RETROFITTING HOMES FOR ENERGY EFFICIENCY: AN INTEGRATED APPROACH TO INNOVATION IN THE LOW-CARBON OVERHAUL OF UK SOCIAL HOUSING

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ABSTRACT

Ambitiously, the UK aims to cut greenhouse gas emissions by 80 per cent by 2050. Since the use of housing accounts for about 27 per cent of UK CO_2, and most new-build adds to the number of homes rather than substituting for them, housing's biggest contribution to better energy use and lower carbon emissions in the UK will come from retrofitting the country's existing stock. Moreover retrofitting particularly matters to registered providers of social housing, who seek guidance about the energy efficiency of their properties. This paper argues that an exclusive focus on just one of the technical, economic or social aspects of retrofit is inadequate. Using both theory and case-based experience, it discusses a number of ways, both technical and qualitative, of best measuring what retrofitting can do. It concludes that an integrated, comprehensive understanding of the retrofit process is essential to the making of informed decisions on the energy efficiency of homes, particularly at the scales required.

1. INTRODUCTION: THE RELEVANCE OF RETROFITTING HOMES TO THE ACHIEVEMENT OF UK CLIMATE TARGETS

There is considerable uncertainty about whether projects to renovate British homes and lower the carbon emissions associated with them can be rolled out at the scale in which they are needed [1]. *The overall use of h*ousing accounts for about 27 per cent of the UK's emissions of CO_2; if electricity is excluded, the greenhouse gases (GHGs) emitted directly from activities in the home amount to 15.3 per cent of the UK's total emissions. The UK has set itself a highly ambitious target of an 80 per cent cut in overall greenhouse gas emissions by 2050, compared to 1990 levels. Though emissions fell between 1990 and 2010, the drop now required on 2010 levels of emissions is still very considerable – 74 per cent [2]. Significant cuts in emissions are, therefore, required from UK housing, which is some of the oldest in Europe.

At least 87 per cent of the UK's housing stock – 22 million dwellings – will still be standing in 2050, even taking into account the country's rate of demolition, which amounts to two million dwellings over the past 40 years [3]. Since most new housing in the UK will supplement, not replace, the existing housing stock, the latter will need to be very substantially improved if official emissions targets for 2050 are to be met.

About 90 per cent of UK homes are heated with natural gas, and a key feature of older properties is their relatively large space standards, poor insulation and leaky building fabric; together, these factors mean that most energy use and CO_2 emissions result from space heating by burning gas. The majority of the remaining energy demand and emissions is satisfied by the use of gas to heat water, and of electricity for lights and appliances, plus a small amount derived from the use of electricity, and other fuels, for heating [4]. Therefore as mechanisms for reducing CO_2, insulation and air-tightness in the existing stock of UK housing must have the highest priority.

Links between the physical fabric and energy performance of a building, and the health, wellbeing and finances of its inhabitant, suggest that, in the quest for energy efficiency, approaches to retrofitting need to be comprehensive. Those links hint, too, at the range of product and process innovations that need to be integrated if retrofits are to achieve serious improvements in energy efficiency.

1.1. Learning by doing

This paper suggests a process for retrofitting, beginning with the establishment of a small interdisciplinary team and following some familiar stages in project management – from project initiation and laying down the particulars of the brief through to scoping, modelling and testing technological options for technical performance, suitability and affordability. It discusses planning and design for a *whole-system solution*, in which the 'system' applies not just to the home, but to the street, estates or neighbourhoods, and communities. It shows how a 'fabric first' approach to air-tightness and insulation must precede the fulfilment of tasks around mechanical services and renewable energy.

The paper also proposes a process innovation, namely that combining systematic project management with off-site construction methods offers significant benefits to the quality of the retrofit process. Finally, the measures and metrics appropriate for a simple retrofitting strategy are summarised – emphasising the importance of project parameters, processes and phasing rather than particular technical fixes.

Responding to the global climate change agenda is part of the requirements and context in which we all build; and learning from the climate context is something we have historically undertaken and something that needs to be re-understood [5] As construction professionals learn by doing, evidence-based design and planning has to emerge from reflective practice [6]. This paper summarises some of the lessons learnt on Retrofit for the Future projects, executed in Newcastle and Leicester, for Britain's Technology Strategy Board (TSB). Specialists drawn from both academia and commercial development shared those lessons. In a consortium, they brought together expertise in project management, architectural design, building services, building monitoring and evaluation, and Modern Methods of Construction, which involve labour-saving approaches, and an emphasis on off-site work. [i]

Throughout these projects, an interdisciplinary, team approach has been vital to understanding the importance of what we call *whole systems*, at the scale of both homes and communities. This collective team experience, supported by facilitated learning and knowledge transfer, has highlighted the inadequacies of many current techniques when such techniques are confronted with real-world integrated knowledge and the practical application of research [7].

2. REGISTERED PROVIDERS AND THE TSB'S RETROFIT FOR THE FUTURE PROGRAMME

About 30 per cent of the UK housing stock is social housing – that is, it is owned or managed by Registered Providers (RPs) and by local authorities. With both kinds of owner, the majority of tenants are on low incomes. RPs have several strong incentives to develop an energy-efficient stock:

- It is part of their mission to provide good quality accommodation with low running costs
- Lower fuel bills reduce overall housing costs, so that rents are more affordable, and fuel poverty is reduced
- A well maintained, efficient stock lasts longer and is future-proofed against fuel price rises
- Refurbishment work can significantly increase the capital value of the property and thus the overall asset base of the RP. That can support further borrowing, investment and/or development
- Energy costs are likely to become a significant factor in tenants' choice of provider. [8]

In Britain the quality of housing has historically been high in the social sector, both for new construction [9] and in refurbishment. This is due in part to the stick of regulation, combined with the carrot of incentives from central government agencies. Previously, much of the improvement work for RP homes has been under the Decent Homes standard [10], which had an emphasis on improvements to kitchens and bathrooms, adequate sound insulation from outside, and key structural and system components being in good order. Under Decent Homes, there was only one specific criterion regarding thermal comfort. That referred the achievement of good levels of comfort without excessive cost, and was not explicitly about energy efficiency. However, Decent Homes work usually included a modern gas boiler and programmable controls. When they were used to replace older system, these usually

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[i] The National Audit Office first outlined Modern Methods of Construction as a distinct approach in 2005, at the request of the government. See NAO, Using Modern Methods of Construction to Build Homes More Quickly and Efficiently, 22 November 2005, NAO, London, available at http://www.nao.org.uk//idoc.ashx?docId=56fa1566-a4fd-4aa3-a86d-d3756d3fbfcf&version=-1 (accessed 27 August 2012).

saved a lot of energy – about a third of gas consumption. Also, Decent Homes schemes often included double-glazing; but rather than bring savings in energy, this measures was mainly aimed at replacing poor windows, reducing maintenance (painting), improving sound insulation, and enhancing the overall security of homes.

