Authors' version of manuscript accepted 20/12/17

A co-evolutionary approach to understanding construction industry innovation in renovation practices for low carbon outcomes

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Abstract

Energy consumption in buildings is a large contributor to global CO_2 emissions. Renovations of existing buildings can reduce their impact by integrating technologies which increase efficiency or generate renewable energy on-site. Doing this well and at scale is a collective action problem, which transcends the agency of individual entrepreneurs.

This paper reports a cross-case comparison of four previous studies focused on low-energy renovation of housing, using a co-evolutionary framework in which five systems are mutually interdependent: ecosystems, technologies, user practices, business strategies, and institutions. Innovations across the five systems are described in terms of variations, selection pressures and transmission.

The analysis serves a dual purpose: to draw out common themes from the four previous studies, and to reflect on how well the co-evolutionary framework accounts for innovation in the particular field of housing renovation for low-energy outcomes. Business strategies emerge as an important (and often neglected) source of innovation. The framework generally accounts for innovation in this area quite well, although two important issues are a less easy fit: the use of energy (and other finite resources) is rather indirectly accounted for by the term 'ecosystems'; and the complexity of interactions between multiple users, businesses and technologies is partly elided.

Introduction

Energy use in buildings accounted for 32% of total global final energy use in 2010 (Intergovernmental Panel on Climate Change, 2014: 675). Buildings have greater technical and economic potential for carbon reduction than sectors like transport and industry (Intergovernmental Panel on Climate Change, 2014). For the UK to meet its long-term climate policy goals, all buildings will need to be effectively zero carbon by 2050 (Committee on Climate Change, 2014). As the vast majority of buildings that will be in use in 2050 are already here (SDC, 2006), reducing energy consumption in existing buildings is a major challenge requiring significant innovation in construction processes, products and business models.

The focus here is on low-energy renovation of an entire national housing stock, which can be seen as a collective action problem, requiring a coordinated response at several scales simultaneously (Ostrom, 2010). For existing housing to achieve low energy performance as a matter of course requires the transformation of an entire sub-sector of the construction industry (Killip 2013a) The focus is therefore not on individual entrepreneurs or innovative projects, but on framing innovation at a systemic scale.

In 2014 the UK housing stock amounted to 28.1 million dwellings (Department for Communities and Local Government 2017), which accounted for 29.8% of final UK energy demand (Office for National Statistics 2015). Energy demand and associated CO_2 emissions can both be significantly reduced through the design and installation of (and user interaction with) technologies of various kinds: insulation and airtightness materials to reduce heat loss; efficient heating systems and ventilation systems to ensure indoor comfort and health; appliances and lights providing energy services; building-integrated renewable energy systems, such as solar panels (Roberts 2008), as well as an effective interface with occupants as technology users.

For ambitious energy standards to be achieved, new configurations of technologies and pre-existing buildings need to be well designed, installed and intelligible to users: to do this, the construction industry needs to address issues about systems of knowledge, management, and communication - not just new technology (Zero Carbon Hub 2014).

The market for energy-related retrofit services is very small, but the processes of making physical changes to buildings have much in common with the much larger market for repair, maintenance and improvement (RMI) projects for homes. RMI activity is not typically motivated or driven by energy-related issues (Hand et al., 2007; Maller et al., 2012; Wilson et al., 2013). However, RMI businesses are uniquely well placed to carry out low-energy retrofit work (Maby and Owen, 2015; Janda and Killip, 2013). The RMI sector operates at a scale that is consistent with the scale of the climate challenge, representing over £26bn of economic activity in 2016 (Office for National Statistics, 2017), supporting tens of thousands of mainly small and micro-enterprises operating locally (Maby and Owen, 2015). Larger firms are also present, particularly in materials manufacture and supply. In this paper, we re-analyse four previous studies of renovation and potential innovation through the analytical lens of co-evolution, using the five interdependent systems proposed by Foxon (2011): ecosystems, institutions, user practices, business strategies, and technologies. Using a co-evolutionary framework allows consideration of several systems at once, forcing us to consider the reciprocal relationships between systems.

