture, and allows for possibilities such as urban and vertical farming or the retrofitting of existing commercial and residential greenhouses. A test structure was constructed from the ETFE-covered panels. This paper will report on the impacts of solar radiation on the thermal environment as well as the relative humidity within this enclosure so that a more holistic understanding of the thermal comfort can be obtained. The second section will explore the internal daylighting environment including analysis of the daylight factor within the structure and luminance mapping to examine brightness and visual performance and its effect on the perception of space and objects within. The paper will conclude that the temperature within the enclosed ETFE structure can become too high during the summer months and may require heating when occupied during the winter months. The research also finds that the daylight levels can be too bright if the internal space were to be used regularly by occupants, although this may be beneficial for plants. In both cases, overheating and solar gain issues can be resolved through appropriate shading and ventilation.

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Introduction

Ethylene tetrafluoroethylene (ETFE) foil (or film) is a relatively new highly-translucent construction material which is being used more widely in architecture and horticulture due to the benefits that the material provides over existing materials. The pneumatic cushion system has become a popular option for architects creating transparent roofing and curtain wall systems due to the materials high transparency, mechanical strength, thermal performance and light weight (Robinson-Gayle et al. 2001; Knippers et al. 2011). The cushion systems are made up of two or more layers of ETFE foil which are heat-welded together and inflated by means of small electric fans to create tension across the film. Due to their light weight, these cushions are able to cover large spaces without the need for secondary structures and with reduced primary support structure, which makes them ideal as an alternative to glazing on large areas (Wu et al. 2011). However, more recently, ETFE foil cladding has been investigated for smaller architectural applications, especially in relation to creating a modular unit that can be installed in a way similar to standard glazing whilst exploiting the benefits of the ETFE foil material, e.g., light weight, high transparency and high mechanical strength. This would also create an ideal solution for horticultural applications where modular units can be assembled into green houses at a relatively low cost compared to the cushion system.

The ETFE-panel system studied in this paper uses the heat shrink properties of the ETFE film to tension the material across an aluminium frame and creates the modular unit which requires no inflation and can be easily installed similar to glazing but still has all the benefits of ETFE such as the light weight, high transparency and high mechanical strength. This paper investigated the new ETFE panel system that has been developed for modular applications and assessed the thermal and lighting performance of a test structure built in Grantham, UK.

Benefits of ETFE in Construction

ETFE has a high transparency of approximately 95 % depending on the thickness of material used and also transmits a larger portion of the UV spectrum of light compared to traditional glazing (LeCuyer 2008). This has the benefit of creating a healthier environment internally; especially for plants as the UV light prevents mould and enhances plant growth (Stefani et al. 2007). As a result, ETFE is seen as an ideal solution for botanical gardens, swimming pool and exhibition spaces.

This can be seen in ETFE structures such as the Beijing Aquatics Centre in China and the Eden Project in Cornwall, UK (Hu et al. 2014). Due to the ETFE transmitting longwave radiation, treating this material similar to other glazing materials can cause errors when studying the structure and evaluating its performance (Mainini et al. 2014; Chilton 2013).

One of the reasons lighting conditions under ETFE must be evaluated differently is that daylight striking the ETFE material gets diffused after it enters the enclosed space. This creates a continuous luminous surface which changes its intensity as the position of the sun changes. This gives ETFE structures an advantage in that users inside the building are aware of changes in the weather happening externally and are also benefited by the high daylight factor (Mollaert and Forster 2004). This can mean that on a cloudy day a user in an ETFE enclosed building may carry out their activities without the need for artificial lighting. However, under sunny sky conditions, the excessive solar ingress can cause high brightness contrast which might lead to discomfort glare, thus there is a need to firstly, understand the lighting conditions under the ETFE roof and secondly, to develop workable solutions to enhance and enrich the luminous environment.

A published study by Dimitriadou and Shea with a focus on understanding how the thermal performance of ETFE against glass, looks into the comparison of single skin ETFE film against a single glazed unit. The paper concluded that ETFE and glass provided a steady and satisfactory performance to maintain a comfortable interior environment and that ETFE was more successful than glass in maintaining the desired internal conditions under overcast skies. However, under a clear sky it was found that the internal environment of an ETFE box would have a higher temperature during the day and a lower one at night. This was due to the longwave radiation permeating through the ETFE material during the day and increasing the temperature but then at night, when solar radiation is absent, the longwave radiation can escape from within the internal space (Dimitriadou and Shea 2012).

The ETFE Panel and Test Structure

An ETFE test structure in Fig. 5.1 was constructed from the panel system, so that a study could be undertaken to analyse its environmental performance. The panels are designed to be installed in a similar manner to a modular glazing unit and thus a typical garden room structure was used. The structure, measuring approximately 4100 mm wide by 6500 mm long, is a composed of aluminium extrusions framing ETFE foil-covered wall panels of approximately 800 mm wide and 2100 mm long. Longer panels form a sloping roof. The ETFE structure has no openings except for a door located on the northwest side facing the house, as shown in Fig. 5.1. This door was kept shut permanently during the testing to examine the thermal environment in the absence of ventilation.

Fig. 5.1 The ETFE-foil panel test structure

The panels are made up of a square hollow section aluminium frame which is then encapsulated using a patented system to create two skins of ETFE foil which are then tensioned to create a flat surface, much like a glazing unit. The aluminium frame provides an air gap of 30 mm between the two skins of ETFE foil and this allows for some thermal insulation.

The test structure is located near Grantham, Lincolnshire in the UK. The longer axis of the structure is oriented to the northeast and southwest and the shorter axis towards southeast and northwest, see Fig. 5.2 right.

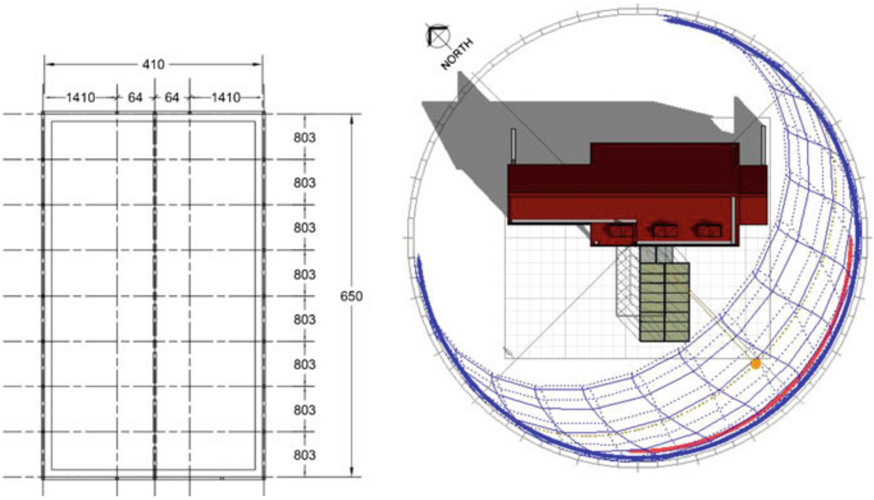

Fig. 5.2 Site plan and orientation of the test structure

Research Method

Monitoring was carried out over two different seasons to look into the effect that the weather conditions had upon the internal environment. Temperature data was first collected over the summer months from 16th June 2014 to 29th July 2014. This was then repeated in winter running from 15th January 2015 to 5th March 2015. The monitoring equipment is listed in Table 5.1.

Tinytag Ultra 2 TGU-4500 data loggers were placed within the structure at varying locations as shown in Fig. 5.3. During the summer testing, 16 internal data loggers were used with 9 situated in a grid pattern at 1600 mm from the ground and

Table 5.1 Description of measurement equipment

Measurement type	Equipment
Internal temperature and relative humidity	Tinytag Ultra 2—TGU-4500
External temperature and relative humidity	Tinytag Plus 2—TGP-4500
Weather data	USB wireless weather forecaster
Light levels (Lux)	Multimetre
Luminance patterns (CD/Sqm)	PHOTOLUX luminous mapping software

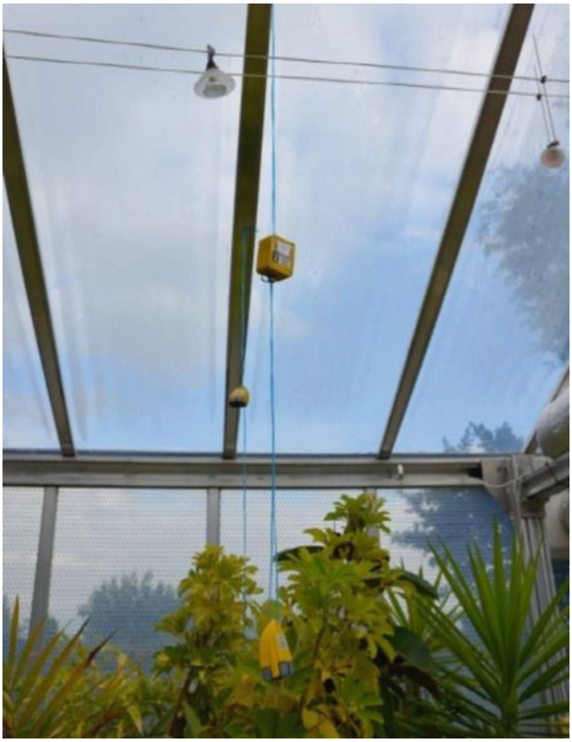

Fig. 5.3 Data loggers installed in the test structure

7 placed at 2400 mm from the ground. During the winter testing, 9 data loggers were used, all placed in a grid pattern at 2400 mm from ground level. Site weather data was collected from a USB Wireless Weather Forecaster placed outside the test structure along with an additional external Tinytag Plus 2 TGP-4500 data logger to ensure accuracy. Data loggers and the weather station were set to measure and record data at 5 min intervals.

Lighting analysis of the test structure was carried out during the installation of the data loggers during the summer months and this was carried out using equipment shown in Table 5.1 consisting of a multimetre and computer software called Photolux which can capture an image and generate the luminance map. The light metre was used to measure the internal luminous levels of the ETFE test structure at certain defined grid points as well as defined points externally. These readings were taken at each point at a level of 1 m from the ground to examine the lighting conditions of the test structure. A daylight illuminance analysis was performed and the daylight factor of the space was calculated. Daylight factor isolux contour map indicating the quantity and distribution of light under overcast sky condition was generated.

The Photolux application allows the researchers to take a picture and then the application creates a luminous map in which the luminance pattern and value at specific points can be obtained. The scale shows the minimum and the maximum values of luminance (in cd/m^2) in the selected scenes. The luminous mappings have been used to evaluate the test structure in terms of the luminance distribution patterns, brightness and contrast, so as to investigate the effects that ETFE envelope has on the perception of spaces and objects inside it.

Research Results

Thermal Environment

The temperature data collected over the monitoring periods is shown in Fig. 5.4. This shows the average daily recorded values for each month January, February, June and July to demonstrate the variations of the seasons. The data shows the average indoor temperature and average external temperature during the testing. It can be observed that, in both summer and winter months, there is typically a 2 °C difference between the internal and external temperatures during the night when there is no solar radiation. However, during daylight hours, it can be seen that there is a dramatic increase in the difference in temperature between the internal and the external average temperatures, with a maximum difference of 15.44 °C.

The data in Tables 5.2 and 5.3 show that the maximum temperature achieved during the winter months for an average day externally was 8.5 °C. However, on the inside of the ETFE test structure the temperatures reached 18.25 °C. During the

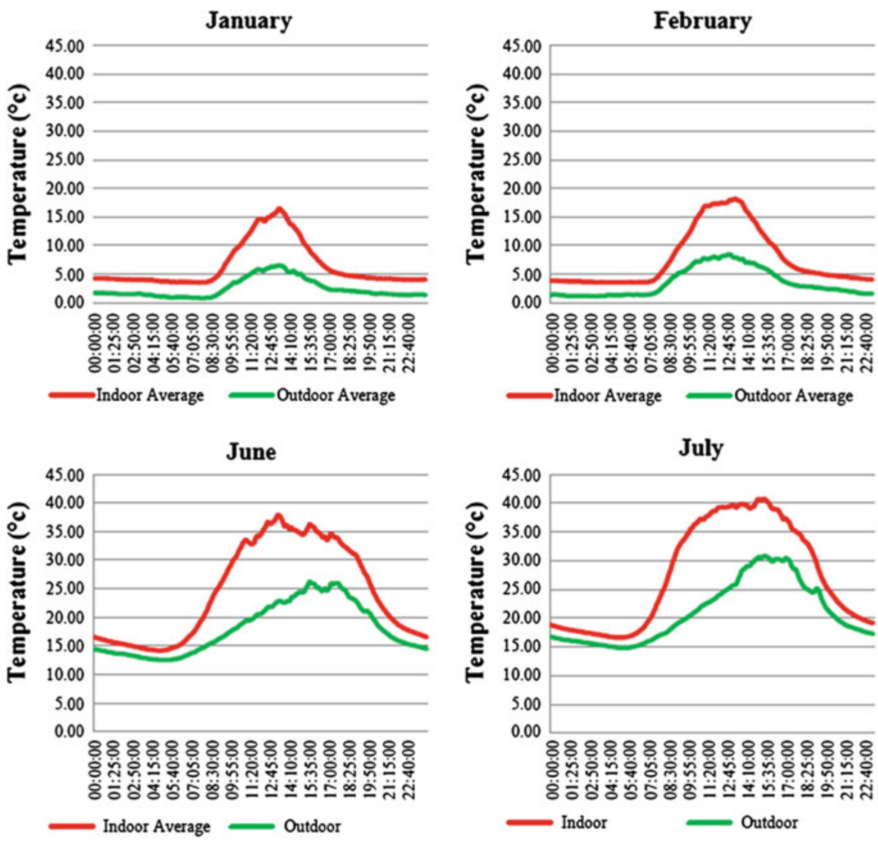

Fig. 5.4 Recorded average daily temperatures (°C)

Table 5.2 Recorded average temperatures internally (°C)

	January	February	June	July
Maximum internal average daily temperature	16.51	18.25	37.90	40.73
Minimum internal average daily temperature	3.50	3.54	14.19	16.61
Internal average daily temperature	6.47	7.73	24.51	27.55
Standard deviation	3.87	5.03	8.40	9.07

Table 5.3 Recorded average temperatures externally (°C)

	January	February	June	July
Maximum external average daily temperature	6.51	8.50	26.26	30.84
Minimum external average daily temperature	0.74	1.12	12.51	14.84
External average daily temperature	2.46	3.54	17.99	20.93
Standard deviation	1.67	2.45	4.48	5.28

Table 5.4 Difference in average temperatures (°C)

	January	February	June	July
Maximum difference in average daily temperature	10.00	10.42	15.20	15.44
Minimum difference in average daily temperature	2.43	2.13	1.62	1.69
Average difference in daily temperature	4.01	4.19	6.53	6.61
Standard deviation	2.23	2.62	4.54	4.90

winter months of January and February, the maximum difference in temperature achieved as shown in Table 5.4 are around 10 °C and the average difference in temperature between the internal and external is about 4 °C.

During the summer months the maximum temperature externally was measured at 30.84 °C whereas the internal temperature at its maximum was 40.73 °C. The maximum daily average temperature difference was 15.44 °C which is higher than the average difference in the winter months. The data also show that during the summer months the minimum average temperature difference is lower than during the winter months and the standard deviation shows that the difference between the temperatures recorded was more variable during the summer months when there is generally a higher temperature range both internally and externally. This is confirmed by the data in Table 5.2 which show the variation in the recorded data is higher during the summer months. In addition, Fig. 5.5 shows the difference in temperature between the indoor and outdoor environments and shows the increasing temperature variations throughout the day in the summer months compared to the winter months.

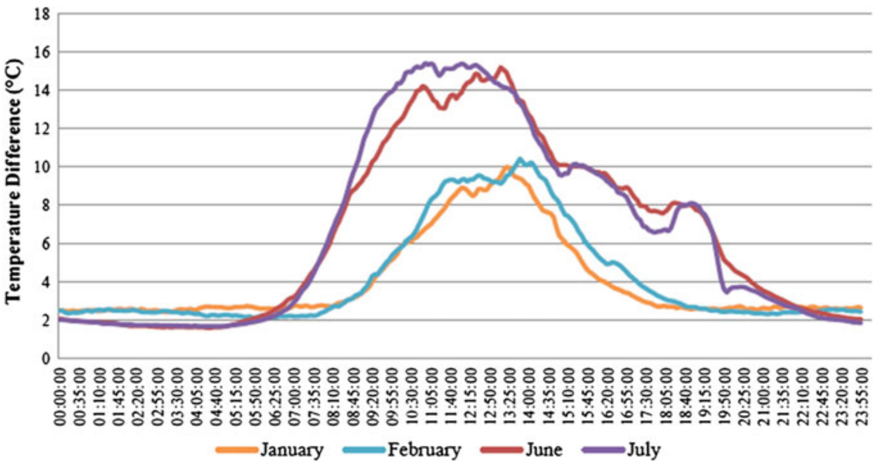

Fig. 5.5 Average difference in temperature between the indoor and outdoor environments (°C). This graph should be read in conjunction with Fig. 5.4 above

Lighting Data

A daylight illuminance analysis has been undertaken using the data collected from the light metre during the survey carried out on an overcast day, and daylight factor of the space was calculated. Daylight factor results indicate the quantity and distribution of light under overcast sky conditions.

The images in Fig. 5.6 indicate that the maximum measured illuminance level under the ETFE structure is 1171 Lux and the minimum value is found to be 478.67 Lux. The average illuminance level inside the structure was found to be 919.5 Lux and the average daylight factor was 56.4 %. The daylight factor was found to be very high. This reflects the predominant use of ETFE foil as a construction material for translucent building envelopes.

Figures 5.7 and 5.8 indicate the luminance values of the photo taken within the test structure and show the luminance distribution patterns under the ETFE structure. This was undertaken using the Photolux application to assess the brightness and contrast levels within the structure.

The task-to-immediate surround and the task-to-general surround luminance ratios of these images are summarised in Table 5.5.

The luminance ratios obtained above shows that the task-to-immediate surround and task-to-general surround luminance ratios are in a reversed order or they are

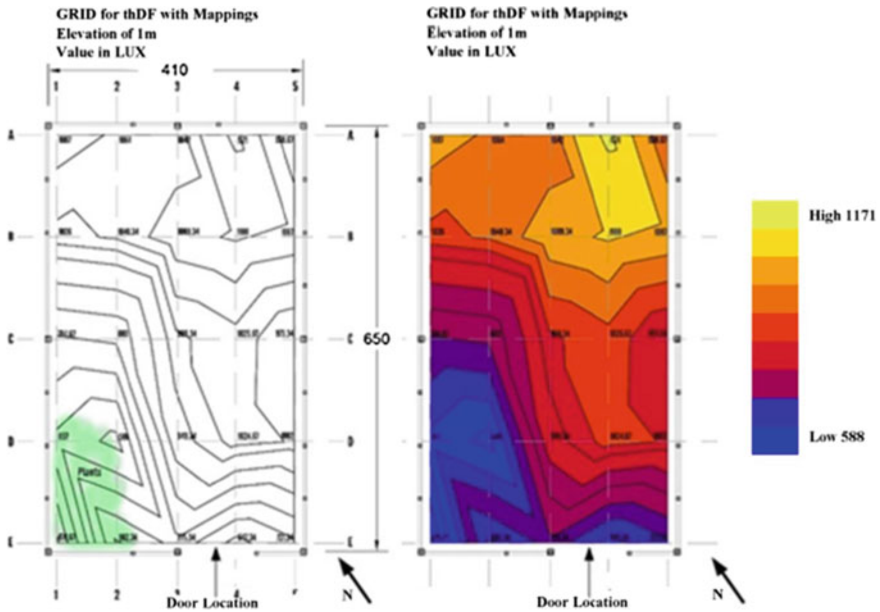

Fig. 5.6 The illuminance level inside the ETFE test structure under overcast sky conditions

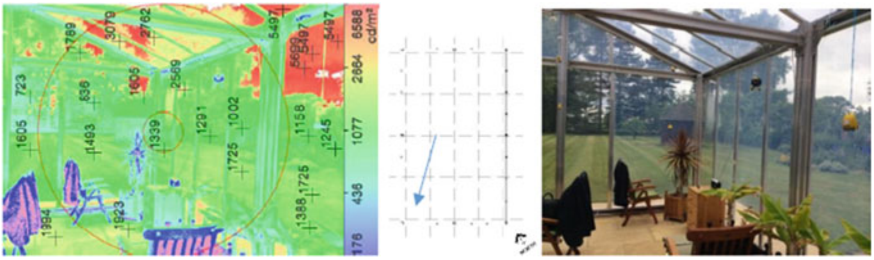

Fig. 5.7 View point A within the ETFE structure

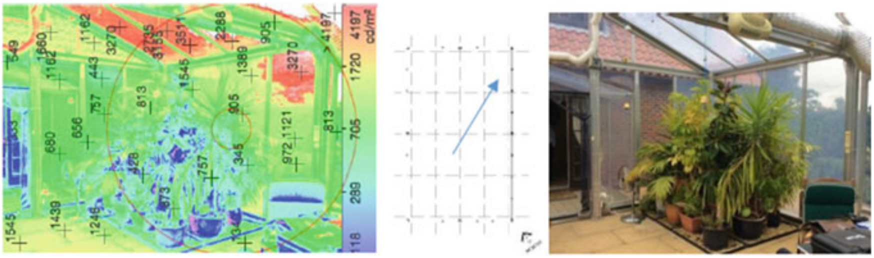

Fig. 5.8 View point B within the ETFE structure

Table 5.5 Table of luminance ratios

	Task-to-immediate surround	Task-to-general surround
View point A	1:1.36	1:2.17
View point B	1:3	1:3.6

close to a 1:1 ratio. This is caused by the excessive uniform luminous field which either the background is slightly brighter than the task or they have similar luminance values. The reversed luminance ratio means the details of tasks become less visible. This is also the case with the equal luminance ratios which make it difficult to see the task details and differentiate the task from the background clearly. The maximum recommended luminance ratio between the task and general surround is in the order of 1:10 and the results obtained from the field work show that the luminance ratios in the selected scenes inside the test structure under overcast sky conditions are much less than this and have not exceeded this ratio. This implies that a dull and uninteresting visual perception will be experienced by the occupants of this test structure.

Discussion

On-site monitoring results showed that the maximum average daily internal temperature reached over 40 °C in the summer months in the deliberately unventilated space. This is related to the high transparency of the material as suggested by Dimitriadou and Shea (Dimitriadou and Shea 2012). These high temperatures are well beyond normal comfort level but may create an ideal environment for certain plant growth.

This shows that an appropriate ventilation strategy should be introduced to moderate temperatures within the structure at times of high insolation. Also, alternative environmental control strategies could be investigated to absorb excess heat for storage and release during cooler periods. In addition, solar shading could be applied to reduce the solar transmittance of the ETFE-foil envelope, although this would adversely affect the more moderate internal environment in winter. In addition to this, external solar shading could be applied to the ETFE structure to reduce the solar radiation penetrating through the ETFE membrane (Poirazis et al. 2009). There are several different methods through which this strategy could be applied as shown in other studies carried out (LeCuyer 2008; Chilton 2013).

The results of the daylight analysis have shown that the daylight factor and illuminance levels within the test structure were also high for visual comfort. This field work was carried out under overcast conditions during the summer months and it reveals the impact of the transparency of the ETFE foil. Under sunny sky conditions, it could be expected that the illuminance level would become even higher and the brightness contrast in the field of view could be excessive and potentially cause discomfort glare. The luminance distribution patterns obtained from the luminance mapping of the internal views of the ETFE-panel structure show that the background is either brighter than the task or having similar luminance value of the task, which can affect the visual environment in the field of view. This can be rectified through properly designed shading strategies or varying the opacity of the ETFE panel envelope to reduce solar gain/glare and to enhance perception. However, striking the right balance between utilising the high transparency of the ETFE film especially for UV and the slight diffusion of the light allows for an ideal environment for plants to prosper and providing desirable thermal and luminous environment in the ETFE panel structure for human inhabitation would need to be carefully considered.

Conclusion

The results of the field studies showed that the temperature within an unventilated enclosed ETFE-panel structure can become too high for occupant comfort during the summer months. Conversely, the enclosure may require heating during the winter months. However, there were extensive periods of time when the thermal environment within the panel structure was comfortable for human occupants but more so for plants. The need for appropriate ventilation and shading strategies to extend periods of comfort was demonstrated and discussed.

A study into the luminous environment found that the overall brightness within the structure was acceptable but that it could be regarded as rather high for occupants during periods of intense insolation. However, plants would prosper under the slightly diffused light and due to the higher levels UV light. The visual environment inside the ETFE panel structure tends to be uniform and dull under overcast sky conditions, however, potentially more dynamic luminance patterns could be experienced under sunny sky conditions.

The current research development on the ETFE panel structure continues into developing the most appropriate strategies to enhance human comfort inside the enclosures and also to maximise plant growth where the panels are used for horticulture and potentially for urban and vertical farming.

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Chapter 6
Double-Skin Façades for the Sustainable Refurbishment of Non-domestic Buildings: A Life Cycle Environmental Impact Perspective

Francesco Pomponi, Poorang A.E. Piroozfar and Eric R.P. Farr

Abstract In developed countries, existing buildings have the biggest share in the building stock. Given the age of construction, the property versus land values, and their slow replacement rate, low-carbon refurbishments are arguably one of the most sensible ways to mitigate environmental impacts (EIs) in the construction sector and meet the greenhouse gas (GHG) reduction targets. In this respect, Double-skin façade (DSF) has been defined as one of the most effective ways to efficiently manage interactions between outdoors and indoors, and its benefits span from passive heating and cooling to the enhancement of thermal comfort of the occupied spaces. A plethora of research does exist on the operational behaviour of the DSF. However, life cycle energy figures and EIs are yet to be established fully and comprehensively. This paper reports on findings of an on-going research project aimed at filling such a gap. More specifically, life cycle assessment (LCA) and building energy modelling (BEM) have been combined to build a methodology to help assess life cycle energy figures in a more holistic manner. Primary data have been collected from manufacturers from across Europe about all the life cycle stages and processes related to a DSF refurbishment. Results show that if on the one

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hand, the life cycle energy balance actually is negative, hence supporting a wider adoption of DSFs in refurbishments, on the other hand, there exists ecological and EIs that the DSF bears; that cannot be easily overlooked if a more responsive approach to the EIs is to be undertaken. Not only do these findings inform a more energy-efficient deployment of DSFs, but they also highlight the need for a more holistic and impact-driven design approach to ensure that the environmental burdens are not just shifted from one impact category to another.

Keywords Double-skin façade · Life cycle assessment · Low-carbon refurbishments · Office refurbishment

Introduction

In countries like the UK, the existing buildings stock is where the greatest opportunities for improvement lie, and reducing energy demand through retrofitting deserves to become a priority. It is expected that by 2050, 75–90 % of the existing buildings will still be standing and their upkeep is one of the major challenges to achieve the carbon reduction targets (IEA 2014). Given this context, improvements to buildings' façades can arguably be amongst the most effective interventions from a sustainability point of view. More specifically, glazed Double-Skin façades (DSFs) are amongst the best façade technologies to reduce energy consumption and greenhouse gas (GHG) emissions, while helping provide comfortable conditions to the occupied spaces (Shameri et al. 2011). In refurbishments, a DSF consists of a second, glazed skin installed in front of the existing building façade, which creates an air space that acts either as a thermal buffer or a ventilation channel or a combination of both. Operational behaviour of the DSF has been widely studied and, in temperate climates, this technology promises significant reductions of 30–60 % in heating and cooling loads (e.g., Cetiner and Ozkan 2005). To the contrary, existing knowledge is extremely limited about DSF embodied energy (EE), embodied carbon (EC) and life cycle environmental impacts (LCEIs).

This paper aims to address such a knowledge gap through a comparative assessment of DSFs and up-to-standards single-skin (SS) refurbishments solutions. Specifically, the LCEIs of DSFs for office refurbishments are assessed through a cradle-to-grave LCA with a twofold aim. Firstly, Cumulative Energy Demand (CED) and Global Warming Potential (GWP) are used as impact assessment methods to answer the following research question: can DSFs be considered as a low-carbon refurbishment solution for the UK? Secondly, a more comprehensive impact assessment method, i.e. ReCiPe, is used to reveal what additional impacts the DSF bears despite its energy and carbon saving potential.

LCA in the Architecture Engineering and Construction (AEC) Industry

Sustainability assessment of buildings throughout their life cycle is currently not regulated by policy in Europe (Moncaster and Symons 2013). LCA scenarios are inconsistent and varying with regard to settings, approaches and findings, and there are major impediments in the way of consolidation and comparison of results. Different lifetime figures, lack of parametric approaches, little clarity in the functional unit (FU) considered, diverse methodologies and methods for conducting the studies, and the focus mainly on real buildings are the most important reasons (Cabeza et al. 2014). Such diversity is justified by and originates from the inherent complexity of the construction sector where each of the materials used has its own specific life cycle and all interact dynamically in both temporal and spatial dimensions. Additionally, the long lifespan of buildings combined with the change of use during their service life imply lower predictability and higher uncertainty of variables, parameters and future scenarios. Such difficulties eventually lead to taking a 'reductionist' approach in many recent LCAs, where the term 'simplified' often recurs (Bala et al. 2010; de Benedetti et al. 2010; Malmqvist et al. 2011; Wadel et al. 2013—amongst others).

To address and facilitate some of these issues, the European Technical Committee CEN/TC 350 has developed standards that look at the sustainability of construction works with the aim of quantifying, calculating and assessing the life cycle performances of buildings (BSI 2010). Those standards have recently been used to develop tools to evaluate the embodied carbon and energy of buildings (Moncaster and Symons 2013). These tools echo the focus on GWP as the assessment method when analysing impacts of buildings and their components from a life cycle perspective (Ardente et al. 2011; Hammond and Jones 2008). The emphasis on the use of GWP as a method to assess GHG emissions has been described as a crude approach but also beneficial to ease understanding and enhance transparency (Weidema et al. 2008). Nevertheless, GWP fails to account for important impacts (Asdrubali et al. 2015) such as eco- and human-toxicity, or water and land use, and may lead to erroneous judgments about environmental consequences (Turconi et al. 2013).

In the specific case of buildings, they are large, complex, unique and involve a broad range of materials and components which, in turn, hold various environmental impacts (EIs) that are not only difficult to track but also challenging to assess and interpret (Dixit et al. 2012). Therefore, when considering LCA as a facilitator to help determine the least damaging alternative, the adoption of more comprehensive impact assessment methods combined with life cycle energy and carbon assessments is arguably a sensible way forward.

LCAs of DSFs

Only two studies exist where DSFs have been examined in detail from a life cycle perspective (de Gracia et al. 2013; Wadel et al. 2013). This alone represents a gap in knowledge with reference to a technology widely used in the AEC industry with a strong belief that it delivers "green" buildings, and is thus able to reduce EIs. Furthermore, both studies refer to specific façade typologies, located in well-defined and particular contexts, thus increasing the difficulty in comparing and replicating results and methodologies. Additionally, both the DSFs considered in the studies are innovative products which do not represent the current practice in the AEC industry.

Wadel et al. (2013) adopt a *simplified* LCA for an innovative type of DSF with vertical shading devices placed at specific intervals. The use phase is not incorporated in the LCA and impacts assessed throughout the study are limited to embodied energy and CO_2 emissions, the FU being 1 m^2 of the façade with a lifespan of 50 years. With reference to those two impact categories the DSF, in its best configuration, is capable of a 50 % reduction in energy consumption and CO_2 emissions, compared to conventional façades (Wadel et al. 2013).

At an even more specific level, de Gracia et al. (2013) conduct a cradle-to-grave LCA of a DSF with phase change materials (PCM) in its cavity. They utilise the Eco-Indicator 99 (EI99), an impact assessment method based on endpoints. This means that results from different impact categories are normalised and brought together to contribute to a final, single, cumulative score (known as the 'endpoint') for the product/process under examination. The FUs used are two cubicles constructed in Spain, one with the DSF, the other without, with a lifespan of 50 years; the former reduces the EI by 7.5 % compared to the reference case (de Gracia et al. 2013).

Notwithstanding the importance of regional and local foci in LCAs, neither study allows for the generalisations needed for better informed applications of DSFs. More generic perspectives could allow for a broader use of the methods and could also ease comparison of results within different contexts. A less context-specific EI assessment of office façades has been done by Kolokotroni et al. (2004). A specific DSF configuration is just one amongst many more options they assessed for both naturally ventilated and air-conditioned offices, and therefore the authors had to sacrifice the depth for the breadth of their investigation. Embodied energy and EI99 have been used as methods and the DSF has the highest embodied energy but the lowest EI99 score. Apart from these three studies, DSFs have not been investigated from a life cycle perspective, nor have they been studied in a refurbishment context in comparison with SS solutions. Consequently, primary data related to DSFs are still largely missing in the literature. In other words, the LCEIs of DSFs are yet to be established comprehensively. This is mainly due to a lack of data for glass processes, and echoes a known issue in the LCA community: the lack of reliable and complete data about buildings materials and assemblies which, if they existed, would allow for greater environmental benefits (Reap et al. 2008).

Research Methodology and Methods

For this research, a cradle-to-grave LCA has been conducted based on the aforementioned TC350 standards. Specifically, a clear distinction is considered between the thermal behaviour of the building, i.e. the energy analysis of the DSF models, and the embodied impacts in pre- and post-occupancy phases, and end of life stages. These will be addressed in the next two subsections, followed by details for the EIs assessment.

Operational Phase

Yearly operational energy consumption for space heating has been simulated through IES VE, a building energy simulation (BES) software used by academics and practitioners alike, and successfully deployed in DSF studies (e.g., Kim et al. 2013).

IES includes a natural ventilation analysis module which addresses phenomena such as single-sided and cross-ventilation, and flow in cavities due to wind and buoyancy effects. Additionally, elements such as infiltration and thermal mass are also suitably dealt with. The DSF structure obstructs to some extent the flow in the cavity, and the software vendor recommends correction in such cases, which have then been applied (IES 2014). Full details for the replicability of the study are given in Table 6.1. Reviewed LCA literature has shown that studies are often based on specific buildings, thus hindering generalisation of the conclusions and comparability of the results. Therefore, a generic yet representative office (Fig. 6.1 left) with

Table 6.1 Full details of dynamic thermal simulations

Element of the building fabric	Corresponding U-value
Roof	0.18 W/m^2 K
Ground floor	0.22 W/m^2 K
External walls	0.26 W/m^2 K
External windows	1.60 W/m^2 K
DSF glazing	4.62 W/m^2 K
Heating and occupancy profile	ASHRAE 8 am to 6 pm M-F
Heating set point/system	19.5 °C/radiators
Internal gains	21.5 W/m^2
Max sensible people gain	73.2 W/person
Occupancy density	13.93 m^2/person
Infiltration max flowrate	0.167 ach
External windows open at	22 °C
Cavity opens at	15 °C or 20 °C out. temp

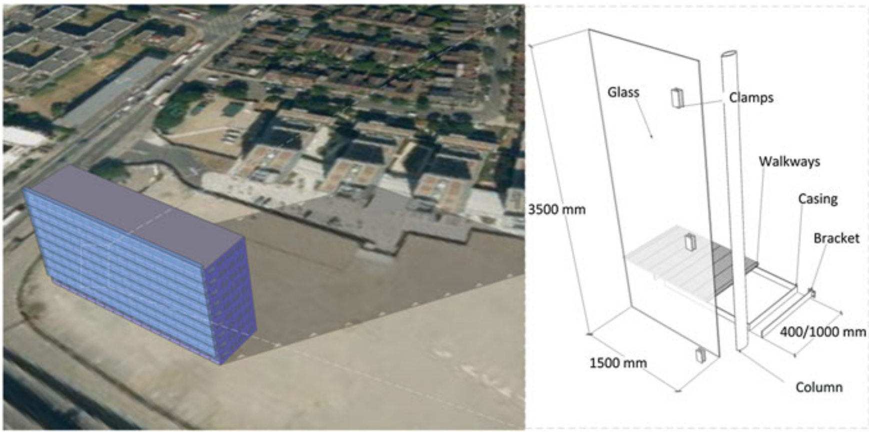

Fig. 6.1 Office building model (*left*) and exploded view of the FU (*right*)

a very slender built form has been selected; which is the most common office building type in England (Steadman et al. 2000).

The building is characterised by an open plan layout of the internal spaces. The building is located in London (weather file: Heathrow EWY). It consists of 9 floors of 66.6 m × 16 m, totalling 9590 m^2 of treated floor area (TFA). Window to wall ratio (WWR) equals to 0.25 which is a typical and highly correlated value to offices of this type (Gakovic 2000). The building is naturally ventilated, as are the majority of existing offices in the UK (CIBSE 2013). The façade service life is assumed at 25 years in line with studies specifically focused on building façades in the UK (Jin and Overend 2013). The DSF is equipped with a basic form of building management system (BMS) that opens the bottom and the top of the cavity when either outside air temperature exceeds 20 C or cavity temperature exceeds 15 C. These values are the result of an optimisation process aimed at minimising overheating of the indoor spaces in summer.

Embodied Impacts

DSFs are defined by several parameters, including the geometry of the cavity and its width. The configuration chosen here is multistorey, consisting of a cavity with no horizontal or vertical partitions. Regarding cavity width, narrow and wide categories are widely acknowledged and both are considered. Geometry of the building, data collected from visits to construction glass manufacturing facilities, interviews with a leading façade engineering and manufacturing company and the construction specifications, all helped determine the FU—which is 5.25 m^2 of façade (Fig. 6.1 right)—and the choice of additional parameters, leading to the options in Table 6.2. The combination of the parameters in Table 6.2 leads to a total of 128 assessed

Table 6.2 Realised and assessed options

Parameter	Options	Code(s)	No.	Details
Cavity	Narrow	CN	2	400 mm wide
	Wide	CW		1000 mm wide
Glass composition	Monolithic	M	2	12 mm thermally toughened (TT)—Heat Soak Tested (HST)
	Laminated	L		8 mm TT + 8 mm TT + 1.52 mm PVB
Glass coating	Clear	CL	2	Clear Float Glass
	Coated	CO		Solar Control Glass
Structure manufacture	Central Europe	Eu	2	Lorry Euro 4 (500 km)
	China	Int		Transoceanic ship (20,070 km)—Train (140 km)—Lorry Euro 4 (120 km)
Orientation	All combinations with 45° step	E, NE, N, NW, W, SW, S, SE	8	

options. Furthermore, eight additional SS scenarios (one for each orientation) were also realised and assessed in order to allow operational energy comparisons.

Current regulations mandate that operations needed for a SS refurbishment (e.g. improvement of wall insulation) are necessary in a DSF refurbishment as well. Therefore, common elements shared between the two refurbishments are excluded, and we drew the system boundaries around additional elements, (sub)assemblies, processes and stages that a DSF would bear. In doing so, this study accounts for the surplus of materials and processes involved when double-skin façade refurbishment is compared to single façade. These are represented in Fig. 6.2 which shows the flow-chart for the FU and its system boundaries. Data collection has been conducted systematically starting from the macro-assemblies as shown in Fig. 6.2 through a process-based analysis that refers to a mix of processes, products and location-specific data to calculate and establish the EI of a product system. In LCAs of buildings and their components, it appears to be the most reasonable and detailed choice (Hammond and Jones 2008); it is also suggested by the TC350 standards. White boxes in Fig. 6.2 indicate assemblies and stages for which EcoInvent data have been used. End of life treatments, i.e. recycling/waste figures, have been modelled according to the waste/recycling scenario available for England in EcoInvent.

Environmental Impacts Assessment

Attributional LCA (ALCA) and consequential LCA (CLCA) are known to be the main two methodological approaches commonly used by the LCA community. Due to the specific focus of this research on DSFs as a product, ALCA is the approach

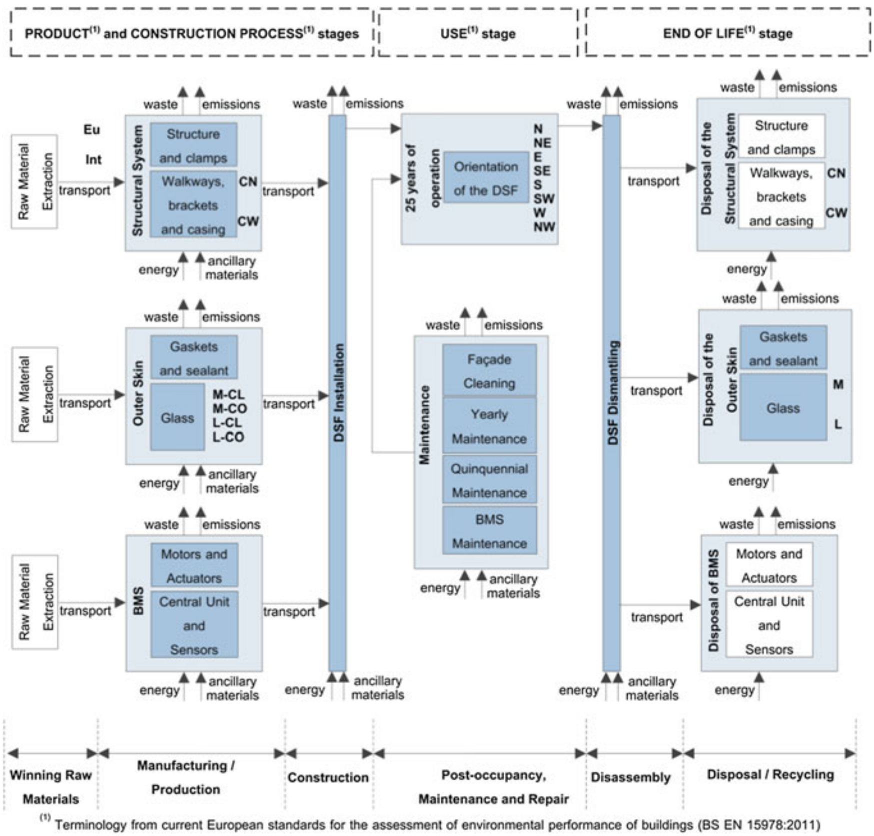

Fig. 6.2 Flowchart for the FU and its system boundaries

chosen for its focus on physical flows to and from a life cycle and its components. It is also recommended in the British Standard, PAS 2050:2011, to assess GHG emissions of goods and services (BSI 2011) in order to define the inputs and their associated emissions/impacts related to the delivery of the product FU. SimaPro, the most widely used LCA software, is the tool adopted for this study.

As aforementioned, two different impact assessment methods have been used to assess the low-carbon potential of the DSF: the CED (Frischknecht et al. 2003) and the GWP over a 100-year horizon (IPCC 2013). Additionally, ReCiPe hierarchic perspective midpoint v1.10 (Goedkoop et al. 2013)—which is a multi-category method commonly used in LCAs—has been used to assess additional ecological and EIs other from climate change. Midpoint modelling allows for higher transparency and lower uncertainty, whereas endpoint modelling shows things with more relevance but can be less transparent and harder to compare (Blengini and di Carlo 2010). Due to the unavailability of data for DSFs, midpoint modelling with an aim at maximising transparency was chosen.

Results

Figures 6.3 and 6.4 show energy and carbon results, respectively, for the assessed options. Specifically, 16 data series are presented that describe unique combinations of the DSF parameters considered. Each of them includes 8 data points that refer to the orientations of the building with that specific DSF configuration, thus totalling 128 data points. Dashed lines are indifference curves: data points below those lines have a negative life cycle balance (positive outcome).

As Fig. 6.3 shows, life cycle energy results are very promising with 120 out of 128 options (93.75 %) showing a negative life energy balance. The eight options with a pejorative life cycle energy balance are all characterised by a wide cavity and a SE orientation. Successful options drop to 72.65 % (93 out of 128) when the focus switches to carbon (Fig. 6.4). This is due to the actual source of energy that is being saved by the DSF (natural gas for space heating) versus the source of energy needed for the augmented embodied impacts of the DSF (mainly mid-voltage electricity for manufacturing activity). More specifically, gas and electricity have different GHG conversion factors (i.e. 1 kWh_{GAS} = 0.20155 $kgCO_{2e}$; 1 kWh_{ELEC} = 0.59368 $kgCO_{2e}$) thereby shifting options with a negative life cycle energy balance into options with a positive (pejorative effect) life cycle carbon balance. Amongst the options with a pejorative effect only two have a narrow cavity and both are SE-oriented models.

Table 6.3 shows the EI assessment results from ReCiPe with a colour scale to indicate highest/lowest impact within different categories. Orientation of the building models is omitted since it does not influence the embodied environmental

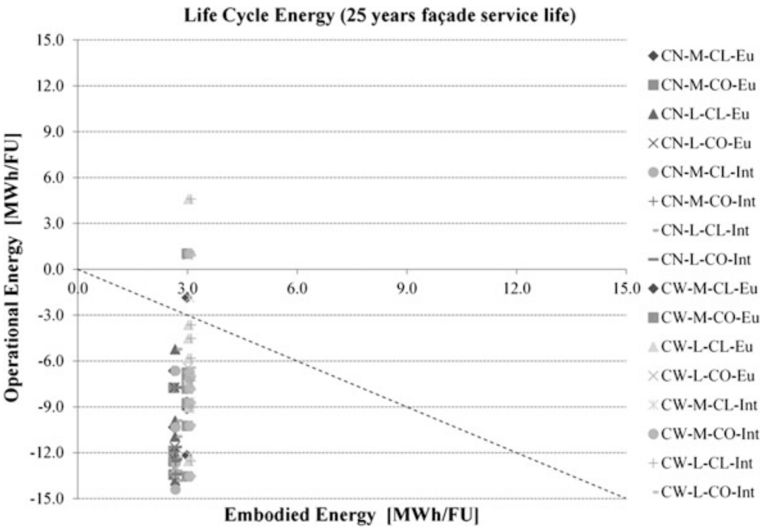

Fig. 6.3 Life cycle energy results (for abbreviations please refer to Table 6.2)

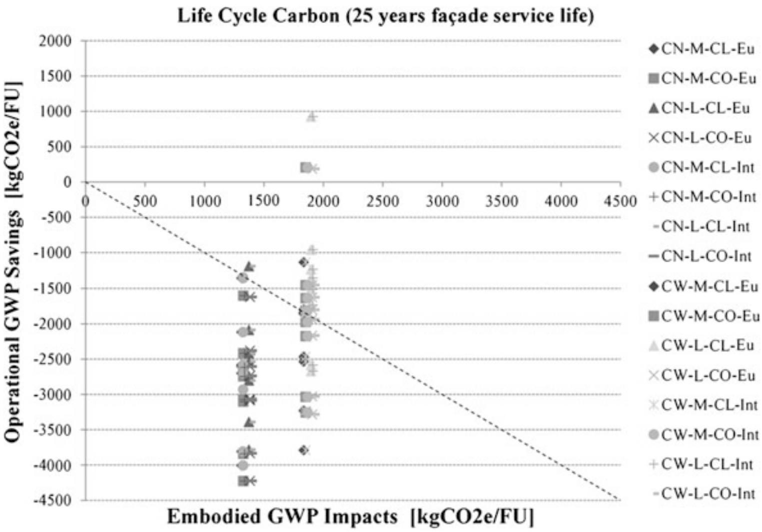

Fig. 6.4 Life cycle carbon results (for abbreviations please refer to Table 6.2)

Table 6.3 ReCiPe results (green = lowest impact; red = highest impact)

Options	IMPACT CATEGORIES (ICs) - ReCiPe hierarchic perspective midpoint v1.10																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CN-M-CL-Eu	1312.8	91.7	7.5	561.4	0.4	672.1	6.3	3.3	0.1	27.1	25.2	162.0	13.6	5.2	2.3E-02	10066.0	151.5	184.4
CN-M-CL-Int	1324.9	92.4	7.7	561.6	0.4	672.5	6.6	3.4	0.1	27.1	25.3	162.8	13.6	5.2	2.3E-02	10068.0	151.5	188.9
CN-M-CO-Eu	1327.0	92.8	7.6	570.0	0.4	677.4	6.4	3.4	0.1	27.1	25.3	168.5	13.9	5.2	2.3E-02	10143.0	151.5	184.4
CN-M-CO-Int	1339.0	93.5	7.8	570.2	0.4	677.7	6.6	3.5	0.1	27.2	25.3	169.3	13.9	5.2	2.3E-02	10145.0	151.5	188.9
CN-L-CL-Eu	1374.6	92.9	7.6	575.1	0.4	692.6	6.5	3.4	0.1	27.5	25.7	174.8	17.3	5.4	2.2E-02	10170.9	151.6	186.7
CN-L-CL-Int	1386.6	93.6	7.9	575.3	0.4	692.9	6.7	3.5	0.1	27.5	25.7	175.6	17.3	5.4	2.2E-02	10172.9	151.6	191.2
CN-L-CO-Eu	1384.6	94.0	7.7	584.6	0.4	687.7	6.6	3.4	0.1	27.5	25.6	181.2	17.2	5.3	1.5E-02	10253.6	151.6	185.7
CN-L-CO-Int	1396.6	94.7	8.0	584.8	0.4	688.0	6.8	3.5	0.1	27.5	25.6	182.0	17.3	5.4	1.5E-02	10255.6	151.6	190.2
CW-M-CL-Eu	1836.7	126.9	9.1	752.7	0.6	924.0	7.5	4.6	0.2	42.6	39.3	251.2	16.3	7.1	2.2E-02	16993.6	204.6	198.5
CW-M-CL-Int	1853.3	127.9	9.5	752.9	0.6	924.4	7.8	4.7	0.2	42.6	39.4	252.3	16.4	7.1	2.2E-02	16996.4	204.6	204.5
CW-M-CO-Eu	1850.9	128.0	9.2	761.2	0.6	929.2	7.5	4.6	0.2	42.7	39.3	257.8	16.6	7.2	2.2E-02	17070.6	204.6	198.5
CW-M-CO-Int	1867.4	129.0	9.6	761.5	0.6	929.6	7.8	4.7	0.2	42.7	39.4	258.9	16.6	7.2	2.2E-02	17073.4	204.6	204.6
CW-L-CL-Eu	1898.5	128.1	9.3	766.4	0.6	944.4	7.6	4.6	0.2	43.1	39.7	264.0	20.1	7.3	2.1E-02	17098.5	204.7	200.8
CW-L-CL-Int	1915.0	129.1	9.7	766.7	0.6	944.8	7.9	4.7	0.2	43.1	39.8	265.1	20.1	7.3	2.1E-02	17101.3	204.7	206.8
CW-L-CO-Eu	1908.5	129.2	9.4	775.9	0.6	939.5	7.7	4.6	0.2	43.0	39.7	270.5	20.0	7.3	1.4E-02	17181.2	204.6	199.8
CW-L-CO-Int	1925.0	130.2	9.8	776.2	0.6	940.0	8.0	4.8	0.2	43.0	39.7	271.6	20.0	7.3	1.4E-02	17184.0	204.6	205.8

ICs: 1=Climate Change [kg CO_{2eq}]; 2=Ozone depletion [mg CFC-11_{eq}]; 3=Terrestrial acidification [kg SO_{2eq}]; 4=Freshwater eutrophication [g P_{eq}]; 5=Marine eutrophication [kg N_{eq}]; 6=Human toxicity [kg 1,4-DB_{eq}]; 7=Photochemical oxidant formation [kg NMVOC]; 8=Particulate matter formation [kg PM_{10eq}]; 9=Terrestrial ecotoxicity [kg 1,4-DB_{eq}]; 10=Freshwater ecotoxicity [kg 1,4-DB_{eq}]; 11=Marine ecotoxicity [kg 1,4-DB_{eq}]; 12=Ionising radiation [kBq $U235_{eq}$]; 13=Agricultural land occupation [m^2a]; 14=Urban land occupation [m^2a]; 15=Natural land transformation [m^2]; 16=Water depletion [m^3]; 17=Metal depletion [kg Fe_{eq}]; 18=Fossil depletion [kg oil_{eq}]

and ecological impacts. In the results from ReCiPe, operational savings are no longer significant. By contrast, assemblies and stages of the DSF show their embodied impacts that suddenly become worthy of closer attention.

Discussion of Findings

With respect to the research question that this study aims answering, i.e. can DSFs be considered as a low-carbon refurbishment solution for the UK?, results have shown that for the vast majority of the options assessed DSFs perform extremely well when looked at from a life cycle perspective. More specifically, 93.75 and 72.65 % of the options performed better than their SS counterparts in terms of life cycle energy and carbon, respectively. DSFs application to the refurbishment of existing non-domestic buildings therefore, can be recommended in the contexts similar to the one studied here, with the aim of mitigating GHG emissions. The parametric approach adopted in this study allows for some significant insights in terms of sensitivity analysis regarding the options that showed a positive life cycle balance (negative outcome). Cavity width and orientation are, in such order, the most significant parameters both energy- and carbon-wise. Wider cavities imply a higher amount of construction materials to be manufactured, transported, installed, and disposed of, thereby increasing significantly both embodied energy and carbon. Wider cavities also imply a higher mass of air that needs to be solar heated prior to 'activating' the thermal buffer behaviour of the DSF. Such an aspect explains why narrow cavities show slightly better operational energy savings.

Regarding the orientation, SE is the common underlying characteristics of most of the unsuccessful options. A SE-oriented building can benefit from a fair amount of solar gain and, in fact, the SE-oriented SS model is the one with the least energy consumption amongst the eight SS options. In the DSF model, the solar gain increases the temperature of air in the cavity that eventually reaches the threshold which activates openings at the bottom and the top through the BMS. Therefore, for the majority of the occupied time the cavity is open and its thermal buffer effect is almost counteracted, and so is its energy saving potential. Glass type and glass coating, in such order, follow in terms of significance, with monolithic glass to be preferred over laminated glass, and clear glass over coated glass. When looking at the two parameters combined, their significance implies that M-CO options are always better than L-CL options (glass type predominant over glass coating). Source of the materials is the least impacting parameter, with EU-sourced materials showing lower impacts than those coming from China.

In contextualising our results with the only LCA of DSFs that provides sufficient detail to attempt a comparison (Wadel et al. 2013), specific values are in line energy-wise whereas there exists a big difference for what concerns carbon. Specifically, the embodied energy of the 128 options we assessed ranges from 1793.11 to 2127.93 MJ/m^2, which are values significantly close to the 2273.08 MJ/m^2 of Wadel et al. (2013). To the contrary, their embodied carbon equals to 178.64 kg CO_{2e}/m^2

whereas we found a range of 250.06–366.67 kg CO_{2e}/m^2 which is up to more than twice as much. A possible reason lies in the significant amount of primary data we collected from manufacturers that allowed us to assess embodied figures with less uncertainty and fewer assumptions. However, the DSF assessed by Wadel et al. (2013) represents an innovative system made out of recycled materials and such an aspect could play a significant role in lower carbon figures.

Regarding the ReCiPe results (Table 6.3), the options with the highest and lowest impact categories, identified with reference to the GWP, i.e. climate change, are often also those which score the most and the least in most other categories. This, however, does not necessarily hold true when looking at options with the second/third, etc. highest/lowest impact within different categories (colour scale in Table 6.3). Additionally, there is nonetheless little in common when the impacts are analysed in detail. In fact, had the decision about which the best/worst DSF options are had been made based merely on life cycle energy and carbon balances, the logical consequence would have been to focus on the most significant reduction in those. Still, it was shown that other impact categories also suggest significant impacts for other assemblies and stages of a DSF life cycle, such as the production of elements of the outer skin, their maintenance and disposal—which are worthy of further investigation. Therefore, our study echoes encouragement for a shift in the current practice of LCA within the construction industry. More specifically, the choice of impact categories needs to be revisited and customised to the specifics of each and every case, depending on the context, focus and purpose of the assessment.

Conclusions

This study has shown that the vast majority of the DSF options assessed perform better than their SS counterparts when used in office refurbishments in the UK. The combined use of life cycle energy and carbon assessments not only showed how significant the energy reduction potential is but it also indicated which options are critical when the focus switches to carbon, thus taking into account the specific type of energy that is being saved. Additionally, the use of ReCiPe as a multi-category impact assessment method highlighted that energy and carbon analyses tend to miss out key information that may influence the interpretation of, and conclusions from, the assessment. In the case of DSFs, ReCiPe results indicate that more attention should be paid to the structure of the façade and its maintenance, and to more efficient disposal solutions, rather than focusing solely at optimising DSFs' operational performance, which seems to be where research in the field is mostly heading. The focus on specific climate, i.e. London, and a specific structure, i.e. aluminium, in addition to the lack of uncertainty analysis of the data through, for instance, Monte Carlo simulation can all be seen as limitations of this study and surely represent important and interesting areas for further research.

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Chapter 7
Off-the-Shelf Solutions to the Retrofit Challenge: Thermal Performance

David Farmer, Chris Gorse, Dominic Miles-Shenton, Matthew Brooke-Peat and Callum Cuttle

Abstract The potential to reduce energy demand and thus carbon emissions from the built environment is considerable. As well as benefitting the environment, good energy efficient retrofits can reduce energy bills and improve thermal comfort; however, the discrepancy between expected and actual performance can mean the anticipated benefits are not fully realised. If thermal upgrades are to be accepted and adopted the retrofit solutions should be simple and effective and deliver the performance expected. This paper summarises part one of a two-stage Saint-Gobain funded research project which investigated the change in thermal performance resulting from a number of 'off-the-shelf' thermal upgrade measures applied to a circa 1900 solid wall end terrace house situated in an environmental chamber. The project involved a phased programme of upgrades to the thermal elements of the test house; thermal upgrades were applied either individually or in combination. Presented are the quantitative measurements of thermal performance at each test phase which are compared against baseline values measured while the test house was in its original condition. The heat loss coefficient (HLC) of the fully retrofitted dwelling was 63 % lower than the dwelling in its baseline condition. 72 % of the HLC reduction was attributable to the application of a hybrid solid wall insulation system. The fully retrofitted test house had a measured air permeability value that was 50 % lower than in its baseline condition. There was close agreement between the calculated upgrade U-value and that measured in situ for most thermal upgrade measures. The primary conclusion of the paper is that dwellings of this type, which

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represent a significant proportion of the UK housing stock, have the potential to be retrofitted using off-the-shelf thermal upgrade measures to a standard which meets design expectations and can significantly reduce their requirement for space heating and currently associated CO_2 emissions.

Keywords Building performance · Heat loss coefficient · In situ U-values · Airtightness · Full scale test facility · Off-the-shelf solutions · Retrofit

Introduction

A third of global anthropogenic CO_2 emissions come from buildings, their use and contributing processes. The UK's, the built environment contribution is proportionally higher representing 45 % of the carbon footprint (Prism Environment 2012: Report for the European Commission; Palmer and Cooper 2013). The domestic sector accounts for approximately 29 % of UK carbon emissions (DECC 2013a, b); with the heating of buildings being responsible for the greatest proportion of emissions, representing 62 % of the total energy used in homes (DECC 2013a, b; 2014). Reducing emissions from the built environment should be a relatively straight forward proposition, without such action the UK Governments legally binding target to reduce greenhouse gas emissions by at least 80 % in 1990 levels by 2050 set out in the Climate Change Act 2008 (HMSO 2008) will be almost impossible to achieve (Oreszczyn and Lowe 2010; Gorse 2015). The carbon contribution of the construction industry represents a significant burden, the built environment being responsible for the largest share of emissions by some way, thus action towards greater energy efficiency is required.

The European Energy Performance of Buildings Directive (2010/31/EU) which demands that all new buildings should be zero energy buildings by 2020 represents a significant challenge to the construction sector. While the new-build targets are considered challenging and improvements are currently on the conservative side to achieve the zero energy target, the existing building stock is proving even more resistant to regulation. Despite government support schemes and information provided on the potential savings that retrofit measures could achieve, the uptake in energy efficiency upgrades has not been as rapid as expected (Reeves et al. 2010). For many, it is the complexity of retrofit and financing that present a barrier to intervention and uptake (Dowson et al. 2012). The UK Government's aspirations could be considered ambitious, especially since there are relatively few studies that show actual savings, have measured thermal performance of whole buildings and understand how they behave and respond, as they do, when heated (Gorse et al. 2015a). There are, however, a few studies showing what can be achieved.

It is possible to retrofit homes to make them energy efficient (Stafford 2012a); furthermore, substantial reductions in emissions and heating costs have been achieved in demonstration and research projects (JRHT 2012; Killip 2008; Miles-Shenton et al. 2011). However, the distinct lack of measurement and almost anecdotal studies of deep-retrofit buildings means that designers have little data to guide their specifications when working with the new energy efficiency targets (Gorse et al. 2015a). The difference between design aspirations and actual thermal performance achieved in the field represents a real challenge for the industry (Stafford 2012b).

To achieve the desired reductions in CO_2 emissions currently associated with heating homes, improvements in thermal performance must be achieved in practice. Unfortunately, significant differences between the designed thermal performance and that actually achieved have been reported (Stafford et al. 2012a, b), this phenomenon is known as the *performance gap*. Furthermore it is not uncommon for new dwellings, where standards of energy efficiency are considered easier to achieve, to experience 60 % greater heat loss than expected (Gorse et al. 2013). Most of the studies that report the performance gap examine new build construction, where it is suggested, that there are greater levels of control and certainty. The performance gap for retrofit buildings have received less attention than new buildings, there is a relative dearth of research in this area. UK Government thermal performance programmes have attempted to account for the performance gap by applying a penalty known as an *in-use factor* to potential savings from thermal upgrades (DECC 2012a, b). The build, materials and properties of existing building represent a largely unknown and challenging quantity (Dowson et al. 2012). Until a full building survey has been undertaken on an existing building, the assumptions regarding the building fabric is often very limited. To understand thermal performance of retrofit measures, the properties of the existing building must first be understood. Only once the properties of the existing buildings properly captured by survey can the designed interventions be specified and potential improvements be determined (Doran et al. 2014). Furthermore, research into existing building behaviour and the way the behaviour changes as new materials are introduced is essential to inform understanding of retrofit measures and their performance. Where attention is not given to surveys and properties of existing buildings, retrofit measures do not work as expected. (Doran et al. 2014). Doran et al. (2014) notes that the impact of change in thermal retrofits is often different to that expected due to inadequate building information, limited details in design and inadequate method of installation such as: poor workmanship, poor standards on site, gaps in the insulation, changes in the specifications, poor execution of details at junctions and poor site care.

While the potential reductions in carbon emission are considerable, care should be taken as the building stock is diverse and the technical, economic and social issues require consideration (Stafford et al. 2012a, b). However, the primary gains will only be achieved through improved retrofit fabric performance of the existing building stock (Killip 2008). The replacement of buildings is slow and the trend is to hold on to and upgrade buildings, extending their useful life. By 2050 70 % of the total building stock still in use, 40 % will be pre-1985, pre-dating the introduction of energy efficient measures (Part L) to the Building Regulations Building

Regulations for England and Wales (Better Buildings Partnership 2010). Hartless (2004) offers an estimate of new build, replacement and renovation rates in a number of European member states. While annual replacement rates in the UK are low at around 0.1 % of existing stock, due to low demolition and new build rates, the rate of renovation and refurbishment are likely to be much higher at around 2.9–5 % of existing stock for domestic buildings per annum. However, for energy efficiency and reduction in emissions to be achieved, fabric thermal upgrades, that are effective, should be incorporated within regulatory reform. A significant proportion of the existing building stock is considered difficult to treat, solid wall construction representing approximately 34 % of the existing building stock falls in this category (Doran et al. 2014). Identifying simple methods to achieve the thermal performance improvements for such housing is important to achieving the carbon reduction targets. Equally, ensuring that realistic performance targets are set and true tolerance factors are agreed plays an essential part in performance economics and 'pay-as-you-save' models. To do understand how the building systems work and behave requires research into actual performance.

Upgrading the building stock represents an even greater challenge than that faced by the new build sector, but one where the greatest benefits are to be gained (Dowson et al. 2012; Killip 2008). The first step should be to understand the performance of whole buildings and undertake detailed enquiry into specific elements of performance. Thermal performance of a building relies on its ability to resist air penetration as well as its ability to prevent heat exchange through the structure. In much of the existing stock air leakage is a particular problem (JRHT 2012).

The paper presents a summary of an investigation into the change in thermal performance resulting from a number of conventional 'off-the-shelf' upgrade measures to a replica circa 1900 end terrace house that is situated in an environmentally controlled chamber at the University of Salford Energy House test facility (refer to Appendix for details). The investigation was undertaken by Leeds Beckett University in collaboration with the University of Salford and Saint-Gobain Recherché.

Methodology

The objective was to measure the steady-state thermal performance of the test house at each stage of the upgrade process. By undertaking measurements at each phase of the thermal upgrade, the change in the thermal performance and behaviour characteristics can be compared against a baseline value measured with the test house in its original condition. The programme enabled a comparison to been made between the calculated and measured increase in thermal performance, which enabled any performance gap to be identified and quantified.

Quantitative measures of the thermal performance of the test house obtained during the test programme included: in situ U-values of thermal elements, whole house heat loss (heat loss coefficient (HLC)), airtightness testing and surface temperatures. Figure 7.1 provides an image of the test set-up in one room. Qualitative data were also collected which enabled the research team to gain insight and provide comment on the behaviour of the test house throughout the test programme; this included: thermographic surveys, construction observations, air leakage/infiltration detection using thermography and smoke and borescope inspections. Thermal bridging calculations were also used to model the behaviour at the junctions.

The Energy House test facility provided a controlled environment in which a steady-state can be achieved and maintained; furthermore, conditions in the test chamber can be repeated across successive test periods. Consequently, any changes in the thermal performance characteristics of the test house can be attributed to the specific retrofit measures with a higher degree of confidence than would otherwise be the case in the external environment, as the uncertainties caused by dynamic environmental factors such as large variations in external temperature, solar radiation and wind are removed.

Additional blind measurements of the teat house HLC were undertaken by Saint-Gobain Recherche using the Quick U-Value Method (QUB) which provided an opportunity to validate the results and analysis (refer to Alzetto et al. 2015). The QUB method can be found in Pandraud et al. (2014) and the results between the tests are reported in detail in the full report (Farmer et al. 2015).

Test Programme

The test house underwent a phased process of thermal upgrade measures. The thermal elements of the test house were upgraded individually, or in combination;

Fig. 7.1 A 360° image of test set up in bedroom one of the test house. Heat flux plates (*red discs*) are positioned on the on the external thermal elements

the configuration of the test house at each phase of the test programme is provided in Table 7.1.

At each phase of the test programme the following measurements of thermal performance were obtained: steady-state in situ U-values, steady-state HLC, air permeability/leakage rate, and surface temperature measurements.

These measurements provided either the *baseline* or *upgrade* value for each intervention. The thermal performance attributable to a thermal upgrade was calculated as the measured change from the baseline value. Because the upgrade process was performed in reverse order, the upgrade value was measured prior to the baseline value.

In addition to the programme of fieldwork undertaken at the Energy House test facility, a number of the test house's junctions was also thermally modelled to provide baseline and upgrade values for thermal bridging characteristics.

Test Methods

Steady-State Environment

To be confident of accurate and precise measurement of steady-state in situ U-values and HLC requires a steady-state test environment where a level of temperature control can be achieved. The test environment allowed stable temperature control on

Table 7.1 House configuration at each test phase (*shading* represents retrofit installed)

<table>
<tr><th rowspan="2">Test phase</th><th colspan="4">Condition of thermal element at each test phase</th></tr>
<tr><th>External wall</th><th>Roof</th><th>Glazing</th><th>Floor</th></tr>
<tr><td>Full retrofit</td><td rowspan="4">Hybrid solid wall insulation system
90 mm EPS EWI to gable and rear walls
80 mm PIR IWI to front wall</td><td rowspan="2">270 mm mineral wool</td><td rowspan="2">A+++ glazing, argon fill, low e</td><td>200 mm mineral wool & membrane</td></tr>
<tr><td>Full retrofit (no floor)</td><td rowspan="6">Uninsulated (suspended timber)</td></tr>
<tr><td>Solid wall 1</td><td rowspan="3">100 mm mineral wool</td><td rowspan="2">1980s style double glazing units</td></tr>
<tr><td>Solid wall 2</td></tr>
<tr><td>Glazing</td><td rowspan="3">Uninsulated (solid wall)</td><td>A+++ glazing, argon fill, low e</td></tr>
<tr><td>Loft</td><td>270 mm mineral wool</td><td rowspan="2">1980s style double glazing units</td></tr>
<tr><td>Baseline (original)</td><td>100 mm mineral wool</td></tr>
</table>

either side of the thermal envelope. At each phase of the programme the test house and chamber were left undisturbed for a minimum duration of 72 h. A steady-state was considered to be achieved if the heat flux density or total power input differed by less than ±5 % from the value measured in the previous 24 h period.

Steady-State in Situ U-Value Measurements

The thermal transmittance of a building element (U-value) is defined in ISO 7345 as the "*Heat flow rate in the steady-state divided by area and by the temperature difference between the surroundings on each side of a system*" (ISO 1987, p. 3). U-values are expressed in W/m^{2}K. In situ U-value measurements were undertaken in accordance with ISO 9869 (ISO 1994).

In situ measurements of heat flux density, from which in situ U-values were derived, were taken at 75 locations on the thermal elements of the test house using heat flux plates (HFPs). Only measurements of heat flux density obtained from those locations that were considered not to be significantly influenced by thermal bridging at junctions with neighbouring thermal elements (typically at distances greater than 1000 mm from the junction) were used in the calculation of the baseline and upgrade in situ U-values. Measurements were taken at the junctions, however, these are not reported here.

The measured baseline in situ U-values were compared to predicted U-values calculated in accordance with BS EN ISO 6946 (BSI 2007) and/or the RdSAP assumed U-value (BRE 2012). This was undertaken to test the robustness of these values when assessing the thermal performance of the existing housing stock.

To account for the actual thermal performance of the baseline thermal element, the calculated U-values for elements which were thermally upgraded have been based upon the measured baseline in situ R-value (1/U-value) of the original element plus the additional R-value of the thermal upgrade materials and calculated in accordance with BS EN ISO 6946.

Steady-State Heat Loss Coefficient Measurements (Whole House Heat Loss)

The heat loss coefficient is the rate of heat loss (fabric and ventilation) in watts (W) from the entire thermal envelope of a building per kelvin (K) of temperature differential between the internal and external environments and is expressed in W/K. A modified version of Leeds Beckett University's Whole House Heat Loss Test Method (Johnston et al. 2013) was used to obtain measurements of the test house HLC during each steady-state measurement period.

HLC measurements were used to compare the change in whole house heat loss resulting from individual and collective thermal upgrade measures. The change in HLC captures the aggregate change in plane element, thermal bridging and ventilation heat losses of the test house.

Airtightness Testing and Building Pressurisation Tests

Building pressurisation tests using a blower door in accordance with ATTMA L1 (ATTMA 2010) were performed to establish the change in the airtightness of the test house resulting from each thermal upgrade. An estimation of the background ventilation rate was derived from the air leakage rate at 50 pascals; this value was used to isolate the ventilation heat loss components of the HLC using the $n_{50}/20$ rule (Sherman 1987). The conditions present during the pressurisation tests provided the opportunity for leakage/infiltration identification. During building pressurisation, leakage detection was performed using a smoke puffer stick at individual locations within the test house and a whole building smoke leakage detection test was undertaken using a high volume smoke generating machine. During depressurisation, the elevated temperatures within the dwelling enabled infrared thermography to be used to observe and record any areas of air infiltration.

Thermal Bridging Calculations

Thermal bridging calculations were performed at the junctions to ascertain the linear thermal transmittance (ψ-value) and minimum temperature factor (f_{min}). Thermal modelling was used to calculate thermal bridging. Modelling was undertaken using the Physibel TRISCO version 12.0w (Physibel 2010). Conventions BR 497 (Ward and Sanders 2007) were followed where appropriate.

Results and Discussion

The results are provided with the caveat that the tests were conducted in the absence of dynamic environmental factors, such as wind, thus similar levels of thermal performance cannot be guaranteed in the external environment.

Heat Loss Coefficient (Whole House Heat Loss)

It was not possible to accurately compare upgrade HLCs against predicted values as thermal bridging calculations were not performed for all junctions and single zone tracer gas techniques used to ascertain the background ventilation rate, from which ventilation heat loss is derived, were found not to be suitable for the test environment. This also precluded the estimation of the HLC from in situ U-value measurements.

The HLC measured at each phase is provided in Fig. 7.2 and Table 7.2. The full retrofit resulted in a whole house heat loss reduction of 63 %.

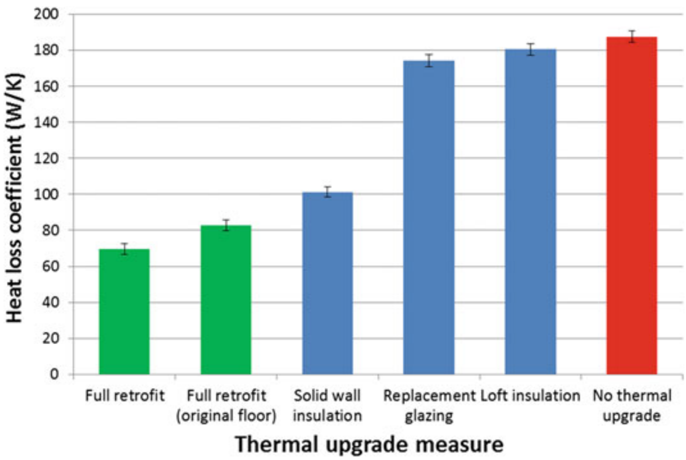

Fig. 7.2 Whole house heat loss value of the test house in each condition (*blue bars* represent the test house HLC following a single thermal upgrade measure, *green bars* represent thermal upgrade measures in combination)

Table 7.2 Impact of thermal upgrade measures on a similar house in the external environment[a]

Thermal upgrade measure	HLC (W/K)	Reduction on baseline (W/K)	Annual space heating energy reduction[b] (kWh)	Annual space heating cost reduction[c] (£)	Annual space heating CO_2e reduction[d] (kg)
Full retrofit	69.7	117.8	6497	348	1449
Full retrofit (original floor)	82.7	104.8	5777	310	1289
Solid wall insulation	101.2	86.4	4761	255	1062
Replacement glazing	174.2	13.4	737	39	164
Loft insulation	180.5	7.1	390	21	87
No thermal upgrade	187.5	n/a	n/a	n/a	n/a
Floor upgrade[e]	n/a	13.1	720	39	161

[a]Cost and CO_2 equivalent emission reductions assume the dwelling is heated using mains natural gas with an 82.5 % efficient condensing boiler and located in Manchester, UK (efficiency-based on Energy Saving Trust Field Trails of Boiler Efficiency (though includes DHW) 2009)
[b]All values calculated for reduction in annual heat demand are based on the previous 5 years (2008–2012) mean annual heating degree day value of 2297 measured at Manchester Airport (base temperature 15.5 °C), data sourced from BizEE (2013) and assumes condensing gas boiler efficiency of 82.5 %
[c]Based upon average gas price for Manchester during 2012 of 4.42p per kWh, data sourced from ONS/DECC 2013a, b
[d]Based upon June 2013 value for natural gas of 0.18404 kgCO_2e per kWh, data sourced from the Carbon Trust 2013
[e]Values for the ground floor are calculated as the difference from the full retrofit test HLC

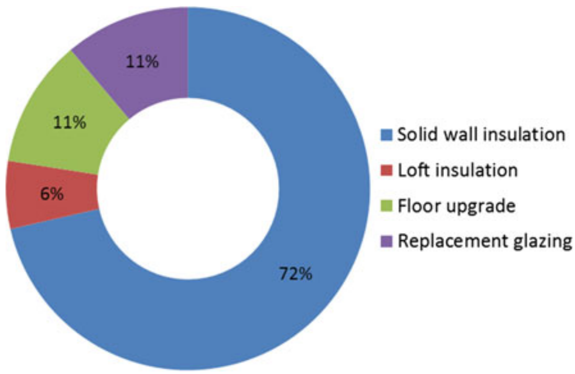

Fig. 7.3 Contribution of each thermal upgrade measure to the reduction in whole house heat loss of the fully retrofitted test house

Solid wall insulation was the thermal upgrade measure which resulted in the largest individual reduction (46 %) in HLC from the baseline value; it can be seen in Fig. 7.3 that this measure comprised 72 % of the total reduction in HLC in the fully retrofitted test house. It must be noted that the contribution of each thermal element to the reduction in HLC is highly dependent upon the proportion of elemental surface areas (e.g., end terrace dwellings will have a proportionally higher external wall surface area than mid-terrace dwellings).