In addition, many RPs have insulated their homes more, mainly in lofts, and also through some cavity wall insulation. However, many properties have solid walls or other form of construction that cannot be cavity-filled. Even if all possible simple and relatively low-cost measures were carried out, this would leave a large gap between the RP stock and a level of retrofit that would deliver the very large cuts in carbon emissions that government has called for. So RPs are officially encouraged to seek large cuts in carbon emissions, implying radical retrofitting approaches; but at the same time they have been given limited financial inducements to upgrade their housing stock to a minimum level of performance – a level that, while not being quantified in any meaningful way in terms of energy use and carbon emissions, also falls far short of the ambitious targets cited by national government. In addition, upgrading properties to a minimum level has, in an unforeseen manner, made it more potentially difficult and costly to address further upgrading in pursuit of large scale cuts in carbon emissions. For example, replacing double-glazed windows or oversized heat and hot water systems after only a few years of use is operationally and politically difficult.

All these difficulties are also partly true of the owner-occupied and private rented sectors. However, RPs are generally in a better position to make improvements. Their size allows them to reap economies of scale; they also have access to and an understanding of both grant funding and working capital.

2.1. Retrofitting for deep emissions cuts: projects in Leicester and Newcastle

The TSB recognised that a step change in energy improvements would be needed to achieve large carbon reductions and lower bills for householders across the whole RP housing stock. To explore the options available to social landlords and evaluate performance of any innovations ‘on the ground’, the TSB instigated the Retrofit for the Future competition in 2009. This was designed to retrofit a cross-section of the UK’s social housing stock to meet targets for future CO_2 emissions and energy use. The programme was fully funded over two stages: initial design, and practical retrofit projects selected after the initial design stage. A total of 86 projects were completed nationally, with the aim for the aggregate of projects, at least, to reach the UK’s planned 80 per cent cut in CO_2 emissions.

The authors were associated with four first-stage and two second-stage retrofit projects. These introduced a range of technical and procedural innovations. The key observations for this paper have been drawn from the completed dwellings – Project Cottesmore in Leicester, and the Walker Garden Suburb project in the east end of Newcastle upon Tyne. These two projects were characterised not just by project management whose integrated style was innovative, but also by the use of Modern Methods of Construction.

Project Cottesmore, shown in Figures 1 and 2, was the retrofitting of a small, empty, late 19th century back-of-pavement terrace with solid walls and a modern rear extension. Work was based on a high level of internal insulation for floors and walls. This was complemented with high-performance replacement windows and, throughout the property, air-sealing to a level that required a mechanical ventilation system to be installed. A new efficient boiler provided hot water and was supplemented by solar thermal panels linked to a thermal store. Novel heating controls and energy-efficient voltage regulation were part of the package.

Figure 1. Project Cottesmore, Leicester: installing a roof pod manufactured off-site. Earlier retrofitting of the house to a low-carbon specification had led to the extensive use of bulky internal insulation materials, and so to unfortunate reductions in room size and available space. The roof pod compensated for this loss of space, and exemplifies the social factors that must be taken into account in any quest for residential energy efficiency

Beyond these fairly standard measures, there was also the intention to fabricate a new roof room using off-site methods. The reason: on the back-of-pavement Leicester property, internal insulation reduced usable internal floor area by between 10 and 15 per cent. The proposed pre-fabricated roof pod was considered a means to compensate for this loss of space, while maintaining the number of bedrooms and living areas required by future tenants.

Figure 2. snug fit: the completed property, with an additional room in the roof to compensate for the loss of internal space

Walker Garden Suburb, Figures 3 and 4, was a typical inter-war suburban house, comprising a brick cavity construction with a floating floor (one not nailed or glued down) and a cold roof. However, the property had a hybrid structure that included a solid floor in a 1980s rear extension.

The retrofitting strategy consisted of external structural cladding that included a new two-storey bay window manufactured as a module off-site. The purpose of this module was largely to address what thermal imaging had identified as one of the house's worst areas of thermal bridging – the phenomenon of conductive components within a layer of insulation frustrating the effects of that insulation. By contrast with Project Cottesmore, the refurbishment was carried out with the tenants continuing to live on site for part of the work period.

Figure 3. The Walker Garden Suburb project, in the east end of Newcastle upon Tyne: installing one of a pair of two-storey bay windows manufactured off-site. With one window, installation was done while the home in question was still being occupied; with the other, the premises were vacated for five weeks. These new, large bay window units made for increased energy efficiency

Figure 4. Systems in situ: both bays in place, after minimal disruption

2.2. Limitations of a purely technical approach

Working on these projects at both design and delivery stages, it became clear that a purely technical approach was inadequate. While all of the interventions were composed of building fabric and systems hardware, this was not significantly adding to the knowledge of the RPs and project partners, and would not necessarily begin to address the major cuts in CO_2 emissions that would be possible if the projects were to be scaled up. Our collective approach to innovation was to treat these projects as 'proof of concept' exercises that would become relevant to large-scale refurbishment works. In factors such as speed of delivery, quality control and impact on sitting tenants, this approach was reflected in the ambitions of the TSB and in the project briefs.

While the TSB clearly pursued a range of projects using a typology based on typical ages and forms of construction, it also recognised the need to change the behaviour of the sitting tenant, through education and incentives. In so doing, many tools for technical evaluation became less predictive, because design and construction decisions often involved non-technical issues.

The most significant aspects of this more-than-technical understanding of the project challenges and associated briefs involved exploring the potential for off-site manufacturing for both projects. Once again the idea here was to speed delivery, ensure quality control and lessen impacts on tenants. The idea was also to cut costs for multiple but bespoke fabric 'products'. All these factors become significant when retrofitting is undertaken at a larger scale. For example: the roof pod in the Leicester property was the product of a number of interconnected lessons – one example of which was that the earlier retrofitting of the building to a low-carbon specification had led to the extensive use of bulky internal insulation materials, and so to unfortunate reductions in room size and available space.