This analysis serves a dual purpose: to gain insights into the governance[1] of innovation in the fragmented RMI supply chain in the UK; and to provide sector-specific reflections on how the co-evolutionary framework can be tested and further developed. The rest of the paper is structured as follows: first, a contextual account of the nature of innovation in housing renovation is given. The next section describes the cross-case comparison method used to synthesise evidence from four previous studies, which are then briefly summarised. This is followed by results of a thematic analysis, organised by the key processes of variation, selection and transmission. Having laid out how the renovation system can be understood in co-evolutionary terms, we are able to highlight some of the overlooked factors that influence innovation in housing retrofit. The paper concludes with a section discussing the analysis and its implications, as well as indicating where the co-evolutionary framework might be further developed to improve its power in analysing construction activities.

[1] Here we use governance to refer to 'patterns of influence over decision-making at multiple scales.'

Innovation and the context of housing renovation

Renovation and retrofit are overlapping terms. Renovation is improving amenities and services of a building (such as installing heating, replacing a bathroom, fixing a leaking roof, or building an extension); retrofit refers to interventions to the fabric and heating or ventilation systems with the express purpose of reducing energy consumption in use, or improving energy efficiency. While renovation and retrofit may involve some common activities the key difference between renovation and retrofit lies in the purpose of the construction activity. Another term, widely used in the construction industry, is ‘repair, maintenance and improvement’ (RMI), which refers to the full range of construction activities - both general renovation and specifically energy-related renovation, or retrofit. Within the current RMI market, the overwhelming market demand and delivery capability is for renovation, not for retrofit.

Despite the construction industry’s reputation for conservatism and poor customer care (Egan 2002; Wolstenholme et al., 2009), innovation can be found, especially in relation to practices and processes (Killip 2013b). Renovation innovations may include any combination of technology, policy, design, installation, business models or management. They may also be observed at different stages of the renovation process, from pre-design through design, installation, hand-over and operation. Innovation may come from national or regional government (e.g. through funded competitions and programmes); from design or installation firms working alone or in partnership; from clients (property owners, whether owner-occupiers or landlords); or from firms in the technology supply chain (manufacturers, distributors, retailers).

The sector operates within local and regional markets, each with a unique constellation of pressures and actors including: building materials, buoyancy of housing markets, planning policy, available skills, supply chain networks, trade networks, and users' practices (Wade et al, 2016; Owen et al., 2014; Owen, 2015). Retrofitting the UK's existing housing stock is a national policy objective (Committee on Climate Change, 2014) but delivery, and management or promotion of innovation, would need to be devolved and multi-dimensional: this is a sector where a single technical prescription does not (and cannot) fit all projects.

The long-term perspective of climate change mitigation leads to a challenge to ensure that low-carbon objectives continue to be met, not just once but over future cycles of renovation. This should align with the characteristics of renovation work; renovation of buildings is a repeat process made up of multiple projects over time, responding to the need to do maintenance and repairs, but also to adapt and improve living spaces to the changing needs of residents (Brand 1995).

The Co-evolutionary Framework

Our analysis uses Foxon's (2011) co-evolutionary framework, comprising five systems: ecosystems, technologies, business strategies, institutions and user practices (Figure 1). Each system will include a variety of actors, including individuals and organisations.

[insert figure 1]

Figure 1: Foxon's (2011) co-evolutionary framework, after Norgaard (1994)

Foxon (2011) acknowledges the confusion that often arises when the Darwinian term ‘evolution’ is applied to fields of study outside biology. A key point is that the term involves change but does not imply any pre-determined goal or end-point; outcomes are emergent properties of the evolutionary process. Two systems can be said to ‘co-evolve’ when (and only when) ‘they both have a causal impact on each other’s ability to persist’ (Murmann, 2003, cited in Foxon, 2011: 2262). In other words, co-evolution describes change in inter-dependent systems where influences are multiple and reciprocal.

