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Lai Fong Chiu, Robert Lowe, Rokia Raslan, Hector Altamirano-Medina & Jez Wingfield

a UCL Energy Institute, University College London, Central House, 14-16 Upper Woburn Place, London WC1H 0NN, UK
b Bartlett School of Graduate Studies, University College London, Central House, 14-16 Upper Woburn Place, London WC1H 0NN, UK
c The National Energy Foundation, Davy Avenue, Knowlhill, Milton Keynes MK5 8NG, UK

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A socio-technical approach to post-occupancy evaluation: interactive adaptability in domestic retrofit

Lai Fong Chiu¹, Robert Lowe¹, Rokia Raslan², Hector Altamirano-Medina² and Jez Wingfield³

¹UCL Energy Institute, University College London, Central House, 14–16 Upper Woburn Place, London WC1H 0NN, UK
E-mails: laifong.chiu@ucl.ac.uk and robert.lowe@ucl.ac.uk

²Bartlett School of Graduate Studies, University College London, Central House, 14–16 Upper Woburn Place, London WC1H 0NN, UK
E-mails: rookia.raslan@ucl.ac.uk and h.altamirano-medina@ucl.ac.uk

³The National Energy Foundation, Davy Avenue, Knowlhill, Milton Keynes MK5 8NG, UK
E-mail: jez.wingfield@nef.org.uk

Understanding the process of domestic retrofit is important for learning and innovation. This is particularly the case for low carbon retrofits such as those undertaken under the UK’s Retrofit for the Future (RftF) programme, with its aim to achieve an overall 80% carbon reduction by 2050. Current post-occupancy evaluation (POE) research has both theoretical and methodological limitations with implications for technical and behavioural research in the built environment. Drawing on relevant ideas and concepts from social practice theory and science and technology studies, principally prefiguration (constraints/enablement), black-boxing, heating and cooling practices, this paper demonstrates how the relationship between buildings and people could be reconceptualized as mutually constitutive and co-evolving through a process of ‘interactive adaptation’. The concept of ‘interactive adaptation’ is explored through a novel approach to integrating physical and social data collected from a sample of dwellings selected from the RftF programme. Analysis yields insights into the influences and pathways of interactive adaptation resulting from retrofit technology and practices. The implications of these insights for policy-makers, the research community and practitioners are discussed: end-use energy demand policy needs to be informed by a socio-technical approach.

Keywords: adaptive behaviour, heating/cooling practices, inhabitants, interactive adaptation, low carbon retrofit, post-occupancy evaluation

Introduction
The ambition of successive UK governments to achieve significant cuts in carbon emissions from existing the housing stock has stimulated policies such as Feed-In Tariffs (FITs), Green Deal and the Renewable Heat Incentive to provide financial support for innovation and investment. To encourage the construction industry to take advantage of the transition to a low carbon economy, the Retrofit for the Future Programme (RftF) was launched in 2009 to explore how retrofit capacity could be radically improved. Domestic low carbon retrofits are qualitatively different from those undertaken through earlier programmes such as the UK’s Community Energy Saving Programme (CESP). While CESP retrofits have been characterized by draught-stripping, low cost insulation measures, replacement boilers and lighting, low carbon retrofit projects typically require the installation of a collection of advanced energy-saving measures and appliances, as well as energy-generating technologies such as photovoltaic (PV) and/or solar thermal. Although these technologies have great potential, predicted performance and energy savings are not often guaranteed.
The design-built performance gap is widely known (e.g. Lowe, 2000). Bordass and Leaman (1997) cautioned that the operation and management of complex technical systems is crucial for achieving optimal performance, and through the 1990s developed Post-Occupancy Evaluation (POE) (Cohen, Standeven, Bordass, & Leaman, 2001) as a systematic way to assess building performance and occupants' satisfaction. In recognition of the increasingly complex technologies installed in green buildings, Cole, Robinson, Brown, and O'Shea (2008) called for a more integrated approach to understanding the interactions between building inhabitants and new technologies, defining the process as 'interactive adaptation'. They suggested that the potential for and realization of 'interactive adaptivity' is critical for the design and development of green buildings. Since the 1980s there has emerged a socio-technical perspective on building and energy efficiency (e.g. Hutchison & Handegord, 1983; Guy & Shove, 2000; Shove, Chappells, Lutzenhiser, & Hackett, 2008) and, within this, a body of empirical research (e.g. Fouleds, Powell, & Seyfang, 2013; Gram-Hansen, 2010; Karvonen, 2013; Tweed, 2013) representing an alternative approach to investigating issues related to buildings and energy.

Challenging the assumptions underpinning some of the applications of POE, the current authors argue that the limitations and consequences of current POE methods have the potential to undermine learning and innovation if applied uncritically or without modification. Drawing on relevant ideas and concepts from social practice theory and science and technology studies, this paper demonstrates how the relationship between buildings and people could be reconceptualized. Within this framework, the concept of 'interactive adaptation' (Cole et al., 2008) is explored through an integration of physical and social data collected from a sample of dwellings selected from the RtfF Programme.

Research context

To address the challenge of the UK's national CO2 reduction target of 80% by 2050, the Technology Strategy Board's (TSB) RtfF programme established 86 exemplar projects in the social housing sector across the UK (TSB, 2009a, 2009b). It assumed that the 80% reduction target would apply at the level of the individual dwelling, leading to a target carbon emission rate of 17 kgCO2/m²a, evaluated through a modified version of the Standard Assessment Procedure (SAP). The reductions would be achieved through a combination of energy saving and energy-generating measures. To enhance learning from the programme, TSB worked with the European Regional Development Fund (ERDF) to co-fund the Facilitation, Learning and Sharing programme (FLASH), coordinated by the Institute of Sustainability. The FLASH programme specifically aimed to provide construction industry practitioners with practical, research-based information on sustainable development and retrofit to enable them to take advantage of commercial opportunities offered by the prospect of large-scale domestic retrofit.

As a condition for funding, TSB required project teams to undertake a prescribed programme of POE, consisting of 'before-and-after air permeability tests, thermography studies, post-construction reviews and occupancy surveys' (TSB, 2013, p. 3, 2009c). Although physical evaluation of energy performance based on temperature measurements and pressure tests is relatively well developed and routinized, concerns were expressed by evaluators regarding the lack of critical analysis of occupants' feedback that would be possible (Gupta & Chandiwala, 2010) if the approach to occupant surveys were not modified. It was also clear to the present authors that there was no standard way of dealing with post-construction (hindsight) reviews. These limitations afforded opportunities for different approaches, to which the FLASH project (Lowe, Chiu, Kaslan, & Altamirano, 2012) described in this paper was a response.