The sum of the reductions in HLC resulting from individual thermal upgrade measures differs from that measured during the two full retrofit test phases (when upgrade measures were installed in combination) by <1 %.[1] This finding suggests that the full retrofit provides no additional thermal performance above the cumulative sum of the individual thermal upgrade measures in this instance. The close agreement also increases confidence in the whole house heat loss test method to measure the effectiveness of thermal upgrade measures in this environment.

Reduction in Space Heating Cost and Emissions

Based on the assumptions provided with Table 7.2, a notional dwelling of similar heat loss characteristics, subject to a similar thermal upgrade programme, could reduce annual space heating costs from £554 (no thermal upgrade) to £206 (full retrofit) with annual CO_2e[2] emissions associated with space heating reducing from 2.31 tonnes (no thermal upgrade) to 0.86 tonnes (full retrofit). Though assumptions

[1]This calculation uses the reduction in HLC of 84 W/K measured during the Solid wall 1 test phase which represents the condition of the external walls during the full retrofit test phases.

[2]Equivalent carbon dioxide.

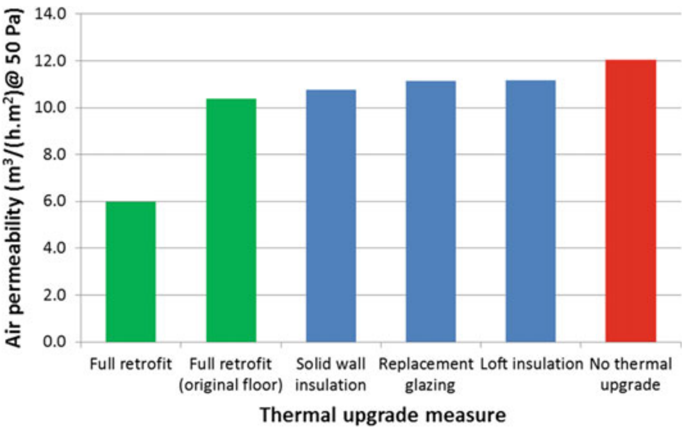

Fig. 7.4 Air permeability value of the test house in each condition (*Blue bars* represent the test house HLC following a single thermal upgrade measure, *green bars* represent thermal upgrade measures in combination)

are made as to the heating regime of the notional dwelling, it is clear that substantial reductions in a dwelling's HLC can help to reduce the financial and environmental cost of solid wall dwellings.

Airtightness

The full retrofit of the test house resulted in a 50 % reduction in air permeability from its original condition. From Fig. 7.4 it can be seen that the upgrade measures to the floor resulted in the greatest increase in airtightness of the test house, a reduction of 42 % from the baseline value.[3] The increase can be primarily attributed to the airtightness membrane. Had the membrane been sealed to the walls and not the skirting board it was anticipated that the measured airtightness would have seen a greater improvement. A whole building smoke leakage detection test performed under building pressurisation during the full retrofit test phase showed the suspended ground floor (via the underfloor void and airbricks) to be the most visible air pathway. This observation was also evident using thermography under building depressurisation.

[3]The baseline airtightness value for the ground floor upgrade measures was measured during the Full retrofit (original floor) test phase.

In Situ U-Values

Figure 7.5 provides a summary of the baseline and upgrade in situ U-value measurements and Table 7.3 compares the difference between the calculated and measured upgrade in situ U-values with in-use factors.

Most thermal upgrades measured were within the statistical uncertainty of the in situ U-value measurement. The in-use factor for all thermal upgrades is greater than any in situ underperformance measured and suggests that, where installation methods are effective in meeting the performance demonstrated here, there is potential for in-use factors to be reduced. The upgrade measures were performed by

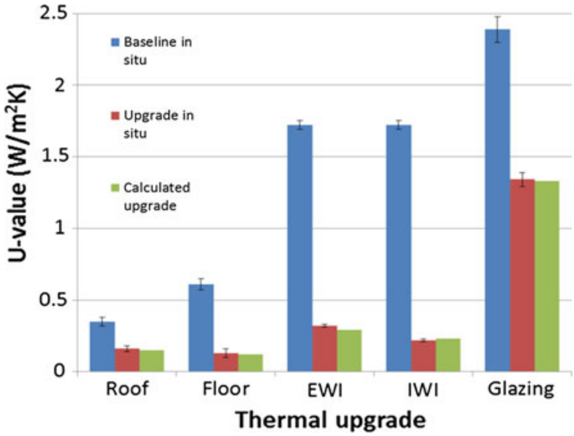

Fig. 7.5 Summary of the in situ baseline and upgrade U-value measurements. Upgrade U-value measurements are compared to those predicted by U-value calculations

Table 7.3 Measured in situ U-value performance versus in-use factors

Thermal upgrade	Calculated upgrade U-value (W/m^{2}K)	Measured upgrade in situ U-value (W/m^{2}K)	Discrepancy from calculated upgrade U-value (%)	In-use factor (%)
Roof	0.15	0.16 (±0.02)	+7	35
Floor	0.12	0.13 (±0.03)	+7	15
EWI	0.29	0.32 (±0.01)	+10	33
IWI	0.23	0.22 (±0.01)	−4	33
Glazing	1.33	1.34 (±0.05)	+1	15

installers considered competent and selected by the manufacturer. However, no additional information was provided to the installers, their competence was deemed important in achieving this level of practice and resulting performance. The initial findings suggest that the installation methods are an important determinant of performance. In these tests the products have performed very close to that expected by design.

Performance of Individual Thermal Upgrade Measures

Solid Wall Insulation

There was a 10 % discrepancy between the calculated and measured increase in R-value of the external walls upgraded with EWI. Measurements suggested that air movement between the EWI EPS boards and the external leaf of masonry was responsible for the underperformance; this could be caused by the temporary nature of the installation preventing the application of an adhesive coat. The IWI performed in close agreement with design expectations, the high-level of performance is thought to be due to the good contact between the IWI and the plaster finish of the wall. The IWI was applied to a smooth, flat surface with little potential for air movement and thermal bypassing of the insulation layer. The construction record also showed good attention to detail during installation.

The addition of EWI to the external wall increased the distance at which in situ U-value measurements were affected by thermal bridging at nearby jambs a finding that which corroborated the thermal bridging calculations. Thermal modelling revealed that insulating opening reveals with EWI would reduce the Ψ-value at these locations. It must be noted that the opening reveals were deliberately left uninsulated by the design team, therefore, further improvement at these junctions would be possible.

Insulating the external walls of the underfloor void with EWI was found to reduce heat loss from the ground floor by ~ 3 % and resulted in warmer underfloor void temperatures.

The behaviour of the EWI and IWI systems showed differing characteristics to change in internal temperature between steady-state measurement periods and their thermal inertia response. Heat fluxes measured on walls insulated with IWI stabilised and reached a steady-state far more rapidly than walls insulated with EWI. Walls insulated with IWI did not demonstrate the capacity to release heat back into the test house following the removal of space heating.

Loft Insulation

The mean of the upgraded roof in situ U-values measured suggests the top-up loft insulation achieved the intended level of thermal performance. However, there were differences recorded in the in situ U-value measured between different locations on the first floor ceiling (up to 95 % difference recorded). Loft insulation was fitted twice during the test programme and on each occasion a discrepancy between locations was measured. The discrepancy was not measured during test phases with the original 100 mm loft insulation in place. This could highlight an inconsistency with the retro filling of the cold roof spaces using mineral wool roll; though it was suggested by the installation team that it was not practical to insulate some areas of the loft because of the atypical roof structure. The most prominent inconsistencies were observed at the eaves junction, where installation was impractical because of the shallow roof pitch. Had a greater consistency of insulation top-up been achieved in the loft, it is probable that the reduction in HLC resulting from the upgrade measure would have been greater.

Ground Floor

The thermal upgrade of the suspended timber ground floor appeared successful. The mean of the in situ U-values measured was in close agreement with the calculated predicted U-value. There was a 46 % difference in upgrade in situ U-values between the two locations measured on the ground floor, whereas the in situ U-values measured on the uninsulated floor were similar. The discrepancy is not thought to be due to inconsistencies with the insulation fill between floor joists. Thermography revealed a high-level of thermal consistency across the ground floor and the photographic record and correspondence with those present during the ground floor upgrade suggest that the insulation fill between floor joists was highly consistent. The reason for the discrepancy is thought to be because of a combination of additional heat input from the neighbouring dwelling and a significant change in the ventilation characteristics of the upgraded floor. Both of these factors reduce confidence in the in situ U-value measurements.

Chimney Breast

An in situ U-value of 0.44 (±0.06) W/m^{2}K was measured on the chimney breast in the living room. The in situ U-value was 0.65 (±0.26) W/m^{2}K when the loft was insulated; it is thought that this increase was due to the loft insulation reducing the temperature of the cold roof space by 1.5 K, thus increasing the ΔT within the chimney flue. As the fireplace was sealed for the duration of the test period it is thought a partially open convective loop thermal bypass was in operation throughout the test programme. The heat loss measured is comparable to the U-value of 0.50 W/m^2K assumed in Part L1a of the 2010 Building Regulations for an unfilled cavity party wall with no effective edge sealing (HM Government 2010). This heat loss mechanism is currently overlooked in heat loss calculations such as RdSAP. This finding suggests that the application of certain thermal upgrading measures has the potential to increase the heat loss from other areas of a dwelling.

Conclusions

The research presented in this paper has demonstrated that dwellings of this type, which represent a significant proportion of the UK housing stock, have the potential to be retrofitted using off-the-shelf thermal upgrade measures to a standard which can significantly reduce their requirement for space heating and currently associated CO_2 emissions. The 63 % reduction in HLC measured is impressive, but is highly specific to the test house and the configuration of thermal upgrade measures. If the baseline dwelling had an uninsulated roof and single glazing, the reduction in HLC could have been greater. Conversely, had the test house been a mid-terrace, the HLC reduction would have been less due to lower external wall surface area. The important lesson for policy makers and the retrofit industry is that the improvement in thermal performance of each element was generally very close to that predicted. The reason for the level of thermal performance achieved is thought to be due to the high standard of workmanship and the absence of product substitution. This demonstrates that with suitable attention to detail to design, specification and installation, off-the-shelf thermal upgrade measures can realise the reduction in U-values anticipated.

The research also suggested that the in-use factors applied to the thermal upgrade measures have the potential to be reduced. However, the retrofit measures were not exposed to environmental factors which are known to affect performance, such as: wind, rain and solar radiation. Similar research should be performed in the dynamic external environment to ascertain if similar levels of thermal performance measured at the energy house can be replicated and achieved consistently in the field. This should include the random testing of retrofitted dwellings in which the manufacturer and contractor has no prior knowledge that the thermal performance of the retrofit will be measured.

The precision and accuracy of the thermal performance measurements that was achieved in the environmental chamber cannot currently be replicated in the field. The removal of confounding factors that is known to increase measurement uncertainty enabled the behaviour of the test house and retrofit materials to be characterised with a level of confidence not possible in the field and allowed the identification of phenomenon often masked by noise; many of which are not presented in this paper. Testing at a whole house level in an environmental chamber not only improved understanding of building physics, but also increased understanding of measurement techniques used to quantify thermal performance. It is recommended that research of this type continues and is extended to other common housing archetypes. No prior reports on such tests of whole buildings were found.

Appendix: Energy House Drawings

See Figs. 7.6, 7.7, 7.8, and 7.9.

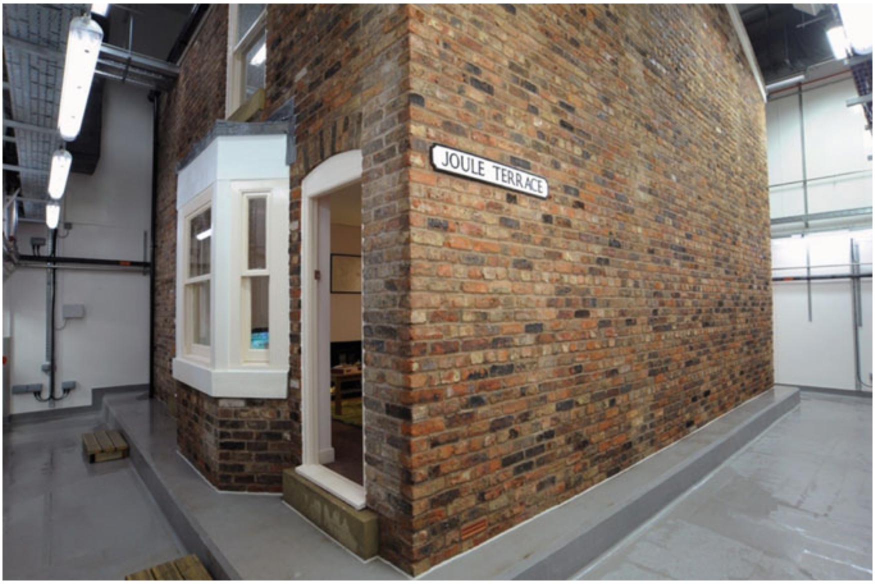

Fig. 7.6 Image of the Salford energy house and chamber

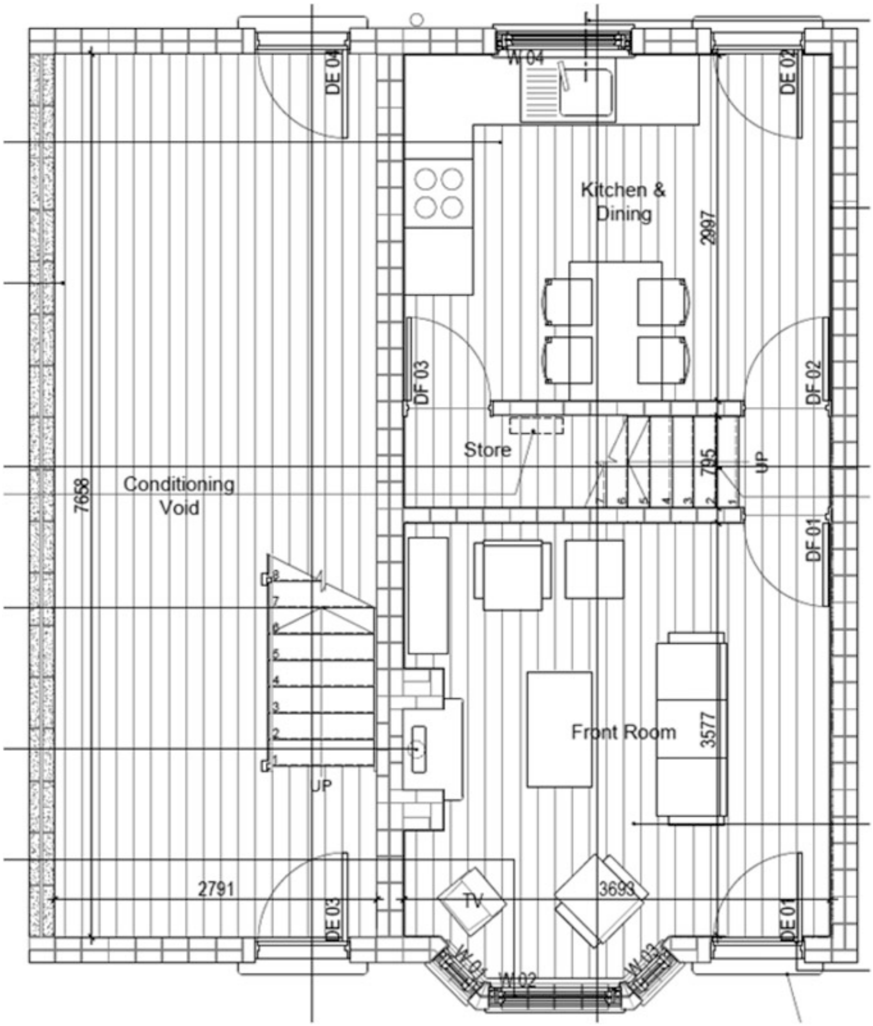

Fig. 7.7 Salford energy house ground floor plan

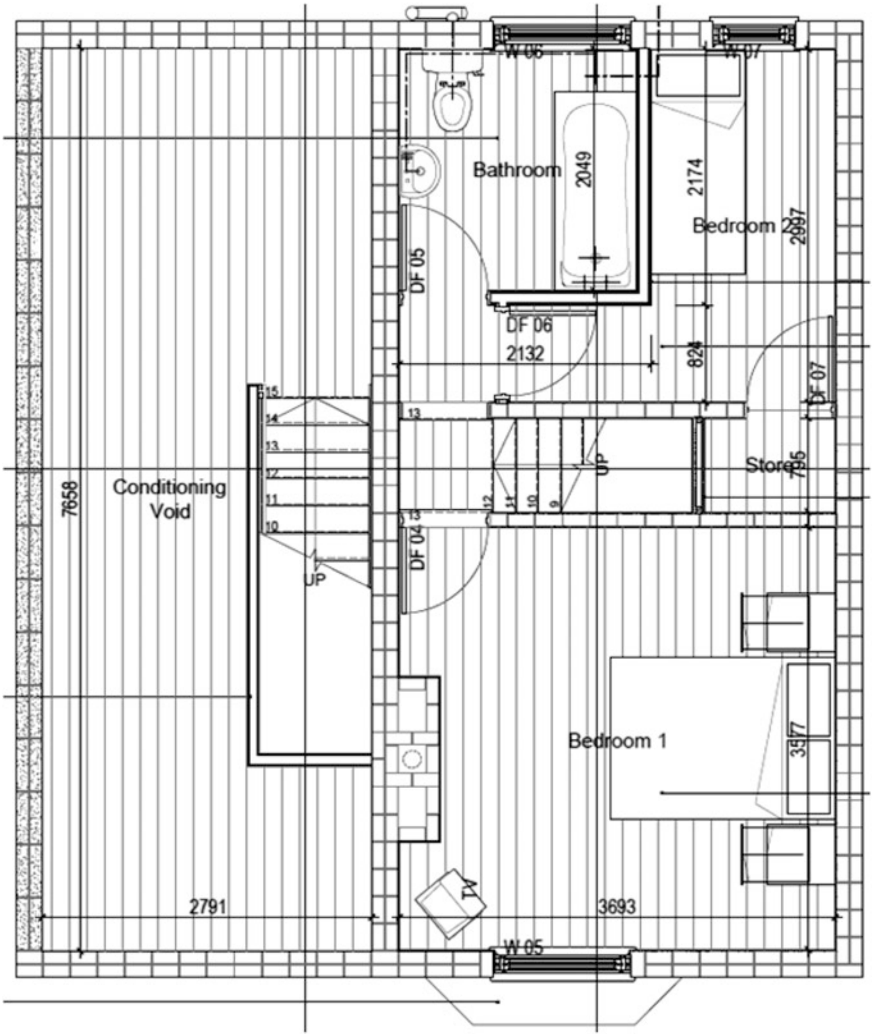

Fig. 7.8 Salford energy house first floor plan

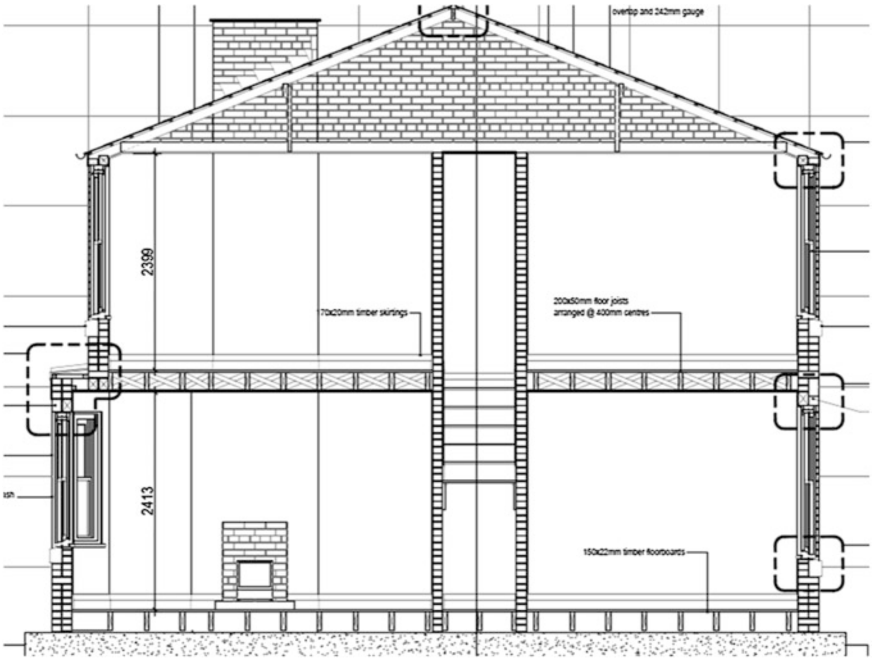

Fig. 7.9 Salford energy house section

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Chapter 8
African Energy-Plus Construction—A Case Study of House Rhino

Christopher Allen and Katharina Crafford

Abstract Due to the energy crisis that South Africa has experienced over the past seven years, challenging preconceived ideas by creating attractive, affordable, energy-efficient buildings has become critical to offsetting massive cost increases for electricity, whilst providing a proof of concept project that professionals can reference. This paper reports on a case study of an energy-plus residential building in South Africa, one of the first of this project type on the African continent. House Rhino, located on the outskirts of the south-eastern coastal city of Port Elizabeth, provided an unprecedented opportunity to research the potential for a residential energy-plus building as a proof of concept for a future where energy and water are rare commodities. House Rhino combines active and passive features in a modern residential design that has been created as a living lab. By means of an illustrative case study including site observation, interviews with the project team and analysis of on-site project data, this research has provided a benchmark against which future projects can be measured. Findings include that an energy-plus building can be constructed in a warm climate environment at a competitive price and that residential biogas generation has challenges in production and usage to make it viable. The results of the research suggest that although the benefits of sustainable construction are well known, the ability to create viable energy-plus buildings using alternative construction techniques can now be proven in a warm climate environment. This study reports on a single case study, which was justified due to its uniqueness (Yin in Case study research: design and methods. SAGE, Los Angeles, 2014). The project is located in South Africa and its design and choice of construction method challenge standard South African construction techniques whilst

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incorporating energy and water efficient technologies for an African climate environment—although not without unique (South African) challenges. Its findings are limited to the warm climate as well as to the African construction standards, methods, economy, workforce and workmanship. Although several studies about Net-Zero Energy Buildings (NZEB) were conducted in South Africa, the authors were not able to find any academic study about Net-Energy-Plus Buildings let alone about residential NZEBs. Research in energy efficiency construction concentrates on commercial and office buildings in Africa.

Keywords Energy-plus · Renewable energy · Alternative construction · Sustainable design

Introduction

Changing perceptions on the need to create a more sustainable built environment is challenging in any market, even more so within a conservative built environment culture prevalent in Sub-Saharan Africa. South Africa (RSA) has in recent years faced an energy crisis, which has led to massive cost increases for electricity as well as regular planned and unplanned power outages, all of which have created a negative effect on the quality of living experienced by all South Africans.

This is one of the major drivers explaining why South African green building activities are expected to triple from 2012 to 2015, which is the highest growth predicted by McGraw-Hill Construction (2013) for any of the nine countries included in their study (see Fig. 8.1).

This paper looks at the response to this changing perception of the local housing market in the form of a case study of an energy-plus residential building in South Africa. House Rhino is located in the Crossways Farm village, an eco-village on a working dairy farm on the outskirts of Port Elizabeth, a city situated in the southeast

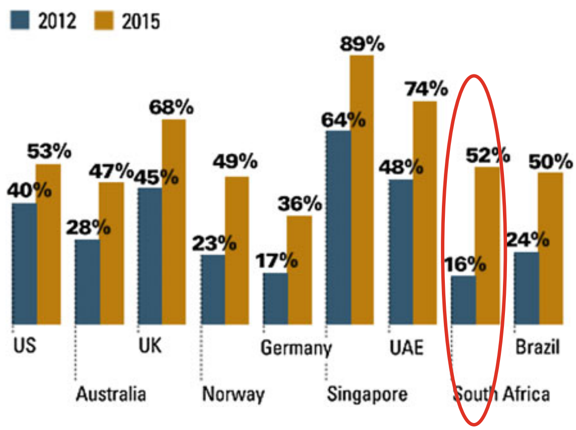

Fig. 8.1 Percentage of firms with more than 60 % of work green (2012 and expected for 2015) (McGraw-Hill Construction 2013)

corner of South Africa. Its design and construction techniques challenge the traditional South African building standard and set out to prove that residential energy-plus buildings can be constructed in the warm African climate—although not without some unique South African challenges.

House Rhino combines active and passive sustainable features in a modern residential design, using the building as a living lab, which has provided an unprecedented research opportunity. Through an illustrative case study which combined site observations, interviews with the project team and analysis of on-site project data, this research has provided a template for the future and a benchmark against which future projects can be measured.

Traditional Residential Construction

South African residential buildings are traditionally single storey brick buildings of 90–130 m^2 with a double pitched roof, which generally has little overhang. Roof covering consists typically of concrete tiles or metal corrugated sheeting with a plasterboard ceiling on the inside. It can be said that until recently architects and clients have not paid enough attention to the orientation of the building or to thermal heat gain/loss, although vernacular buildings performed extremely well in this regard. In addition, the conservation of energy used for heating, cooling and lighting has been almost non-existent.

Concrete ground slabs are traditionally laid directly on the excavated earth without any thermal barriers and floor covering is placed directly on top without an insulated screed. The external and internal walls are most frequently constructed of brick or block with the external walls only having a cavity in the coastal region (without insulation). Windows have traditionally been single-glazed steel frame, although single-glazed aluminium frames have become more popular in recent years due to the perception that they are better from a thermal performance perspective. However, little attention has been given to the use of thermal barriers in frames as well as to the type of glazing and its ability to reduce heat gain/loss. A typical 3-bedroom house would, until the introduction of the South African National Standards (SANS) 10400-XA (energy efficiency) regulations, have been equipped with a 150L electrical geyser to heat and store hot water, with little consideration for solar water heaters despite the excellent solar energy potential. The introduction of the revised standards and '78 % real price increase in electricity' (Deloitte 2012) since 2008 have, however, created widespread awareness and responsiveness to energy-efficient design, explaining to some extent the expected triplication of green building activities in South Africa as reported by McGraw-Hill Construction (2013).

Changes to Building Standards

On 23 June 2009, the Minister of Energy in her budget vote speech stated that: “The Department will ensure that one million solar water heaters (SWHs) are installed in households and commercial buildings over a period of five years”. (Department of Energy n.d.). This was the first inclination that government was becoming serious about creating a more sustainable built environment, due to South Africa’s commitments to the Kyoto Protocol agreements as well as the challenges in providing sufficient energy for all its people. The commitment to this technology and subsequent demand side management program incentive scheme (Department of Energy 2010) provided the catalyst for an escalated roll-out of SWHs and Heat Pumps, due in part to the increased affordability and reduced pay-back period afforded customers. In addition, in 2011 the construction professionals welcomed the introduction of the new building regulation, SANS 10400-XA, which prescribed for the first time in South African history minimum energy efficiency requirements for buildings. The new regulation is oriented to meet the goals of the National Energy Efficiency Strategy of the Republic of South Africa, issued by the Department of Minerals and Energy (2009), aimed at a 20 % reduction by 2015 of energy use for the commercial and public building sector, and 10 % reduction for the residential sector.

‘Green Building’ in South Africa

Green buildings are defined as “energy efficient, resource efficient and environmentally responsible” (GBCSA n.d.). In South Africa, the Green Building Council of South Africa (GBCSA) assesses and awards green building rating certifications by the means of the Green Star South Africa rating system. Windapo (2014) states that the establishment of the GBCSA in 2007 and the progressive development of the Green Star SA rating tool provided the industry with an initial framework for financing, developing and investing in sustainable buildings. However, the Green Star SA fails to provide a benchmark for single-family residential buildings, although the GBCSA does have a multi-unit ratings tool and is working with the World Bank aligned International Finance Corporation (IFC) to introduce the Excellence in Design for Greater Efficiencies (EDGE) tool for single residential buildings.

Despite the fact that research from countries including Australia, the United Kingdom (UK) and the United States (USA), have proven the benefits of green building features, there are still challenges and barriers within the South African property industry that result in green building measures not being adopted (Milne 2012). By comparison to international standards, green building is still in its infancy in South Africa and relatively few built environment professionals have the expertise to provide accurate information (Le Jeune et al. 2013). The result is that green buildings are perceived to cost more, although there is little evidence to prove this (GBCSA 2012). In addition research has highlighted that the main challenges for sustainable design and construction in South Africa is that of higher initial capital costs and lack of political support/incentives (McGraw-Hill Construction 2013).

Developers are interested in green construction, but a lack of knowledge and research into the costs of green construction provides a hurdle for private clients/investors and developers to consider the implementation of green buildings features (Hankinson and Breytenbach 2013). Growth in the sector is further hampered by a lack of suppliers, with clients looking to construct in a more sustainable manner and facing challenges in terms of product access at a reasonable cost as a result. Whereas cost premium margins of green commercial construction vary from negative to 1.5 % average internationally, green-star rated South African developments' premiums range between less than 1 and 10 % (Milne 2012).

The second barrier to greater implementation is education and the lack of experience in green design. Green building projects are only slowly entering the market in South Africa, and exposure to these projects for professionals is minimal (Hankinson and Breytenbach 2013). In addition, there is 'inadequate coverage of green buildings and green concepts at tertiary institutions' and 'a lack of relevant professional education and training in South Africa' (Milne 2012 supported by Hankinson and Breytenbach 2013). It is therefore somewhat surprising that a report by McGraw-Hill Construction (2013) shows South Africa having the highest level of green activity in the residential marketplace, with over a third (36 %) of firms reporting planned green activity for low-rise residential projects (one to three floors). The reasons for this, as defined in their 'Driving Future Green Building Activity in South Africa' report (see Fig. 8.2) appears to show a link to rising energy costs alongside a need to comply with regulations and improve the quality of the environment they live in.

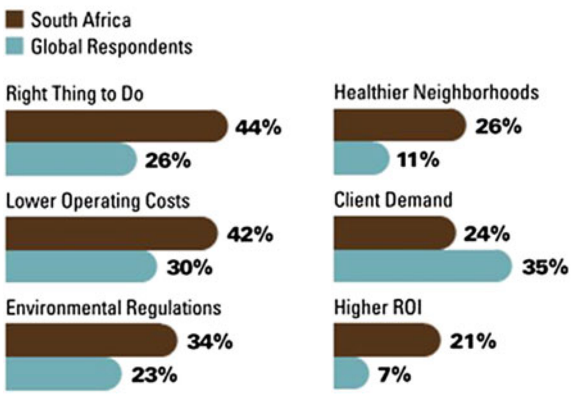

Fig. 8.2 Driving Future Green Building Activity in South Africa (McGraw-Hill Construction 2013)

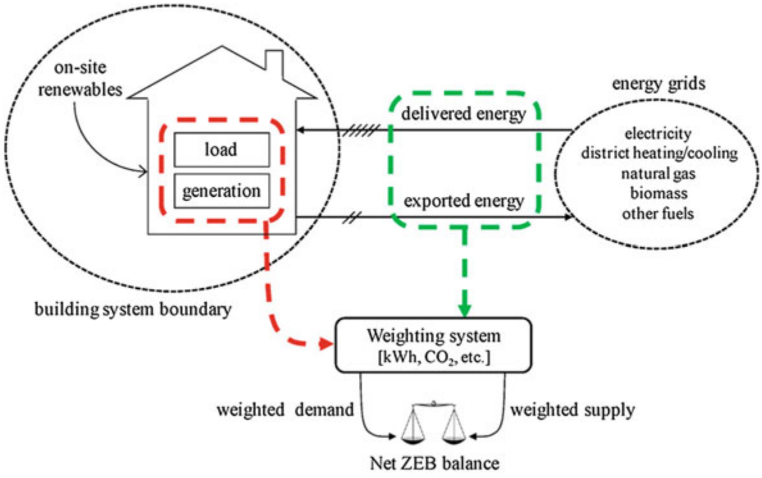

Fig. 8.3 Sketch of connection between buildings and energy grids showing relevant terminology (Sartori et al. 2012)

Net-Zero Energy and Net-Energy-Plus Buildings

Van Wyk (2012) noted that the concept of a Net-Zero Energy Building (NZEB) has received increased attention not only in South Africa but also worldwide. Despite the attention given to NZEBs, Sartori et al. (2012) claim that the definition of NZEB remains generic and that no international standard exists. Nevertheless, there is a general understanding of NZEBs as energy-efficient buildings able to generate energy from renewable sources in order to compensate for energy used in its operation over a period of time (see Fig. 8.3). Consequently, if the amount of energy produced by the building exceeds the amount of energy used during operation the building is considered 'Net-Energy-Plus'.

In South Africa only a small number of buildings qualify as NZEBs, but advances in renewable energy technologies, energy saving building materials and construction techniques make Net-Zero Energy and Net-Energy-Plus Buildings feasible (Van Wyk 2012). Coupled to the double-digit electricity increases experienced since 2008 (Deloitte 2012) and the expected annual increase of 12.69 % (NERSA 2014) for the next 5 years, NZEB's are starting to become an affordable, feasible option.

Research Review and Methodology

In order to understand in-depth the decision-making process undertaken and to investigate the positive and negative outcome of the project, a case study was deemed to be the most appropriate research approach. A single case study was justified because it was unique (Yin 2014). It was the first known residential Net-Zero Energy Building in South Africa. By means of an illustrative case study which combines site observations, interviews with the project team and analysis of on-site project data, this research has provided a benchmark against which future projects can be measured. The researchers combined semi-structured interviews with the principle project team members and the client, design information from the architects and six site visits, both during construction as well as following project completion, in order to document the design and construction process thereby illustrating comprehensively how the energy-plus project was conceived and executed. In addition, by coupling this to documentary data from the house's Building Management System (BMS), the research provides documentary evidence to confirm the results of the theoretical concepts implemented.

Case Study

What do you need to do to create an Energy-Plus residential building in a warm climate environment? That is a question that House Rhino client and the Rhino Industries Group Managing Director, Brian van Niekerk, regularly asked himself when he first proposed the creation of such a house in 2008. Confronted by architects and engineers who regularly told him it was impossible, he forged ahead, in the interim creating new business opportunities and simultaneously achieving his initial goals. The researchers combined with the client and his delivery team on this unique project to record the process and outcomes as a learning document for future energy-plus buildings in similar climatic conditions.

So what was the initial objective of this project? As Brian explains it, his philosophy on our environment revolves around sustainable creation and use of food, water and energy. The design professionals he engaged showed little interest in the use of active energy systems and water saving measures for the building. Being a supplier to the industry, he was well aware of how built environment professionals stuck to what they knew, so he set out to prove to the industry that the information they based their decisions on was factually incorrect.

From a research perspective, it was imperative to cross reference the areas identified in the literature that encapsulate an energy-plus (or Net-Zero Energy) house in order to best evaluate House Rhino. Using three references (Jacobs 2012; Greyling and Vester 2011; Van Wyk 2012) the following areas were defined as key to achieving an energy-plus building:

1. Sustainable design (Passive solar design);
2. Renewable energy;
3. Solar water-heating systems;
4. Thermal performance;
5. Lighting systems.

Passive Solar Design

Norton (2014) suggests that there are five design components that should be included in passive solar design, which include energy efficiency, orientation, glazing, thermal mass and heat distribution. From the interviews with the client and Rhino Green Buildings design specialist, it was highlighted that these aspects formed the basis for the design process.

Figure 8.4 clearly defines the elongated east–west orientation of the public and private spaces whilst the steeply sloping nature of the site was cleverly used to cascade the building from south to north, with a narrow spine linking the two sections. This enabled extensive glazing to the north-facing elevations of both wings by raising the south section above the shadowing cast by the north section and when combined, the narrow footprint of these spaces allows extensive solar penetration in winter, maximising winter solar gains, whilst summer gains are limited through the use of extended roof overhangs. This alignment is in keeping with best practice design theory for a moderate, temperate climate within which the house is sited. Using a 110 mm thick floated concrete floor slab, the mass to capture the excellent solar radiation levels present in the winter months was also provided, creating a natural heat sink (Fig. 8.4).

Roaf et al. (2013) indicate that today's passive solar design systems can typically provide 30–70 % of residential heating requirements, depending on the size of the system, the level of energy conservation in the building envelope and the local climate. However, in a warm climate, a major challenge is not just heating but also cooling (SANS 10400-XA: South African National Standards 2011). This has been highlighted in XA specifically with respect to the quantity of glazing allowed and the control of solar gains through this. The fenestration percentage on this project, at above 70 % of the floor area, is extremely high (SANS 10400-XA deemed-to-comply option is 15 %) and has, as a result, provided more than sufficient passive solar heating, particularly in the cold winter days, when the local climate provides abundant clear sky days. However, the benefits of this passive design aspect are being challenged, as a result of the underfloor heating system coming on at night in summer! This is not what any of the design team expected and is counter-intuitive to the perceived opposite, a need to use night time cooling in a hot climate environment (Tramontin et al. 2012), although the local micro climatic conditions may have had a part to play in this anomaly. The building management system (BMS), which controls the system, is being activated by low indoor ambient temperatures in the living areas, most likely due to the large glazed areas losing excessive heat to the atmosphere. With limited heat gain in summer during the day, due to the compliance requirements of the legislation requiring the design to mitigate for the large north-facing glazing (extended overhangs for shade and demisters to cool the air around the perimeter of the building), the building is now using energy to heat itself in summer! As a result of this, double-glazed units, combining a pane of

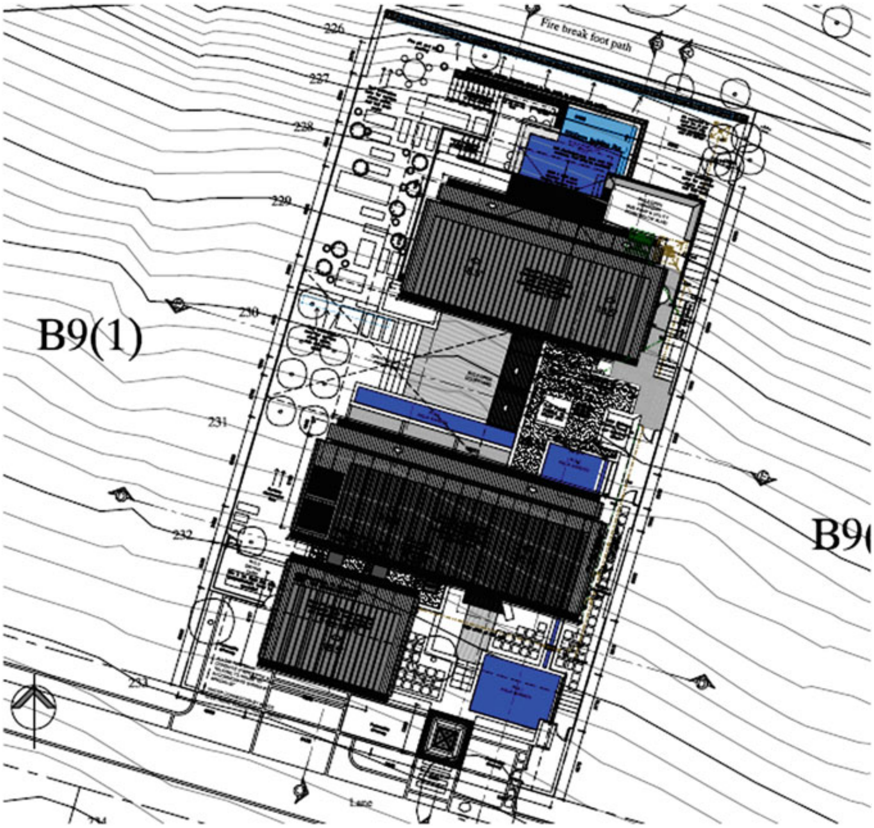

Fig. 8.4 Site plan

clear glass externally with low emissivity glass internally, are currently being specified to better control heat loss from the building.

In addition, it has been noted that the initial design of the building did not take enough cognisance of the solar gain on the west elevation, and therefore additional shading devices have been added to these areas and also to the clerestory level windows. The BMS also looks to adjust the ventilation of the building according to the ambient temperature in the house at any given time. Vertical cooling though the thermal chimney is one mean of achieving this, whilst the extensive use of clerestory windows further increase the cross ventilation in the building as a result of its orientation to the predominantly south–west (winter) and south–east (summer) wind flows prevalent in the region. These passive design measures have worked extremely well enabling the building to remain cool on the hottest days without use of the underfloor cooling system.

Renewable Energy

Due to the probability of significantly higher energy costs in the future and also because of its environmental impact, energy consumption remains the single most important building issue (Kibert 2012). At House Rhino, the off-grid design was to prove that it could be profitable to do so even on a small scale confirming Yudelson's (2007) view that onsite energy production in green residential buildings can be achieved through solar, wind, small hydroelectric and geothermal systems. Seventy-four 230 W panels were used in this installation generating a maximum DC output of 17 kW whilst the AC generation levels sits at approximately 16 kW/h. Some of these panels power the pool pump during daylight hours, limited by the BMS on energy production. The solar panels installed are deemed more than sufficient as the energy usage is much less than the energy required to power the home, with generation parity achieved by 2.30 p.m. in winter and as early as 11 a.m. in summer (Fig. 8.5).

The generation capability versus energy usage equation is so high in favour of generation (see Figure), that the inverter manufacturer (SMA), are creating software to enable surplus energy to be synchronised with the grid, as currently the system is 'washing' excess energy ±35 % of the time. In addition, the only time that energy has been taken from grid is after extended days of cloud in the low energy periods of August/September. This is not as a result of insufficient energy but rather to prevent deterioration of the batteries once they reach the 40 % threshold for optimum battery life. In just over a year, the total energy generated is nearly 44,000 kWh, whilst the total energy used during construction and when it has rained continuously limiting generation is a total of 2400 kWh (Fig. 8.6).

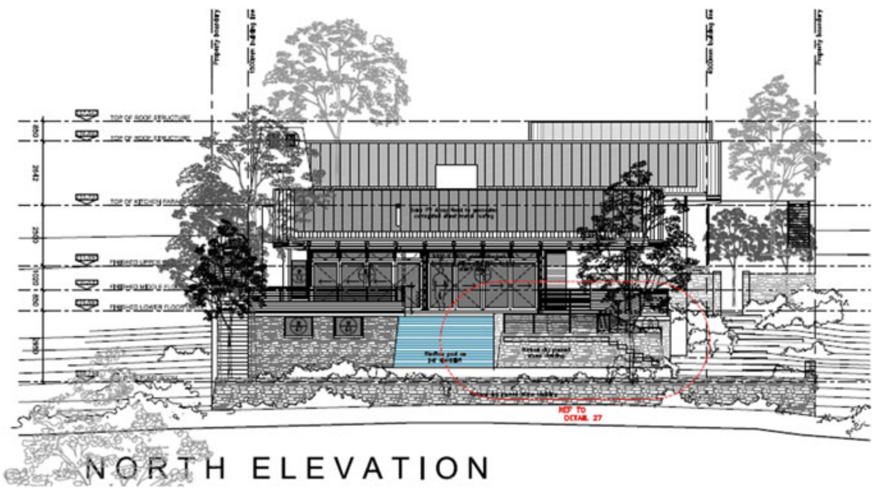

Fig. 8.5 North elevation showing extensive PV panels

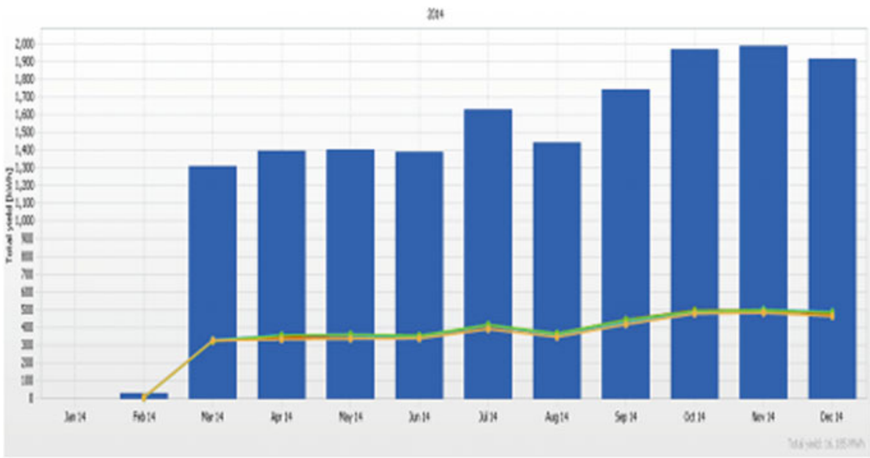

Fig. 8.6 Rhino House Energy Yield (2014)

Cost of installation for the off-grid PV system on this project is around R34 (£1.90)/W including the bank of zero maintenance batteries which make up almost 50 % of the cost. This compares with around R18 (£1) to R25 (£1.40)/W for a grid-tie PV system which is competitive with the installation costs for a similar size system in the US $4.30 (£2.75)/W (Roselund 2014) and the UK £1.33/W(Judd and Kerai 2013). Electricity costs in South Africa have risen to around R1.35 (£0.075) kWh vs UK (£0.14 kWh) (DECC 2014), so with average households using similar levels of electrical energy to those in the UK at 400 kWh's per month (DECC 2014) the cost to go off-grid is still prohibitive, taking more than 15 years to pay off the system. In addition, due to the legislative regime currently in place, costs were still incurred related to a mains supply as home owners in South Africa are forced to connect to the electrical grid, as municipalities have yet to realign their income generation models in line with customer preference to be energy independent. However, as electricity is predicted to cost approximately R2.20 (£0.12) kWh in 5 years (NERSA 2013), the long term viability of particularly a grid-tie system becomes more plausible as an alternative energy supply.

In addition to the more common energy production from the sun, the house also incorporates a bio-digester producing methane gas used to run the hob and oven, with much of the water boiled on the premises using this as an energy source. Although many rural communities in South Africa use septic tanks to process waste water, only a small percentage use the gas produced as a result of that process, most simply venting this into the atmosphere, wasteful in an energy-poor country. This technology, therefore, has much scope to improve the sustainability of even poor income households, something the client is keen to see happen.

Solar Water-Heating Systems

According to Kibert (2012) water heating can consume large amounts of energy and in most residences there is a heavy demand for hot water. Solar water heating systems, heat pumps and gas water heaters are technologies that can be used to reduce the energy demand for heating water. At House Rhino, a 300L flat-plate thermo-syphon solar water heating system has been installed alongside a heat pump (sited internally in the garage) from which most of the domestic hot water demand is generated. In addition, a commercial heat pump has been installed to heat the house through the under floor heating system. A solid fuel fireplace supplements the heat pump as it generates heat that is captured by a heat exchanger in the flue that augments the heat pump on particularly cold days whilst simultaneously increasing the ambient temperature in the house. Through the use of the BMS, the client has also been able to control the release of hot water thereby offsetting the extensive cooling occurring in the early evening. With the likes of the insulation and mass concrete in the floor, the system can still be 34 °C at 5 a.m. without the input of any additional energy, a major cost saving.

Thermal Performance

It is important that the thermal performance of a building envelope be maximised. House Rhino's client states quite categorically that in terms of the design process 'designing a house within a South African climate is more difficult than a cold climate as the lifestyle gets in the way of good design protocol'. In particular, the tendency to incorporate large stackable or sliding doors to link interior and exterior spaces creates challenges in terms of the thermal control of the building interior. In particular, the large temperature differential between summer and winter maximums (36 °C vs. 12 °C) and diurnal ranges (April: 30 °C daytime; 9 °C at night) make creating a comfortable living environment challenging. In addition, there is a need for buildings to respond rapidly due to the changing climatic conditions experienced particularly in this region of South Africa in winter. Berg (mountain/katabatic) winds increase temperatures to +30 °C, then cold fronts sweep through bringing with them rain and very cold conditions, with temperatures below 10 °C. As Tramontin et al. (2012) proffer, 'proper balance between thermal resistance and thermal inertia should be achieved for external window walls', a balance House Rhino is battling to achieve. The design process objectives needed to be changed so that energy efficiency and not aesthetics are the focus.

According to Kibert (2012) energy transmission through the building envelope should be minimised by introducing a tight thermally resistant envelope. The building envelope should control solar heat gain, conduction or direct heat transmission, and infiltration or leakage of heat. "In most South African climate areas, the main summer requirement for indoor comfort is the protection from solar radiation, which mostly falls on the roof surface". Roof assembly must, therefore, "have good thermal resistance (directly on roof or on ceiling), also possibly with reflective external layer and ventilated airspace" (Tramontin et al. 2012) These issues can also be addressed through the application of higher insulating materials such as double-glazed windows and insulation in the floors, walls and ceilings. Double-glazed units were initially installed but had to be replaced due to vapour between the panes, whilst the folding stack doors had problems with air leakage between frame sections caused by the seals.

The biggest problem from an insulation perspective appears to be the steel frame structure, which is ±15 m^2 of exposure, and aluminium window frames without thermal bridges. Instead of the steel frame, which was preferred by the architect due to the industrial aesthetic the house was conceptualised as, timber would have provided a better thermal performance option. Any additional costs would have been more than offset by the additional labour and material costs incurred to install infill to steel I-sections as well as other insulation requirements to the columns. The aluminium frames have also produced a negative thermal performance, with uPVC or timber frames providing a more costly but more efficient thermal barrier (with the uPVC having very limited maintenance costs). Unfortunately, due to their limited use in Southern Africa (one manufacturer at time of tender), thermal break aluminium frames were too costly to be considered an option.

Conclusions

Although there were a number of challenges encountered, House Rhino's client believes the project has been successful, particularly the energy aspects. The data from the Building Management System, that records the energy consumption as well as water consumption, hot water and gas generation, supports this perception whilst the cost of the project at around R15550/m^2 (£1000/m^2) is commensurate with upmarket homes built using traditional methods at R15000/m^2 (AECOM 2013). The problems encountered in construction never resulted in any major delays in the build programme, so the project could be deemed a success when compared with traditional brick and mortar construction in the region (an Insulated Concrete Form (ICF) construction system was used for the majority of the walls with the only brick and mortar the garage). The live nature of the project provided additional challenges for the design and construction teams as systems were being amended or completely replaced during construction which affected the ability of the project team to meet the delivery schedule. An improved project management process would have likely sorted out technical aspects earlier, i.e. a better understanding of the technology to be used, which would have provided an improved delivery benefit. An example of this is the under floor heating system, which, where it is laid as an electrical mat, has become a routine installation operation, but in this instance proved extremely complex due to each pipe having to terminate at the main distribution point (as in an electrical wiring installation).

Furthermore, the workforce was challenged by the requirements of the new legislation. An example is the installation process for the reflective roof foil and its role in achieving the requirements of the energy efficiency regulations, which themselves need improved understanding to achieve the desired outcome. As a result, the cost and practicality of compliance make doing it debatable, meaning the process followed for compliance needs to be researched further. It is ours and the client's opinion that the construction challenges rest with education of a semi-literate workforce, especially when a lack of understanding leads to damage of expensive modern materials such as the ICF system. There is therefore a need to increase training in the use of alternate construction methods as identified by Milne (2012) and supported by Hankinson and Breytenbach (2013) mentioned in the literature review. Greater knowledge is needed up front by all stakeholders involved in construction which will increase the demand for energy-efficient building (Milne 2012). Building Inspectors need to be better educated as well as the National House Builders Registration Council (NHBRC) so that they enforce compliance correctly. There should therefore be a greater link to liability aligned to insurance and regulations with oversight aligned to this.

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Chapter 9
Smart Badge for Monitoring Formaldehyde Exposure Concentration

Houssem Eddine Fathallah, Vincent Lecuire, Eric Rondeau and Stéphane Le Calvé

Abstract Formaldehyde is used by many industrial processes (e.g., paper, wood, textile). The World Health Organization classifies formaldehyde in category 3 of carcinogenic substances and defines exposure limits in professional context. The objective of CAPFEIN project funded by the French National Research Agency is to develop smart systems to estimate formaldehyde exposure concentrations of employers working in a closed environment. This research project gathering researchers in chemistry and information and communication technologies is composed of three parts: the development of sensor measuring indoor formaldehyde concentrations, the implementation of indoor positioning systems and the design of smart communication systems capable of calculating personal exposure concentrations from formaldehyde sensor and tracking system. Different solutions were investigated based on centralized or distributed approaches. In this paper, only the latter is described and focused on the development of a smart badge. The employer wears a badge embedding (1) infrared interface for communicating with the positioning system, (2) Wi-fi interface for collecting data from formaldehyde sensors, for displaying information on employer's mobile phone, etc. (3) processor for offering users' services and algorithms to estimate personal exposure concentration and (4) memory for locally storing the history of formaldehyde exposure. The specific issue discussed in this paper is about the amount of memory and energy required to

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store and process historic data on the badge. The method tested in this paper is exponential weighted moving average (EWMA). EWMA method is implemented in a badge prototype and assessed. It shows a significant reduction of memory and computation costs, and consequently energy consumption. Besides, the badge designed in CAPFEIN project is generic and can be used for other air pollutants. In addition, the optimization of memory space, processing time and energy consumption based on EWMA method allows the badge to manage several air pollutant sensors.

Keywords Air quality · Smart sensor · Personal exposure concentration · Formaldehyde

Introduction

The human health consequences of air pollution are considerable. The World Health Organization (WHO) estimates that 800,000 people per year die from the effects of air pollution (WHO 2002). The most important environment in relation to our health is the indoor environment, where people spend a substantial portion of their time (Chao et al. 2003; Molhave 2011). Human exposure was defined as the interface between humans and the environment. The impacts of air pollution on an individual's health are related to their exposure concentrations in the different locations in which they spend time. However, the worker's exposure assessment in the occupational environment is complex to estimate. Two pieces of information are necessary to estimate personal exposure: the concentration of pollutant in different microenvironments and the individual time activity (Ott 1982). Many exposure models are developed in order to quantify human exposure to air pollutants in the indoor environment on the basis of direct measurements, biological monitoring or indirect methods (Conti and Cecchetti 2001; Freeman et al. 1991; Lioy 1995). Direct human exposure measurement using personal samplers or biomarkers is expensive, very time consuming and hard to apply on real-time occupational health and safety systems in order to protect the safety, health and welfare of people engaged in work. In addition, there are no real-time personal samplers for several air pollutants such as formaldehyde. Thus, indirect methods are the best way to assess human exposure to air pollutants. Indirect estimates of exposure may be made by combining measurements of pollutant concentrations at fixed sites with information on personal real-time indoor coordinates. Our real-time occupational exposure assessment method is based on smart badge, as illustrated in Fig. 9.1. The workplace is divided into microenvironments. Each microenvironment is equipped with a multi-pollutant sensor unit, for measuring air pollutants' concentrations, and a positioning system (zone locator) to identify in real-time worker's localization.

Personal monitoring of human exposure to air pollutants requires that each employee must wear a unique smart badge. A smart badge is composed of a number of units; energy unit, alert management, memory block, communication interfaces including infrared and Wi-fi technologies and processing unit. The communications

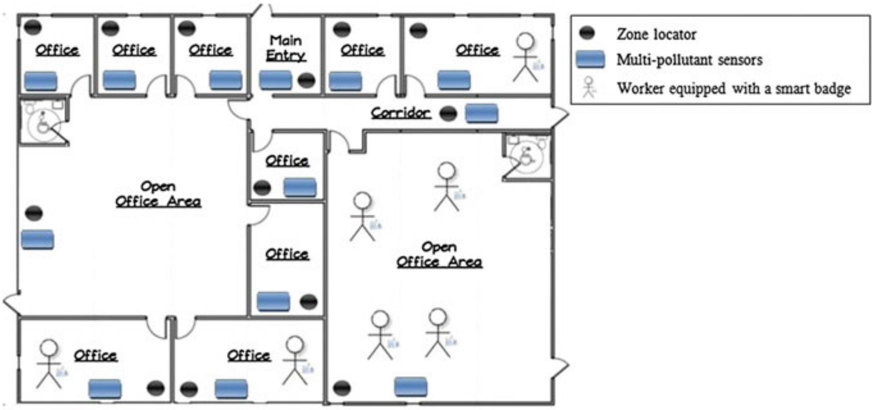

Fig. 9.1 Example of real-time occupational exposure assessment implementation

between the smart badge, the zone locator and the multi-pollutant sensor are shown in Fig. 9.2. The smart badge periodically receives from the zone locator, a message (Location.ID) which contains the multi-pollutant sensor unit identifier placed in the related microenvironment. Based on this information, the smart badge can interface

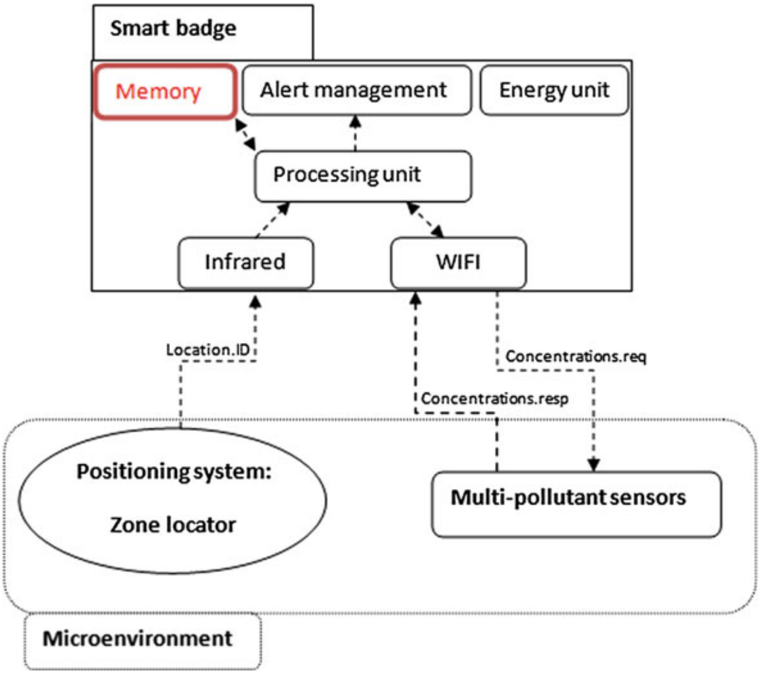

Fig. 9.2 Overview of smart badge interactions

with the identified multi-pollutant sensor and send a request message (concentrations.req) for the newest pollutant measured concentration. Then the smart badge receives a response message (concentrations.resp) from the multi-pollutant sensors unit and updates the time-weighted average individual exposure.

Devices used for personal monitoring, such as our smart badge, should be as unobtrusive as possible and minimally interfere with the activities of the worker whose exposure is being monitored. Accordingly, wearable devices need to be basically small, lightweight and cheap, so such devices are typically resource-constrained, with very limited processing speed, memory size, battery capacity and communication capability. For example, increasing the capacity of the battery and over satisfying the autonomy constraint might violate the weight and size constraints of the system. This paper proposes a method based on the Exponential Weighted Moving Average (EWMA) to estimate in real time the time-weighted average personal exposure in order to minimize memory size and reduce energy consumption and data processing time.

Related Work

Recent personal monitoring studies are based on a geographic information system (GIS) for people tracking combined with personal or fixed air pollution monitors. For example, GPS receivers have been applied successfully in human exposure studies (Elgethun et al. 2003; Lioy 2010; Zwack et al. 2011) but there are limits to the general applicability of this technology due to the qualification of indoor activities where GPS sensors cannot receive a signal. The main problem when using GPS devices is the poor coverage of satellite signals inside buildings or near certain materials, such as body panels and metals, decreases its accuracy and makes it unsuitable for indoor location estimation. GPS spatial resolution is around 3 m outdoors and 5 m inside buildings (Elgethun et al. 2003).

More efficient methods for indoor personal monitoring are based on latest technological capabilities, e.g., radio frequency, ultrasound and infrared technologies. In Negi et al. (2011), a wearable monitor with real-time and continuous personal monitoring was developed to measure concentrations of total hydrocarbons and total acids in real time, and send the data to a cell phone using wireless communication. The same approach is used in Brown et al. (2014). However, these wearable monitor systems may not be used to detect all air pollutants or as a multi-pollutant monitor, due to sensor size, weight and cost constraints. This approach is limited to a number of air pollutants where its concentrations can be measured using small integrated sensors. For example, there is no small sensor for formaldehyde. Moreover, wearable personal monitoring devices generally do not locally store and process the historical data of air pollutant exposure concentrations. Data is stored and processed remotely at a desktop or a distant server.

Our approach differs from the previously mentioned ones, in the sense that data is processed on the smart badge. It is therefore memory, energy and processing constraints to take into account. This problem is addressed using an Exponentially Weighted Moving Average method (EWMA). EWMA methods are generally used in the financial field, for example, to calculate historical volatility (volatility is the most commonly used measure of risk), and network performances studies (Woo and Culler 2003; Benaissa et al. 2005). To the best of our knowledge, no previous study has employed EWMA in environmental monitoring systems.

Methodologies

In this section, the real-time personal monitoring model is firstly explained and then the use of EWMA method to estimate worker exposure concentration is presented. The effectiveness of this method is tested on monitoring application basis in worker exposure to formaldehyde concentration.

Real-Time Personal Monitoring Model

The model estimates personal exposures by combining the information on the measured concentration of pollutants, as an example formaldehyde (HCHO), the movements of a worker in various microenvironments and the time duration a worker spent in each microenvironment. In order to protect the occupational safety and health, Time-Weighted Average Individual Exposure E_{TWAI} is updated periodically and compared with the $E_{TWAI\ Limit}$ based on guidelines values and country regulations. In case of exceeding individual exposure limits, alert management unit triggers the appropriate action (warning, ventilation, ask worker to take a break time, etc.) to ensure personal health and risk prevention. An overview of real-time personal monitoring model is shown in Fig. 9.3 where C_{MEj} is formaldehyde concentration in microenvironment j and E_j is individual exposure to formaldehyde in microenvironment j.

In order to protect workers' health, E_{TWAI} is estimated for each duration related to guideline values, for example, formaldehyde durations are 15, 30 min, 1, 2, 8 and 24 h, and updated when a new measure of pollutant concentration is collected by the smart badge. E_{TWAI} can be calculated using the simple moving average. In the case where the smart badge operates in synchronous mode, i.e. personal exposure is updated periodically when a new pollutant concentration is available, the formula is:

$$E_{TWAIt} = \frac{1}{N}\sum_{k=0}^{N-1} C_{t-k} = \frac{C_t + C_{t-1} + C_{t-2} + \cdots + C_{t-N+1}}{N}$$
$$= E_{TWAIt-1} + \frac{C_t - C_{t-N}}{N} \quad (9.1)$$

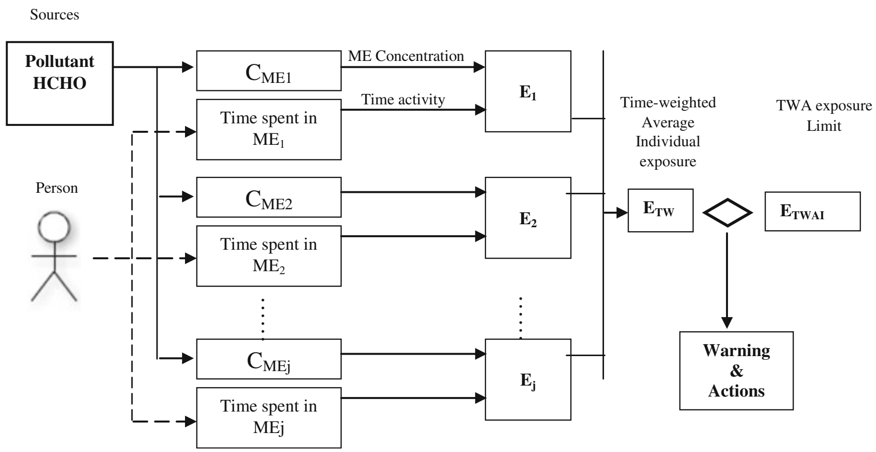

Fig. 9.3 Conceptual model for real-time occupational health and safety

where $E_{\mathrm{TWAI}t}$ is the newly time-weighted average individual exposure, $E_{\mathrm{TWAI}t-1}$ is the last time-weighted average individual exposure, C_{t-k} is the $\mathrm{t}-k$ personal pollutant exposure concentration and N is the number of personal pollutant exposure concentration samples. The formula 9.1 indicates that during the process of personal exposure assessment, it needs to store N data, where N is the guideline value duration divided by the measurement period. As N increases, more storage is needed. Simple moving average is not a memory efficient method for long-term exposure assessment and multi-pollutant personal monitoring. Due to the smart badge resource constraints, it requires as small historic concentration storage as possible and as low computational complexity and energy consumption as possible.

Exponentially Weighted Moving Average

The exponentially weighted moving average method is used in this paper to estimate real-time worker exposure concentration. The EWMA estimator is very simple and memory efficient and enables the quick update of data. EWMA method depicts as follows:

$$E_{\mathrm{TWAI}t} = (1-\alpha)E_{\mathrm{TWAI}t-1} + \alpha C_t \tag{9.2}$$

where $E_{\mathrm{TWAI}t-1}$ is the mean of historical data, C_t is the last personal pollutant exposure concentration, and $0 < \alpha \leq 1$ is the smoothing parameter. The implementation of EWMA will take 4 bytes (in floating point format) to store $E_{\mathrm{TWAI}t-1}$ and the amount of computation involved is 2 multiplications and 1 addition. The difficulty with EWMA estimators lies in the choice of the smoothing parameter α.

The parameter α determines the rate at which historical data enter into the calculation of the newly time-weighted average individual exposure. Assume that historical data represents 86 % in the calculation of $E_{\mathrm{TWAI}t}$.

$$\begin{aligned}
&E_{\mathrm{TWAI}t} = (1-\alpha)E_{\mathrm{TWAI}t-1} + \alpha C_t \\
&E_{\mathrm{TWAI}t} = (1-\alpha)^2 E_{\mathrm{TWAI}t-1} + \alpha C_t + \alpha(1-\alpha)C_{t-1} \\
&E_{\mathrm{TWAI}t} = (1-\alpha)^N C_0 + \alpha\left[C_t + (1-\alpha)C_{t-1} + (1-\alpha)^2 C_{t-2} + \cdots + (1-\alpha)^{N-1} C_{t-N-1}\right] \\
&\text{Therefore } (1-\alpha)^N = (1-0.86) \\
&\text{Therefore } \alpha = 1-(1-0.86)^{1/N}
\end{aligned} \tag{9.3}$$

where N is the number of personal pollutant exposure concentration samples.

Application to Formaldehyde

The classification of formaldehyde as a known human carcinogen by IARC is based on previous studies of workers exposed to formaldehyde (Hauptmann et al. 2004). Additional health effects of exposure to formaldehyde include respiratory and eye irritation and contact dermatitis (U.S. Environmental Protection Agency 1988). Formaldehyde is a major industrial chemical for numerous industrial processes. It has three basic industrial uses: as an intermediate in the production of resins, as an intermediate in the production of industrial chemical and as a bactericide or fungicide. In the wood industry, formaldehyde-based resins are used to make oriented strand board and other wood-based products (particle board, oriented strand board, high-density fibre board, medium density fibre board, plywood) (Godish 2001). Formaldehyde is also used as a resin added to sanitary paper products and in textile treating. Moreover, formaldehyde is present in consumer and industrial products as preservatives or bactericides (e.g., shampoos, hair preparations, deodorants, cosmetics and mouthwash). An aqueous solution of formaldehyde can be useful as an effective disinfectant and preservative that may be used in hospital wards and pathology labs (CPI 2005).

The wood product manufacturing and hospital industries are among the largest exposed industrial groups. In wood panel manufacturing, formaldehyde is released when heating adhesives, which can expose press operating and maintenance workers. Health care professionals are exposed to formaldehyde during the use or clean-up of medical products and equipment.

Several international safety and occupational health organizations proposed guideline and reference values of formaldehyde by inhalation. Indoor guideline values are classified according to duration of exposure (see Table 9.1). A guideline value of (100 μg m^{-3}, 30 min) was defined as a safe concentration as regards the carcinogenic effect of formaldehyde in the human organism (WHO 2006).

Table 9.1 Guideline values and recommendations for formaldehyde in indoor air

Duration	Value (μg m^{-3})	Country or organization
15 min	500	ANSES-France
30 min	100	Australia-Japan-Norway-U.K.-WHO
1 h	123	Canada
	100	China
	94	USA
2 h	50	France
8 h	50	Canada
	120	Singapore-Korea
	33	USA
	100	Poland-Hong Kong
24 h	50	Poland
	60	Norway

Guideline values between 94 and 123 μg m^{-3} are specified for a 1 h exposure (OEHHA 1999). France discusses guideline values of the order of 50 μg m^{-3} for a 2 h exposure (AFSSET 2007). Long-term exposure values in indoor guidelines are based on 8 and 24 h time duration, guideline values between 33 and 120 μg m^{-3} are proposed for 8 h exposure. In Poland and Norway, guideline values of 50 and 60 μg m^{-3} are respectively proposed for 24 h exposure. These time-weighted average values were set to protect the worker in occupational environments from the chronic effects of formaldehyde.

The EWMA method is implemented and tested based on the configuration shown in Table 9.2. EWMA method is compared with simple moving average method in terms of memory and computation costs, and consequently the energy consumption. Table 9.3 shows the energy consumption and computation time for each operation related to our smart badge hardware configuration (Nannarelli and Lang 1996; Suzuki et al. 1996a, b; Microship 2013).

Table 9.2 Use case system configuration

Duration	$E_{\text{TWAI Limit}}$ (μg m^{-3})	Measurement period	N	A
30 min	100	10 min	3	0.48075059
2 h	50	10 min	12	0.15112449
8 h	33	10 min	48	0.04013313

Table 9.3 Energy consumption and processing time per operation

Operation	Energy (nJ)	Cycle
Addition	16	1
Division	40	18
Multiplication	25	1
Memory read	2.3	5
Memory write	18.5	37

Results and Discussion

In this study, personal exposure levels of formaldehyde were monitored for more than 11 days with the smart badge monitor. The smart badge was programmed to collect formaldehyde concentration every 10 min. Figure 9.4 shows the record of individual formaldehyde exposure levels in a smart badge worn by a worker. Time-weighted individual average exposure level of formaldehyde was estimated using EWMA and simple moving average methods. Figures 9.5, 9.6 and 9.7 show a comparison between E_{TWAI} estimated using EWMA method (dotted line) and E_{TWAI} calculated using simple moving average method (solid line) for 30 min, 2H and 8H exposure durations, respectively. The horizontal dashed line represents the threshold $E_{TWAI\ Limit}$.

The results show, for any scale of duration, that all threshold overruns are detected when our smart badge uses EWMA to estimate E_{TWAI}. Consequently, the alert management unit is always activated at time. The EWMA method involves a loss of precision in the estimated E_{TWAI} which is less than 10 %. That is acceptable because, in general, the precision of formaldehyde sensor is 10 % at 2 ppm level (NIOSH 2009). The trade-off gained from losing precision to monitor E_{TWAI} is gained by eliminating external memory and reducing processing time costs, and consequently reducing the energy consumption (see Table 9.4).

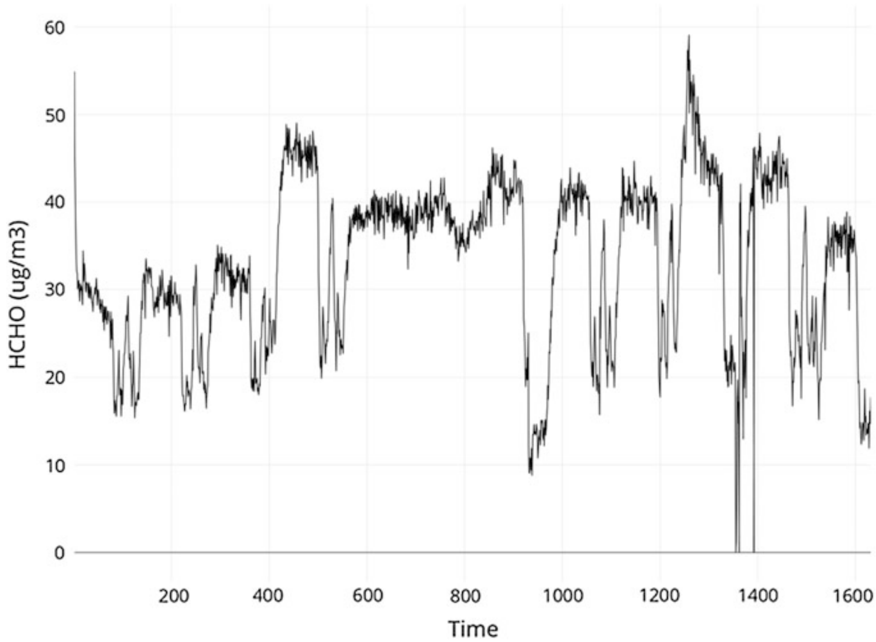

Fig. 9.4 Individual exposure levels of formaldehyde

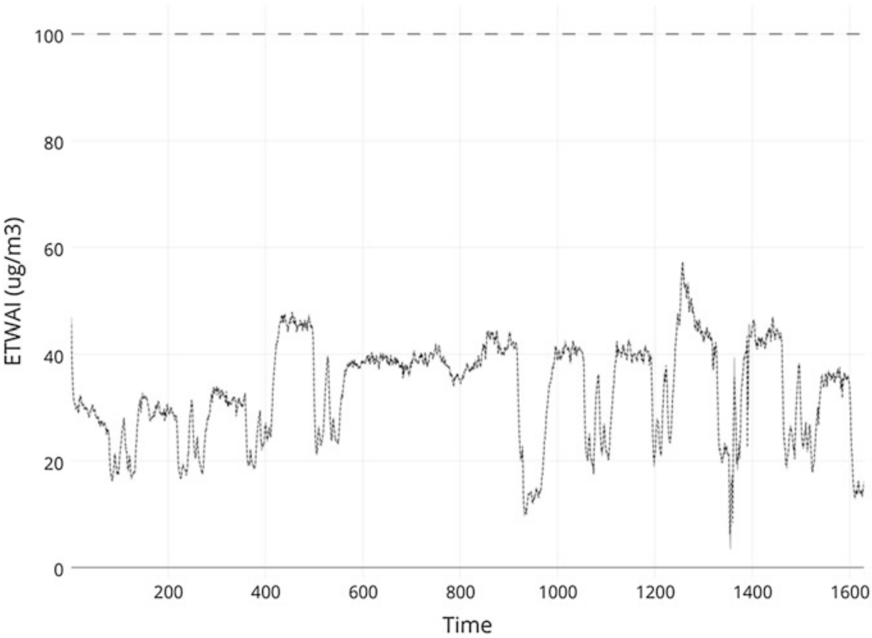

Fig. 9.5 Simple moving average method versus EWMA method for 30 min E_{TWAI}

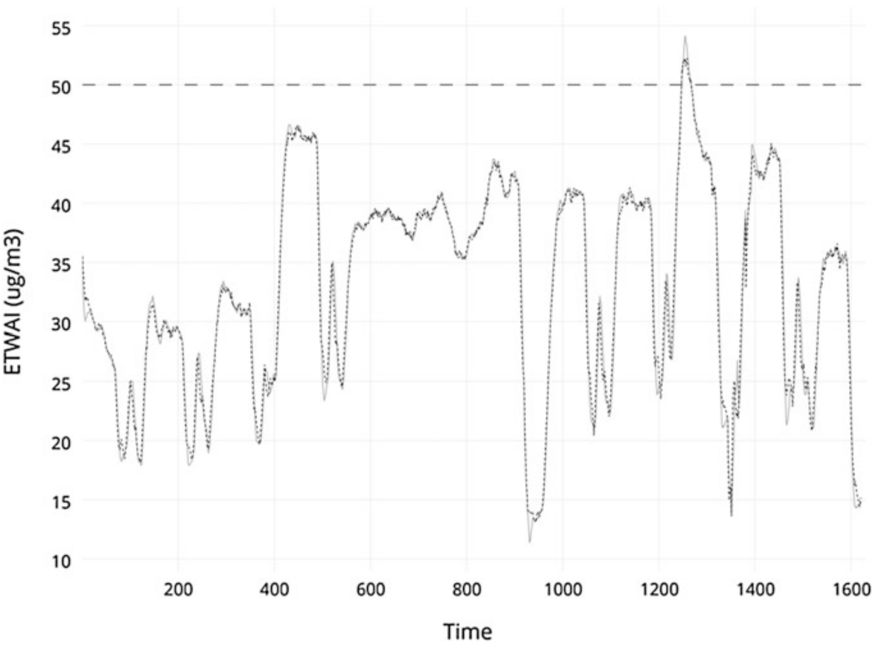

Fig. 9.6 Simple moving average method versus EWMA method for 2 h E_{TWAI}

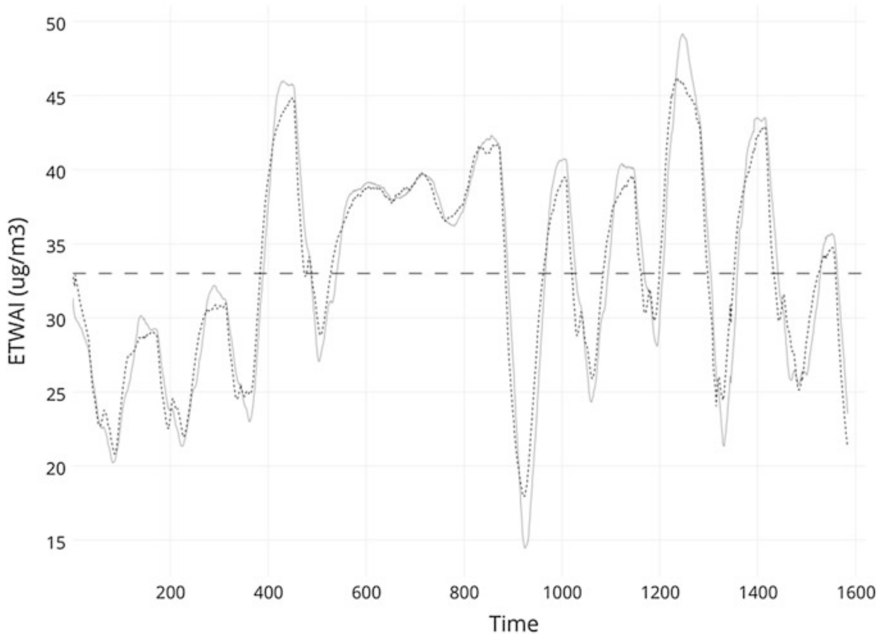

Fig. 9.7 Simple moving average method versus EWMA method for 8 h E_{TWAI}

Table 9.4 Simple moving average method versus EWMA method resources costs

Duration	External memory (bytes)	CPU memory (bytes)	Energy (μJ)	Processing time (Cycle)
	Simple moving average method			
30 min	6524	16	169.96	141857
2 h	6524	16	191.97	141686
8 h	6524	16	325.00	141002
	EWMA method			
30 min	0	16	107.64	4893
2 h	0	16	107.64	4893
8 h	0	16	107.64	4893

Conclusion

This study has shown that the exponentially weighted moving average (EWMA) method can be used by our smart badge and all personal monitoring devices for E_{TWAI} estimation and real-time worker safety and health protection. Despite the loss of E_{TWAI} precision, the smart badge detects successfully the threshold overrun. EWMA method shows a significant reduction of external memory and computation costs, and energy consumption and consequently allows the smart badge to monitor several air pollutants. Results from this study will permit a more robust epidemiological exposure study to be designed. The smart badge will be used as a new tool for monitoring personal exposure and will lead to a better understanding of the nature air pollutant exposure, and its links to human health. EWMA method was implemented and tested with a synchronic measurement system. In the future work, our research will be focused on the evaluation of EWMA method with non-synchronic measurement system taking into account any change in worker's physical location between air pollutants concentrations measurements.