The Retrofit for the Future programme was introduced to identify ways by which the social housing sector could reduce the carbon footprint of its stock. Problems mount up to the extent that properties are occupied. This in turn means restricting either what can be done or how it is done – for example, whether householders remain living on site or decamp from their homes, with all the physical and financial disruptions that follow from that.

A further feature of many social housing properties is that they are often scattered ('pepper-potted') across communities. When this is the case, they do not lend themselves to the economies of scale available to contiguous dwellings.

Altogether, what seemed to be largely a technical and financial exercise, as is the case with simple insulation measures, turned out to be much more complicated. It lacked an adequate framework by which different technologies could be properly assessed. The scope for innovation in retrofitting houses for energy efficiency, therefore, lies as much in the complete process as in the particular technologies adopted. The next section will explore some of the opportunities for process innovation (implementation) and product innovation (fabric and technology) in retrofitting.

3. PROCESS AND PRODUCT INNOVATIONS AROUND RETROFITTING FOR ENERGY EFFICIENCY

Each of the retrofit projects was managed around a generic process following principles [11] for refurbishment. This idea of following a loose strategy, rather than being overtly focussed on details, is a consistent theme throughout the academic and practitioner literature [12], particularly when there are not the straightforward building typologies, methods of construction or socio-cultural conditions to make standardised responses suitable. Underlying this strategy is a tacit hierarchy of 'hard' physical and 'soft' management interventions, as well as the knowledge that practitioners build up directly from experience [13]. There is also an argument for following an integrated approach to design that links policy, metrics and construction [14] and highlights the potential for innovation in policy, practice and householder behaviour.

In reality, many case studies in retrofitting residences attest to the dominance of overly technical interventions and ways of trying to cut down on household energy use. With few exceptions,[ii] strategic advice has been targeted at the individual householder, and thus at properties rather than structures. Often such properties have themselves been considered merely as the separate building elements of wall, floor, roof and services. That can foster hierarchal and incremental retrofitting processes, and building solutions that gradually become cost-effective [15][iii]. However, an integrated project is different from a series of incremental actions, and more complex in practice. For example, designing for optimal energy performance is dependent upon demographic variations and levels of occupancy levels. In the Leicester case, the ethnic profile of the RP tenants meant that two sitting rooms (one for males and ones for females) were often expected; in the Newcastle project, extended and stepfamily arrangements varied the occupancy between two and five people at different times.

There are significant issues in trying to transpose the technical knowledge gained from an individual household into a strategy appropriate for an RP. The links between different interventions, and the way in which owners, trades and householders perceive them, are often overlooked. So, too, is the way these perceptions change over time.

While this paper argues for a reflective and whole-systems approach to low-carbon retrofitting of homes, the potential paradoxes arising from this emergent process also need to be taken into account. The Rebound Effect, whereby the economic benefit of low carbon interventions can stimulate alternative, higher-carbon activities, provides one example of this [16].

[ii] For European examples of strategies for multi-occupancy and terraced properties, see Richarz, C., Schulz, C. and Zeitler, F., Energy-Efficiency Upgrades, Birkhäuser, Munich, 2007.

[iii] A range of construction types, including cavity masonry, timber frame, metal frame and a range of ground floor and ceiling construction details, is considered in detail in Energy Saving Trust, Enhanced Construction Details: Introduction and Use, EST, London, 2008, available at http://www.energysavingtrust.org.uk/content/download/2540/60566/version/2/file/Enhanced+Construction+Details+introduction+and+use+CE297.pdf (accessed 27 August 2012). This document was initially published in response to the fresh challenges of meeting the ambitious government targets for reducing carbon emissions – a policy shift that wasn't fully reflected in appropriate incentives for individual householders and occupants, due the relative low cost of energy and corresponding long-term payback periods.

3.1. Process innovations (1): Planning, design and the involvement of suppliers and occupants

> *"A great deal of savings are to be had in prior modelling of refurbishment plans … (t)he planning stage is where a good investment of time should be made in order to minimise mistakes and maximise savings in terms of value for money and value for carbon."* [17]

It is hard to overestimate the potential of process innovation – of bringing a structured approach to overall project management. Indeed, without some adequate level of holistic, integrating project management, many stages in any plan of works [18] would not be included. A key observation from some of the members of the retrofit project team [19] was the uniqueness of the approach to project management, supporting initial tenant involvement, capacity-building and training, project closure meetings,[iv] a peer review of the tasks undertaken and planned knowledge transfer within and outside partner organisations.

There were benefits when representatives from the supply chain became actively involved in the design team. They rapidly came to understand the interaction between their building elements and the optimum operation of other elements of the fabric and of the services supplying it. For example, optimal operation of a mechanical ventilation and heat recovery (MVHR) system has a strong relationship with levels of air-tightness. Here the MVHR system supplier had a significant input into the range of speeds at which air was allowed to infiltrate. In another example, suppliers of the solar thermal system were used to specifications that were based on requirements for space heating. Once they began to understand the performance of a super-insulated property and the minimal space heating needed, the sizes of their solar thermal panels and their hot water store could be reduced to meet the more modest demand for hot water.

Through an integrated approach, technical specialists and stakeholders, including residents, could begin to master the aims of a retrofit and help draw up its overall design. Where it was possible to work with existing or proposed occupants, the principles of co-design were found to be invaluable [20].[v] It has been rare for larger projects with imposed output parameters to allow much scope for occupants to become involved in setting basic requirements in design and project management. When occupants have been involved, they have typically considered levels of operational disturbance, structural change and impacts on existing decoration and finishes and, where relevant, the location of supply-side elements of the local energy system. Nevertheless, the preference of occupants is one of the factors most likely to become sidelined whenever there are budget restrictions, or ignored when no participatory metrics are included from the outset of a project.

[iv] These were formal project review meetings that embraced all the partners involved. They assessed the lessons learnt from the individual tasks and interventions undertaken

[v] Co-design is about defining the requirements of end-users, through their involvement in the drafting of the brief for the project in hand, and on to the potential for their participation in concept design, the testing of options and the drafting of detailed proposals. There should be close working with the end-user – often, but not always, the client – to get the parameters of the brief right, to test concepts and directly review the detailed designs directly.