Limitations of POE

POE, and more generally, Building Performance Evaluation, has a long history. Until the early 1980s, the primary emphasis of POE was on building design and its impact on occupants (Hadri & Crozier, 2009; Preiser, Rabinowitz, & White, 1988; Zimring & Reizenstein, 1980). In the UK, this approach is embodied and exemplified by the work of Tom Markus and the Building Performance Evaluation Unit at Strathclyde University, between 1967 and 1971 (Markus et al., 1972).

Concern over energy efficiency, security of energy supply and climate change in the last four decades has led much energy research, tacitly or explicitly, to adopt the Physical–Techno–Economic Model (Lutzenhiser, 1993, p. 248). This model:

has characterized consumer behaviour and choices as instrumental, purposeful, and rational and secondary to the devices, machines, and appliances that are seen as the actual users of energy (Lutzenhiser et al., 2009, p. II)

and has significantly influenced energy analysis, policies and interventions. In the UK, the techno-economic view of energy efficiency has led the evaluation of building performance to shift from design to physical and energy performance, based on monitoring of
temperatures and energy consumption (Guy & Shove, 2000). This was exemplified in the UK by the Post-occupancy Review of Buildings and their Engineering (PROBE) project (Cohen et al., 2001). From 1995, PROBE studied occupant responses, together with physical and energy performance of buildings, primarily to understand the latter. A key component of POE in the UK has been the Building Use Studies (BUS) occupant survey method, which was originally designed mainly for surveying occupants in non-domestic buildings for the purposes of comparison. The occupant survey method is structured around broad themes ranging from occupants’ reported levels of comfort and satisfaction to the degree to which they perceive their needs are being met by the building’s internal conditions. The domestic version (Housing Survey) was also developed to include questions on lifestyle, environmental design features covered by the Code of Sustainable Homes (CLG, 2010) and energy billing information.

The publication of the PROBE studies and the patenting of the BUS survey enabled POE to be standardized and routinized. In turn, this allowed TSB to make it a formal requirement for RfF programme. In addition, responsibility for the POE of the 86 RfF projects was divided between different contractors: responsibility for undertaking the BUS survey was allocated to one contractor, and for its analysis to another. This fragmentation of the research process had consequences. While it facilitated the aggregation of quantitative data, it made meaningful analysis difficult in general and coherent integration of physical and social data almost impossible.

Recognizing the limitation of the BUS survey for obtaining fuller feedback (Hadjri & Crozier, 2009) from occupants, Gupta and Chandiwala (2010) and Sunikka-Blank, Chen, Britnell, & Dantsiou (2010) responded by designing bespoke questionnaires. Despite modifications, surveys have continued to focus primarily on collecting quantitative data (thermal comfort on the seven-point American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) scale, external and indoor temperatures, thermostat set-points, and patterns of use of electrical appliances) related to space heating. The implicit assumptions underpinning these choices of data are:

- occupants’ behaviours contribute significantly to variations in the design-built performance gap
- occupants’ behaviours are influenced by occupants’ perceived thermal comfort
- ‘rebound’ or ‘take-back’ is seen as one possible explanation for the gap between predicted and actual energy saving after retrofit

However, current approaches remain primarily concerned with quantifying aspects of occupants’ behaviours that contribute to energy consumption. Until now there has been a dearth of projects that have attempted to understand occupants’ experiences in the process of low carbon retrofit and how they interact with or adapt to their changing environment.

**Understanding rebound**

Rebound, a key concern of policy-makers and research funders, was originally an effect predicted and observed by economists. Its key feature is increasing consumption of energy services after an improvement in technical efficiency of delivering those services (Greening, Greene, & Difiglio, 2000; Khazzoom, 1980; Saunders, 1992; Sorrell & Dimitropoulus, 2008). From this perspective, in the context of energy efficiency in housing, one would expect internal temperatures in the space heating season to rise as the marginal cost of providing heating falls.

Statistical analysis of secondary data indeed shows that increasing building efficiency (broadly defined) results in increased internal temperature (Kelly et al., 2013; Santin, 2012), with under-heating in poorly insulated dwellings and higher temperatures in well-insulated dwellings (Sunikka-Blank & Galvin, 2012). One of the consequences of aforementioned approaches to understanding impacts of retrofit is a tendency to support the uncritical attribution of post-retrofit higher temperatures to active occupant behaviours.

In principle, higher temperatures in energy-efficient dwellings can result from a number of mechanisms, including:

- poorly designed control interfaces, which make it difficult for occupants to control their heating
- compensation by occupants for variations in internal temperature caused by variations in fabric performance or poorly balanced heating systems
- physical consequences of intermittent or partial heating
- the larger impact of incidental heat gains (solar etc.) in highly insulated dwellings
- active decisions on the part of occupants to take advantage of energy efficiency by raising heating system set-points

Each item above is layered and involves complex interactions between building fabric, heating systems,
occupants and the supply chain. Little of the empirical work to date has explored these mechanisms in detail and statistical work is largely unable to reveal interactions between physical and social systems.

The above exemplifies how attempting to understand occupants’ behaviour without a thorough understanding of the building physics before-and-after retrofit and in the absence of qualitative data from occupants, makes it difficult to disentangle the relative contributions of buildings and people to energy consumption. Achieving such a disentangling requires a reconceptualization of building performance evaluation and POE practice and a close integration of research into physical and social elements of retrofit, based on a wide range of contextual data.

**Reconceptualizing POE: a socio-technical approach**

This section presents the context and concepts that provided the theoretical underpinning of the FLASH project.

This journal’s special issue on ‘Comfort in a Low Carbon Society’ (Shove et al., 2008) marked the emergence of a socio-technical perspective on built environment research. Acknowledging agency and complexity, Cole et al. (2008) presented a wider notion of comfort that included psychological and socio-cultural meanings as well as the physiological dimension of comfort. This in turn gave rise to the concept of ‘interactive adaptation’ between buildings and people.

Contemporaneously, social practice theory has come to play an increasingly important role in expanding the understanding of occupants, comfort and energy consumption, through the concepts of heating and cooling practices (e.g. Gram-Hanssen, 2010); occupants’ responses to retrofit and impacts of use of space on energy consumption (Tweed, 2013); and community-based programmes as a strategy to achieve systemic change in domestic retrofit of the UK housing stock (Karvonen, 2013).

**Taking a socio-technical perspective**

Recognizing that energy use in buildings is not a technical but a socio-technical phenomenon requires redefinition of the relationship between people and technology. This is characterized by acknowledgement of:

- the mutually co-constitutive, co-evolving nature of social actors and technology (e.g. Elzen, Geels, & Green, 2004) and
- the enmeshing of technological artefacts (such as fabric, ventilation, glazing, etc.) and bundles of social activities in webs of social relations (Schatzki, 2001): ‘What enables and constrains actions, however, is not actions alone. Artifacts, organisms, and things, typically in combination and as arranged, also do so’ (Schatzki, 2002, p. 45).