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Part III
Surveying, Measuring and Modelling

Chapter 10
A Case Study of the Metrics of Capturing the 'Green' Improvements on a New Office Building

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Abstract In 2014 Skanska sponsored a WGBC report; 'Health, Wellbeing, and Productivity in Offices; a new chapter for green building'. This proposes a framework of metrics for monitoring green building performance relating to the physical environment, employee perceptions, and financial costs/benefits of variation in occupant health and wellbeing as a result of occupying green office buildings. This paper sets out a methodology in a case study of a recently constructed Skanska office in Bentley (Yorkshire) called Neelands House, where these metrics are being applied in a state-of-the art green facility. This will provide before and after comparisons of how the old/new buildings affect employees, as well as a form of web-based Post Occupancy Evaluation (POE) which could begin to change the way investors approach green refurbishment opportunities. This paper sets out the methodology adopted, lessons learned, and outputs from the initial occupant surveys, however, this research process is ongoing, with the first conclusions on financial and physical metrics to be drawn 18 months post occupancy in the summer of 2016. Skanska are active in the refurbishment market in the UK, demonstrated through their presence on public procurement frameworks for EPC such as RE:FIT, Essentia, and CEF, as well as having carried out green refurbishments to a number of their own offices. A major deterrent for green build/refurbishment appears to be poor understanding of how to deliver projects successfully post-implementation through adopting the necessary operational procedures. Concepts such as the performance gap, and perceived poor ROIs make investment unattractive and a lack of understanding on how best to operate and

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evaluate sustainable buildings in use, are slowing uptake. The business case for green build/refurbishment is primarily based on operational savings. While significant, these only account for a fraction of an organisation ongoing costs, and the case for investment is far from compelling. Decision makers for Green interventions are not increasing uptake rates as quickly as desirable. We see a need to lead in this area, and are now applying this framework of metrics to Skanska's own office buildings in order to develop the methodology further.

Keywords Green · Environment · Metrics · Operational savings · Post occupancy evaluation

Introduction

Skanska

Skanska is a leading project development and construction company, employing about 57,000 staff globally. The UK unit was established in 2000 and is now a leader in public private partnerships (PPP), (green) construction, civil engineering, utilities and building services. In 2000, Skanska became globally ISO 14001-certified, and they have gradually stepped up their green commitment, of which low-carbon office refurbishments constitute a key element. In recent years this has involved 2 low-carbon retrofit projects on Skanska's own office buildings (in Woking and in Maple Cross) where POE has been carried out, through structured workshops and interviews. This case study represents an evolution of that POE process and will serve as a case study upon which to base a template for delivery of people centred, POE on Skanska's future projects.

Background

Against an economic backdrop in the UK of stimulating economic growth amid the worst economic crisis for decades, and achieving challenging carbon reduction targets, the successful demonstration and quantification of economic returns delivered through health, wellbeing, and productivity improvements in sustainable workplaces has the potential to drive a to date stagnant low-carbon refurbishment market, both in the UK and abroad.

Since the rise of the concept of Sick Building Syndrome in the 1980s (Sentman 2009), understanding of health and wellbeing in the workplace, and links to the building an organisation occupies, has increased greatly, to the extent that research is now demonstrating considerable benefits for organisations which occupy high quality sustainable buildings (WGBC 2014; Newsham et al. 2012; Miller et al. 2009; Singh 2010; Sentman 2009).

Buildings in the UK account for almost 40 % of total national emissions (CCC 2014), and in excess of 80 % of the buildings which will stand in the UK in 2050 already exist today (CLG 2008). From 2007–2013 the UK achieved an average annual carbon emissions reduction of approximately 1 % per annum, amid economic growth of approximately 1 % per annum (CCC 2013), and emissions from buildings fell by around 8 % during that period (CCC 2014). However, the total emissions reduction rate would need to increase to 3 % per annum until 2025 (CCC 2011), and then to 6 % thereafter (CCC 2013), if the UK is to reach ambitious emissions reduction targets. Global figures reveal a similar shortfall; in order to avoid uncontrolled global warming global carbon intensity would need to decrease by 6.2 % per annum. From 2000–2014 the average reduction was less than 1 % revealing a huge gap between what needs to be done and what is being done (The Carbon Trust 2015).

Previous UK building regulations meant that new-build developments would achieve high energy efficiency standards as a matter of course and deliver 'zero-carbon' new-build domestic (2016) and commercial properties (2019) Although the current Government look likely to scrap that policy imminently, the new-build market only accounts for between 1–2 % of UK built stock at any given time, meaning this policy measure alone (if pursued) would not achieve wholesale reductions in emissions from UK buildings.

This iterates the critical message for UK property stakeholders that refurbishment of the UK's existing building stock is absolutely essential if targets on emissions reductions are to be met.

In spite of the UK public sector's aspiration to lead on energy efficiency in buildings, and the emergence of market driven innovations for delivering energy efficiency in existing buildings,[1] in a climate of economic cuts and increasing risk associated with ageing estates, uptake of investment in sustainable construction and refurbishment is happening far too slowly to date in order to deliver on national reduction targets.

This is a result of a number of interacting factors including; weak external drivers (The Carbon Trust 2015), scepticism amongst the investment community over the ability of refurbishment projects to deliver target utility savings (the performance gap) (De Wilde 2014), interest on capital extending payback models (often) beyond 10 years, and a lack of low-interest 'green' funds when considered against the scale of the requirement for investment. This has made investment unattractive to the bulk of decision makers, who tend to approach investment in addressing sustainability on a rational basis with the purpose of maximising shareholder value, as such the case is not yet compelling and few individual businesses are fully engaged in addressing sustainability issues (The Carbon Trust 2015), through delivering low-carbon retrofit design solutions to operational estates.

[1]Such as the emergence of Energy Performance Contracting- a cost-neutral means of delivering sustainable refurbishments to large estates whereby initial capital investment can be 3rd party, or self funded, and paid back through guaranteed utility and operational cost savings over the course of a prescribed payback period.

Refurbishment can be extremely time consuming, disruptive to operational continuity, and limited in terms of financially viable interventions by the restrictions imposed by the parameters of the existing building.

Energy efficiency is a key objective globally, and, while energy prices have increased significantly over recent years, they make up only a small fraction of a typical organisation's operational costs. While reduced energy usage, and increased energy security is an attractive future scenario, energy efficiency is clearly not the only benefit to operating high quality sustainable buildings. Indeed asset related and human benefits of occupying sustainable buildings are said to greatly outweigh energy cost savings (WGBC 2013). This raises the issue that as an industry if we are looking to energy efficiency as the sole value driver for sustainable refurbishment, then we are missing the key value delivered to organisations who do invest in sustainable buildings.

There are numerous benefits to occupying sustainable buildings, not least the considerable increases in asset values, occupancy rates, rental yields, and brand enhancement which can come as a result of building green (WGBC 2013). However, these factors are often considered too volatile to be modelled into business cases, and subsequently shape investment decisions. Therefore business cases are based almost entirely on energy and associated operational cost savings.

Thus, the key benefit of occupying high quality sustainable workplaces, as yet, remains uncaptured by these value equations (WGBC 2013, 2014).

A typical organisation spends around (often less than) 1 % of its annual operational expenditure on energy, around 9 % on rent, and the remaining 90 % is spent on staff and benefits (Browning 2012; WGBC 2014). Therefore being able to demonstrate just a fraction of the health, wellbeing and performance related benefits experienced by building users in sustainable workplaces, and quantify them reliably, could completely change the way we look at sustainable building design whereby the relationship between building, energy efficiency, and occupant health and wellbeing is optimised to deliver a holistic sustainable solution. Just a 1 % reduction in people costs would more than double the financial returns of a 40 % reduction in energy consumption, and such improvements can feasibly be delivered through occupying higher quality buildings, and adopting more pro-active operational procedures.

The challenge now facing industry is to identify and quantify these benefits to the extent that they are deemed reliable enough to be factored into business cases for investment in sustainable refurbishment.

The UK Government's 'Soft Landings' policy refers to a strategy for ensuring that the transition from construction to the operation of a sustainable building allows for optimisation of operational performance. Part of this policy is POE; a series of comparisons, structured workshops and interviews, to gain feedback on a building's 'in-use' performance and highlight 'teething problems', identify gaps in communication/understanding which impact building operation, provide lessons to improve operation, and aid a process of benchmarking for comparison over time (BRE 2015).

This case study sets out a process whereby POE has been delivered electronically to occupants of the Neelands House office, and is being used as a vehicle for the delivery of the WGBC's (2014) framework of health, wellbeing, and productivity in office buildings. This is an ongoing process and while initial perception surveys have been carried out, long-term trends in terms of resource consumption, and in terms of impacts on health and attitudes of occupants will become more apparent over time.

Literature Review

Research into the workplace and its operational practices has long looked at ways of quantifying and improving employee productivity, from Taylor's Scientific Management of the workplace, and the factory production lines of the Ford Model-T at the start of the 20th Century, to the Hawthorn studies, and the emergence of the Gallup studies into engagement and workplace productivity since the 1930s (Haynes 2007a, b; Harter et al. 2002; Gallup 2010). However, earlier studies of workplace productivity benefited from the quantifiable nature of the work under scrutiny, whose outputs are more easily quantifiable than is the case with modern knowledge-based office work. This is particularly the case with factory processes, earlier office work, and more recently sales, and call centre work, where productivity can be easily defined and quantified in terms of employee or process outputs such as widgets per day/per hour, or calls per hour, sales per, etc.

Modern office work, often referred to as knowledge-based working, yields less clearly defined productivity outputs, especially in the age of rapidly advancing Information Technology, the emergence of the 'global meeting', and the prominence of networking as a means of generating business. Skanska as an organisation provide a good example of this where the range of roles and disciplines is considerable; some specifically involve generating business and revenue; while others provide a supporting function for revenue generating elements of the business, and thus represent a net cost to the organisation. This would clearly be reflected badly if 'productivity' was considered solely as the extent to which an individual generates revenue for their company.

The term productivity can bear many meanings in the modern workplace, it is an extremely complex concept to define, and more so quantify and link to certain causal elements. While the evidence discussed in this paper demonstrates indisputable links to health, wellbeing and performance improvements for building occupants, it is necessary to use learning on this topic to estimate the impact on bottom-line finances of occupying sustainable buildings, a process which is likely to require development and refinement, and is likely to incorporate a number of metrics (or proxies) of health, wellbeing and productivity.

There is a wealth of evidence in this area, however, the disparity of organisations, buildings, geographical locations, building types and end uses, research organisations, research methodologies, and metrics employed across this research base is striking. Such disparity undermines the evidence base and dilutes its impact on the investment community, as those who need to see it (decision makers) are unlikely to search out such a range of research and draw conclusions on its messages as a whole. It is therefore desirable to put all of that evidence in one place, adopt a common methodology for researching such benefits, and begin to gather data and benchmarks for what constitutes a healthy building. This is a process that was set out in the WGBC Healthy Offices report of 2014. The research process presented in this paper, forms part of Skanska's commitment to leading in this area through applying the 'Common Metrics' proposed by the 2014 WGBC report in our own buildings, and sharing learning on their application and outcomes.

Sustainable building design can significantly benefit occupant health, wellbeing and productivity, as well as organisational bottom-line finances. Newsham et al. (2012) found that green buildings outperform their conventional counterparts in terms of job satisfaction, organisational commitment, health and wellbeing, environmental attitudes and commuting behaviour (Newsham et al. 2012). This confirms the findings of Miller et al. (2009), whose meta-analysis concluded that the cost of providing healthier green workplaces is greatly outweighed by the benefits of reduced sick leave, increased productivity, and higher staff retention rates (Miller et al. 2009). Newsham's findings when taken in the context of Harter's review of the Gallup Studies begin to demonstrate how engaging employees on occupying and operating a sustainable building, as well as the IEQ improvement that comes in tandem, can lead to improved performance amongst employees through providing a vehicle for engagement with employees. Indeed Harter et al. found that that positive emotions of interest, joy, love (or caring), or a sense of contributing to larger entity (person-environment-fit) can lead to a greater cognitive range and subsequently more productive employees. As much as a 5th to 1/4 of variation in adult life satisfaction is accounted for by satisfaction at work (Harter et al. 2002; Gallup 2010).

It is also possible to link positive human and financial outcomes to specific design features of green buildings. Seppanen et al. (2005, 2006) found that temperature has a profound effect on occupant productivity and there is an ideal operating temperature band (21–25 °C) to support optimal productivity. Fisk (2000) found strong links between air quality and improved health and productivity, and makes national estimations of this effect which state that in the USA alone productivity gains from reduced occurrences of respiratory illnesses could be worth between $6–$14 billion per annum. In a later study, Fisk (2012) estimates considerable financial benefits of increasing ventilation rates within buildings, for example by increasing ventilation rates from 8 l/s per person to 10 l/s per person would deliver $13 billion in annual productivity improvements in the USA. Wyon (2004) confirms these findings through a series of 5 h experiments which demonstrated that reducing pollutants within an office, or increasing the ventilation rate would deliver benefits which exceed costs by a factor of 60 and would pay back in around 2 years. Satish et al. (2012) found that increasing levels of CO_2 contamination in buildings can have a large, and economically significant impact on performance. This reiterates Wyon's assertion that the energy cost of increasing ventilation rates in order to clear the build up of indoor contaminants, is far less significant than the financial impact caused by the loss of productivity in poor air quality conditions. As such the challenge to practitioners of sustainable building design is to provide the optimal ventilation rates at different times of the working week through passive, and renewable strategies, i.e. strategies which yield minimal negative environmental impact.

Evidence on the benefits of healthy building design is not restricted to office work, Ulrich (1984) demonstrated that access to a view of a tree (as opposed to a view of a brick wall) had a significant effect on patient recovery times after surgery in a hospital. Patients with a view were released on average 9 % sooner than those without a view. Additionally there were less negative notes attached to patients with a view, and they required fewer moderate or strong painkillers throughout their recovery (Ulrich 1984).

Similarly, research in the education sector demonstrates large potential benefits. Bako-Biro et al. (2012) found that increasing ventilation rates in classrooms delivered significant improvements to student performance.

Other design elements have also been linked to improved health, wellbeing and productivity for building occupants. For example access to local amenities, biophilia, interior design and layout (Barrett and Barrett 2010; Barrett et al. 2013), noise and acoustics (Banbury and Berry 2005), have all been shown in academic research to have positive outcomes for building occupants.

Metrics

While there is no guarantee that a sustainable building is healthy, there are clear overlaps between sustainable and healthy building design. Therefore, a key development in this process of gathering data, monitoring building and occupant performance, and better understanding how buildings affect occupants, will be testing and selecting the ideal metrics for capturing the impact, feeding lessons back into design processes, and leveraging the maximum possible benefits to occupants of good IEQ in order to enhance the business case for investment.

This methodology applies metrics in three categories which have been established with three key criteria in mind; they are able to be applied easily, cheaply, and reliably in a corporate setting if they do not fit this requirement then they simply would not be applied by organisations; secondly that they provide an insight into the relationship between building, occupant, and occupant outputs; and finally that they are replicable across a number of buildings and facilitate comparability, contributing towards a process of benchmarking and identifying good practice.

Physical Metrics

In order to monitor the indoor environment of the office space, CubeSensors were purchased with a view to being placed in the office for a two week period and logging Temperature, Air Quality (CO_2), Humidity, Noise, and Light levels.

To date, it has not been possible to connect the sensors in the new (or the old) facility due to issues with IT security settings. This is an issue which is currently being dealt with by the Skanska IT Service Desk, however, early indications suggest these units will need to be connected on a temporary basis with a mobile data-network.

This represents a significant unforeseen issue with applying the metrics that this methodology sets out and an area for learning in terms of setting up a protocol for rating IEQ. Skanska are currently reviewing available solutions for providing robust and reliable ratings of 'in use' indoor environment parameters.

One item currently under consideration is to apply an (established) independent IEQ building rating to the office. This benefits from requiring only a one-day survey to apply a rating, circumnavigating connectivity issues posed through the currently available IEQ monitoring technologies. Additionally this approach offers greater validity and credibility to the findings as it provides an 'in use' rating of a building's IEQ and is distinguishable from other design ratings for that reason. It is also likely to be an independent national rating tool which can be applied globally without any need for adaptation. This adds credibility through independence, in that Skanska will have no involvement in determining the ratings achieved in their own buildings. However, this approach would only provide a 'snap-shot' of the building's IEQ on a given day, as opposed to a data log which demonstrates how the IEQ fluctuates over a period of time as internal and external conditions change. In the long term this appears a viable option for creating a replicable approach, and will be evaluated accordingly.

Financial/Organisational Metrics

The following metrics were proposed by the 2014 WGBC report:

- Absence rates (pre-move/post-move)
- Staff turnover rates (pre-move/post-move)
- Medical complaints (pre-move/post-move)
- Medical costs (pre-move/post-move)
- Revenue (pre-move/post-move)
- Physical complaints

As with the physical metrics there have been certain issues with the application to date. Firstly within such a large and dispersed corporation as Skanska there are some barriers to accessing what we term as 'HR data' due to ethical concerns of divulging personal or sensitive information. As such, for the purpose of this process we have looked specifically at absence rates for the office building both pre and post-move, and staff turnover rates. These metrics have been applied to a sample of the same office population both pre and post-move, who whilst aware (through participation) of the pre-move/post-move surveys detailed below, were not made aware that financial metrics are also being evaluated.

In order to access this information it was necessary to request Skanska IT Service Desk to set up a process of automatic reporting of this data. While Skanska already reported on these metrics, the requirement in the past had never been to break down this data on a building by building basis. This automatic reporting has now been developed and put into place at Skanska, however, to date insufficient time has passed for any reports to have been produced. This will form part of our ongoing monitoring and POE process at Neelands House.

Regardless of this development, with occupants having only moved into the new facility at the end of 2014, the most significant outcomes from evaluating absence rates and causes, staff turnover, and medical complaints, are likely to come through observing long-term trends.

Perceptual

Pre-move and post-move occupant surveys were distributed via Survey Monkey to assess occupant ratings of the following design features of the building (as set out in the evidence section of the WGBC report):

- Air Quality
- Temperature and Comfort
- Daylighting and Lighting
- Office Layout and Noise
- Facilities and Location

Temperature and Comfort relates to employee perceptions of Thermal Comfort as defined by the ASHRAE (2010) definition of comfort as: *that condition of mind which expresses satisfaction with the [thermal] environment* (CIBSE 2015; p. 23) in relation to the sub-categories of thermal comfort included in the perception surveys (set out below).

In addition the post-move survey included sections on:

- Attitudes towards the workplace, engagement and sustainability
- Rating the most important office features

This provides information on the importance employees place on Skanska's investment in green building design. It asks what this represents in brand and social terms, and the extent to which this shows investment in Skanska's people, impacts employee pride and future career decisions.

The results section of this paper digests the outputs of these surveys, drawing conclusions on how the occupants receive the buildings, the importance they place on certain building design features, the extent to which they perceive an improvement in both the indoor environment of the building, their wellbeing, and working outputs as a result.

Methodology—Developing an Enhanced Post Occupancy Evaluation Product

This research project adopts and develops a methodology set out by the World Green Building Council report of 2014: 'Health, Wellbeing and Productivity in Offices; A new chapter for green building' (WGBC 2014). This report sets out a three-part framework of metrics for assessing the human benefits of occupying green buildings.

Skanska are now applying this methodology in their own office buildings to gain a better understanding of the relationship between building and occupant, estimate savings, and inform future design processes.

Within Skanska this methodology has been adopted as a means of delivering an enhanced Post Occupancy Evaluation process which qualifies Neelands House for 1 BREEAM point in the Aftercare category.

The objective being to use this framework of metrics to develop a clear process template for delivering POE in a manner which is less intensive on human resource, and thus costs whilst also delivering information on the social and economic outcomes of sustainable building design and monitoring its energy efficiency performance. This will form part of a replicable approach to monitoring building performance across the economic, environmental, and social strains of sustainability.

The intent is to continue to implement biannual surveys to employees (at the end of the heating season, and at the end of the summer) in order to identify seasonal issues which cause discomfort (as defined by the counterpoint to ASHRAE's definition of comfort), or a poor IEQ at different times of the year. Delivering POE via electronic surveys offers every employee the opportunity to have their say on building issues through a process which is less resource intensive than the previous method of structured workshops and interviews.

This will allow for estimation of the impact of any given issue on both the IEQ, and on employee performance, through identifying common issues, soliciting perceptions of occupants, and identifying economic impacts through financial metrics. As such it is the intent to set out a POE process which is able to identify and rate the impact of each issue, and facilitate a process of prioritising practical actions for improving the indoor environment in any given season.

This enhanced POE product will become cheaper and simpler to deliver, it will prioritise actions based on the impact of problems, and it will gauge the ability of a building to support a healthy and productive working environment for its occupants, as well as providing a process of monitoring and enhancing energy saving measures and delivering design savings. It is believed that such a process will capture the essence of POE as set out in the PROBE studies of the 1990s, and address the issue of the numerous operational practices which cause buildings to fail to achieve their design savings (Bordass et al. 2001).

The Case Study Project

This paper presents the case of an office move for Skanska employees from a 1926 office facility (Bentley Works) into a new, pre-fabricated, 'BREEAM Excellent', modern office facility (Neelands House). As experienced integrators of complex sustainable building solutions, confidence in the ability of the facility to deliver on design energy efficiency targets is high, however, Neelands House has also been designed with the occupant in mind. So what benefit has it delivered to its occupants? This paper presents the first stages of a process of research whereby a framework of metrics is being applied in an attempt to establish and quantify those human benefits of occupying a top-class sustainable office facility.

The Site

Skanska Cementations have occupied the site at Bentley (South Yorkshire) since 1926. The site consists of fitting, machine and fabrication workshops, plant storage facilities and office accommodation which houses a Finance team, Human Resources and an IT Service Desk enabling function, Skanska Civils, Facilities Services, Cementation Northern, and Ground Engineering/Rail Business streams. This totals to approximately 170 employees who are based on this site.

In addition to the new workshop facility, which has been built to Skanska Deep Green, and BREEAM 'Outstanding' accreditation, the office facility is a 1800 m^2, pre-cast concrete 'insulated sandwich panel' construction, designed with both environmental impact, and occupant health and wellbeing in mind.

New-Build Sustainable Technologies/Strategies

The new office design maximises natural ventilation and daylight through a light well which allows for more efficient cooling and ventilation and optimises ingression of natural (direct/diffuse) light into the office spaces, and controls glare. The low fabric U-values, and low air permeability of the building envelope minimise occurrence of uncontrolled heat loss/gain and air infiltration, respectively.

The design sought net-zero energy through a number of innovative strategies. The heat generation at the site employs a mix of re-use, renewable technologies and efficiency measures, including:

- Heat load met through a combination of reused (waste) oil from the Cementations Factory, Biomass Boilers, and Air Source Heat Pumps
- Heat is distributed through an underfloor heating system set within underfloor concrete slabs-providing thermal mass to store and evenly distribute heat around the office space
- Cooling is provided through an innovative ‘evaporating mist’ cooling system
- Electrical Load is met entirely by an 800 m^2 PV array installed on the workshop roof

In addition to saving energy a number of these measures are expected to improve occupant comfort, satisfaction and wellbeing, leading to improved overall health and productivity.

Results

The pre-move survey was conducted over a 10 day period in December 2014, and the post-move survey in April 2015. The surveys received 43 and 58 complete responses, respectively, out of an office population of approximately 100 occupants.

The ratings occupants gave to the old and the new office facility are tabulated below (Table 10.1). Scores represent the mean rating on a scale of 1–10 which were derived by calculating a weighted average from −2 to +2, this means all ‘No Opinion’ responses carry the neutral value of zero, and those weighted averages were then applied to the scale; where 0–1.9 represents Very Unsatisfactory, 2–3.9 Unsatisfactory, 4–5.9 No Opinion, 6–7.9 Satisfactory, and 8–10 Extremely Satisfactory. Respondents were asked to rate a number of sub-features within the categories given and responses have been rolled up into a mean overall category rating.

As can be seen from the pre-move survey results, only 2 of the ratings fell in the ‘Satisfactory’ band, and the rest in the ‘No Opinion’ band. This reflects an element

Table 10.1 Pre-move/post-move occupant ratings

Design Category	Pre-move	Post-move	Shift (absolute: percentage) (%)
Lighting and daylight	5.4	6.6	+18
Indoor air quality	5.8	7.0	+17
General layout and noise	6.5	7.0	+7
Amenities and location	4.4	7.8	+43.5
Temperature and comfort	6.0	5.7	−5
General building rating	5.7	7.6	+25

of indifference amongst occupants towards the old office facility, and the improved ratings in the post-move survey reflect an improved attitude towards their workplace. While this indifference (pre-move) may represent a reduced motivation for change in the old office, the motivation for investment in this facility was based on a need to provide a world class facility, reflect Skanska values, lead on green, and demonstrate commitment to Skanska employees, i.e. indifference amongst users before the move is deemed largely irrelevant to the motivation for change, however, the more positive responses (post-move) demonstrate an additional (social) benefit to having made the decision to invest.

The results show significant improvements over the old office facility in all categories except for Temperature and Comfort. This category consists of 4 sub-categories:

1. Temperature in winter is it warm enough?
2. Temperature in summer is it cool enough?
3. Personal control of temperature
4. Overall thermal comfort

As can be seen from the breakdown of this category in Tables 10.2 and 10.3 below, the lower post-move rating can largely be explained by a far lower score in the Personal Control subcategory (in **Bold**). This is to some extent to be expected due to the nature of the two facilities.

When applied to the ratings scale the figures in **Bold** equate to 6.5 (pre) and 5 (post) out of 10, a 23 % reduction post-move. However, by removing the Personal Control element of this category the ratings look somewhat different, as shown in Tables 10.4 and 10.5.

Under this scenario the Temperature and Comfort ratings are 5.6 (pre), and 5.7 (post) demonstrate a slight improvement, however, ratings remain in the neutral band on the rating scale, showing little significant change.

Table 10.2 Temperature and comfort (pre-move survey)

	Extremely satisfactory	Satisfactory	Neither/no opinion	Unsatisfactory	Extremely unsatisfactory	Count	Weighted Ave (−2 to +2)
Temperature in winter (hot enough)	7	18	3	13	2	43	0.35
Temperature in summer (cool enough)	5	15	13	9	1	43	0.33
Personal control of temperature	9	17	8	9	0	43	**0.6**
Overall thermal comfort	7	15	7	14	0	43	0.35
Overall weighted average							0.4

Table 10.3 Temperature and comfort (post-move survey)

	Extremely satisfactory	Satisfactory	Neither/no opinion	Unsatisfactory	Extremely unsatisfactory	Count	Weighted Ave (−2 to +2)
Temperature in winter	4	26	14	9	3	56	0.34
Temperature in summer	2	23	26	4	1	56	0.38
Personal control of temperature	1	14	24	15	3	57	**−0.09**
Overall thermal comfort	3	34	11	6	2	56	0.54
Overall weighted average							0.29

Table 10.4 Pre-move temperature and comfort (excluding personal control)

	Extremely satisfactory	Satisfactory	Neither/no opinion	Unsatisfactory	Extremely unsatisfactory	Count	Weighted Ave (−2 to +2)
Temperature in winter (hot enough)	7	18	3	13	2	43	0.35
Temperature in summer (cool enough)	5	15	13	9	1	43	0.33
Overall thermal comfort	7	15	7	14	0	43	0.35
Overall weighted average							**0.26**

Table 10.5 Post-move temperature and comfort (excluding personal control)

	Extremely satisfactory	Satisfactory	Neither/no opinion	Unsatisfactory	Extremely unsatisfactory	Count	Weighted Ave (−2 to +2)
Temperature in winter	4	26	14	9	3	56	0.34
Temperature in summer	2	23	26	4	1	56	0.38
Overall thermal comfort	3	34	11	6	2	56	0.54
Overall weighted average							**0.31**

In Figs. 10.1 and 10.2, the outputs of the two additional sections in the post occupancy survey are presented.

Mean attitude responses (Fig. 10.1) demonstrate that respondents appear engaged and invested in Skanska's focus on sustainable construction. It also

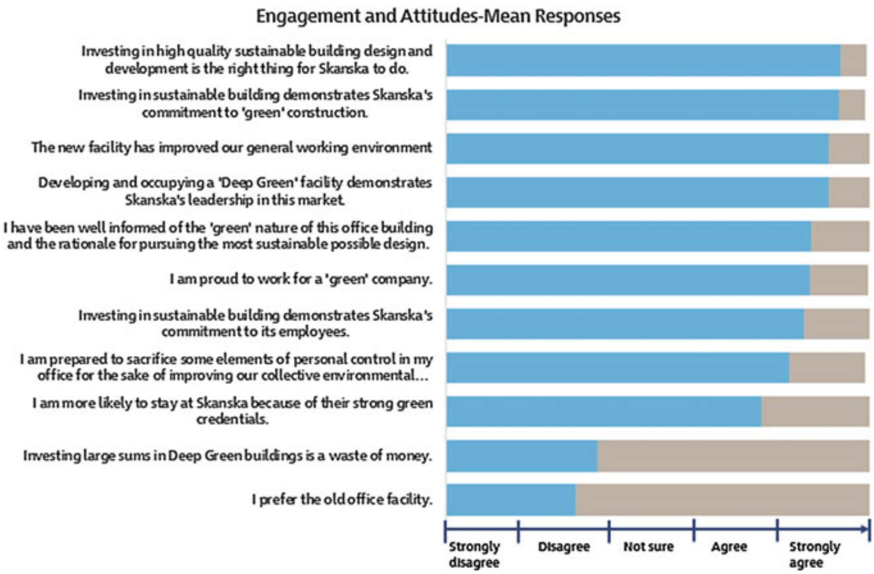

Fig. 10.1 Engagement and attitudes-mean responses

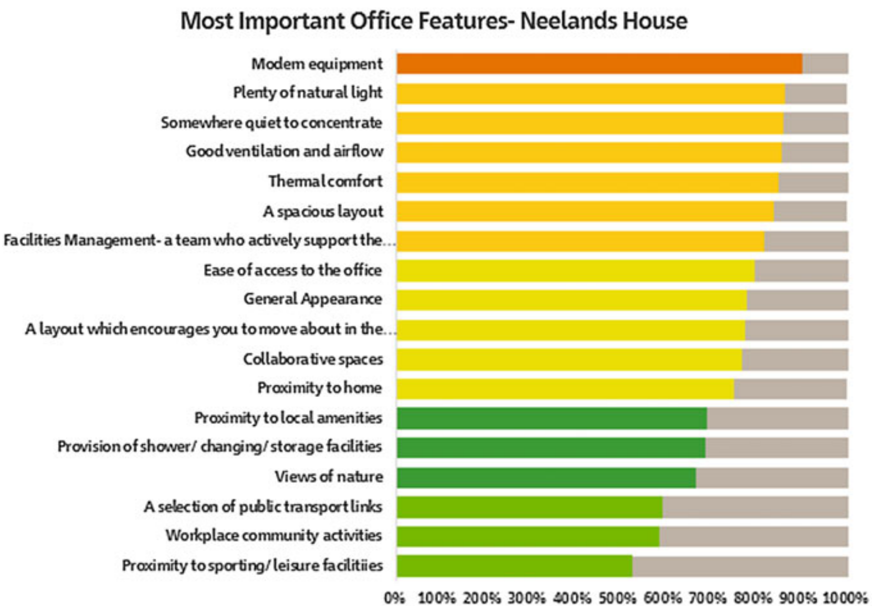

Fig. 10.2 Most important office features

demonstrates that Skanska may see a reduction in staff turnover as this strategy continues to grow in importance, and more 'green' Skanska offices are developed/refurbished.

The mean importance ratings above highlight the importance employees place on daylight, air quality, and temperature as an influencing factor on their wellbeing and productivity.

Discussion

The framework of metrics set out in the WGBC report of 2014 is intended to provide insight into the relationship between building, occupants, and finances, and it is the correlations between physical, perceptual, and financial metrics which are expected to provide the most telling learning for practitioners of sustainable building design, development, and operation.

It is of course expected that the occupants receive the new facility very well-clearly a brand new office represents an improvement on an older facility. It is a point of interest within this process to see whether the ratings for the new facility deteriorate in later versions of the post-move survey (next survey: post-summer 2015) as that novelty dissipates. However, this framework attempts to look at the relationship between the buildings performance in each of the design categories and how these affect the attitudes of occupants.

Notwithstanding the impact of 'novelty', the initial results of the pre and post-move surveys are promising, and demonstrate that occupants perceive a significant improvement in IEQ. Additional to this, the surveys highlight the value of investing in high quality sustainable office accommodation in terms of how it, and engagement on the topic, impacts employee attitudes towards the organisation as a whole, represents a significant consideration in future career decisions, and enhances the sense of pride in working for Skanska. When related back to the literature, and the findings of Harter et al. (2002), and Gallup (2010) that the positive impact of creating a sense of person-environment-fit in the workplace is one of the principle influences on improved workplace productivity, it appears the longer term process of carrying out POE at Neelands house will yield significant economic benefits both through delivering enhanced IEQ and its associated impacts, and through engaging occupants on the topic of the building, its environmental features, and its operation on an ongoing basis.

By and large these results back up the literature relating to improved perceptions of office, company, and self perceptions of health and wellbeing. This suggests that this should lead to a greater sense of belonging to the organisation which in turn can be expected to manifest itself through financial benefits.

Improvements in all building design categories (barring Temperature and Comfort) demonstrate that the sustainable design features inherent in achieving the BREEAM 'Excellent' rating, have delivered a higher quality facility in the eyes of occupants. Key to this process now is whether or not these improvements are apparent in the IEQ testing, and if they manifest themselves into bottom-line financial benefits.

Early indications suggest this will be the case as not only did the respondents rate the new building favourably, but they also indicated that daylight, air quality, and thermal comfort are amongst the most important features of an office in terms of supporting health, wellbeing, and productivity. Excluding the overall Temperature and Comfort post-move rating, this suggests that the new facility, which shows significant improvements in the first two of these categories, should over time lead to better general wellbeing, and the bottom-line financial benefits that this process is designed to demonstrate.

The Temperature and Comfort category yielded a slight deterioration in the rating for the new office facility. This is explained by a lower weighted average rating in the Personal Control subcategory which dropped by 23 % from 6.5/10 (pre) to 5/10 (post). By excluding this subcategory, however, we see that those ratings shift to 5.6 (pre), and 5.7 (post) ('No Opinion'), however, this is likely to be for different reasons. Anecdotal evidence suggests that Thermal Comfort in the old facility was generally poor due to the ageing heating system and associated controls, which is likely to have led to a high range in indoor temperature throughout the week. However, work spaces were largely cellular, and supplementary personal heaters allowed a certain element of control for many employees of their immediate surroundings such control, however, clearly came with an associated energy penalty. The new office is open plan, and as such heating, ventilation, and cooling is automated, meaning occupants have little control over this process other than to request settings adjustments by the Facilities Team. It is expected that when the IEQ of the new facility is tested it will reveal a relatively narrow temperature range, which is generally within the 21–25° optimal band for productivity as set out by Seppanen et al. (2005, 2006). In this scenario, it appears feasible that in physical terms the thermal environment has indeed improved by virtue of the fact that it remains within the optimal temperature band, yet perceptions of comfort have diminished due solely to the reduction in personal control in the new facility.

In the 'Temperature in summer' subcategory, 46 % of responses were 'No Opinion', this again is to be expected, as the first post-move survey was conducted in April, meaning that occupants are yet to experience a full summer. When the post cooling season occupant survey is conducted in autumn 2015, it will be a point of interest to observe any fluctuations in this category. Clearly this high proportion of neutral responses nullifies the effect of the positive and negative responses in producing a mean rating, therefore there is potential for some movement in this category (positive or negative) as occupants do experience a full annual weather cycle.

This process has also highlighted some other 'teething problems' inherent in adopting this methodology, and represents a process of learning and development for the practitioners, and areas of refinement and improvement in order to increase the robustness and reliability of this research process. This has highlighted some key issues.

Firstly a bespoke process for reporting data on a building by building and even a zonal basis should be established early in the process in order to gain the maximum possible insight into what absence, staff turnover, medical, and revenue-based data reveals.

The dispersed nature of Skanska as an organisation means that the most meaningful findings are likely to come from the (minority) proportion of the workforce who are based on one office all, or most, of the time.

The optimal solution for rating the IEQ of an office is yet to be established. Addressing this task has revealed some useful learning:

- There is a lack of technology solutions on the market which monitor the majority of IEQ parameters (light, IAQ, noise, humidity and temperature). Currently the products which do this are better suited to (and marketed for) domestic use. Industrial solutions tend to require purchase of several monitoring items which must be budgeted for from the outset.
- Most solutions require a Wi-Fi internet connection to operate which can incur labour and hardware costs in order to implement in large organisations with large IT Servers and associated security firewalls.

As a result of this learning, and dissemination among peers, it appears that by using an established 'in use' building IEQ rating system it is possible to circumnavigate these issues, and add credence to the outcomes through the independence of the rating system. This is a development which is currently under discussion as it may better facilitate a replicable and robust methodology for rating IEQ, and ultimately relating IEQ parameters to human performance outcomes. The merits of both approaches will be evaluated over the coming weeks.

As such, while data is still pending from Physical and Financial metrics the outcomes of this research process represent a qualified success in that it has yielded positive and insightful outputs on employee perceptions, it has led to significant learning on the implementation of such a process, and represents for Skanska robust and enhanced POE process which captures and enhances the financial, social, and environmental benefits of sustainable buildings, while creating a less resource intensive mode of delivery.

Conclusions

New approach This template for research on environmental, social, and economic performance of a building is a new and innovative approach, and as such has faced some obstacles and barriers which have slowed the process to some extent. However, as opposed to pressing through research solutions which do not ideally fit the requirements for a replicable and robust approach, the researcher has sought the best solution available to facilitate a long-term, replicable approach to conducting this research on multiple buildings globally. Therefore lessons learned during this process have been logged and will be taken into account in developing the final template for collecting both physical and financial data. Through developing these reporting processes in Skanska with the collaboration of the relevant departments this will inform the development of that final reporting process. This approach has good foundation, is relatively simple, and when fully refined will produce meaningful data from which conclusions will be drawn which wouldn’t have previously been possible. As such, some delays to the research process are entirely acceptable provided the final process is tailored to its objectives.

Caution is required It is necessary to interpret results with an element of caution for two main reasons:

1. Occupant perceptions of productivity and wellbeing can be unreliable, therefore it is necessary to interpret this data in relation to both the physical and financial data outputs for each dataset to corroborate the validity of occupant perceptions.
2. Time is required in order to gather the meaningful results from perceptual and financial data. There is the potential for a novelty factor to influence perceptions of a building within the first month or two of occupancy. It is believed that with the building having been occupied for approximately 4 months prior to the post-move survey this was sufficient time for that initial novelty to wear off for the occupants. Future versions of the post-move survey may feasibly demonstrate less positive perceptions of the building as that novelty continues to dissipate. However, with surveys conducted at the end of the heating season and the cooling season, there is potential for seasonal variations in perceptions of the building as either the heating or cooling season raises its own specific problems to occupants.

Results (to date) support the literature Literature on the topic points out a number of benefits of occupying green buildings, from improved sleep patterns, reduced stress, better health, satisfaction, feelings of belonging and engagement, to increased sense of pride in working for Skanska and subsequently an improved likelihood for employees to remain Skanska employees in the future. However, for the reasons outlined above, these results must be interpreted with an element of caution at this stage, until they are supported by data outputs from the physical and financial metrics in due course.

This precedes a process of trial and error where solutions are sought for identified building issues and the impacts of interventions are monitored. Observing high level financial data will provide some indication of this impact, however, it is the evidence base within the literature review which will provide greatest insight into how best to enhance occupant health, wellbeing and productivity, in the most resource efficient manner.

Future potential This research has raised some topics for evaluation and consideration for carrying this process forward to achieve optimal impact on encouraging sustainable building refurbishment:

- Potential to rate all offices based on IEQ (regardless of energy efficiency ratings) could show conclusive trends for better IEQ meaning better productivity and lower absence and recruitment costs
- Should metrics demonstrate consistent benefit there is excellent potential to use the growing evidence base to optimise building performance relating to energy efficiency and supporting a productive IEQ
- There is a need to pursue the ideal data reporting framework for making the best use of data and linking performance to specific design features (daylight, ventilation etc.)
- Potential new business case which conclusively demonstrates the organisational benefit of investing in IEQ improvements in workplaces in tandem with delivering energy efficient upgrades
- This remains a work in progress, and will be developed and refined over the coming years. However, the evidence and findings to date demonstrate significant value in pursuing this theme of research
- Successful demonstration of health wellbeing and productivity benefits in new build green workplaces could inform learning and development of lowcarbon refurbishment design in order to optimise the relationship between building, people, and resource use.

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Chapter 11
Building Surveys to Inform Assessment of Initial Conditions in a Property Prior to Thermal Upgrade

Melanie Smith

Abstract Building surveys of existing properties can be useful when considering thermal upgrade. One aspect of the performance gap, when thermally refurbishing an existing property, is a miscalculation of its performance prior to intervention. If better than expected and the performance following intervention is worse, then gains and pay-back periods will be unfavourably affected. Additionally, some individual aspects may be identified which preclude certain design decisions. To assess the performance there are four levels of inspection: a desktop assumption, a brief visual visit, a short condition assessment, and a full building survey with initial performance testing taking some hours or even days to determine actual construction and performance rather than theoretical. One prerequisite assumption for thermal upgrade design is that the property construction and condition is known to the extent of the fourth level of survey, whereas in practice, only a desktop assumption or brief visual inspection may have been made. Resources of time, money and size of estate are usually restricting factors on the level of survey undertaken. The requirements of an initial survey have been explored. This would determine where the construction, materials, and condition of the property may impact on its pre-works performance and where these may adversely affect its performance following the thermal improvement. Specific reference is made to moisture levels in the construction. Standard levels of survey are compared and assessed against the information required for effective thermal improvement. A protocol for an initial survey assessment of a property's construction, condition and performance is offered.

Keywords Building surveys · Thermal upgrade

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Introduction

In the drive to reduce energy usage in the built environment, the UK government has established various initiatives to encourage property owners and developers to improve thermal performance. Once a decision has been made to carry out intervention on an existing property, the choice of which intervention or interventions needs to be determined. The decision process may include some level of survey to recognise what will be encountered for each property. This paper concentrates on thermal upgrade which includes interventions to the external walls for domestic properties.

Performance gaps between designed or expected and actual performance have been recognised both for new build and for refurbishment (Stafford et al. 2011; STBA 2012). When an existing property is being thermally refurbished, one aspect of this performance gap is a miscalculation or misunderstanding of its performance prior to interventions. This is important because to determine the need for improvements, the initial condition must first be known. If the initial performance is better than expected and the performance following intervention is worse, then gains and pay-back periods will be affected.

During a survey some individual aspects may be identified which preclude certain design decisions for the intervention. Better design decisions for expected challenges for performance can be identified. Aspects of refurbishment tend to result in a compromise between two or more opposing attributes therefore the physics and consequences of these attributes need to be recognised.

The aim of this research was therefore to determine a practical approach to surveying properties prior to intervention for improving thermal performance.

Research Review and Methodology

The theoretical framework used for this research was based on professional building surveying. A desktop study of survey methods was conducted. As part of a team investigating building performance after intervention and carrying out field research of 41 properties, relevant requirements of the building survey and pertinent construction aspects which can affect post-intervention performance were identified. Surveys were carried out before, during and following intervention.

The field work resulting in this paper was part of a wider project of intensive measurement of properties for thermal performance. This paper is limited to the research work to produce an initial building survey proforma used to collect construction data useful for both full performance testing and, when completed without full testing, for the intervention design process.

The surveys were informed by requirements of building physicists, performance testers and contractors. The building pathology aspects raised were checked against standard texts and guidance used in the industry and relevant research papers.

This resulted in an iterative approach to designing a proforma and protocol for building survey assessment of a property's construction and condition prior to thermal upgrade works.

Research Results

The desktop study of survey methods identified many different types of survey and many more methodologies. The research concentrated on surveys of domestic properties including individual properties and estate stocks. The RICS, the Royal Institution of Chartered Surveyors, is regarded as one of the main international authorities on surveys, and state what is required by a specific survey, but not exactly how to record it, which is left to the professionalism and competence of the surveyor. The Royal Institute of British Architects, the RIBA, provides similar advice, as does the Institute of Structural Engineers and the Chartered Institute of Architectural Technologists. However, as the published guidance documents giving RICS advice are extensive, these were found the most useful. English Heritage (now Historic England) advocates assessment of a property and "understanding the building" before carrying out upgrading works (English Heritage 2012). Although their advice is mainly for historic buildings, this publication also purports to be relevant for traditional buildings.

There are various tools for recording findings. For example, the surveyor could use computer notepads programs, long proforma complete with pre-set paragraphs, short memory checklists, or, if experienced, rely on a blank notebook and personal recorder (RICS 2005, 2013).

The type of survey to be carried out will be formally or informally decided. For a single element in a property, the type of survey can vary between four basic levels: a desktop assumption of type and condition from estate records (RICS 2005), a brief visual assessment solely for design purposes, a short condition survey using usual surveying equipment, or a full structural building survey with initial performance testing taking some hours or even days (RICS 2013). Building surveys are carried out for a variety of reasons, but can usually be summarised as aiming to inform the client what, if anything, is wrong and why, what damage has occurred, how serious this is, what is needed to put it right, how much this is likely to cost, when the remedial work should be carried out, who is responsible, and what further action is to be taken (RICS 2010). Building surveys for research or auditing purposes can also be carried out to determine, as far as possible, actual construction rather than theoretical, whether the construction is in compliance with set requirements, and/or to understand patterns of behaviour or performance.

Measured surveys are normally carried out by architectural technologists, architects, contractors and other designers of intervention works but are not normal parts of a building survey (RICS 2013). It was found that the building physicists required details of internal floor areas and internal volumes. A simple measured survey was therefore added to the protocol. Additionally they required knowledge of existing boiler and heating arrangements, the presence of bath or shower, and what type of fuel, gas or electricity was used for cooking.

From the desktop study, documents discussing the types of intervention and their application were found to have a prerequisite assumption for the intervention design that the existing property construction and condition is known to the extent of the fourth level of survey. This level was briefly described above as the full structural building survey with initial performance testing. Whereas in practice, especially where the client has a large portfolio, a desktop assumption or brief visual inspection only may have been made. Time, money and size of estate are usually restricting factors on the level of survey undertaken (RICS 2005). Although limited surveys are useful for determining average commercial conditions for improvement of the properties, each individual property is likely to have its own idiosyncrasies and anomalies to the extent that no individual property will actually perform as the averaged model.

The RICS, RIBA and other professional bodies require the professional to assess the needs of the client. This necessarily involves considering the extent of any investigations of the building to be made and undertaking an impartial and professional assessment of the property and its condition, reporting to the client in the detail and extent necessary to provide a balanced professional opinion (RICS 2004). Therefore, it is crucial to consider the scope of the survey, before undertaking an impartial and professional assessment, and then offering a balanced, professional opinion with sufficient detail and extent.

The surveyor is advised to initially carry out a desk study to ensure that they have all the necessary background information to enable professional assessments to be made on site, although in certain instances some information is obtained after the inspection. The surveyor may consider relevant site information (e.g., exposure), the age and apparent construction of the main property and the additions or alterations, details of obvious alterations and works, conservation area or listed building status and any available technical reports relating to the property. This list of information is not exhaustive (RICS 2004).

Once on site, the RICS guidance notes state that as a general principle it is advisable that surveyors carrying out building surveys identify, where possible, the particular construction and materials used in the property. The notes do not emphasise that without this, the surveyor may not be able to report upon the likely consequences of any interventions. Determining the particular construction or material is not always straightforward. The field research identified the need to take copious photographs in order to assist office-based research.

The surveyor's available equipment (RICS 2004) should include a tape measure, binoculars, compass, 3 m ladder, spirit level, plumb bob, crack gauge or ruler, electronic moisture meter, torch, and bradawl. Electronic moisture meters need to be used with caution and experience as the presence of salts (common in older existing buildings) can produce misleading readings (English Heritage 2011). Other equipment might include for example moisture meter accessories including surface temperature probe, humidity sensor, air temperature sensor, deep insulated probes, and a boroscope. In addition surveyors' equipment increasingly includes an infrared camera, a laser distance measurer, and a tablet-based software package. A new addition to the tools is an unmanned aerial vehicle as a replacement for an elevated work platform, scaffolding or tall ladders. These are used to view, via a camera, parts of roofs and other high level inaccessible areas. During the field research, binoculars, bradawl, moisture meter, thermal camera, ladder and torch were used.

Within the scope of the terms and conditions of engagement the surveyor is responsible for carefully and thoroughly inspecting the property and recording the evident construction and defects. The surveyor should therefore, within the limits of the agreed instructions, view as much of the property as is reasonably accessible, inspecting all relevant parts of the property as closely as possible, whilst considering their inter-relationship. For most properties, however, a full inspection is prevented by physical conditions. Surveyors can give rough estimates of the time required for the survey, but are advised not to limit the time for inspection taking the time required for the property in question (RICS 2004). During the field work this was not found to be practicable. Attendance by the occupant or contractor was usually necessary and reason therefore restricted the survey time to about an hour. If considering a survey of an estate's stock, even with more than one surveyor, an hour given to every property would be untenable. It is acknowledged in the guidance (RICS 2010) that balancing time, cost and quality in order to achieve the client's objectives is frequently difficult.

Surveyors are trained to recognise that older buildings were designed and constructed differently to modern buildings. This point is not just applicable to 'historic' buildings but to all buildings of a traditional type. Works resulting in changes in the intended performance of a traditional building can have detrimental consequences on its condition (STBA 2014). English Heritage (2012) describes traditional solid walled properties as 'breathing' structures, exchanging moisture readily with the indoor and outdoor environment, thereby limiting moisture within the wall fabric to below risk thresholds for decay. Problems can occur with the entrapment of moisture by impervious materials used in repair and maintenance such as cement-based renders, pointing, plasters and more modern paints. Historic Scotland state that understanding how a building was intended to perform and changes to that performance is important in successfully determining a building's existing and future condition (Historic Scotland 2007), whilst English Heritage (2015) goes further stating that "It is vital to ensure that insulation is not applied to a damp wall, or to a wall with a history of damp problems that have not been conclusively eradicated. Adding insulation is very likely to make the damp problem worse, and have little or no thermal benefit." Damp testing is therefore a major part of the pre-intervention survey.

English Heritage (2011) suggests a range of non-destructive testing, including air-pressurisation tests, infra-red thermography, dampness measurements, in situ U-value measurements, boroscope investigation, monitoring energy consumption and environmental data logging. Some of this testing is essential for designing specific interventions for a particular property and most are essential for a thorough testing of the property. These tests were conducted on the properties included in this research and can be expensive, time-consuming and require specialist services.

In isolation and without the benefit of understanding the building as a whole and its constituent materials, these tests may not be beneficial. However the publication (English Heritage 2011) omitted to suggest a building survey which can identify important features to understand the building, within a tight timescale and provide a holistic assessment.

It was found that although guidance was supplied by the professional and statutory bodies, a protocol and proforma for a building survey of a property specifically for improving thermal performance was not publically available. The emphases identified by the RICS placed on aspects of other types of surveys did not specifically highlight danger signs when surveying for thermal refurbishment. The desktop and field research identified that construction type, specific construction materials, moisture and breathability issues are vital aspects to record. Therefore the survey protocol was revised with emphasis on the property's condition which may be sensitive to alterations in its breathability, rain screen measures, and moisture equilibria.

For the field work, typical UK construction periods were included in the research properties: 1870–1910 back-to-backs and through terraces both of 225 mm external brick walls, and 1960s to 70s terraces of 200 mm, externally rendered, reinforced no-fines concrete walls. Each has its own challenges, as well as similarities, and it is imperative to consider the risks of remedial work at design stage to overcome these or at least to appreciate what risks are being built in.

Solid brick or stone walls are neither "solid" nor homogenous. Traditionally, they are built nominally of two leaves in close contact, tied together with intermittent brick spans, and some sporadic infill of mortar. More modern methods, particularly in the mid-20th century, include solid block or concrete construction with external render (Marshall et al. 2013). Moisture is able to enter and pass through the wall originating from rain (walls and roof), ground, leaks, and condensation. Render is often used to avoid moisture penetration, but where this has been applied to damp walls it can seal the moisture into the structure. Where render fails by cracks or spalling, moisture is able to enter the wall, but is deterred from drying out (Melville and Gordon 1973).

The outer portion of a solid wall is the rain shield, whilst the inner supports the built-in timbers, for example the floors, roof window lintels, door lintels, jamb fixings, and brick substitutions. If any of these get and remain damp, they are at risk of decay (Ridout 2000; English Heritage 2012).

To avoid moisture rising through capillary action from the ground, damp proofing measures need to be effective and at a height not to affect any floor joists. To stop moisture being driven from rain to the inside, the brick faces and pointing need to be in good condition (Melville and Gordon 1973). Deteriorated or incorrect pointing can seriously reduce the performance of a wall and by implication, a building. Water can become trapped behind dense mortar, not evaporate out and cause physical damage to stone and brick (EHS 2006). To assist drying out, the wall should be breathable from the inside to the outside. If a damp wall is sealed internally or externally during intervention, the moisture remains in the construction. Permanently damp external bricks are at greater risk from freeze-thaw action

(Ibstock 2010). The protocol therefore needs to include assessing damp proof courses, pointing condition, wall fractures, and sealing of junctions around openings and initial moisture levels of external walls.

Surveys in the field during and following intervention were able to identify common aspects of interventions likely to result in future problems. The surveyor needs to be aware of proposed designs for the intervention in order to advise the designer.

For external wall insulation, common findings included those illustrated in Figs. 11.1, 11.2 and 11.3. Figure 11.1 shows a scheme where properties were having external insulation applied but the design did not include extending the eaves to accommodate the extra thickness of insulation, nor altering the gutter and downpipe arrangements. The darker section at the top of the thermal image showed the thermal bridge resulting. There were other cut-outs or omissions of external insulation to accommodate external plumbing. These would similarly result in thermal bridging.

External insulation is likely to affect rainwater goods including gutters, downpipes and gulleys, and also waste and foul pipes on the external walls. The gulleys and inspection chambers at ground level may also be affected. The proforma

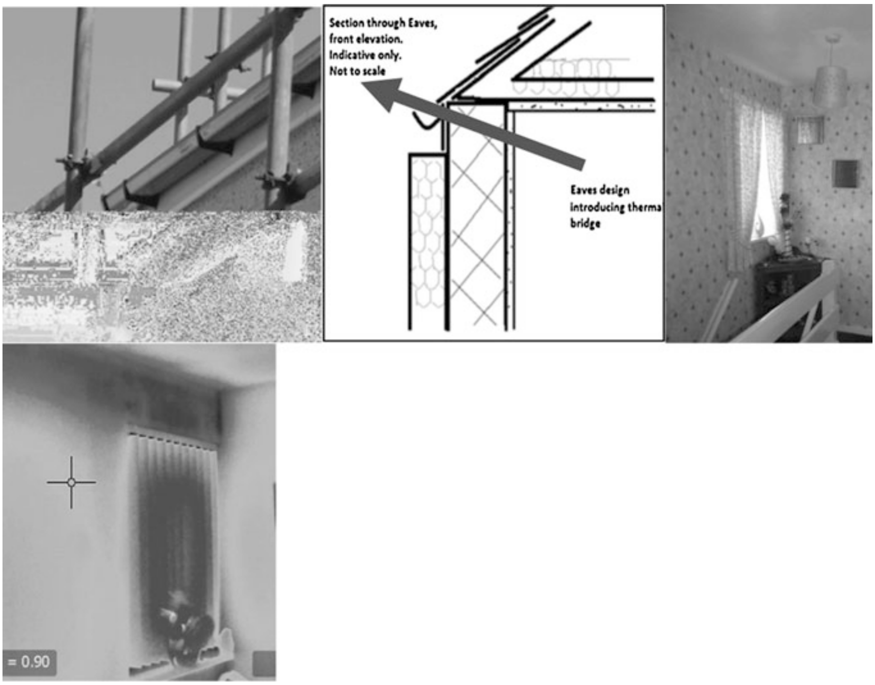

Fig. 11.1 External wall insulation without amending eaves and gutter. From *left to right external view* illustrative section sketch where the *arrow* shows a designed-in thermal bridge; *internal view* thermal image where the darker row at wall/ceiling junction indicates the thermal bridge

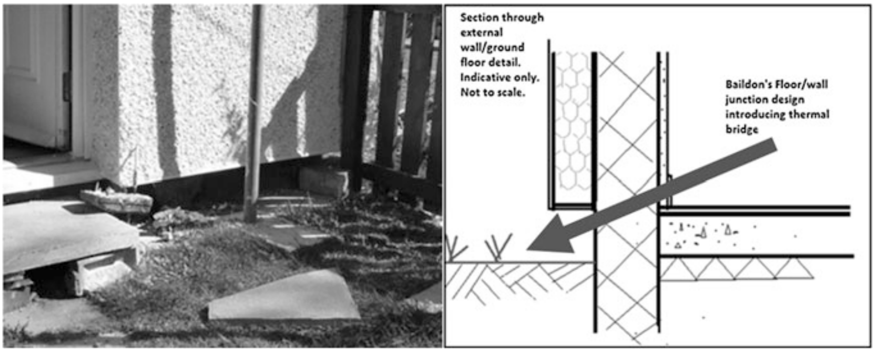

Fig. 11.2 External wall insulation at ground level. *Left to right external view* illustrative section sketch where the *arrow* shows a designed-in thermal bridge

Fig. 11.3 Openings in the thermal envelope. *Left to right* passageway between terrace houses giving access to back gardens; bin store as internal enclosure between properties

therefore needs to identify the presence and position of any rainwater, waste and foul goods and the likelihood of these affecting the intervention design or performance.

The illustrations at Fig. 11.2 show where the external wall insulation was taken down to the damp proof course level finishing around 150 mm above ground level. This is normal to avoid splashing bypassing the dpc and wetting of the insulation. However as the finished floor level was also at this level and no works were being carried out to the uninsulated solid floor, this would result in a thermal bridge at the wall and floor junction.

The proforma therefore needs to identify the position and condition of any damp proof course, the ground level, the presence of existing render, and likelihood of these affecting the intervention design.

Openings into the thermal envelope need to be considered at design stage. The two illustrations at Fig. 11.3 show examples of such openings which may not have been included in the proposed intervention design. Providing external wall and soffit insulation to the passageway may restrict access for people and refuse bins, whilst insulating the internal walls of the bin store may restrict space to store the bins.

The protocol therefore needs to include identification of openings such as those illustrated in Fig. 11.3 and with respect to proposed interventions, the highlighting of any prospective issues.

Internal wall insulation also brings challenges. Avoidance of thermal bridges resulting from breaks in the wall insulation at floor and ceiling levels was an aspect that needed early design decisions. The position of the last joists parallel to an external wall needed to be determined to assess its proximity to that wall. Typically it was found that they are positioned so that the gap between the joist and the wall is 25–50 mm which is too narrow to effectively place internal wall insulation. It is common to have no wall plaster or render in the floor void, which increases the likelihood and amount of air infiltration. Frequently, especially in back-to-backs, the joist ends of these joists also showed signed of decay and fungal attack. Poor design choices included omitting insulation at floor voids (thereby creating thermal bridging and air permeability) and putting small sections of insulation between the joist and wall (creating pathways for heated air to move through to the external wall). Other contractors moved the joist, giving a 100–150 mm gap to permit the external wall insulation to be carried down the wall from roof void to basement without break.

Where the floor and ceiling joists are perpendicular to the external wall, further consideration of the issues of air-tightness, thermal bridging and aggravated decay conditions is needed. Joist ends, built into a wall having internal wall insulation, are likely to encounter differing conditions from those expected at construction. Because of the insulation, the masonry is likely to be colder and damper and remain so for longer periods, increasing the risk of rot and decay to timbers within the wall thickness and frost damage to the masonry at the surface (English Heritage 2012). Frost damage will consequently permit more water ingress from the environment, thus increasing the moisture content of the wall and exacerbating the problems (BRE 1998).

The proforma therefore needs to identify the floor and ceiling joist directions and, where discernible, the proximity to the external walls.

Where window and external doors are not positioned in the walls so that they overlap the new wall insulation, this introduces a thermal bridge. If these are replaced in the intervention, they can be positioned to avoid this, but if this is not the case then additional jamb, sill and lintel insulation may be required. Windows and doors should overlap wall insulation by 30 mm in order to avoid thermal bridging (Wingfield et al. 2011).

Thermal breaks can be caused due to basements access where the basement is outside the conditioned envelope. It was found that spandrels (e.g., between basement stairs and kitchen, or basement stairs and hall), the soffit of the stairs to

Fig. 11.4 Sloping bedroom soffits. Showing from *left to right* the bedroom wall, soffit and ceiling; the roof void above showing apparently reasonably laid insulation; section sketch showing thermal bridge position; thermal image of the bedroom wall, soffit and ceiling where the darker sections indicate the thermal bridging

first floor, or the door down to the basement were sometimes not insulated. These elements and fittings are now forming the boundary to the conditioned envelope (in effect the same as an external wall/door) and therefore need to be to the same standards of thermal performance and air-tightness where relevant.

The proforma therefore needs to identify the likely positions of the continuous thermal envelope, where any breaches might exist due to the existing construction so that the designer can make provisions for these.

Roof voids generally cause few challenges for increasing insulation but a common design in existing properties is sloping soffits in the bedrooms. Figure 11.4 gives an illustration of this.

The survey protocol should include full inspection of the roof voids to determine the existence, thickness, extent, and position of any insulation. It was found during the field work that apparently well-insulated roof voids had sections where the insulation was omitted (particularly at eaves and loft hatch positions), displaced, compressed, or damp, all of which will result in thermal bridging. If additional horizontal roof void insulation is to be added, the ventilation levels should be checked to ensure that increased risk of condensation and consequential timber decay does not result (BRE 2002). As well as the threat from fungal decay, damper timber is more susceptible to beetle infestation (BRE 1991). The intervention design may need to include increasing ventilation to voids.

The proforma therefore needs to specify the proposed interventions and give an assessment of the existing roof insulation, ventilation and any particular challenges, which may need a detailed design.

The offered 2-page proforma is included at Figs. 11.5 and 11.6. The proforma requires descriptive text from the surveyor and does not offer a "tick-box" presentation because of the number and complexity of options this would necessitate

Ref	Address					Front faces:		Date:
Approx age	Weather					Ext temp:		Int temp:
Property type	B to B	Terr	End Terr	Semi	Det	Flat	Maisonette	
Storeys & heights	Basement		GF	FF	2F			Conditioned volume
Approx floor areas								0 m3
Estimated original external wall U-value								
Intervention:								

Walls External	1 2
Party	LHS RHS Rear Extend to ridge?
Extension	1 2
Bay	1 2
Dormer	1 2
Internal	1 2
Chimney breasts: flue used / not used ; flues vented N / Y / where? Relationship external ground level to internal floor level DPC presence type position	
Wall insulation	External walls: External wall/intermediate floor treatment: Lower bay walls: Window reveals: Party walls: Int walls jn with ext: Chimney breasts: External walls/ground floor treatment: Basement walls: Stair spandrel with basement: Stair soffit over basement: Dormer apron: Dormer cheeks:
Floors	Floor joists run: To party walls. Front to rear Ground floor over basement: Ground floor suspended timber over void: Stair soffit over basement stair:
Floor insulation	Ground floor over basement: Floor voids to external walls:
Roof & covering	Main: Main 2: Dormer: Extension 1: Bay: Extension 2: Extent of eaves overhang:
Roof void insulation	Noted on site: or As Spec: Not viewed: Verbal statement: Pitched, in line with rafters: Horizontal: Horizontal at eaves and at apex: Dormer soffits: Dormer apron: Dormer cheeks: Hatch to roof voids: Bay roof: Extension roofs:
Windows/doors	Replaced with: Windows: Front door: Fanlight: Rear door: Dormer: Door to basement:
Thermographic survey notes	

Fig. 11.5 First page of offered proforma for building survey prior to thermal improvement intervention

Spot moisture meter readings									
Ground floor:		Front wall:				Front floorboard:			
		Rear wall:				Rear floorboard:			
		Party walls:							
		Chimneybreast front:				Chimneybreast rear:			
Basement:		Front wall:				Front ceiling:			
		Rear wall:				Rear ceiling:			
Upper floors:									
Heating / hot water / cooking / ventilation						Ventilation types:		House	
Hob type:	gas	electric	Oven type	gas	electric	Boiler	Bathroom	Kitchen	
Shower:	Y N	Bath:	Y N						
Space heating:		Gas	Electric	Other	Secondary		Water heating:		
Walk round plan layouts									

Fig. 11.6 Second page of offered proforma for building survey prior to thermal improvement intervention

and the restrictions this would present. An electronic version may overcome some of these difficulties, but would probably require additional sections for descriptive text.

Accompanying the proforma, and held on record, would be the copious site notes, site sketches, digital photographs and infrared photographs taken on site, as is normal for a fourth level survey as discussed [described by the RICS as "service level three" (RICS 2013)].

Conclusion

The research aim was to determine a practical approach to undertaking a building survey of a property prior to intervention for improving thermal performance. For the protocol, the surveyor needs to be aware of proposed designs for the intervention. The survey carried out prior to intervention for improving thermal performance of a domestic property should carry out a range of non-destructive testing, which may include a combination of dampness measurements, boroscope investigation, and infra-red thermography. More detailed investigations could be used for full thermal testing. The survey protocol should include assessment of:

- the particular construction and materials used in the property under inspection
- aspects of the property's condition, which may be sensitive to alterations in its breathability, rain screen measures and moisture equilibria
- damp proof courses, the ground level, external wall pointing condition, wall fractures and sealing of junctions around openings and initial moisture levels of external walls

- the presence, condition and position any rainwater, waste and foul goods and likelihood of these affecting the intervention design or performance
- existing render and condition thereof
- openings, passageways, stores, etc. incorporated into the thermal envelope
- window position in walls, in relation to proposed insulation
- floor and ceiling joist directions and proximity to external walls
- full inspection of the roof voids to determine the existence, thickness, extent, quality of positioning of any insulation
- existing roof insulation, ventilation and any challenging aspects requiring a detailed design
- basements, access and including the position of the proposed planes of thermal envelope
- likely positions of the continuous thermal envelope, noting where any breaches might exist due to the existing construction to enable detailed design at these points
- nominal measured survey and sketch plans
- space, water and cooking heating and use types

These have been included in the offered proforma held at Figs. 11.5 and 11.6. Accompanying the proforma, and held on record, would be the site notes, site sketches, digital and infrared photographs.

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Chapter 12
A New Experiment and Modelling Work to Jointly Identify the Building Envelope's Thermal Parameters and a Physical Solar Aperture

Guillaume Lethé

Abstract Co-heating tests have been used by many researchers for the characterisation of the heat loss coefficient (HLC) of building envelopes. Measurements may be analysed through static, transient or dynamic approaches. A reliable identification of the HLC is obtained by the joint identification of multiple parameters including the solar aperture. The solar gains continuously depend on the relative position of the sun with regard to the building's glazed components and on the type of emitted radiation, ranging from diffuse (overcast sky) to beam (clear sky). However in state-of-the-art static co-heating tests, only the daily mean solar radiation is analysed, leading to the identification of a static solar aperture (A_w). Practitioners then have to rely on several weeks of continuous measurements under representative but not extreme weather conditions to derive regression lines with acceptable correlation coefficients between the daily means of the measured variables. Finally, the obtained results do not allow performing dynamic predictions since the model is static. This paper first explains the advantages of the newly developed experimental protocol itself, compared to other dynamic tests recently applied in situ. It also presents a new methodology to better take the solar gains into account during the dynamic analysis of a short experiment. The proposed methodology jointly enables a more accurate identification of the general heat loss characteristics of the building and of a physically-interpretable and climate-independent solar aperture. It can be seen as the equivalent total solar transmission coefficient of the envelope under normal incidence, multiplied by the total glazed surface of the whole building envelope, and is denoted as $gA_{eq,tot,\perp}$ (replaces A_w). The proposed method can be applied to characterize the static energy

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performance of the building and also to predict (or even control) the energy consumption under specific weather forecasts or normalized conditions.

Keywords Co-heating test · Control · Dynamic sequence · Grey-box model · On-site measurement · Solar aperture · Solar pre-processor · Thermal performance

Introduction

On-site measurement campaigns and data analysis require in-depth and balanced skills regarding the test environment, the experimental procedure and the data analysis. While the *in situ* measurement and identification of static performance indicators of building components are already covered by a standard (ISO 2014), global building envelopes are still under investigation as exemplified in (Gorse et al. 2014). The Heat Loss Coefficient (HLC in W/K) expresses the heating power that is lost by transmission and exfiltration (under sealed ventilation system) through a building envelope under a temperature gradient of 1 K. Methods to determine a building's thermal dynamics go along with an accurate identification of its response to temperature changes, solar radiation, exfiltration rate and its effective thermal capacity (Bacher and Madsen 2011; Johnston et al. 2013; Pandraud et al. 2013; Bauwens and Roels 2014). The application of a 'hybrid' dynamic thermal solicitation sequence and subsequent data analysis has been investigated, while better taking the solar gains into account thanks to a new methodology developed in this paper.

The short hybrid dynamic thermal solicitation sequence of the building has been presented in (Lethé et al. 2014), was partly been inspired from (Subbarao et al. 1988; Bacher et al. 2010; Bacher 2013; Steskens et al. 2014), and is the baseline for the present paper. This sequence combines characteristics of smoothly assembled segments of quasi-static, pseudo-random binary sequences (PRBS) and multi-sine operation eventually aimed at enforcing optimal decorrelation of the acquired data series used as inputs and output of the dynamic model to be identified. Air change rate was also measured in order to enable us to identify with good reproducibility the specific transmission part of the total heat loss coefficient in various wind conditions and independently of the air exfiltrations. This was necessary for the present case study where the exfiltration heat losses exceeded 15 % of the total heat losses on average, with sealed ventilation system.

Various treatments of the solar radiation measurements, already developed in (Lethé et al. 2013), are used in detail in this study in order to determine what we have called here the equivalent total solar transmission coefficient of the envelope (mainly the glazed components) under normal incidence, $gA_{eq,tot,\perp}$.

Below, we firstly (see Section "Energy Balance of a Building Envelope") write the dynamic energy balance of the building envelope that was used in this study, in conformity with the notations of the EN ISO 13789 standard. We then (see Section "A Rich and Short Hybrid Dynamic Solicitation Sequence") describe the (hybrid) dataset that has been generated and used. The dynamic analysis of the data (see Section "Dynamic Data Analysis") allowed us to compare the results obtained with the state-of-the-art solar model and the newly enhanced one. Finally (see Section "Conclusions") we sketch advantages and drawbacks, opportunities and remaining questions towards better dynamic thermal modelling and performance identification of buildings.

Energy Balance of a Building Envelope

Various modelling, from the very simple towards more complex (static, transient, dynamic), are already developed (Bacher and Madsen 2011; Pandraud et al. 2013; Bauwens and Roels 2014; Subbarao et al. 1988). We briefly expose the dynamic model that has presently been used.