Some incentives for involvement in demonstration projects were provided to tenants where these were judged likely to help reduce energy consumption. Incentives ran from the provision of energy-efficient electrical appliances, through to re-laid carpets, curtains and even lighting, all of which can make small contributions to levels of air inflow and of energy consumption.

3.2. Process innovations (2): Whole-structure solutions, 'fabric first' solutions

In residential retrofitting, holistic solutions make sense because of their balance of benefits to costs, the technical difficulties of phased works, and the fact that impacts elsewhere within the system can be sub optimal and/or unpredictable.

At the scale of the individual property, what is needed is a *whole-house* solution that integrates improvement both to building fabric and services. The holistic approach will have different implications as scale increases. The difficulties in scaling up a whole-house solution and strategy are many. For example issues around terraced houses, multiple owners and multiple forms of tenure differ from those around single owners, such as housing associations, which may own portfolios that are geographically highly dispersed. Even with semi-detached typologies such as the Newcastle project, poor quality and leaky party walls meant that the benefits of quality and performance in the rest of the external fabric works could only be reaped with the cooperation of the adjacent tenant. These factors, combined with hybrid or mixed methods of construction, cultural and demographic differences among householders, the difficulty in understanding the thermal properties of existing constructions and the lack of purpose-specific modelling tools all question the wisdom of generic approaches that do not account for contextual variability.

An understanding of the wider policy context, including the interrelated issues of climate change and growing levels of fuel poverty, reveals that the existing literature on retrofitting through whole-structure solutions is pretty limited. A further subtext is that adapting UK's existing housing stock for energy efficiency presents easier challenges than those that surround freshly built homes, not least because much of this stock is situated in better locations and can make use of existing infrastructure in a ways often unavailable to new developments.

> *"The occupation of old houses, combined with performance improvement measures, is the most energy-efficient form of property development."* [21]

The existing housing stock has merits as a target for intervention, through retrofitting. These merits are separate from the fact that the fabric of the existing stock already embodies large amounts of energy, for they also include justifications based on site, location, local facilities and many other factors – factors that, though they affect sustainability, lie outside the control of the individual household.

Given all this, it is clearly difficult to generalise about retrofitting innovations for older properties. However the common processes adopted point to initial problems with fabric (poor insulation and glazing, poor air-tightness and draught-proofing), and corresponding implications with oversized and inefficient heating systems. Practical advice will obviously vary for different ages of property; but the overall strategy can remain fairly constant, namely fabric first improvements to increase insulation levels,[vi] followed by enhancement to the performance of targeted building components, such as windows using secondary glazing insulating blinds, where necessary.[vii] After this come improvements to heating systems and levels of control for the occupant, including better management of the existing systems.

3.3. Process innovations (3): Taking into account the specificity of older properties

One of the peculiarities of many older UK properties has been the incremental approach used in their past upgrades, an approach that has very often emerged as a result of changes in use and the subdivision of houses into smaller units. The result is that the UK has a complex range of property typologies that are based on original structures plus subsequent alterations. Varied internal space standards and dimensions have to be considered: for example large floor-to-ceiling heights cause temperatures to be stratified. The selection and sizing of any heating system will need to have regard for such internal specifications and variations. For members of our Retrofit for the Future consortium, such points exemplified how many technical decision support tools could not adequately provide a 'best-guess' approach to retrofitting complex, hybrid structures.

It proved useful to draw lessons from the original design strategy for the property being treated, and to think about subsequent repair, maintenance and replacement strategies as much as the actual retrofitting. For example, original design features often gave thought to internal thermal comfort. Another issue surrounded the use of internal shutters that could be controlled by the occupants and insulated to form part of low-disruption improvements. How integral features such as shutters compared to more contemporary solar blinds was considered, alongside whether these could or should be taken into account in any u-value calculations for windows.[viii] A further example: it was expected that solid wall construction, using the existing stone/brick wall, [22] would act as a thermal store. In turn, that would impact on any subsequent decisions about external 'warm wall' insulation [23] and the associated risks of interstitial condensation and more rapid heating and cooling.

[vi] These improvements can include 'breathable' hygroscopic insulation materials such as sheep's wool. It is useful to note that significant improvements to air tightness can be achieved in older properties, even with the need to maintain a breathable building skin: air tightness testing allows for diagnostic approaches to difficult and/or leaky areas.

[vii] For further details regarding older properties and the use of an optimal performance gap of 20mm for secondary glazing, see English Heritage, Energy Efficiency and Historic Buildings: Secondary Glazing for Windows, English Heritage, London, March 2012, available at http://www.english-heritage.org.uk/content/publications/publicationsNew/guidelines-standards/eehb-secondary-glazing-windows/eehb-secondary-glazing-windows.pdf (accessed 27 August 2012).

[viii] A u-value is a measure of thermal transmittance per unit area, used to calculate heat loss and annual heating demand.

3.4. Process innovations (4): Air-tightness deserves continuous testing and better training

The UK lacks comparative data on the air-tightness of its housing stock, but a recent study of a 100 new dwellings showed considerable variation, including a significant percentage of newly built properties that fail to meet building regulations [24]. Despite this, air-tightness is the first step in progress to low- and zero-carbon dwellings, and in the reduction of energy demand. Until the 2006 Building Regulations, uncontrolled infiltration provided sufficient fresh air ventilation, but also caused a lot of unnecessary heat loss. Separating deliberate, useful ventilation from uncontrolled infiltration is a key part of low-energy design, but is widely misunderstood.

Guidance about air-tightness does however exist [25], and aims to overcome some of the associated concerns – for example, that it creates stuffy or sick buildings. It also holds costs to be negligible in the light of potential energy savings of up to 40 per cent – on commercial buildings, at least [26] Technical guides use tried-and-tested alternatives to standard details that are targeted at the most common sources of air leakage within buildings, reinforcing the potential confusion between planned air changes and unplanned air leakage. Heat loss due to infiltration has become an increasing proportion of the overall loss, because of improvements in insulation levels in new and existing buildings [27].