The usefulness of this theoretical position for examining retrofit is that it privileges neither the technical nor the social. It postulates that constraints and enablement inherent in material and social arrangements prefigure social practices, and condition their trajectories (Schatzki, 2002). This perspective transcends the dualistic notions of ‘agency’ and ‘structure’, and the separation of ‘technology’ and ‘people’.

**Interactive adaptation**

In recontextualizing comfort, Cole et al. (2008) came close to this mutuality by highlighting the possibility of interactive adaptation between occupants and new technology. Informed by social theorists’ work on human agency (Bourdieu, 1977; Giddens, 1984; Habermas, 1989) they suggested that engagement, dialogue and communication at all stages are required to enable occupants to play an active role in operating increasingly complex systems associated with buildings. However, Stevenson and Rijal (2010) subsequently applied the concept of ‘interactive adaptation’ to the investigation of occupants’ behaviours and perceptions regarding comfort and control with the aim of enhancing build performance evaluation. Amongst social practice theorists, comfort is seen as something people achieve through performance of a web of other household practices (‘doing’ and ‘saying’) such as cooking, washing, cleaning, that differ culturally, spatially and temporally (Hitchings, 2011; Shove, 2003). These practices include the use of heating and cooling systems (Shove, 2003) and natural ventilation (Hitchings, 2009). Concentrating on accounting for ‘doing’ rather than merely quantifying individuals’ specific behaviours (e.g. opening/closing windows, adjusting thermostats), social practice theory broadens and re-orientates ‘interactive adaptation’ (originally conceived as an extended notion of comfort), showing how it can be captured, analysed and interpreted by examining heating and cooling practices as bundles of activities that include artefacts and people.

**Black-boxing**

Bruno Latour’s concept of ‘black-boxing’ within his Actor Network Theory is a powerful tool for understanding the limitations of current POE practice and how they might be overcome. A black box is a single case (consisting of long-lasting associations of both
human actors and artefacts, referred to by Latour as *actants* (Latour 1999, p. 183). Latour also describes:

> the way scientific and technical work is [often] made invisible by its own success. [...] Thus, paradoxically, the more science and technology succeed, the more opaque and obscure they become [...]. (p. 304)

The black box is seldom opened or questioned.

The concept of black-boxing can be applied to retrofit. A successful retrofit depends on a collection of *actants* – the house itself, a collection of energy-saving and -generating technologies, and the occupants – and the associations between them. The performance of the retrofitted dwelling emerges from an integration of all the parts with the everyday life of occupants. As technologies mature, they tend to become increasingly black-boxed. However, large-scale low carbon retrofit is still in its infancy, glitches and malfunctions abound, and underperformance is pervasive. Learning is therefore essential, and this requires researchers to look into the black box. The problem is that current POE practice forecloses this option.

**Methods**

The FLASH project used a multiple case study design (Gray, 2004, pp. 123–151) with a concurrent mixed-method approach for data collection and analysis (Creswell, 2003, pp. 208–227). Cases consisted of a sample of dwellings selected using a maximum variation (MV)-purposeful sampling strategy (Patton, 2002) from the RtfF programme. The goal of MV sampling (sampling for heterogeneity) was to maximize sample diversity across project teams, house types, occupant–household compositions and demographic backgrounds. The sample initially consisted of 12 dwellings/households (four of which belonged to a single terrace), but full datasets were ultimately only available for ten of them (Table 1).  

<table>
<thead>
<tr>
<th>Case</th>
<th>House age/type</th>
<th>Total floor area (m²)</th>
<th>Location in London</th>
<th>Occupants</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1992, three-bed mid-terrace</td>
<td>83.7</td>
<td>East</td>
<td>Family of five</td>
</tr>
<tr>
<td>B1</td>
<td>1970, three-bed end-of-terrace</td>
<td>95</td>
<td>North</td>
<td>Family of four</td>
</tr>
<tr>
<td>B2</td>
<td>1970, three-bed mid-terrace</td>
<td>95</td>
<td>North</td>
<td>Family of four</td>
</tr>
<tr>
<td>B3</td>
<td>1970, three-bed mid-terrace</td>
<td>95</td>
<td>North</td>
<td>Family of three</td>
</tr>
<tr>
<td>C</td>
<td>Victorian, three-bed end-terrace</td>
<td>87.4</td>
<td>East</td>
<td>Single elderly female</td>
</tr>
<tr>
<td>D</td>
<td>1960s, four-bed mid-terrace</td>
<td>100</td>
<td>East</td>
<td>BME family of eight</td>
</tr>
<tr>
<td>E</td>
<td>Victorian, two-bed mid-terrace</td>
<td>80</td>
<td>South</td>
<td>Single male</td>
</tr>
<tr>
<td>F</td>
<td>1960s, four-bed semidetached (extended)</td>
<td>130</td>
<td>North West</td>
<td>Family of seven</td>
</tr>
<tr>
<td>G</td>
<td>Edwardian, four-bed end-terrace</td>
<td>76.82</td>
<td>East</td>
<td>BME² family of five</td>
</tr>
<tr>
<td>H</td>
<td>Inter-war three-bed detached</td>
<td>83.64</td>
<td>East</td>
<td>Elderly couple</td>
</tr>
</tbody>
</table>

Two of the households (cases F and G) had been allocated to newly retrofitted properties due to previous overcrowding, and therefore did not experience the retrofit process directly.

**Brief profiles of sample households**

The houses selected ranged from 1990s’ semidetached and terraced houses, through a mid-20th-century detached house, to Victorian end- and mid-terrace houses in conservation areas. Interestingly, six of the ten dwellings, including the terrace, were of cavity wall construction.

The households in the study ranged from a singleton to a family of eight. The majority of the households had low incomes. Most adult occupants in the sample were economically inactive with average-to-low educational attainment. Where there were children, they ranged in age from very young to adult. Two of the ten households were from black and minority ethnic (BME) communities.

**Post-construction stakeholder (hindsight) and occupant interviews**

Retrofits were performed by project teams that consisted of designers, constructors and social landlords. Cases B1–B3 (in the terrace of houses referred to above) were carried out by one team, and cases D and H by another. The other five cases were carried out by separate teams. Thus, a total of seven hindsight interviews were undertaken. Project teams were asked to reflect upon their perceptions of occupants’ experiences, lessons learned in terms of the overall design challenges and viability of different technical solutions, and to identify future opportunities, and other factors (constraints and enablement) that influenced retrofit
processes (Lowe, Chiu, Raslan, & Altamirano, 2013). The occupant interviews took place in occupants’ own homes during the heating season, November 2011–April 2012. A semi-structured interviewing guide was developed to explore occupants’ experiences while satisfying TSB’s requirements for quantification of behaviours and occupants’ satisfaction. The interview incorporated a ‘walk-through’ procedure whereby occupants were encouraged to discuss any aspects of the new installations. At the same time as documenting and photographing technical systems and energy-saving appliances, features suggesting changes in the configuration of space and problematic issues were also recorded. The walk-through procedure is a visual/spatial technique that has the advantage of evoking occupants’ memories, promoting a richer account of the retrofit process and of their experiences with the technology installed. Interviews lasted typically about 90 min. All were digitally recorded and transcribed verbatim for analysis.