The most promising analysis methods are parameter identification methods applied on well decorrelated dynamic data sets. The following grey-box stochastic model is used to represent the entire building. It is rather simple but often appears suitable:

$$\mathrm{d}T_i = \frac{(T_e - T_i)}{R_{ie}C_i}\mathrm{d}t + \frac{Q_h}{C_i}\mathrm{d}t + \frac{A_w q_s}{C_i}\mathrm{d}t - \frac{Q_V}{C_i}\mathrm{d}t + \sigma_i d\omega_i \tag{12.1}$$

$$\mathrm{d}T_e = \frac{(T_i - T_e)}{R_{ie}C_e}\mathrm{d}t + \frac{(T_a - T_e)}{R_{ea}C_e}\mathrm{d}t + \sigma_e \mathrm{d}\omega_e \tag{12.2}$$

$$\frac{1}{R_{ie} + R_{ea}} \cong HLC - \frac{Q_V}{T_i - T_a} = UA \tag{12.3}$$

where T_i, T_e and T_a are respectively the indoor air, the building envelope and the ambient (outdoor air) temperatures, R_{ie} is the thermal resistance between the interior and the building envelope, R_{ea} is the thermal resistance between the building envelope and the interior thermal medium, C_i and C_e are the heat capacities of the interior (internal walls) and of the building envelope (external walls), Q_h is the energy flux from the heating system, $A_w q_s$ is the solar aperture multiplied by the energy flux density from the solar radiation (further defined in Section "Dynamic Data Analysis"), Q_v is the energy flux from the exfiltrations, ω_i and ω_e are standard Wiener processes, and σ_i and σ_e are the incremental variances of the Wiener processes. The corresponding one-dimensional whole-building equivalent RC-network is presented in Fig. 12.1:

The interior temperature is the output state of the model and is associated with a thermal capacity (air and furniture). The (unobservable) building fabric envelope temperature is assumed to be aggregated in one single node and is obviously associated with a thermal capacity. The overall thermal resistance offered by the

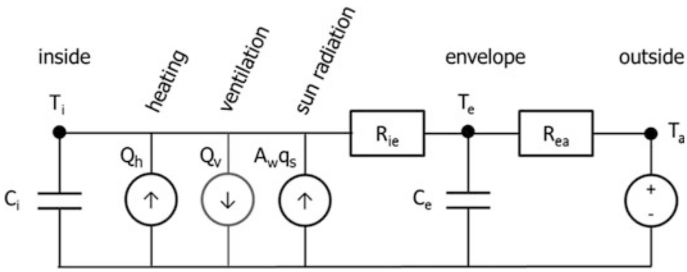

Fig. 12.1 Equivalent RC-network of the whole building envelope thermal model

envelope against the heat losses is represented by two thermal resistances in series. The ambient temperature is chosen as input. Finally, the system is subjected to three other inputs: the electric heating power, the exfiltration losses and the solar radiation, all predominantly acting on the inside air node temperature. The exfiltration loss has been obtained from an instantaneous air change rate measurement using tracer gases at a constant concentration, the instantaneous temperature gradient $T_i - T_a$ and the known volume of the building.

The solar radiation is given in W/m^2 and is associated to an aperture coefficient that gives an equivalent surface through which the radiation is fully transmitted. In this paper, we compare two methodologies to integrate the solar gains. First, the crude global vertical south solar radiation ($q_{s,v,south}$) is used as input, and the parameter A_w is identified. Second, a pre-processed solar radiation, corresponding to the equivalent beam normal incidence total solar radiation ($q_{s,eq,tot,\perp}$), is used as the input and the parameter $gA_{eq,tot,\perp}$ is identified. This second methodology takes into account the relative position of the sun with regard to each glazed component, and the type of radiation received (combination of diffuse and beam radiation).

In order to determine the Heat Loss Coefficient more accurately and detach the individual influence of the solar radiation, the temperature states and the heating power, dynamic data sets and analysis are recommended. Smooth dynamic evolution of the variables of the system, such as the heating power, is preferable to facilitate the statistical validation of the identified model (Lethé et al. 2014), while the temperature homogeneity inside the building has to be guaranteed as much as possible (Johnston et al. 2013). For these reasons an infrastructure that can manage the heating powers of each zone of the building individually and gradually has been used. An optimization analysis scheme (Fig. 12.2) is then applied on the collected data to identify the parameters of the model.

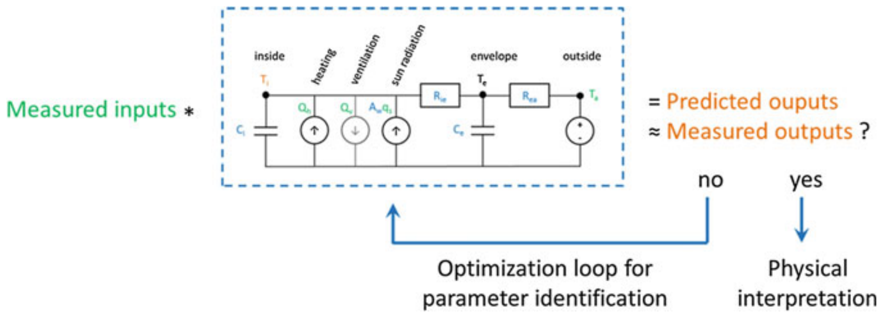

Fig. 12.2 Optimization scheme to identify the parameters of the dynamic model (grey-box model or transfer function) between inputs and outputs

A Rich and Short Hybrid Dynamic Solicitation Sequence

Background Information About the Infrastructure

Dynamic heating sequences have been investigated in order to develop an adapted dynamic co-heating test[1] that more accurately and more robustly identifies the dynamic characteristics of a building envelope model. The optimized developed protocol required individual and continuous sliding control of the injected power (control cycles every 100 s with pulse-width modulation), to ensure smooth data and best temperature homogeneity under all circumstances. The full infrastructure is sketched in Fig. 12.3:

The control and acquisition program has been developed in LabView. In order to ensure best temperature homogeneity when performing power-driven tests, the explicit spread of the total injected power among the zones is obtained with:

$$Q_i^{n+1} = \frac{Q_{tot}^{n+1} Q_i^n / T_i^n}{\sum_i Q_i^n / T_i^n} \tag{12.4}$$

where the Q_i and T_i terms are the zonal powers and temperatures of the preceding cycle and Q_{tot} is the total power required. The superscript $^{n+1}$ stand for the new starting cycle. Additional controls (semi open and closed loop) are included to ensure a robust (no bias) and stable (damped) behaviour of the system. It has been shown (Lethé et al. 2014) that this infrastructure was able to produce smooth transitions and seamless data sets (5 min recording intervals), and to reduce the temperature inhomogeneities by a factor 4 compared to non-adaptive infrastructures using *inter-room* air circulation fans.[2] The comparison means is an indicator expressed as the ratio between the degree-hour difference between the instantaneous hottest ($T_{i,max}$) and coldest ($T_{i,min}$)

[1]The term « co-heating » is not limited here to measurements under constant indoor temperature.

[2]The experiments under investigation are controlled in power and not in temperature.

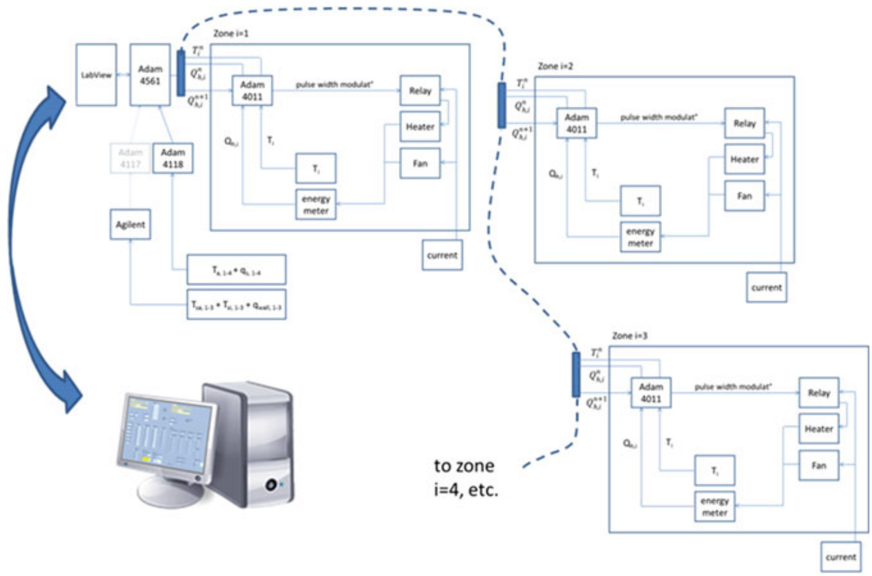

Fig. 12.3 Representation of the infrastructure network. In each zone multi-functional kits are connected to the PC control and acquisition program through a serial port

rooms and the degree-hour difference between the (volume-weighted) average indoor air temperature ($T_{i,mean}$) and ambient air temperature (T_a):

$$\int_{t1}^{t2} \frac{\mathrm{T}_{i,\max}(t) - \mathrm{T}_{i,\min}(t)}{\mathrm{T}_{i,\mathrm{mean}}(t) - \mathrm{T}_a(t)} \mathrm{d}t \tag{12.5}$$

Note that when temperatures are near-homogeneous, the aggregated indoor air temperature extracted from the volume-weighted average is extremely close to and perhaps even more relevant than the one extracted from a principal component analysis (PCA), which can be sensitive to special conditions and hence not always physically correct.

A Short-Term Hybrid Dynamic Sequence

The developed infrastructure sets the basis for the design of hybrid dynamic heating sequences, exemplified in Fig. 12.4. This sequence is programmatically designed such that the system variables are the least correlated possible and such that the segments are seamlessly connected to avoid harsh residuals in the model output (making the grey-box model validation easier). The entire sequence may last for 4 days if the third day is sunny. It is expected that 5 days are sufficient in most

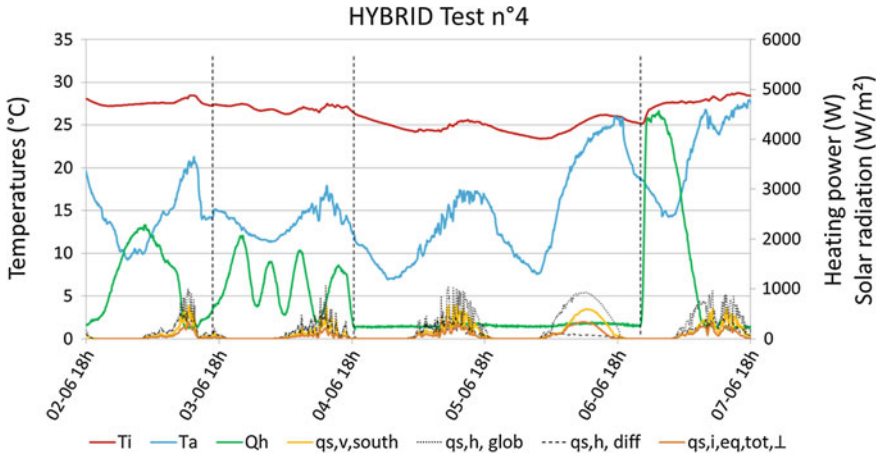

Fig. 12.4 Illustration of the hybrid 4-segments heating sequence

cases if the measurement is planned when the weather forecasts are propitious. More details about this experiment are given in (Lethé et al. 2014).

The infrastructure developed is highly scalable and allows many other types of sequences to be designed. For example, the following function could be used to control the global heating power injected in the building (pure power control):

$$Q_{h,tot} = n \times [sign(\sin(bt^c)) \times abs(\sin(bt^c))^a + d] \tag{12.6}$$

such that the solicitation signal wipes through many frequencies (thanks to the exponent c), related to the typical time constants of interest of the building envelope (thanks to the parameter b) and provides a relatively good signal/noise ratio (thanks to the exponent a and the parameter d). Taking t in hours and the sine function in radians, the parameters a, b, c, d could respectively have the value of 0.25, 3.8, 1.4, and 1.5 (see Fig. 12.5), with n the suited estimated nominal power to achieve a temperature gradient of 10–15 K during the experiment. Other possibilities include an emulation of a residential or tertiary usage of the building, with daily or weekly patterns and a pure thermostatic control.

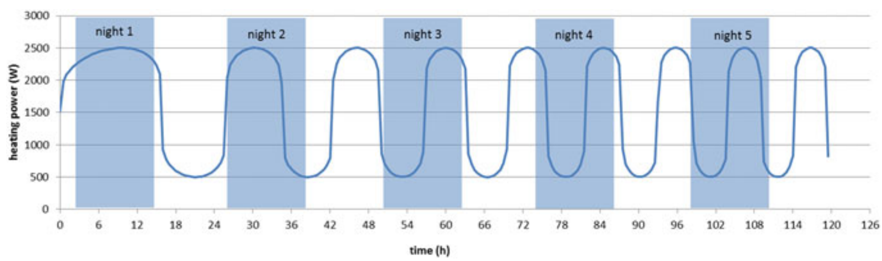

Fig. 12.5 Illustration of the Sine-Sign-Sweep heating sequence

Dynamic Data Analysis

Background on the Test Environment

The detailed test environment description can be found in (Lethé et al. 2014). We here only recall the overall localisation of the equipment inside the house in Fig. 12.6. The ground floor has seven defined zones with the doors widely open. The attic and the basement are disconnected from the ground floor and are each one single volume. The temperature in the attic (not air tight) is highly correlated with the outdoor temperature, such that we consider the ‘ceiling-attic-roof’ system as a single complex component. The temperature in the basement (faintly ventilated) is quasi-static and close to the outside test-mean temperature (the mean temperature difference between both variables is 1.2 K, i.e. one order of magnitude lower than between the interior and ambient air temperatures). Excluding the basement air temperature to the grey-box model is then found adequate as well. Optimal reproducibility of results under various weather conditions would nevertheless require that the basement temperature be always ‘homothetic’ to the outdoor and indoor temperatures which is not the case by nature. Results dispersion in function of the temperature conditions in the adjacent spaces is not negligible in general but can be neglected in this particular study. Figure 12.7 presents the four temperature variables discussed here.

Dynamic Analysis of the Data According to Two Methods

In this section, which is the core of the study, we analyse the results obtained following two different methods. The first is the state-of-the-art method where the crude solar data is used as input and the solar aperture is assumed to be a static parameter.

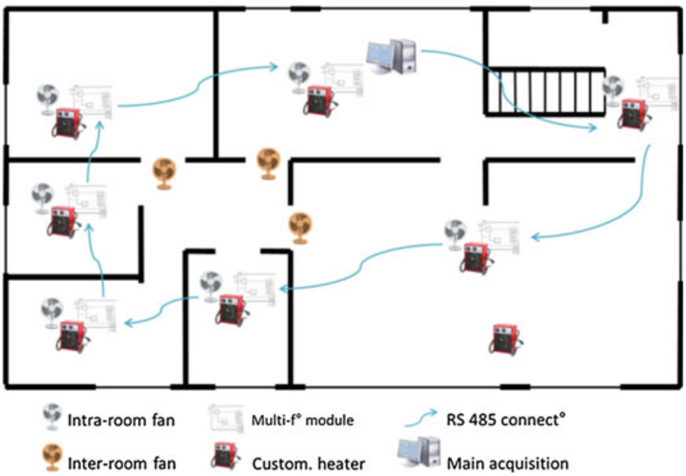

Fig. 12.6 Co-heating infrastructure components and positioning in the house

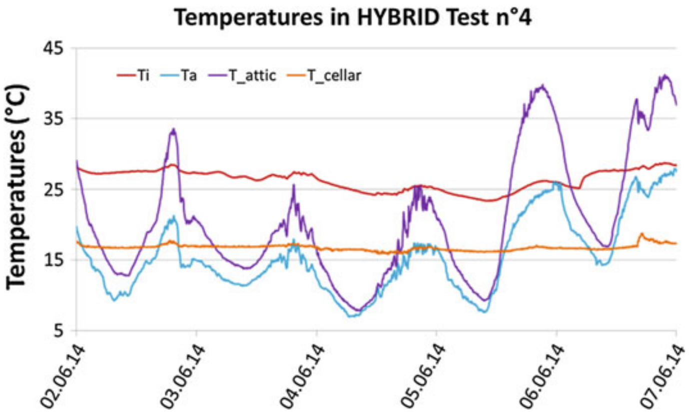

Fig. 12.7 Time series of the main aggregated temperature variables (including attic and cellar)

As explained in the introduction, in a dynamic context, the solar aperture is not a static parameter since the solar gains are not purely proportional to the intensity of the solar radiation. They also depend on the relative angle of the sun with regards to the glazed components on the one side, and on the type of emitted radiation which can range from diffuse (overcast sky) to beam (clear sky). We therefore introduce a more detailed approach.

The newly proposed methodology is expected to produce a more accurate and reliable model identification of the thermal dynamic behaviour of the building (conduction heat losses through the building envelope). The new method also has the advantage that the identified "solar aperture" becomes physically interpretable. It can be seen as the equivalent mean solar transmission coefficient of the envelope (mainly the glazed components) under normal incidence, multiplied by the total glazed surface of the whole building envelope, and is denoted as $gA_{eq,tot,\perp}$ (replacing A_w in Eq. 12.1).

Both analyses have been done using 30 min sample time data, which has been found to be a good compromise between stability and aliasing for this type of modelling and other conditions mainly related to the building, the experiment and the weather.

State-of-the-Art Method Using Global South Vertical Solar Radiation Data

Using the "classic" approach, we obtained the results shown in Fig. 12.8.

The autocorrelation of the residuals is very close to white-noise but there is a clear signal left in the data from what can be seen in the cross-correlations between the main system variables and the residuals of the identification.

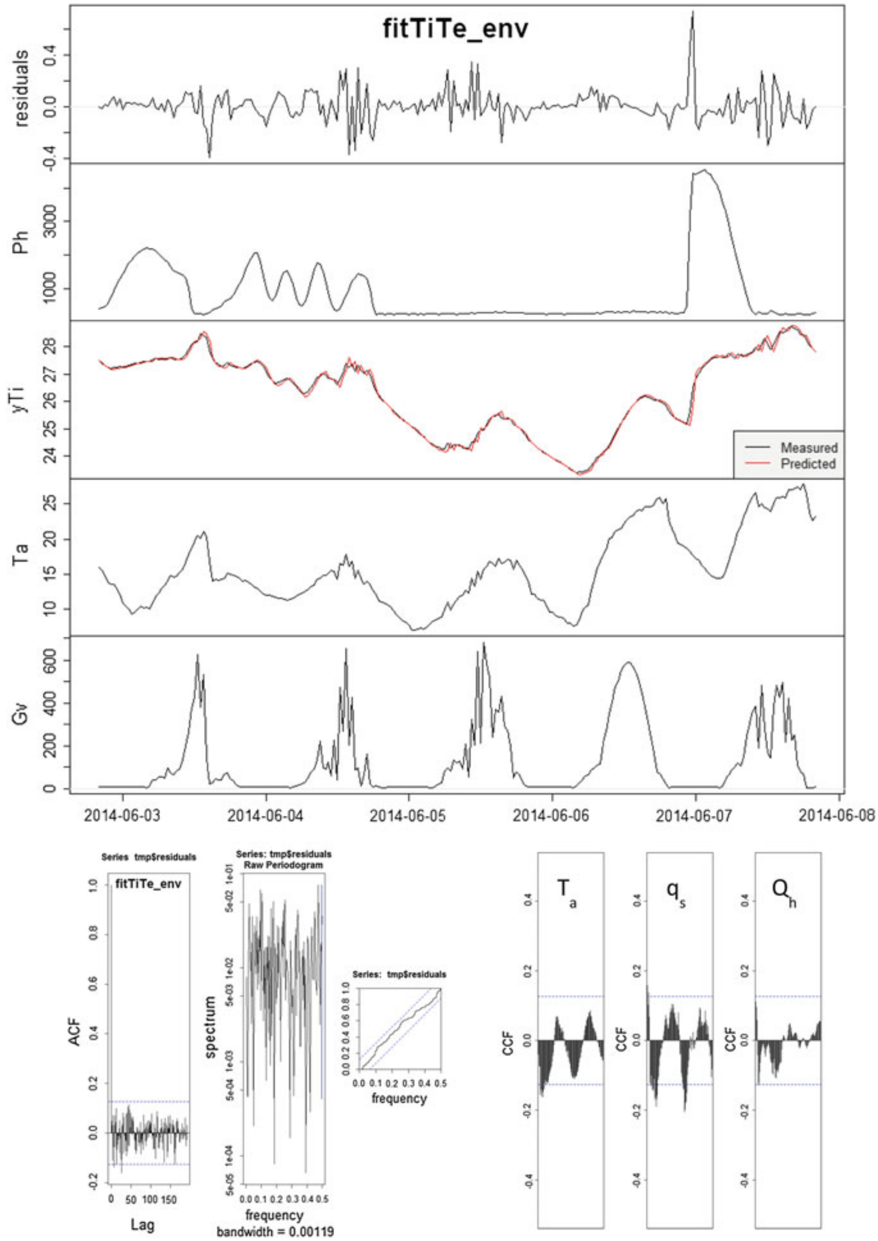

Fig. 12.8 On the *top* the residuals between the measured and predicted output of the model, the heating power, the inside and ambient air temperatures and *vertical south* solar radiation *bottom left* autocorrelation of the residuals, raw and cumulated periodograms (T_i) *bottom right* cross-correlations between the residuals and input variables (T_a, $q_{s,v,south}$, Q_h)

The identified UA-value is 143.25 ± 5.54 W/K. It has a confidence interval limited to 4 % which is very small. Note that the total heat losses were corrected with the exfiltration losses in the modelling, such that the result is expressed in terms of the UA-value instead of the HLC. Using the vertical south global solar radiation ($q_{s,v,south}$) as input, the identified solar aperture (A_w) is 5.4 ± 3.4 m^2. It has a confidence interval of 63 % which is very big. Moreover, intuitively, one could consider that the result is small compared to the total glazed surface of the building (23 m^2), and even of the glazed surface of the south façade only (15 m^2). Nevertheless, since the solar aperture does not have any physical interpretation, such an assessment is not allowed, and we only can state that the result carries a big uncertainty. This uncertainty very probably comes from the fact that the solar radiation that was used as input in the model is not a good explanatory variable of the evolution of the interior temperature and is not very suited for the kind of dynamic analysis we made.

We will see in Section "Analysis Results" that a bigger result is found. Nevertheless it is important not to simply compare the magnitude of both results, since the underlying definitions are different. In the newly proposed definition, the aperture is to be understood under normal radiation, which obviously better transmits the radiation than under global radiation composed of beam but not specifically normal and diffuse parts.

New Method Using Pre-processed Equivalent Normal Solar Radiation Data

Methodology for the Pre-processing of the Data

The methodology used in this paper has already been developed in (Lethé et al. 2013). The transmission through glazed components[3] is a non-linear decreasing function of the incidence angle (see norm EN 410 § 4.2). Moreover, the solar radiation is never a pure beam and the glazed components of the building are orientated (and possibly inclined) specifically for each façade. Therefore, we are aiming in this paper at identifying solar aperture coefficients that physically relate to distinct surfaces and under a normalized solar radiation. Under this definition of the solar aperture, we expect that results based on pre-processed inputs to be more replicable to various periods of the year and geographic climates too (it is expected that the same HLC is obtained for an exact same house built in various countries and monitored in different periods).

[3]We here neglect the transmission through opaque components since it is more than one order of magnitude lower for relatively highly glazed building envelopes, often encountered in some residential building sectors aiming at maximizing free solar gains. The reader can refer to (Gorse et al. 2014) and in the norm ISO 13792:2005 § 4.2.3 for more information.

The modified inputs for each façade are calculated as described below. A distinct treatment is applied to the beam and the diffuse parts of the solar radiation. In both cases, some approximations have been required.

First, a numerical model (CAPSOL, Physibel) is used to obtain the position of the sun in the sky (altitude and azimuth) at each time step. The ground albedo was assumed isotropic and stable, with a value of 0.2 (green grass surrounding the building). Based on the measured global and diffuse horizontal solar radiations, an anisotropic sky model (Muneer, embedded in CAPSOL) reproduces the direct and diffuse radiations for each façade. These have been found consistent with the direct measurements (especially for the highly glazed south façade). This process is time-consuming but useful if a lot of façades with different orientations are present, since only two measurements of solar radiation are required. Refinements in the modelling are required in case of surrounding buildings or obstacles to the solar radiation, which was not significant in our study.

Next, the angle of incidence (hereafter, AOI) between the beam radiation direction and each façade are computed, and a decreasing normalized function is evaluated to simulate the generic transmission behaviour of the glazing (see Fig. 12.9) and obtain the instantaneous reduction coefficients. This function is a simplification function from EN 410 § 4.2:

$$c = 1 - (\tan(AOI/2))^{2.5*2} \tag{12.7}$$

which correctly evaluates to 1 for a normal incidence and to 0 for a grazing angle of incidence.

In case the building is equipped with a mix of double and triple glazing, the choice of the tangent function exponent requires some optimisation. In our case, only double conventional glazing is present, and the proposed function is very close to the reference behaviour of these transparent components. More generally, this approximation is better than neglecting the angular effect in the transmission properties of glazing as done by default by most practitioners.

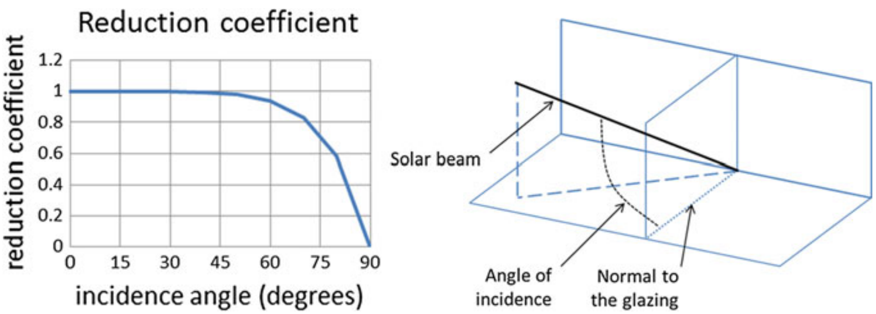

Fig. 12.9 Reduction coefficient for the transmission as a function of the AOI and the definition of the angle of incidence according to the norm EN 14500 § 3.3

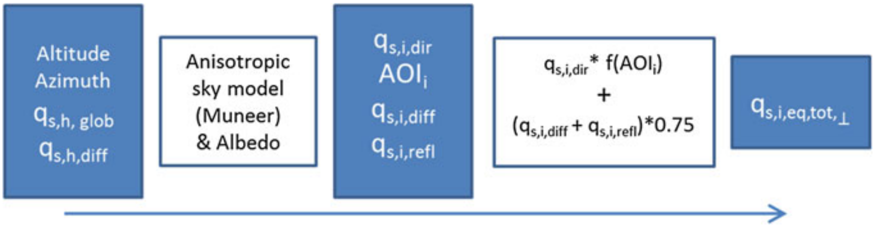

Fig. 12.10 Process to obtain the equivalent beam normal incidence total solar radiation on each façade

For the diffuse part of the solar radiation (both from the sky and reflected on the ground), previous experiences, e.g. with the WIS software (Window Information System), indicated that a reduction factor of 0.75 could be applied as a default approximation. Obtaining more accurate approximations is clearly out of the scope of this paper and probably too complex to be applied systematically.

Finally, the solar radiation terms are each multiplied with their reduction coefficients and summed to obtain the equivalent beam normal incidence total solar radiation ($q_{s,eq,tot,\perp}$) already mentioned in Section "Energy Balance of a Building Envelope", that is used as the input, and the parameter $gA_{eq,tot,\perp}$ can be identified.

The complete preparation process is represented in the Fig. 12.10, where the blue cells correspond to data and the white cells to computing steps. In this figure, $q_{s,h,\ glob}$ and $q_{s,h,diff}$ are the global and diffuse horizontal solar radiation, $q_{s,i,dir}$, $q_{s,i,diff}$, $q_{s,i,refl}$ are respectively the direct, diffuse and reflected solar radiation on the glazed components (of the façade) of index i and $q_{s,i,eq,tot,\perp}$ is the equivalent beam normal incidence solar radiation for the glazed components (of the façade) of index i.

Finally, to obtain the modified input to be applied to the building as a whole, we make a surface-weighted average for all the façades (the surfaces A_i are the surfaces of the glazed components):

$$\frac{\sum A_i q_{s,i,eq,tot,\perp}}{\sum A_i} \tag{12.8}$$

Implementation of the Pre-processing on the Full-Scale Hybrid Experiment

The full process explained in § 0 has been applied on the hybrid experiment data presented in Fig. 12.4.

Figure 12.11 shows the correspondence (ratio) between the crude and the modified solar radiation variables ($q_{s,v,south}$ and $q_{s,eq,tot,\perp}$). Globally, the modified input is about 56 % of the crude vertical south solar radiation. We nevertheless see that the ratio evolves during the day and that the daily pattern also depends on the type of sky. The pattern is especially time-varying during the fourth day which has

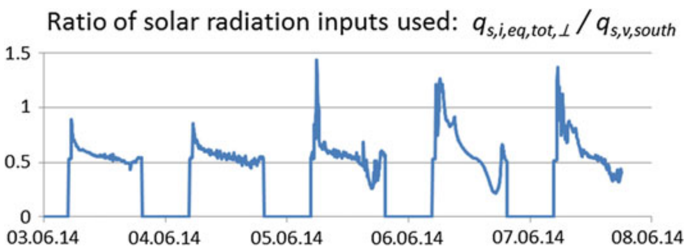

Fig. 12.11 Ratio between crude and modified solar radiation input

a clear sky (mostly beam radiation). For that reason, neither a static aperture coefficient nor a fixed daily curve should be applied if a highly accurate representation of the building system dynamic is desired.

Nevertheless, this observation should be tempered since known methods have shown that obtaining the steady-state Heat Loss Coefficient is possible without paying in-depth attention to the detailed modelling of solar gains. Contrarily, some methods concentrate the measurements at night when there is no solar radiation and some others try to minimize the solar gains using screens on the windows or closing the shutters.

Analysis Results

Using the new method, we obtained the results shown in Fig. 12.12.

The autocorrelation of the residuals is very close to white-noise and it also seems this time that very few specific cross-correlations remain between the system variables and the residuals of the identification, although the model still can be improved from what can be seen in the cumulated periodogram, for example, by a discretization of the building envelope with two serial capacities.

The identified UA-value is 144.4 ± 25 W/K. It has a much bigger confidence interval than in § 0 (17 % instead of 4 %) but the estimated centre value did not change significantly (>1 % difference).

Using the equivalent beam normal incidence total solar radiation ($q_{s,eq,tot,\perp}$) as input, the identified solar aperture ($gA_{eq,tot,\perp}$) is 18.8 ± 6.5 m^2. It has a confidence interval of 34 % which is still big but about half the value found previously (63 %). This time, we can compare the estimated centre value with the total glazed surface of the building (23 m^2). By making the ratio, we obtain an equivalent mean g-value of 0.82 which seems physically very reasonable compared to a solar factor of a conventional double glazing, and demonstrates the capability of the method to identify a physically-interpretable solar aperture.

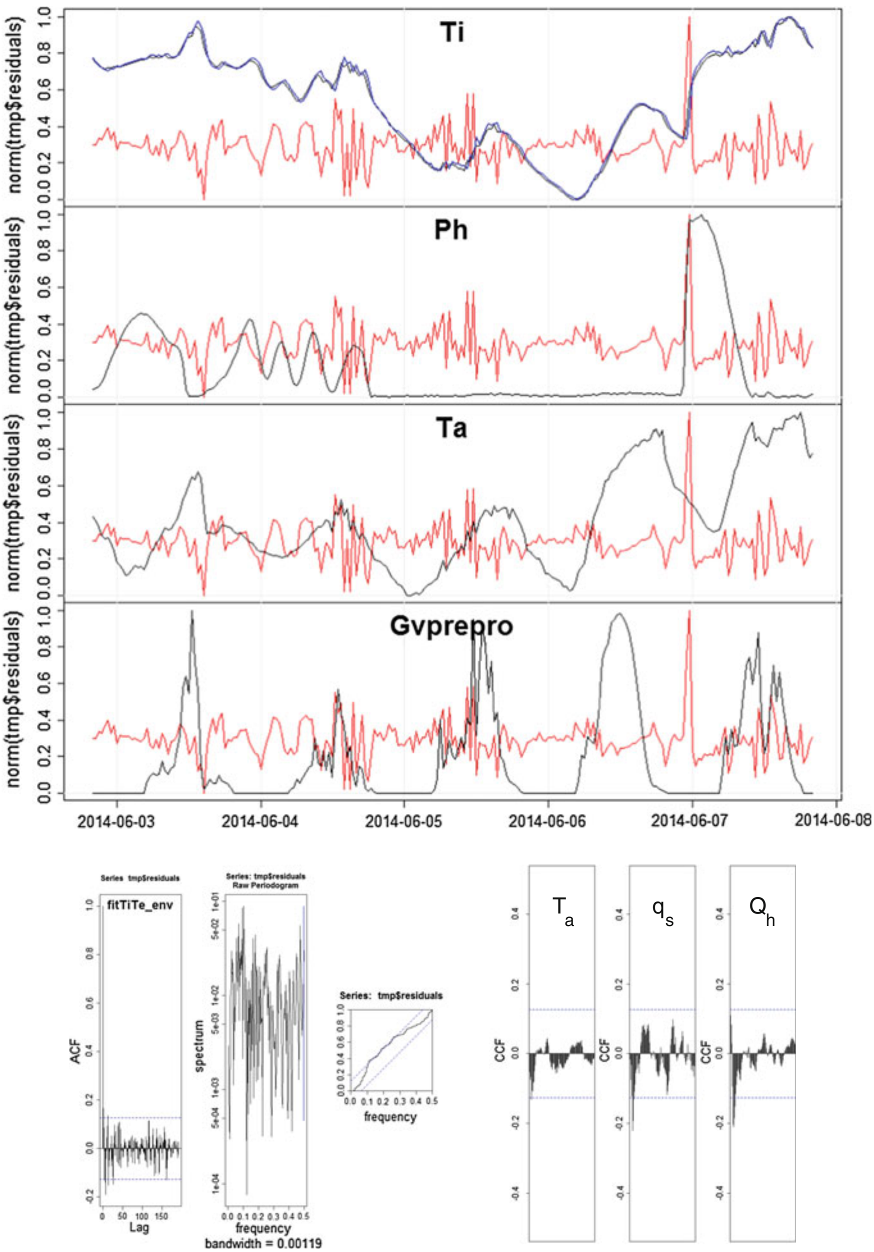

Fig. 12.12 On the *top* the residuals between the measured and predicted output of the model, the heating power, the inside and ambient air temperatures and *equivalent* solar radiation *bottom left* autocorrelation of the residuals, raw and cumulated periodograms (T_i) *bottom right* cross-correlations between the residuals and input variables (T_a, $q_{s,eq,tot,\perp}$, Q_h)

Comparison of the Approaches

We can also compare the order of magnitude of the two ‘solar aperture’ estimated values and the two solar radiation inputs. We saw that $q_{s,eq,tot,\perp}/q_{s,v,south}$ yielded a mean value of 0.56. Hence, computing the ratio $A_w/gA_{eq,tot,\perp}$ could be expected to yield a similar value. Nevertheless, it is only 0.29. This difference can of course be due to the non-linearities present in the physical problem, but might also reveal that the identified solar aperture A_w was underestimated. Though, in this case, it does not seem to have had a significant impact on the estimation of the UA-value, only slightly smaller than the UA-value obtained with the advanced method. Yet, it is probable that the second method is more accurate in a prediction or simulation context (required for example for model predictive control). Above all, it looks clear that the second method provides stronger results in terms of the solar aperture, which was the purpose of the study.

Looking now at the estimation of the UA-value, we also notice that the confidence interval has significantly increased when moving from the classic to the more detailed methodology. Additionally, the cumulated periodogram seems less optimal, even though the average of the residuals became slightly lower. It is not sure whether the log-likelihood criteria might be used in this context to compare both approaches, since the number of variables and parameters remain unchanged. These criteria respectively give 175 and 199 which is very similar anyhow. The reasons of that unexpected result are not well understood. We can argue that the quality indicators loose some consistency when measured data gets pre-processed, even though physical results and estimates make good sense. Maybe the pre-processing of the solar data impacted the optimisation space such that it became less convex for the UA-value, hence producing larger confidence bounds. Maybe the relatively high (and invariable) value assumed for the albedo could also explain such a pattern. A lower value (such as 0.15) would probably provide sharper results. These observations offer new challenges to the physical and statistical practitioners, although the obtained results are already very interesting and probably complex enough for large scale *in situ* applications.

Conclusions

To reliably determine the main parameters of a building model or building component requires that the test environment, but also the experimental procedure and data analysis are treated carefully. Then, the heat loss coefficient and more specifically the transmission losses can be estimated with various methods and for different purposes. The infrastructure and methodology developed in this paper showed the following advantages compared to existing ones:

– short dynamic testing (5 days) thanks to the optimisation of the decorrelation of the system variables making the test less expensive and more applicable to buildings that cannot be left empty for a longer period, required both for static co-heating tests (15 days) and conventional dynamic ones (10 days).
– control of the heating power injected to produce smooth data sets and hence facilitate the residual analysis and the results validation.
– adaptive multi-zone spread of the power injection to increase the temperature homogeneity inside the building, hence the accuracy of the aggregated indoor air temperature and eventually the temperature gradient with respect to the ambient temperature.
– higher accuracy of the identification of the solar aperture and its physical interpretation that allows a sanity-check of the result and better dynamic prediction models.

As a drawback to the latter point, compared to conventional techniques, the measured solar data needs to be pre-processed and the albedo and surrounding obstacles have to be modelled, or extra pyranometers have to be used to avoid this preparation work. Moreover, the surface and orientation of each glazed component must be known precisely enough.

Alternatively, measurements could be concentrated at night when there is no solar radiation or solar gains could be minimized using screens on the windows or closing the shutters. The resulting model is in this case less informative and is primarily aimed at extracting the static heat loss coefficient.

Another alternative to the ‘nearly white-box’ modelling presented in this study might be located closer to a ‘nearly black-box’ modelling: the solar aperture is then represented by a daily curve, encapsulating all the solar-related physical phenomena. Two distinct solar aperture curves are required for the beam and for the diffuse radiation to obtain good results, as was shown in Fig. 12.11. This should be further investigated.

Several other questions which were not extensively developed here and might be significant regarding:

– the correct estimation of the exfiltration losses for buildings that are not extremely airtight.
– other weather conditions such as the wind speed and orientation, and the sky temperature.
– the general treatment of adjacent spaces, heated or unheated and possible thermal by-passes.

The identification of informative and detailed models have several applications such as the estimation of the (steady-state or integrated) energy performance of the building, the prediction and control of the energy consumption and interior comfort, under specific weather forecasts (for model predictive control) or normalized weather conditions (for energy signature labelling).

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Part IV
Measuring

Chapter 13
Quantifying the Effect of Window Opening on the Measured Heat Loss of a Test House

Richard Jack, Dennis Loveday, David Allinson and Kevin Lomas

Abstract Opening windows is a common method for controlling air temperature, moisture, air quality and odours in dwellings. Opening a window in winter will increase the heat loss from a house, the additional heat loss will depend on the size of the window opening and the length of time for which the window is open. However, window opening behaviour is unpredictable, varying widely between different dwellings and occupants making it difficult to incorporate into predictions of energy consumption. This paper reports the results of an investigation to quantify the impact of window opening on the measured airtightness and total heat loss in a detached, timber framed test house built in the year 2000 to contemporary building standards, and located at Loughborough University. Blower door tests were used to measure the increase in ventilation caused by opening windows. The additional heat loss due to this ventilation was predicted using a simple model and then compared to the whole house heat loss as measured by a co-heating test. A linear relationship between window opening area and additional ventilation was found, independent of window location. This relationship was used to quantify the additional heat loss for a variety of window opening behaviours. The results show that window opening does not significantly increase heat loss rates in this particular house for all but the most extreme window opening behaviours. The implications of these results for different types of dwelling are discussed.

Keywords Heat loss measurement · Window opening · Airtightness · Co-heating

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Nomenclature

Air permeability envelope area	For air permeability testing, this includes the area of all perimeter walls, the roof of the highest storey included in the test and floor of the lowest storey. The volume of the dwelling is contained within these boundaries (ATTMA 2010).
HLC	Heat Loss Coefficient, a measure of the rate of heat loss from a dwelling measured in Watts/Kelvin.
In-use	A term used to describe a dwelling which is occupied.
n50	Is a measure of airtightness; it is the proportion of the air contents of the house that is replaced per hour at a pressure difference of 50 Pa. It is calculated by dividing the air leakage rate at a pressure difference of 50 Pa by the building volume and has units of 1/h, sometimes also written as ACH/h (air changes/hour) (ATTMA 2010).
q50	Another common measure of airtightness; the air leakage rate at a pressure difference of 50 Pa is divided by the envelope surface area of the building, with units of m^3/hm^2 (surface area). This is the metric used in UK building regulations (ATTMA 2010).
SAP	The UK Government's Standard Assessment Procedure for Energy Rating of Dwellings, which is the standard method used in the UK to predict thermal performance and energy consumption of domestic buildings. There is also a Reduced Data Standard Assessment Procedure (RdSAP), which is used for existing dwellings.

Introduction

Window opening is a commonly used method for controlling temperature in dwellings, but is also often used to control other conditions such as moisture, air quality and odours. During the winter heating season, this window opening will cause an increase in heat loss from the dwelling which will depend upon the duration and extent of opening. This paper uses an experimental approach to quantify the size of the additional heat loss that is due to window opening in a single detached house, for a variety of window opening behaviours. This is then compared with the total heat loss from the house as measured by co-heating tests to provide an insight into the relative effect that window opening could have in comparison to other heat loss mechanisms.

Clearly, the relative impact of window opening will be dependent both upon window opening behaviour and the thermal performance of the dwelling. For

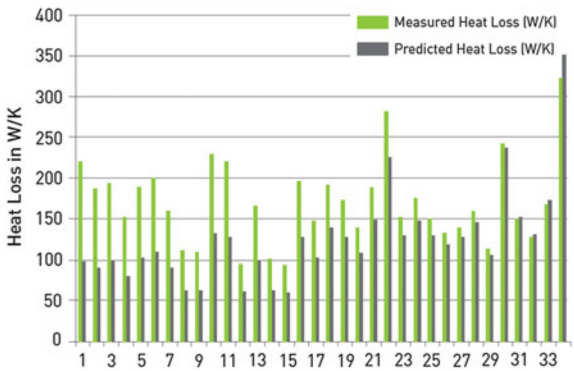

Fig. 13.1 Co-heating test results measured by Leeds Beckett University, *image sourced* from (Stafford et al. 2012)

dwellings with a lower HLC (i.e. which are higher performing), the same window opening behaviour will be relatively more significant in comparison to the baseline performance of the dwelling. This relationship is investigated and the implications for window opening in a variety of dwelling types are discussed.

The co-heating tests carried out by Leeds Beckett University represent the largest dataset of HLC measurements currently in existence (Fig. 13.1) (image sourced from Stafford et al. 2012). These results give some context for the typical HLC of UK dwellings, although most of the measurements were carried out in newly-built dwellings and the dataset is therefore likely to be skewed towards dwellings with higher thermal performance.

The findings of this study will be useful in post-occupancy evaluations of building performance. They may help to explain commonly observed discrepancies between predicted and in-use energy consumption, where energy consumption is almost always higher than predicted (Zero Carbon Hub and NHBC Foundation 2010), as the effect of winter window opening is not accounted for in models such as the UK's SAP (BRE 2013). They also provide guidance as to effect a variety of window opening behaviours, which is important given the wide variation of possible window opening behaviours and the consequent difficulty in defining 'typical' window use.

This research has been integral to the development of the Loughborough In-Use Heat Balance (LIUHB) method, a new test which uses monitored data to measure the HLC of a dwelling while it is in-use, with little impact on the occupants (Jack et al. 2015). The findings presented in this paper have contributed to calculating the estimated accuracy of the HLC measurement by an LIUHB test of ±15 %.

There have been several studies investigating window opening behaviour across Europe. Fabi et al. (2012) presented a comprehensive literature review of the collected evidence. This showed that window opening in domestic buildings is driven primarily by external temperature, but also a wide variety of further contributing factors such as solar radiation, wind speed, rainfall, age, gender, dwelling type, orientation of the windows, occupancy, time of day, room use and indoor air quality (ibid). A particular significance for this study is that window opening during winter was commonly found to occur, though at a reduced rate compared to other seasons due to the reduced temperature (ibid). This finding was repeated in an on-street survey carried out in the UK by Fox (2008). The literature also suggests that window opening is linked to occupancy, and therefore is more likely in the morning and evening (Dubrul 1988; Fox 2008; Johnson and Long 2005), and that the rooms in which the windows were opened most frequently were the bathrooms, bedrooms and the kitchen (Fox 2008).

Only one paper reporting a similar aim to this study, i.e. measuring the link between window opening and additional ventilation was found. For that paper, Howard-Reed et al. carried out more than 300 air change rate measurements in two occupied houses in the USA using a tracer gas decay method (Howard-Reed et al. 2002). The measurements showed a linear relationship between the measured increase in air change rate and window opening width, measured at a single window in each house (Howard-Reed et al. 2002).

Methods

Two methods of building performance measurement have been used in this study: blower door tests and co-heating tests. The blower door test is the industry standard method for measuring the airtightness of dwellings, as demonstrated by its mandated use in the UK's building regulations (H.M. Government 2013). The test involves applying a pressure differential across a building envelope, usually using portable fans installed in a temporary door frame (an example of which is shown in situ in Fig. 13.3), and measuring the air flow rate required to maintain this pressure differential (ATTMA 2010).

One disadvantage of blower door tests is that the airtightness is measured at an elevated pressure difference, meaning the airtightness at a natural pressure difference cannot be directly determined (ASTM 2012). Tracer gas decay methods can also be used to measure the airtightness of dwellings and allow direct measurement of the airtightness at natural pressure difference. The technique involves monitoring the decay of an introduced tracer gas (commonly CO_2) from which the volume flow rate of outgoing air can be inferred (ASTM 2012). It has also been shown that this method can be carried out in occupied dwellings using the CO_2 produced by the occupants as the gas source (Roulet and Foradini 2002). The tracer gas decay method has the disadvantage of requiring a time period of several hours in order to carry out a measurement (ASTM 2012).

Co-heating has become the most widely used method to measure the whole house thermal performance of dwellings (Stafford et al. 2012). It involves, carefully measuring the energy required to electrically heat the interior of a house to a constant elevated temperature (typically 25 °C) for an extended period (usually around 2 weeks) (Johnston et al. 2013). The output of the test is the HLC of the house, which is calculated based upon the rate of heat input and the internal–external temperature difference after the influence of solar heating has been accounted for (ibid).

Various methods have been suggested to account for solar gains (Butler and Dengel 2013), in this study the method described by Siviour has been used (Everett 1985). The Siviour method uses a linear regression analysis to correct for the influence of solar gains; the daily mean values for global solar irradiance and electrical heating power are plotted against each other, with both terms divided by the temperature difference (ΔT) as shown in Fig. 13.2 (ibid). The y-intercept of a linear regression is the measured HLC, so that the HLC in the hypothetical example shown in Fig. 13.2 is 183 W/K.

All testing was carried out in the Holywell test house located on the Loughborough University campus, in the East Midlands area of England (a test house simply refers to a normal house which is used specifically for experimentation). The Holywell test house is a small, timber framed, detached building with a total floor area of 59.8 m^2 and an envelope surface area of 166.1 m^2 (see Fig. 13.3). It was built in 2000 to contemporary building standards, and has been used as a test house since 2009. The house has uninsulated suspended floors, insulated cavity walls and 200 mm of loft insulation installed. An RdSAP assessment (BRE 2011) of the house resulted in an estimated total Heat Loss Coefficient (HLC) (including ventilation heat loss) of 180 W/K.

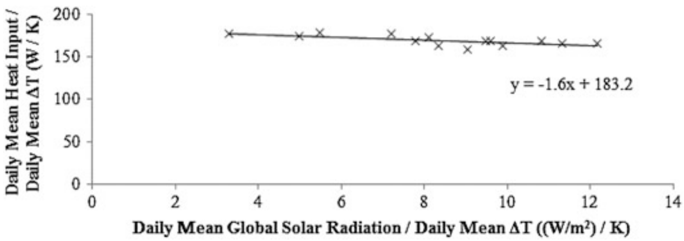

Fig. 13.2 Hypothetical example of the Siviour co-heating analysis method. Each data point represents the mean readings taken over a 24-hour period

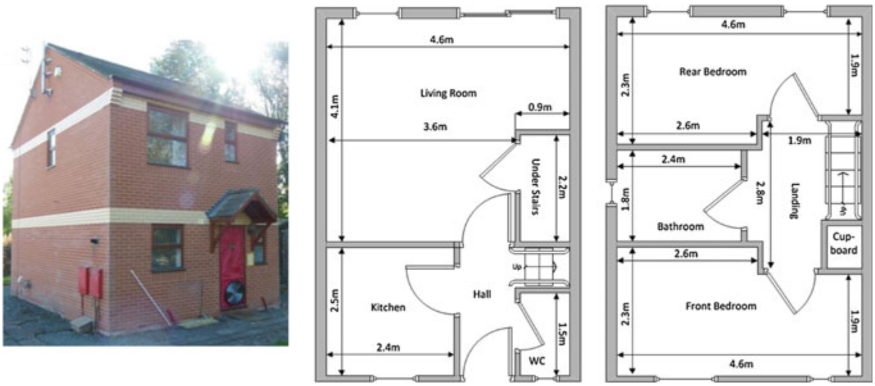

Fig. 13.3 The Holywell test house (*left*), ground floor plan (*middle*) and first floor plan (*right*)

The HLC of the house was measured by co-heating tests; in total, three tests were carried out over a period of one year and the mean measured HLC from the three tests was taken as the final measurement. The tests were carried out according to the method described by Johnston et al. (Johnston et al. 2013), and the data was analysed to correct for solar gains using the method described by Siviour (Everett 1985). The uncertainty of the HLC measured by co-heating tests is difficult to estimate directly due to the process of estimating the solar gains, though some research has suggested that an accuracy of approximately ±10 % is reasonable (Alexander and Jenkins 2015).

The baseline infiltration rate of the house, with all openings closed, was measured using the blower door method (ATTMA 2010) and Model 4 Minneapolis Blower Door equipment (shown in place in Fig. 13.3). To ensure a reliable baseline measurement, the test was repeated three times, with the equipment located in both the front and patio doors. No significant variation was found between the results.

The added ventilation due to window opening was also measured using the blower door apparatus. Each manually operable window in the house was opened to different extents and a blower door test was carried out for each window opening state. The windows were located throughout the house in the kitchen, living room, bathroom, front and rear bedrooms; in total eight blower door tests were carried out.

The range of tests that could be carried out was limited, as after the window opening area exceeded approximately 0.6 m^2, there was too much variation in the building pressure measurement to record accurate results. The air change rate at 50 Pa pressure difference across the building (n50, units 1/h) was measured by the blower door test, and was converted into an infiltration rate at normal pressure difference using the K-P model (Sherman 1987), in which the n50 value is simply divided by 20.

Local weather conditions were measured at the Loughborough University weather station, which is located approximately 1 km from the Holywell test house.

Results

Three co-heating tests were carried out to establish the baseline HLC of the Holywell test house. The three tests gave a very consistent set of results (Table 13.1), and the mean of the three measurements, 170 W/K, was used as the baseline HLC.

Table 13.1 Results of the co-heating tests

Test	Test date (month)	HLC (W/K)
1	November 2012	169
2	June 2013	173
3	October 2013	167
Mean		*170*

Three blower door tests were carried out to establish the baseline air infiltration rate of the Holywell house (Table 13.2), the mean measured infiltration rate of 0.87ACH/h was used as the final measurement. The baseline measurements show that the Holywell house is relatively leaky, with a q50 value of 15 m^3/hm^2, which is considerably higher than the 10 m^3/hm^2 limit required of new dwellings in the current building regulations (H.M. Government 2013).

The blower door tests to measure the effect of various window openings were carried out consecutively on the same day as the baseline measurements (19/11/13) to ensure that there was little variation in the testing conditions between measurements. The heating in the house was left off during the day prior to the test to equalise the internal and external temperature as much as possible and the wind speed was relatively low on the day of testing (Table 13.3).

The results of the nine blower door tests showed a close linear relationship between the measured infiltration rate and the additional opening area caused by the window opening (which was measured for each test). There was an additional measured infiltration rate of 3.8 air changes per hour for each additional m^2 of opening area (Fig. 13.4). This relationship was independent of which storey, room and facade in which the window was located (Table 13.4).

The linear relationship found between window opening area and additional air infiltration allows the additional heat loss associated with a given window opening area and length of opening to be easily calculated, for a set of internal and external

Table 13.2 Results of the baseline blower door tests (all openings closed)

Test	q50 (m^3/hm^2 @ 50 Pa)	n50 (ACH/h @ 50 Pa)	n (ACH/h)
1	15.2	17.6	0.88
2	14.9	17.3	0.87
3	15.1	17.5	0.87
Mean	*15.0*	*17.5*	*0.87*

Table 13.3 Mean conditions during the blower door tests

Internal Temperature (°C)	External Temperature (°C)	Wind Speed (m/s)
8.2	4.0	2.0

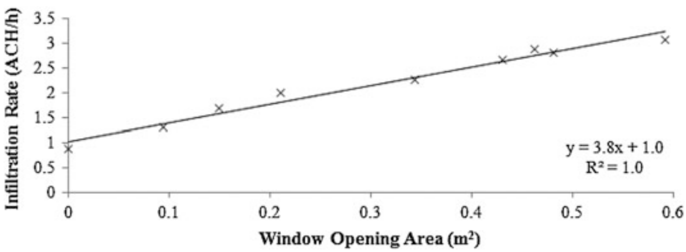

Fig. 13.4 Results of the blower door tests with window opening

Table 13.4 Details of the window openings and results for each blower door test (also shown in Fig. 13.4)

Test	Window	Opening area (m^2)	q50 (m^3/hm^2)	n50 (1/h)	n (ACH/h)
1	Rear bed right	0.09	22.5	26.1	1.3
2	Rear bed right	0.15	29.1	33.8	1.7
3	Rear bed right	0.21	34.4	40.0	2.0
4	Bathroom	0.34	39.0	45.2	2.3
5	Kitchen	0.43	46.2	53.6	2.7
6	Rear bed left	0.46	49.8	57.8	2.9
7	Living room left	0.48	48.4	56.1	2.8
8	Front bed right	0.59	53.3	61.8	3.1

conditions in the Holywell house. The estimated additional heat loss for this house due to window opening (ΔQ_w) is:

$$\Delta Q_w = \rho C_P \Delta T \, \Delta v \, V \tag{13.1}$$

where ρ is the density of air (kg/m^3) at the volumetrically weighted mean indoor temperature during the window opening, C_p is the specific heat capacity (J/kgK) of air at the volumetrically weighted mean indoor temperature, ΔT is the internal-external temperature difference (K), Δv is the additional ventilation due to window opening (converted to ACH/s) and V is the internal volume of the house (m^3). It is likely that the air temperature close to the window, where the air infiltration occurs, will be slightly different from the mean indoor temperature. As the heat loss is being considered from the house as a whole and the open window could be located anywhere in the house, the volumetrically weighted mean internal temperature was used to calculate the additional heat loss.

The empirically defined relationship between window opening area and additional ventilation in the Holywell house (3.8 additional ACH/h per m^2 opening area) has been used to create Fig. 13.5, which shows the measured additional heat loss that a variety of window opening behaviours would cause. In order to give a visual reference, the total HLC of the Holywell house with all windows closed is been displayed on the y-axis; this figure is included as a reference value and is not an additional heat loss as indicated by the axis label.

It is clear in Fig. 13.5 that window opening does have the potential to cause a significant additional heat loss in comparison to the total heat loss of the house. In order to judge the size of the impact, the window opening behaviour in the house would have to be defined. As described earlier, this is likely to be highly variable between houses and it is extremely difficult to define a 'typical' window opening behaviour.

Figure 13.5 shows that in the Holywell house, a window opening of area of 0.94 m^2 (which could occur in a single window or a combination of different windows) for 24 h per day would double the heat loss rate of the house. This seems to be a very unlikely scenario during winter however; a more realistic estimate of the effect of window opening is shown by an X in Fig. 13.5. This shows the effect of one possible daily

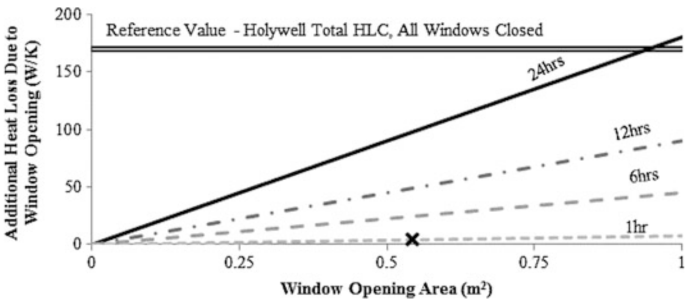

Fig. 13.5 The relationship between window opening and additional heat loss in the Holywell test house. The labelled trend lines show the effect of a window opening area of different sizes for different lengths of time per day, the X shows the additional heat loss due to the window opening behaviour defined below

window opening behaviour where the kitchen window is opened between 18:30 and 18:45 (during cooking), the bathroom window is opened between 7:30 and 8:00 (during washing) and windows are opened in both bedrooms between 8:00 and 8:15 (after sleeping). In all cases, the windows are opened to their largest possible extent.

This window opening behaviour has been included simply to provide an indication of the effect of a plausible example of window opening behaviour and is chosen based upon the literature that is available regarding the time of use of windows (Dubrul 1988; Fox 2008; Johnson and Long 2005). The estimated additional heat loss caused by this window opening behaviour is 4.1 W/K, which is 2.4 % of the total HLC of the building.

The impact of window opening relative to the total heat loss from a dwelling is associated both with window opening behaviour and the baseline performance of the dwelling. The total heat loss is comprised of two components, the fabric and infiltration heat loss:

$$\begin{aligned}\text{Total heat loss} &= \text{Fabric heat loss} + \text{Infiltration heat loss}\\ &= \sum \text{UA}\,\Delta\text{T} + 1/3\,\text{n}\,\text{V}\,\Delta\text{T}\end{aligned} \tag{13.2}$$

where $\sum$UA is the sum of the U-value of each building element (W/m^2) multiplied by its surface area (m^2), n is the air permeability of the dwelling (ACH/h), V is the internal volume of the dwelling (m^3) and ΔT is the internal-external temperature difference. For ease of comparison, both sides of the equation can be divided by ΔT, so that it is stated in terms of heat loss rates rather than total heat loss. The total HLC of the Holywell test house, as measured by co-heating tests, is broken down into a fabric component of 130 W/K and an infiltration component of only 40 W/K (infiltration heat loss = 1/3 n V, as in (Eq. 13.2)):

$$\begin{aligned}\text{Total HLC} &= \text{Fabric heat loss rate} + \text{Infiltration heat loss rate} = 130 + 40\\ &= 170\text{W/K}\end{aligned} \tag{13.3}$$

Window opening only affects the infiltration heat loss from the building, specifically by changing the air permeability of the house. A comparison of Eqs. (13.2) and (13.3) makes it clear that a very large change in the air infiltration rate would be required in order to cause a significant change in the total heat loss rate from the Holywell test house. Clearly, this is a relationship specific to a particular dwelling, though the heat loss due to window opening is related to the opening area and therefore is not affected by the fabric performance of the dwelling or its airtightness. This means that in dwellings with lower heat loss rates the effect of window opening will be relatively larger. Comparison of the equations also suggests that the effect of window opening will be more pronounced for smaller dwellings (with a lower internal volume).

The relationship between the total HLC of a dwelling and the relative impact of the window opening (shown as a percentage increase in the total heat loss from the dwelling) for a range of window opening behaviours is shown in Fig. 13.6. The figure shows the impact of a range of window opening behaviours, causing additional heat losses ranging from 1 W/K to 15 W/K; the relationship for the window opening behaviour defined in this paper is shown by the solid line on the chart.

Figure 13.6 highlights that the additional heat loss due to window opening for most behaviours is relatively small for the majority of dwellings, but rapidly increases in dwellings of higher thermal performance (and hence a lower HLC) or for more extreme window opening behaviours. The window opening behaviour defined in this paper (shown by a solid line in Fig. 13.6) causes an additional heat loss of greater than 5 % for dwellings with an HLC lower than 75 W/K, and greater than 10 % for dwellings with an HLC lower than 40 W/K. It is important to note that the relationship shown in Fig. 13.6 is specific to a dwelling of the same internal volume as the Holywell test house and to the window opening behaviour scenario applied in this study.

By comparison with the window opening behaviour defined in this paper, which causes an additional heat loss of 4.1 W/K, a window opening behaviour which leads to an additional heat loss of 15 W/K seems rather extreme. If it were to occur however, this window opening behaviour would cause an increase in the total heat loss from a dwelling of more than 10 % for dwellings with an HLC of 145 W/K or lower. This demonstrates that window opening could cause a significant additional heat loss in some higher-performing houses, or for more extreme window opening behaviours.

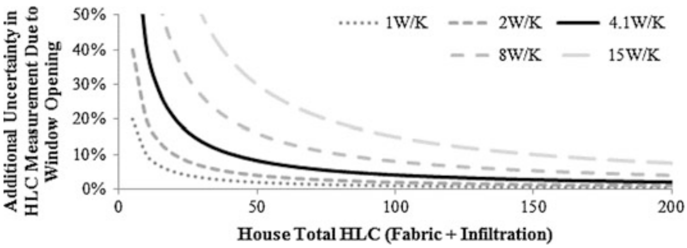

Fig. 13.6 The relationship between the total HLC of a house and the percentage additional heat loss caused by a range of window opening behaviours. The window opening behaviour defined in this paper (which results in 4.1 W/K additional heat loss due to window opening) is shown by the *solid line*

Discussion

A linear relationship between infiltration rate and window opening was revealed by this study which concurs with the results of the only other similar study found in the literature (Howard-Reed et al. 2002). This study was carried out in two occupied houses in America using a tracer gas decay method, which allowed measurements in different weather conditions over a period of several months and with different combinations of open windows. This is particularly significant as it is likely that different combinations of window openings, particularly in different facades, would cause different airflow paths through the house. This is a phenomenon which is not investigated by the method employed in this study where measurements were taken with only one window opened at a time. The fact that a linear relationship was discovered using a tracer gas decay measurement method also adds to the confidence in the findings of this study given the limitations of the blower door testing method. The common findings of the Howard-Reed et al. study in occupied houses and those measured in this study act to build confidence in the observed linear relationship between window opening area and additional air infiltration; though it must be noted that they represent a sample of only three houses. Confidence in this relationship is important as it allows the additional heat loss due to that window opening to be simply calculated.

It is likely that the relationship between infiltration rate and opening area would be temporally affected by weather conditions such as a changes in wind speed and direction, or internal-external temperature difference which would cause a different pressure gradient across the dwelling. The effect of these changing conditions cannot be investigated using the blower door method in which a controlled pressure difference is applied evenly across the dwelling, rather than the natural variations that occurs in real-life. However, this effect could be offset by research that shows that window opening is less likely for lower external temperatures and higher wind speeds (Fabi et al. 2012; Johnson and Long 2005).

The influence of window opening during the winter heating season is not included in SAP, and could therefore be a possible cause for the discrepancy between predicted and in situ energy performance when using the SAP calculation method. The findings of this study do not support this hypothesis for most dwellings and window opening behaviours if causes for a large discrepancy are sought, though they do show that an additional heat loss of 5 % or less due to window opening is reasonable.

As shown in the results section (Fig. 13.6), the effect of window opening relative to the total HLC of a dwelling is dependent upon both the window opening behaviour and its thermal performance. The results of the co-heating tests carried out by Leeds Beckett University (Fig. 13.1) can be used to give some context of typical levels of thermal performance of UK dwellings. Despite the likely skew towards higher-performing dwellings described in the introduction, 24 of the 34 dwellings shown in Fig. 13.1 have a measured HLC of 145 W/K or higher. This is the threshold under which a seemingly extreme window opening behaviour (causing an additional heat loss of 15 W/K) was shown to cause a greater than 10 % increase in the total heat loss from a dwelling (Fig. 13.6). It therefore can be said that window opening is unlikely to cause a very significant increase in the heat loss from a dwelling relative to its baseline performance, except in cases of unusually high thermal performance and extreme window opening behaviours.

This is a particularly pertinent finding in relation to post-occupancy evaluation techniques, such as the newly-developed Loughborough In-Use Heat Balance (LIUHB) test (Jack et al. 2015). In such evaluations, the additional heat loss due to window opening is likely to represent an unknown variable due to the difficulty and consequent expense of measuring the time and extent to which windows are open. This unknown also operates in only one direction, acting to erroneously increase and never decrease the measured HLC. The findings of this study provide evidence that acceptably accurate measurement of the thermal performance of most buildings can be taken while a house is occupied, due to the relatively low impact of window opening compared to the total HLC in most houses.

This conclusion is true as long as the window opening behaviour is not 'extreme', however this is currently a subjective judgement as there is a paucity of evidence to define 'typical' and 'extreme' window opening behaviours. A detailed study of window opening behaviour in dwellings is required to establish well-founded estimates of common and extreme examples of real-life behaviour to allow a more objective appraisal.

The results of this study have shown that window opening has the potential to cause a significant additional heat loss relative to the baseline performance of a dwelling in cases of high thermal performance or extreme window opening behaviours (Fig. 13.6). This finding suggests that a method such as the LIUHB test may not be suitable in dwellings of high thermal performance. In these dwellings, it is likely that the effect of window opening could introduce a large source of uncertainty to the test, moving the measurement uncertainty outside of the test's estimated accuracy level of ±15 %. For instance, in a dwelling with a HLC of lower than 40 W/K the window opening behaviour defined in this paper would cause an additional uncertainty of larger than 10 %. This finding also highlights the importance of an effective ventilation strategy in dwellings of high thermal performance, and especially high airtightness, to provide the requisite ventilation without the need for window opening.

Conclusions

- A strong linear relationship was observed between the area of window opening and the measured additional air infiltration by a blower door test independent of window location. This finding, based upon blower door measurements, repeats that of Howard-Reed et al. who used a tracer gas decay method (Howard-Reed et al. 2002).

- The relationship between opening area and airtightness has been used to calculate the additional heat loss due to a wide variety of possible window opening behaviours.
- It has been shown that window opening does not cause a significant (greater than 5 %) additional heat loss from this particular house compared to the baseline heat loss rate (with all openings closed), except for very extreme window opening behaviours.
- Further analysis suggests that window opening is unlikely to cause a significant additional heat loss relative to the baseline heat loss rate in the majority of dwellings, though it will become increasingly influential in houses of higher thermal performance.

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Chapter 14
A Methodology for Identifying Gaps Between Modelled and Measured Energy Performance in New-Build Social Housing

Agnieszka Knera, James Parker and Alan Poxon

Abstract Registered social landlords (RSLs) that deliver new-build housing have a vested interest in providing energy efficient, thermally effective dwellings. The methodology presented in this short paper focuses on a new-build programme that is delivered by an RSL's own Direct Labour Organisation (DLO). This allows for much closer control of site operations to help ensure that design intent is met as closely as possible. Due to RSLs retaining ownership of the new-build dwellings throughout their life-cycle, it offers them a unique opportunity to complete long-term monitoring of building energy performance. A methodology is described in this paper for an RSL to become an informed client with the ability to evaluate the energy performance of proposed designs, assure quality standards on site and measure the long-term energy use and thermal performance of new-build social housing. As part of this methodology, designs will be evaluated using dynamic thermal simulation (DTS) software which will provide a more detailed prediction of energy performance than regulatory compliance calculations. These predictions will then be compared with in-use monitoring data. Collectively, this data and analysis will allow them to identify gaps in performance and help them to define processes that can mitigate these in future projects.

Keywords Social housing · Thermal performance · Dynamic thermal simulation · Resilient construction

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Introduction

Housing associations, social landlords and private developers are under pressure to deliver a substantial number of houses that will be required to meet the rising demand for new homes, especially for first-time buyers, homes for affordable rent and accessible homes, meeting the demands of an ageing population. Data recorded up to 31st March 2014 confirmed that there were 23.4 million dwellings in England (DCLG 2015). An increase of 137,000 dwellings (0.59 %) on the previous year was recorded. Approximately 17 % of housing stock can be classified as social or affordable rented dwellings which include private registered providers and local authority tenures. While private rented stock and owner occupied stock both increased between March 2013 and March 2014, the social and affordable rented stock decreased by 1000 dwellings and the other public sector stock decreased by 9000 dwellings (DCLG 2015).

The UK government, through the Climate Change Act 2008 (CCA), set an ambitious target of an 80 % reduction in the net UK carbon emissions from the 1990 levels, by 2050. Approximately 30 % of the UK's total CO_2 emissions can be allocated to domestic buildings (DECC 2013). The housing stock therefore has a great part to play in meeting those targets and tackling climate change.

At the same time, a growing body of research has identified a significant performance gap between the energy consumption predicted by regulatory compliance design calculations, including the Standard Assessment Procedure (SAP), and actual performance (Bordass et al. 2001; Carbon Trust 2011; Austin 2013).

Wakefield and District Housing (WDH) is committed to addressing the housing shortage issue, required reduction in carbon emissions and inflexible methodologies of energy evaluation informing their decision-making processes. It also aims to tackle fuel poverty by providing energy efficient, thermally effective dwellings. To achieve these goals WDH has invested in a research programme where energy performance of proposed designs will be evaluated and procedures will be developed to assure quality standards on site. Long-term monitoring of the energy and thermal performance of new-build social housing is part of the planned study.

This short paper introduces briefly the proposed methodology developed to ensure WDH's dwellings meet the set efficiency standards and budget targets.

Literature Review

The Standard Assessment Procedure (SAP) is the calculation method used by the UK Government to assess and compare the energy and environmental performance of dwellings. It verifies the compliance with Building regulations, specifically Part L: *Conservation of Fuel and Power* (HM Government 2010a, b). The SAP and reduced data SAP (RdSAP) calculations are used to evaluate newly built and existing buildings respectively. Clarke and Reason (2008) and Kelly et al. (2012) all question the effectiveness of SAP. Kelly points out the lack of variation in weather data across regions, rigid occupancy profiles and heating/cooling set points. The SAP is a methodology for estimating dwelling energy performance based on the design specification. Newly built dwellings are required by law to have an 'as-built' SAP assessment, although this does not currently apply to extensively retrofitted properties.

WDH acknowledges the fact that SAP has a limited role in the energy efficiency decision-making process, as its accuracy cannot be ensured at a single dwelling level. In addition, it does not provide the ability to analytically examine alternative design scenarios and the potential to optimise building performance.

Various research methods and tools have been used in an attempt to quantify the gap between modelled and measured energy performance. Variations in occupant behaviour can have a significant impact on energy performance (Bordass et al. 2001). It is however difficult to understand and, in particular, model the impact of these behaviours. In contrast, building fabric is a factor which can be specified and modelled accurately and its performance can be tested in situ. Established methods for evaluating whole fabric performance include the *Primary and Secondary Terms Analysis and Renormalization* (PSTAR) method and the co-heating test methodology (Subbarao 1988 and Johnston et al. 2013). The PSTAR approach utilises short-term energy monitoring (STEM) tests to help refine thermal model input parameters, which are then extrapolated to produce annual simulations. Both the PSTAR and co-heating approaches can be used to forensically examine the performance of as-built building fabric. The co-heating test methodology is not necessarily new but has been refined by Leeds Beckett over recent years and is described as: "…a quasi-steady state method that can be used to measure the whole dwelling heat loss…" (Johnston et al. 2012, p. 4). Monitored power input is compared with the difference in internal and external temperatures to derive a whole-house Heat Loss Coefficient (HLC).

Dynamic Thermal Simulation (DTS) models can provide a means of accurately predicting the thermal performance of a dwelling over a full year (8760 h). Accuracy is dependent on how closely the input parameters reflect the actual, real-life conditions. The models can be adjusted to simulate 'real' thermal behaviour. Such calibration techniques have been widely researched and are described by Reddy (2006). The selection of techniques used in this project is described in the following section.

Research Method

Design Requirements and Evaluation

Homebuilder (HB) is an integral part of the WDH Ltd. business. It builds homes under supervision of its internal client, the Investments Directorate. The decisions of the internal client are linked to government and private funding streams. The client might specify certain levels of energy efficiency for the final product by requesting it to meet, for example, Passivhaus or Zero Carbon standards. For all WDH projects, British Board of Agrément (BBA) approved products are required by the client to ensure a high quality final product.

To achieve the required level of regulatory compliance, performance goals, target dates and budget, all specified at an early stage of the project, HB utilises internal processes of product and systems analysis. Those largely rely on the knowledge and experience of best practice of the team members, product specification supplied by the manufacturer and design stage SAP calculations. The SAP calculations are provided by an external consultant. In some cases predictions of thermal performance of proposed design options can also be provided by the architects. Those are comparative values between proposed options and are largely indicative.

Research Aims and Introduction of New Methods at WDH

HB would like to accurately predict and evaluate the performance of the dwellings they deliver and also potentially question the need to achieve certain levels of specification. If it is proven that a particular solution provides little value for money for both the internal client and the final user, the company is then in the position to take an informed decision on the profitability of their actions.

To be able to ultimately review their design requirements and develop evidence-based specification within the organisation, the method of Dynamic Thermal Simulation (DTS) is to be applied. This will allow a dynamic analysis of the energy performance implications of proposed construction options. Unlike the external consultant produced SAP estimates, the DTS models can also be used to examine multiple scenarios and combinations of different technologies. The whole house represents a complete system and specification changes influencing certain elements can have an impact on the performance of others. DTS analysis allows for this interdependant relationship to be explored. It can also be used to inform optimisation of design in terms of energy and cost.

In this study, the DTS models are to be created in Design Builder (DB), software version 4.2.0.054 (or later). Design Builder uses EnergyPlus as its building physics engine. Various case study buildings will be selected from recently specified, constructed and currently occupied family houses (two and three bedroom homes). This study is expected to cover existing new-built houses and homes built in the future to allow for evaluation of building performance through the cycle of design, build and occupancy.

Knowing that the DTS models are not an exact and perfect representation of the real world (all models are effectively a simplification of a highly complex physical universe), a process of calibration will be undertaken. An iterative update approach will be used to calibrate case study models. Manual, iterative and pragmatic updates will be based upon improved data inputs taken from as-built details and test results.

An iterative calibration approach can be supported using ‘calibration signatures’ and ‘characteristic signatures’ (Claridge 2011). Calibration signatures are best suited to the calibration of heating and cooling system energy consumption. Although actual weather data allows for the most accurate comparisons, signatures can also be compared with actual performance using Test Reference Year simulation weather files. This is useful in this instance as site-specific actual weather files are unlikely to be available.

Special tests/analytical procedures also belong to the calibration techniques described by Reddy (2006) and others. Those will include short-term energy monitoring (STEM) and fabric performance measurements. It is intended that air-tightness testing, co-heating test data, in situ U-value measurements and in-use energy monitoring will provide sufficient information to ensure the required accuracy of the DTS models.

Site Operations and Standards

To ensure that the required level of quality of processes and workmanship are in place, the Site Managers follow Quality Management Systems (QMS) procedures. The site operations are therefore dependent on the knowledge and experience of site managers as well as the quality assurance procedures. A project’s set budget has a strong implication on the speed of construction. Site operations are conducted with the use of Direct Labour Organisation (DLO) and occasional employment of external contractors.

The quality of construction is continuously reviewed by Building Control and the National House Building Council (NHBC) at various stages of the project (superstructure, foundations formation, structures, fittings, etc.) to ensure regulatory compliance and to guarantee that the warranty requirements are met.

Regular meetings (pre-start meetings, weekly progress meetings, design meetings) ensure that the teams are briefed on the progress of the project while contractors are informed about internal requirements, on-site restrictions or safety.

So-called *Snagging Lists* are created by site managers and project officers. Those contain faults in processes, noted mistakes or poor quality of finishes. Incorrect use of products will be recorded here as well as faults in a product itself when delivered on site. All the above are later addressed in corrective processes. A *Corrective Action Request* (*CAR*) is used to respond to a non-conforming product, service or process. It is used to determine the root cause and take actions to correct it and stop it from reoccurring.

Value engineering is a common practice in the construction industry. This, timescale planning, as well as the quality of site operations, dependant on the skills of the workforce, will have a great impact on the thermal performance of the final product. It is intended that outcomes from the performance gap analysis that is the basis of this work are fed back into this process to help isolate key issues that will impact on energy performance.

Improvements in Site Operations and Standards

A requirement to reach specific SAP ratings governs the need to obtain specific quality of build which is later partly established in an air-tightness test. Although the airtightness of a building is important, achieving good airtightness is only effective when considered as part of the whole system. Currently there are no specific procedures, however, to test the *as-built* whole-house thermal performance or plane elements of the building.