As noted before, understanding the necessary levels for air tightness has implications for the specification and sizing of heating systems, to the point of setting targets for air-tightness through the optimal operation of MVHR systems [28]. There are varied arguments about the potential of Modern Methods of Construction has, as a result of the improvements in quality control that can be achieved in a factory setting, for achieving appropriate levels of air-tightness. These arguments are of particular significance when the aspiration is to achieve the levels of air-tightness specified by the *Passivhaus* standard,[ix] or the higher levels specified in the British government's *Code for Sustainable Homes*, an integrated standard for sustainability that was first launched in December 2006 [29].

Without any improvement or remedial work using an integrated air barrier, European and particularly German examples of both new-build and retrofit have been able to get to *Passivhaus* levels of air-tightness. These levels are achieved through better control of build quality in the use of traditional brick and block construction, with internal wet-lining, external render and simpler detailing. The achievement suggests that one means of achieving air-tightness is through improvements in skills and training. Accordingly, training should include a diagnostic – judgement-based – approach to building air-tightness, as well as continuous testing. Experience with our two Retrofit for the Future projects suggested that training was important. Sometimes this was because of a mix of conflicting advice from different suppliers, who did not know exactly where air paths and leaks were – in part because of their reluctance to

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[ix] The *Passivhaus* standard is defined as a building 'for which thermal comfort can be achieved solely by post-heating or post-cooling of the fresh air mass, which is required to achieve sufficient indoor air quality conditions – without the need for additional recirculation of air'. See www.passivhaus.org.uk/standard.jsp?id=122 (accessed 27 August 2012).

access and pay for elaborate smoke tests. On other occasions, joining ground-floor membranes with external barriers, as well as treating connecting properties, presented difficulties which training could have addressed [30].

3.5. Grasping the relevance of air-tightness as an indicator of cultural change

In energy-efficient dwellings, core concepts such as air tightness were often not part of the language of RP estates managers, project managers or contractors – or part of the experience of their on-site workers.

> *"I never thought of, or understood the relevance of, air-tightness before, but now we will carry out tests on all our properties. … Initially the lads got fed up with me, for example over air-tightness; but after a time they got it, and became obsessive themselves."* [31]

The acceptance and understanding of air-tightness, or receptivity toward it [32], illustrates a cultural change that is required of policymakers, suppliers, on-site trades and householders. It is necessary to tailor mechanisms for communicating this insight, and the message developed, to the relevant audience [33, 34]. It was recognised that new concepts needed to be communicated before they could be incorporated into a new work ethos.

The existing culture did not necessarily relate to bad practice (for example, the production of waste on site), but to the changing of habitual good practice. An insulation membrane 'skirt' around the replacement windows was trimmed to size, rather than leaving the excess necessary to enable an airtight corner joint. In addition, the functions of the materials were not clearly understood. For example, the effectiveness of insulation is reduced if the material is pierced or poorly joined, because movement of air circumvents insulation and removes heat. This required the contractors to avoid piercing or cutting into insulation panels.

These knowledge issues, the understanding of low-carbon interventions and the skills necessary for achieving those interventions formed the main reasons why the Leicester project ran over time and over budget.

3.6. Product-led innovations (1): In insulation, a strategy of keeping things simple isn't always possible

Much of the detail for appropriate insulation is subject to technical suitability and the sourcing of products. Ideally, this should be based on a *whole-structure approach*, in preference to simply treating individual building elements sequentially. One reason for taking such an approach is the ability of an insulation strategy to provide appropriate levels of air-tightness. An integrated approach, comprising insulation with both vapour and air barriers, is normally the best one, as the performance of the insulation layer is dependent both on air-tightness and on avoiding air gaps [35] – even if it has been recognised that such tactics are neither always possible, nor desirable [36].

A 'keep it simple' insulation strategy may, counter-intuitively, turn out very complex. Take an apparently simple strategy that bases itself on external and cavity wall insulation:

- When installed, external insulation is usually quite secure from occupier impact or damage. It is thus usually installed before internal insulation. However when this happens, the risk of interstitial condensation can arise

- Cavity wall insulation tends to settle and deteriorate over time, and is seldom of thick enough on its own to achieve high performance retrofitting. It does not provide an adequate airtight barrier
- External roof insulation systems – what are known as warm roof solutions – have proved difficult to implement. They require thick insulation, and are particularly problematic for terraced housing.

Altogether, keeping things simple isn't always possible. Raising floor levels with solid insulation board, or something like, it will affect door heights, skirting boards and stairs. There are key design features that exist throughout the existing housing stock that create particular concerns for maintaining a simple insulation strategy. Traditional features such as frontage bays, dormer windows and extensions are the most common form of hybrid structures with mixed forms of construction. The Newcastle property, for example, had a traditional 'floating' floor of timber joists and boards next to a solid concrete floor in the rear extension. These required considered approaches to edging details, the joining of elements and the impact of thermal bridging. Project experience suggests the use of a single strategy to dealing with hybrid elements, with the choice being made as much around lowering cost and disturbance to householders as around improvements in insulation. It was found that, faced with mixed construction elements, the scalability of a technique was less of a concern than simply finding a technique that worked.

There have also been instances where required products, such as service hatches and loft doors, have been unavailable at the required performance specification. Design responses have included the construction of bespoke elements with the use of local trades – in effect adding some additional skills training, but limiting any potential for scaling up. Based on knowledge of available products, design responses have also included compromises over the level of performance specification.

Hatches and loft doors stand in contrast to the wider availability of high-performance windows and doors, where the temptation has been to over-specify so as to get the best available product to compensate for potential underperformance in the other elements mentioned above. Similar dilemmas have occurred whenever new product innovations appear. Innovations in vacuum insulation, voltage regulation and reflector blinds have been used on exemplar projects; but they are unlikely to be used more widely until convincing evidence of better performance becomes available.

A related consideration is the need to take account of the lifestyle and knowledge of the householder. What we call the cat-flap paradox [37] illustrates this. If the planners or designer fails to consider lifestyle issues such as pet ownership, it will be left to occupants to introduce well-insulated and airtight cat-flaps. What is more likely is that occupants will install standard, rather draughty cat-flaps, so undermining energy efficiency.