Analysis
Transcripts and corresponding photographs were sorted into cases. Shortly after each interview, the interviewer, a social scientist, met with the team’s building scientist to review the transcript and photographic evidence. Notes and memos arising from these discussions have been retained as the basis for further analysis. Further corroboration of interviewing data with other quantitative and descriptive data (including architectural drawings and plans) about the property provided by the database of the RfTf was also carried out before writing up each case report. The analytical framework used matrices to juxtapose evidence on physical arrangements and occupants’ experiences. This framework provided the basis for cross-case comparison and analysis. Further corroboration with available quantitative data and data from hindsight interviews was also undertaken.

Findings
Prefiguring adaptability: altered aesthetics and reconfiguration of space
According to Schatzki (2002, p. 45), prefiguration is ‘how the world channels forthcoming activity’. In this context, prefiguration refers to how interactive adaptability is conditioned by physical arrangements and the practices of retrofitting.

Apart from installing an array of renewable energy production technologies (e.g. heat pumps, PVs), low carbon retrofit projects typically involve a careful consideration of fabric, heating and ventilating systems (Table 2). Altered aesthetics and reconfiguration of

Table 2  Summary of the fabric, ventilation and heating strategies

<table>
<thead>
<tr>
<th>Case</th>
<th>Fabric strategy</th>
<th>Ventilation strategy</th>
<th>Heating strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Hybrid: front internal and back external</td>
<td>Mechanical ventilation heat recovery; PV = positive input ventilation</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>B1-B3</td>
<td>All internal envelope insulation</td>
<td>Mixed: natural and single-room ventilation units</td>
<td>Communal heating</td>
</tr>
<tr>
<td>C</td>
<td>Mixed: front internal and back external and wall party</td>
<td>Exhaust air heat pump</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>D</td>
<td>External and internal</td>
<td>PIV</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>E</td>
<td>External wall and internal party wall</td>
<td>MVHR</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>F</td>
<td>Mixed: front internal and back external</td>
<td>MVHR</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>G</td>
<td>External</td>
<td>MVHR</td>
<td>Condensing combi boiler</td>
</tr>
<tr>
<td>H</td>
<td>External</td>
<td>MVHR</td>
<td>Condensing combi boiler</td>
</tr>
</tbody>
</table>

Note: MVHR = mechanical ventilation heat recovery; PIV = positive input ventilation.
space are obvious physical consequences of the application of these technologies.

The application of external insulation impacted on the appearance of properties (directly relevant to occupants in all except the reallocation cases, F and G), even though in some cases changes were only visible at the back. The change of appearance was especially pronounced for dwellings retrofitted to the Passivhaus standard (cases B1–B3, D and H) and those that had opportunistic extensions (cases D and F). Occupants’ reactions to these changes ranged from seeing the final result as being ‘bland’ compared with the original brick finish (e.g. case B3) to fearing that it could be seen as a form of conspicuous consumption (case A) that might attract unwelcome attention in a social housing estate. Occupants of properties with heritage status (cases C and E) perceived the preservation of the original appearance at the front, and applying external insulation to the back, as a good compromise.

Mechanical ventilation heat recovery (MVHR) systems and internal wall insulation used to preserve the heritage status of the dwelling often impinged on the configuration of the internal space. As a result, several households saw their living and storage spaces reduced and reconfigured. For example, bookcases (case E) and wardrobes (case D) had to be rebuilt because of internal wall insulation, storage space and ceiling heights reduced to accommodate MVHR units and ductwork (e.g. cases B1–B3, D). While cases B1–B3 retrospectively lamented the loss of interior space, case D actively complained during the retrofit process and successfully had a section of ductwork redirected through unused space within a chimney breast, and negotiated an increase of space through bringing an existing outside toilet into the new thermal envelope.

Some occupants found the location and physical appearance of MVHR units hard to accept (cases B1–B3 and A). Occupant A rejected an MVHR unit that was integrated into the cooker-hood in the kitchen because of its disproportionately ‘huge’ size and loud noise. The occupant commented:

They put in [something that] looked like a tumble dryer, it was huge, it sounded like an aeroplane taking off [...] when they put it up and when they boxed it like in the centre over the cupboard [...] and then I contacted them and asked them to take it down.

Acknowledging the problem of the MVHR system and recognizing that the occupants of this house were smokers who also made heavy use of a tumble dryer, the project team came up with an alternative strategy. Key features of this were:

- custom-made high-performance windows with side vents to allow good ventilation without compromising U-values when shut; occupants could feel entirely secure even with vents open (Figure 1)
- an automated roof-light built into the previously unused roof void, providing space for storage, drying clothes and a workstation, as well as allowing natural light into the stairwell and hall (Figure 2)
Both cases A and D successfully negotiated with respective design teams to transform a dark ground floor room (case D) and a dark hallway (case A) into brighter and more spacious living space by the use of skilful interventions that combined the goals of energy saving with other non-energy goals. These cases highlight the uncertainties and indeterminacy inherent in retrofit design and installation. Disruption to the build process and occupants’ lives can make visible the material arrangements that prefigure adaptability. However, engagement and communication amidst difficulties altered the pathways of some retrofits. Sensitive design enabled occupants to benefit from enlarged and improved space through extensive reconstruction (cases A and D). The following discusses these processes and associated interactions in more depth.

Constraints and enablement

In practice theory, constraints and enablement are conditions present in material and social arrangements ‘making some actions [adaptation in this case] easier and harder or more direct or circuitous than others’ (Schatzki, 2011, p. 10).

The thermal environment of a retrofitted home is the resultant of a combination of fabric, glazing, heating and ventilation strategies. Low carbon retrofit tends to involve nominal opaque fabric $U$-values of around 0.1 W/m$^2$K, and a high degree of air-tightness. One of most notable concomitant changes is the introduction of ventilation technologies to reduce ventilation heat loss while providing fresh air. In the FLASH project sample, ventilation solutions ranged from the relatively simple mechanical extract ventilation (MEV) to more complex systems such as MVHR and, in case E, an exhaust air heat pump (EAHP) system. Heating was integrated with ventilation in several of these systems (Table 2). This section examines how choices of heating and ventilation system may constrain or enable adaptability.