A part of this work will aim to establish the gap between the specified thermal performance of the construction elements, and the actual performance of the finalised dwelling. If a gap is identified, further forensic investigations will be carried out to establish the potential causes for deviations. Reasons can be varied and can include construction defects and substituted materials that deviate from the original specification.

The *Snagging Lists*, *Corrective Action Requests* (*CAR*) and additional inspections by the member of staff involved in the study will be utilised to inform updates of DTS models and produce revised forecasts of performance. This process provides WDH with a unique opportunity to conduct a continuous evaluation and feedback loop in their specification and construction programme.

Currently an airtightness test, determining the building's air permeability rating, is conducted by an external consultant at the final stage of the construction. This gives only the final air permeability ($m^3/hr/m^2$) at the testing pressure of 50 Pa (as per regulatory requirements in the UK).

Thermographic surveys will be conducted on completed dwellings. Under relevant conditions it is possible to identify (but not quantify) thermal bridges and air leakage. This, and air pressurisation tests, are the two methods which are going to influence the site operations most. When established as a regular quality assurance procedure, they will drive further change aimed at improvements in the building fabric.

Post Occupancy Evaluation

Post occupancy evaluation is currently an incidental result of tenants' surveys or tenants' direct feedback recorded in the form of repairs report, complaints or compliments.

In order to complete a meaningful analysis of tenants' satisfaction with the thermal performance of the homes they live in, a Post Occupancy Evaluation (POE) will be conducted including long-term monitoring of occupied houses. Dwellings considered in the study will be divided into specific construction type groups with subdivisions considering other building characteristics including: size, location, services and type of tenure. Continuous monitoring of gas and electricity usage will be implemented, accompanied by records of internal and external temperature and relative humidity (and potentially CO_2). This will be done using integral sensors and data loggers. The data will be gathered, stored and analysed using remote access technologies allowing for easy access, instant comparison and benchmarking.

To understand the impact the occupants have on a building's thermal performance and consequently on the overall energy consumption in their household, both quantitative and qualitative data will be collected. Repeated semi-structured interviews are planned to be conducted to understand the underlying reasons for patterns of energy use as well as changes in other monitored factors. Potential issues with design solutions and incorporated technologies are expected to be highlighted during this primary research.

Such analysis, based on robust research and benchmarking methodologies, will provide WDH with a deep understanding of property operational demands and the impact of construction specification choices. It will also provide realistic data inputs for the calibration of DTS models. Analysis of the revised models in comparison with actual performance data will allow the potential causes for gaps in

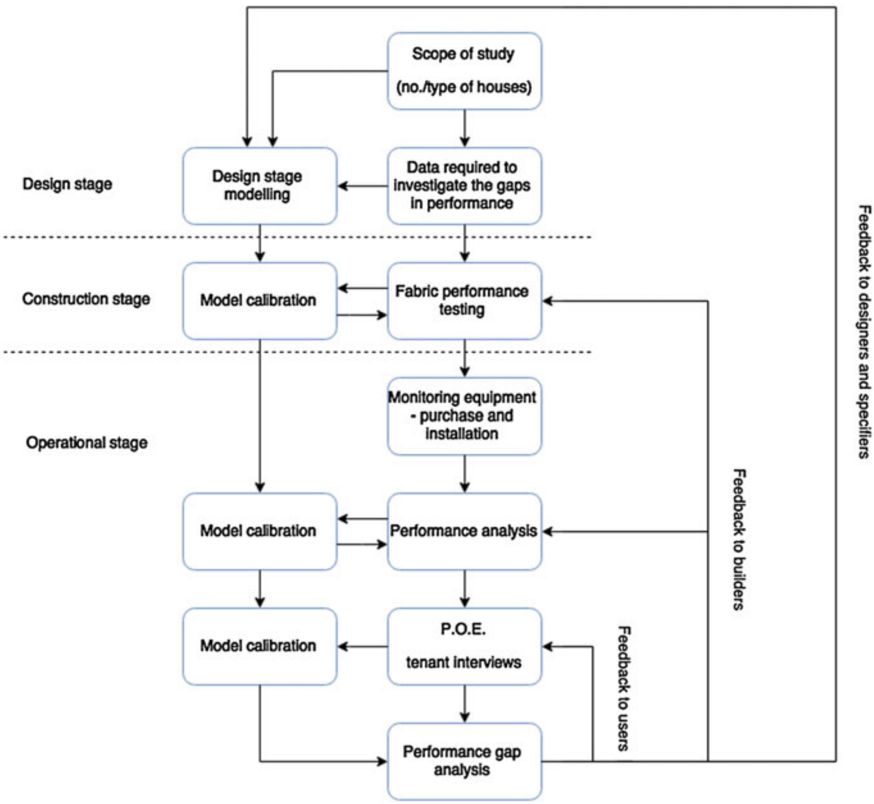

Fig. 14.1 Development of research methodology

performance to be identified and addressed through either improved design and build processes or tenants briefings, helping them to understand the operational demands of their homes.

The Fig. 14.1 illustrates the research approach and development of methodology.

Conclusions and Further Work

As initially stated, this paper aims to provide the outline of a method that has been designed to develop the capacity of WDH to evaluate the in situ and operational performance of the homes that they build. The project itself is in its very early stages and the research method will inevitably be refined as the work progresses. Despite this, some early outcomes have already been achieved.

Intermediate air pressurisation testing has already been initiated, which highlighted primary leakage areas at the completion of the air barrier. A report issued to the site team is now forming a base for developing a new Quality Assurance Management Procedure for various construction methods used by Homebuilder. It has been noted that raising awareness among those most able to influence building airtightness is crucial. Actions will be incorporated into the project plans to allow time and resources to address this.

The DTS software has also been employed to analyse the impact of alternative ground floor slab specifications on the overall energy performance of a specific archetype. The outputs from the DTS model were used as part of a cost/benefit analysis which in turn informed the specification of the final design.

Ultimately, the calibration of DTS models against actual consumption data will help to identify specific issues that lead to gaps between forecast and actual performance. These models will help to quantify the impact of any changes in construction or details and also to help understand the impact of user behaviour on the whole house energy performance. Lessons learnt through this process will be fed back into the design, construction and operational phases of future developments. This will include guidance and specifications for designers, improved site practices and practical advice for WDH tenants.

Up to twenty six properties spanning across eight different development sites will be included in the project as a whole. Outcomes of the research will be implemented and reviewed as the project progresses with the intention that refined processes and practice will be fully embedded in WDH procedures by 2017.

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Chapter 15
Evaluating Natural Ventilation in Future Climate Scenarios as Part of a Long-Term Non-domestic Retrofit Strategy for an Educational Facility

James Parker

Abstract Natural ventilation is an established strategy that can help to reduce the energy consumption associated with conditioning buildings and weather conditions in the UK are suitable for the use of natural ventilation to help control summer overheating. However, there is now scientific consensus that anthropogenic emissions of carbon dioxide are leading to climate change and that global temperatures are set to increase as a result of this. It is likely that this will lead to longer and more intense summer heat waves. This paper presents a case study of a multi-use naturally ventilated university office building in the north of England. Dynamic thermal simulation software has been used to evaluate the thermal conditions in the case study facility. Potential overheating using current weather files is compared to predicted overheating in future climate scenarios using morphed weather files. Results from this overheating analysis are then considered as part of a long-term retrofit strategy for the case study facility; this case study is used to demonstrate how this type of analysis can help to evaluate existing building performance and to inform investment-grade decision-making.

Introduction

The recent Intergovernmental Panel on Climate Change (IPCC) assessment report confirmed that the world's climate is changing due to anthropogenic carbon dioxide (CO_2) emissions (IPCC 2014). Approximately 34 % of man-made CO_2 emissions

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come from the built environment (United Nations Environment Program 2007), accounting for 45 % of the UK's total carbon footprint (The Carbon Trust 2009). Energy used for space conditioning remains the greatest source of CO_2 emissions in domestic and non-domestic buildings (Pérez-Lombard et al. 2008) and in the UK, heating loads account for the greatest proportion of this. It is therefore understandable that the majority of retrofit work is designed to retain heat in winter months. However, overheating is increasingly being acknowledged as a problem in UK buildings and one that has the potential to become worse (Levermore and Parkinson 2014). Temperate countries, like many of those in Europe are forecast to experience more frequent and severe heat waves in the future (Meehl and Tebaldi 2004; IPCC 2014).

Natural ventilation can be described as a passive measure and in many cases will have no associated energy consumption (Nicholls 2009) although a natural ventilation strategy could consume a small amount of energy if, for example, powered actuators were used to control openings (Schulze and Eicker 2013). It therefore offers a low-carbon alternative to both mechanical ventilation and full air conditioning for both new-build and retrofit projects. A natural ventilation strategy, as with many low-carbon building solutions, can be more easily integrated during the design stage of new-build projects (Baker 2009) but, as it is estimated that approximately 87 % of existing buildings will remain operational by the year 2050 (Kelly 2009), retrofit has the greatest scope for reducing overall emissions. As mentioned above, the majority of retrofit work aims to improve the ability of a building to retain heat which has the potential to exacerbate potential overheating. However, as there was no baseline data for the pre-retrofit building this was outside the scope of this study.

The contents of this paper describe a case study which evaluates the impact of introducing a natural ventilation strategy in a multi-use university office building as part of a large scale retrofit project; the dynamic thermal simulation (DTS) models included in this work are based upon as-built and as-occupied parameters. The case study building and models are described in more detail in section three of this paper. Experiments presented in this work were designed to predict overheating across the top three floors of the retrofitted building. Potential overheating was first estimated for a Design Summer Year (DSY) based upon site-specific historic weather data. Further simulations use a series of weather files that have been morphed to simulate future climate scenarios. The results of these simulations have then been used to assess the existing retrofit strategy and to consider further retrofits required to reduce future overheating as part of the building's natural refurbishment cycle.

A literature review follows this introduction within which studies of overheating in UK facilities are described and the retrofit of non-domestic facilities is explained further, with a particular focus on natural ventilation. In section three of this paper, the research methodology followed to produce this work is defined, including a description of the case study building, simulation techniques used to evaluate overheating, metrics used to quantify overheating and the weather files that are used to simulate future climate scenarios. Section four presents the results from the simulations and analyses these data in the context of future overheating and additional retrofit measures that could be used to mitigate this. The final section presents the conclusions of this research and makes recommendations for further work in this area.

Literature Review

Overheating has not traditionally been considered as an extensive problem in UK buildings but it is becoming more common in both existing, older structures as well as in exemplar low-energy developments (Good Homes Alliance 2013; Taylor 2013). Avoiding excessive overheating by making an allowance in design to minimise summertime solar gains is now acknowledged in the UK building regulations for new-build and extensive retrofit projects (HM Government 2010a, b); there is currently no requirement to model buildings in the predicted future weather conditions. Some dynamic simulation modelling (DSM) software is approved for the analysis of potential overheating in non-domestic buildings (HM Government 2010c); one of these software packages was used in the analysis presented in this paper ('dynamic thermal simulation' software is a more appropriate description of the applications used in this work than DSM, which is a less specific term). Many factors influence internal temperatures including: building geometry and surrounding structures; building orientation; building fabric; solar gains; air tightness; internal heat gains from occupants and equipment; and shading from solar radiation and wind (Taylor et al. 2014). This complex interaction of variables makes DTS software the most effective means of evaluating proposed natural ventilation strategies.

There is a growing body of work that considers the extent of overheating in UK dwellings and non-domestic buildings that has also used morphed weather files to analyse future overheating. A large amount of this research focuses on overheating in dwellings (Porritt et al. 2012; Gul and Menzies 2012; Jenkins et al. 2013) but some has also considered overheating in naturally ventilated non-domestic buildings (Barclay et al. 2012; Du et al. 2011). Although none of these case studies use the same archetype examined in this work, the fundamental methodologies are very similar; they all use DTS models in conjunction with future weather files to estimate overheating in climate change scenarios. Conclusions in these publications suggest that naturally ventilated domestic and non-domestic buildings alike will experience overheating in future climate scenarios that exceeds the thresholds defined in a selection of ranking metrics. Numerous mitigation measures can be introduced that help to reduce the risk of overheating and these include: solar shading (internal and external), increased natural ventilation, additional mechanical ventilation and additional air conditioning (Butcher 2014; Porritt et al. 2012). Solar shading and natural ventilation offer passive measures that can mitigate overheating without increasing overall CO_2 emissions. Modelling provides a useful means to help avoid the thermal comfort of occupants being compromised.

The Chartered Institute of Building Services Engineers (CIBSE) have published guides for using climate change scenarios in building simulation and for future climate design (CIBSE 2009; Butcher 2014). Results from a series of case studies are presented in the document edited by Butcher (2014) and have been used to identify key considerations when designing for a future climate. It has been advised that design teams need to work with clients at an early stage to understand the potential impact of climate change scenarios and also that there are some limitations when using building simulation tools (Butcher 2014). These are particularly relevant to localised external shading (from trees for example) and localised cooling from ceiling fans. One case study identified a 20 % reduction in whole life costs due to passive adaptation strategies introduced at design stage compared with a base case air conditioned version of the building (Butcher 2014). These case studies include one mixed use and one university building. Although these case studies do not consider the natural ventilation system as part of a long-term retrofit strategy, they follow similar methodologies in terms of the simulation software, morphed future weather files and overheating metrics that are used.

Non-domestic Retrofit

Estimates suggest that less than 1.5 % of the UK building stock is newly constructed each year (Baker 2009) and existing non-domestic buildings provide "… numerous opportunities for deep reductions in energy use…" (Harvey 2006). If maintained and refurbished effectively, the service life of a building can be over one hundred years if the structure is safe and the facility remains useful; this differs from the design life (or economic life) which is an assumed period for which costs and benefits can be evaluated (Kohler and Yang 2007). The age of a building's components will influence its natural refurbishment cycle. The Leeds Beckett University's Estates department use twenty-five years as a design life span for this type of building. This would mean that assuming the structure remains sound and the building fit for purpose that another major retrofit would be scheduled for the year 2040.

It is recommended by Jenkins et al. (2009) that equipment, lighting and building fabric retrofits are considered before upgraded plant and HVAC systems are specified as they will have an impact on the heating and cooling loads. The same advice is published by the Carbon Trust as part of a guide to retrofitting non-domestic buildings (The Carbon Trust 2009). This published advice is useful in formulating a retrofit strategy but practically it must be considered alongside the operational life spans of specific building elements in the case study building; some building elements will need replacing more often than others. Estimates of elemental service lives used here are referenced from the Building Cost Information Service (BCIS) and are based upon professional surveyors' experience of actual buildings (BCIS 2006). As stated, service life could be over one hundred years which would lead up to 2067 for the case study building. Other service lives of

Table 15.1 Typical service lives of building components based upon surveyed evidence

Building component	Typical (service life in years)	Maximum (service life in years)
Foundations/ground floor slab	100	120
Reinforced structural concrete frame	60	100
Reinforced concrete flat roof with slabs	65	100
Aluminium framed double-glazing	40	50
Lighting (luminaires)	15	20

building components that are relevant to the case study building are shown in Table 15.1. The term 'typical' refers to the most commonly observed service life and 'maximum' refers to the absolute service life observed.

The service lives of the components relate to the morphed future weather files that can be used in the simulation software. These effectively cover the periods 2020–2039 (referred to as the 2030s weather file), 2040–2059 (referred to as 2050s) and 2060–2089 (referred to as 2080s); these are described further in the following methodology section. Based upon the BCIS data, the structure would last until 2067 although this would be subject to survey at the time and, if sound and safe, could surpass this service life. Windows are being replaced as part of the latest refurbishment so are likely to be replaced in the 2050s and lighting is likely to be replaced in the 2030s.

Research Methodology

This section is split into three parts. The first describes the case study building and notes the key data inputs for the DTS model that has been used to evaluate overheating. The second subsection describes the simulation software and the weather files used in the modelling exercises. Metrics used to evaluate overheating are then described in the final subsection.

Case Study Building

The Leeds Beckett University Calverley building is used in this work as a case study. It was built in 1967 and is an eleven-storey reinforced concrete frame structure that houses approximately 6931 m^2 of occupied space. As part of a major refurbishment project insulation is being significantly upgraded and a natural ventilation strategy is being introduced throughout the building. Renovation work is being completed in vertical phases with the top three floors the first to be

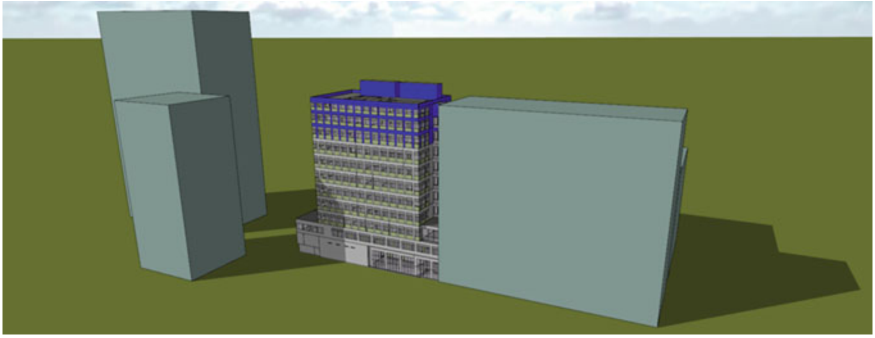

Fig. 15.1 Model of multi-use university building with top three floors highlighted in *blue*

refurbished. At the time of modelling, final floor plans and occupancy figures were available for the top three floors and it is these areas that are used in the analysis of the natural ventilation strategy. External wall insulation is being upgraded and the U-value used in the model was 0.228 W/m^2/K for the concrete sections of the façade; low emissivity double-glazing and insulated opaque glazed panels were input at values of 2.489 and 0.208 W/m^2/K, respectively, based upon materials specification. There is some local shading from surrounding buildings as can be seen in Fig. 15.1. The building is orientated at 210° from north meaning that a large area of the façade is exposed to solar irradiation.

Most of the occupied spaces on the top three floors are used as offices but the facility as a whole incorporates a wide range of functional space. The model uses zone type classifications that are described in the National Calculation Method (NCM) and these have been used to characterise the building's functional space (DCLG 2011). Actual occupancy numbers were used for the office spaces on the top three floors (floors 8, 9 and 10) which are shaded blue on Fig. 15.1. Interview room and meeting room zone type occupant densities were calculated using the Leeds Beckett University 2012/13 Room Use Audit Report. The Estates Services at Leeds Beckett University compile this report on an annual basis and reported data were used to estimate occupancy profiles for meeting rooms and interview spaces. This data were also used to control the occupancy schedule for office spaces. Occupancy density and duration is important as humans account for one source of internal heat gain. Additional internal heat gains come from equipment and lighting. The simulation inputs for lighting were calculated from specification documents and the equipment gains were calculated based upon monitored data within Leeds Beckett University office spaces. The IES software includes default NCM thermal templates to control internal gains and these were used as inputs for occupant, lighting and equipment in circulation spaces, tea making facilities, toilets and storage areas.

Natural ventilation is supplied through opening windows and high-level vents. In all occupied spaces, the windows units are made up of a small (0.66 m × 1.45 m) and large (1.19 m × 1.45 m) window both of which can be opened to an angle of

10 °. These dimensions are taken from the 8th floor. The opening windows on the 9th floor are slightly shorter (1.25 m); opening windows on the 10th floor are shorter still (1.15 m) and there are no high-level vents on this floor either. All windows are manually operated and are assumed to be opened fully when the internal temperature reaches 21 °C as per the original design. The high-level vents (1.85 m × 0.55 m) are automatically controlled and allow for 10 l/s/person of air exchange. All openings operate between 8 am and 6 pm.

Simulation Software and Weather Files

As previously mentioned, DTS models were produced using IES Virtual Environment software which has been validated against international standards and is approved for UK Building Regulations compliance calculations (IES 2013). The 'Apache' application was used for the dynamic thermal simulation calculations and the 'MacroFlo' application was used to control the natural ventilation in the building.

The simulation weather files used in these calculations were produced as part of the Prometheus project which uses UK Climate Projections 2009 (UKCP09) data to morph weather files to account for projected changes in the future climate and are described in more detail by Eames et al. (2011). These files are created using sample weather data for Test Reference Year (TRY) and Design Summer Year (DSY) periods which are then morphed to reflect climate change in medium and high emission scenarios (Eames et al. 2011). Within each scenario, weather files were produced for the 2030s, 2050s and 2080s as mentioned above. For each scenario and year, there are probabilistic predictions for the 10th (unlikely to be more than), 33rd, 50th, 67th and 90th (unlikely to be less than) percentiles. The following analysis uses the 50th percentile files for the medium risk scenario. Simulations were completed using the baseline 2005 DSY, 2030s, 2050s and 2080s weather files for comparison.

It is important to note that the baseline weather files used in this work are not those produced by CIBSE and approved for use in regulatory compliance calculations for non-domestic buildings in the UK. The Prometheus files are freely available for academic use and offer a wider range of probabilistic data based upon the most recent UKCP09 forecasts. The researchers that produced the Prometheus weather baseline files found that there was little difference between their own baseline files and those used by CIBSE even though they were collected over different time periods; 1961–1990 as opposed to 1986–2003 (Eames et al. 2011). However, in the comparison of modelled results using both the CIBSE and Prometheus DSY baseline files for Leeds presented in Fig. 15.2 there is a significant difference. The coordinates from the weather stations used to collect the comparative data show that the CIBSE data are collected in the very centre of Leeds in a high-rise dense urban environment whereas the Prometheus weather data source is situated two kilometres southwest of the city centre in a green space adjoining a

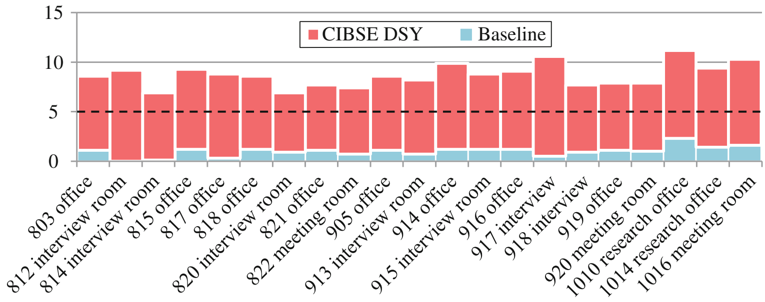

Fig. 15.2 Comparison of the percentage of occupied hours exceeding 25 °C when using the CIBSE and Prometheus DSY weather files for Leeds

low-rise urban environment. It is possible that these results are indicative of the urban heat island effect but this requires further investigation and is outside the scope of this research; it will be investigated in the future work.

Overheating Metrics

Metrics used in the original design stage analysis were used to evaluate overheating. The percentage of occupied hours that exceed 25 °C and the percentage of occupied hours that exceed 28 °C are used as benchmarks; at 25 °C overheating is deemed unacceptable when the percentage exceeds 5 % and at 28 °C when the percentage exceeds 1 %. These values are defined by CIBSE in their 'Environmental Design: Guide A' document. These absolute thresholds were superseded in 2013 by 'TM52: Limits of Thermal Comfort: Avoiding Overheating' to reflect adaptive comfort scenarios (CIBSE 2006, 2013). The former were used to allow simple comparison with design stage analysis. As previously stated, the occupied hours for the office spaces were set as between 8 am and 6 pm, Monday to Friday. The rooms have also been assessed using the updated TM52 metrics to demonstrate the impact of introducing adaptive comfort ranges. Based upon international research, adaptive comfort levels have been introduced to account for peoples' tolerance of warmer internal temperatures during cumulative periods of warm external temperatures (CIBSE 2013). The TM52 document provides a full guide to the three assessment criteria.

Data Analysis

The first two charts in Figs. 15.3 and 15.4 illustrate the percentage of occupied hours exceeding the two temperature thresholds in the occupied rooms. Room numbers beginning with the number 8 are on the 8th floor, with number 9 on the 9th

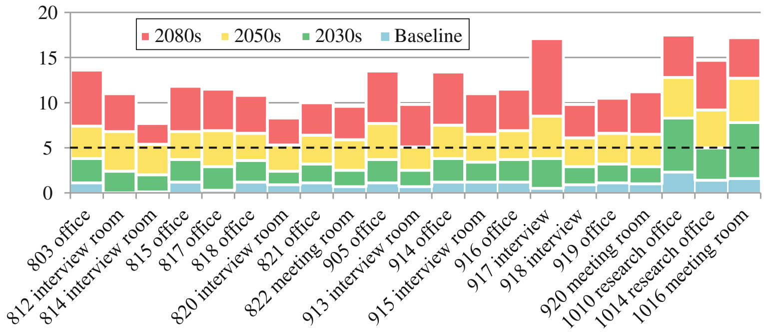

Fig. 15.3 Percentage of occupied hours exceeding 25 °C in alternative future climate scenarios

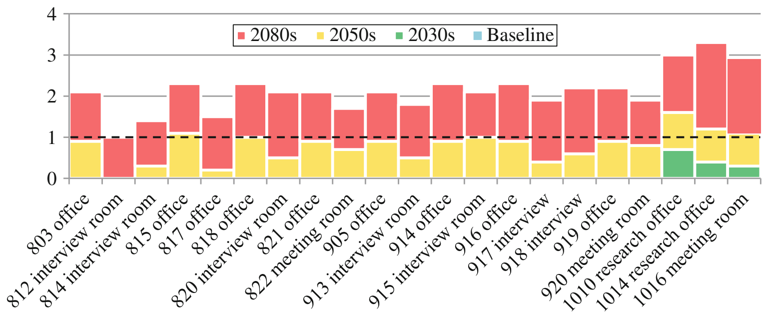

Fig. 15.4 Percentage of occupied hours exceeding 28 °C in alternative future climate scenarios

floor and with number 10 on the 10th floor. Forecast overheating for the baseline scenario does not exceed either threshold for overheating suggesting that the existing natural ventilation strategy is fit for purpose assuming that building occupants open windows as defined in the model schedule.

Intuitively, it would be assumed that the baseline year indicates current performance. This weather file was created using data collected between 1961 and 1990. The research team that produced the weather files found that there was little difference between the average 1961–1990 weather conditions and those found in the CIBSE files based upon weather data collected between 1983 and 2004 suggesting that average weather conditions have changed little during this time (Eames et al. 2011). For the purposes of this analysis, the baseline year will be taken to represent current conditions as it is closer to the 2004 date than 2030s.

In the 2030s medium scenario, only the occupied rooms on the 10th floor exceed the 5 % threshold. It is the same rooms that exceed the 1 % threshold for hours above 28 °C. These results suggest that the current ventilation strategy would avoid excessive overheating in the medium emissions scenario within the majority of rooms analysed. In the projected climate conditions for the 2050 scenario, the rooms begin overheating much more frequently. All rooms exceed the 5 % of hours above 25 °C thresholds but only four rooms exceed the 28 °C in the medium emission scenario. Both thresholds are exceeded by all rooms in the 2080s scenario. Based upon life expectancy of building components and the internal twenty-five year life span used by Leeds Beckett University, the building would go through another retrofit phase during the 2050s which is considered in the final subsection of data analysis.

Adaptive Comfort Metrics

To provide a comparison with the absolute overheating metrics utilised during the early design stage for the current building retrofit, overheating has been analysed using the 2013 CIBSE TM52 criteria. In the table, the C1, C2 and C3 abbreviations refer to the overheating criteria defined in TM52. Criterion 1 measures the number of hours that exceed a comfort threshold; Criterion 2 sets a limit for exceeding a daily weighted limit which takes account of the severity of overheating rather than frequency; and Criterion 3 sets an absolute value between internal and external temperature which cannot be exceeded. A full explanation of these metrics and the research that has informed them can be found in TM52 (CIBSE 2013). The results from this analysis are visualised in Fig. 15.5.

To meet the revised standards of adaptive thermal comfort, a room must pass at least two out of the three overheating criteria. It is only the values shaded in red that fail any of the criteria in Fig. 15.5. There are eight rooms that fail one of the criteria in the 2050s meaning that all rooms would be deemed to not be at risk of

	Baseline			2030s			2050s			2080s		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
822 meeting room	0	0	0	0	0	0	0.3	2.5	1	0	0	0
818 office	0	0	0	0	0	0	1.3	14.5	4	0.4	3	1
817 office	0	0	0	0	0	0	0	0	0	0	0	0
815 office	0	0	0	0	0	0	1.4	15.5	4	0.4	3.5	2
814 interview room	0	0	0	0	0	0	0	0	0	0	0	0
812 interview room	0	0	0	0	0	0	0	0	0	0	0	0
820 interview room	0	0	0	0	0	0	0.1	1	1	0	0	0
821 office	0	0	0	0	0	0	0.9	10	3	0.1	1.5	1
803 office	0	0	0	0	0	0	0.6	8.5	2	0	0	0
913 interview room	0	0	0	0	0	0	0	0	0	0	0	0
915 interview room	0	0	0	0	0	0	1.3	12.5	3	0.3	3	1
916 office	0	0	0	0	0	0	1	12	3	0.2	3	1
917 interview	0	0	0	0	0	0	0	0	0	0	0	0
918 interview	0	0	0	0	0	0	0.1	1.5	1	0	0	0
919 office	0	0	0	0	0	0	0.8	10	3	0.1	1	1
920 meeting room	0	0	0	0	0	0	0.3	2.5	1	0	0	0
905 office	0	0	0	0	0	0	0.4	4	1	0	0	0
1010 research office	0	0	0	0	0	0	0.3	3.5	1	0	0.5	1
1014 research office	0	0	0	0	0	0	0.5	5.5	2	0	0	0
1016 meeting room	0	0	0	0	0	0	0.1	1	1	0	0	0
914 office	0	0	0	0	0	0	0.5	7.5	2	0.1	2	1

Fig. 15.5 Rooms failing the TM52 criteria for existing buildings

overheating. Data presented in Fig. 15.5 provide a good demonstration of how the adaptive comfort criteria correlate with cumulative periods of warmer temperatures. It can be seen from these results that overheating in the context of adaptive comfort tolerances is predicted to fall during the 2080s when compared to the 2050s. Although this may seem counter-intuitive, a considerable amount of research has been completed across Europe which supports the theory of adaptive comfort increasing tolerance to warmer periods of weather (CIBSE 2013).

Future Retrofit

A retrofit package designed to mitigate overheating in the future climate scenarios was applied to the model. In reference to the design and service lives of building elements, it is likely that only the windows will need to be replaced in the time frame that would help to mitigate overheating in the 2050s. Opening windows are obviously a crucial aspect of the natural ventilation strategy. Retrofit windows have been specified with a high reflective coating and a wider opening angle (30°). Night time purge ventilation has also been introduced using the same opening thresholds; this may however require the installation of automated actuator systems. Lighting would be due for replacement by the 2050s but LEDs were installed in the current retrofit so have not been included in this upgrade as they are already very efficient. As the top floor rooms overheat more frequently, external insulation and a high reflective roof covering have also been included. This would however represent an additional cost as the existing roof covering would not be due for replacement as part of the natural refurbishment cycle. Predicted overheating following retrofit is illustrated in Figs. 15.6 and 15.7. The diagonally hatched bars represent the predicted overheating without retrofit.

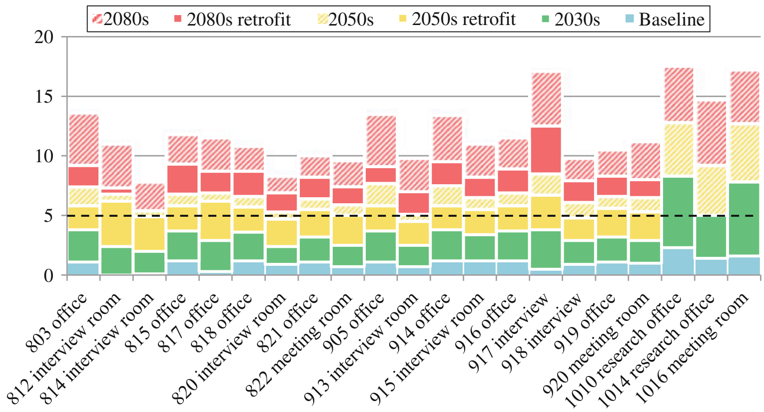

Fig. 15.6 Percentage of occupied hours exceeding 25 °C following retrofit

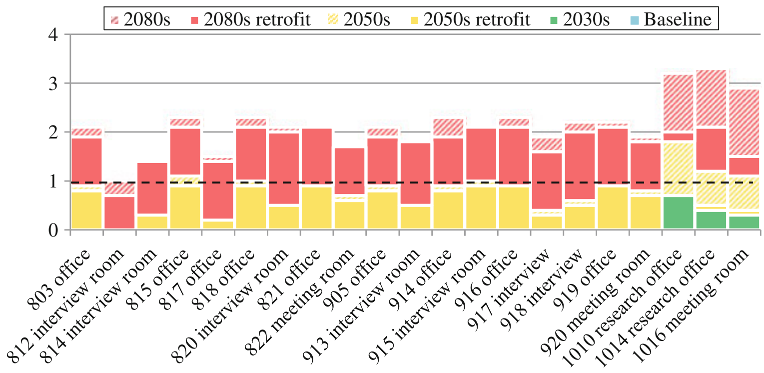

Fig. 15.7 Percentage of occupied hours exceeding 28 °C following retrofit

As can be seen from the results in Fig. 15.6, potential overheating during the 2050s can be largely mitigated through the proposed retrofit changes although many of the rooms marginally exceed the threshold for 25 °C. The 1 % threshold at 28 °C is avoided entirely following retrofit. Overheating in the 10th floor rooms is actually reduced below the level found in the 2050s. It is however not possible to avoid overheating through these measures in the 2080s scenario. The building may be reaching the end of its service late this far into the future so further upgrades would not be relevant. It is only through reducing internal heat gains from equipment that overheating in the 2080s can be avoided. The energy consumption (and therefore internal heat gain) from ICT equipment has been forecast to fall but this could not be relied upon as historic trends have generally seen a rise in this consumption (Jenkins et al. 2009). When using the adaptive comfort criteria to assess overheating, all rooms fall below the thresholds for the 2050s and 2080s meaning that overheating under these metrics is completely avoided.

Conclusions

The research presented here supports a number of findings from other case studies completed in this field. The most holistic of these is the need for design teams and clients to achieve a clear understanding of the simulation methods and data inputs, particularly the simulation weather files. There are a range of morphed future weather files available for this type of application. There are a set of files based upon the CIBSE regional data for both the UKCP02 and UKCP09 projections. The files used here are based upon the UKCP09 projections but are morphed from different baseline data. As already stated, the researchers who produced the Prometheus files found little difference between their own and CIBSE's baseline data. However, as shown here, there is a considerable difference between predicted overheating using the baseline Prometheus and CIBSE files for Leeds. This could be an isolated case but requires further investigation. It does however emphasise the importance of understanding the model input data and the options available. This also extends to the emission scenarios and probabilistic predictions; the worst case scenarios have not been examined in this paper.

Analysis of the results in this work validates the natural ventilation strategy that forms part of the current refurbishment work. Results show that no excessive overheating should be experienced under current climatic conditions but suggest that the facility management team should pay close attention to the 10th floor office space as this may overheat during the 2030s. It would be prudent to monitor internal temperatures in this space and, if possible, the window opening frequency in as many areas as is feasible. It is important to remember that the ventilation strategy relies on occupants opening windows in certain conditions. It may be possible to further mitigate overheating in the 10th floor rooms by using localised fans which highlights another limitation in the simulation software which cannot mimic these effects.

In terms of a retrofit and investment strategy, these results indicate that there would be no financial incentive to alter the current retrofit strategy due to the majority of spaces not significantly overheating until the 2050s. Results show that potential overheating should be reassessed when the next phase of refurbishment is due. Any necessary upgrades can then be tailored to the specific building and, most cost effectively, to the specific rooms at the greatest risk of overheating. There is also a case for incorporating assessment of climate trends as part of an overall retrofit planning strategy, especially with a large diverse estate such as those owned and operated by universities. If climate trends follow those predicted then more confidence can be placed in the morphed simulation weather data and more robust financial analysis can be produced using the model outputs. Future work in this field could incorporate investment appraisal techniques such as Net Present Value or Internal Rate of Return analysis that take account of the time-value of money. This type of analysis can help to evaluate whether it is more financially viable to future-proof conditioning strategies or to reassess thermal performance further into a building's retrofit cycle.

It is of particular note that very few of the rooms exceed the adaptive comfort metrics used to assess overheating, even in the future climate scenarios. This supports the introduction of these measures as they will allow for more flexible passive design solutions to be utilised in both new-build and major retrofit projects. There is however a significant difference between results calculated using the absolute and adaptable metrics which further supports on-going environmental monitoring in at risk spaces.

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Part V
Building and Infrastructure

Chapter 16
Thermally Modelling Bio-composites with Respect to an Orientated Internal Structure

Joe Williams, Mike Lawrence and Pete Walker

Abstract To wean us from our destructive fossil fuel dependency we must produce buildings that are better in both their occupied energy use and their embodied energy content. Bio-composites formed from cellulose aggregates and binders have a low embodied energy and provide an excellent balance of insulation and thermal inertia; when used correctly they can produce efficient and healthy buildings with considerably lower embodied energy than traditional alternatives. These materials are however naturally variable depending on their production method and this has hindered their uptake in a culture of standardised, performance-based codes. In order to gain wider use, it is important that we can model their behaviour representatively. An important, overlooked factor in the behaviour of these materials is the internal structure on a macro scale, in particular the orientation and distribution of the aggregate. As the particles have a defined aspect and orientated structure themselves, the orientation of the particles within the composite may have a considerable influence on the hygrothermal properties. While this is a concept widely acknowledged, the internal structure of bio-composites has not been characterised or adequately incorporated into behavioural models. This work implements a novel method of material characterisation based on digital image analysis to classify the internal structure of specimens of hemp-lime. The results indicate that the internal structure is highly anisotropic with strong directionality in the hemp particles governed by the construction process. A parameter corresponding to degree of directionality has been developed together with a thermal conductivity model based on a weighted average between bounding conditions.

Keywords Bio-composites · Image analysis · Thermal conductivity

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Introduction

Buildings are a major contributor to emissions and energy use, both in their embodied content and in their service life through occupation; in the UK buildings account for 50 % of the total carbon dioxide emissions (Department for Business 2010). This is seen both here and around the world as an area of significant saving potential. The materials used in construction and retrofit of buildings are critical as not only do they affect the quality of the indoor environment but also have a large influence on how well the building will perform over its life, the energy cost of its creation and how readily it can be decommissioned and recycled.

Hemp-lime, also referred to as hempcrete and lime hemp is the most widely known bio-composite concrete. It is produced by mixing chopped hemp stalk (known as shiv), powdered lime binder and water to form a loose granular mix that is cast into shuttering (Fig. 16.1) or sprayed against a substrate. Once dried and set the resulting material is a low strength lightweight insulation with a modest U-value for standard 200 mm wall thicknesses in the order of 0.36 W/m^2K (Bevan et al. 2008). The unique porosity of hemp-lime and the interaction this has with moisture produces an effective thermal mass that can dampen the effect of external temperature fluctuations and reduce space heating and cooling needs if employed correctly and allows it to outperform other comparable constructions in dynamic conditions (Evrard 2006, 2008; Lawrence et al. 2011; Le Tran et al. 2010). In addition, hemp-lime buffers moisture, improving the internal environment (Evrard 2006), captures VOCs and provides all of this at a net absorption of around 36 kg of CO_2 per square metre of waling (Ip and Miller 2012).

Despite the benefits of hemp-lime, it is not yet widely used. The construction industry rightly considers hemp-lime as a variable product, requiring special training and carrying associated risk. When cast on site has a very slow drying time that is worsened in wet climates; it is all but impractical to cast hemp-lime in the UK during the winter months (Allin 2012; Harris et al. 2009; Skandamoorthy and Gaze 2013). In addition to this it is hard to accurately specify and design as performance varies significantly with mix formulation and method of application. To overcome this, prefabrication is seen as an important tool as it removes a lot of the problems associated with onsite work (Walker and Thomson 2013) and has

Fig. 16.1 Stages of hemp-lime production: Hemp shiv, powdered lime binder, cast wet material, resultant dried material

certainly worked for other natural materials such as straw and sheep's wool, where prefabrication has allowed for a certified, low risk products. In order to produce the most competitive prefabricated hemp-lime product, or bring more consistency to the performance of hemp-lime cast on site, it is important that we understand the behaviour of the material and can accurately predict its performance.

Thermal conductivity is a crucial performance criterion for any insulation. Efforts have been made to predict the thermal conductivity of hemp-lime based on its constituents with some success (Arnaud 2000; Pierre et al. 2014). A large perceived gap in our understanding of hemp-lime however is the impact of the macro scale structure formed as a result of the casting or spraying process. It is often acknowledged in the literature that hemp-lime is anisotropic (Elfordy et al. 2008; Magniont et al. 2012; Nguyen et al. 2009; Tronet et al. 2014) but this anisotropy has not been classified and thus not properly incorporated into our understanding of performance. This is slowing the development of the material and hindering our ability to predict the properties.

In this work, a novel image analysis method to classify the macro structure of bio-composites has been employed. This describes and numerically classifies the degree of orientation within the structure allowing links to be drawn directly to the method of forming. A model of thermal conductivity has been proposed that incorporates the observations and accounts not only for the nature and ratio of the constituent materials but also the nature of the internal structure. The internal structure of hemp-lime.

There are already several established relationships between the mix design of hemp-lime and the thermal properties. The ratio of hemp to lime used in the mix has been shown to be critical to both the structural and the thermal properties of the material with a higher binder content improving the strength but increasing the density and thermal conductivity (Arnaud and Etienne 2012; Collet and Prétot 2014; Magniont et al. 2012; Murphy et al. 2010). In addition it has been shown that compaction of the mix has a similar effect as it consolidates the particles, removing voids and producing a stronger but more thermally conductive material (Elfordy et al. 2008; Nguyen et al. 2009). The nature of the constituents, grading of shiv and the formulation of the binder, has also been examined (Benfratello et al. 2013; Hirst et al. 2010; Murphy et al. 2010). Generally the effects of changing these was found to be of significantly smaller magnitude than those observed for changes in binder ratio and compaction and indicates that the interaction between the components may govern the overall properties rather than the properties of the individual constituents. A stronger lime binder for example will not necessarily increase the compressive strength and can even be shown to reduce it (Hirst et al. 2012).

Hemp shiv particles are generally of an elongated form due to the nature of the plant stalk and the method of harvest (Bevan et al. 2008). Most of the literature attributes directionality within the internal structure to the way these particles align in the forming process. In the case of cast hemp-lime walls, it is considered that the particles of shiv will tend towards the horizontal plane as material is placed and compacted downward, with sprayed, that they will tend towards the plane perpendicular to the direction of projection (Duffy et al. 2014). It was noted by

Gross (2013), that hemp-lime composites cast to the same mix specification and the same direction, but tested structurally in different orientations, not only exhibit a different failure strength but also a different failure mode.

As the layout of the shiv structure will determine the distribution of the air voids within the material, it follows that the thermal conductivity of hemp-lime will not be isotropic. Nguyen et al. (2009) considered heavily compacted samples of hemp-lime made using a range of hemp/binder ratios and compaction levels. Thermal conductivity was measured in two directions: parallel to and perpendicular to the compacting force and the results showed a consistently higher value of thermal conductivity perpendicular to the compaction direction by a factor of almost one and a half. A perceived visual directionality of particles was also noted.

A study by Pierre et al. (2014) considered thermal conductivity of sprayed hemp-lime samples in two directions, parallel and perpendicular to the direction of projection, and also found a discernible difference but of a lower magnitude than Nguyen. The work goes on to apply Krischer's model of thermal conductivity to model the behaviour. Krischer's model proposes thermal conductivity of a mixture can be described by a weighted harmonic mean of two cases where the components are in series and parallel respectively, and the weighting factor relates to the material structure (Carson and Sekhon 2010; Krischer and Kast 1978). The model was accurate at predicting the experimental results and demonstrates the appropriateness of this type of model. It should be noted that in this study the weighting factor used, as well as two other material parameters, were estimated from fitting the model to the thermal conductivity data. As a result the weighting factor was determined to be the same in both directions while the porosity was found to alter; a result that by inspection not representative.

The nature of hemp shiv particles means that the traditional aggregate grading method of sieving is inappropriate. To overcome this the use of digital image analysis has been adopted by many to allow a more representative form of grading to be conducted (Arnaud and Etienne 2012; Glé et al. 2013; Nguyen et al. 2009). The method entails the imaging of the two dimensional elevation of arranged hemp particles using a flatbed scanner. The images are processed and particle analysis software is used to identify and classify the particles allowing the production of frequency grading of both size and shape. Image analysis methods have already been used in situ on other composites like asphalt (Bessa et al. 2012; Coenen et al. 2012; Roohi Sefidmazgi and Hussain 2014) and naturally orientated materials like soils (Shi et al. 1998) in order to determine the distribution of aggregates within their makeup. By doing this it has been possible to classify the internal structure of these materials and link it to both the forming process and the resultant physical properties.

In this study, image analysis is used to classify the internal structure of hemp-lime. The findings are then incorporated into a modified weighted harmonic mean model of thermal conductivity, where the critical weighting factor is representative of the structure. This is an improvement on existing models as it accounts for the materials manufacture and orientation as well as the mix ratio and environmental conditions.

Methodology

Nine 150 mm cube, specimens of hemp-lime were produced using Tradical® HB blended binder and construction grade hemp shiv produced in the UK. All specimens were produced using a small pan mixer by first mixing the binder with water to form slurry before adding the hemp and mixing briefly until evenly combined and transferring to moulds. Six specimens were produced using a standard "wall mix" of 21 % hemp, 36 % binder and 43 % water by weight. Half of these were lightly tamped with the other tamped firmly to use 20 % additional material. The target dry density for the samples was 400 and 330 kg/m^3, respectively. The other three samples were produced using a lower binder ratio of 1:1.7 and again lightly tamped to give a target density of 275 kg/m^3. The samples were all conditioned at 20 °C and 60 % relative humidity for a minimum of 28 days.

Image Acquisition

To produce the sections for imaging, two specimens from each mix were cut into six 25 mm thick slices using a fine-toothed band saw. One specimen was sliced parallel to the direction of compaction, YZ plane, and one was sliced perpendicular to the direction of compaction XY plane (Fig. 16.2). To enhance the contrast of the components a pigment was added to the lime giving it a distinctive hue and a coloured resin was used to fill surface voids. The resin also enhances the durability of the samples allowing the faces to be sanded to a smooth finish, thereby removing any marks made by the cutting process that could be misidentified by the software. Image collection from the fully prepared samples was conducted using a flatbed scanner at a resolution of 2400 dpi producing images of the central 115 mm by 115 mm square of each face to ensure any impact of the mould edges were minimised.

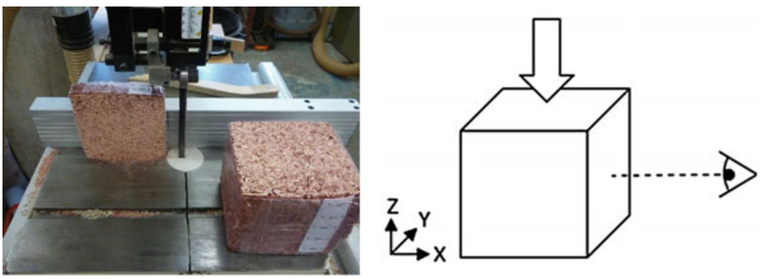

Fig. 16.2 The sectioning of a pigmented hemp-lime sample using a band saw, the reference axis used where the arrow indicates the direction of compacting force

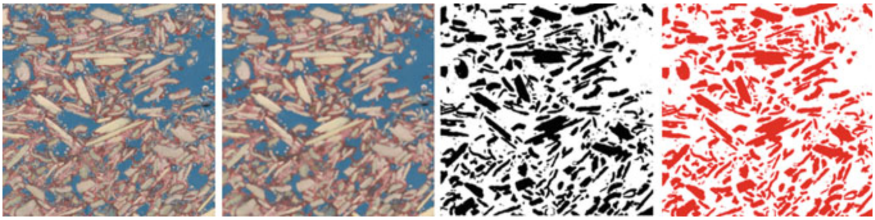

Fig. 16.3 The stages of image enhancement: scanned image, median filtered, threshold filtered, opened

Image Enhancement

Image enhancement was used to aid the correct identification of particles utilising a similar set of processes as used for other materials (Bessa et al. 2012; Coenen et al. 2012; Roohi Sefidmazgi and Hussain 2014) as well as for hemp grading (Arnaud and Etienne 2012). A median filter with 20 px radius was applied to remove anomalies and noise. A colour hue threshold filter of 15<hemp<50<air<230 was applied to segregate out the components and convert the image into binary. Finally, three iteration of opening algorithm were used to clean the edges of the binary image and remove any noise produced in the threshold operation. The stages of the process are shown in Fig. 16.3. The values used were those visually judged to give the most reliable identification of particles out of a total of 288 considered permutations.

Image Analysis

Image analysis was conducted using the program ImageJ and the inbuilt measure and particle analysis tools. The measure tool was used to determine the percentage area of the component parts while the particle analysis tool was used to identify all discrete binary objects, representing particles of shiv, and calculate a selected set of properties for them. The Feret Angle was used to classify a particle orientation and is defined as the angle to the horizontal that the Feret Diameter makes, where the Feret Diameter is the longest line possible between two perimeter pixels. To produce a useable output from the particle data, it was necessary to group the data to produce a statistical representation of particle orientation for the slice. Groupings of 10 degrees were used as it has proven to provide good results for similar analysis of other materials (Shi et al. 1998).

Results

Table 16.1 gives the grouped frequency distribution of particle orientation for all six specimens analysed. A clear degree of orientation was found in all three mix variations with all the specimens sectioned in the ZY plane exhibiting a strongly biased distribution towards the horizontal. Transversely all the specimens sliced in the XY plane were found to have a much more even distribution. Figures 16.4 and 16.5 show the cumulative grouping of the 330 target density samples sliced in the XY plane and YZ plane respectively and demonstrates the striking difference between the two orientations.

In order to easily compare the frequency data, second order polynomials were fitted to the distributions to estimate the form of the continuous distribution. The fitted polynomials for all three samples sliced in the ZY plane are shown in Fig. 16.6. The degree of orientation varies with degree of compaction and more broadly density, with denser samples showing a higher degree of directionality.

In addition to the degree of orientation, the volumetric ratios of components observable at the macro scale was also found to vary with density. Table 16.2 shows the average volumetric percentage of the components in all six specimens and indicates, as would be expected, that the volumetric ratio of air observed at this scale decreases with increasing compaction and density.

Modelling

A theoretical model of thermal conductivity that accounts for the anisotropic structure has been developed. Krischer's model (Krischer and Kast 1978) proposes the conductivity of a mixture, λ (Eq. 16.1), can be described by the weighted harmonic mean of two situations in which the constituent materials are aligned, in parallel, λ_p (Eq. 16.2), and in series, λ_s (Eq. 16.3), respectively. These cases can be thought of as the theoretical maximum and minimum bounds for the given ratios of the components; the weighting factor, f, therefore accounts purely for their arrangement and structure (Carson and Sekhon 2010). If r_h, r_l, r_w, r_a and λ_h, λ_l, λ_w, λ_a are the volumetric ratios and thermal conductivities of hemp, binder, water and air respectively:

$$\lambda = \frac{1}{\dfrac{f}{\lambda_p} + \dfrac{1-f}{\lambda_s}} \tag{16.1}$$

$$\lambda_p = r_h\lambda_h + r_l\lambda_l + r_w\lambda_w + r_a\lambda_a \tag{16.2}$$

$$\lambda_s = \frac{1}{\dfrac{r_h}{\lambda_h} + \dfrac{r_l}{\lambda_l} + \dfrac{r_w}{\lambda_w} + \dfrac{r_a}{\lambda_a}} \tag{16.3}$$

Table 16.1 The frequency distribution of shiv orientations for 3 mixes observed in 2 directions

Specimen ID	Frequency as a percentage of the total								
	0 ≤ X ≤ 10	10 ≤ X ≤ 20	20 ≤ X ≤ 30	30 ≤ X ≤ 40	40 ≤ X ≤ 50	50 ≤ X ≤ 60	60 ≤ X ≤ 70	70 ≤ X ≤ 80	80 ≤ X ≤ 90
275 YZ	10.07	9.97	6.99	6.40	4.28	3.24	2.31	1.97	1.44
330 YZ	10.75	11.84	9.74	6.38	4.51	3.01	2.67	1.76	1.35
400 YZ	11.99	13.73	9.83	7.14	5.00	3.24	2.09	1.64	1.07
275 XY	3.91	6.29	6.38	5.56	5.91	5.94	6.08	6.10	3.82
330 XY	4.04	7.14	7.03	6.80	5.76	5.70	5.40	5.32	3.05
400 XY	3.68	6.24	6.22	6.27	6.33	6.56	6.17	6.69	4.00
Specimen ID	90 ≤ X ≤ 100	100 ≤ X ≤ 110	110 ≤ X ≤ 120	120 ≤ X ≤ 130	130 ≤ X ≤ 140	140 ≤ X ≤ 150	150 ≤ X ≤ 160	160 ≤ X ≤ 170	170 ≤ X ≤ 180
275 YZ	1.57	2.47	2.63	3.45	5.71	6.96	9.22	10.84	10.47
330 YZ	1.35	1.48	1.85	2.97	3.70	6.19	9.01	10.34	11.09
400 YZ	0.93	1.14	1.78	2.38	3.55	4.66	7.78	10.66	11.38
275 XY	3.98	6.15	5.96	6.17	5.72	5.98	6.60	5.70	3.75
330 XY	3.61	5.09	5.28	6.02	5.47	6.28	6.72	6.94	4.33
400 XY	3.95	5.99	5.85	5.47	5.11	6.17	5.95	5.51	3.84

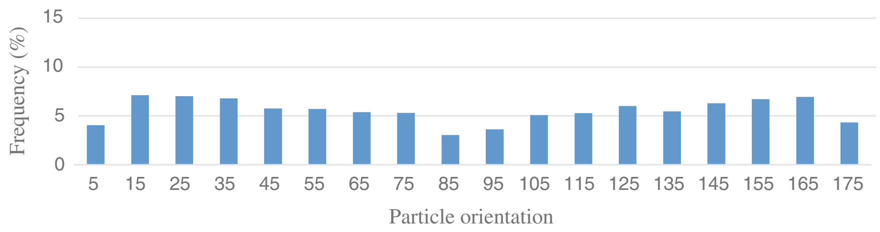

Fig. 16.4 Frequency distribution of shiv orientations of the 330 kg/m^3 target density sample sectioned in the XY axis

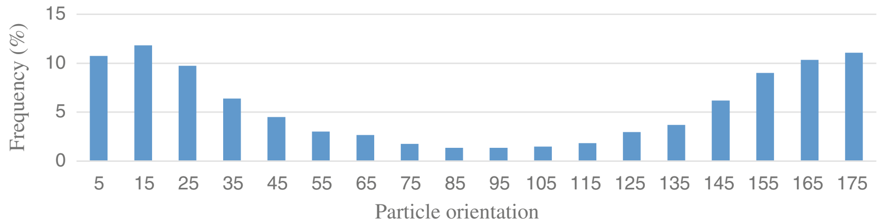

Fig. 16.5 Frequency distribution of shiv orientations of the 330 kg/m^3 target density sample sectioned in the YZ axis

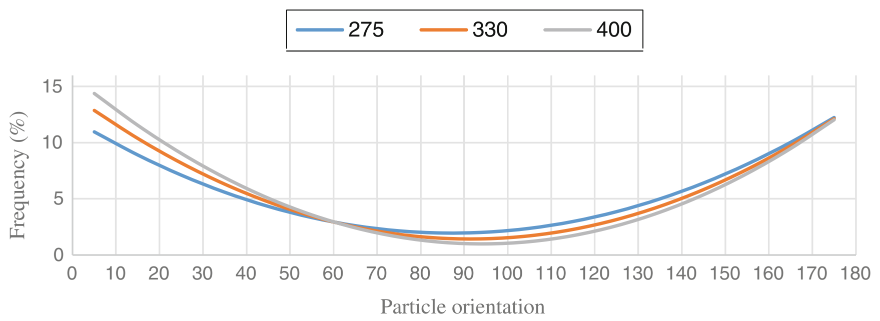

Fig. 16.6 Frequency distribution of shiv orientations of specimens sectioned in the YZ axis

Through consideration of the internal structure, it is proposed that f should be dependent on the degree of orientation and connectivity of the hemp and binder observed at the macro level: an increase to either logically produce a tendency towards a parallel arrangement. It is proposed that f is therefore the function of two indexes I_1 *and* I_2 that are derived from image analysis of any plane parallel to the axis of consolidation force, Z (reference Fig. 16.2). A linear relation is proposed for both variables where a, b and c and constants:

Table 16.2 The average volumetric percentages of components air, hemp and lime observable at the macro scale

Specimen ID	Percentage of observable voids	Percentage of observable hemp	Percentage of observable binder
275 YZ	61.72	25.41	12.88
330 YZ	31.04	35.34	33.62
400 YZ	22.50	40.76	36.74
275 XY	69.58	20.28	10.14
330 XY	38.92	34.23	26.85
400 XY	23.63	44.39	31.98

$$f = aI_1 + bI_2 + c \tag{16.4}$$

It is proposed that index I_1, reflective of orientation, should be the ratio of particles tending towards a parallel with heat flux out of the total observed and so generally could be considered to have one of two values depending on the direction of heat flux. For heat flux parallel to the Z axis, where n is the number of particles with an orientation between the stated bounds and N is the total number of observed particles:

$$I_{1Z} = \frac{45 < n \leq 135}{N} \tag{16.5}$$

For heat flux perpendicular to the direction of compaction, XY plane, only a half of the observed particles should be considered, as the compaction only influences the probability of particles tending to the Z axis and thus there is still a random distribution of orientations in the XY plane as observed in the results, Fig. 16.4, therefore:

$$I_{1XY} = \frac{1 - I_{1Z}}{2} \tag{16.6}$$

For a given material, density varies in proportion to the volume of air voids and this is reflected in the model through the volumetric ratio of the components. The voids however can be considered at two scales: the macro (visible caused by spaces between particles), and the micro (naturally occurring within the hemp and lime) and the ratio of these alters the structure and critically the connectivity between the solid components and so should be reflected in the weighting factor. It is therefore proposed that the index I_2, should be the ratio of observed air voids out of the total area:

$$I_2 = \frac{A_{air}}{A_{total}} \tag{16.7}$$

Through linking the weighting factor f to the two indexes the model is able to reflect not only the mix ratio and moisture content of the sample, but also the methodology of production and the anisotropic nature. Calibration is however required in order to find the nature of the function in Eq. 16.4 through fitting to experimental results.

Discussion

The image analysis, conducted in two directions with respect to consolidation force, provides clear evidence that the forming process has a distinct impact on the structure of the material at the macro scale. This is consistent with the theories within the literature that propose any applied force will encourage particles to rotate towards a perpendicular plane. This work only considered a few examples of cast hemp-lime and so has not as yet evaluated whether this is also true of sprayed material or material formed through other methods of forming. It is however considered likely that a similar phenomenon will be observed.

A comparison of the 330 kg/m^3 target density samples and the 400 kg/m^3 target density samples, formed using the same mix constituents but different degree of compaction, indicates that an increased amount of compaction does increase the extent of orientation found as well as the density. It is possible to then infer from the model that compaction would increase the global thermal conductivity but also increase the disparity between the thermal conductivity measured parallel and perpendicular to the compaction. This is supported by the literature where two independent studies considering different densities found a distinct difference in the discrepancy between the thermal conductivity considered in the two directions (Nguyen et al. 2009; Pierre et al. 2014).

A comparison of the 330 kg/m^3 target density samples and the 275 kg/m^3 target density samples, produced to differing mixes but the same perceived level of compaction, was found to produce a similar change in degree of orientation. It is possible that an increase in the binder content encourages orientation through providing more bonds between particles and increasing self-weight and thus natural compaction. While this may account in part for the results, it is more probable that the degrees of compaction were not even. Compaction was controlled by altering the amount of fresh material used to achieve a target dry density. The target densities and mixes were taken from the standard densities for the mixes when used in industry and not from test specimens compacted with the same force; it is therefore not possible to claim that the two sets were compacted to the same degree. By measuring the wet mix bulk density without any compaction the true level of compaction may be found and compared for mixes of differing design in the future tests.

The volumetric ratios of visible components found in the image analysis indicate how the level of macro scale air voids varies with consolidation. This inherently indicates that as the material is consolidated the ratio of macro scale air voids to micro scale air voids changes significantly, something that is not reflected in the measure of porosity or density and is likely to be influential in the behaviour of the material. The results are supported by the findings of Cerezo (2005) who produced graphical representations of the constituent volume ratios of several densities of hemp-lime.

The model used for thermal conductivity, an adapted version of Krischer weighted harmonic mean, is based on established principles from other areas and has already been adapted to hemp-lime with a good degree of success. The model proposed here builds on the work of Pierre et al. (2014) but critically allows all the key parameters to be obtained from measurable properties that can be linked to the construction process, making it a potential design tool. In addition, the model fully accounts for the anisotropic nature of the material and the broader nature of the macrostructure by linking the weighting parameter, acknowledged as a reflection of the internal structure, to indexes that classify the macro scale structure of the material. The model is therefore able to account for the entire range of mix parameters, the moisture content, the forming process and the direction of heat flux.

Currently the model is theoretical only and a large amount of additional work will be required in order to calibrate it and determine its effectiveness. The calibration is needed to determine the nature of the function in Eq. 16.4 that links the dimensionless indices describing the structure to the weighting factor that accounts for structure in the model. Until this has been completed it is unknown if the model will be successful. However, it is evident from the results of image analysis that there are distinct variations in the macro scale structure that must be accounted for. If the model is found to successfully represent the data, it could provide a valuable tool for improving bio-composite concrete design and may provide a springboard towards the improved modelling including other properties.

Conclusion

A novel approach to classifying bio-composites using digital image analysis was developed and used on samples of hemp-lime formed with three mix variations. A high degree of orientation of the hemp particles was observed with a clear tendency towards alignment in planes perpendicular to the direction of consolidating force. A simple numerical parameter extracted from the image analysis, related to the degree of orientation within the material, was used in a simple but versatile model of thermal conductivity. The model requires minimal data input and accounts for wide range of variations thus could be used to tailor and optimise the composition of the material to meet requirements. The importance of the macrostructure in regards to the global material properties is clearly evident and will be important in taking the material forward and realising its potential.

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Chapter 17
Strength Related Geotechnical Testing of Lateritic Soil Prior to the Application of Microbially Induced Calcite Precipitation Treatment

Anthony J. Smith, Martin Pritchard and Alan Edmondson

Abstract Microbially induced calcite precipitation (MICP) is an emerging solution to issues faced by geotechnical engineers that has yet to turn its attention to strengthening fine particle clays, including lateritic soil. The lateritic clays found in tropical regions have long been used as a low cost construction material for earth roads linking rural village clusters. However, earth roads are exposed to prolonged tropical wet seasons and become inundated with rainwater, deteriorating their ability to bear traffic. MICP soil strengthening may provide a low cost, sustainable solution that would allow earth roads to remain usable. This paper presents the first phase of geotechnical strength related tests undertaken on a lateritic soil, prior to any MICP treatment, including plasticity index, Proctor compaction, Californian bearing ratio (CBR) and unconfined compressive strength (UCS). They have been undertaken to provide the baseline data against which future MICP treated samples can be assessed. The results indicate that the lateritic sample was a low plasticity clay, which may be prone to turbulent shearing when past its semisolid/plastic limit of 12 %. When tested at 12.5 % moisture content, the values of CBR and UCS fell by 96.4 and 87.4 %, respectively, when compared to samples tested at 7.5 % moisture content.

Keywords Lateritic soil modification · Microbially induced calcite precipitation · Rural earth road

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Introduction

Lateritic soils are found most often in regions located between the Tropics of Cancer and Capricorn (Tardy 1997), regions often associated with developing areas (e.g. equatorial South America, Southeast Asia, sub-Saharan Africa and subcontinental India). Developing areas commonly use in situ lateritic soil material to construct low cost wearing surfaces for rural road networks (Thagesen 1996). Lateritic earth roads in the tropics have to endure the wet season that is driven by the north–south migration of the intertropical convergence zone (ITCZ). Exposure to the heavy rainfalls brought by the ITCZ soon leads to the drainage capacity of earth roads being exceeded, and the soil material becoming saturated. The resultant reduction in soil shear strength translates into a reduction in the bearing capacity of the soil stratum. The bearing capacity of a soil is its ability to support vertical loads without succumbing to shearing in the active/radial zones (Lee and Eun 2009). Additionally, rainwater run-off erosion and the force from tyres of passing vehicles cut grooves into the weakened wearing surface that remain after the roads have dried out. Soil damage also occurs when the cyclical wet and dry seasons cause the soil to swell, followed by shrinking and cracking, which accelerates the disintegration of the wearing surface. The total impact of the annual wet seasons can lead to earth roads becoming impassable to vehicles for many months, impinging on the ability of the people of rural areas to increase the value of their capital assets. Hine and Rutter (2000) defined five types of capital assets available; natural (e.g. harvested or mined goods), social (e.g. access to kin/labourers for assistance), financial (e.g. seeking more favourable market prices elsewhere) and human and physical (e.g. access to welfare, healthcare and education services). Infrastructure research has investigated multiple soil modification techniques to improve rural earth road networks so as to further the prosperity of its rural populous.

MICP as a Modification Technique

MICP treatment of soil for geotechnical applications is an emerging area of civil engineering research (Ivanov and Chu 2008). In MICP, ureolytic soil microbes supplied with water (H_2O) and urea $CO(NH_2)_2$ excrete molecules of carbonate (CO_3^{2-}) into the soil pores. These molecules ionically bond with calcium ions (Ca^{2+}), initiating the precipitation of calcium carbonate ($CaCO_3$) crystals between soil particles.

The ability of ureolytic bacteria to initiate $CaCO_3$ precipitation, as per Eq. 17.1, arises from their possession of the natural catalysing enzyme urease (Ng et al. 2012). Precipitated $CaCO_3$ crystals act as a cementation agent between soil particles, increasing the shear strength of the soil as a whole. The cementation also allows any stresses to be more evenly distributed through the soil matrix, raising the amount of force required to initiate a failure.

$$CO(NH_2)_2 + Ca^{2+} + 2H_2O \overset{\text{Urease}}{\longrightarrow} 2NH_4^+ + CaCO_3 \tag{17.1}$$

MICP Cost and Sustainability

Ivanov and Chu (2008) evaluated the costs of the sustainable raw materials required to treat soils, while assuming the placement costs of the biogrout comparable with chemical grouts. These costs are summarised in Tables 17.1 and 17.2, and further discussed in the literature review.

Literature Review

The modification of lateritic soils for engineering applications has been the focus of numerous contemporary research publications, e.g.: Gui and Yu (2008), Fall et al. (2011), Joel and Agbede (2011), Shankar et al. (2012), Jaritngam et al. (2013), Ojuri (2013) and Quadri et al. (2013). These researchers, *inter alia*, have looked to

Table 17.1 Approximate cost of raw materials for chemical grouting (Ivanov and Chu 2008)

Material	Price (US$/kg)	Amount of additives required (kg/m^3)	Cost of additives (US$/$m^3$)
Lignosulphites–Lignosulphonates	0.1–0.3	20–60	2.0–18
Sodium silicate formulations	0.6–1.8	10–40	6.0–72
Phenoplasts	0.5–1.5	5.0–10	2.5–15
Acrylates	1.0–3.0	5.0–10	5.0–30
Acrylamides	3.0–3.0	5.0–10	5.0–30
Polyurethanes	5.0–10.0	1.0–5.0	5.0–30

Table 17.2 Approximate cost of raw materials for microbial grouting (Ivanov and Chu 2008)

Material (including microorganism costs)	Price (US$/kg)	Amount of additives required (kg/m^3)	Cost of additives (US$/$m^3$)
Organic wastes	0.05–0.2	10–20	0.5–2.0
Molasses	0.1–0.2	5–20	0.5–4.0
Iron ore and organic wastes	0.1–0.2	10–20	1.0–4.0
$CaCl_2$ and urea	0.2–0.3	20–30	4.0–9.0

partially or wholly replace the expensive and environmentally undesirable classical modification techniques of cement and lime stabilisation, with cheaper and more sustainable solutions. Most recently, investigation of partial cement replacement (up to 12 % by dry weight of soil) with corncob ash (CCA) by Akinwumi and Aidomojie (2015) yielded increases in the CBR and UCS values of lateritic soil samples of up to ~50 and ~33 %, respectively. Up to 1 % (by soil mass) of Arecanut coir was added to lateritic soil by Lekha et al. (2015), and when accompanied by 3 % of bonding cement it improved the soil's CBR and UCS values by ~50 and ~75 %, respectively. Enzymes added to lateritic soil were shown via UCS testing by Khan and Taha (2015) to produce only moderate improvements that failed to show a persistent pattern.

In comparison to standard soil modification techniques, MICP is emerging as a low cost, sustainable alternative (Ivanov and Chu 2008) that allows civil engineers to stabilise soils used in the construction of embankments, retaining walls, tunnels and earth dams. End bearing capacity of piles can be increased, or the bearing capacity of a soil without piling could alternatively be improved. Mining applications include reinforcing boreholes to prevent collapse or providing impermeable barriers to unwanted drainage (Kucharski et al. 2005).

The ability of ureolytic bacteria to excrete carbonates that bond with Ca^{2+} has been known since Drew (1913). Such excretions were suggested by Whiffin (2004) to be suitable agents for the modification of the shear strength of sands, and termed *biocementation*. Refinement of MICP techniques enabled the creation of a 100 m^3 sand test bed by van Paassen et al. (2010). Ivanov and Chu (2008) compared the cost of chemical grouts and MICP raw materials, the costs of grouts ranged from US$2 to US$72 per m^3 of soil. For microbial grouting, the cost range was from US$0.5 to US$9 per m^3. In cases where carbon sources were derived from organic waste materials, cost savings of up to eightfold are attainable. The usage of waste material as a carbon source makes the technique sustainable in nature, whilst also providing a non-toxic alternative to acrylamides, lignosulfonates and polyurethane.

So far in the literature, it appears MICP has not been applied to lateritic soil because pore size may inhibit the technique. Rebata-Landa (2007) states the optimal grain size for MICP is between 50 and 400 μm, because bacterial activity may be restricted in very fine soils, such as lateritic soil. Ng et al. (2012) also discussed the importance of the geometric compatibility of the chosen MICP bacteria to the porous soil media they are being used to treat. Soil microbes move through the soil via the pore throats found between particles, and it is suggested that small pore throat sizes within fine clays restrict the passage of MICP bacteria. The efficacy of MICP to strengthen sandy soils has been consistently demonstrated, but at the time of writing no studies into the efficacy of MICP with residual soils, like lateritic soils, can be found to support or dismiss the potential of MICP working in such fine material.

If it is possible to close the gap in the literature concerning MICP efficacy with fine clays like lateritic soils, increasing the ability of lateritic earth roads to resist the damage caused by wet season water inundation may emerge as one practical application. Increased rural mobility will help towards rural communities increasing their capital assets, reducing their exposure to conditions of poverty. In this respect, the lack of research into using MICP with lateritic soil is potentially depriving the developing nations of tropical regions, where the usage of lateritic earth roads is most common, of a low cost technique of rural infrastructural improvement. Therefore, if an investigation into the potential efficacy of MICP-driven lateritic soil improvement returns a positive outcome, it will open this geotechnical method to areas and populations most in need of its low cost/impact character.

Research Review and Methodology

This study aims to subject a lateritic soil sample to strength related tests, so as to establish its natural engineering qualities prior to any soil modification treatment. The generated test values form the baseline data against which subsequent MICP treated samples will be assessed, so as to quantify the level of efficacy of using MICP soil modification with lateritic soil material. As the objectives of the research are measurable values, the experimental design naturally uses an experimental approach. The strength related tests, carried out in accordance with BSi1377:1990, included plasticity indexing, Procter compaction, CBR and UCS, all of which were conducted under controlled conditions in a suitably equipped materials testing laboratory at Leeds Beckett University. This study utilises these tests to ensure the desired repeatability and validity expected of published geotechnical research.

Research Method

All geotechnical testing was carried out on a single master sample *M1*, obtained from the outskirts of Kampala village, close to the Lunza Township in Malawi, Africa. The sample was extracted from the surface of an earth road, before being double polythene bagged and shipped via air freight. The sample was visually inspected on arrival at the laboratory, and any invertebrates or obvious vegetable matter entrapped in the sample was removed. The whole sample was extracted in a disturbed manner, leading to the requirement that all samples be recompacting prior to testing, and this will be discussed in more detail in the relevant sections below.

Plasticity Index

The plasticity index (I_p) of the soil was derived by inserting the plastic limit (ω_p) and liquid limit (ω_L) of the soil into Eq. 17.2. The value of ω_p is defined by BS1377-2:1990 5.3 to be the moisture content (ω) at which 3 mm threads of the sample become brittle enough that, when rolled between the forefinger and thumb, they will begin to shear both longitudinally and transversely. The value of ω_L is defined by BS1377-2:1990 4.3 as the ω at which the sample will be soft enough that, when held in a brass cup, it will allow 20 mm of penetration by a 50 g cone (satisfying BSi2000-49:2007 5.1) falling under its own weight for 5 s. Both the ω_p and ω_L were investigated by following the methodologies outlined in BS1377-2:1990 5.3 and 4.3, respectively, for two subsamples of *M1*. The value of ω for each test sample that began to exhibit behaviour consistent with reaching their ω_p and ω_L as described above, was calculated using Eq. 17.3 and the following masses: m_1, the mass of an empty container, m_2, the mass of a wet soil sample in the container, and finally m_3, the mass of the soil sample after drying in the container. The soil was dried by placing it in an electrically powered oven for ~24 h at a controlled temperature of 105–110 °C, ensuring no further loss of mass was occurring before accepting the measured value of m_3.

$$I_p = \omega_p - \omega_L \tag{17.2}$$

$$\omega = \frac{m_2 - m_3}{m_3 - m_1} \times 100 \tag{17.3}$$

Proctor Compaction

A 6 kgportion of soil was extracted from *M1* and placed onto a metal tray for drying in an electrically powered oven for ~24 h at 105–110 °C. This provided a dry mass of soil (m_d) to which a required volume of water ($m_{r\omega}$) could be added to create subsamples with an intended ω, as calculated in Eq. 17.4 (e.g. subsample *M1-4-7.5 %a* is a sample with an intended ω of 7.5 %). In accordance with BS1377-4:1990 7.2.1.3, subsamples with an intended ω were created by placing m_d in a polythene sack, and slowly adding and mixing in $m_{r\omega}$. The sack was then sealed and placed upon a shaded shelf for 24 h to allow the moisture to dissipate evenly through the subsample. Upon the completion of this period, the sample was compacted into CBR moulds satisfying BS1377-4:1990 7.2.2.2, using a 2.5 kg rammer in accordance with BS1377-4:1990 7.2.4.4. Prior to sample compaction, the mass of the empty CBR mould and one attached baseplate (m_1) was recorded. Post compaction, the mass of the now filled CBR mould and one attached baseplate (m_2) was also recorded. From this the mass of the compacted sample (m) was determined using Eq. 17.5. The value of m and the known volume (V) of the CBR mould (2304.522 cm^3) was inserted into Eq. 17.6 to give the bulk density (ρ_b) of the sample. Finally, two small representative samples were removed from the top and bottom of the compacted sample, allowing their actual ω to be discerned using Eq. 17.3. With the value of actual ω known, the dry density (ρ_d) was calculated using Eq. 17.7.

$$m_{r\omega} = m_d x\left(\frac{\omega}{100}\right) \tag{17.4}$$

$$m = m2 - m1 \tag{17.5}$$

$$\rho_b = \frac{m}{V} \tag{17.6}$$

$$\rho_d = \frac{100\rho_b}{100 + \omega} \tag{17.7}$$

California Bearing Ratio

All California bearing ratio (CBR) tests were applied, prior to the extraction of representative ω samples, upon the subsamples described in 4.2. Top and bottom CBR penetrations were immediately undertaken after the completion of each Proctor test.