3.7. Product-led innovations (2): Treating thermal bridging with off-site products can work, but the contiguity of structures can make this quite difficult

As an overall structure becomes better insulated, areas of thermal bridging within it have a disproportionate impact on heat loss. One outcome of the planning stage is the identification of such areas through thermal imaging. Some of these areas can be treated with simple construction detailing, using standard air-sealing products; some can only be treated with radical intervention in the fabric of the structure. Usefully, the Energy Saving Trust has considered and modelled an extensive range of archetypical structures as part of its Enhanced Construction Details. Modelling tools such as THERM (Two-dimensional building Heat transfer Modelling) can support the exploration of options to address problem areas.

Products made through off-site systems can address some of those elements within existing structures that are failing and that add to thermal bridging. However, both benefits and difficulties arise from add-on products that form part of a strategy for external insulation and air-tightness. There can be issues of contiguity and separate ownership within single structures. Alternatively, snags can result from the contiguous elements of larger structures, such as the continuous roofing on terraces.

3.8. Product-led innovations (3): Installing a roof pod and a bay window that were made off-site

The need for an additional room in the roof of the Leicester property brought to the fore a cultural difference between those project members with a background in manufacturing and those with one in construction. Those members who hailed from manufacturing were very demanding about tolerances, and were keen to adopt an off-site approach to retrofit. Those with a construction background were more forgiving of low tolerances, and felt that the only practical way to deal with variability within buildings was to undertake work on-site.

In the event, an offsite solution was decided upon, in large part due to confidence that manufacturers could be found who would be able to produce a bespoke roof pod. To some extent, this was based on another exemplar project – the prototype SOLTAG ‘sun roof’ [38], a prefabricated roof refurbishment solution that was funded, in partnership with Velux, through the European Commission’s Sixth Framework Programme for Research and Technological Development (2002-2006). However, confidence in roof pod manufacturers proved, ultimately, to be misplaced, and it was only through the pursuit of a network of acquaintances that a small firm was identified that could, and would, develop the product. As one team member said of the small firm:

> “We were impressed… even if they built it in a shed. Their enthusiasm and knowledge re-invigorated the project; [they had a] ‘can-do’ attitude. Before this we had nothing – [we were going to have to] build from scratch…. I did not believe the tolerances could be achieved – using a plumb line, in the hot loft for four hours – [but the] rafters [were only] out by 1.5 degrees on four metres…. [It was] very impressive and confidence revived – albeit with some subsequent problems. It was a mad rush.” [39]

The use of a plumb line to measure up in great detail on site for the pod highlighted another paradox around innovation in retrofitting. Here a ‘state of the art’ intervention, in the shape of the off-site fabricated roof pod, was installed with the help of traditional techniques and expertise. However, it is probable that, in future, the take-up of off-site approaches will be accompanied by the adoption of equivalent innovations in measurement and manufacturing.

In the Newcastle house, off-site construction appeared easier. Identifying the north-facing bay window as a major area of heat loss, on account of the thermal bridging brought about by poor detailing and construction of the original bay, was a step forward. The bay window problem affected the remainder of the properties in the estate, which were also being refurbished. Yet there was a challenge: to find a solution that not only met technical performance targets, but could also be installed while the property was still being occupied.[x]

The best strategy turned out to be a new larger bay window unit that could fit around the existing structure or gap in the fabric once the original bay was demolished. That allowed the new foundations to be constructed well in advance of any demolition. It was possible to anticipate tolerances in joining details and in the use of an adjustable internal floor level. This was necessary for the bay to tie into existing ground and first-floor structures. A detailed approach to delivery and installation was also planned well in advance. In practice, the demolition of the existing bay and replacement with the off-site manufactured one was carried out in less than a day, with the actual installation of the bay requiring just 30 minutes.

3.9. Process innovations (5): Fuels, renewable energy, and the importance of scale and skills

Retrofit projects require a strategy for the fuels from which a home derives its energy. That fuel strategy should be based on

- The performance of the fabric
- The benefits of passive design – solar heating, day lighting, ventilation and cooling
- Any requirements for renewable energy.

Within any building design process, satisfactory energy solutions are best achieved by the thoughtful integration of energy systems into structure and fabric at the earliest possible stage [40]. This ‘law’ has been most evident with MVHR systems. To work well, these systems do not just require low filtration rates, but also need to be installed properly.

There are some concerns about how much energy – typically, electricity – an MVHR system needs in operation. Obviously this use of energy is set against the energy savings that the system brings. In retrofitting such a system, it is often impossible to follow the optimal layout, owing to the position of joists and of load-bearing walls. In addition, vents are usually placed in positions that form a compromise between competing constraints.[xi]

In recent years, some significant research into retrofit has focused on the integration of renewable energy systems with improvements in fabric efficiency [41]. Appropriate solutions will depend upon the scale of intervention [42], and thus upon ownership and

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[x] In practice the project undertook similar work on the second of what was a pair of semi-detached properties. One property remained occupied during construction, while one family was re-housed for a five-week period.

[xi] Part F of Britain’s Building Regulations, on ventilation, relates to the design of new-build developments, and not to the retrofitting of existing homes.

control. Local authorities and large RPs could implement many of the larger solutions. Clearly, both the Leicester RP, with more than 15,000 dwellings, and the Newcastle Arms Length Management Organisation, a body that manages more than 30,000 properties for Newcastle City Council, has considerable influence. They can use a mix of statutory powers [43] and incentives to gain significant carbon savings. [xii]

To date, however, the policy focus in retrofitting has been on fiscal incentives centred on individual properties: on Feed-in Tariffs (FITs), the Renewable Heat Incentive (targeted at levels of energy generation below 5MW), and, prospectively, the Green Deal for householder energy efficiency improvements. Yet many renewable energy systems, such as combined heat and power, cannot easily be scaled down to meet the reduced levels of energy demand that come with smaller households [44]. In renewable energy technologies, larger, shared or community systems make the most sense, especially when retrofitting homes to reduce demand for energy tends to make renewable space heating systems less viable.

It has already been argued that a range of skills is vital to meeting performance standards. Some resources have been produced at a local level to begin this accreditation process [45]; but any significant approach will require some sort of national organisational infrastructure, as well as support from partner organisations. Part of such training has to be an awareness of the interconnectedness of different energy production and management systems, and of the relationship between building fabric and services. There are likely to be plenty of overlaps across useful training materials, and in the products and specifications included in maintenance guides and manuals for the users of buildings. Training needs to be targeted both at the installation of systems, and at their maintenance.