The occupant of house E was keen to save energy and wanted to manage his system actively. He described explicitly how he liked to run his house at a low temperature (he said 15–16°C) and used the thermostatic radiator valves (TRVs) on his radiators to regulate temperatures around the house. He was also proud of the motorized vent installed in the hall and said that he used it to cool the house when it was too hot in summer. However, he was baffled and frustrated by his inability to understand or control the ventilation system:

Hear the hum? That’s the heat pump. […] But I don’t understand why is it doing it now? Because it is supposed to be pumping hot air from the bathroom and the kitchen which aren’t being used and that’s still pumping. Why? And most of the time it’s like that. I hardly […] I only ever use the shower once a day and heat in the kitchen once a day [so where is the extra heat]? […] But it’s boring! I don’t understand why it has to be on all day.

He resorted to using mineral fibre insulation to muffle the noise from the heat pump and turned it off when he was on holiday.

Occupants B1–B3 also found their MVHR and communal heating system incomprehensible. Not long after the installation, the occupants discovered that the MVHR system was not functioning. Occupant B3 was completely baffled by it, but tried hard to explain how it worked to the interviewer:

the way we were sold it [how we would save energy], was we will be able to if it were too hot down here [in the living room] that we could send the heat upstairs. So that excess heat from when you are cooking in the kitchen would go to heat upstairs [the MVHR] and through filters they would take out the cooking smell upstairs. Well, which I can’t see […] how’s it gonna function? So I don’t think that is connected up to do that anyway […] Yeah, I don’t know where it is. Because to me, it only blows air. So obviously, you got to send it upstairs you got to have an intake as well to draw it out to send it upstairs […] which you know, the little time it was working and blowing out cold air, you know […] it’s not working.

The male occupant of case F, although previously a plumber by trade, was unclear how his positive input ventilation (PIV) system worked or indeed whether it was working at all, and became frustrated and disengaged. Most occupants found control interfaces complex and counterintuitive; many were put off by them and fell back onto the up-down buttons on their thermostats as the main or only controls that they used.

Cases A, D and H were clearly satisfied with their retrofit systems. The multifunction automated roof-light and high-performance windows with side-panel vents won the heart of the occupants of case A, through transparent function and purpose, ease of use and promised low maintenance requirements. Occupants of case H were an elderly couple with chronic health conditions. With the support of a very attentive housing liaison officer, they displayed good awareness of their MVHR system, and were delighted, in particular, with its ability to clear the house of any unwelcome odours: ‘if you’re cooking so much fish and it’s a bit [smelly] and [if] you wanted to, you can give it a boost for [a few] minutes’. However, they remained
unaware that the system could supply ample fresh air even if they kept their windows closed in winter. During the walk-through, it was observed that they had their bedroom windows wide open for fresh air, with the radiator under the windows on full, on a very cold winter’s day.

Case D appeared to have actively adapted to living with the retrofit technologies installed. Despite earlier complaints about the encroachment of the ventilation ductwork into their living space, they were delighted with the effects of the ventilation system on their family members’ health and knew how it should be operated and maintained: ‘In the winter, we never had to open the windows [to ventilate].’ The interviewee summed up the benefits of MVHR when working in conjunction with the heating system as a whole:

First of all, the temperature. It’s always warm. During winter we didn’t have to turn on the central heating much. It was like five or six times during the whole winter, we switched on the central heating and it was only for ten to twenty minutes. The temperature from the cooker used to warm up the house. That’s one of the amazing things! It’s a huge difference. And the other thing is the air – the freshness of the air. My dad used to get hay fever every season. You know, this season he didn’t get hay fever [neither did] my brother’s eczema.

It turns out that the project team had visited the dwelling regularly and had worked with the occupants, dealing promptly and competently with issues arising. Remedial work included re-insulating the eaves of two cold front bedrooms and unblocking a vent in the kitchen. They had also provided tailor-made information on all aspects of the retrofit design and systems in an easy to understand format (Figure 3).

Understanding how things work and what people do is far from simple. The above analysis reveals how occupants’ adaptability to the retrofit systems could be constrained in a variety of ways by the different systems’ functionality, intelligibility and controllability, none of which might be guaranteed at the outset. However, it is clear that in some cases adaptability was made easier by attending to the quality of information and communication (Chiu, Lowe, Raslan, & Altamirano, 2012), as well as engagement and support from the project team.13

Understanding adaptability through heating and cooling practices

In order to understand whether occupants had changed their heating or cooling practices in a new environment, they were asked to describe their indoor conditions and how they lived with them, before and after the retrofit.

Figure 3  Case D: a retrofit information board for occupants
Source: Bere Architects
All occupants, except in cases B1–B3,14 had experienced varying degrees of ‘thermal discomfort’ prior to retrofit. Occupants recalled details of their thermal environment and what they did to make themselves comfortable both before and after the retrofit.

Most occupants had lived through conditions that were draughty, damp and cold, and described how it was impossible to keep warm in the winter, even though they had the heating on most of the day (cases A, C, D and H). Occupant C recalled that her windows used to ‘rattle in strong winds’ and to keep warm she had to keep moving her electric heater from one room to the other. Case D’s single-glazed metal-framed windows had severe condensation: the occupants had coped with this by mopping up water on windowsills:

[We] used to clean the water in the morning and also before we [went] to sleep. [...] We used to have some sort of cloth [...] like a t-shirt [...] that sucks up the water, but sometimes it spills onto the carpets from the windowsill.

Although the occupants in cases F and G had not experienced their present homes prior to retrofit, they also described the thermal conditions of their previous homes as uncontrollable (too cold in winter and too hot in summer).

Paradoxically, most occupants (six out of ten) initially said that they were ‘comfortable’ before retrofit. However, their initial use of the term ‘comfortable’ should be understood in the context of strategies to cope with and adapt to an objectively difficult thermal environment, e.g. ‘the house [got] cold very quickly – in a couple of hours after heating turned off’ and ‘to keep warm, I used draught-excluder[s] and electric blankets’15 when the house was cold in winter; conversely, they would ‘open windows and jar open doors’ to keep cool on hot summer days.

Those occupants (in cases C, D and F) who indicated their thermal conditions as ‘cold’ on the ASHRAE comfort scale described emphatically how they coped with such conditions. For example, occupant C said that she had only one gas fire (a main source of heat) in the living room, and had to use the gas burners (i.e. intended for cooking) in the kitchen to warm the house up.

Although occupants of house D had central heating installed before retrofit, the house was impossible to keep warm. They said the heating was on ‘most of the time [...] because the property wasn’t insulated, the heat used to get out of the house. After an hour or two, it gets cold again’. They used secondary heaters in the backroom as it opened onto a big window and a partly glazed door that were ‘constantly running with condensation’.