For each penetration, the CBR mould containing the compacted subsample was placed into a CBR load frame. A 2 kg surcharge ring was seated upon the top surface of the sample (as per BS1377-4:1990 7.4.3). The sample was slowly raised towards the face of the force plunger, until a seating load of <10 N was registered by the dial gauge on the plunger's proving ring. A strongly magnetic appendage was attached into position on the side of the CBR mould, in contact with the base of a dial gauge plunger, so as to measure force plunger penetration. Penetration was undertaken at 1 mm/min, while readings of dial gauge divisions of loading ring deformation were taken at penetration intervals of 0.25 mm. According to the manufacturer (ELE, Ltd.), each ring division represented 25.48 N of force on the plunger. The percentage value of CBR at 2.5 and 5 mm of penetration was derived using Eqs. 17.8 and 17.9, respectively.

$$\text{CBR value @ 2.5 mm of penetration} = \frac{\text{force on plunger}}{13.2} \times 100 \tag{17.8}$$

$$\text{CBR value @ 5 mm of penetration} = \frac{\text{force on plunger}}{20} \times 100 \tag{17.9}$$

Unconfined Compressive Strength

The unconfined compressive strength (q_u) of the soil samples was derived using measurements of the strain (ϵ) experienced by a cylindrical sample as axial compressive stress (σ_1) was being applied to the top of the cylinder at a strain rate of 1 mm/min. Cylindrical samples were extracted via a U38 tube from each completed

CBR test, and trimmed to the dimensions of a 76 × 38 mm split-former mould. The trimmed samples were then placed into a loading frame that measured load (P) and any change in sample length (ΔL) from the original length (L_o), using a digital load cell and digital dial gauge, respectively. L_o was taken from the length of the sample, while the original cross-sectional area of a sample (A_o) was calculated from the sample's diameter. The amount of ε was calculated using Eq. 17.10, while the amount of σ_1 was calculated using Eq. 17.11. According to BS1377-4-1990 7.2.5.6, q_u is defined as the peak value of σ_1 recorded in the first 20 % of ϵ.

$$\epsilon = \frac{\Delta L}{L_O} \tag{17.10}$$

$$\sigma_1 = \frac{P(1-\epsilon)}{A_O} \times 1000 \tag{17.11}$$

Results

Plasticity Indexing

The values of average cone penetration, along with the corresponding ω values have been graphically represented in Fig. 17.1, through which a linear line of best fit has been inserted. The best-fit line infers that the theoretical ω required to

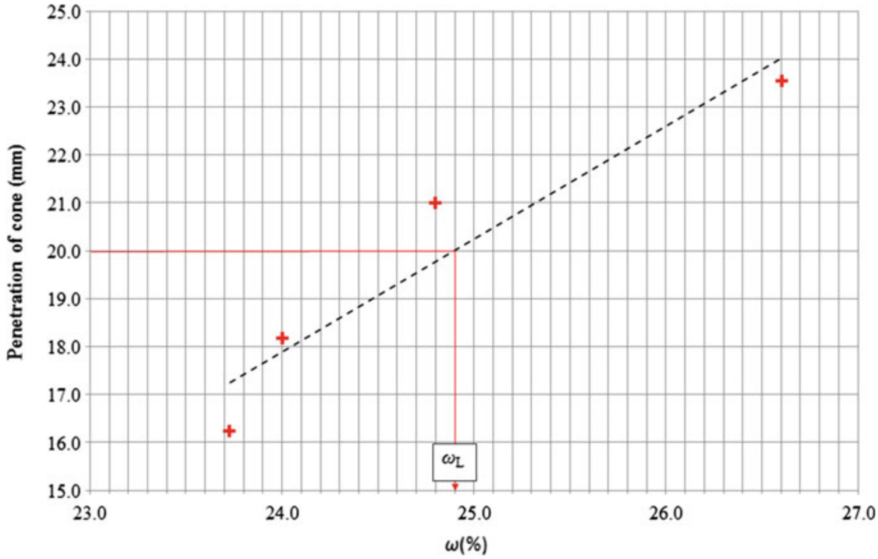

Fig. 17.1 Graphical representation of ω_L

Table 17.3 Plasticity indexing values

Sample *M1-2*	
ω_L (%)	24.9
ω_p (%)	12
I_p	12.9

achieve a penetration of 20 mm is 24.9 %, and this value represents the ω_L as per BS1377-2:1990 4.3.4.5.

The ω_p of *M1* was found to be 12 % following BS1377-2:1990 5.3.3.7, and reported in line with BS1377-2:1990 5.3.4. The value of I_p was calculated to be 12.9 by using Eq. 17.2. All plasticity indexing values are summarised in Table 17.3.

Proctor Compaction

The values of ρ_d were derived using Eq. 17.7 and the values of ρ_d against ω are plotted in Fig. 17.2. The parabolic trend line generated from the spread of the data points indicates that the soil will theoretically reach a ρ_{dmax} of 1.96 Mg/m^3 if compacted at an optimum moisture content (OMC) of 13.3 %.

The particle densities (ρ_s) of all clays typically lie between 2.60 and 2.70 Mg/m^3 (Hillel 1980). Therefore, assuming the value of ρ_s for all soil samples to be 2.65 Mg/m^3 represents no more than a possible 1.9 % degree of error. Inserting this

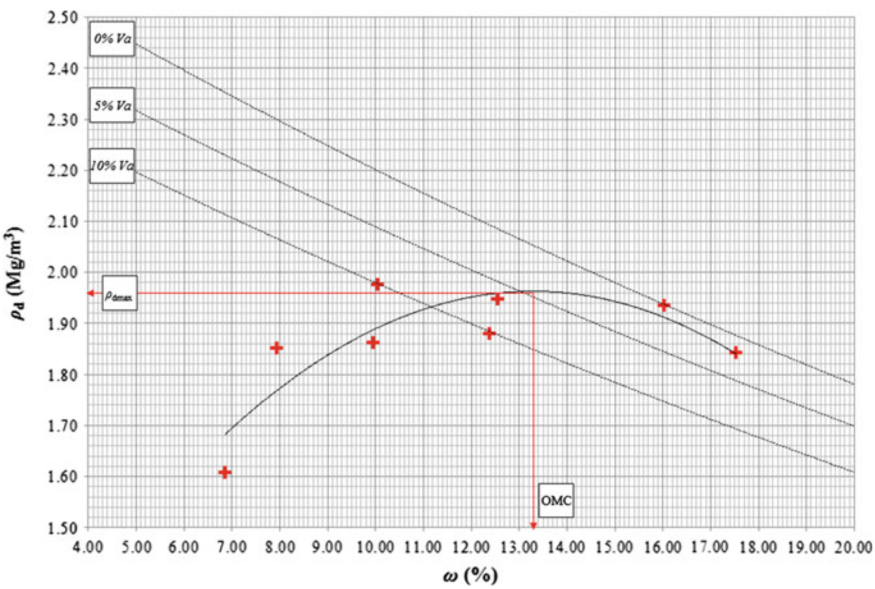

Fig. 17.2 Graphical representation of OMC at ρ_{dmax}

value into Eq. 17.12 and rearranging allow lines of constant percentages of air voids (V_a) to be plotted onto Fig. 17.2. The V_a ratios plotted shows that at ρ_{dmax} the soil has attained a little over 95 % compaction.

$$\rho_{\mathrm{d}} = \left(\frac{1 - \frac{V_a}{100}}{\frac{\rho_\omega}{\rho_s} + \frac{\omega}{100}} \right) \tag{17.12}$$

CBR

Table 17.4 shows the CBR values calculated for subsamples with intended ω between 7.5 and 12.5 %. The CBR values were derived from these values using Eqs. 17.8 and 17.9. The recorded values of actual ω are also shown. Figure 17.3 shows the average force on plunger versus plunger penetration curves for each intended ω. The curves and CBR values show a negative correlation with increasing ω.

UCS

Figure 17.4 shows the average recorded values of σ_1 versus ϵ as recorded during the UCS test for each intend ω. The actual ω of each subsample tested is the same as that shown in Table 17.4. Figure 17.4, shows a positive correlation between intended ω and the value of ϵ at the point of sample failure, and a negative correlation between intended ω and the peak value of σ_1 at the point of sample failure.

Cessation of Testing at 12.5 % ω

Disturbed soil samples were compacted for testing up to ω values of 17.5 %, which proved sufficient to generate the parabolic trend line that established the OMC value during the Proctor compaction test. However, the strength related data retrieved from the CBR and UCS testing on subsamples with ω values in excess of 12.5 %

Table 17.4 Best returned CBR values

Subsamples	ω (%)	Calculated CBR (%)—best returned value (top vs. bottom)
M1-4-7.5 %a	7.9	7.3
M1-4-7.5 %b	6.9	11.9
M1-4-10 %a	10.1	8.2
M1-4-10 %b	10.0	7.2
M1-4-12.5 %a	12.6	0.4
M1-4-12.5 %b	12.4	0.3

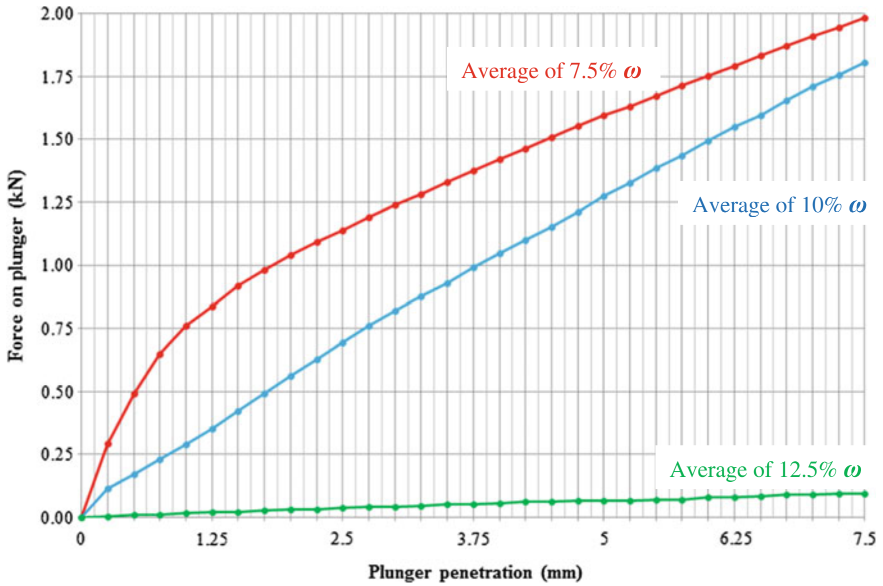

Fig. 17.3 Averaged values of force on CBR plunger

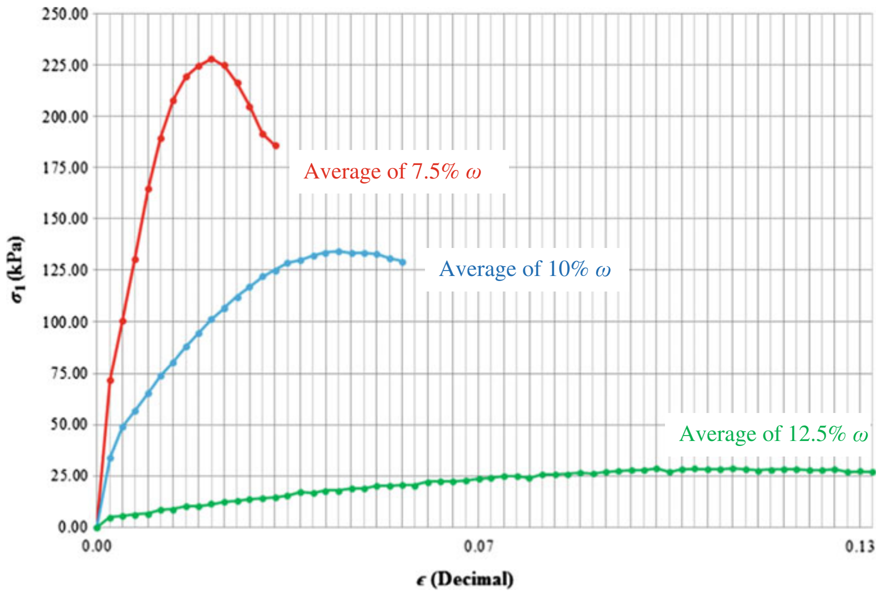

Fig. 17.4 Averaged σ_1 values from UCS test

were practically indistinguishable from the values representing the soil strength of the 12.5 % ω subsamples. Therefore, this data has not been reported in the strength related results above.

Analysis and Discussion

Comparison of the value of ρ_{dmax} obtained at the sample's OMC, with the ρ_{dmax} cited in current studies investigating lateritic soils confirms that 1.96 Mg/m^3 is similar to the typical value of ~1.80 Mg/m^3 they report (Amandi et al. 2015; Emeka and Emeka 2015; Kamtchueng et al. 2015). Only the strength tests conducted at 12.5 % ω were within 1 % of the OMC at ρ_{dmax} and, as mentioned, tests at 12.5 % ω returned the worst strength performances of all the subsamples. It can therefore be asserted that the magnitude of ρ_d of each subsample has not had an apparent, correlative effect on strength performance.

The plasticity indexing of the soil identifies *M1* as being a clay of low plasticity (CL). Vaughan et al. (1978) differentiates low plasticity clays as those with a value of $I_p < 25$ %. High plasticity clays possess a value of I_p that is >30 %. Clays that possess a value of I_p between 25 and 30 % are considered as transitory. The assessment of the *M1* as a low plasticity clay is corroborated by the A-line chart of Fig. 17.5. *M1* is represented by the cross indicating where the I_p value of 12.9 % intersects with the ω_L of 24.9 %. It is generally expected that the undrained strength of low plasticity clays will be predominantly controlled by the level of ω within the sample (Jardine and Potts 2004). It is therefore unsurprising that the stress–strain related curves of Figs. 17.3 and 17.4 display obvious declines in the strength performance of *M1* with only slight increases of ω.

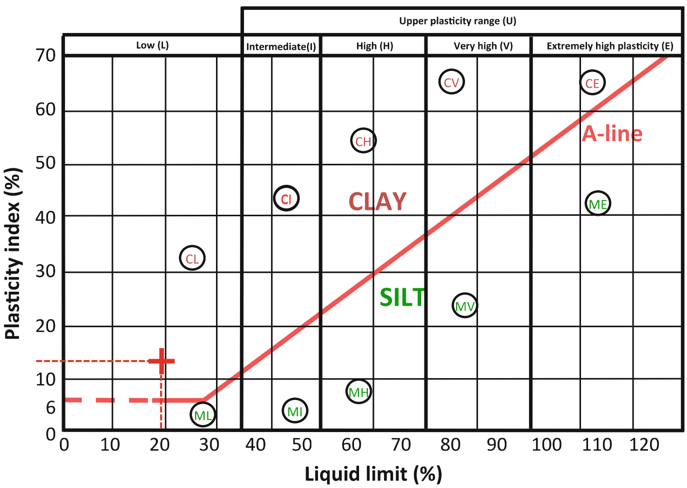

Fig. 17.5 A-line chart (adapted from Whitlow 1996)

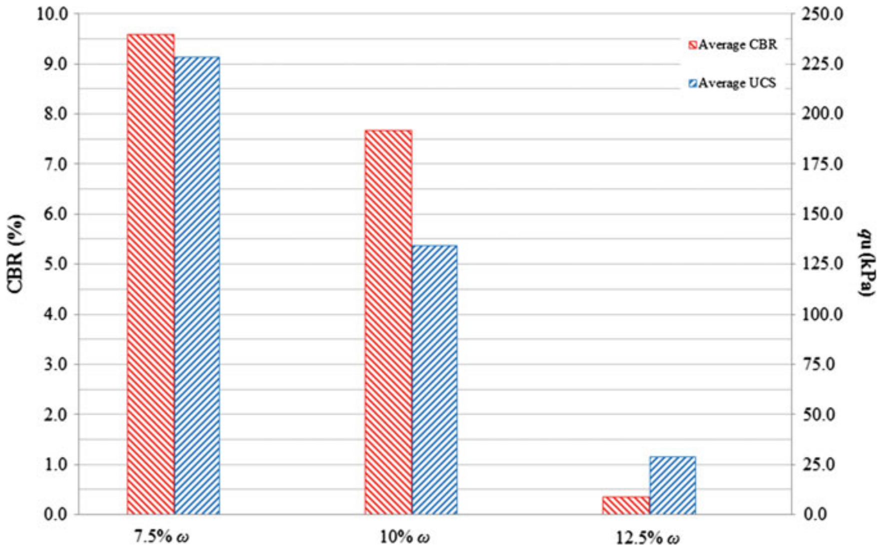

Fig. 17.6 Average CBR and UCS values

As all subsamples were identically prepared and compacted, with only a minimal variance in ρ_d as shown in Fig. 17.2, the large variance in average strength performance shown in Figs. 17.3 and 17.4 must be associated with the value of ω for each curve. Therefore, it can be asserted that during all of the tests, *M1* appears to be responding in accordance with the ω driven, low plasticity behaviour described by Jardine and Potts (2004). Figure 17.6 best summarises this behaviour, as it quantifies the small increase in each subsample ω against large changes of average sample peak strength measurements; best returned CBR percentage and q_u. Here, ω has increased by only 5 % overall, but the average CBR value has fallen from 9.6 to 0.3 % while q_u falls from 228.7 to 28.7 kPa. This change in CBR and q_u values corresponds to a representative reduction in strength of 96.4 % for the CBR test samples and 87.4 % for the UCS test samples.

The mechanism behind this behaviour appears to be centred on low plastic clays being prone to critical loses of internal frictional resistance (Φ). Vaughan et al. (1978) proposed that low plasticity clays can be predicted to fail by undergoing turbulent shear, as opposed to sliding shear. Sliding shear is facilitated by the flat, platy clay micelles found in high plasticity clays aligning and sliding past each other. The relative lack of micelle alignment in low plasticity clays increases Φ, and at failure will lead to turbulent shearing.

In lateritic soils in particular, greater levels of Φ can also be attributed to the mineralogical fabric of the soil. It is common in residual soils, like laterite, for clay micelles to coat larger mineralogical remnants of the weathered parent geology (Mitchell 1976). Such remnants will disrupt the potential for sliding layers of micelles to form in the soil fabric. Additionally, the interlocking of mineral remnants contributes to the fabric's Φ. An increase in ω does not reduce inter-mineral friction between non-clay minerals like quartz if their surfaces are clean and in direct contact, as water actually acts to disrupt the normally lubricating adsorbed films on their surfaces. However, Φ of the clay sheet minerals that coat the larger non-clay minerals in residual soils is responsive to increasing ω. Before wetting, their adsorbed film is thin and not fully hydrated, and so is resistant to disruption. Upon wetting, the adsorption layer thickens and experiences ion hydration, allowing the film to become more mobile, aiding lubrication (Mitchell 1976). Therefore, the strength performance of a drier, low plasticity residual soil will benefit from good levels of Φ, but increases of ω lead to lubrication of the soil fabric, resulting in shearing.

Turner (2015) observed partially dissolved quartz accounting for 46 % of the fabric of a lateritic soil sample, along with sand content, as shown in Fig. 17.7. This sample was taken from very close to the location from which *M1* was extracted. Assuming *M1* possesses a similar quartz content, it may explain why it is prone to turbulent shear.

This turbulent shear behaviour, bought by the vulnerability to increasing ω is perhaps best demonstrated in Fig. 17.4; the results of the UCS testing. The drier 7.5 % ω subsamples both have high peak values of σ_1 that occur with relatively low values of ε. This indicates a brittle mode of failure where Φ is high, but once it is overcome the sample yields quickly. The 10 and 12.5 % subsamples exhibit lower peaks with longer failure strains, indicating that the modes of failure are becoming more plastic. This is what should be expected if the increasing influence of greater ω is mobilising the adsorption layers and inducing more turbulent shearing.

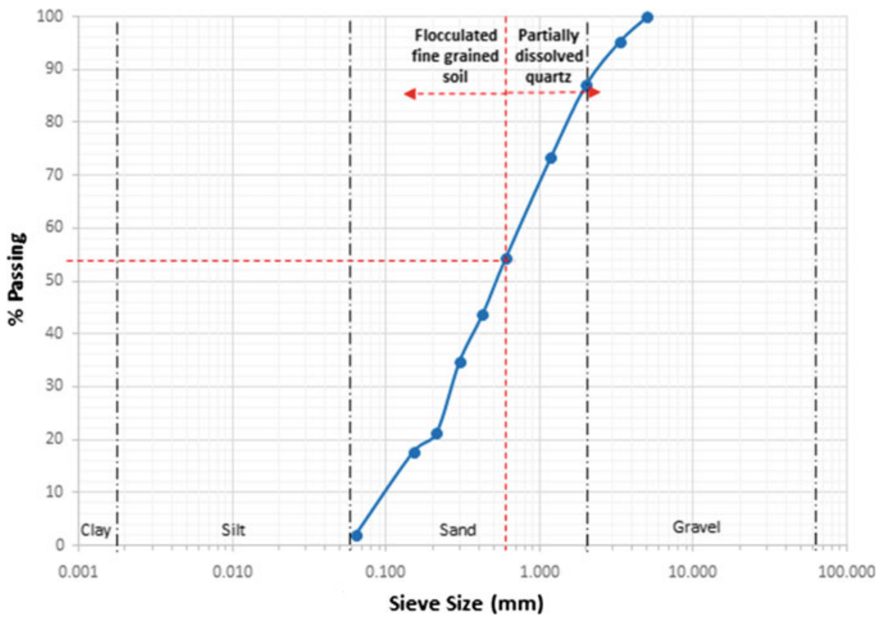

Fig. 17.7 Particle size distribution of lateritic soil from Malawi (Tuner 2015)

Conclusions and Further Work

Geotechnical testing of sample *M1* has returned test data that reveal it to be a low plasticity, lateritic clay prone to turbulent shearing at relatively modest water contents. Increasing ω from 7.5 to 12.5 % induced CBR results to fall from an average value of 9.3 %, down to 0.3 % (96.4 % decrease), and the UCS results to reduce from an average q_u, of 228 kPa, down to 28 kPa (87.4 % decrease). Changes in ρ_d did not present a recognisable correlation to changes in soil strength performance. The profound strength reduction of *M1* under a small increase of 5 % ω suggests that the soil's strength is heavily influenced by the ω of the soil, in line with the expected behaviour of low plasticity soils outlined in the literature discussed. Such reduction in the soil strength is believed to be the result of low water content being sufficient to hydrate, and therefore mobilise the adsorption layers, reducing the amount of Φ in the soil. Further testing of this soil using unconsolidated undrained triaxial testing could confirm that changes in ω do indeed induce sufficient changes in Φ to provide the mechanism for the rapid soil strength reduction demonstrated in this paper. If the above connection between Φ and ω is established, the next phase of MICP research should explore the ability of MICP treatment to reinforce the amount of Φ in the soil through biocementation of the soil particles. The strength performance of the soil at $\omega \leq 10$ % does not warrant the attention of MICP research, as firstly the reduction in strength performance was not as relatively severe until approaching the wetter end of the semisolid state. Secondly, a ω of 12.5 % means that the sample should be very close to the OMC for optimum compaction. This will reduce the size and frequency of void spaces within the soil that MICP would have to bridge to in order to have the desired cementation effect.

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Part VI
Water

Chapter 18
Development of Sustainable Drinking Water Quality Solutions for Rural Communities in the Developing World

Martin Pritchard, Alan Edmondson, Tom Craven and Theresa Mkandawire

Abstract In developed countries potable water is usually taken for granted, where advanced infrastructure and a strong economy has allowed waterborne diseases (such as cholera and dysentery) to be virtually eradicated. In contrast, developing countries have poor infrastructure, lack development, stability and vibrancy. Consuming untreated, and potentially contaminated, groundwater extracted from shallow wells is the only option. The primary aim of this study was to undertake an extensive field water quality-sampling programme in rural villages throughout Malawi. About 95 % of all the wells tested failed to meet safe drinking water values for untreated water in the wet season, while about 80 % of the wells failed in the dry season. The main forms of contamination emanate from bacteriological and physical constituents. As noted in the United Nations post-2015 water agenda, water quality is just as important as water quantity—the two are inextricably linked. Hence, there is currently a great need to develop more appropriate, cost-effective options to treat water; particularly to reduce the 3.5 million deaths related to inadequate water supply and sanitation each year. Subsequently the aim was directed towards investigating a sustainable, yet appropriate, way to treat shallow well water to significantly improve quality. The most suitable method to remove coliforms and

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turbidity from water is via the process of coagulation, using aluminium sulphate (alum) or ferric sulphate (ferric). The limited availability and relative expense of these chemicals has led to other more appropriate indigenous coagulants being sought for developing countries. Natural plant extracts have been available for water purification for many centuries. However, the science and engineering application of the use of plant extracts have not really been developed. To start to address this, Leeds Beckett University and the University of Malawi—The Polytechnic have shown that a locally available plant extract, Moringa oleifera, which grows wild throughout rural villages in developing countries, can be used to improve water quality in the order of 80–94 %. The flocculent capacity of M. oleifera is closely comparable to that of a well-established chemical coagulant, alum.

Keywords Developing world · Drinking water quality · *Moringa oleifera* · Shallow wells

Introduction

Water is a medium for thousands of microorganisms, some of which are pathogenic. Pathogens (e.g. bacteria, viruses, protozoa and helminths) cause a variety of diseases, such as

- **Cholera**: Caused by the bacterium *Vibrio cholerae*. Results in severe diarrhoea leading to dehydration. Sufferers can die within hours unless treated.
- **Cryptosporidosis**: A diarrhoeal illness, arising from acute short-term infection of the intestines of mammals. This is caused by a protozoan parasite called *Cryptosporidium* and can be fatal, particularly when subjects are immunocompromised.
- **Dysentery**: There are two types, amoebic and bacillary; they result from protozoan and bacterial infection of the digestive system respectively. These cause severe diarrhoea and internal bleeding.
- **Rotavirus diarrhoea**: There are five types (A–E), of which, Rotavirus A is the most common type found to infect adults and children worldwide. It infects and damages the cells that line the small intestine and causes gastroenteritis. It is the most common cause of diarrhoea in adults and young children globally.
- **Typhoid**: Caused by *Salmonella typhi* bacteria that multiply in the human small intestine and results in a series of symptoms from severe fever to diarrhoea.

The treatment of water to render it fit for human consumption has become a problem of vital importance for both developing and developed countries. In developed countries, water is purified at water treatment sites and is supplied directly to the consumer through a piped network. Advanced coagulation, filtration and chlorination techniques are all used in these sites to produce potable water that complies with the World Health Organisation (WHO 2011) guidelines for drinking water quality.

The supply of safe drinking water in developing countries faces more constraints than in the industrialised countries due to high cost of importing the water treatment chemicals and the lack of reticulated water distribution systems due to abject poverty. Within Africa groundwater is the main source of drinking water, particularly for rural villagers—the water being consumed without treatment. The Millennium Development Goals (MDGs)—target 7c, aimed to halve the proportion of people without sustainable access to safe drinking water between 2000 and 2015 (UN 2015a). It is noted that this target has been met globally, but not comprehensively throughout sub-Saharan Africa (UN 2012). During this period, non-governmental organisations (NGOs), and the alike, constructed shallow wells to try to meet target 7c; however they did not implement testing/monitoring programmes to ensure that the water was/remained potable. The preconception was that because these people have an engineered well, they have an adequate drinking water source. This is often far from the case and around 80 % of all illnesses in developing countries still relate to waterborne diseases. Statistically, this is greater than that of malaria, HIV/AIDS and measles combined (GLAAS 2010). The population at the greatest risk are children, people living under unsanitary conditions and the elderly. Currently, the United Nations post-2015 water agenda aims to address water quality in parallel with water quantity—the two being inextricably linked (UN 2015b).

If a low-cost, technological, innovative solution can be found to enable the use of more appropriate and sustainable materials to be used to treat groundwater, an important step could be made to provide significantly improved water sources throughout the developing world. This should have a positive effect on the ability to improve the quality of drinking water for rural populations. In turn, it should counteract some of the horrific humanitarian statistics on waterborne diseases that should not be permitted in the twenty-first century.

Literature Review

The literature review is presented in two main sections. The first section contains a general overview on water quality parameters, with particular reference to Malawi. The second section highlights relevant literature on plant extracts that have been used to improve water quality, particularly in reference to *Moringa oleifera*.

Water Quality

Water quality is assessed by a wide range of parameters, with limiting values being quoted in various guidelines, as provided in Table 18.1. However, not all parameters can be assessed due to time and financial constraints. The choice of the parameters to be assessed depends on the degree of consequences. In developing

Table 18.1 Water quality guideline/standard (maximum) values

Parameters/guideline values	WHO (2011)	MBS (2005)	MoWD (2003)	Units
Biological				
Total coliforms	0[a]	0[a]	50	per 100 ml
Faecal coliforms	0[a]	0[a]	50	per 100 ml
Physical and organoleptic				
Turbidity	5	0.1–1	25	NTU[b]
Total dissolved solids	1000	450–1000	2000	mg/l
Electrical conductivity	–	70–150	3500	µS/cm
pH	6.5–8.5	5.0–9.5	6.0–9.5	–
Colour		5.0–10.0	50	TCU[c]
Taste		Acceptable		–
Odour		1–5/odourless		TON[d]
Chemical (macro-determinants)				
Sulphate	250	200–400	800	mg/l
Hardness	500	500	800	mg/l
Nitrate	50	6.0–10.0	100	mg/l
Nitrite	3	6.0–10.0	–	mg/l
Ammonia	1.5	0.2–1.0	–	mg/l
Calcium		80–150	250	mg/l
Chloride	–	100–200	750	mg/l
Fluoride	1.5	0.7–1.0	3	mg/l
Magnesium	–	30–70	200	mg/l
Potassium	–	25–50	–	mg/l
Sodium	–	100–200	200	mg/l
Zinc	–	3.0–5.0	15	mg/l
Chemical (micro-determinants)				
Arsenic	10	10.0–50.0	50	µg/l
Aluminium	–	150–300	500	µg/l
Antimony	20	5.0–10.0		µg/l
Cadmium	3	3.0–5.0	10	µg/l
Chromium	50	50–100	50	µg/l
Cobalt	–	250–500		µg/l
Copper	2000	500–1000	2000	µg/l
Cyanide (free)	70	30–50	50	µg/l
Cyanide (recoverable)	–	70–200		µg/l
Iron	–	10–200	3000	µg/l
Lead	10	10.0–50.0	50	µg/l
Manganese	400	50–100	1500	µg/l

(continued)

Table 18.1 (continued)

Parameters/guideline values	WHO (2011)	MBS (2005)	MoWD (2003)	Units
Mercury	6	1.0–2.0		μg/l
Nickel	70	50–150		μg/l
Selenium	10	10.0–20.0	10	μg/l
Vanadium	–	100–200		μg/l

[a]Not detected in 95 % of the samples taken throughout any 12-month period
[b]Nephelometric turbidity units
[c]True colour unit
[d]Threshold odour number

countries, particular reference is given to bacteriological analysis since the detection of faecal pollution of water is very critical where water-related disease incidences are rife—causing fatalities within hours or days. Most chemicals are of concern only with long-term exposure—years or decades are typically required for problems to manifest. Some of the major parameters used in assessing the safety of water, their sources and effects are summarised in Table 18.2.

The majority of diseases resulting from microbiological pollution are essentially contracted from water contaminated with human faecal matter. The range of potential pathogens is far too wide for specific detection in water to be worthwhile even in the developed world. Therefore, the principle for assessment of faecal contamination involves the use of indicator organisms. The most commonly used indicator organism for faecal contamination is *Escherichia coli* (*E. coli*)—a normally harmless gut commensal in the large intestine of mammals. The detection of *E. coli* in water indicates faecal contamination and hence the likely presence of pathogens. The total coliform (TC) group includes *E. coli* but may also contain a variety of environmental bacteria, which do not necessarily indicate faecal contamination. The faecal coliform (FC) group is more specific for *E. coli*, but may also include some environmental bacteria.

Malawi uses the Malawi Bureau Standards (MBS 2005) guideline values for treated surface water. These national guideline values are very similar to the World Health Organisation (WHO 2011) guideline values. Slight differences between these two standards exist (Table 18.1), which probably emanate from various local, geographical, socioeconomic and cultural factors (WHO 1997, vol. 3). The WHO (2011) guideline values are frequently referred to in Malawi, as these are internationally recognised guideline values. In 2003, the Ministry of Water Development (MoWD) introduced temporary guideline values for water that is used without treatment, such as well water (MoWD 2003). The limiting values are higher than those for WHO (2011); MBS (2005). In particular, these temporary guideline values allow for up to 50 TC and 50 FC to be present in water per 100 ml, while WHO (2011), MBS (2005) guidelines do not allow any such coliforms to be present in all water intended for drinking.

The mortality rate arising from the use of unsafe water in Malawi is a major concern for both government and international institutions. This is a big challenge

Table 18.2 Water quality parameters

Water quality parameter	Source(s)	Impacts/effects
Colour	Oxides (e.g. iron, manganese), algae, decomposing vegetation, industrial wastes (e.g. textile, slaughter houses)	Dissolved solids may exert chlorine demand, makes water unsuitable for some processes (e.g. food processing) and the staining effect
Taste and odour	Dissolved inorganic salts, biological reactions end products (anaerobic degradation that results in products like hydrogen sulphide, methane) algae, decaying vegetable matter, chlorination products	Associated with pollution, displeasing to consumers
Temperature	Natural heat, industrial wastewater	Accelerates algal growth and reactions in water if high
Turbidity	Suspended and colloidal matter, microorganisms, detergents	Provides adsorption sites for pathogens, may impart taste, colour and odour
Pathogens	Human and animal excreta	Water-related illnesses e.g. cholera, dysentery, typhoid
Total dissolved solids	Organics and inorganics (e.g. dissolved minerals)	May impart colour, some chemicals are toxic
Alkalinity	Bicarbonates, carbonates	Imparts taste
Hardness (Ca, Mg)	Calcium salts from industrial wastewater, rocks	High soap consumption, scale formation in boilers and pipes and staining effect
Fluoride	Rocks (sedimentary and igneous rocks)	Staining of teeth and skeletal damage at much higher concentrations
Lead	Lead piping and tanks	Cumulative body toxin
Nitrate	Agricultural practices, e.g. farming (chemical fertilizers), sewage effluents	Causes methaemoglobinaemia 'blue baby' disease in children
Nitrite	Natural waters from nitrogen cycle, nitrite in conjunction with high ammonia levels indicates pollution from sewage	Harmful to fish and other aquatic organisms
Arsenic	Agricultural practices, e.g. animal farming (dip tanks). Can be found in surface waters from areas of metalliferous ore. More usually it is the result of pollution from weed killers and pesticides containing arsenical compounds or from runoff from mining wastes	Skin pigmentation. Gastrointestinal, haematological and renal disorders

(continued)

Table 18.2 (continued)

Water quality parameter	Source(s)	Impacts/effects
Aluminium	Occurs in many natural waters resulting from corrosion of aluminium utensils, tanks and pipes or from incorrect dosing of aluminium sulphate as a coagulant	Toxic to fish at high levels, affects kidneys
Chloride	Industrial effluents (e.g. battery processing wastes), natural mineral deposits from seawater, agricultural or irrigation discharges, sewage	Imparts salty taste (affects acceptability of water) affects people suffering from heart or kidney disease
Ammonia	Domestic effluents, industrial wastewaters, decomposing vegetation sewage	Harmful to fish and other aquatic life, affects chlorine dose for disinfection
Sulphate	Occurs naturally in water, industrial effluents where sulphates or sulphuric acid have been used in processes such as tanning and pulp paper manufacturing, dissolution of gypsum and other mineral deposits containing sulphates, seawater intrusion, oxidation of sulphides, sulphites and thiosulphates	Corrosion to metal work, damage to cement

for Malawi due to the country's economic problems where over 40 % of the people are categorised as suffering from 'extreme poverty'—unable to meet food requirements based on the monthly cost of the food basket (GOM/EP&D 2008). The search for locally available low-cost materials for treating groundwater is therefore inevitable, particularly to address water quality issues in rural communities.

Plant Extracts

The most suitable method to remove coliforms and turbidity from water is via the process of coagulation. Coagulants are normally positively charged particles that have the ability to attract negatively charged particles to form agglomerated particles (flocs), which then settle under gravity leaving a supernatant free from impurities, i.e. the purified water. The two chemical coagulants commonly used in developed countries are aluminium sulphate ($Al_2(SO_4)_3$) and ferric sulphate ($Fe_2(SO_4)_3$), termed alum and ferric, respectively. The limited availability and relative expense of these chemicals has led to other more widely available indigenous coagulants being sought for developing countries. Natural plant extracts have been available for water purification for many centuries throughout the developing world. For example, *Strychnos potatorum* was being used as a clarifier between fourteenth and fifteenth centuries Schultz and Okun (1984) and Sanghi et al. (2006) reported that seeds of the nirmali tree (*S. potatorum*) were used to clarify turbid river water 4000 years ago in India. It is further reported that in Peru, water has been traditionally clarified with the mucilaginous sap of tuna leaves obtained from certain species of cacti. *Zea mays* was used as a settling agent by sailors in the sixteenth and seventeenth centuries.

M. oleifera has also been used historically for several purposes, including food, oil extraction, fertilizer, folk medicine and water treatment. For example (WHO 2015):

- Sanskrit writings record the use of vegetable substances, namely the seed contents of *S. potatorum* and *M. oleifera* for household water treatment (Gupta and Chaudhuri 1995).
- Extracts from the *M. oleifera* seeds have shown the potential to be effective as a simple and low-cost coagulant-flocculent for turbid surface water, which can be used for household water treatment (Jahn and Dirar 1979; Jahn 1981, 1988; Olsen 1987).

More recently, it has been noted that the active component for coagulation by *M. oleifera* is commonly referred to as a natural organic protein that acts as a cationic polyelectrolyte with a molecular weight ranging from 6 to 16 kDa (kilodaltons), with an isoelectric point value between 10 and 11 (Ndabigengesere et al. 1995; Kwaambwa and Maikokera 2007; Maikokera and Kwaambwa 2007). However, the efficacy of the extract as a coagulant in reducing microbes from groundwater with varying turbidities, and any potential toxic elements embedded within the extract still needs to be addressed to determine its suitability as a replacement for alum (or ferric) for rural communities.

Summary of Literature

There has been very little data on the quality of water from shallow wells in rural villages in Malawi. In addition, there has been very little research work into the use of plant extracts to purify groundwater. Research studies on water purification have mainly been carried out in developed countries focusing on more expensive water purification systems using a coagulant and a disinfectant. These systems are rarely viable for rural communities due to abject poverty. The science and engineering application of the use of plant extracts have not really been developed. Hence, there is a vital need to develop cheap, simplistic, sustainable ways to significantly improve the quality by using local readily available materials.

Research Review and Methodology

Malawi was selected as the focus country for this study as poverty is extremely grave. It is one of the poorest and most undeveloped countries in sub-Saharan Africa (Aneki 2010) There is insufficient nutrition/potable water, poor medical services, inadequate schooling, widespread infection with HIV/AIDS and lack of fair trade/minimum wage. These have all been exacerbated by the lack of foresight by past governments, governmental restrictions, corruption and the misuse of international donations. *Inter alia,* this results in the life expectancy for a Malawian to be 54.6 years.

Soil types in Malawi are usually of alluvial origin and, combined with the sub-tropical climate, provide relatively high water tables all year round (EOE 2010). This means groundwater is a practical source of water for rural areas. Groundwater is usually accessed by the use of shallow wells or boreholes. Shallow wells are hand dug wells, usually less than 15 m deep and up to 1 metre in diameter. This is in contrast to borehole wells, which are often far deeper, up to 80 m, 0.2 m in diameter and mechanically drilled to penetrate deep aquifers. Despite the fact that shallow

Fig. 18.1 Different types of shallow wells found in Malawi

Fig. 18.2 *M. oleifera* trees providing shelter to a rural community in Malawi

wells are more prone to surface contamination than deep borehole wells, they are very commonplace and provide a relatively cheap method of groundwater extraction, especially for poor rural communities (Fig. 18.1). Construction is possible in these communities, because, unlike deep borehole wells, shallow wells do not require the use of heavy plant equipment and can be dug and built primarily by hand using local materials.

Many different types of plants, which grow wild throughout rural villages in developing countries, yield proteins that can provide a coagulation function. Such proteins can be derived from various parts of the plants and/or trees such as the seeds, leaves, pieces of bark, sap, roots or fruit. Plant extracts indigenous to Malawi include *M. oleifera, Jatropha curcas,* Guar gum, *S. potatorum,* and *Hibiscus sabdariffa*—the most common being *M. oleifera* (Fig. 18.2).

Research Method

Water Sampling

To provide a detailed investigation of groundwater quality, around 17,000 rural Malawians' drinking water was sampled in southern Malawi. This resulted in over 2,700 samples being analysed from 50 shallow wells for microbiological, physical and chemical contamination. Water samples were obtained and analysed from the wells at four different times within a period of a year; two different batches of samples were taken in both the dry and wet sessions. This allowed data to be established on the change in water quality during the changing of the seasons within a typical year.

Deterioration of certain water quality parameters, particularly microorganisms, can occur between sample collection and laboratory analysis, especially for rural monitoring programmes (AWWA 1995). Thus, a portable membrane filtration and incubation test kit was used to determine microbiological contamination in accordance with the WHO (2011), MBS (2005) and MoWD (2003) guidelines. The required volume of sample water (i.e. 100 ml after dilution) was filtered in situ through a 0.45 μm membrane and placed onto Petri dishes containing membrane lauryl sulphate broth (MLSB). After a recovery period of one hour, to allow resuscitation of microbes, membranes were incubated at 37 and 44 °C for TC and FC respectively. Following an incubation period of 24 h, viable colonies that were a distinct yellow colour and of a diameter of at least 1 mm were counted (Paqualab Manual 2005). Water from untreated sources such as shallow wells (which is normally expected to be of poor quality) needed to be diluted to make sure that the number of coliforms counted on the Petri dish was within the recommended guideline of 20–80 coliforms per 100 ml. For diluted samples, the dilution ratio was accounted for to represent the count per 100 ml of actual sample water. Values for turbidity, total dissolved solids (TDS), electrical conductivity and pH were obtained in situ using the appropriate test meters so that the parameters did not change with time. From each well one litre of water was also collected for laboratory analysis, which was undertaken on the following day, i.e. within the 7-day time period as stated in MBS (2005), for levels of ammonia, fluoride, hardness, nitrate, nitrite and sulphate. These measurements were obtained using a photometer in conjunction with the appropriate reagents. Each test was undertaken in duplicate and comparable results averaged, essentially to reduce any errors related to measurement. Incomparable results were investigated and retested where possible.

Water Purification and Toxicity Tests

Good quality seeds (not rotten) of *M. oleifera* were ground to a powder. The powder was then sieved through a 600 μm sieve (Diaz et al. 1999; Buptawat et al. 2007). A mixture was then prepared by introducing 10 g of powder in 100 ml of distilled water. The suspension was then stirred at high speed for 30 s to extract the active element (Muyibi and Evison 1995). The suspension, which was termed the crude aqueous extract of *M. oleifera,* was prepared fresh every time it was needed in order to avoid deterioration (Jahn 1986). An appropriate volume of solution was then measured and poured into a 1000 ml of sample water to obtain the desired concentration.

Sedimentation jar tests then were used to determine the coagulation properties of the crude aqueous extract of *M. oleifera* ranging from 0 to 500 mg/l. Water samples were mixed at a high speed of 200 revolutions per minute (rpm) for one minute, as recommended by Peavy et al. (1985) followed by a gentle and prolonged mixing for 15 min. The solution was then allowed to stand for 30 min (Peavy et al. 1985; Ndabigengesere et al. 1995; Katayon et al. 2006) to allow the coagulated particles to settle to the bottom. Turbidity of the supernatant was then measured using a turbidity meter. FC were only measured using the optimum extract concentration that produced minimum turbidity. The number of coliforms was determined using the membrane filtration method on MLSB at 44 °C for 24 h (WHO 2011), in a controlled laboratory environment. Each test was duplicated and comparable results averaged, essentially to reduce any errors related to measurement.

The toxicity of *M. oleifera* was also examined in respect to the crude aqueous extract and the supernatant of the treated water. Cytotoxicity tests using Chinese Hamster Ovary (CHO) cells and ecotoxicity using *Thamnocephalus platyurus* were performed. The use of both a cell line (CHO) and a crustacean (*T. platyurus*) allowed an element of duplication to be considered, by using two different test methods. The former method is more relevant to testing in a controlled laboratory environment; whilst the latter allows a less controlled (field type) environment for the test. Cytotoxic effects were determined using qualitative means (BS EN ISO 10993-5 2009), where cells were examined microscopically using cytochemical staining. Ecotoxicity tests were undertaken with reference to the '*Thamnotoxikit F.* Standard Operational Procedure Manual' (undated).

Results

Figures 18.3 and 18.4 indicate the average dry and wet season results for TC and FC values respectively, together with the acceptable MoWD (2003) guideline value of 50 colony forming units (cfu)/100 ml (for both TC and FC values) plotted horizontally on the graphs as a dotted line.

Figure 18.5 indicates the average dry and wet season results for turbidity values, together with the acceptable MoWD (2003) guideline value of 25 NTU plotted horizontally on the graph as a dotted line.

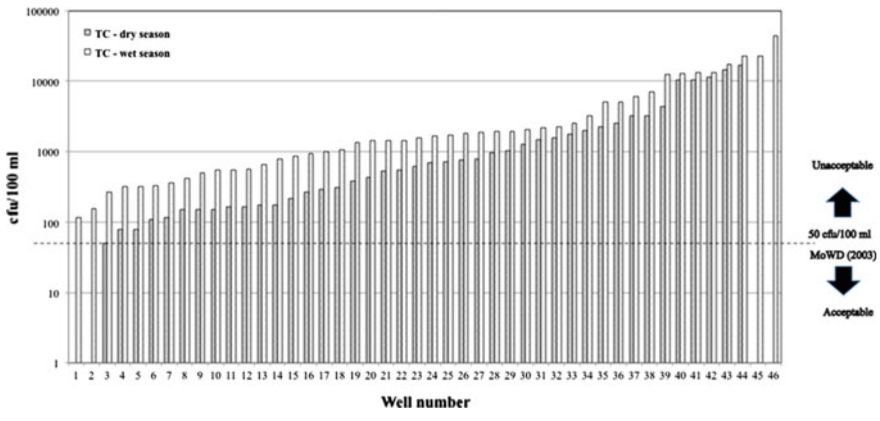

Fig. 18.3 Amount of total coliforms (TC) in water from shallow wells—dry/wet season (A number of shallow wells could not be sampled throughout the testing programme, hence have been omitted from these plots. The main reasons for this included failure of the pump mechanism or the pump failing to yield water, which typically occurred in the dry season.)

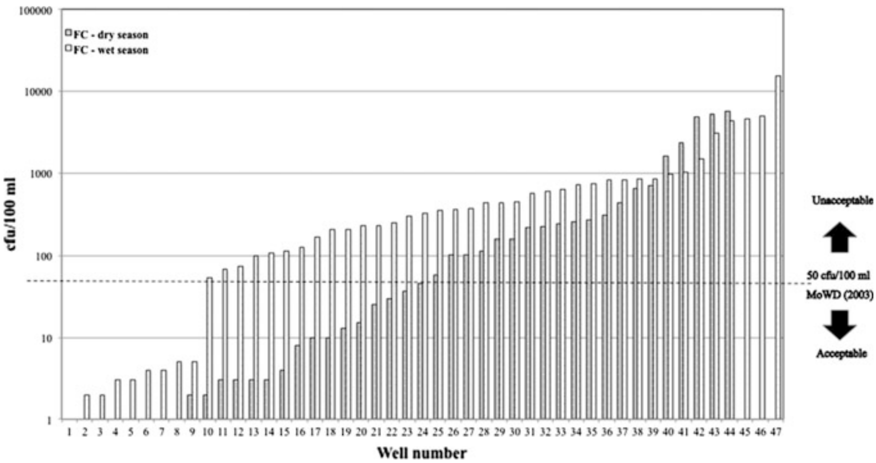

Fig. 18.4 Amount of Faecal coliforms (FC) in water from shallow wells—dry/wet season (A number of shallow wells could not be sampled throughout the testing programme, hence have been omitted from these plots. The main reasons for this included failure of the pump mechanism or the pump failing to yield water, which typically occurred in the dry season.)

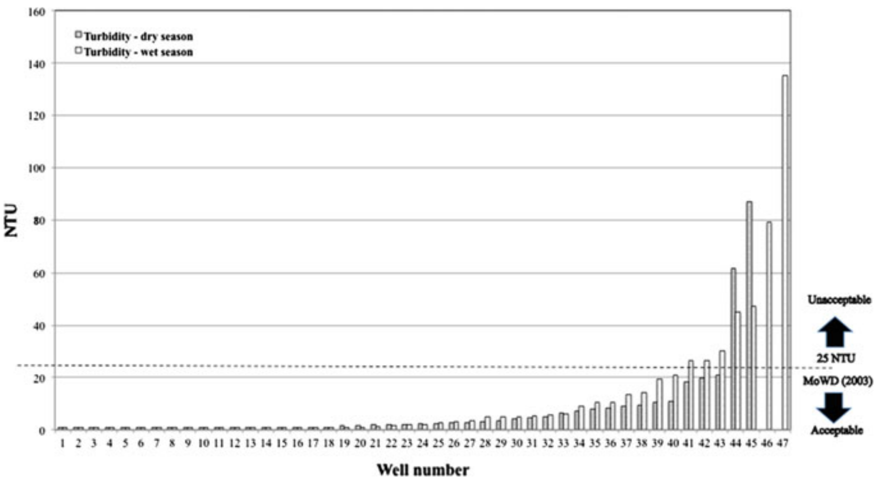

Fig. 18.5 Turbidity of water found in shallow wells—dry and wet season (A number of shallow wells could not be sampled throughout the testing programme, hence have been omitted from these plots. The main reasons for this included failure of the pump mechanism or the pump failing to yield water, which typically occurred in the dry season.)

Table 18.3 presents an overall summary of the values obtained throughout the dry and wet seasons in reference to the MoWD (2003) temporary guideline values for untreated water supplies. The shaded values indicate those that lie outside the recommended values.

Table 18.3 Summary of overall water quality values obtained + MoWD (2003) values

Parameters/guideline values	Average dry season	Average wet season	Maximum MoWD (2003)	Units
Biological				
Total coliforms	2220	4840	<50	per 100 ml
Faecal coliforms	540	1003	<50	per 100 ml
Physical and organoleptic				
Turbidity	7.2	17.9	<25	NTU
Total dissolved solids	369	338	<2000	mg/l
Electrical conductivity	605	564	<3500	µS/cm
pH	6.9	6.8	6.0–9.5	–
Temperature	27.5	26.5		°C
Chemical (macro-determinants)				
Ammonia	0.15	0.11	<1.5	mg/l
Fluoride	1.8	2.1	<3.0	mg/l
Hardness	163	213	<800	mg/l
Nitrate	0.38	0.51	<100	mg/l
Nitrite	0.01	0.11	<3.0	mg/l
Sulphate	48	43	<800	mg/l

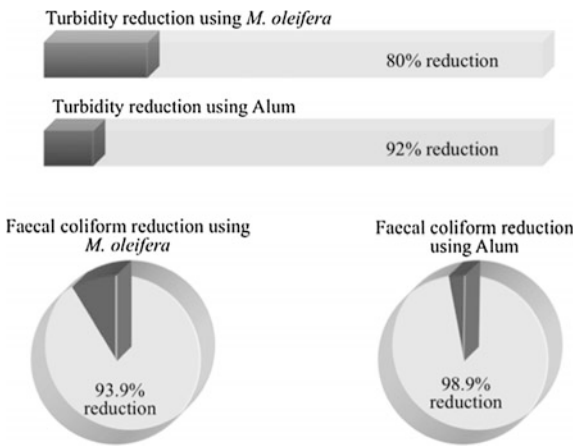

Fig. 18.6 Reduction in turbidity and faecal coliforms (FC)—*M. oleifera* versus alum

Figure 18.6 summarises the maximum reduction in turbidity and FC that can be achieved by using *M. oleifera* as a coagulant. This figure also denotes a direct performance comparison of *M. oleifera* to that of, alum.

(a)

	-ve control (5% saline)	+ve control (10% DMSO)	25 (mg/l)	50 (mg/l)	75 (mg/l)	100 (mg/l)
1	0	4	0	3	4	4
2	0	4	1	2	4	4
3	1	4	1	3	4	4
Average	*0.333*	*4*	*0.667*	*2.667*	*4*	*4*

(b)

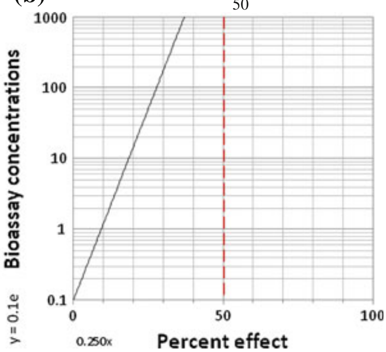

Fig. 18.7 Toxicity results from crude aqueous extract of *M. oleifera*. **a** Cytotoxicity. **b** Ecotoxicity

For the cytotoxic tests, healthy cells appear elongated while damaged cells appear squashed. Scoring ranged between one and four, i.e. from no destruction of cells to complete destruction of cells, respectively. A score of numerical grade larger than two is considered a cytotoxic effect—as indicated by the shaded column in Fig. 18.7a. The Thamnotoxikit tests aimed at determining the 50 % lethal concentration (LC_{50}) of the crude aqueous extract. This is the concentration that would kill about 50 % of the sample population in a 24 h period using the freshwater anostracan crustacean *T. platyurus* (Fig. 18.7b).

Discussion

The results indicated that shallow well water was heavily polluted microbiologically. The pollution level was significantly higher in the wet season. About 95 % of all the wells tested failed to meet the TC guideline value of 50 cfu/100 ml in the wet season, while about 80 % of the wells failed in the dry season (Fig. 18.3). Approximately 83 % of all the wells tested failed to meet the FC guideline value of 50 cfu/100 ml in the wet season, while about 50 % of the wells failed in the dry season (Fig. 18.4). The increase in the number of coliforms existing in the wet season could be due to the fact that there is an increase in the mobility of contaminants during the rainy season. In addition, there is a significant difference in the number of coliforms between some wells, with some having a very high level of contamination. This may be a result of livestock roaming free and poor sanitation close to these wells. FC values in excess of 1000 cfu/100 ml were noted in around 13 % of the water samples. This would suggest that such wells were grossly contaminated, with a very high probability of pathogens existing in the water.

The majority of chemical and physical parameters were within recognised guideline values (Table 18.3). Turbidity values (Fig. 18.5) were overall higher in the wet season than in the dry season. About 8 % of all the wells failed to meet the

MoWD (2003) guideline in the dry season. This figure increased to around 11 % in the wet season. It would be anticipated that turbidity levels would be higher in the wet season due to colloidal particles being transported more easily by the rains, which has been noted by Palamuleni (2002), Ndolo et al. (2002) and Msonda et al. (2007). However, in a few isolated cases, the inverse was true. This difference was ascribed to sampling being undertaken on non-rainy days or a dilution effect. Despite aesthetics, colloidal particles, which cause turbidity, can harbour pathogenic microorganisms. Hence, there is also a specific need to minimise this form of pollution in drinking water.

Sedimentation jar tests showed that the addition of the *M. oleifera* plant extract could considerably improve the quality of shallow well water. About 94 % reduction in FC and 80 % in turbidity was noted at optimum conditions (Fig. 18.6). Typically optimum dose concentrations for the *M. oleifera* crude aqueous extract ranged between 25 and 50 mg/l, and were dependent on the initial state of the water. Even though this amount of reduction does not quite match that of alum (about 99 % and 92 % for FC and turbidity respectively), treatment with *M. oleifera* significantly improves the quality of water.

At concentrations of <50 mg/l, the *M. oleifera* crude aqueous extract did not yield a toxic response from either the cytotoxicity or the ecotoxicity data. However, above this value the results appeared somewhat contradictory in that, around 50 mg/l, a toxic response was noted in cytotoxicity tests (Fig. 18.7a). However no toxic response was yielded from the ecotoxicity tests up to 1000 mg/l (Fig. 18.7b). According to a number of researchers (e.g. Jahn and Dirar 1979; Jahn 1984; Litherland 1995) there is no evidence that the toxin found in the cotyledon of *M. oleifera* seeds may have short-term toxic, long-term chronic or carcinogenic effects on humans. The cytotoxicity test was then repeated on the supernatant of the *M. oleifera* coagulated water and was found to be nine times less toxic, i.e. toxicity effects occurring around 450 mg/l. A point to note is that alum is highly toxic when used at incorrect concentrations—this was clearly demonstrated when 20 tonnes of the coagulant, mistakenly, entered the water supply at Camelford, Devon, UK in 1988 (Bestic 2012).

Conclusions and Further Work

The results indicated that shallow wells were grossly polluted with faecal matter exposing rural communities to high risk of water-related diseases. The pollution level was higher in the wet season especially soon after the onset of the rains, compared to the dry season in all the districts.

Apart from turbidity, the majority of other physical and chemical parameters were typically within acceptable values and did not change significantly with season. The overall average turbidity value had more than doubled in the wet season, with a small percentage failing to meet the appropriate guideline value.

Overall, water extracted from shallow wells does not meet appropriate guideline values, hence is unfit for human consumption. The use of a locally available natural coagulant, *M. oleifera,* has been demonstrated to significantly improve (by 80 %–94 %) water quality in terms of turbidity and coliform reduction.

To implement the use of local plant extracts, grown throughout rural villages, a novel small-scale 'bolt-on' shallow well water purification system is being developed. Initial field data demonstrates that improvement in shallow well water quality of around 80 % can be achieved. Hence, if implemented for every shallow well in Malawi around 1.5 million Malawians could have significantly improved water sources.

Further work is also on going in the microbiology laboratory at Leeds Beckett University to fully understand the toxic response observed from the cytotoxicity tests. Interest in applying the technology on a larger scale has been expressed by NGOs and the private sector and will be further developed once the full-scale site trial including toxicity testing has been completed and the appropriate protocols implemented. It is hoped that such a system will provide a unique sustainable and economical solution to significantly reduce waterborne diseases to some of the poorest people in the world.

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Chapter 19
Management of Water Resources in the Amazon Region

Nicola Caravaggio and Martina Iorio

Abstract Brazil has an energy matrix which is based on 45% of renewable sources, and more than 70 % of this electricity is drawn from hydroelectric plants. The present work tries to show how big hydroelectric projects, even if it is globally acknowledged as clean, can hide several threats for both humans and the environment. With this aim, the analytical tool of cost–benefit analysis (CBA) has been applied on two hydroelectric projects: the Tucuruí dam (already in operation—attempting to simulate an ex-ante analysis but using actual data) and the Belo Monte dam (not yet fully operating—using forecasts). The evaluation of the feasibility of both these projects is obtained by calculating the ENPV (economic net present value) and the B/C Ratio (benefits to costs ratio). Then subsequent arguments are proposed as to why a technical and quantitative comparison of these projects is difficult to implement in practice, due to uncertainties as to which SDRs (social discount rates) should be applied or upon which distinct formulas should be used to evaluate the amount of the CO_2 emissions.

Keywords Amazon region · Belo monte · Brazil · Cost–benefit analysis (CBA) · Hydroelectric · Tucuruí · Water

JEL Code O54 · Q25 · Q42

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Environmental and social damages and economic compensation for the existence of dams: A Cost-Benefit Analysis of two hydroelectric power plants (Tucurui and Belo Monte).

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Introduction

With a gross domestic product (GDP) of US$ 2.253 trillion in 2012, Brazil is currently the seventh wealthiest economy in the world (World Bank 2014). The country's recent growth has led to the increasing demand for energy and electricity, this has been driven growing urbanization and industrial capacity (Goldstein and Trebeschi 2014; Caracciolo 2014). Over the last decade, the continued debate surrounding the detrimental environmental impacts of fossil fuels has begun to shift energy production away from fossil fuels and towards renewable technologies. An abundance of natural resources appropriate for the production of clean energy and electricity has placed Brazil in a favourable position (ANEEL 2012). For example, hydroelectric schemes are widespread in the Brazilian Amazon region. This approach forms the key focus of this paper. With the aim of evaluating the feasibility of *big projects* such as hydroelectric power plants, the cost–benefit analysis (CBA) was applied to the case studies of Tucuruí and Belo Monte (European Commission 2014). The former is related to an *operational* power plant (which is appraised using historical data), whilst the latter is a proposed project (that is apprised using forecast data) (Eletrobrás 2014; NorteEnergia 2014).

However, new concerns about the potential of pollution from hydroelectric schemes have recently come to the fore. The present work aims to evaluate the real impact of the so-called clean energy technologies, such as hydroelectric plants (Fearnside 1999, 2000, 2001). It was undertaken as a part of the *AguaSociAL* network, an European FP7 joint exchange program that aimed to strengthen research cooperation and knowledge sharing between Brazil and Europe within the water-related sciences and social innovation.

Development and Economic Growth in Brazil

Brazil is the fifth largest country in the world, in terms of both geographical area and number of inhabitants, where the natives live together with dozens of ethnicities from around the world (De Masi 2014). It is a mega-diverse country with great abundance of natural resources (Goldstein and Trebeschi 2014). Brazil hosts the greater part of the Amazon region (64 %), the *Amazônia Legal* (Brazilian Legal Amazon), that is the largest socio-geographic division in the country, containing all nine Brazilian Federal States in the basin (Portal Amazonia 2014). Brazilian rainforest is well known all over the world for its fabulous biodiversity and the 20 % of the total fresh water in the world comes from the discharge of the Amazon River into the sea. The expansion of the electric energy sector has impacted Amazonian water resources (Fearnside 2000; Pinto 2012). The exploitation of these water resources for energy production represents a major driver for regional development. But this process, if not properly managed, can interfere with other economic, environmental and social variables which have an important role in both economic and human development; and could lead to water-related disputes, increase in equalities and penalizes indigenous and local people (PRODES 2001; UNDP 2014; FUNAI 2014).

Brazil has the most favourable condition in Latin America in terms of natural resources (especially water), and this makes the country a super power within its "subcontinent" (Caracciolo 2014). Brazil's GDP rate of growth peaked at 7.5 % in 2010, and it was widely considered that the country would maintain such rapid growth in the manner of Asiatic Tigers. But this has not been so. The Brazilian path was too much similar to a *voo de galinha* (Goldstein and Trebeschi 2014; Cauti 2015), and this was due to an adverse combination of structural factors, such as lack in infrastructure, taxation barrier, poor education and corruption. These resulted in the need for rapid intervention in some pivotal areas, satisfied by the implementation first of the PAC (2007) and then of the PAC2 (2010) (*Programama de Aceleração do Crescimento*). Brazil's demand for electricity is constantly increasing (annual +3, 9 %), this has led to a series of specific acceleration programs in the country's energy sector (e.g. *Agua e Luz para Todos*). In 2014, a federal program of financial concessions to private investors allocated US$ 74 million to be used in the energy sector: the Government of Brasilia have promoted important programs for the development of the electricity grid (SIN, *Sistema Interligado Nacional*) and have supported the augmentation of the installed capacity and boosted the diversification of the energy matrix, as part of wider efforts to ensure a fairer access to electricity throughout the country (Goldstein and Trebeschi 2014; PAC2 2014; EPE 2014).

The hydroelectric sector supplies 70 % of total Brazilian electricity demand. In fact, Brazil is the second greatest producer of electric energy from hydroelectric technology in the world, with 415 TW per hour, following only China's performance (872 TW/h); moreover, the country is also the third in the world for its net installed capacity of 84 GW, thus becoming one of the most efficient producers too (IEA 2012).

There are a significant number of power plants in the southern region of Brazil (ANA 2014). However, the greatest potential for developing the country's hydroelectric capacity appears to rely on the Amazon basin, as this is the less exploited area with the greatest availability of water resources. The future exploitation of the Amazon water resources seems to be unavoidable, although such schemes will surely introduce a large-scale change in the local hydrological cycle, in ecosystem services and in the connectivity between terrestrial and aquatic ecosystems. Presently, in the Amazon region there are 100 dams in operation (74 located in the *Amazonia Legal*) and 137 other dams that are going to be built (94 located in the *Amazonia Legal*), while—according to the PAC programme–8 of the new hydroelectric power plants related to the new dams above mentioned are planned to be built in the State of Pará (Belo Monte is one of these). This will affect a region of mega-diversity with profound consequences for the South American continent and for the planet (Tundisi et al. 2014; PAC2 2014).

The Hydroelectric Challenge in the Amazonia Legal. The State of Pará

During the eighteenth century, the emergent rubber industry (obtained from the latex extracted from rubber trees in Brazilian Amazon) attracted to the States of Pará and Amazonas an intense migration of people from other parts of Brazilor from abroad. That entailed a wide transformation of the Amazon region: sudden urbanization, wide occupation of the surface, creation of an urban net, improvement of fluvial navigation and intensification of non-fluvial axis (Trindade et al. 2014).

Following the decline of the rubber era, nut farming achieved a growing importance in the local economy: during this period much of the rubber work force remained in the region, moving to Belém or Manaus and turning these into central commercial centres (Rocha 2008; Trindade et al. 2014). Both of the phases above had a role in changing the morphology of the Amazon economy especially in the state of Pará. The local population continued to grow and resulted in an increasing demand for energy (to boost industry) and electricity (both for personal and industrial use). This led to the improvement of the energy installed capacity of the country, achieved by means of the construction of new *big projects*, such as hydroelectric plants. Due to the availability of local water resources, these developments were largely based on hydroelectric technologies. This caused some conflicts with respect to land occupation and river–forest protection. The first plants constructed in the state of Pará were Tucuruí and Curuá-Una, while the most important current project is that of Belo Monte (Rocha 2008; Eletronorte 2014).

A Cost–Benefit Analysis on Tucuruí and Belo Monte Projects

The Tucuruí Hydroelectric Power Plant is the largest engineering project ever undertaken in the Amazon region, and is located on the Tocantins River, about 350 km south of Belém. With a present capacity of 8.370 MW, it was built in two phases between 1984 and 2002. The project has a discharge capacity of 110.000 m^3/s, which is similar to the Three Gorges Dam in China. Its reservoir flooded 2.850 km^2 of land, making it one of the biggest reservoirs in Brazil (Eletronorte 2014). The Belo Monte Hydroelectric Project is located in the Volta Grande of the Xingu River, next to Altamira city. The original project dates back to 1975 but the construction work only commenced in 2011. The original proposal, with a reservoir area of about 1.200 km^2, that would have flooded some indigenous lands, has undergone a number of revisions. The final proposal provides two dams and two different reservoirs with a total flooded area of 516 km^2. Despite these modifications, protests against the realization of Belo Monte are still significant. Construction works at Belo Monte should conclude in 2019. The finished scheme should have an installed capacity of 11.233 MW, making it Brazil's biggest hydroelectric power plant and the fourth in the world. In fact, its anticipated annual average production of 38.790.000 MWh, is roughly equivalent to the annual production of the Fukushima Nuclear Power Plant in Japan (Norte Energia 2014).

Methodology

A CBA is presented for both the Tucuruí and the Belo Monte hydroelectric power plants. CBA is an analytical tool aimed at judging the economic advantages or disadvantages, of an investment choice. The CBA approach appraises project costs and benefits in order to assess the *welfare chang*e attributable to it. (European Commission 2014), which is based on both the amount and distribution of income and the presence of other social and environmental conditions required for reasonably comfortable, healthy and secure living.)

The CBA analytical framework refers to a list of concepts. First of all, opportunity costs are taken into account, which are the potential gains from the best alternative, when a choice needs to be made between several mutually exclusive alternatives. Secondly, a long-term outlook is adopted. Thirdly, the CBA is set giving a monetary value to all the positive and negative welfare effects. Finally, the CBA typically uses a microeconomic approach and the overall performance is measured by the *Economic Net Present Value* (*ENPV*), expressed in monetary values.

The analysis is generated by a simplified CBA version of the type generally used in the European Contest (European Commission 2014), taking into account previous empirical applications (EMGESA 2014; Júnior and Reid 2010; Commerford 2011; Chutubtim 2001; WCD 2000). It is also underpinned by field studies that were undertaken in Brazil. In fact, this is based upon field data (IBGE and local surveys). The study focuses on certain benefits and costs rather than others taking into account both the studies previously illustrated and the data availability).

In both of the case studies (Tucuruí and Belo Monte), a number of cost variables were selected and grouped into three macro areas: initial costs (meaning general or realization costs); environmental costs; and social costs. Then, economic, social and environmental benefits have been taken into account (Table 19.1).

The analysis left out several important variables—such as, loss in fisheries, loss in further deforestation, lack of management skills, urbanization and energy security. These omissions were due to the difficulty of the quantification and/or monetization of specific impacts (Table 19.2).

Moreover, there is the need to actualize flow values of costs and benefits at year zero. For both of the analyses, a social discount rate of 5 % has been chosen—as suggested by Cohesion countries (European Commission 2014). According to European Commission, the time frames—to be considered to evaluate big hydroelectric projects—varies from 15 to 25 years. In the present study, Belo Monte refers to a 25 years' time frame (EMGESA 2014) while in the Tucuruí case the reference period is of 30 years (age of the plant).

Table 19.1 Economic, social and environmental costs and benefits

	Tucuruí		Belo Monte	
Costs	*Basic Costs*			
	General Costs (construction costs and O&M)	Eletronorte (2014), WCD (2000)	Realization Costs (construction costs and O&M)	Norte Energia (2014)
	Environmental Costs			
	CO_2 emissions of reservoir (direct)	Commerford (2011), Steinhurst et al. (2012)	GHGs emissions	Demarty and Bastien (2011), Steinhurst et al. (2012), Teodoru et al. (2010)
	Deforestation (as uncaptured CO_2)	WCD (2000), INPE (2014)	Deforestation (as uncaptured CO_2)	INPE (2014)
	Social Costs			
	Reallocation of population	WCD (2000)	Reallocation of population	Commerford (2011), Eletrobrás (2009), IBGE (2014), WCD (2000)
	Loss of land for timber use	WCD (2000), IBGE (2014)	Losses in economic activities (i.e. agriculture and pasture)	IBGE (2014), Trindade et al. (2014)
Benefits	*Economic and Social Benefits*			
	Opportunity costs of Electricity (compared to Natural Gas)	Da Silva et al. (2005), Norte Energia (2014), Rocha (2008)	Opportunity costs of Electricity (compared to Natural Gas)	Norte Energia (2014), WCD (2000)
	Royalties on land and water usage	WCD (2000), Eletronorte (2014)	Transfers and Compensations Employment (direct and indirect)	Norte Energia (2014)
	Job opportunities (direct)	Eletrobrás/Eletronorte (2011)		Norte Energia (2014), IBGE (2014)
	Environmental Benefits			
	Lower GHGs emissions (compared to Natural Gas)	Commerford (2011), Menezes (2014), Steinhurst et al. (2012), WCD (2000)	Lower GHGs emissions (compared to Natural Gas)	Norte Energia (2014), WCD (2000)

Table 19.2 Omitted costs and benefits

Omitted Variables	*Omitted Costs*
	Loss in fisheries and in other economic activities
	Loss in further deforestation
	Loss in biodiversity
	Effects on indigenous population and lack of management skills of affected population
	Malaria and mosquitoes plague
	Omitted Benefits
	Urbanization
	Energy security

The Counterfactual Scenario

A CBA is a typically *ex* ante economic model, and it would compare a scenario *with-the-project* with a counterfactual baseline scenario *without-the-project*. A counterfactual is defined as what would happen in the absence of the project.

Firstly, projections are made for the situation with the "proposed" project; then, the CBA only considers the difference between the scenario *with-the-project* and the counterfactual scenario *without-the-project*. This approach is useful to understand where a new investment (i.e. the construction of an hydroelectric plant) affects the social welfare and where it does not.

The hypothesis of a scenario *without-the-project* is feasible—and useful to be analysed—for the Belo Monte case study, which is still in construction. But that approach is neither appropriate nor useful for Tucuruí, as it is not possible to go back in time. In fact, in the Tucuruí case the project has been completed almost 30 years ago. It represents an exception inasmuch it has been appraised by an *ex post* CBA, and it makes a nonsense trying to evaluate its background without-the-project.

An alternative strategy would be to substitute the comparison between different scenarios at each site (i.e. with, and without, the completed project for each one of the power plants) with a comparison between the two *projects* themselves, Tucuruí and Belo Monte. Unfortunately, this is not a straightforward exercise due to a range of factors that distinguish Tucuruí from Belo Monte. Firstly, these obstacles include: the different time frames considered (30 years/25 years), the different geographic areas (Tucuruí/Altamira), the different political set-ups (dictatorship/democracy), the change in currency (*cruzeiro real*/*real*) and variation in inflation. Secondly, we applied a classical (but simplified) *ex ante* scheme on Belo Monte project, whilst using an unusual *ex post* approach in the Tucuruì case. Moreover, these two CBA applications compared output generated as a consequence of a change in the calculation of the CO_2 emissions from the reservoir according to different methodologies highlighted in the literature (i.e. these changed from the Commerford formula for Tucuruí to the Steinhurst et al. one for Belo Monte).

In conclusion, the main future challenge of the present model—in terms of counterfactuals and the future comparisons—remains levelling out methodologies and outputs of calculations. That will allow a fairer comparison between the two projects, providing new tools for managing the future projects as well as the work-in-progress phase of BeloMonte.

Results

The *Economic Net Present Value* (ENPV) is calculated in order to appraise the convenience of the project, as costs and benefits have been obtained. The ENPV shows the difference between the discounted total social benefits and the discounted total social costs and it is obtained by the following formula (EMGESA 2014; European Commission 2014)

$$\sum_{\mathrm{t}=0}^{\mathrm{n}} = \frac{B_{\mathrm{t}} - C_{\mathrm{t}}}{(1+i)^{t}}.$$

B_{t} = Benefit at time t
C_{t} = Cost at time t
i = Social discount rate
n = Number of years

A positive economic return shows that the society is better off with the project, i.e. the expected benefits on society justify the opportunity cost of the investment (European Commission 2014).

The final analysis for the Tucuruí plant shows a positive ENPV during the considered 30 year time frame. The benefit/cost ratio is about 52,66 (US$ 292.839.599.311,36/US$ 5.561.352.747,89), this means that each US$ cost generates 52,66 US$ of benefits.

As regards Belo Monte, results indicate a positive ENPV of US$ 956.113.156,68 (US$ 11.683.627.107,94/US$ 10.727.513.951,25) and a B/C Ratio of 1,09, this means that each US$ cost generates US$ 1,09 of benefit.

Therefore, considering the variables used and the obvious limitation of this analysis, the final results show a positive net benefit resulting from the realization of both of the considered hydroelectric plants.

Discussion

The obtained positive results are not very impressive since a lot of detailed studies have pointed out substantial negative impacts from both the social and the environmental points of view. The discrepancy between the output of the model and those practical observations would be related to different causes.

Several costs have never been declared by the government due to the country's former dictatorship (i.e. this would only apply in the case of Tucuruí), while compensations are often documented better than costs when representing a credit for the authorities. Moreover, compensations are very small compared with the great amount of the loss they generate and biodiversity is almost always not included. On the one hand, even if the biodiversity monetization methodology is both not unanimously agreed and very complicated, it does not mean that hydroelectric plants do not affect it. On the other hand, if it had been included, it would have strongly influenced the final result.

Even if the social discount rate used is fixed at 5 % for both of these cases (as per European Commission 2014), it should really have been selected by considering all the key factors that could potentially affect it. Given all the environmental and social issues generated by the realization of the power plants both of Tucuruí and of Belo Monte, a social discount rate of 5 % would seem to be too low in both the cases. That is because actually, not taking into account all social and environmental issues means erroneously moving the social preference on the realization of these *big projects* to present time. The SDR would rocket instead due to those factors up to achieve an ENPV <0. A simplified sensitivity analysis (as performed by EMGESA 2014) is practicable by varying the intertemporal discount rate for society (SDR). The higher the SDR the lower the incentive to launch the new projects. Variations of the economic net present value (ENPV) and the benefit/cost ratio due to changes in the social discount rate are shown (Charts 19.1, 19.2). These variations are made in order to consider the change of society's intertemporal preferences.