The framework is designed for empirical analysis, at different scales, of the challenges for innovation and its adoption for a lower carbon future. Many researchers in the transitions field have declared co-evolution as its proper ontological perspective, for instance Rotmans et al. (2000), and Shove and Walker (2007). Co-evolution takes place where entities in two (or more) systems causally influence each other’s evolution, through affecting the processes of variation, selection and/or transmission in each system (Norgaard 1994, Murmann 2003, Manning, Boons et al. 2012). In each system, evolution can be described as follows: variation occurs (from purposive innovation or through other means) and, over time, some of these new forms or ideas become selected for projects. Those forms or ideas that are selected and deemed to be successful are then applied to multiple projects, this is ‘transmission’, so that the make-up of the entities in the system changes, to consist of elements that have been successfully selected previously. Thus, a transition occurs for the system as a whole.

Co-evolutionary approaches have been used to show how cross-system influences have led to socio-technical system changes in the past, and how co-evolutionary processes between technologies, institutions and organisations have led to path-dependencies and positive feedbacks that have reinforced the status quo, locking in high carbon systems (Unruh 2000). Co-evolution is a relevant framework for this paper because there are several systems involved in retrofits and RMI that can influence each other. We use the co-evolutionary framework to identify and specify cross-system influences that might otherwise be missed.

We now consider each of the five co-evolving systems from Figure 1 in turn, exploring how each system is represented in the specific case of renovation.

Ecosystems. The natural world provides the policy context for renovation. Concerns over climate change impacts lie behind the UK's Climate Change Act 2008 and accompanying carbon budgets, which require all buildings to be effectively zero carbon by 2050 (Committee on Climate Change, 2014). Climate change also has implications for the comfort and usability of buildings in the future. For example, an increase in average external temperature may reduce energy demand for winter heating, but also increases the risk of summer over-heating.

Institutions. Following Foxon (2011) again, the term 'institution' is used here as North (1990) used it: to refer to ways of structuring human interactions, including regulatory frameworks, property rights and standard modes of business or agency organisation. It is not intended to mean a long-established organisation; nor to refer to social norms of individuals or small groups (see 'user practices' below). There are formal policies that are connected to how RMI is undertaken, including planning policy, building regulations, industry policy and energy policy. Equally relevant are uncodified customs and cultural effects, such as the conventional distinctions between different building trades (carpenter, plumber electrician, etc). Formal and informal rules adopted by groups are all treated here as 'institutions'.

Business strategies. Three distinct types of business are readily identified in renovation: manufacturers, merchants and construction firms.

Manufacturers develop products and also building systems, which are families of products designed to be cross-compatible in terms of installation and performance in use. For example, insulation systems may incorporate a strategy for reducing the risk of structural damage from the build-up of moisture, which can arise at the junction of insulation with the building structure in certain conditions. The technical logic for using such systems (not mixing products from different systems) is one reason why manufacturers sometimes engage in training for product installers.

The businesses who operate between technology producers and technology installers are the merchants and wholesalers. This group encompass a range of characteristics. They may specialise in a family of products or technical systems e.g. insulation products or fixings, operating nationally but carrying a wide range of possible technical solutions. Or they may be more geographically focused, carrying a wider range of products and services but reflecting the needs of an area and its building stock type and condition (Owen, 2015).

Finally, there are the construction firms, who deploy the technologies through carrying out RMI work. These three types of business are not always rigidly separated between different organisations. It is not unusual for large manufacturers of construction materials to also supply materials sourced elsewhere, or for technology producers to act as suppliers to wholesalers and as wholesalers themselves, dealing directly with major contractors, although different parts of the organisation operate those different functions.