Occupants of case F recalled their previous home as ‘old and quite draughty, with very high [fuel] bills’. Although the property was double-glazed with central heating, they had to ‘turn up [the heating] to 25–30 degrees’ in cold weather throughout the day to keep warm. And in summer, some parts of the house could get ‘too hot’ to the point that ‘it would be too hot to walk in the room, it needed [to] cool down [...]’ by letting the door open and sliding the curtain across.

Case H recalled that their house was so cold and draughty that they had to wrap themselves up in a duvet when they first moved in some years ago. Only case G had experienced a thermal environment as being ‘quite warm’ (point +1 on the seven-point ASHRAE scale) before moving into their retrofitted home. The interviewee reported that she had had to keep the window open to keep cool. It is clear from the above that occupants who had experienced severe ‘thermal discomfort’ prior to retrofit all seemed to have developed a set of heating and cooling practices to keep warm in winter and cool in summer. Reported practices included putting on more clothing or wrapping themselves in duvets to keep warm, closing windows, using draught excluders, using other heating equipment such as electric heaters and electric blankets, turning their central heating up to a high temperature and keeping it on in an attempt to keep the house warm. Cooling practices included opening windows and doors, and drawing curtains or blinds.

Examining changes in practice through integrated analysis
After retrofit, all occupants (except cases B1 and B3) experienced improvements in thermal comfort. However, the degree of improvement varied from case to case, and the ways in which occupants adapted to their new thermal environments also varied. For example, noting that her retrofitted house ran at around 24°C, occupant A said that she preferred an indoor temperature that allowed her to ‘walk around in t-shirt and pyjama shorts’. She did not perceive a need to set her heating programmer, as the programme had been preset by the installer, or to use TRVs to control temperatures around the house.

Similarly, the occupant in case H marvelled at the very noticeable change in the clothing that they could wear inside the house:

I like it the way it is now, it’s just grand unless you open the window of course [...] it’s just lovely, you know what I mean? You can walk around with no clothes and just socks [laughs]
you can walk around in a nightie actually and feel no cold […]

Conversely, case E preferred to live in a colder house and had been careful about setting his radiator thermostats in each room to save energy. He described his energy saving actions in detail:

Now, my heaters, for instance, I don’t have any heating on the top [floor]. I’ve got five radiators in this house. One is on, not full, but one is on about thermostat 3, which is in the hall, that [living room] was on thermostat 2, the bathroom one is on thermostat 2, one upstairs are not on at all. In the depth of winter, I might find that I’ve got to turn them up.

These reported and observed heating and cooling practices were supported by physical monitoring data, where they were available. A plot of temperature data for the first four months of 2013 (January–April) internal temperatures in case E followed the trend in external temperature, indicating partial heating (Figure 4). Internal temperatures ranged between 15 and 20°C until mid-April when external temperatures rose by around 10°C. Measured temperatures in January were in the range 15–18°C, compared with the occupant’s declared preference for 15–16°C. Electricity usage was very low at 3.3 kWh/day. Also, there is no relationship between electricity use and internal temperature or external temperature. Unfortunately, gas consumption data was not available for this dwelling.

Although cases C and D reported the same level of thermal improvement (from ‘Much Too Cold’ to ‘Comfortable’) on the ASHRAE scale, the ways in which they both adapted to their new thermal environments could not have been more different. Case C, an elderly woman, said that she was not interested in adjusting the internal temperature by using the heating programme, but did appreciate that the temperature that had been preset for her was comfortable. When she got too cold, she would, as she always had, ‘turn on her little [electric] fire to top it up’.

In contrast, case D found he understood how the systems worked and how to use the thermostat and MVHR controls. However, he found that the house was now so comfortable that they ‘did not need to turn on the central heating much’. He exclaimed ‘Yeah, [it is] a big improvement’ and the house is so warm that ‘It was like [only] five or six times during the whole of winter [that] we switched on the central heating.’ The only minor complaint he had was the high-performance windows were a bit heavy to operate when the house got too warm or stuffy.

It appears from the above that while designers assumed that an improved thermal environment with optimum energy saving would involve programming the heating system, not all occupants could or would use the controls and thermostats provided. Several appeared to use the same set of heating and cooling practices that they always had, finding it easier to turn the main system or a supplementary heat source on or off to keep comfortable.

Cases B1–B3 were in a terrace of houses which was externally insulated to Passivhaus standard and heated with a small communal heating system. Each
of the houses had its own MVHR and warm air heating system. One might expect the high-performance thermal envelope to have resulted in relatively little variation in thermal environment between these three houses. But, interestingly, during the interviews, different occupants reported significantly different experiences, over a period during which heating and MVHR systems had all been turned off due to technical problems. Occupant B1 felt that she could no longer control the temperature inside the house, with rain coming in around her back door, and draughts coming through the ill-fitted windows and doors. She complained about how the temperature often fluctuated and how she coped:

Well I like it warm, but not very hot, you know. When you've got the heating on [before the retrofit] and it gets too hot you can turn it off, can't you? But now, if you've got the oven on, you're cooking, for two or three hours, the whole house goes like a baking, you know, like a very hot sunny day, that is what it is like. And then we have to open all the windows and then suddenly the house goes freezing. So, you can't win whatever you do [...].

Without any central heating for almost a year, B1 appeared to have resorted to using her tumble dryer to keep the house warm and consequently was not in a position to save any energy and money. When asked whether the retrofit had influenced her energy saving behaviour, she said:

No, not really [saving energy by turning anything off], 'cause I'm using the tumble dryer a lot. The tumble dryer takes most of the money up, 'cause I'm using it 24 hours sometimes. It can go on all night.

Physical monitoring data shows case B1 bedroom temperatures were relatively stable, but that the lounge temperature fluctuated, with an unknown ‘heating source’ coming on in response to falling temperature in the room. On its own, the data suggest a significant uncontrolled heat loss in the lounge. This interpretation is supported by the interview data, from which it appears that the replacement high-performance windows arrived on site wrongly measured and were then badly installed, causing draughts and rain penetration.

The fact that case B1 had roughly three times the UK average electricity consumption, and that monthly electricity consumption correlated strongly with monthly external temperature (highest monthly consumption was 1031 kWh at 384 degree-days in March 2013, lowest monthly consumption 576 kWh at 80 degree-days in September, 2012) is consistent with the use of electricity for heating.

The response of the lounge temperature to the electricity load can be seen in 5-minute data for 25 January 2013 (Figures 5 and 6). The shape of the electricity profile, dominated by plateau at roughly 2.5 and 5 kW, is consistent with the use of probably two large electrical appliances for heating purposes.

Occupant B2 indicated that they perceived no change in their thermal comfort before and after the retrofit. With no heating, they reported keeping their windows closed throughout the winter to keep warm. When quizzed about whether they opened and closed their windows like before, the response was:

Upstairs, maybe in my bedroom, I do. In the kitchen when we are using the oven we keep it open. It is not open now, but during the summer, we probably would.