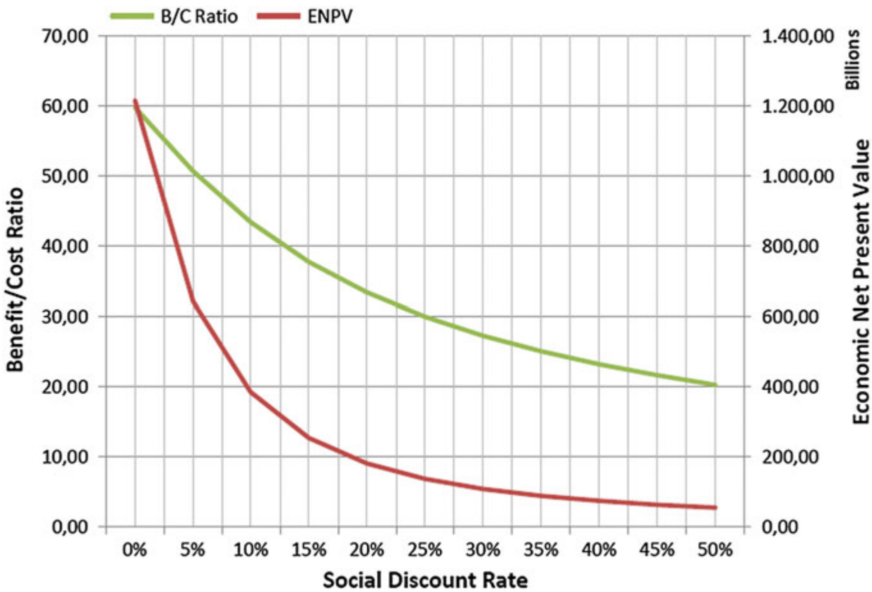

Chart 19.1 Sensitivity analysis (ENVP and B/C ratio with social discount rate variation)—Tucuruí

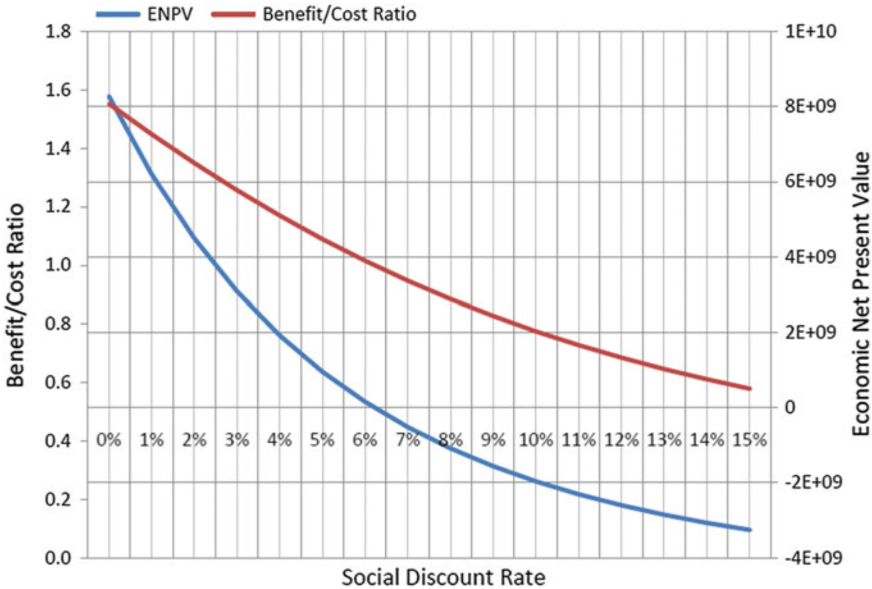

Chart 19.2 Sensitivity analysis (ENVP and B/C ratio with social discount rate variation)—Belo Monte

Unfortunately, it is not easy to achieve an accurate evaluation for all these factors, making it difficult to accurately quantify the level of the variation of the SDR, for both the cases.

Eventually, besides all the matters above, both the lack of capability in money management of beneficiaries and the waste of money due to the corruption could strongly affect the final results.

Conclusion

The energy sector in Brazil is certainly among the most promising in the country. The Federal Government has a growing interest in the development of renewable, especially as regards the electricity generated by hydroelectric plants. Unfortunately, hydroelectric dams have generated serious environmental damages and have brought immense sufferings to indigenous and local people, who can rarely enjoy their potential benefits. In fact, these kinds of plants could be also even more polluting than coal plants, mostly because of their greenhouse gases emissions. But enthusiasm for large dams today is still very strong. The Brazilian project of Belo Monte on the Xingu River is going to provide low-cost electricity and will become the third largest scheme in the world. It will flood a large portion of land, causing huge devastation to the rain forest and reducing the availability of fish which many indigenous tribes depend on (Survival International 2010), learning little from the previous experience of Tucuruí (Fearnside 2001; Pinto 2012). The Eletronórte, the state electricity company owned by Eletrobrás, built the dam of Tucuruí in the 1980s to supply power to mining projects and now the Tucuruí dam produces a sixth of the greenhouse gas emissions from all over Brazil (INPA 2014). The dam also has evicted several indigenous peoples and destroyed the stocks of other tribes. WWF calculated that the catch has declined by 60 % after the close of the dam (Survival International 2010).

According with the CBA results, both Tucuruí and Belo Monte must be considered as positive as they contribute to enhance the social welfare in Brazil. Nevertheless, since the construction of the Tucuruí plant several debates have occurred about the actual sustainability of this kind of technology. Academics such as Philip Fearnside and journalists such as Lúcio Flávio Pinto have suggested that this also represents an important case study to identify the four key lessons that should be learned in order to ensure a fairer scheme is achieved at Belo Monte (Pinto 2012; Fearnside 2001). Firstly, it is important to control all costs: new tools to improve the evaluation of costs are available, and that is an important starting point to avoid the systematic underestimation of costs, often combined with overestimation of benefits (Tundisi et al. 2014). The second step is considering the matter of the individuation of real beneficiaries: "To whom the benefits (of the entire hydropower project, of course) accrue?" (Fearnside 1999). Thirdly, in the process of decision making in this kind of project, clearly concerning the public interest, the central Government should grant its decision to be occurred without any external influence, especially if related with private interests and especially in the absence of dictatorship. Finally, information has a pivotal role: publicity of information about great projects generates more awareness within the local population and allows affected—directly or indirectly—persons to actively and consciously participate in public decisions and, of course, better succeed in influencing them. According to the opinion of Lúcio Flávio Pinto, the history of the hydroelectric plant of Belo Monte, is characterized by the same changes in direction as was the Tucuruí project. But, while Tucuruí was conceived during a dictatorship period, Belo Monte is a great public work produced by democracy. It is absurd that lack of transparency and presence of corruption combined with the persistent behaviour of the government in underestimating impacts are still dominating new projects, jeopardizing this *earthly paradise* to be used only as a peripheral provision source, creating a solid barrier to the real economic and human development of the region (Pinto 2011, 2012).

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Field Materials (Interviews and Tours)

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Guided visit of the hydroelectric plant of Tucuruí with Mr. Anderson (Eletronorte) (2014).

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Interviews with Brazilian citizens of the Pará State.

Interviews with various professors of UFPA, UEA and INPA (Instituto Nacional de Pesquisas da Amazônia).

Part VII
Cities and Neighbourhoods

Chapter 20
Overcoming Barriers to Making Cities More Sustainable: How Can Short-Term Thinking Help Achieve Long-Term Goals?

Rachel Huxley

Abstract Cities are critical to addressing sustainable development: over 50 % of us live in cities; they consume 75 % of global resources, over two thirds of all energy and account for 70 % of global CO_2 emissions. Cities have responded to this challenge with a large number committing to sustainable visions and/or initiatives such as the C40 Cities Climate Leadership Group or ICLEI Local Governments for Sustainability network. Whilst there are pockets of best practice, we are not seeing the speed or scale of change required in terms of resource use, carbon emissions or well-being. Cities are struggling to achieve long-term goals in the face of short-term pressures, capacities and practices such as budgeting, political cycles and procurement approaches. Rapid change and uncertainty, especially in technology, is also a challenge. This paper reviews the transition literature to identify and evaluate how transition theory can be used to understand and overcome this implementation gap. The findings show that the transition management model offers a promising approach but with significant weaknesses and gaps. However, these can be addressed by drawing on other theories and models of change. The paper concludes by proposing a new framework for change incorporating short-term processes, demand drivers and evaluation into the transition management model, and proposing areas for research.

Keywords Cities · Climate change · Sustainability · Transition

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Introduction

From the author's experience as a practitioner in the field of sustainable cities, there is genuine commitment from many cities to become sustainable, the problem is that these (or indeed any other) cities are not achieving the scope or speed of progress required. This is backed up by the literature which acknowledges that progress is insufficient (Bulkeley et al. 2010; Newman and Jennings 2008; Rauschmayer et al. 2015) and by the 'science' in terms of, for example, the findings of the IPCC fifth assessment report.

The fact that cities remain unsustainable despite commitments to the contrary is the rationale for this research. Why does this implementation gap exist between cities' long-term aspirations and their short-term realities?

This paper reviews the transition literature as a potential solution to understanding and solving this dilemma. The aim is to provide: first, a brief introduction to sustainable cities; second a brief overview of transition theory; third, a review of the weaknesses and gaps in transition theory; and fourth, a proposal of how it could be strengthened by drawing on other theories and models, together with research recommendations for how this might be applied to the challenge of sustainable cities.

Sustainable Cities

Why Are Sustainable Cities Important?

> There will be no sustainable world without sustainable cities
> (Girardet 1999)

There is a strong agreement about the need for sustainable cities (Satterthwaite and Dodman 2013; Bulkeley et al. 2010; Newman and Jennings 2008; Girardet 1999; Guy and Marvin 1999). Cities are home to over half the world's population, and they continue to grow; by 2050 it is estimated that over 75 % of us will live in cities (United Nations 2012). As such, cities are significant sites of consumption and have a significant environmental impact; they occupy less than 2 % of the earth's surface yet they consume 75 % of its resources, over 2/3 of all energy and account for 70 % of global CO_2 emissions (Environmental Translation Project 2010; IEA 2009). In the UK, the 64 largest cities accounted for 45 % of emissions (Clarke et al. 2013).

But as well as being key contributors to our current unsustainable situation, cities also offer huge potential for solutions. As centres of creativity and industry, they can innovate and act; for example the world's leading cities are already taking over 4700 actions to tackle climate change (C40 2013). As dense, efficient urban systems they can provide efficiencies; cities in the UK have 17 per cent lower per capita emissions than the rest of the country (Centre for Cities 2013). As concentrations of people, they can deliver social benefits; it is easier to provide, and access, services like potable water, health care and education in cities (WHO and UNICEF 2011). And as economic centres, they can deliver growth; cities outperform other areas, the world's largest cities achieved either GDP per capita and/or employment growth rates that exceeded national averages in 2012 (The Brookings Institute 2012).

Given the challenge and potential of our cities, if we are going to solve sustainable development then cities will have to play a leading role.

What Are Sustainable Cities?

Most sustainable city definitions apply the generally accepted principles of sustainability to the city; the concept of inter- and intragenerational equity and the triple goal of environmental, social and economic sustainability (Bulkeley and Betsill 2005; Brundtland 1987). Giradet (1999, p. 13) for example, gives the following definition: "A 'sustainable city' is organised so as to enable all its citizens to meet their own needs and to enhance their well-being without damaging the natural world or endangering the living conditions of other people, now or in the future."

However, whilst there is broad consensus regarding the overarching principles of sustainable cities the details of this, i.e., defining the practical elements of sustainable cities, are 'hotly contested' (Smith and Stirling 2010; Bulkeley and Betsill 2005).

Both sustainability and cities are hard to define, so combining these concepts is even more challenging (Muñoz-Erickson 2014; Guy and Marvin 1999; Camagni et al. 1998). Sustainability is an inherently ambiguous, complex concept and detailed end goals are not possible to define (Voss et al. 2009). And the complexity and scale of cities means attempts to define them are 'doomed to failure' (Scott and Storper 2014).

To add to this debate, Guy and Marvin (1999) argue that a single definition of sustainable cities is not realistic or helpful. Given the variety of cities and the complexity of sustainability, no single definition will work for all. Instead multiple definitions and pathways to sustainability are required. Newman and Jennings (2008) also state that within overarching principles each city will have to define the details for themselves.

Finally, Whitehead (2003) observes that even where definitions are agreed they are not then fixed or static, instead as products of an ongoing discourse they are dynamic and constantly evolving.

The Sustainable Cities Implementation Gap

The challenge of how to plan, build and manage socially and environmentally vibrant cities has been pursued for centuries (Cook and Swyngedouw 2012). However, there is broad agreement in the literature that the goal of sustainable cities is not being achieved (Bulkeley et al. 2010). Owens and Cowell (2002) refer to an 'implementation deficit' with little evidence of real sustainable progress in cities. So the question of how to achieve sustainable city visions, i.e., how to achieve real change on the ground, remains paramount. This leads us to the main aim of this paper; a review of the transition literature as a potential solution to understanding and solving this dilemma.

Transition Theory

Transition theory has developed in response to the persistent sustainability problems that society faces and the challenge of achieving transformative sustainable change (Markard et al. 2012; Grin et al. 2010; Voss et al. 2006; Loorbach 2004). Grin et al. (2010) state that persistent problems are particularly tricky given they are (1) a result of modern society and (2) beyond the capacity of our current, modernist systems to resolve. Geels (2010) adds that the 'new environmental problems' we are facing now are more complex and 'wicked' than those of the 70s and 80s and refers to the need for 'substantive transitions.' Voss et al. (2006) highlight that the complexity of sustainable development precludes 'blueprint' thinking, proposing that a more reflexive approach is required—a change from command and control to a more learning and adaptive form of management.

Sustainable transitions are defined as "a fundamental transformation towards more sustainable modes of production and consumption" by Markard et al. (2012, p. 995) and by Grin et al. (2010, p. 1) as "a radical transformation towards a sustainable society as a response to a number of persistent problems confronting contemporary modern societies." Transition theory has a normative sustainable goal and seeks to address two central questions: one, how does change occur? and two, can we steer it? (Grin et al. 2010).

A Brief Overview of Transition Theory

Grin et al. (2010) provide a comprehensive overview of the emerging sustainable transitions field and its theoretical underpinnings. They outline the three main approaches within the transition field: analysis of historical transitions from a socio-technical perspective; development of a management approach for contemporary transitions using a complexity perspective; and review from a governance perspective using structuration theory and the concept of reflexive modernisation.

They highlight two common underlying concepts; the multi-level perspective (MLP) and coevolution. The MLP uses the concept of three levels: the macro or landscape level where broad, overarching political, social and cultural trends occur at a gradual pace; the meso or regime level where dominant actors and practices operate in a dynamic equilibrium where change is constant but incremental; and the micro or niche level where experimentation occurs and successful innovations (and their supporting coalitions and systems) develop to the stage where they can breakthrough into the regime, change at this level is fast paced. It is the nature and timing of interactions between levels that shape transition pathways.

The concept of coevolution describes how interaction between and within levels influences the dynamics, and evolution, of the levels. Technical and social aspects coevolve and subsystems of e.g., energy and water coevolve.

Gaps in Transition Theory

Transition theory is an emerging field, it offers huge promise for understanding and resolving sustainable challenges but there are also weaknesses and gaps that still need addressing (Markard et al. 2012). This section looks at the key gaps as relevant to this research agenda on the sustainable cities implementation gap.

Understanding the Long- and Short-Term of Sustainable City Visions

It is unclear whether transitions are, can or should be, vision led (Kern 2011). The historical analysis to date concludes that past transitions have not been vision led (Geels and Schot 2007; Voss et al. 2006). However, current transition management work seeks to do just that (Rotmans et al. 2001; Loorbach 2004), but transitions take generations to occur so it is still too soon to judge if attempts at steering have been successful or not (Grin et al. 2010). This begs the question; are long-term visions being translated into the system processes that drive short-term decisions. If the current city system is not being changed as a result of, and in line with, long-term visions then how will change from the status quo occur? Voss et al. (2009) state that so far transition management in practice has been ‘layered’ over the current system without fundamental system change. Seyfang and Haxeltine (2012) observe a disparity between short-term action and long-term goals in their analysis, the transition town movement. And Kemp et al. (2007) highlight the headache policy makers have in setting short-term steps towards long-term goals, and they note that there is a lack of theory on this.

Other scholars also raise this issue but articulated from the reverse perspective; how can we understand the impact of today’s policies on tomorrow’s outcomes (Markard et al. 2012; Arts et al. 2006). And still others call for a process versus vision-oriented approach; another articulation of the long-term vision and short-term system processes (mis)alignment (Chatterton 2013; Cook and Swyngedouw 2012).

Measuring and Evaluating Progress—Is Our Short-Term Direction on Course for Our Long-Term Destination?

Transitions occur over generational timescales (Loorbach and Rotmans 2006). This raises the problem of how to judge success, or otherwise, of transitions until the generational change process has concluded; therefore how can we know if we are on course or not? This is important for three reasons. First, in order to determine if cities are affecting the change they envision they need to be able to measure progress in the short term. Second, in order to monitor the risk of unforeseen consequences associated with large-scale transformative change (Smith and Stirling 2010; Shove and Walker 2010; Smith et al. 2005). Third, transitions require reflexive governance where learning is ongoing and management is continually adapted (Voss et al. 2006). Without the means to measure and evaluate progress, there is no information to inform this reflexive governance.

Power, Politics and Agency

One of the major criticisms of transition management is the lack of attention to power and agency and the apolitical approach to a very political issue (Rauschmayer et al. 2015; Geels 2014; Meadowcroft 2011; Foxon 2011; Smith and Stirling 2010; Smith et al. 2005). The assumption of largely rational actor behaviour means the role of power and agency are neglected (Geels and Schot 2007; Smith et al. 2005). Highly political questions around the 'winners and losers' of transitions are also not adequately addressed (Smith and Stirling 2010).

Understanding Regime Processes—The Day-to-Day Decisions

Another key criticism of transition theory is the emphasis on innovation at the niche level, an obsession with the novel as the solution (Geels and Schot 2007; Berkhout et al. 2004). Whilst this has provided a strong body of work on niche innovation, there is a relative gap in work at the regime level; a much greater understanding of regime processes is needed (Geels 2014). Geels (2014) highlights active resistance to change from the incumbent regime as one of the major factors in creating, or resisting, transitions. Therefore, citing regime destabilisation as key to the processes of change, and calling for greater understanding of this destabilisation processes.

An additional issue with the emphasis on innovation is the concurrent emphasis on technology and supply-side drivers (Geels 2014; Shove and Walker 2010). Responding to the technology focus, Geels (2014) calls for further research into non-science and non-technical innovations, e.g., civic and urban innovations.

Responding to the supply-side focus, Shove and Walker (2010) highlight the importance of user practices in transitions and state that they have are 'routinely ignored.'

Research into resistance, destabilisation, practices and demand-side drivers would provide a fuller picture of the regime processes that govern day-to-day, short-term decisions and their impact on long-term transition agendas.

Empirical Data—A Good Case for Sustainable Cities

There is a growing number of case studies on historical transitions (Geels 2005a, b; 2006), however there is a lack of current empirical research. Cities with ambitious sustainable visions provide potential case studies for transitions. As argued at the start of this paper, cities are critical for sustainable development so building a body of empirical research on the transition journeys of cities is a hugely important task. Bulkeley and Betsill (2005) refer to the range of scales of governance acting on cities, the role of power and capabilities and the entrenched policy communities relating to cities—all of these aspects make for good case studies.

In addition to this, transition theory has been applied at the subsystem level as the unit of analysis (e.g., energy, water) (Grin et al. 2010). Whilst tackling change at subsystem level is a practical approach it does inherently reinforce subsystem silos. Sustainable cities pose a particular challenge as integrated management across systems is required (Bulkeley et al. 2010). So from a sustainable cities perspective, there is a gap in transition work on whole-system approaches where the unit of analysis is geographical (in this instance the city) not systemic.

Filling in the Gaps—How Can Theory from Other Fields Help?

A number of scholars have suggested possible approaches to strengthen the existing transition theory. This paper looks at six approaches as particularly relevant to researching sustainable city implementation gap:

Quasi-Evolutionary Approach

Smith et al. (2005) propose a quasi-evolutionary approach to help understand transitions. They use the term quasi-evolution in recognition that evolution in this context is not blind, unlike biological evolution. Regime change is conceptualised as a function of two processes; shifts in selection pressures and changes in the capacity to adapt. They note that selection pressures have to be perceived and articulated by actors before they have an impact. This quasi-evolutionary approach can be used to understand what drives short-term decisions within the regime; what selection pressures and adaptive capacities are helping or hindering the short-term steps towards long-term goals.

Institutional Theory

Scott (1995) has synthesised institutional theory to develop three pillars: regulative (e.g., regulations, laws), normative (e.g., values, standards) and cultural-cognitive (e.g., heuristics, cultural trends). Geels and Schot (2007) reference these 'rules of the game' as a useful framework for understanding system transitions. This institutional approach can help identify drivers of short-term decisions across the institutional spectrum; from formal, enforced regulations to habitual, unconscious practices. Institutional theory helps to analyse where and how decisions within the current regime are made; what current institutional processes and practices helping or hindering short-term steps towards long-term goals?

System 'Failures'

Weber and Rohracher (2012) have combined findings from innovation systems and MLP work to generate a 'failures' framework. They take the established four market failures (information asymmetries, knowledge spill over, externalisation of costs, over exploitation of the commons) and add four additional structural system failures taken from innovation studies (Infrastructural, institutional, network, capabilities), as well as themselves developing a further four transformational system failures (directionality, demand articulation, policy coordination, reflexivity failure). They use the notion of 'failures' in order to resonate with the policy discourse and legitimise calls for system change.

Power and Politics

Geels (2014) acknowledges the neglect of power, agency and politics in transition theory, but suggests that it can be incorporated. Firstly by analysing the relations between incumbent firms and policymakers within the regime—Geels states that the political power of the industrial networks is so well orchestrated it needs to be the central focus. Secondly by understanding how regime actors mobilise power in order to resist change—Geels proposes four forms of active resistance: instrumental (actors using resources in immediate interactions); discursive (shaping what is discussed and how); material strategies (using technical and financial resources to improve the regime); broader institutional power (embedded political cultures, ideology and government structures).

Practice Theory

Shove and Walker (2010) propose the use of practice theory in understanding and governing transitions in 'everyday life.' Practice theory can provide insights into how new practices come into being, and what impact this might have on the selection pressures and adaptive capacities of the demand side of the regime.

Capability Approach

Rauschmayer et al. (2015) have in a similar exercise to this paper, looked at the weaknesses of transition management and drew on other theory to create a stronger model (though not with a sustainable city emphasis). They incorporated practice theory for similar reasons as outlined above. In addition, the capability approach is used as a method to evaluate progress, addressing the measuring and evaluation issues outlined in Section Gaps in Transition Theory.

A Hybrid Framework for Further Research

Figure 20.1 shows a potential hybrid framework based on: (1) transition theory as the foundation; (2) using a quasi-evolutionary approach to analyse decision drivers in terms of adaptive capacities and selective pressures; (3) using institutional theory to gain depth of understanding drivers across the spectrum from formal regulatory factors to unconscious cultural-cognitive factors; (4) drawing on potential drivers identified within the literature—12 system failures, 4 forms of active resistance, user practices; and (5) using the capabilities approach to measure and evaluate progress.

Not all the elements would need to be utilised, the nature of the research would determine the relevant ones. For example, the measurement and evaluation element might not be relevant for research looking only at drivers within the regime.

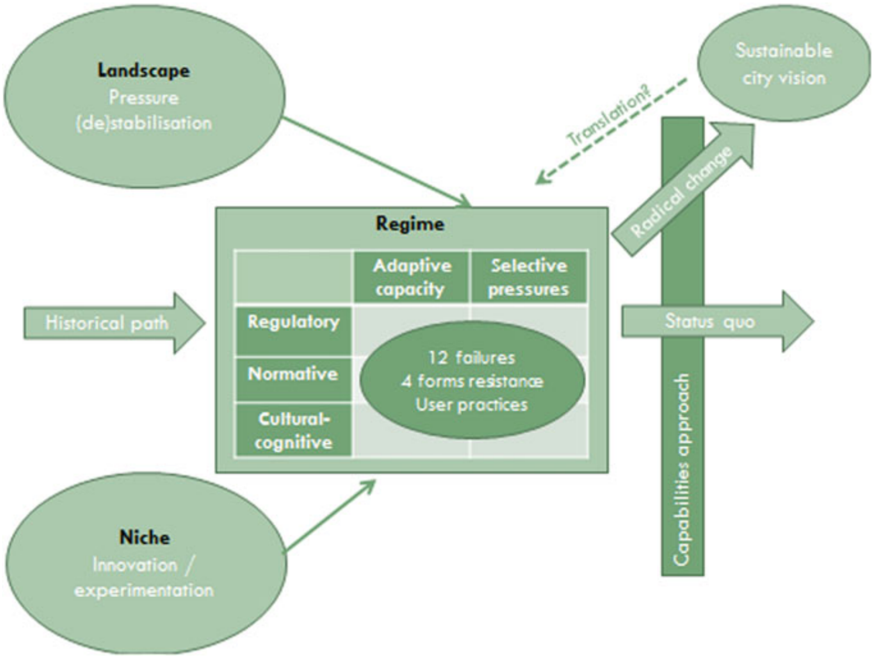

Fig. 20.1 Hybrid framework for analysis

Calls for Further Research

The following research areas are proposed based on the gaps in transition theory and the potential areas the hybrid framework can help explore—as specific to this sustainable city implementation gap research agenda:

1. Research to identify what the drivers (pressures, capacities, processes and practices) of short-term decisions are and how they constrain or enable progress towards long-term sustainable city visions.
2. Research to better understand both the translation of long-term visions into short-term systems, as well as the implications of short-term (policy) decisions on long-term visions. Identifying policy and practice recommendations for changes to the current system (drivers of short-term decisions) in order to achieve long-term goals.
3. Empirical research to test the drivers identified in the literature to determine size and frequency of occurrence, and to identify any additional drivers acting on sustainable city actors.
4. Case studies of sustainable city transition experiments to provide contemporary empirical data on transitions and to look at whole-system change (vs. subsystem analysis).

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Chapter 21
The Rejuvenation of a Historical Neighbourhood in South Africa

Chuma Sineke and John Smallwood

Abstract In South Africa, many cities have retrogressed over the years. Disinvestment in the inner cities and the flight to suburbs in the 1980s and early 1990s by business and retail was propelled by the manifestation of deteriorated buildings, an increase in slums and crime and a shabby, poorly managed urban environment. Central Hill, Port Elizabeth, as in many other cities in South Africa, was unable to escape this phenomenon. There have been efforts to revive the area abounding the central business district (CBD), however, those efforts have often overpowered by the overwhelming challenges that are associated with Central Hill, such as a lack of resources, the prevalence of drugs, prostitution and general crime. Twenty interviews were conducted with individuals from different backgrounds both professionally and socially to determine the challenges faced by Central Hill, the causes of the challenges, and possibly, a solution to the challenges. These included residents, business people, built environment professionals and property developers closely affiliated with Central Hill. The salient findings show that drugs, prostitution, poorly managed buildings by landlords and residents, security and crime are major challenges in Central Hill. Conclusions include that there is a need for a new meaning, plan and vision for Central Hill that it can be identified with, and carried forward. Recommendations include the development of a strategic plan incorporating all stakeholders to carry the vision of a rejuvenated Central Hill forward, in addition to interventions such as law enforcement, and incentives for landlords.

Keywords Decay · Neighbourhood · Rejuvenation

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Introduction

Cities play a crucial role as engines of the economy, as places of connectivity, creativity and innovation and as centres of services for their surrounding areas. More and more people are moving to cities in the hope of finding jobs, as well as having better access to services and amenities, not least in South Africa. However, many cities have retrogressed over the years. Disinvestment in the inner cities and the flight to the suburbs in the 1980s and early 1990s by business and retail was propelled by the deterioration buildings, the increase in slums and crime and a shabby, poorly managed urban environment. Central Hill, Port Elizabeth (PE), as in many other cities in South Africa, was unable to escape this phenomenon. It is therefore important that a study of this nature be conducted not only because of the rich history of Central Hill, but also because the lack of regeneration results in disinvestment, and disinvestment has major implications.

Duncan and Landau (2014: 1) mention that disinvestment has different potential outcomes, i.e.:

- Limitations on facility use—in terms of capacity, size or weight;
- Degradation of facility performance—in terms of speed or reliability;
- Sporadic consequences—in terms of incident risk, and
- Catastrophic failure—leading to loss of life, cargo or service.

There have been numerous international initiatives relative to socio-spatial challenges in historic landscapes. These include:

- the Round Table on the Renewal of Inner City Areas by the UNESCO Social and Human Sciences Sector (1996);
- the Conference on City Centres: Ethical and Sustainable Socio-economic Rehabilitation of Historical Districts (2002), and
- the UNESCO publications: Socially Sustainable Revitalisation of Historical Districts (2002) and Historic Districts for All: a Social and Human Approach for Sustainable Revitalisation (2008).

Gunay (2012: 4) states that the initiatives focused on the idea that the rapid, uncontrolled and ambitious development, while resulting in socio-spatial segregation, is transforming urban areas with the potential to deteriorate urban heritage with deep impacts on community and their collective values; and they build up strategies in facilitating socially sustainable and inclusive conservation-led regeneration strategies in historic landscapes.

Central Hill, was once a clean, safe neighbourhood, bustling with economic activities and a sense of belonging for the residents. According to Nelson Mandela Bay Tourism (2015: 1) before the upcountry gold and diamond booms, PE developed as one of the main commercial cities in South Africa (SA), trading in wool, mohair and ostrich feathers. As a result, the harbour became a bustling port. People travelled to the city in search of trade and labour opportunities. The diverse community lived in Central Hill as it was in the centre of all the activity. Today, many of the characteristics that made Central Hill barely exist. Crime is rampant, litter is found all around the streets of Central Hill, dilapidated buildings paint an unpleasant image of the Central skyline, and residents are disconnected from each other opting to stay indoors as a result of safety concerns as well as lack of attractions.

Masuku (2003: 30) reports that in a survey conducted by the Institute for Security Studies in late 2002 with respect to victimisation in the Nelson Mandela Metropolitan Municipal (NMMM) area, where 3300 people were interviewed, 23 % claimed to have been victims of crime in 2002. These crimes ranged from theft, burglary followed by violent crime aimed at property, such as robbery. Of those crimes addressed in the survey, the most common crime occurring in the NMMM area in 2002 was burglary of homes, followed by robbery, and theft out of motor vehicles.

According to Pityana (2006, cited by Wingate-Pearson 2006: 7), "PE is the largest city and the fastest growing economy in the Eastern Cape (EC), and is well positioned to take advantage of the opportunities available to it." However before an area such as Central Hill can take advantage of the opportunities available, it needs to get the basics right, basics such as delivering services at a reasonable price and that means picking up garbage on time, providing clean water, installing street lights and rendering a safe and secure environment. Once the basics are in order, Central Hill can embark on a rejuvenation project, which will include urban renewal through infrastructure development and capturing the cultural diversity in PE.

How a neighbourhood can transform from being safe and clean, with a lot of economic activity to one that is the complete opposite of that is the first reason for the study. It is important to understand the cause for such changes before rejuvenation can be implemented. The root problem needs to be understood and completely rooted out to ensure that it does not resurface in the future and that is the approach and focus of this particular study, undertaken to address and evolve solutions to the challenges, as well as to rejuvenate Central Hill.

Review of the Literature

Central Inner City Decline

A city is generally an active place with an interconnected web of relationships. Businesses are reliant upon people, who in turn, need a home for shelter, parks to relax, libraries and theatres, shops and town halls, functions which are intertwined and dependent on one another for success. Bearing the above definition and information in mind, the first change to many cities and their CBDs in South Africa was the "the flight of the traditional white business and residential base to the suburbs that left abandoned and mothballed buildings in its wake" (Hattingh 2013). These buildings were then occupied by previously disadvantaged individuals, who, after the abolition of Apartheid and many of the Apartheid laws had the opportunity to live in the city.

Crank (2007: 1) states that the inner city core of PE is a place characterised by opposites with the one hand, during the daylight hours it is a vibrant, multi-layered space which is embodied by highly commercial edges and informal vendors who cater to the mass traffic which flows through the main street of Govan Mbeki Avenue daily. On the other hand, when the nine to five business hours are over, the vibrancy fades and what is left is the empty, run down, single function buildings.

The City of Redlands (2011: 2) states that adverse physical changes to the environment from economic effects generally manifest themselves in the form of urban decay. Although the term 'urban decay' has not been defined by either State statute or judicial decision, it is generally defined as, among other, characteristics, visible symptoms of physical deterioration that invite vandalism, loitering and graffiti, that is caused by a downward spiral of business closures and long-term vacancies. The outward manifestation of urban decay includes, but is not limited to, boarded doors and windows, dumping of refuse, deferred maintenance of structures, unauthorised use of buildings and parking lots, littering and dead or overgrown vegetation, a situation which is ever so prevalent in Central Hill. In addition to the political changes in South Africa, as well as adverse changes to the environment from economic effects as stated above, Lanrewaju (2012: 424) mentions urbanisation, overpopulation, poverty and all kinds of pollution as some of the causes of degeneration in a city. An inner city will always pose challenges. Much attention is paid to the physical condition of a particular city and every so often, real issues such as crime and unemployment are often overlooked.

Central Is Unsafe

Crime is a global concern; however, although many countries and cities are able to manage crime, others are not so fortunate. South Africa is one of the countries that is faced with high levels of crime, and as a result of this, people with the means of doing so, often choose to live in places where it is perceived that crime is managed or that is at a low level, and that is often in suburbia, behind high security walls and electrical fences. For the rest of the people who do not have the means of moving into suburbia with high security walls and electrical fencing, living in the inner city, townships and other places, which are not as safe is the only option. Momberg (2012: 75) states that disinvestment in the Johannesburg inner city and the flight to the suburbs in the early 1980s and 1990s by business and retail was propelled by the manifestation of deteriorated buildings, an increase in slums and crime, and a shoddy and poorly managed urban environment. The statement by Momberg regarding Johannesburg paints a very candid picture of Central Hill, with crime being the central figure in disinvestment in the city, negative perceptions towards Central Hill, inter alia, as well as the safety concerns in general, for current residents, visitors as well as potential investors, be it potential home owners or businesses.

The Mandela Bay Development Agency (MBDA), an organisation which according to the Mandela Bay Development Agency Economic Barometer 2009—2013 (MBDA Economic Impact Barometers 2014: 1), has strived towards promoting urban renewal in the Port Elizabeth CBD through various construction projects in the Central area, states that several years of disinvestment by local property owners has seen a gradual decline in appearance of the area. The deterioration of the area has also lead to an increase in crime both real and perceived.

However, the police cannot successfully enforce law and order without assistance from the community; hence it is important to include members of the Central Hill community. If members of a community can be more involved in supporting the police in crime prevention, the police will be empowered in the work that they do and communities will be safer (Department of Safety and Security (1997: 15B, cited by Morrison 2011: 144). Central Hill relies on effective policing by the SAPS as private security would prove costly in the long term, particularly when considering the income group/range of Central Hill, which is a low-income group, that is struggling as it is, to maintain their homes and effectively pay the municipal rates. Masuku (2003) reports that in a survey conducted by the Institute for Security Studies in late 2002 with respect to victimisation in the NMMM area, where 3300 people were interviewed, 23 % claimed to have been victims of crime in 2002. These crimes ranged from theft, burglary, followed by violent crime aimed at property, such as robbery. Of those crimes addressed in the survey, the most common crime occurring in the NMMM area in 2002 was burglary of homes, followed by robbery, and theft out of motor vehicles.

Loitering by Unemployed Residents

Cities play a crucial role as engines of the economy, as places of connectivity, creativity and innovation and as centres of services for their surrounding areas. Cities are, however, also places where problems such as unemployment, segregation and poverty are concentrated. According to the MBDA Economic Impact Barometers 2014 Results (2014), 86 % of the population in Central is employed, with 14 % unemployed and 4.6 % of those unemployed are discourage workers. In a study conducted by Altindag (2011), explaining the link between unemployment and crime, he states that individuals with potentially better current and future opportunities in the legal labour market are less likely to commit crime. Therefore, when focusing on an individual level framework, participation in criminal activity is associated with the employment status of the individual. As long as the current and future employment prospects of individuals are influenced by the legal labour market opportunities in the country, the changes in the unemployment rate will affect the crime rate which is an aggregation of individuals 'criminal activities. The relationship between unemployment and crime is expected to be stronger for property crimes such as burglaries, larcenies and motor vehicle thefts which involve pecuniary benefits. Unemployment can lead to individuals being desperate, thus inducing motivation to earn income illegally. Loitering is often an abuse of municipal by-laws.

Buildings Deteriorate and Become Unsightly, Thus the Emergence of Slum Lords

On arrival in Central Hill, a person is greeted by a skyline of high rise buildings, many of which, due to Central Hill's position within the city, overlook the beautiful Indian Ocean and PE harbour. As a result of the position of the buildings, as well as their accompanying views, in a city such as Cape Town for example, they would be very expensive and would be prime real estate. So the question 'Why are the buildings not similar to those in cities such as Cape Town or maybe even Miami in the United States of America?' could be posed.

A number of factors are the cause of this, however, in this particular case, attention is paid to the state of buildings in Central Hill, and how they deteriorate and become unsightly and the effects of that. Schmitz (2004) states that owners can finance buildings through either equity or debt. Equity is money invested into a building/project, while debt is money loaned to the entity undertaking a building/project. Having mentioned equity and debt, one common factor between the two is that money is made available towards the financing of the construction and management of the building, in the case of potential owners, financing to purchase the unit, however, at the end of it all, the money has to be paid back, and/or investors need to make a return on their investment. This then places sustainable pressure on the building owners to lease or sell as many units as possible in order to make returns on their investments.

When there is increased demand for property, developers or building owners are able to command higher amounts for the properties and vacancies are low. A decrease in demand will thus be problematic as building owners and investors require returns on their investments. Central Hill boasts the largest number of apartment blocks in PE, however, with the large supply of buildings in Central Hill, rentals tend to drop, as owners are trying to entice tenants and buyers. However, as the prices and rentals are low, land owners tend to not focus on maintenance of the buildings and are merely concerned with accumulating as much money as possible, and hence buildings eventually deteriorate and slum lords who are focused on making as much money as possible from the buildings emerge. More problems start to surface as a result of building owners not paying attention to and maintaining the buildings, as well as overcrowding, problems such as, lack of water, lack of sanitation, overcrowding and non-durable housing structures, four indicators which according to the United Nations, express physical conditions of slums. A large number of buildings, which according to the four physical indicators can be classified as 'slums', can be found in Central Hill and Pieterse (2008) anticipates that all future growth of slum populations will occur exclusively in the developing world.

Negative Perceptions Exist with Regards to Central Hill

A number of the perceptions with regards to Central Hill are negative, probably because of crime, deteriorating buildings and lack of attractions in Central Hill. These prevailing negative perceptions are some of the causes of the stigma attached to Central Hill and the lack of development there. Trueman et al. (2007) state that negative perceptions can undermine regeneration and destroy the confidence of local communities, leading to the notion of a 'lost' city with no clear identity. People perceive a number of issues in their own way. The issue of crime for example, has caused residents of different communities to take the law into their own hands. Masiloane (2007) refers to a study conducted in 2000 by Bronwyn Harris, where the respondents in the study indicated that the police's inefficiency and reluctance to address crime is the reason people take the law into their own hands. They believed that vigilantism was a necessary and inevitable reaction to police lethargy.

This is corroborated by a study published in 2006 which revealed that the police's slow reaction time to complaints, their poor detective work, a failure to follow-up on cases and police corruption are reasons why the community has lost trust in them. Corruption causes deterioration in relations between the citizens and the police, thus compromising effective policing. When this happens, when the public perceives police to be inefficient and corrupt, the public is tempted to resort to vigilantism or private security. Crime threatens the lives and livelihoods of people across the social spectrum and when people perceive a place to unsafe, that perception could cause people to either, move away from the area, not visit that area and advise others of the negative element of that particular case, and this is the problem experienced by Central Hill.

In a study conducted by the ISS with respect to youth experiences and perceptions of crime in the NMMM area with the focus groups originating from the PE Central Hill. The first perception by the majority of the youth was that crime in their area was rising with participants citing robbery, burglary, theft, drug dealing and drug abuse as the most prevalent crimes in their area. Masuku (2004a, b) reports that the participants mentioned negative community attitudes that tolerate crime, as well as poor living conditions and family violence as contributory factors to the high levels of crime and perceived the police as corrupt, ineffective and as drunkards. The study went further and required respondents to indicate which crimes they thought occurred the most often in their areas and according to Masuku (2003), their perceptions of the most recurrent crimes correspond with actual crime levels as reported by victims of crime in the survey. The high rate of robberies reported to the Nelson Mandela Metro police stations is disturbing, many people being aware thereof, hence the negative perceptions towards certain areas. This type of crime impacts negatively on the public image of the area, and often increases public fear of crime.

Disconnection from the City

A people's disconnection from a city, in this case, Central Hill, could possibly lead to a city's regression. When people feel as though there is no connection between themselves and the city, not entering that place or moving away from that place is very often, a step many people take. People's prevailing negative perceptions towards a city based on pre-conceived ideas of crime, lack of safety, deteriorating buildings, or whatever the case may be, often deter people from the city. Another reason could simply be a lack of attractions. Many people, particularly young people often want to experience new and different things and to have variety. However, a person cannot ignore other groups and thus the concept of Cultural Tourism could be a good option to appease everyone.

Adina and Medet (2012: 548) define cultural tourism as "visits by persons from outside the host community motivated wholly or in part by interest in the historical, artistic, and scientific or lifestyle/heritage offerings of a community, region, group or institution." Attractions and particularly cultural attractions have become particularly important and play an important role in tourism at all levels. They are also increasingly being placed at the centre of urban and rural development and constitute an important aspect of social and cultural lives of the residents.

According to the MBDA, the population of Central Hill was 12,863 in 2012, with many being young people, students, young professionals as well as other age groups. However, many of those students, many of those young professionals often have to travel to other parts of the city to obtain different experiences. Adina and Medet (2012: 551) emphasise the need to take into consideration the need to attract students to cultural events, such as festivals, exhibitions and performances and have some festivals organised in historical places or use cultural themes for attracting more visitors and creating a cultural image for the city and for the community. These kinds of events have a major impact on the development of cultural tourism.

Reconnection of the city with the introduction of more parks, recreational areas, open spaces, places of attraction could result in not only an increase in property value, but could also result in bringing people back into Central Hill, increasing the amount of visitors, encouraging the establishment and upkeep of businesses as well as playing the role of a community development tool. City parks and open space improve our physical and psychological health, strengthen our communities and make our cities and neighbourhoods more attractive places to live and work. City parks make inner-city neighbourhoods more liveable; they offer recreational opportunities for the youth, low-income children and low-income families, and they provide places in low-income neighbourhoods where people can experience a sense of community (Sherer 2006: 6, 7).

Lawlessness Prevails

Crime is one of the most difficult and challenging issues facing South Africa in the post-apartheid era. The country's crime rates are among the highest in the world and no South African is extinct from its effects. Consequently, it is important to understand the factors that contribute to crime. According to the ISS Crime Hub (2014: 2), incidents of murder for example, increased from 16,259 murders in 2012/13 to 17,068 in 2013/14, which is 809 more people murdered than in the previous year. South Africa's murder rate increased from an average of 45 murders per day to 47 murders per day, in actual fact, according to the ISS Crime Hub (2014: 2) South Africa's murder rate is about five times higher than the 2013 global average of six murders per 100,000.

Lawlessness and crime in Central Hill, just as the rest of South Africa in general, has seen many businesses and residents move away from Central Hill, in an attempt to escape the lawless nature of the area and to live and establish businesses in safer environments. The above statement is supported by Hattingh (2013: 46) when mentioning how the change to many cities and their central business districts (CBDs) in the Republic of South Africa (RSA) was a result of the flight of the traditional white business and residential base to the suburbs that left abandoned and mothballed buildings in its wake.

The majority of people residing in Central Hill are from the lower to middle income groups. A study by Demombynes and Ozler (2005) implies that people living in communities with lower to middle income groups are highly likely to engage in criminal activities and have little regard for the law. The high level of inequality in Central Hill thus places residents and businesses in a complicated position of being victims of crime and lawlessness.

Morrison (2011) states that several studies have shown that the SAPS has been ineffective in preventing crime. Of critical importance was the assertion by the Minister of Safety and Security, that most crimes occur in poor socio-economic areas where conventional policing makes little difference, which highlights the need for other forms of policing (Masiloane 2007: 30). Municipalities such as the NMMM, in which Central Hill falls, has to play a critical path in combating lawlessness. Masuku (2004a, b: 16) states that The White Paper on Safety and Security outlined three areas of intervention for municipalities:

- Crime prevention through social development;
- Crime prevention through environmental design, and
- Law enforcement, including by-laws.

Many of the challenges facing the NMMM are associated with criminality. According to the SAPS area officials, the police are under-resourced in terms of staff infrastructure and equipment. Masuku (2004a, b: 39–40) mentions that, although measures have been implemented to deal with the shortage of resources, the management of these limited resources is also challenging.

The municipality is armed with a number of by-laws and regulations that can be effectively used for crime prevention. According to Rauch et al. (2001: 16), common by-law violations/problems are associated with:

- Street trading
- Control, supervision and inspection of commercial buildings
- Conduct at public places
- Noise control
- The use of non-approved structures for dwelling and business purposes.

By-law violations will always be a major problem as a result of the unwillingness of councillors, municipal officials and the SAPS to embark on an aggressive by-law enforcement programme and as a result, the council, councillors and municipal officials will always have a poor image of being uncommitted to the rule of law (Masuku 2004a, b).

Research

Research Review and Methodology

A qualitative research approach was adopted for the study, which was conducted by means of interviews with selected individuals that form part of the sample strata. The aim of this central task was to evolve a general description of the phenomena as seen through the eyes of the people who have experienced it first-hand, and to focus on the common themes in the experience despite diversity in the individuals (Leedy and Ormord 2005).

In order to fulfil the aims and objectives of this study, an empirical study using a qualitative approach was conducted. The qualitative study entailed the interviewing of 20 individuals, which included property developers, built environment professionals, restaurateurs, estate agents, business people, as well as residents of Central Hill. It was important to first determine the cause(s) for the decline which led to the need for the rejuvenation of Central Hill, and to evolve a general description of the phenomena as seen through their eyes as they experience it first-hand, and to focus on the common themes in the experience.

The following steps as mentioned by Leedy and Ormrod (2005: citing Creswell 1998) were followed upon conclusion of the transcription of the interviews:

- Identifying statements that relate to the topic;
- Grouping statements into meaningful categories;
- Seeking divergent perspectives and
- Constructing a composite.

The Research Results

The empirical research was structured around five questions which were posed to the respondents. In response to the question ‘In your opinion, what is Central Hill’s current status?’ the following are some of the verbatim responses:

- “Run down, needs development, restoration.”
- “Not nice, not safe, lots of crime.”
- “Central Hill is in a continuing state of anarchy.”
- “There was degeneration, but people are now starting to reinvest.”
- “Has potential… it is critical that Central Hill is saved, there‘s too much history.”
- “Too many drugs, too many Nigerians, too many blacks.”
- “Work in progress.”

Table 21.1 presents a quantitative summary of the interviewees’ responses to question 1.

In response to the question: ‘What are the challenges with regards to Central Hill?’ a range of responses were received, many of which were similar to those received in response to the previous question. Drugs, prostitution, foreigners and landlords were again most prevalent, and in this particular case, ‘challenges’ with regards to Central Hill. The interviewees raised concerns with respect to safety and security, which is threatened by some of the challenges.

Table 21.2 attempts to display the challenges raised by the interviewees, and just as the previous table, each of these challenges are inserted on the table according to the number of people who identified that particular factor.

Table 21.3 attempts to display the factors that have contributed to Central Hill’s decline as per the interviews/interviewees responses.

In response to the question ‘What should be done to improve Central Hill?’ it is difficult to evolve a single conclusion or rather synopsis as the responses were divergent with almost every interviewee having a different suggestion from the other. The responses can, however, be categorised under Safety and Security, appearance, and the future/way forward. The following are some of the responses recorded verbatim:

- “Bring people back to Central Hill.”
- “Make space better so as to attract people back to Central Hill.”
- “Foreigners must leave… stop them from selling drugs… it will be hard to stop them, but we must try.”

Table 21.1 Interviewees’ comments with respect to Central Hill’s current status

Views	Total No.	Percentage (%)
Pessimistic	12	60.0
Optimistic	7	35.0
Pessimistic and optimistic	1	5.0
Total	20	100

Table 21.2 Interviewees' comments with respect to the challenges with regards to Central Hill

Challenge	No./Total No.	Percentage (%)
Drugs	10/20	50.0
Changing mind sets	5/20	25.0
Controlling crime	5/20	25.0
Prostitution	4/20	20.0
Landlords	4/20	20.0
Foreigners	4/20	20.0
Forging a new vision	4/20	20.0
Municipality's shortcomings in enforcing regulations	3/20	15.0
Safety and security	3/20	15.0
Deteriorating buildings	3/20	15.0
Cleanliness	2/20	10.0
Overpopulation	2/20	10.0
Corruption	1/20	5.0
Petty theft	1/20	5.0
No commercial bond finance (needed to include new black residential owner)	1/20	5.0
Getting the right tenants	1/20	5.0
Illegal/non-registered businesses	1/20	5.0
Maintenance	1/20	5.0
No challenge	1/20	5.0

Table 21.3 Interviewees' comments with respect to the factors that have contributed to Central Hill's current status

Factor	No./Total No.	Percentage (%)
Drugs	8/20	40.0
Landlords	7/20	35.0
Foreigners	5/20	25.0
Crime and criminals	4/20	20.0
Municipality	3/20	15.0
MBDA's upgrades	3/20	15.0
Other Negatives	2/20	10.0
Empty buildings	2/20	10.0
Vagrants	2/20	10.0
Prostitution	2/20	10.0
Unemployment	1/20	5.0
Poverty	1/20	5.0
Building upgrades	1/20	5.0

- "Proper security… threaten/warn foreigners about kicking them out of the country… this is what happened in Zimbabwe."
- "Remove the 'bad apples', drug dealers and prostitutes… implement more security."
- "No sitting on the fence… be proud of the area…get involved… landlords have to work… adopt a mind-set of revival."
- "Police patrolling the streets, searching people, and removing loiterers."

With respect to safety and security, the comments from the interviewees highlighted the importance of safety and security not only in enabling the greater Central Hill community to be free to walk around without any fear, but also in improving the image and general nature of Central Hill. In order to adequately improve safety and security, the members of the community need to get more involved in the safety and security of their communities/neighbourhoods, need to be actively involved in supporting the police in crime prevention. This will then empower the police in the work they do and communities will be safer (Department of Safety and Security (1997: 15B, cited by Morrison 2011: 144)). With respect to appearance, what can be taken from the comments made by the interviewees, a dirty area/community does not promote confidence, not only to outsiders and potential investors and business owners, but also to the existing residents of Central Hill. Neither does it encourage efforts from the broader Central Hill community to improve and keep it clean

Then a view of some of the interviewees is that there is a need for a greater vision for Central Hill and that it must rediscover itself. What is Central Hill's purpose, what should Central Hill be known for? Answers to some of these questions can lead to urban design interventions that are unique to Central and its people. However, all that will not be possible unless a greater vision for Central Hill is evolved.

Another common response is that of dealing with drugs and foreigners. A common trend in all the responses to questions previously asked has been drugs and foreigners, be it in relation to the challenges with respect to Central Hill or the factors contributing to Central Hill's status. Therefore, it is fitting that some of the interviewees suggested dealing primarily with these two issues in order to improve Central Hill.

Discussion

The review of the literature pointed to a number of factors/ issues worth noting. One of the main factors stated in the literature is that many CBDs in South Africa experienced tremendous change, due to traditional businesses and residents moving to the suburbs. This gave rise to a trail of abandoned buildings. Another important point raised by the literature with regards to the declining state of cities is that, an inner city will always pose challenges. It mentions that much attention is paid to the physical condition of a particular city and every so often, the real issues are often overlooked.

This is where the findings from the interviews align/agree with the literature. From the interviews, it was determined that drugs, prostitution, poorly managed buildings by both landlords and residents, security and crime are major challenges with respect to Central Hill.

Furthermore, there is not a lot of faith in the municipality in terms of effectively managing Central Hill, as well as implementing by-laws. The interviewees also believe that the prevalence of foreigners, particularly those selling drugs, have, to a large extent, contributed to the decline of Central Hill.

Conclusion

From the interviews conducted, there are different factors identified with Central Hill's decline, i.e. crime, drugs, litter, dilapidated buildings, etc. However, the overarching factor with regards to Central Hill and its decline is 'management'. Central Hill is poorly managed in many facets. The municipality is perceived to be not be effectively managing Central Hill as well as implementing its by-laws; there is a lot of criminal activity occurring in Central Hill which raises questions with regards to how effective the police are at managing crime; landlords are not effectively managing their properties causing the buildings to dilapidate, and residents too, are not effectively managing their properties. The common theme around many of the above mentioned issues is one of management, or a lack thereof.

It is easy to simply say that all the undesirables have been the cause of Central Hill's decline, and it is easy to simply point fingers, be it to the municipality, drug dealers or landlords. It is however evident from this study that there is a common understanding/concurrence among individuals, be it residents or visitors of Central Hill, or businesses and business owners within Central Hill, that Central Hill is in decline, and are aware of the contributing factors to this decline. These individuals also have ideas with regards to how the objectives of the study can be accomplished. Therefore, as opposed to merely pointing fingers, it is possible to evolve effective solutions to address issues concerning Central Hill by creating platforms where individuals can express their concerns as well as solutions.

The question posed at the beginning of this study was 'What is/was the cause for the decline in Central Hill?' Rejuvenation as mentioned earlier, is not only concerned with the physical aspects of the neighbourhood, it goes deeper than that as so identified by this study. There are numerous areas of further research, such as implementing some of the findings from this study/how to best implement some of the findings of the study, as well as sustaining the rejuvenation of the neighbourhood, to name but a few.

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Part VIII
Comfort, Behaviour and Payback

Chapter 22
Modelling the Delivery of Residential Thermal Comfort and Energy Savings: Comparing How Occupancy Type Affects the Success of Energy Efficiency Measures

Erica Marshall, Julia Steinberger, Tim Foxon and Valerie Dupont

Abstract There is a significant challenge in residential energy efficiency retrofit. Typically, people are incorporated in building modelling work through the standardised occupancy pattern of a typical household. However, there is strong evidence to show that the influence of individual users on domestic energy use is significant. The purpose of this work is to enhance building energy modelling capabilities by incorporating insight into how occupants live in their homes and considering the effectiveness with which heating systems deliver thermal comfort. Energy efficiency measures (EEMs) of thermal insulation and heating controls are compared for three distinct household occupancy patterns; working family, working couple and daytime-present couple. These are compared based on heating energy demand savings and on how well they can deliver thermal comfort using a novel factor, the Heating Comfort Gap (HCG). The model uses engineering building modelling software TRNSYS. The results from this modelling work show that successful reductions in energy consumption depend on the appropriate matching between EEMs and occupancy type. This work will help to improve the accuracy of

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calculations of energy savings in peoples' homes which could have significant benefits for policies such as the UK's Green Deal. It could also progress the tools available for giving tailored advice on how best residential energy use can be reduced.

Keywords Building energy simulation modelling · Energy efficiency measures · Occupancy · Thermal comfort

Introduction

In the UK, domestic energy consumption accounts for about a third of total energy use (DECC 2014a), 60 % of it attributable to space heating (Palmer and Cooper 2013). Residential building retrofit is a key government policy and addresses the twin aims of reducing domestic energy consumption as a contribution to reducing greenhouse gas emissions and tackling fuel poverty by making it more affordable to heat homes to a comfortable temperature. Two key energy efficiency measures (EEMs) which are commonly promoted are insulation of the thermal envelope of the building and control of heating systems.

This paper focuses on the heating of homes as a key domestic energy service by which fuel such as natural gas, or final energy carriers such as electricity deliver thermal comfort to the occupant. The chain from primary energy to welfare has been considered in the literature (Haas et al. 2008; Nørgård 2000; Lovins 1976), but attempts to quantify this are less common. In this paper, the effectiveness of EEMs is evaluated in contribution to both energy savings and in improving the delivery of thermal comfort.

Domestic energy consumption is a well-researched area across the disciplines of engineering, social science, energy studies and psychology. It has often been shown that the level of energy consumption in homes varies greatly (Gram-Hanssen 2004, 2012), even in studies of physically similar dwellings (Gill et al. 2010). This variation can be ascribed to different types of householders with different occupancy patterns and energy-related behaviours.

Building energy simulation models are commonly used for the purpose of reducing domestic energy consumption, both on the macro scale for national or city level planning or on the micro, building-specific scale, for predicting the energy consumption of a building and recommending energy-reducing retrofit options. The complexity of these building models can vary greatly, from single or two zone steady state models (such as SAP, the standard assessment procedure which is the model behind policy tools such as the Energy Performance Certificates and the Green Deal Assessment) to multi-zone dynamic models (such as EnergyPlus or TRNSYS).

The aim of this paper is to compare the success by which energy efficiency measures (EEMs) of thermal insulation and heating controls contribute to energy demand savings and the improved delivery of thermal comfort for different types of occupant. First, thermal comfort is discussed and the use of the term thermal comfort for this paper is defined. This is followed by an outline of the modelling methodology along with an explanation of the EEMs and occupancy patterns used in the modelling. A novel factor for quantifying thermal comfort is presented, called the HCG. The results of the modelling work are presented and these are given further consideration in the discussion. The paper is concluded, including limitations of the work and further steps which can be taken to gain further insight into how EEMs can best be suited to occupancy patterns in order to maximise energy savings and the delivery of thermal comfort.

Theory: Thermal Comfort

Thermal comfort is a well investigated concept and may be defined as a psychological state of mind or achievement of specific conditions as prescribed by national standards (Fanger 1967; De Dear 2004). It may be synonymous with describing a desired temperature, relative humidity and air movement velocity (Tap et al. 2011) or be used directly as a building design constraint or optimisation variable. The values assigned can depend on many factors from a person's clothing level or activity level to emotional state or cultural expectations (Rudge 2012; Shove 2003). The most common methodology for quantifying thermal comfort in building analysis is Fanger's approach of Predicted Mean Vote (PMV)) and Percentage of People Dissatisfied (PPD) (Crawley et al. 2008; Szokolay 2007).

In this paper, thermal comfort is given a narrow definition of an occupied space being at a desired temperature. The desired temperature may vary for different people, as well as the amount of time which the space (a home or room) is occupied.

Research Method

Building Energy Simulation Modelling

Modelling is undertaken using commercially available and widely used simulation software, TRNSYS (version 17). TRNSYS is a transient and dynamic system simulation programme, well suited to building simulation with a flexible library of components (or 'types'), which can be utilised to model complete and complex systems.

The building style implemented in TRNSYS for this study is a typical semi-detached (or duplex) single family home (single storey, internal floor area 91 m^2). This is incorporated into TRNSYS as multi-zone building, Type 56. Within this component, the building construction is detailed as a typical UK solid wall

Table 22.1 Data for model parameters and inputs

Weather data	Meteonorm weather file for London (supplied with TRNSYS) Average temperature during heating season 7.3 °C
Heating season	1 October–30 April
Infiltration	0.75 ACH (air changes per hour)
Radiator	Max power: 1000 W; Inlet temperature 55 °C

property. Data for the modelling parameters and inputs have been taken from sources of academic and industry literature where appropriate. These are given in Table 22.1.

The model is used to compare heating energy demand and satisfaction of thermal comfort upon the introduction of EEMs of thermal insulation and heating controls. Thermal insulation in this case comprises wall and roof insulation. Typical U-values of a wall and a roof before and after insulation have been found in the literature.

For the wall, the U-value of an un-insulated solid wall is commonly assumed the value of 2.1 W/(m^2K) (BRE 2014), however, published research (Stevens and Bradford 2013; Baker 2011; Rye and Scott 2012; Li et al. 2015) has shown this value to commonly be lower. A value of 1.45 W/(m^2K) is therefore to be used for an un-insulated solid wall. Further, despite building standards requiring a U-value of 0.3 W/(m^2K) following insulation, this value is most commonly not achieved and therefore a higher U-value of 0.44 W/(m^2K) is to be used (Stevens and Bradford 2013).

In the UK, 99 % of homes have some roof insulation (DECC 2013b), hence it was deemed appropriate that the pre-insulation U-value should include a small amount of insulation. Therefore, a pre-insulation U-value for the roof is taken as 0.98 W/(m^2K), representing 0.03 m layer of mineral wool insulation. Since roof insulation is usually more straightforward to install than wall insulation, and in the absence of literature to prove otherwise, the building standards level of 0.16 W/(m^2K) has been used as a realistic figure for an insulated roof.

For the heating control types, the most extreme situation is room thermostat only with no timer control. The next level of heating control is the use of a manual on–off control and a room thermostat. Beyond this, the third level of heating controls is the use of a room thermostat, central programmable timer and thermostatic radiator valves (TRVs); this combination is estimated to be present in around half of homes (DECC 2014b) and is the mandatory level in new homes. The final option for heating control is termed 'advanced control' and represents controls such as NEST[1] and Hive.[2] These products have been widely available on the market since around

[1]https://nest.com.

[2]https://www.hivehome.com/.

2011 and offer the capability to control heating remotely, for instance from a computer or smart phone, and to vary the temperature in different zones of the house.

In order to compare EEMs for different occupancy patterns, daily heating profiles have been created which represent temperature control option scenarios for three typical occupancy types; working family, working couple, and daytime-present couple. The profiles for the working family and the working couple have periods of occupancy in the morning and evening, whilst the daytime-present couple occupies the house throughout the day. Both the working family and the daytime-present couple have a similar profile every day, whereas that of the working couple is more variable, in which they arrive home in the evening at 18:30 four days per week and 21:30 three days per week. Table 22.2 shows the scenarios being compared in this work.

To calculate the heating demand of the house for the occupancy profiles, varying levels of insulation and different heating controls, the model is run with each combination for a year period with a time-step of 15 min. The temperature profiles characterise the set-point temperatures for the internal heating function of the type 56 building component. The value for the total annual heat demand is the sum of the heat demand in each room (zone) over the time-steps of the year. The temperature profiles for each combination are generated using a radiator component, Type 362, controlled by a PID (proportional-integral-derivative) control radiator valve, Type 320. This was implemented in a simplified single zone simulation representing the main living room only (walls adjacent to other rooms in the house are set with the boundary condition that the temperature is identical on the other side). The average daily temperature profile is created from a temperature profile calculated over a month of the heating season, and averaged for each 15 min period of the day.

Model Validation

TRNSYS is a well-validated modelling tool (Judkoff 2008; Crawley et al. 2008) and is well suited to performing analysis of energy demand in homes. In order to ensure that results generated are within the expected range for this typical house, the results are compared to statistical benchmarks.

Statistical benchmarking has been undertaken using the dataset made available by the National Energy Efficiency Data-framework (NEED) produced by the UK Government's Department of Energy and Climate Change (DECC). The dataset contains analysis of gas and electricity data from 3.5 million UK homes, classified by location, house type, number of bedrooms and types of energy supply. For comparison to the results in this paper, data for a three-bedroom semi-detached house from the East of England has been selected.

Table 22.2 Data for model inputs related to EEMs

Insulation	
No	Wall: 0.36 m brick, 0.03 m plaster. U-value: 1.45 W/(m^{2}K) Roof: 0.03 m mineral wool insulation. U-value: 0.98 W/(m^{2}K)
Yes	Wall (Solid): additional 0.065 m mineral wool insulation U-value: 0.44 W/(m^{2}K) (Stevens and Bradford 2013) Roof: 0.25 m mineral wool insulation U-value: 0.16 W/(m^{2}K) (according to building standards)
Heating controls	
0: Thermostat control	Whole house heating to 21 °C with no time-based heating control. This applies to all occupancy patterns. No time-based heating control
1: On-off control	House set-point set to 21 °C when daytime occupied and 12 °C otherwise (signifying heating switched off) *Working Family*: heating on 07:30–08:30, 16:30–22.30 *Working couple*: heating on 07:30–08.30, and 18:30–23:00 four days/week or 21:30–23:00 three days/week *Daytime-present couple*: heating on 07:30–22:00
2: Programmed timer control and TRV	Room set-points set to occupied temperature[a] half an hour before daytime occupied. Set-back temperature of 14 °C when house unoccupied and 17 °C overnight *Working Family*: heating on 07:00–08:30, 16:00–22.30 *Working couple*: heating on 07:00–08.30, and 18:00–23:00 (everyday) *Daytime-present couple*: heating on 07:00–22:00
3: Advanced control	Room set-points set to occupied temperature[a] half an hour before daytime occupied with times of room occupancy taken into account Set-back temperature of 15 °C when room unoccupied, 14 °C when house unoccupied and 17 °C overnight *Working Family*: heating on 07:00–08:30, 16:00–22.30 (except bedroom 1 (parent): evening heating 22:00–22:30, bedroom 2 (children): heated 21 °C 16:00–20:30 and 19 °C 20:30–21:00, and kitchen: evening heating 18:00–21:00) *Working couple*: heating on 07:00–08.30, and 18:00–23:00 four days/week (except bedroom: evening heating 22:00–23:00, and kitchen: evening heating 18:00–21:00) or 21:00–23:00 three days/week (except bedroom: evening heating 22:00–23:00, and kitchen unheated during the evening) *Daytime-present couple*: heating on 07:00–22:00 throughout, (except kitchen, heated 07:00–09:00, 12:00–14:00, 18:30–21:00)

[a]Living room, bathroom: 21 °C; Hallway, Kitchen: 19 °C; Bedroom: 17 °C

According to 2011 government statistics (DECC 2013a), 77 % of energy consumption of typical gas usage (space heating, domestic hot water heating and cooking) was used for space heating. Therefore, in order to compare calculated energy demand values for space heating and measures of gas use, a factor of 0.77 will be applied to the statistical benchmark values. To convert from energy demand to energy consumption, a typical boiler thermal efficiency of 0.8 is applied.

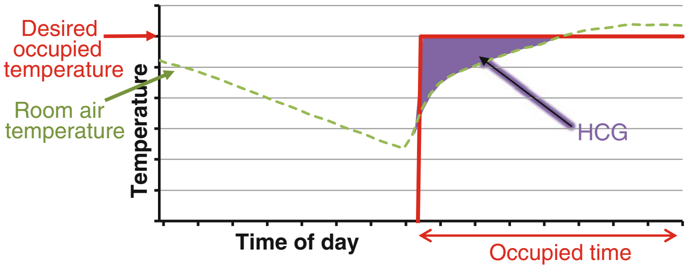

Fig. 22.1 Illustration of the calculation of the Heating Comfort Gap factor, HCG

Development of Heating Comfort Gap Factor

By quantifying the delivery of thermal comfort, EEMs can be compared on how they perform rather than energy savings alone. A dynamic factor has been developed to enable this and is based on calculation of degree-days, a measure of external temperature over a period commonly used to normalise for weather in energy demand calculations (Quayle and Diaz 1980).

A new measure of thermal comfort satisfaction is introduced in the present work and is called the HCG. It is calculated from the amount of time and magnitude by which the internal temperature is below the desired temperature during the times which the space is occupied, t_{occ}. This is illustrated in Fig. 22.1 and HCG is calculated according to Eq. (22.1).

$$\begin{aligned} &\text{Heating Comfort Gap, HCG} = \int_{t_{occ}} \theta \, \mathrm{d}t \\ &\text{where, for time steps with } T_{measured} < T_{demand},\ \theta = T_{demand} - T_{measured} \\ &\text{else, for time steps with } T_{measured} \geq T_{demand}, \theta = 0 \end{aligned} \tag{22.1}$$

where $T_{measured}$ is the internal air temperature and T_{demand} is the internal temperature deemed to be a comfortable temperature for that space when occupied time, t_{occ}.

A lower value of the HCG factor means that thermal comfort is better delivered and therefore the aim of retrofit work is to minimise the value of HCG.

Research Results and Discussion

Annual heating energy demand values have been generated for three occupancy patterns with varying levels of insulation and types of heating control and the results are shown in Fig. 22.2. The horizontal lines show the statistical benchmark values for comparison. The majority of the results lie close to or within the lower and upper quartile range given by the statistical benchmark values.

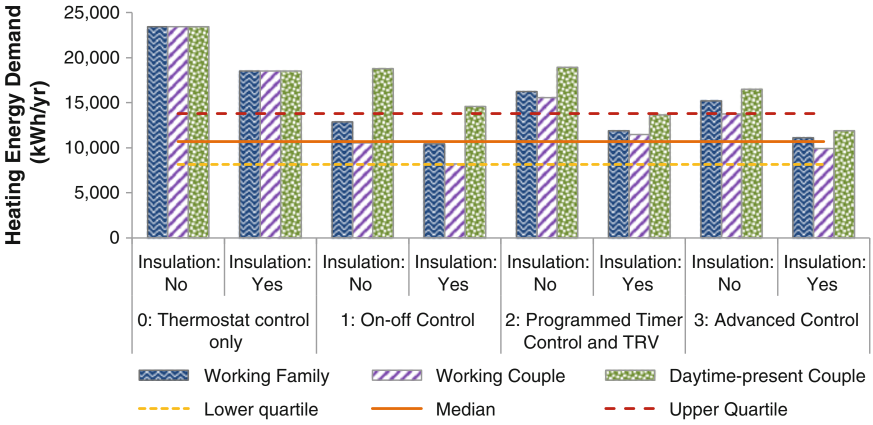

Fig. 22.2 Calculated figures of annual heating energy demand with the introduction of different EEMs. Horizontal lines show statistical benchmark values (DECC 2014b)

The temperature profile of the living room in each combination of heating controls and insulation level are shown in Fig. 22.3. In these figures, the effectiveness with which EEMs satisfy thermal comfort is shown visually, by the degree to which the temperature reaches the desired temperature levels. The values of HCG have been calculated for each heating control and insulation level combination based on the daily profiles in Fig. 22.3 and are shown in Fig. 22.4 for each occupancy profile. The values of HCG are compared to the energy demand savings calculated in each scenario, with reference to a base case of heating control 0, fixed thermostat without timing control, and no added insulation.

Energy Savings

Compared to the base case (no added insulation, fixed thermostat without timing control), both insulation and improved heating controls achieved significant energy savings. When comparing single measures, heating controls lead to greater savings in two out of three cases, (for the working family and working couple). The greatest savings are seen in the working couple scenario, and particularly for the heating control options, which can be attributed to its fewer occupancy hours during the day. The daytime-present couple sees greater savings for insulation relative to heating controls alone, compared to the other patterns and this can be explained by the longer time for which the heating is on. In the working family and working couple scenarios, the savings are greatest for on-off control. The working couple scenario shows the greatest savings with advanced control and the reason for this can be seen in Fig. 22.3b where in occupancy pattern 2, the programmed timer

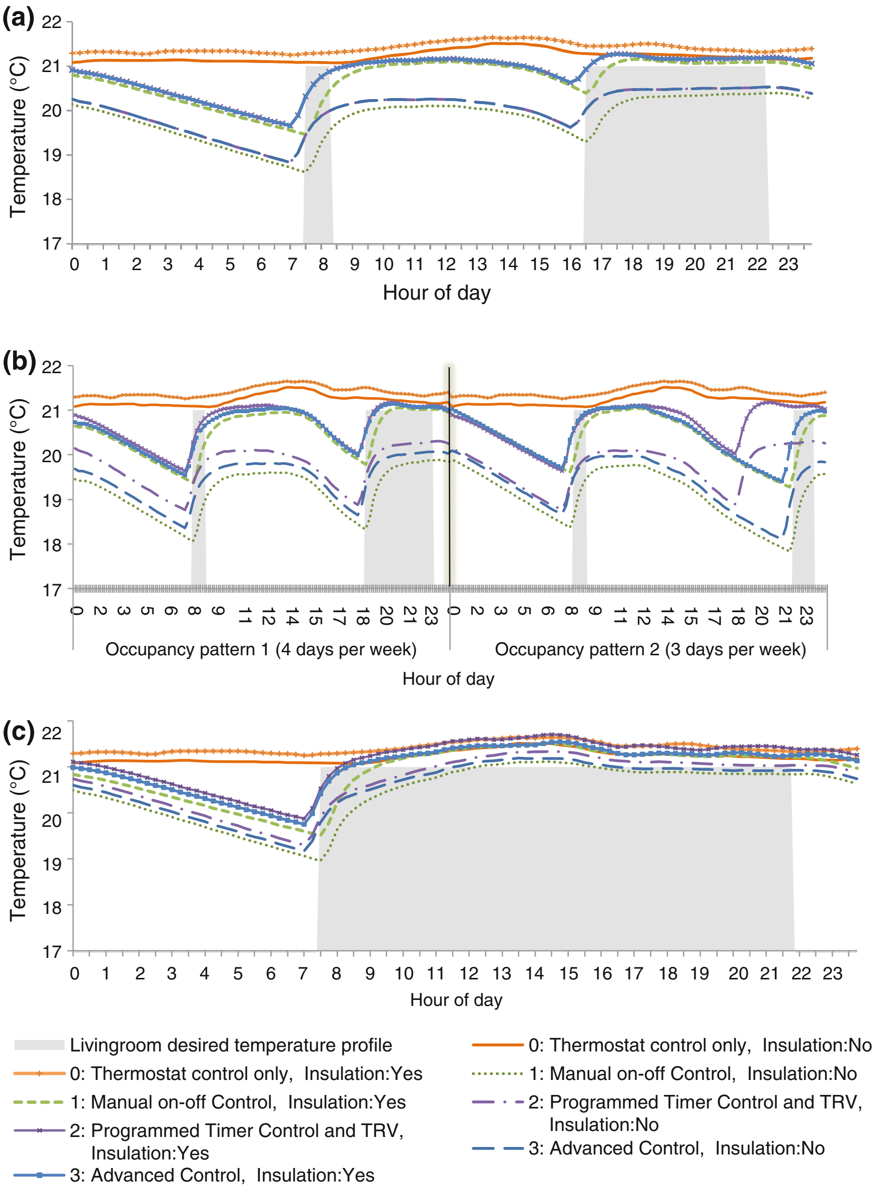

Fig. 22.3 Temperature profiles of living room with EEMs for **a** Working family, **b** Working couple, and **c** Daytime-present couple

controls lead to an unoccupied period of heating. Insulation shows significant energy savings, and the variation between the occupancy types is diminished with higher levels of insulation.