3.10. Process innovations (6): Monitoring and managing properties once retrofitting is complete

> "*Of the environmental renovations that have been evaluated, on average they perform thermally only half as well as predicted. This could be because of poor installation, occupant behaviour or failure of the materials. … (u)ntil (the Retrofit for the Future) results are in, we are dealing with probabilities only.*" [46]

It is important to understand the reasons for the significant discrepancies that often exist between designed energy performance and performance in practice [47]. Often working with models, the limited body of published work on residential energy efficiency predicts definite results; post-occupation evaluation can highlight the significant differences between these predictions and actual results. A common systematic approach to post-completion evaluation exists [48]; it ensures the beneficial use of performance measures, while exhibiting a close grasp of the impact of occupant behaviour on technical performance [49]. At its most ambitious, post-occupancy monitoring can continuously inform the managers of multiple properties about these properties are using energy.

[xii] Monitored results of several community-scale networks and systems are available for download from http://www.concerto-sesac.eu/IMG/pdf/SESAC_Innovative_Sustainable_Construction.pdf (accessed 10 July 2012).

4. HE TYRANNY OF MULTIPLE TOOLS AND METRICS AROUND SUSTAINABILITY

Having looked at examples of product and process innovation within the retrofit process, we now briefly consider these in the context of performance metrics for future projects. In setting out any initial project brief that relates to sustainability, we are forced to acknowledge the confusion around standards and references. Sustainability has been described as a

> *"monstrously ill-defined, abstract concept [that] is likely to be masking the incompetent application of some half-formed idea vaguely related to the use of resources"*. [50]

A recent review of the academic and practitioner literature identified more than 600 tools for assessing sustainability and environmental performance, each with its own definition and means of validation. [51] Britain's Building Research Establishment had done a more in-depth evaluation of such tools, using criteria derived from the most significant and recognisable methods used in planning and building [52].

In response to this confusion, efforts have long been made at a policy level to provide a common language for the scope of sustainability – informed by the guiding principles for sustainable development policy in the UK [53] and structured around the concept of sustainable communities. The 1998 Egan Report, commissioned by the Office of the Deputy Prime Minister, focused on the effective use of natural resources, enhancing the environment, promoting social cohesion and inclusion and strengthening economic prosperity. Yet even with this common language, current British debate on sustainability in housing appears to occur independently from technical considerations.

Policy discussion on buildings today continues to relate to the scope of sustainability [54]. What is the most appropriate measurement for energy efficiency for the performance of building fabric and services, and should that measurement include, perhaps, a mandatory benchmark? Additional considerations include:

- Measures of energy efficiency are somewhat dubious when they derive directly from cost-benefit analysis and calculated pay-back periods for the cost per tonne of carbon saved
- Even with supposedly more precise technical specifications, the definitions of zero- carbon homes are ever-changing [55] [xiii]
- Many local variations surround the precise interpretation of on-site or near-site provision of renewable energy, as well as the nature of any exceptions
- As the scale of buildings increases, so the thinking around it grows more complex. The assessment any project moves from the realm of building regulations into that of statutory planning.

[xiii] The most recent definition of zero-carbon homes is Zero Carbon Task Group, The Definition of Zero Carbon, UK Green Buildings Council, London, March 2008, available at http://www.ukgbc.org/sites/files/ukgbc/Definition%20of%20Zero%20Carbon%20Report.pdf (accessed 27 August 2012). Some UK local planning authorities also make distinctions between no-site and near-site provision, while others take technological viability as grounds for exceptions to be made – or as grounds for financial contributions toward municipal/district heating and energy systems able to bring about cuts in CO2 emissions equivalent to those planned around zero-carbon homes.

Britain's Code for Sustainable Homes deliberately went beyond a simple measure of energy efficiency to embrace other physical resources and softer issues, such as health and wellbeing, within a quasi-statutory definition of sustainable housing [56]. The Code is significant, too, in requiring a structured approach to project management and the formal integration of a registered assessor. Experience suggests that, ideally, this occurs early within a process which properly involves the supply chain, and which backs up home improvements [57].

The Code for Sustainable Homes has provoked some controversy, particularly in regard to the difficulty in achieving its highest level of performance, Level 6. Measurement of even the softest aspects of sustainability included in the code relies upon hard metrics, [58] and the statutory regulations contained within it still require certification for individual homes, rather than larger developments.[xiv]

Despite all the tools and metrics that are available to guide retrofitting exercises in UK residential property, these exercises still lack a unifying, professionally agreed means of measuring their success.

5. AN ALTERNATIVE: COMPLEMENTARY QUANTITATIVE AND QUALITATIVE METRICS

With retrofitting, the most common metrics used are quantitative, and thus have a significant bias towards measures relating to absolute energy usage, carbon emissions and the relationship of these things with the cost per tonne of carbon saved. Often metrics consist of straightforward specifications and design parameters;[xv] typically, too, they include shared metrics that are applicable both to new-build and retrofit projects.[xvi] For new buildings, more technical metrics and measurement tools suitable for use within the detailed design, specification and construction stages of a project exist [59]. Many of these metrics have been translated directly into performance standards – the most relevant, significant and international one being that established by the *Passivhaus* [60]

The difficulty is that, in practice, whether these performance standards can be met is less a technical question, and more one of cost, desirability and social impact. Economic considerations invariably form the premise for policy responses, and, as a result, standards have typically surrounded:

- The cost of all the retrofitting measures, estimated and actual, introduced for the total property
- The cost of each measure [xvii]
- The cost per square metre, including the additional cost per square metre above mandatory minimum building regulations.

[xiv] Statutory regulations are laid out in Homes and Communities Agency, Housing and Regeneration Act 2008, HCA, London, 2008, available at http://www.legislation.gov.uk/ukpga/2008/17/contents (accessed 29 August 2012). Under section 279, the Act requires that a person who is selling a residential property as a new property 'must supply the purchaser with either a sustainability certificate or a written statement to the effect that there is no sustainability certificate for the property'.

[xv] Design parameters used within many of the decision support tools include u-values, air permeability, thermal bridging, product specification, space standards and output from renewable energy provision.

[xvi] Examples of shared performance output metrics include those around primary energy use, and around savings in CO_2 emissions.