While B2 indicated that they ‘don’t like their house too hot’, they were clearly anxious about how they would cope in very cold weather without a space heating system.

Case B3 was the only dwelling on the terrace not to have had central heating before the retrofit. They had always relied on their electric fire and convector heaters to heat their home. The interview with occupant B3 took place on a particularly cold evening in early February 2012. The occupants were dressed in warm clothing, with house slippers. The interviewers observed that the house was running at around 19°C (as shown on the kitchen digital thermometer). The occupants suggested that they ran the house quite cool and that on that particular evening they had been out. They said that they ‘haven’t had it [the electric fire] on much until this cold spell. We might stick it on for an hour or so immediately’. When asked if they would heat their bedrooms, they said that they had electric resistance convector heaters on the landing and ‘the heat goes into the rooms, exactly as before [the retrofit].’

After indicating emphatically that there had been no change (from -1, ‘comfortably cold’) on the thermal comfort scale, occupant B3 did remark that the house kept the heat in more after the retrofit. Asked how they would cope without a functioning heating system, they said that they would continue to do what they always had done – using their electric fire and convector heaters in winter and open their doors in summer to keep cool – to adjust for day-to-day comfort.

Occupant 2: No changes there, same isn’t it, because the heating is not working. Interviewer [ascertaining the answer]: No difference?

Occupant 2 [emphatically]: No difference, because we still like to put this [pointing to the electric fire] on if it’s cold.
Interviewer: It wasn’t too warm in the summer?
Occupant 1: No, not really, because we had the door open, we had it open most of the day so it wouldn’t get too warm if someone’s here [implying the door would be kept open if they were at home in summer].

Overheating and uneven temperatures were concerns in cases D, H and G. For example, the occupant in case H reported how their front room, with a south-facing bay window which receives the afternoon sun, got very hot on sunny days in summer. The heat coming through ‘the triple-glazing would have boiled you and heated you. It literally would have cooked you. So [we] would have to open up the windows’. Although the occupants had experienced some degree of overheating before the retrofit, they perceived that the retrofit made it so hot that at times that they had to move away from the front room. They would open their windows and doors if
they had to, to cope with different temperatures at different times.

After retrofit, most occupants (except for cases B1–B3) said that they were ‘thermally comfortable’. However, as was the case before retrofit, the actual meanings of comfort varied. They variously reported being able to walk around indoors in t-shirts and shorts or nighties, regardless of the outside temperature, running their houses at their preferred temperature (which ranged from 15 to 26°C) either with full control of their heating and ventilation systems, or by making use of a surprisingly diverse range of supplementary heat sources. In most cases the practice of opening windows for fresh air or closing them to keep warm remained unchanged before and after retrofit. It appears that only case D, with MVHR successfully installed and used, controlled their new heating and ventilating system through programmers and other controls.

Summary of heating and cooling practices
From the above, it appears that heating and cooling practices are not defined uniquely by the technologies installed (Table 2). Occupants adapted to their thermal environments using sets of heating and cooling practices as described above rather than through a programmatic adjustment of indoor temperature using the system controls, as energy researchers and designers often assume.

In most cases, pre-retrofit heating and cooling practices persisted following retrofit – only the intensity of these practices appeared to have changed. Technical dysfunction (understandably) appeared to prompt greater efforts to adapt with a wider repertoire of responses. In some cases, old practices persisted (e.g. case B3) because they served occupants well in the face of technological failures.

Discussion
Although much effort has been expended, particularly over the last decade, to improve POE by attending to occupants’ behaviour and satisfaction (Leaman, Stevenson, & Bordass, 2010), methods remain largely quantitative and outcome-orientated, and many studies lack theoretical underpinning. Recent socio-technical research in the built environment and retrofit has begun to draw attention to this issue (e.g. Cole et al., 2008; Foulds et al., 2013; Gram-Hanssen, 2010; Haines & Mitchell, 2014; Ingle, Moezzi, Lutzenhiser, & Diamond, 2014; Judson & Maller, 2014; Karvonen, 2013; Tweed, 2013; Shove et al., 2008; Vlasova & Gram-Hanssen, 2014). This movement and the limitations of current POE have precipitated the authors’ explicit adoption of the socio-technical approach for the FLASH project. Grounding POE in the socio-technical paradigm and social practice theory espoused by Schatzki (2001, 2002, 2010, 2011), and drawing on relevant and related concepts such as prefiguration, constraints/enablement and black-boxing, has enabled the authors to capture the process of interactive adaptation in the context of retrofit through an integrated analysis of both physical and social data.

This paper and the work it describes contains a number of limitations. For reasons set out in the Research Context section, the availability of physical data was limited. Due to space constraints, the treatment of the project teams’ practices in this paper is also limited, which has in turn precluded the presentation of examples of instantiation of retrofit technologies. Nevertheless, by opening the ‘black box’, the analysis has revealed the existence of a dynamic and iterative adaptive process between technology, project teams and occupants. Together, occupants’ and project teams’ accounts highlight how the design and implementation of the retrofits impacted, first and foremost, on living space and aesthetics and how these were regarded and, in turn, prefigured the process and trajectory of adaptation. It is clear that these dwellings were occupants’ homes, whose aesthetics and space were imbued with social and cultural meanings (Despres, 1991). Their disruption and reconfiguration should be seen as concrete examples (instantiations) of retrofit technology in its making, of which occupants were clearly a part.

This paper has alluded to the difficulties of attributing energy consumption to occupants’ conscious actions by relying on temperature data alone, since this is the product of enmeshing social practices and material arrangements. Clearest insights are found in the consideration of comfort (broadly defined), or lack of it (felt keenly by some occupants). The findings suggest that different forms of interactive adaptation may well have contributed to variations in internal temperatures between retrofits. All but one of the mechanisms listed in the section on black-boxing is displayed in one or more of the cases. For example, poorly design control interfaces (cases B1–B3, F and G) made it harder for occupants to control their heating; variations in fabric performance and/or poorly balanced heating systems (cases B1–B3 and G) led to higher temperatures to compensate for variations in internal temperature; incidental heat-gains (solar etc.) led to overheating in highly insulated dwellings (cases D and H); and occupants made active decisions to take advantage of energy efficiency by adapting to higher temperatures with thinner clothing (cases A and H) (Chiu et al., 2012). It was not possible to demonstrate the effect of intermittent or partial heating on internal temperatures due to the absence of internal temperature data before the retrofits. These mechanisms were reflected in occupants’ accounts of their experiences,
as articulated through qualitative interviewing methods. It appears that occupants with good quality retrofits enjoyed even and higher indoor temperatures despite differences in their educational levels and demographic backgrounds (cases A, D and H). Occupants did not report having consciously turned up their thermostat settings (though occupant E actively turned down his heating to save money). But occupants did notice that houses were kept warmer for longer periods of time in winter after retrofit, and that they valued this. However, for the Passivhaus standard retrofits (cases D and H), overheating, particularly in summer, appeared to be an issue. While most dwellings were improved, old heating and cooling practices persisted. Cases B3, C and H continued using secondary heaters to heat rooms and opening windows to keep cool. In some cases, these practices brought no obvious disbenefits; in other cases they helped occupants to cope with discomfort brought on by poor technical performance of retrofit systems.