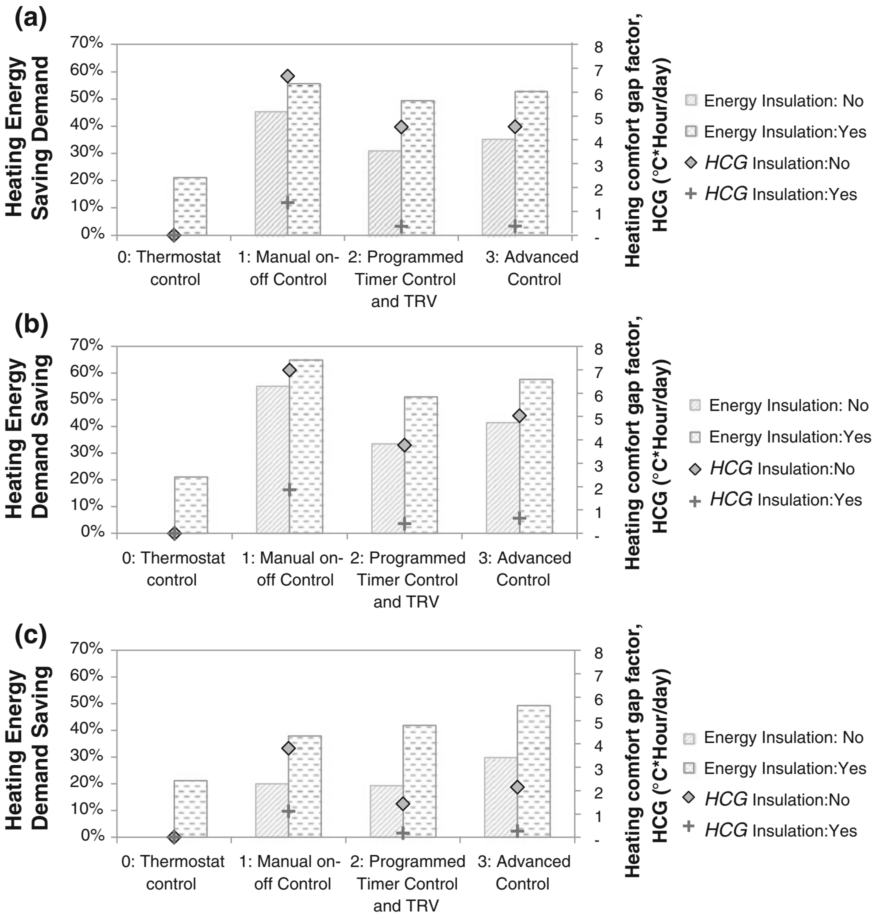

Fig. 22.4 Energy demand savings due to EEMs and Heating Comfort Gap factors, HCG, for **a** Working family, **b** Working couple, and **c** Daytime-present couple

Satisfaction of Thermal Comfort

Insulation is shown to have a large impact on ensuring occupied spaces are at their desired temperature. The profiles in Fig. 22.3 show that with insulation, the rate at which the living room heats up is greater, the temperature drops at a slower rate, and the heating system is able to heat the room to a higher temperature, and closer to the desired temperature of 21 °C.

In comparing the heating controls, the programmed timer control and advanced control switch the heating on earlier than the manual on–off control, and therefore the rooms are closer to the desired set-point temperature at the time of occupancy. This is most relevant in the shorter occupancy periods in which the desired set-point temperature might not be reached throughout the occupied period. For true advanced heating controls, the system should be able to learn how long it takes to heat the space for a given outside air temperature and therefore the variation between desired temperature and recorded temperature would be reduced.

On top of insulation and heating controls, a third option for reducing the HCG, HCG, could be by reducing the demanded internal temperature. If occupants are content with a lower internal temperature, such as by altering their level of indoor clothing, thermal comfort can be satisfied at a lower temperature. However, this would not be applicable in all cases such as when the householders are vulnerable and particularly susceptible to the cold, or when the internal temperature is too low initially such as in the case of a household in fuel poverty.

Suitability of Energy Efficiency Measures to Households

Not all EEMs will be suitable for all households and even if measures are introduced, savings are not guaranteed. Thermal insulation (for solid wall properties in particular) may be unaffordable or difficult to install in certain types of homes. Heating controls typically require more user interaction than insulation and therefore will not suit all households. Rebound effects such as comfort taking can result in higher internal temperatures rather than energy savings following the introduction of EEMs. By aligning the choice of EEM to a particular household, the likelihood of making savings can be better evaluated. There may also be circumstances for which the choice of EEM needs to be made most suitable for the house type, such as cases when the householders are liable to change frequently. Insulation appears to be the best way to make savings which do not depend on who the occupant is so, therefore, best suited to houses with fairly short term tenancies. This means that when applying this work in the case of giving tailored advice, consideration must be given to which EEMs are suitable before making recommendations.

Conclusion

This work has shown that the energy savings achieved with EEMs of thermal insulation and heating control varies according to the occupancy patterns of the households. A novel factor for comparing the delivery of thermal comfort was also introduced, the heating comfort gap factor (HCG). The results show that heating controls were able to lead to greater savings than insulation for a base case of only single thermostat heat control, but the result was a increase in the HCG. Thermal insulation leads to greater satisfaction in thermal comfort as a steeper temperature rise was achieved and a higher temperature was reached during the occupied periods. If controls do not deliver acceptable levels of service they will not be adopted, and conversely, if new controls are liable to increase the energy use, the aims of reducing domestic energy consumption are not achieved. Both factors are important when considering making improvements to home heating systems.

With the introduction of the novel HCG Factor, the delivery of thermal comfort by different EEMs can be measured and compared. This allows the co-benefits of EEMs, beyond only energy savings, to be considered. This factor could be developed by also considering the time for which a space is warmer than the desired temperature. This could both address 'over-heating', the time for which a space is heated unnecessarily, and to consider a cooling comfort gap for the time when the space is uncomfortably hot (especially in warmer climates).

In order to develop this work, further investigation is required to improve upon and strengthen these results. Validating the model needs extending, in particular the accuracy with which savings are predicted. Calculated savings have not been validated yet against measured savings, and addressing this gap could enable greater confidence in the generated values. Savings also need to be calculated through comparison of the situation before and after, and it may not be appropriate to compare only to a heating control consisting of a single fixed thermostat. There is scope to improve the modelling of advanced heating controls in order to incorporate the capabilities of controls which are programmed to learn how long it takes to heat up a room for a given outside air temperature. In regards to the variation with which households live in their homes, only limited scenarios have been considered in this paper, especially with regards to preferred internal temperature. The 'comfort temperature' could also be replaced by a range of temperatures and the level and width of this range would vary for different people. There may be different results for a household which favours lower or higher internal temperatures and these differences could be investigated. This could also include consideration of comfort taking as a rebound effect which would result in lower savings from EEMs. Different house types should also be investigated to broaden the analysis of this work.

The results of this paper show that it is still important for retrofit policies to prioritise the improvement of the thermal envelope of homes, but it is important to include other options such as heating controls for when insulation is not a viable choice.

The quantification of the delivery of thermal comfort could enable the inclusion of co-benefits when analysing retrofit options. This could be useful when prioritising retrofit for the reduction of fuel poverty and other welfare policies. It could also go towards enhancing the information gained in the Green Deal Assessment such that improvements in the delivery of thermal comfort could be valued alongside energy savings.

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Chapter 23
Analysing the Technical and Behavioural Shifts of Social Housing Tenants Following the Retrofitting of External Wall Insulation

Sara Lilley, Gill Davidson, Barry J. Gledson and Zaid Alwan

Abstract Environmental, economic and social issues present local housing associations with many challenges in terms of management of their existing housing stock. Multiple problems arise from poorly insulated properties, and the twin foci of this research regards the performance of residential external wall insulation (EWI), and identifying the additional benefits that EWI provides to social housing tenants,, which are uncovered through means of behavioural and technical monitoring. The research process generated two sets of data points per household relating to the start and the end of the study and comparative analysis techniques are used to identify changes in user behaviours. Qualitative and quantitative data were collected using survey methods that explored environmental knowledge, attitudes, beliefs and everyday behaviours with regard to energy consumption and use. Additional data capture involved temperature logging, meter reading, thermal imaging and the analysis of energy meter readings to monitor changes in usage in the pre and post stages of retrofitting EWI. The results of this study identify changes in the technical performance of the properties and benefits in the well-being and behaviour of the tenants.

Keywords Behaviour change · Retrofit · Sustainability

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Introduction

The UK government's Carbon Plan aims to reduce carbon emissions from buildings to zero by 2050 (HM Government 2011). Domestic energy use amounts to a significant proportion of energy consumption (Wood and Newborough 2003, 2007), which has been estimated as accounting for over 40 % of the UK's overall energy use and is responsible for 25 % of the country's CO_2 emissions (DECC 2011). Reducing domestic energy use—and therefore emissions—is a key part of the UK carbon reduction strategy, yet for many energy has been described as an *invisible* resource and much research has focused on the value of feedback as a means to positively influence occupier behaviour (Branson and Lewis 1999; Burgess and Nye 2008; Hargreaves et al. 2010). Whilst domestic appliances, air conditioning and lighting all result in substantial CO_2 emissions (Wood and Newborough 2003), it is space heating which accounts for around 60 % of energy use in homes (DECC 2012; Fell and King 2012), making this by far the largest component of domestic energy bills. Keeping properties warm by reducing heat loss is a key way to boost energy efficiency in homes and thus minimise unnecessary energy use or energy waste. Heat can be lost through windows and doors, poor insulation, damp spots, leaking pipes and decomposing structures. The average UK monthly household fuel bill in 2014 was £112,[1] although there may be significant variation in domestic energy use according to the size of the property, its level of insulation—which may be a result of building materials, housing design, additional insulation, glazing, or a combination of some or all of these—and the habits of its tenants. Banfill and Peacock (2007) found a big difference in energy bills between identical homes, which suggests that the actions and behaviours of the occupiers are crucial in determining the amount of energy used.

According to the 2011 Census, 17 % of UK residents—around 10.3 million people—live in social-rented properties (ONS 2014a). Social-rented dwellings account for 5 million of the total 28 million strong UK housing stock, with Housing Associations owning around 2.75 million properties (ONS 2014b). Housing Associations are potentially key contributors to carbon reduction targets, which presents them with significant challenges with regard to the management of their existing stock. This paper describes a study which evaluated the performance of External Wall Insulation (EWI) on a selection of residential properties in North East England, as well as identifying the additional benefits that EWI may provide to social housing tenants through the means of in-depth interviews with tenants both before and after EWI installation and technical monitoring of properties undergoing EWI installation.

[1]Source: Santander (2014). Households Underestimate Main Annual Bills by £770. http://www.santander.co.uk/uk/infodetail

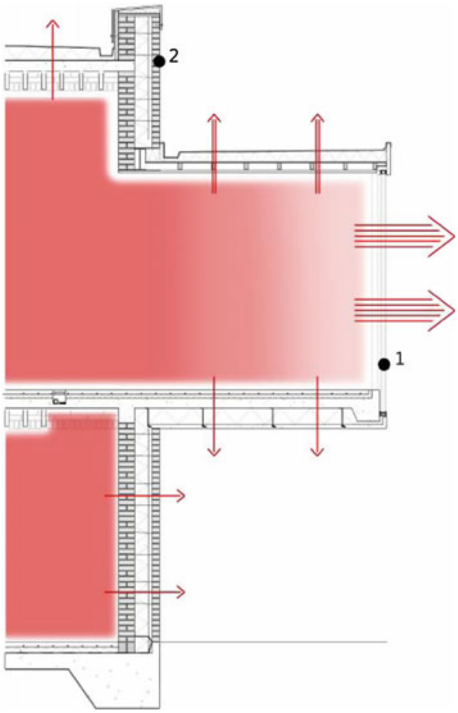
Methodology

The research focused on a 2014 property improvement programme in which two social housing providers in the North East of England jointly provided EWI to over 800 properties. The aim of the research was to evaluate the effectiveness of EWI in terms of both tenant experience and property performance, through a series of semi-structured interviews with tenants and technical monitoring of 15 properties. Interviews were carried out with the tenants at two stages: first before the work had been undertaken (January–April 2014), and second around 8–10 months after EWI had been fitted (November–December 2014). The second phase was purposely delayed to give tenants time to experience and adapt to any changes resulting from EWI. Each time, one adult inhabitant per household took part in an interview lasting for approximately one hour in their own home, with the same person being interviewed in each phase. The interviews were based on a questionnaire developed by researchers from Northumbria University. The questionnaire acted as an interview framework, providing a basis for informal discussion with participants and including sections on environmental knowledge, attitudes and beliefs, everyday behaviours regarding energy usage, water and energy consumption and health and well-being. Interviews enabled the collection of quantitative datasets and allowed further qualitative exploration of particular issues relevant to participants. Tenants were also asked to provide regular readings of their electricity and gas meters to monitor any changes in usage before and after insulation, as well as providing information about their fuel bills.

In order to identify the effects of installing EWI on property performance, temperature logging and thermal imaging were also carried out at the two phases, providing information about insulation levels, heat loss and the identification of cold and damp hotspots. This included an analysis of the thermal performance of specific parts of the properties before and after insulation. Infrared thermography is increasingly used to diagnose pathologies in buildings, such as façade defects and heat loss analysis (Elton et al. 2015). This allows automatic spot recognition of the temperature gradient in the walls with temperature recordings to show where heat loss occurs. The thermal imaging camera can also be used to identify areas of heat loss such as thermal bridges and provide an overall assessment of the effectiveness of external insulation. Heat loss is often greater from glazed areas and from poorly performing envelopes. This can be detected using infrared analysis. Figure 23.1 is a Computerised Fluid Dynamics (CFD) image illustrating the rate of heat loss from various sources; with the intensity of the colour indicating the level of heat loss.

The research process generated two sets of data per household, relating to pre- and post-EWI retrofit (phases 1 and 2 respectively). Comparative analysis was used to identify changes and trends in behaviours, perceptions and energy use between

Fig. 23.1 Illustration of heat loss from a building: inside to outside



the two data points. Fifteen properties were initially identified for inclusion in the research. The aim was to study illustrative examples of each type of property involved in the retrofit programme. The property types were: 2- and 3-bedroom Wimpey No Fines (both mid and end terrace and flat roof); Wimpey No Fines maisonette, 1-bedroom Wimpey No Fines bungalow; 3-bedroom Dorran; and 3-bedroom BSIF. Although this aim was achieved, only 11 properties were included in phase 1 and 8 in phase 2. This was due to a variety of factors including the timing of the works, changes to the programme of works which meant some properties included at phase 1 did not receive EWI; and difficulties contacting tenants or getting them to participate in the study at both phases.

Data Recording and Analysis

The interviews were recorded by the researchers, who took detailed handwritten notes alongside completing the required parts of the interview schedule.

The inductive analysis process involved reviewing the range of responses and identifying emerging themes that were relevant to the research questions, as well as any new or unexpected findings. Written consent was obtained prior to interviews from all participants and all responses were anonymised. The research process generated two sets of data per household, relating to pre- and post-EWI retrofit (Phases 1 and 2 respectively). Once interview analysis was complete for both of the research phases, comparative analysis was used to identify any changes and trends in behaviours, perceptions and energy use between the two data points. The findings from the interviews are presented below.

Findings

This section highlights a small selection of the overall research findings and is structured to reflect both phases of data capture. Of particular interest were tenants' experiences of having EWI fitted to their homes and the impact of EWI on their energy bills and thermal comfort levels, the appearance of their properties and their health and well-being, as well as their overall evaluation of EWI.

Phase 1 Data Capture

Fitting EWI

The EWI installation was carried out between January and April 2014, with tenants remaining in situ throughout. This was a large-scale retrofit programme involving around 800 properties, and it was subject to various timetable changes and delays due to bad weather and other factors. In addition to this it took a number of days—or weeks—to do the work on each property. Scaffolding had to be erected and the previous façade removed before the EWI could be installed, and the scaffolding could be removed. In one case at phase 1, a tenant reported having had the façade removed from their house four weeks previously, yet said they were still waiting for EWI to be fitted. As a result their home was "*very draughty*" and they reported that their energy spending had increased from £130 to £153 per month: "*It's costing a fortune in extra heating while it's like this*". Several other tenants said they were waiting to hear when the work would begin on their homes, and were frustrated by the length of time it was taking and the lack of information they had received about this.

Thermal Comfort

Tenants were asked, '*Are you satisfied with the level of warmth in your home?*' During phase 1 almost half of respondents said that they were. However, this came at the price of high heating use in at least two cases:

> The heating is on constantly though.
>
> It is comfortable when the heating is on all of the time. It is very cold in the bedroom as the radiator is not working.

Just over half of respondents said that they were not happy with the level of warmth and that their homes were too cold. Tenants were asked to rate their homes according to their level of warmth on a scale of 1–10, with 1 being the coldest and 10 being warmest. During phase 1 tenants' average warmth rating was 5.1, with several respondents stating that their homes felt uncomfortably cold:

> Upstairs, 1 (out of ten) at night. I put heating on first thing but it takes so long for the upstairs to warm up, you give up. Downstairs is not so bad, maybe an 8.
>
> It's a cold home.

Tenants were also asked to indicate what, if anything, they felt needed to be done to make their home a better place to live. At phase 1, the three main response types concerned addressing cold and draughts, and fitting insulation, with each of these being mentioned by at least three respondents. Comments included:

> In the room on the end, we had to use wallpaper as the wall is very cold and damp. There is a lot of damp and condensation and mould and mildew in the bathroom. We have had to have another vent put in the ceiling to go into the loft to help with this.
>
> End wall is damp and cold, I think there is draught coming from there, bathroom is damp as well. Front bedroom cupboard is damp as well. Freezing in living room when the heating is on

Thermal Imaging

Thermal images taken of the properties during this phase allowed automatic spot recognition of temperature gradient in the walls, providing vital temperature recordings to show where heat loss occurred. The images work on the principle that all objects above zero degrees Fahrenheit (−17.7 °C) emit infrared radiation that cannot be seen by the human eye. For example, in an external image of a building, an object coloured red indicates heat loss and an inefficient building fabric, while blue indicates heat is retained. In an interior image, blue walls indicate low temperatures, suggesting poor insulation and cold entering the building via the walls. Figures 23.2 and 23.3 show external and internal thermal images of one of the properties before EWI and give clear indications of heat loss from the building.

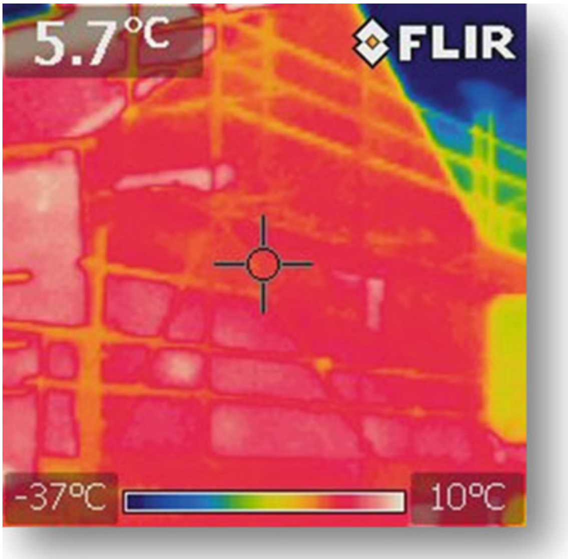


Fig. 23.2 Exterior of end terrace prior to EWI, with *red areas* showing excessive heat loss. Temperature listed as 5.7 °C

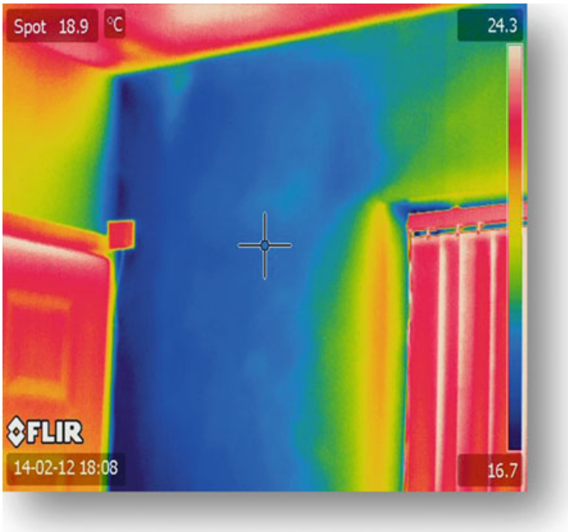


Fig. 23.3 Interior wall prior to EWI. *Blue areas* indicate lower internal surface temperature

Phase 2 Data Capture

Following EWI installation all but one of the respondents said that they were happy with the level of warmth in their homes. Tenants' average rating of the warmth of their homes had risen from 5.1 to 7. Tenants' comments on the improved levels of warmth in their homes included:

Yes definitely a lot warmer.

Definitely, it's been a Godsend

Yes, improved it, we used to have the fire and the heating on, and now we don't use the fire.

Only one tenant said they did not find it warmer as a result of EWI installation. This was in a household where the heating was used very minimally at both phase 1 and phase 2 in order to keep energy costs down. At phase 2 the tenant said they felt that EWI had not influenced the level of warmth of their home, and commented: "*No, it hasn't had any effect, can't feel a difference*". This indicates that while EWI may be effective at retaining heat generated in the home by conventional means, it does not in itself create warmth. This idea is further supported by other tenants' comments at phase 2 that their homes stayed warmer for longer once heated: "*(the house) holds heat longer after the heating is off, we don't have the heating on as often*".

By phase 2, none of the tenants referred to problems with cold, damp or the need for insulation, with regard to improvements they thought their properties needed.

Energy Bills

A key issue for tenants related to their domestic energy use, and whether the installation of EWI meant that their household energy use—and related spending—was reduced. Not all tenants were able to provide this information, but figures for those that did so are shown in Table 23.1.

All tenants who provided this information reported that their energy bills had reduced since the EWI installation, by amounts ranging from 16 to 56 %. The average reduction was around one-third, at just under 33 %. The difference in the amount of energy savings made by different households is of interest. While one household's bills were reduced by more than half following EWI installation, another reported a saving of just 16 %. While all energy savings are of benefit to the tenant and therefore worth pursuing, it may be instructive to investigate differences

Table 23.1 Energy spending by household pre- and post-retrofit

Property	Energy spending in phase 1, pre-retrofit[a]	Energy spending in phase 2, post-retrofit[a]	% change
1	£115	£80	−30
2	£92.50	£41	−56
3	£60	£45	−25
4	£153	£84	−45
5	£120	£100	−16
6	£117	£92	−21
7	£80	£50	−37

[a]Combined gas and electric costs per month

in savings more fully, to find out what factors are influencing energy use in different households. Tenants said that they had noticed saving money since EWI installation. One commented on "*not putting as much money on. Well, putting the same on but it is lasting a lot longer, always got plenty on the key meter*". Tenants were asked if they thought the amount that they spend on energy bills was low or high. At phase 1, five out of eleven respondents felt that their energy spending was high or very high, while at phase 2 only three people described their spending as high, and none as very high.

Property Appearance

Tenants were asked if they were happy with the design and appearance of their homes. During phase 1, seven out of eleven people said they were not. Several remarked that their homes looked "*tatty*" with peeling paint or patched-up pebble dash, while two tenants described their homes as looking like "*a tin shed*" and a "*caravan on bricks*", respectively.

By phase 2, all tenants said that they were happy with the appearance of their homes. Asked if the EWI had any effect on the appearance of their home and others in the area, all tenants responded positively to this question, with typical comments stating that the houses looked "*much better*", "*nicer*" and "*clean and tidy*". One participant went on to suggest that: "*those that haven't had (EWI) done are complaining that it undervalues their home*".

To get an idea of how durable the EWI is once in situ, tenants were asked if the EWI looked the same as it had when it was fitted. The majority of the tenants said that it did, although some mentioned small concerns, namely mud and rain splashes, cat paw marks and guano. However, the EWI had only been in place for 6–10 months by phase 2, and it may be useful to revisit the research and the properties after a longer period to assess the durability of EWI more comprehensively.

Effects on Health and Well-being

At phase 2, seven out of eight tenants said that they thought the EWI installation had a positive effect on their health and well-being. This was strongly related to the increase in warmth, which made people feel happier and more comfortable, as well as reducing the impact of arthritis for two tenants:

> I enjoy being at home more because it's warmer. Pleased it's been done, feel very lucky to have it installed, it's made a big difference.
>
> I don't have to sit with as much clothing on, with hats and gloves, and have less bedding on. I used to have a 15 tog quilt and another one on top, now I don't have a quilt, I just use

> throws. I have arthritis, and had two knee replacements, so it has helped me, I don't have to sit with warm tights on all of the time, my joints are warmer.
>
> I used to go to bed with two dressing gowns on top of the bed but I don't need to now.

One respondent said they felt better because of the change in the appearance of the local area: "*It is more cheerful looking at the houses, in the summer it shines, when you see dirty ones against new ones*". Finally, one person identified the saving on energy bills as having a positive effect on their wellbeing: "*It does ease the thought of paying a lot and I am not frightened of putting the heating on. I know it has helped with the pocket, now I can save the extra money for things I want to do to the house*".

Evaluating the EWI Experience

After the works had been completed, tenants were asked what they felt was the best and worst thing about having EWI installed. The majority of the tenants said that having a warmer home was the best thing. Rooms or areas of their homes that were previously hard to heat were no longer as cold, and their homes retained heat for longer, which meant that they needed to use the heating less often. Three people also mentioned the improved appearance of their home, and one cited the insulating effect against noise which meant their home was quieter than before. No one mentioned savings on energy bills.

> Overall wall insulation efficiency first and then appearance.
>
> You can feel the heat, feel the difference, this is first time we've had to put the heating on… it's definitely made a difference in temperature in the house.
>
> It is warmer and when the heating is off, it lasts longer.
>
> The house is much warmer and it is quieter.
>
> The appearance, they look clean and fresh.

Tenants were also asked what the worst thing about EWI was; only two identified negative outcomes, and these both related to concerns about potential problems, rather than actual problems. Their concerns were that the pale, clean appearance of the newly done EWI would not last, and that it may be easily damaged through every day wear and tear:

> The colour is not gonna [sic.] stay like that for long. When you look at other estates, it looks dirty and there's bits coming off.
>
> It can damage easily which would change the appearance.

One person suggested that it may have been better to put a darker colour at the bottom of property walls so that mud splashes would be hidden, and also suggested that tenants may need guidance on how to keep it clean: "*I'm frightened to hose it down*". Another person said they had tried to wash their EWI with soapy water to remove dirty marks, but also suggested that if the surface were painted it may be easier to wash.

Research Limitations

This was a small scale, short-term study that studied the effects of EWI on a small number of houses. Future similar research incorporating more households, and a bigger range of different types of property over a longer period of time, could usefully add to the knowledge base. Seasonal differences in temperature, and the resulting heating requirements, are important factors which may have influenced the findings. Client requirements meant that the study had to be completed in just under a year; although attempts were made to maximise the amount of time between phases in order to ensure that tenants were able to experience any effects linked to EWI installation over as long a time scale as possible, this was limited due to delays in the programme of works in the first instance, and the need to have the final results ready in time for planning meetings in the second. Phase 1 took place during January–April 2014, and phase 2 during November–December 2014. This meant that the research failed to incorporate the coldest months of the year (see Fig. 23.4). In addition, the North East had particularly mild weather for most of 2014 following the completion of phase 1, and this is likely to have affected tenants' heating demand and levels of thermal comfort.

Although the reduction in energy bills of 33 % following the fitting of EWI indicates a significant benefit for tenants, it must be recognised that at phase 1 (pre-retrofit), recent bills would have been in the colder winter months, while at phase 2, the recent summer months may have helped to reduce tenants' heating requirements. For instance, one tenant said at phase 2 that they paid £40 per month in summer, compared to £100 a month in the winter months (in this case the winter figure was used in the data). Other tenants were wary about speaking of the benefits of EWI because of this. One said that while they were hoping the EWI would lead

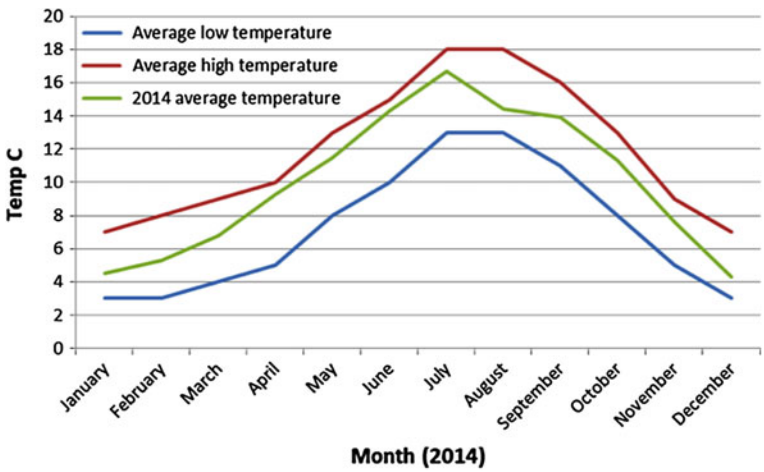


Fig. 23.4 North East England temperatures (2014) and average temp for Gateshead (2000–2012). Data taken from worldweatheronline.com and metoffice.gov.uk (both accessed 21 April 2015)

to a reduction in their energy bills, they could not be sure whether or not the recent mild weather was the real reason their energy spending had gone down:

> Hoping so, I have a friend with a 2/3 bed house and she said her bills have halved (with EWI). I don't know if it's milder or if it is the EWI.

The same person said they would not know for sure how effective the EWI was until the weather got colder, or else they got a bill for their winter energy use.

Thermal imaging is limited as a data-gathering tool, as it only identifies spots within the building envelope which are more susceptible to heat loss. It gives an instant reading which can be used for further investigation of issues relating to heat loss, but in itself tells us little, for instance about changes in heat loss over time. A more comprehensive data collection strategy would be to link infrared thermography with internal monitoring devices to gather data over a longer time period.

Conclusion

This study tested a small number of property types both before and after EWI was fitted to them. The results indicate clear benefits for the occupants, with tenants reporting that their energy bills were reduced by an average of one-third (a range of 16–56%) following EWI installation. All but one reported that their homes felt warmer and did not lose heat as quickly as before. Tenants also thought that the external appearance of the homes had been improved by EWI, and seven out of eight people reported improvements to their health and well-being; this was strongly linked to increased warmth in their homes. No negative outcomes were reported although some respondents expressed concern that the appearance of EWI would deteriorate over time due to dirt and damage. Potential limitations were identified relating to the small sample size of the current study, the need to monitor the properties over a longer time period to provide more evidence of energy saving, and the use of more comprehensive data-gathering strategies.

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Chapter 24
Switch, Don't Save

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Abstract Efforts to meet targets on carbon emission and to reduce the number of people in fuel poverty often focus on building new highly energy-efficient homes and retrofitting existing ones. However, as occupant behaviour is a major predictor of energy use, it is also valuable to provide interventions that help occupants to use less energy. Here, we report qualitative research with 26 occupants in homes retrofitted with external wall insulation and ask what influences the actions they take to reduce the energy they use. Semi-structured interviews, lasting up to one hour, were audio recorded and transcribed verbatim. Taking a social constructionist paradigm, we used a discursive approach to analyse the ways in which people construct and represent their energy consumption and the discursive practices they employ to legitimise their actions or inactions. We identified two main discourses. The dominant discourse positions savvy and responsible consumers as those who switch suppliers to obtain the best energy deals, thereby saving money and enabling them to enjoy a warm and comfortable home. Making efforts to use less energy did not feature in this discourse. Participants' talk was of disappointment and betrayal when the anticipated savings did not materialise. They blamed suppliers and usually switched again. An alternative discourse of changing behaviour to reduce energy use was drawn upon less often, when present it accompanied other life events, such as moving home, a change in work status or a period of illness. Talk centred on trying to offset the increasing cost of energy, with the purpose of reducing energy bills rather than using less energy. Protecting the environment was not a feature of this discourse. We conclude that campaigns that encourage consumers to switch energy providers have the potential to adversely affect interventions to help them reduce the energy they use.

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Introduction

There are two key policy drivers helping households to reduce the energy they consume. First, the 2008 Climate Change Act commits the UK to reducing carbon emissions by 80 % before 2050. A substantial amount of this saving will need to come from the domestic setting as it accounts for 32 % of all energy consumption in the UK (DECC 2011). Second, there is a commitment that, as far as practical, by 2016 there should be no households living in fuel poverty. Alongside the potential to spend less on fuel, there is recognition that living in a warm home can bring benefits that include improvements in both physical and mental health (Marmot Review Team 2011; Cronin de Chavez et al. 2014).

Previous research into occupant behaviour is limited, and primarily focuses on identifying reasons for the performance gap, i.e. why the reduction in fuel use following retrofitting energy efficiency measures is not as great as predicted. Around half of the variation in the amount of energy that people use to heat their homes is due to differences in behaviour rather than the energy efficiency of dwellings themselves (Gill et al. 2010). This can be through occupancy patterns, i.e. the people living there, the number of hours the house is occupied and how the rooms are used (De Meester et al. 2013) as well as the temperature the house is heated to. Sometimes, higher energy use arises from not understanding how to use the heating system effectively (Linden et al. 2006), which can be because occupants were not instructed in how to use their new heating system, or they are reluctant to engage with the technology (Isaksson 2014).

It is clear that a substantial proportion of variation in energy use is due to individual behaviour, which can be changed. Building users play a critical but poorly understood and often overlooked role in building energy efficiency (Janda 2011). There is growing interest, therefore, in understanding how best to change householders' energy-use behaviour. Most interventions focus on providing information (Abrahamse et al. 2005). This is common to behavioural change interventions more generally which often assume that the main barrier to behaviour change is lack of awareness of the risks associated with that behaviour and lack of knowledge of how to change. While many people do not know how much their energy bills cost (Brounen et al. 2013) or how to use their heating and ventilation system (Huebner et al. 2013; Pilkington et al. 2011), provision of this information alone is unlikely to be effective (Blake 1999). Understanding the values that promote energy-efficient behaviours or act as obstacles are important (Mirosa et al. 2013) if change in user behaviour is to be realised. Blake's (1999) research drew attention to the cultural and policy factors that restrict and prevent participation in environmental initiatives. For community and public participation, Blake called for attention to environmental concepts to ensure value in everyday context.

Owen et al. (2014) also identified a distinct lack of understanding between those responsible for installing domestic energy technology and factors that influence home owners to take up and use the technology.

Using a wider range of behavioural change techniques is likely to be more effective in reducing people's energy use. For example, tailored information and feedback about energy use and setting goals for behaviour change was shown to be effective in reducing the amount of energy that people use in their homes (Abrahamse et al. 2007). For the best tailor information, it is important to understand the context of their energy use and the barriers and facilitators to reduce it. One important area that is underexplored is how discursive strategies may also represent barriers to reduce energy use (Kurz et al. 2015).

We, therefore, need to gain a more in-depth understanding of people's accounts of heating their homes and their decisions around energy saving behaviour. Few qualitative research studies have been undertaken, yet this approach has the potential to provide greater insight into energy-use behaviour and the user experience of buildings (Kim et al. 2013). It can explore how people understand energy use and the factors that constrain any changes they make.

In this study, we use a discursive approach to analyse the ways in which people construct and represent their energy consumption and the discursive practices they employ to legitimise their actions or inactions.

METHODS

Paradigm

We took a social constructionist paradigm which rather than focusing on people's descriptions of what they do, explores how they construct their actions in a socio-cultural context. By analysing the language that people use to describe their approach about using and saving energy, we uncover how they negotiate energy saving.

Participants

Twenty-six householders took part in the research. They were recruited as part of a larger study on the effectiveness of energy efficiency interventions used in the Green Deal programme. As such, many of the participants' homes were considered hard to treat and many participants lived in areas with a high index of multiple deprivation. Participants had a range of occupancy patterns, including single-person households, couples, multi-adult households, families with grown-up children living at home and families with young children. Further details of the participants are shown in Table 24.1.

Table 24.1 Occupancy patterns of the different participants

Occupancy Type	Single-person households	Couples or house-shares	Families with all children age 16+	Families with younger children
Participant code	E0, E11, E16, E33, E34, E35, E36	E1, E2, E13, E18, E21, E22	E2, E8, E14, E15, E20	E7, E9, E10, E12, E17, E23, E25, E29

Interviews

Semi-structured interviews with occupants lasted around 60 min. Each interview explored their experiences of heating up their home, including how warm their home is, the cost of their energy bills, their decisions around the temperature they keep their home, and any special efforts they make to reduce their energy bills.

Data Analysis

Interviews were audio recorded and transcribed verbatim. We used a thematic decomposition approach (Stenner 1993) which combines a discursive approach with thematic analysis within a post-structuralist discourse analysis framework. With this method, we use how people talk to explore how they construct or "make sense" of their world and the people, objects and events in it. This then helps us to understand their actions and interactions. Talk is not viewed as a passive means of communicating what people think and do, but rather, it is an active process that cocreates shared meaning. Discourse analysis is, therefore, less concerned with identifying what people actually do or think than with using the ways in which people position themselves and others in the accounts they give to gain insight into their choices and actions.

All the transcripts were read and reread by the first author and text relevant to the research question: "How do participants position themselves with respect to saving energy?" were coded. Codes were then grouped into discursive themes, focusing on the constructions of energy use and the discursive strategies employed.

Results

We identified two discourses in the data. These are described below, with quotes from the transcripts illustrating each discourse.

Switch

The first discourse positions savvy and responsible consumers as those who switch energy suppliers in order to reduce their bills. There are three different aspects to this discourse that indicate how it is used to avoid making any changes to reduce the energy that individuals use.

A Basic Necessity

Participants described keeping warm as a basic necessity and talked about being warm as enjoyable. Warmth was described as essential for comfort. Using a lot of energy for the purpose of keeping warm is therefore positioned as justifiable and even unavoidable. Within this discourse, being economical is something that is laudable and desirable but often unattainable.

> I'm probably not very economical with my heating, to be honest, but I do like a warm house. E9
>
> Well it is a lot [of money to pay for the bills] but I mean, if you want to be warm you've got to use it, haven't you? E19
>
> We've even told the council that if we need to pay for heating we'll do that before they get the rent. E25

In the quote below, E3 contrasts the cold environment she grew up in with modern-day living to justify how warmth is essential and living in a cold home is unacceptable and belong in the past.

> You really like to be comfortable and warm, don't you? That's part of life, really. Yeah, I hate to be cold. I remember when you were a child you used to have ice on the inside of the windows. We don't have that anymore. E3

Participants use the discursive device of positioning the home itself as being the problem rather than with individuals, the energy they use and their preference for a warm internal temperature. Homes are described as being poorly insulated with cold walls, draughty basements and poorly fitted windows. Appliances such as tumble dryers, hair straighteners and computer games terminals are described as essential. Participants' use of energy is therefore described as being unavoidable.

> Well to be honest, we are actually spending a fortune on gas and electricity. You know, we have had a new boiler put in, we have had double glazing put in but we still seem to be going through this thing that when the winter comes in, we turn our heating on and within about three quarters of an hour to an hour, all the heat's gone. So we suspect it's going through the walls. E14
>
> These houses, when it's warm they're warm, when it's cold they're like little ice boxes, and even in the summer when it gets cold of an evening, I put the heating on. I'm just soft, I like to be hot. E5

Participants' accounts served to justify them heating their homes to a temperature that they feel comfortable, when they could tolerate a colder home. They described themselves as being "soft" for feeling the need to be warm and comfortable but justified this by aligning a cold home with old-fashioned living. This discourse holds that in modern-day Britain people should not be expected to live in a cold home. Their poorly insulated home means they are forced to use more energy.

They've Got the Power

Participants' accounts indicate that the providers are constructed as powerful, while consumers are powerless because warmth is an essential part of modern life. In this discourse, because consumers need to use energy to keep their homes warm, with some homes being hard to heat and keep warm, they are positioned as victims "at the mercy of" suppliers who are always looking at ways to extricate more money from consumers. The presence of children or pets in the home was used to stress that a warm home is a necessity and a duty. A responsible parent keeps their home warm.

> I'm struggling to pay the bills but what can I do? My kids have to feel warm. If you don't feel warm you feel miserable. If I didn't keep this house warm my kids will be ill, they don't eat well. So I have to really. E4
>
> Because both me and my partner work inside [our home] and also I've got birds that need certain temperatures and I've got pets, that is an issue that unfortunately I just have to… I'm at the mercy of the energy companies and that's it, really. E14

Energy providers were positioned as malevolent corporate entities that try to exploit consumers for the sake of increasing profits to benefit their shareholders. Suppliers repeatedly increase the cost of energy so that, with no change in the amount of energy used, consumers face increasing energy bills.

> Our plan used to be absolutely superb but then they priced it up and priced it up. E3

This way of positioning energy companies was apparent even in those participants who described having received free insulation and energy saving advice from their energy provider. These actions, according to this discourse, did not exonerate providers from their unscrupulous pursuit of profit.

Participants positioned themselves as an innocent, bewildered as to why their energy bills should be so high. This is despite often presenting a narrative around how many items of electrical equipment their household uses. The amount of energy they use was often described as being due to others in the household and very rarely their own choice. In this way, they distance themselves from any fault or blame around the amount of energy used.

> The gas is fine, our electric has always been humungous; I don't know why. I phoned up several times about why our electric is so much. I keep questioning why is our electric so high, are we paying for all the lights in the village? Maybe we're not economical with electric; I don't know. E9

A few participants talked about having the potential to reduce their energy consumption but generally described this as being too difficult or too much hassle to do.

> If I made a massive effort to not use the dryer and turn everything off I could probably cut it [consumption] down a bit. But you need a life. E23

> I don't know what else to do to cut back on the bills. The boys are absolutely terrible because they're up half the night so all the lights are on and all their equipment is on upstairs, so that doesn't help, but try telling them to turn it off, and it's like—ha! E10

Fighting Back

Within this discourse, consumers are positioned as fighting back against the energy suppliers. Consumers need to be alert to unscrupulous supplier practices and to resist their hegemony by questioning bills and withholding loyalty. Without doing so, consumers are taken advantage of.

> You've got to keep checking what they're up to because otherwise they put you on an expensive tariff. You've got to watch them or you'll end up paying well over the odds. E17

In this discourse, savvy consumers change suppliers in order to get better fuel prices. Because consumers are positioned as being unable to decrease the amount of fuel they use, they therefore need to secure a cheaper energy deal.

> Our philosophy is if we're cold put the heating on. We're constantly looking at where we can save money with the gas bills, looking at different companies, but other than that we just use it as we need to. E12
>
> My daughter talked me into changing energy providers; she's all for saving. E5

Most participants, however, were left disappointed in the amount of money they saved and many talked about feeling cheated when they discovered their energy bills were higher than they had been with their previous supplier.

> It seemed to be, like, I weren't even using as much as before and now I'm with XXX at the moment and they're so steep it's unreal. E15
>
> I changed suppliers about a year ago and it seems that they're charging me three times more. I'm still fighting with them about the cost of my electricity because it is horrendous and obviously I can't change yet because it hasn't been a year but if we don't get to the bottom of it I'll be going back to my old supplier for electricity. E10

Save

The second discourse, which was drawn upon only rarely, centred on trying to reduce the amount of energy used. There were two aspects, described below.

Payback

This aspect of the discourse is about resisting using energy because of fear of being unable to afford the bills. A few participants were frightened to use their heating as often as they would like because of the potential cost and the need to avoid being in a position in which they cannot pay the bill. In the quote below, E33 describes being very conscious of keeping bills under control. Similarly, E36 describes a previous bad experience of a high bill and his account highlights his need to avoid a similar situation.

> If I put the gas on all the time it [the bill] will just rocket so I'm very careful; I can't have it on all the time. E33
>
> A few years ago, a couple of weeks before Christmas, I started putting the radiator in my bedroom for just a couple of hours before I went to bed every night. And they sent me a bill for £400. Just because I was using one extra radiator! I just can't afford that so I just don't use it any more. And I'm not with them [the supplier] any more. E36

A small number of participants positioned themselves as being hardy, able to withstand the cold, or to resist heating their homes because using heating during the warmer months should not be necessary. In the quotes below, E11 positions herself as reluctant to turn the heating on and only does so because her daughter urges her to do so. These subject positions were relatively rare. All participants who used it gave accounts of being able to tolerate the cold and so choosing to live in a cold house, although they also talked about financial constraints that mean they choose not to keep their homes warmer. They needed a reason, often a visitor, in order to justify putting their heating on.

> Sometimes when it gets cold you think "Shall I put the heating on?" and I think, no, it's only September. I'm not putting the heating on. E11
>
> If it's chilly I'll put it [the heating] on when my daughter gets here; she's just getting over breast cancer and she has arthritis and that, you know, and I just don't want her to be cold. She comes up every day, and like I said, if it's chilly I'll put it on when she comes and if not I put it on about teatime. E16
>
> I'm an ex-postie, I'm used to working outside and I'm always warm. If you're cold you just put more clothes on. I have a thermal jacket and I have sleeping bag that I use as a quilt. E18

Times of Transition

When participants described trying to use less energy, they always positioned their motivation as reducing their energy bills rather than reducing environmental impact. When present, the desire to change accompanied other life events, such as moving home, a change in work status or a period of illness. In the quotes below changes in circumstances have meant E9 and E11 both have less income, which has led them trying to reduce the energy they use. Both are making small changes to their energy use suggested by their energy company (E9) and by an advertising campaign (E11).

> I'm trying to reduce my bills 'cause me and my husband separated a few months ago so obviously things have changed. So I am trying to be quite conscious of, you know, trying to use the toaster instead of the grill and things like that. They [the energy company] sent me a booklet of things you can try and do. I'll see if it makes a difference over time. E9

> He's stopped working now, so we're trying to do as much as we can on the Economy 7 cos it's cheaper. But if you use a lot of daytime electric you get stung for it because it goes up a lot higher. We don't leave anything on standby cos that's using electric as well. Switch everything off like that. That's all we can do, really, there isn't anything else. E21

During interviews, participants were prompted about whether they wanted to reduce their energy use in order to protect the environment, very few participants talked about environmental sustainability, and those who did usually talked about it as an abstract concept that they felt a duty to talk positively about. Most, however, did not consider this as personally relevant.

Discussion

We have taken a social constructivist approach to identify the discourses and discursive strategies that people use to defend and maintain high levels of energy use. We found two discourses in the data. The first discourse—Switch—positions responsible consumers as those who switch energy suppliers in order to reduce their energy bills. Several discursive strategies are used, including contrasting how people lived in cold houses in the past with how warmth is an essential feature of modern life. Participants positioned themselves as powerless to reduce their energy consumption, with others being responsible for high usage, or because their children or pets mean they need to heat their homes to a higher temperature than they would personally need to. In contrast, energy suppliers are powerful. The final discursive strategy is the need to fight back against unscrupulous energy companies by withholding loyalty and switching suppliers to get better energy prices.

The second discourse positioned practices to reduce the amount of energy used as being motivated by fear of being unable to pay energy bills and by periods of transition. The discursive strategies used were positioning oneself as being hardy and able to tolerate the cold and identifying unsustainable energy practices on the basis of the ability to pay the bills, rather than being environmentally unsustainable.

While there has been very little previous social constructionist research in the area of energy use, our findings resonate with the constructionist studies we have identified. In their media text analysis of how low carbon housing is portrayed by the media in the UK, Cherry et al. (2015) found that a discourse positioning individuals as having responsibility for adapting more sustainable, less energy-intensive practices was marginal. Instead, discourses of zero-carbon housing, and to a lesser extent, of retrofitting homes were drawn upon more frequently. This supports the current research findings that individuals position others—in this case competing energy suppliers—as having both the power and the responsibility to reduce their energy bills. Individual practices and actions are rarely drawn upon.

Indeed, our research findings illustrate how discursive strategies act as a barrier to individual actions to reduce energy use. Similar tensions have been shown in reducing water use in Australia in which participants positioned themselves as to reduce water but being constrained by their social obligation to use water to keep their gardens, and therefore their local neighbourhood looking attractive (Kurz et al. 2015). Their participants used the discursive device of positioning themselves as an environmental supporter to justify both to reduce water use and being at a loss to identify how to do so. Similarly, our participants wanted to use less energy but talked about being unable to understand how their bills were so high: “are we lighting the whole village?” (E9). Further, similar comparisons were drawn between their own, relatively frugal use, compared to the amount of electricity used by others in their household. However, our participants did not draw on a discourse or use a discursive strategy related to protecting the environment. This might be because our participants were primarily in low-income households, which have been found to be less concerned with the environment than more affluent highly educated households (e.g. Welsch and Kuehling 2009; De Silva and Pownall 2014). Similarly, protecting the environment was not found to be a major motivating factor in participants’ decisions to take part in energy efficiency schemes (Crosbie and Baker 2010).

Our research provides evidence of the need to use theoretical models that include both psychological and social components to understand energy-use behaviour. Theories such as the Theory of Planned Behaviour (Ajzen 1991) posit that behaviour is best predicted by intentions, which in turn are predicted by beliefs about the target behaviour (attitudes), beliefs about what others do and expect (norms) and beliefs about how much control they have over reducing energy use. Behaviour can be changed by targeting any of these sets of beliefs. However, as highlighted by Blake (1999) it is important to move away from the assumption that beliefs can be changed by addressing the “information gap”. Indeed, it is argued that individuals can have many, contradictory and transitory beliefs that they can draw upon in different situations, and that meaning and values are negotiated between different actors in a specific context. Insight into this process is best gained using social constructionist methods and there is a need for further research using these paradigms.

The discursive strategies we have identified can inform future behavioural change interventions. Messages around energy efficiency being an important and easily achievable means of everyday life are appropriate, as are messages around using less energy as being a means of empowering individual consumers. At present, it is important to frame narratives around saving money rather than protecting the environment, as this discourse is largely absent in our target population, although it is likely to be more relevant for higher income groups.

Conclusion

Campaigns such as the Department for Energy and Climate Change’s Power to Switch, which encourages consumers to make sure that they are on the cheapest tariff for their needs, use narrative framing that will motivate consumers to consider changing their tariff or supplier. These messages will not, however, encourage consumers to reduce the overall energy they use. As the majority of participants used narratives that position themselves as being helpless in the face of modern-day energy demands, messages to help them feel more in control over using less energy would be valuable.

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Chapter 25
Analyzing the Payback Time of Investments in Building Automation

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Abstract Smart home implementation in residential buildings promises to optimize energy usage and save significant amount of energy because of a better understanding of user's energy usage profile. Apart from the energy optimisation prospects of this technology, it also aims to guarantee occupants comfort and remote control over home appliances both at home locations and at remote places. However, smart home spending requires an adequate measurement and justification of the economic gains it could proffer before its realization. These economic gains could differ for different occupants due to their inherent behaviours and tendencies. Thus it is pertinent to investigate the various behaviours and tendencies of occupants for similar domain of interest and to measure the value of the energy savings accrued by smart home implementations in this domains of interest in order to justify such economic gains. This paper investigates the energy consumption in rented apartments for two behavioural tendencies (Finland and Germany) obtained through observation and corroborated by conducted interviews. These tendencies alongside the energy measurements from the smart home system is used to measure the payback time and Return on Investment (ROI) of their smart home implementations. The research finding reveals that building automation for the Finnish

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behavioural tendencies seems to proffer a better ROI and payback time due to a relatively higher energy usage for space heating during the dark winter times.

Keywords Energy saving · Building automation · Return on investment · Payback time

Introduction

An automated building is a building that has the capability to adapt itself in various situations to make areas of the building more comfortable for its occupants while sharing a common interface that links it to systems and services outside the building. This system usually involves the installation of a smart gateway that makes standard homes smarter with only a small effort. According to Tejani et al. (2011), this system alongside a power management features could substantially reduce the power consumption of a home which imminently reduces the energy cost and carbon emissions of the building. In this paper, we mainly focus on energy savings and a financial justification for smart home investment.

The smart 2020 report given by Global eSustainability Initiative (2008) proposes that the installation of building management system (smart home system) by occupants to automate building functions such as lighting and heating and cooling could offer a major opportunity to reduce the global CO_2 emissions of buildings by a ratio of 15 %. Also according to the report given by (Energy Star n.d.), 42 % of home energy expenditure comes from house conditioning, however much of this energy expenditure is often used for space conditioning when the home is unoccupied. It was also highlighted by (Energy Star n.d.) that the installation of programmable devices could significantly mitigate against energy wastefulness from negligent occupants and could save approximately 10–30 % of their overall energy bills.

Improving the performance of a building through investment in building automation is associated with a significant investment cost. Results from observations and product research for residential homes indicate that, the investment cost of building automation ranges from 500 to 2000 € (depending on building type). Several authors have proposed the significant chain of environmental degradation (in terms of CO_2 and greenhouse gases reduction); such investment could mitigate and have highlighted the social impact and human consideration of these technologies (in terms of its inherent comfort and control), however:

1. According to the report by (Energy Star n.d.), it is still unproven and unclear how much these technologies could save in terms of energy and cost.
2. There has been no sufficient economic justification for these investments based on any economic metrics (for instance investment return and payback time).

This paper aims to gather and analyze data obtained from building automations in rental apartments in two European countries (Germany and Finland) to

1. compare the energy usage and energy cost for buildings with and without smart system installations, and
2. investigate the payback time and return on investment of building automation installations.

The rented apartments investigated for this study were obtained from occupants with apartments that have home automation already installed and thus the choice of the apartments were based on a correct and complete set of data obtained from the home automation system and occupants.

Literature Review and Other Specific Work Directly Related to the Research

The report given by Bosseboeuf (2012) provides a summary of the energy usage for residential and non-residential buildings in EU states and a comprehensive analysis of how the effects of the economic, energy prices and occupant's behaviours affect this energy usage. The analysis is based on the energy usage data and energy efficiency indicators provided by the ODYSSEE database and website. The energy usage in buildings may vary per country, however this consumption represents in average a total of 41 % of the energy usage in the European Union (EU) and from this lot, residential buildings accounts for 65.9 % of the total energy usage of EU buildings and 27 % of the energy consumption in the EU. For Finland, Spain, Portugal, Cyprus, building energy usage represents 33.33 % of their total energy usage while for Germany, Denmark, France, Poland, building energy usage represent 45 % of the final energy consumption. Also, while the distribution of building energy consumption between residential and non-residential buildings may vary per country, the share for residential building from the total building consumption for Germany and Finland ranges between 60–70 % and the annual consumption per (kWh/m^2) for these two countries are 210 and 325 respectively. This disparity is associated to climatic difference between the two countries. A breakdown of the energy consumption per household for both Finland and Germany in Table 25.1 reveals that space heating represents the largest share of the total household energy usage.

A comparison of the energy usage for space heating from the year 1990 to 2009 reveals a reduction trend for the EU average usage with a ratio of 30–60 %. This reduction was attributed to the implementation of thermal regulations from EU countries for new buildings.

However, the data provided by Enerdata (2015) for heat consumption per m^2 at normal climate conditions reveals that between the year 2000 and 2012, Germany recorded a 17.38 % decrease in energy usage with figures 17.472 koe/m^2 and

Table 25.1 Distribution of building energy consumption per usage category

Distribution	Germany (%)	Finland (%)
Space heating	75	66.7
Water heating	12	14
Electric appliances and lighting	12	19
Cooking	1	0.3

12.436 koe/m^2, respectively, while Finland recorded a 2.18 % increase with figures 15.583 koe/m^2 and 15.923 koe/m^2, respectively. This implies a 21 % energy usage difference for space heating for Finland and Germany for the year 2012.

Comparing the energy usage for electric appliances per dwelling for the year 2000 and 2012, the data given in Enerdata (2015) reveals that Germany recorded a slight 8.81 % increase from 2078 to 2261 kWh respectively and Finland recorded a significant 30.23 % decrease from 4548 to 3173 kWh respectively. This implies a 29 % energy usage difference for electricity for Finland and Germany for the year 2012.

The ecoMOD project by the University of Virginia given by Foster et al. (2007) entails the design, construction and evaluation of houses for energy efficiency. This project aims to achieve three objectives: academic, environmental and social. To achieve energy monitoring, a monitoring system was installed to retrieve sensory and actuation data every second and stores them with timestamps. This monitoring system comprised of cost effective sensors that measure temperature, humidity, air quality, water flow, electric usage for appliances, carbon dioxide level and wind speed. Sensory and actuation data were retrieved through a wireless connection and these were stored on a remotely accessible database. A detailed data analysis was conducted on a 20 day stored data using a custom developed web data-analytical application software and the data analysis results indicates that the HVAC[1] and water heating system constituted the larger portion of the energy consumption with both measuring 38 and 21 % total energy consumption respectively. Also the result indicates a 50 and 45 % reduction in the envisaged energy consumption of the building. The discrepancies between the envisaged consumption and the analysis result for the hot water heater and HVAC was not justified with measured data, however it correlated with the result of a similar study given by Global eSustainability Initiative (2008). This paper will investigate these assumptions for different home scenarios using real automation data and energy measurements obtained through installed home automation server from deployed sensors and actuators.

[1]HVAC (heating, ventilation and air conditioning) is the technology of indoor and vehicular environmental comfort. Its goal is to provide thermal comfort and acceptable indoor air quality. HVAC system design is a sub discipline of mechanical engineering, based on the principles of thermodynamics, fluid mechanics, and heat transfer. Refrigeration is sometimes added to the field's abbreviation as HVAC&R or HVACR, or ventilating is dropped as in HACR (such as the designation of HACR-rated circuit breakers).

Utilizing various wired and wireless media approaches for implementing smart gateway architectures for home automation were extensively discussed by Wei and Li (2011), Skon et al. (2011), Chen et al. (2009), and Han and Lim (2010), however the FHEM[2] platform will be adopted for this study because it enables interoperability between several proprietary devices and smart protocols and this platform enables users to define and select the data types that are logged by the smart system. This enables a somewhat easier understanding of log data and data retrieval for data analysis and computations.

Smart gateways that incorporate power management features to substantially reduce the energy usage, reduce energy cost and carbon emission in residential buildings were introduced by Tejani et al. (2011). Alongside these gateways, sensors which communicate directly with the gateway were installed to feed the system with data regarding light intensity, temperature and motion within and outside the apartment. To achieve energy optimization, automation scenarios were designed to prevent human negligence from resulting into energy wastage. Energy usage of devices was measured when the smart gateway was active and inactive for a year. The energy usage comparison between measurements with and without the smart gateway revealed a significant reduction in energy consumption of lighting, air-conditioner and heater for each room in the apartment. While the energy usage for uncategorized devices (white goods) remained unchanged with/without the gateway. Tejani et al. (2011) justifies the energy usage optimization capability of home automation and it provides a detailed energy measurement of devices and their comparison with and without the smart system. They also suggest that the energy usage of some home appliances (e.g., fridges, laptops, desktop computers, pressing iron, vacuum cleaners, washing machine and the garage doors) cannot be further optimized by smart devices, because their energy usage with or without smart system installations are the same and these appliances will be referred to as other appliances. Also electric fans consume more energy with smart system installations; hence they should be left out of smart system installation. From the foregoing, it is assumed that all automation scenarios aimed at energy optimization should mainly focus on lightings, air-conditioners and heaters.

Research Review and Methodology

The return on investments in Information Technology (IT) as presented by Bruce and Vernon (2002), formulates a model to guide future researches in the evaluation of information technology investment. This was achieved by proposing two general frameworks for considering the return on investment in IT that are measured with

[2]Fhem is a GPL'd perl server for house automation. It is used to automate some common tasks in the household like switching lamps/shutters/heating etc. and to log events like temperature/humidity/power consumption. The program runs as a server, you can control it via web or Smartphone frontends, telnet or TCP/IP directly.

accounting performance measures (e.g. ROA). The first framework shows how IT has a direct and/or indirect effect on business processes which altogether determine the overall performance of the firm. The second framework categorizes how researchers have measured IT, business process performance and firm's performance. This framework highlights three ways in which IT investments are being examined and these are referred to as IT measures. These IT measures include: difference in the amount of money spent on IT; the type of IT purchased and how IT assets are managed. Bruce and Vernon (2002) referred to these as IT spending, IT strategy and IT management/capability respectively. Also as part of this framework, three paths that illustrate the relation between IT and overall firm performance were identified. The first path is a direct link between IT and firm performance thus bypassing the effects of IT on business processes. The second path describes the effect of IT on business process performance and the third path shows how these business process measures combines to determine the overall firm performance. This paper also identified some contextual factors that determine the links between IT and identified performance measures.

As a recommendation, Bruce and Vernon (2002) highlighted some research opportunities that could be further adopted for IT ROI researches from the following observations: most literatures resulted in measuring the direct relations between IT and firm performance thus bypassing the underlying business processes either due to confounding issues or measurement problems. This approach as highlighted by the paper, is often inappropriate and this paper proposes that future works should demonstrate how IT directly affects the intermediate business processes and how a combination of these intermediate processes impacts firm performances.

Taking a clue from this paper, the frameworks presented by Bruce and Vernon (2002) can be adopted as a methodology by examining the direct and indirect effect of smart system on device performance and how a combination of device performances affect the overall building performance. These effects are represented through path 1 and 2 respectively in Fig. 25.1. The smart measures in Fig. 25.1

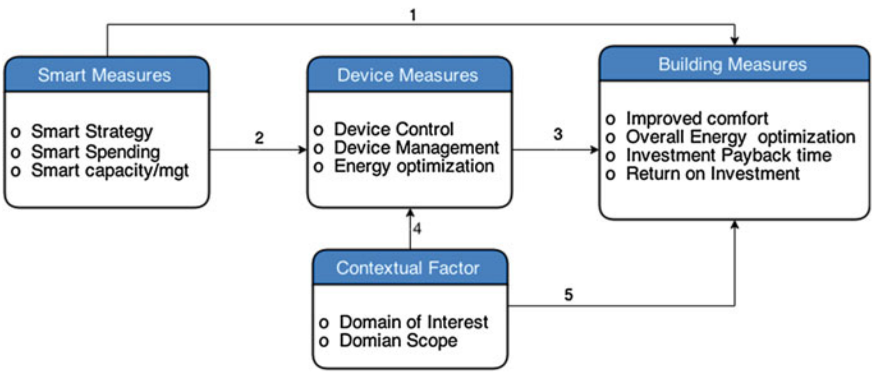


Fig. 25.1 Measures of entity performance

represent metric for smart systems valuation. Irrespective of the smart measure that influences a user's choice, the goal here is to improve the performances of both the devices (appliances in a building) and the overall building and these performances can be measured using the metrics identified in both the device and building measures. The contextual factors are factors that affect the performances of devices and the building irrespective of the smart implementations. A typical example is the location of an apartment. The location of a building determines the climatic range of an area; it determines the cost rate of energy for an apartment and other governmental charges.

As suggested earlier, Path 1 does not provide an in-depth insight into the energy optimisation capabilities of installed smart devices and it will only be utilized when there exists no additional information apart from the overall energy usage of the building with and without home automation.

Research Method

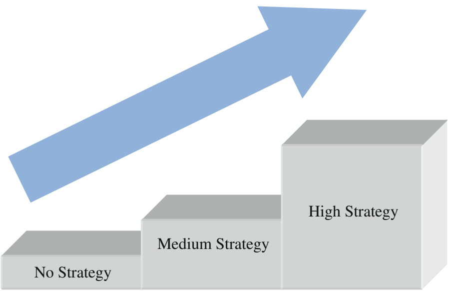
This is a mixed study that integrates both qualitative and quantitative research studies. The quantitative aspect extracts numerical data from the system logs of implemented home automations and these data are used for several numerical computations and statistical analysis and identification of reusable patterns. The qualitative aspect utilizes observation and interviews to extract information from home occupants and end-users to corroborate the quantitative data and extract user behavioural tendencies.

From the data gathered from interviews and observation, the smart implementation for identified residential buildings could be classified into three smart strategies based on the automation scenarios implemented for each identified use cases. And the classification of the automation scenarios implemented for each smart strategy is given in Sangogboye (2015).

These smart strategies are:

1. Low Comfort & Low Energy optimization also known as no smart strategy.
2. Medium Comfort & High Energy Optimization also known as medium smart strategy.
3. High Comfort & High Energy Optimization also known as high smart strategy.

The no smart strategy involves no smart spending whatsoever while the medium strategy represents the first level of smart investment and it is targeted at optimizing the energy consumption in the apartment and achieving basic control. The high strategy aims at achieving high level of comfort for user and an optimized energy usage in the apartment. It is assumed that this case is usually sought after by users that have experienced some medium degree of comfort and relative significant energy saving from the medium smart strategy. High level of comfort is usually achieved by a more sophisticated automation scenario that is enabled by the installation of additional sensors and actuators.



Comfort (%)	0	35	83
Energy optimisation (%)	0	83	92
Total (%)	0	43	70

Fig. 25.2 Degree of smart strategy

From the scenario classification given in Fig. 25.2, the no smart strategy implements no automation scenarios. The medium smart strategy implements 43 % of the total automation scenarios identified, 35 % of the comfort category (comfort and modes) and 83 % of the energy optimisation (heat and electric) category. The high smart strategy implements 70 % of the total automation scenarios identified, 83 % of the comfort category and 92 % of the energy optimisation category. Figure 25.2 illustrates and summarizes these values from a comprehensive list of the automation scenarios and classification is given in the http://goo.gl/ULYlu2.

To determine the energy consumption and energy cost for the no smart strategy, the extracted user behaviours for this strategy are simulated with respect to reusable patterns identified from analysed log data extracted from the smart system. Also since the smart home system mitigates against the standby energy usage of electric devices, the corresponding standby energy consumption for each electric devices as specified in the survey conducted by Ministerial Council on Energy Forming (2006) are cumulatively added to the energy consumption of electric appliances for the no smart strategy. For the medium smart strategy, the smart log data and smart spending of smart installations are presented for this study; hence the log of all smart devices and home appliances are analyzed to derive their usage period, their energy consumption and their overall energy cost. The derived energy cost is weighted against the energy cost of the no smart strategy case to derive the gain of investment. This gain alongside the smart spending is used to compute the payback time and ROI of the medium smart strategy. To determine payback period and ROI of the high smart strategy, the cost of the additional sensors and actuator to achieve a more informed automation scenario are added to the smart spending of the medium smart strategy and the energy usage of the new smart devices are subtracted from the energy gain of the medium strategy. These new figures are used to compute payback time and ROI for the high smart strategy. The ROI is computed by dividing the overall financial gain of home automation (after deducting the spending) by the total smart spending and the payback time is computed by dividing the total smart spending by the financial gain of home automation (before deducting the smart spending). These are illustrated in Eqs. (25.1) and (25.2).

Return on Investment

$$\text{Return on Investment (ROI)}\% = \frac{\text{Total Energy Cost saving} - \text{Smart spending}}{\text{Smart spending}} \tag{25.1}$$

Payback Time

$$\text{Payback Time} = \frac{\text{Smart spending}}{\text{Total Energy Cost saving}} \tag{25.2}$$

Use Case Specification

The rented apartments presented comprises of a living room, a bedroom and a bathroom for both use cases. For the Finnish use case, this apartment also comprises of a Sauna room. As stated earlier, the choice of apartment was based on a correct and complete set of data obtained from the home automation system and occupants. The distribution of electric appliances required automation devices and smart spending for this apartment is given in Table 25.2.

The total smart spending for both German and Finnish use case for medium and high smart strategies are given in Table 25.3.

Also to understand the energy usage profile of occupants prior to smart home installation (no smart strategy), occupants were observed and interviews were conducted to extract their user behaviours in both uses cases. While for the medium and high strategies (post smart home installation), occupant's behaviours was extracted from automation scenarios implemented on the smart home server, patterns identified from the log data presented for the study and conducted interviews. The extracted user behavioural tendencies for both German and Finnish users for the no smart strategy are as shown in Table 25.4.

Research Results

The smart system logs the instances each electric appliance is switched on or off. These data are translated into the duration of usage for these appliances. These durations alongside the wattage of each appliance and the electricity rate of the country is used to derive the cost for powering each appliance.

Table 25.2 Distribution of appliances and smart spending for identified smart strategies

SN	Room	Devices	Automation devices	Smart spending (€)	
				High	Medium
1.	Living	Lamp Heat radiator Stereo	*Sensor* 1. Motion detector *Actuator* 2. Radio wall switch 3. Heating control 4. Wireless switch socket	39.95 33.95 69.95 39.95	33.95 69.95 39.95
2.	Bathroom	Heat radiator Washing machine	*Sensor* 1. Motion detector *Actuator* 2. Heating control 3. Radio wall switch 4. Wireless switch socket	39.95 69.95 33.95 39.95	69.95 33.95 39.95
3.	Bedroom	Heat radiator Wardrobe light	*Sensor* 1. Motion detector *Actuator* 2. Heating control 3. Radio wall switch 4. Wireless switch socket	39.95 69.95 33.95 39.95	69.95 33.95 39.95
4.	Sauna	Lamp Sauna stove	*Sensor* 1. Motion detector *Actuator* 2. ELV FS20 SH switch module for FS20 DIN rail system	39.95 39.95	39.95
5.	General		1. TuxRadio	70.00	70.00

Table 25.3 Total smart spending for identified smart strategies

German use case (€)		Finnish use case (€)	
Medium	High	Medium	High
467.6	621.4	541.5	701.3

Electricity Usage with Smart Device

$$\text{Electricity usage (kWh)} = \text{Power of Device (kW)} * \text{Duration of use (h)} \quad (25.3)$$

Electricity Cost with Smart Device

$$\text{Electricity cost (€)} = \text{Electricity usage (kWh)} * \text{Rate (€/kWh)} \quad (25.4)$$

The log data for heat radiators provides the periods when the heat radiator changes its valve position, when a new desired room temperature is set and a periodic measurement of the room temperature. From these, the valve reading and the duration for each valve reading can be extracted and be used to formulate the following:

Table 25.4 Extracted user behavioural tendencies for Finnish and German users

German user behaviour	Finnish user behaviour
1. All lamps in the apartment are only switched on when they are needed and are switched off when they are not in use 2. All lamps are switched off when the users are asleep 3. To ventilate the apartment, the windows are open and the heat radiator is switched off. This is done every day for a period of one hour 4. The heat radiator knob is set at 57.5 % when the heat radiator is switched on	1. All the lamps in the apartment are only switched on when they are needed. However during the dark winters, these lamps are often in use 2. All lamps are switched off when the users are asleep 3. The apartment is ventilated while the heat radiator is switched on. This is done every day for a period of one hour 4. The heat radiator knob is set at position 4 (out of 5–80%) when the heat radiator is switched on 5. The sauna facility is used for a period of 60 min weekly

Heat Usage with Smart Device

$$\text{S.H.E. (Space Heating Energy) usage } (\%\text{h}) = \text{Radiator Valve Reading } (\%) * \text{Duration of use (h)} \tag{25.5}$$

Given the bill for heating, the cost rate for heat usage and the cost of heating can be derived as follows:

Rate of Heat Usage

$$\text{Rate } (€/\%\text{h}) = \frac{\text{Utility Bill}(€)}{\sum_0^n \text{S.H.E. usage}(\%\text{h})} \tag{25.6}$$

Heat Cost

$$\text{S.H.E. Cost } (€) = \text{Heat usage } (\%\text{ h}) * \text{Rate } (€/\%\text{ h}) \tag{25.7}$$

Given that the rates for S.H.E. usage and electricity usage for Finland and Germany as shown in Table 25.5.

Tables 25.6, 25.7, 25.8, and 25.9 presents the cost of energy usage for electric appliances and heat radiators for both German and Finnish use cases and for the three identified smart strategies.

Table 25.5 Rates for S.H.E. and electricity in Germany and Finland

Germany		Finland	
€/% h	€/kWh	€/%h	€/%h
0.0173	0.25	0.0109336	0.158

Table 25.6 Electricity cost comparison between smart strategies for German use case

SN	Rooms	Appliances	Smart strategy (€)		
			No	Medium	High
1.	Living Room	Lamp	5.218	5.218	5.218
		Stereo + standby	10	0.93855	0.93855
		Flat screen TV (standby)	9.241775	–	–
2.	Bedroom	Wardrobe light	1.8362	1.8362	1.8362
3.	Bathroom	Wash machine (standby)	1.9571625	–	–
4.	Smart System	Raspberry pi	–	6.57	6.57
5.	Other appliances		377.18725	377.18725	377.18725
6.	Total		405.440388	391.75	391.75

Table 25.7 Cost comparison of S.H.E. between smart strategies for German use case

SN	Rooms	Appliances	Smart strategy (€)		
			No	Medium	High
1.	Living room	Heat radiator	602.99	376.7	376.7
2.	Bathroom	Heat radiator	641.59	255.7	255.7
3.	Bedroom	Heat radiator	147.143	174.31	174.31
4.	Total		1391.723	806.71	806.71

Table 25.8 Electricity cost comparison between smart strategies for Finnish use case

SN	Rooms	Appliances	Smart strategy (€)		
			No	Medium	High
1.	Living room	Lamp	3.297776	3.297776	3.297776
		Stereo + standby	6.32	0.5931636	0.5931636
		Flat screen TV (standby)	5.8408018	–	–
2.	Bedroom	Wardrobe light	1.1604784	1.1604784	1.1604784
3.	Bathroom	Wash machine (standby)	1.2369267	–	–
4.	Sauna room	Sauna stove	19.434	19.434	19.434
		Switch module	–	0.28	0.28
5.	Smart system	Raspberry Pi	–	4.15224	4.15224
6.	Other appliances		238.382342	238.382342	238.382342
7.	Total		275.6723249	267.3	267.3

Table 25.9 Cost comparison of S.H.E. between smart strategies for Finnish use case

SN	Rooms	Appliances	Smart strategy (€)		
			No	Medium	High
1.	Living room	Heat radiator	587.24	238.48477656	238.48477656
2.	Bathroom	Heat radiator	593.174	161.88944176	161.88944176
3.	Bedroom	Heat radiator	188.854	110.374692	110.374692
4.	Total		1369.268	510.74891032	510.74891032

Table 25.10 Cost comparison between smart strategies for both Use cases

Smart strategy	German use case		Finnish use case	
	Electricity	S.H.E.	Electricity	S.H.E.
No	405.44	1391.7	275.67	1369.3
Medium	391.75	806.71	267.3	510.749
High	391.75	806.71	267.3	510.749

Table 25.11 Payback time and ROI for both medium and high smart strategies

Smart strategy	German use case		Finnish use case	
	Payback (yrs)	ROI (%)	Payback (yrs)	ROI (%)
Medium	0.78102	28.04	0.625	60.01
High	1.038	−3.653	0.808983	23.61

The additional smart devices that enables an accurate implementation of the high smart strategy are powered by batteries, hence the energy consumption of the high smart strategy is the same with that of the medium smart strategy.

$$\begin{aligned} \text{Electric Cost Saving } (€) &= 405.440388 - 391.75 = 13.690388 \\ \text{Heat Cost Saving } (€) &= 1391.723 - 806.71 = 585.013 \\ \text{Total Energy Cost Saving } (€) &= 13.690388 + 585.013 = 598.703388 \end{aligned}$$

The additional smart devices that enable an accurate implementation of the high smart strategy are powered by batteries, hence the energy consumption of the high smart strategy is the same with that of the medium smart strategy.

$$\begin{aligned} \text{Electric Cost Saving } (€) &= 275.6723249 - 267.3 = 8.3723249 \\ \text{Heat Cost Saving } (€) &= 1369.268 - 510.74891032 = 858.51908968 \\ \text{Total Energy Cost Saving } (€) &= 8.3723249 + 858.51908968 = 866.89141458 \end{aligned}$$

Table 25.10 summarizes the energy cost for all smart strategies in both use cases.

Using Eqs. (25.1) and (25.2), the payback time and ROI for both medium and high smart strategies for the German and Finnish use cases are given in Table 25.11.

Discussion

The return on smart investment or spending for the German Rented Apartment for a year period for the medium and high smart strategy are 28.04 % and −3.653 % and their respective payback times are 9.4 and 12.5 months. The value for this return for the first and second year (given that there are no significant differences in environmental factors from the first year) for a medium smart strategy is 131 and 598 € respectively while the value for this return for the first and second year for a high smart strategy is a loss of 23 € and a gain of 598 €. Depending on the preference of an investor, a payback time of 12.5 months for a high smart strategy might be appropriate for the level of comfort and control the automation scenarios this smart strategy proffers. However from an economic standpoint, it is advisable to progressively invest in a medium smart strategy for the first year and then a high smart strategy for the second year. This is to enable the investor get some returns of 131.1 € for the first year, before investing another some of 153.8 € to attain a high smart strategy to both achieve a higher level of control and comfort and a smart investment return of 576.0 €.

The return on smart investment or spending for the Finnish Rented Apartment for a year period for the medium and high smart strategy are 60.01 and 23.61 % and their respective payback times are 7.5 and 9.71 months. The value for this returns for the first and second year (given there are no significant differences in environmental factors from the first year) for a medium smart strategy are 325.4 and 866.9 € respectively while the value for this returns for the first and second year for a high smart strategy are 165.6 and 866.9 € respectively. From an economic standpoint, the high smart strategy can be implemented from the beginning, this is because a progressive investment for a medium strategy for the first year and high strategy for the second year will yield the same investment return as the initial high smart spending over a two year period.

Conclusion

From the foregoing, it can be observed that the installation of both home automation for the Finnish usage tendencies seem to proffers a better ROI and payback time than for the German usage tendencies. Also while a German investor should initially adopt a medium smart strategy before a high smart strategy for early profitability, a Finnish investor may have the liberty to adopt any of these smart strategies and still accrue a desired profit.

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