[xvii] Some sample figures that include comparison with operating costs are available at www.cepheus.de (accessed 1 November 2011).

The question properly asked of these costs is how they relate to:

- The cost per tonne of CO_2 emissions saved
- Savings on fuel bills with corresponding benefits to levels of fuel poverty and affordable warmth [61]
- The estimated payback period, informed by assumptions about energy pricing and the decarbonising of the UK's national supply network 62].

Within any integrated design strategy, a range of technical measures has to be balanced and traded against a number of qualitative and procedural measures. The metrics that follow are suggested as project indicators that are appropriate for retrofitting, and that allow a degree of flexibility and innovation within the design and construction process.

Qualitative metrics used to complement technical measures

1. Occupant strategy and feedback, achieved through post-completion questionnaires with reference to levels of thermal comfort and understanding of controls
2. Internal air quality for CO_2, humidity and odours that may affect occupant health or behaviour [63]
3. Level of occupant disturbance, construction speed and impact. This metric should compare the level of disturbance caused with other options in retrofitting, or in the selection of systems
4. Household carbon footprints, taking into account overall lifestyle changes that are, in part at least, due to the occupant's involvement in the project, the training provided, the guide for building users, etc
5. Future-proofing, including the level and ease of maintenance (maintenance requirements being set out within guides for building users).

Where possible these measures have been broken down by individual interventions to the fabric and additions to building services, and have been recorded per project, dwelling and square metre. Yet many measures are interdependent and subject to more messy influences, such as:

- Underlying assumptions in energy costs
- Comparisons against a base or control property
- The use of estimates in the absence of historic or current data.

The measures are also framed by a variety of different approaches to energy modelling. Each approach has its own underlying assumptions and emphasise different building elements; thus each produces different results.

The best-known and most used software packages designed to assess the energy performance of buildings are the Standard Assessment Procedure, or SAP, and the Passive House Planning Package, or PHPP (the *Passivhaus* design tool). Discussions over the comparative strengths and weakness of these two models suggest that, while the more accurate model is the PHPP, it is also the most laborious and detailed – making it often inappropriate for modelling at the outline stage of larger design projects [64].

There is some suggestion that the higher levels of the Code for Sustainable Homes, based on the SAP, do not necessarily result in reduced carbon emissions [65]. There is also a debate in the commercial literature and trade press as to whether PHPP, as a fabric-based modelling package, is really suitable for retrofit projects, since it was initially designed for new-build projects, which are relatively simpler. [xviii] Some authorities, however, suggest that PHPP can be accurate for renovations if it is used to weigh up the pros and cons of different strategies [66]. In this application, however, PHPP is more an experimental tool than a predictive one.

In practical decision-making, the principles behind the software packages, as well as fidelity to the design and implementation procedures being followed, are given more weight than the detailed predictions issuing from support tools. The design process therefore needs to retain the tacit knowledge of a broad and integrated team, including the building user, as possibly the most insightful method for assessing how the requirement for energy is likely to turn out when a house is occupied.

In the building of new houses in the UK, there is an emphasis both on tools and techniques, and on the minutiae of definitions about what is sustainable. But a much more vital issue is the significant weakness of metrics for retrofitting existing homes. Such metrics have been delayed because they are largely non-statutory and unenforceable [67]. There is some comparative work on the impact of renovation on levels of energy efficiency in new-build properties [68], and research also looks at qualitative impacts [69]. There is also some assessment of cost per tonne of carbon saved and the integration within future management of a property [70]. [xix] Finally, practical examples of retrofitting are becoming more widely disseminated, covering different kinds of structures [71] and clients [72].

Many reviews of sustainable construction projects highlight the impact of occupation on the actual as opposed to the modelled whole-house energy consumption [73]. It is widely recognised that one must have a strategy for the occupancy that affects a building [74]. [xx] It is also thought wise to monitor behaviour change alongside the hard data recording levels of energy consumption [75]. Yet these social aspects of technological innovation remain the forgotten elements of many schemes.

The suggested means for overcoming many of these modelling concerns is to extend the scope of the project and use mixed and multiple metrics that effectively triangulate from several available software packages and use estimated ranges of performance as opposed to absolutes.

[xviii] There are also connections with affordability and comparisons between new-build and refurbishment standards to CEPHUS (Cost Efficient Passive Houses as European Standards).

[xix] Case study evidence of retrofitting 17 St Augustine's Road, Camden, London, provides outline figures for cost per tonne of carbon saved. With the use of solar photovoltaic panels, it was £17,860; with solar water hearing, £16,000; with special windows, £18,460; with roof insulation, £1,940, and with wall insulation, £3,330.

[xx] At two well-established and large Passivhaus developments – 22 homes at Wiesbaden, constructed in 1997, and 32 terraced units at Kronsberg, constructed in 1998 – the average recorded energy consumption was below the 15 kWh per square metre.

6. CONCLUSION

In common with many areas of planning policy and construction practice, retrofitting social housing appears to suffer from what we might call an *implementation gap*. There is a big gap between policies and fiscal incentives on the one hand, and lessons learned through practice on the other. If there is any consistency across national and local policies on retrofitting, it relates to the role of technical innovations in leading cuts in CO_2 emissions. This focus is reflected in the shared technical performance and economic metrics for both new-build and retrofitting that are often mandated for many social housing projects.

Yet the implementation gap can be filled with a bespoke approach to project metrics that, first, integrates a broader scope of social impacts and outcomes – most significantly regarding the involvement of and benefits for existing and future tenants, the level of disturbance created by capital works, the speed of delivery, and a guarantee of quality control to meet design expectations. Secondly, there should be a simplicity in approach; one that is reflected in the long-term management and maintenance of new systems. Mixed and multiple project metrics, capable of integrating fiscal, social and qualitative measures with some of the more technical and physical requirements, will begin to support the appropriate trade-offs between costs, performance and social impacts.

In the context of process innovation supported by procedural and management measures, we have found that the use of modern methods of construction (both timber and metal frame products) bring measurable benefits in speed of delivery, reduced disturbance to occupants and of impact and assurances on quality, particularly regarding air tightness and addressing traditional build areas of thermal bridging. If and when the UK has a large-scale retrofitting programme that follows similar *Passivhaus* principles, modern methods of retrofitting can provide a means of technically achieving what we set out to achieve in a way that is cost effective and socially acceptable.

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