It is clear that occupants adapted to their retrofitted dwellings in a wide range of ways. Their heating and cooling practices were personal, social and historical, and had been developed, habitualized and constituted in the material environments in which they found themselves.

Conclusion
This paper argues that the routinization and fragmentation of much current POE practice, coupled with a lack of theoretical underpinning, makes meaningful analysis and interpretation of POE data difficult and coherent integration of physical and social data almost impossible. In contrast, a socio-technical and interdisciplinary approach opens up the complex and dynamic nature of the process of interactive adaptation that occurs in domestic retrofit. The detail thereby revealed suggests that effective evaluation of energy performance has to account for the interaction between physical arrangements and social practices.

This has implications for policy-making in this area, which has hitherto been dominated by analysis of survey and aggregated data on physical attributes of buildings and people. Such analysis is unable to provide significant insight into the variation of outcomes of domestic retrofit and the practical problems (both technical and social) facing domestic sector retrofit. End-use energy demand policy needs to be underpinned by the approach described here to ensure that policy-makers are in a position to set realistic targets, and devise appropriate intervention strategies.

For researchers, adopting a socio-technical approach to POE means greater and closer interdisciplinary collaboration. Theoretically, black-boxing and interactive adaptation are complementary concepts that have provided the space for bridging the socio-technical disciplinary divide. On the methodological level, the empirical work set out indicates how richer data and closer integration of disciplines can illuminate retrofit practices, showing, among other things, how better retrofit design and performance can emerge from dialogue and communication between occupants and retrofit teams. This in turn has implications for retrofit policy and practice, e.g. in terms of the merits of decanting or undertaking retrofits with occupants in situ.

Future research needs to explore further the enablements and constraints inherent in material and social arrangements, e.g. existing supply chains that support retrofit, and how these interact with know-how (competence) in relation to design, installation and handover practices that, in conjunction with occupants, produce energy performance. This implies a research agenda that goes beyond the investigation of energy consumption in individual buildings to a deeper investigation of how practices structure energy demand through the built environment. However, the practical realization of such an agenda requires, among other things, consideration of the appropriate level of funding for building performance evaluation and POE in the UK.

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References


### Endnotes

1. The concepts of POE and Building Performance Evaluation are closely related and the terms are sometimes used interchangeably. The more general and arguably preferable term is ‘Building Performance Evaluation’. Nevertheless, this paper uses the former.

2. The BUS Housing Evaluation Survey instrument (c) Building Use Studies 1985–2008) was developed by Leaman and Bordass (2001) and is available from http://www.busmethodology.org/.

3. Guy and Shove (2000, p. 34) write eloquently about the fragmentation of research through contracting that was a feature of UK research procurement in the buildings sector throughout the 1990s. TSB’s approach to RfRF was a logical extension of this.

4. Rebound in the context of energy efficiency in buildings is a term used to describe a situation in which a proportion of the benefits of retrofit are taken as higher internal temperatures rather than reduced energy bills.

5. Such changes may either be prospective or retrospective, anticipating the effects of retrofit or responding to it after its consequences become apparent.

6. In addition to the criticisms of occupant surveys set out in this paper, physical measurements in dwellings in key recent projects have been insufficiently comprehensive to permit reliable estimates of changes in whole-house internal temperatures following retrofit (Hong et al., 2009), or in the case of RfRF, measurements before retrofit have been omitted (Low et al., 2012).

7. To say that the technical and the social are co-constitutive is to state that they are ‘continually interacting and shaping each other with exchanges in both directions’ (Walker & Cass, 2007, p. 459). Shove et al. (2012) have used the example of ‘skateboarding’ to illustrate this idea. They show how materials and their arrangements have enabled and constrained practices associated with skateboarding and, at the same time, evolved under the influence of these developing practices.

8. Latour uses the term ‘actants’ rather than actors to stress that both material entities and human actors are determinants of social interactions and outcomes. So the action of humans actants is shaped by non-human actants. For example, the availability of hot water and power showers have shaped humans’ habits of showering, and thus demand for heat and electricity.

9. Post-occupancy interviews were undertaken with the occupants of only three of the four terraced houses, cases B1–B3. Data from the post-construction review for another of the original ten were also unavailable.

10. Space limitations preclude reports on stakeholder interviews in this paper. But these have been drawn upon to inform the analysis of interactive adaptation (Low et al., 2012).

11. The first author took part in a series of three meetings of a working party convened by the Energy Saving Trust (EST) to discuss and redraft TSB’s approach to occupant interviews in March and April 2011, and contributed to a revision of the occupant survey guide. The resulting semi-structured interview guide is available, courtesy of the EST, at www.energiesavingtrust.org.uk/performace-evaluation.

12. The programmer interface in one of the dwellings was initially set to German rather than English.

13. In the case of retrofit, even more than in normal construction projects, the project team’s role is twofold: to help the occupants understand how things are supposed to work; and to make sure that things do indeed work as they are supposed to. Communication was most effective when things worked more or less as intended.

14. With the exception of cases B1–B3, whose dwellings had undergone significant improvements some years before the retrofit described in this paper.

15. The ‘doings’ and ‘sayings’ of heating and cooling practices are italicized in this section of the paper.

16. In houses that are continuously heated with effective thermostatic control in all rooms, internal temperatures are almost constant. The correlation between internal and external temperatures visible in Figure 4 is most likely to arise from intermittent heating, which allows internal temperatures to fall during heating-off periods. The lower the external temperature, the steeper the fall in internal temperature during such periods. In this particular house, the characteristics of the TRVs are likely to have made an additional, though minor, contribution to the observed correlation. The relationship between internal and external temperature changes qualitatively in the first two weeks of April, representing the effective end of the heating season in this house.

17. This is particularly clear in Figure 6 as events at around 10:00 and 13:30 hours. External temperature was below 3°C throughout the 24-h period shown. In both events, the living room temperature had fallen before the onset of heating – in the case of the 15:30 event, sharply. The more rapid overnight decay in temperature in the living room compared with the two bedrooms shown in Figure 5 suggests that heat loss is significantly greater in the living room. A possible explanation for this, which would be consistent with the occupants’ interview data, would be that air leakage is higher in the living room.