User practices. This system encompasses how technologies are deployed and used. In renovation, this means that the user practices system includes the homeowners and building users who ‘operate’ the building and, importantly, the builders and installers who select and apply technologies and techniques in RMI work. The presence of multiple ‘users’, each with their own practices and preferences, is one of the defining complexities of renovation work. The relationships between these groups are dynamic and heterogeneous, and they can be conflicted as well as harmonious; indeed, a good working relationship between client and contractor is seen by the contractors as one of the conditions in which innovative projects are more likely to be undertaken (Killip, 2013b).

Technologies. Co-evolutionary framing conceptualises technologies as a system in its own right. For retrofit, technologies encompass building components (e.g. insulation materials, glazing, roofing, heating systems) but these end-use technologies are not the only ones. The inherently practical nature of RMI work means that technology also includes tools for installation and for checking compliance (e.g. the requirement to achieve a level of airtightness is clearly linked to the use of testing rigs). Related to the multiplicity of users and user practices is a wide range of different relevant technologies: for design (e.g. computer-aided design software); for installation of products and technologies (power tools; manual tools; tools for access, health and safety, etc); for monitoring (temperature and humidity sensors; energy meters; airtightness testing equipment); and for operation (user controls).

The co-evolutionary framework can be applied to describe existing industry culture, as the following account illustrates. Of critical relevance to the policy agenda is the large and persistent gap between design intent and real-life performance of ‘low-energy’ buildings, including in housing renovation projects (Topouzi 2013, Topouzi 2015). The causes of the design-performance gap have been summarised as a combination of three issues related to the management of project teams: a lack of technical understanding among team members; unclear boundaries between different roles and responsibilities; and poor communication skills (Zero Carbon Hub, 2014). In co-evolutionary terms, this can be understood as impacts on ecosystems resulting from the nexus of selection pressures between the other four systems in the framework:

- individual **business strategies** focus on avoiding risk and liability, rather than working in genuinely collaborative ways to find solutions;
- in terms of **institutions**, these business strategies are often codified in contracts which entrench adversarial positions; and regulations are satisfied by 'in theory' design studies rather than monitored, real-life performance data;
- **user practices** (in the shape of project clients) also typically exert pressures in terms of cutting budgets and demanding work be finished quickly; for building users, the lack of adequate hand-over means that user practices are improvised, with control systems often inaccessible or incomprehensible to those who operate them
- **technologies** often do not work seamlessly when they are combined with other technologies, including (in the case of renovation) the set of technologies which make up the pre-existing building

This brief account shows how the co-evolutionary framework can be used to describe the status quo; can it also be used to provide insights into processes of change?

Methods

The study uses secondary analysis of primary data from four previous studies. The interpretations of data from the previous studies are not called into question, but are instead treated as the raw data for the secondary analysis (Weed 2005). The comparison was of lessons already learned, not of the source material providing those lessons. The studies chosen were all ones on which one or other of the current authors was closely involved, including in conducting interviews and other fieldwork. The advantage of this selection method is that the comparison could draw on the full richness of data and experience of researchers involved in these earlier studies, which is inevitably much more than can be gleaned from published papers alone. The main potential drawback of this approach is that the previous studies may not be comparable enough to draw satisfying conclusions in the secondary meta-analysis, leading to vague or meaningless results. This risk was evaluated repeatedly as the secondary analysis was carried out by questioning whether the themes identified were genuinely common to all four studies.

Thematic analysis began with the five elements of the co-evolutionary framework; only once it was clear that the five elements (co-evolving systems) could be identified in each of the four previous studies did the analysis proceed. The second stage of the analysis used the three processes of co-evolution (variation, selection, transmission) to investigate the dynamics of innovation observed in the previous studies.

Other themes emerged during the secondary analysis, as described in the rest of the paper. In the next section, the four studies are briefly summarised, and then an initial comparison is made using the framing of variation, selection pressures and transmission. Other emergent themes and points of comparison are included under Discussion. Finally, the

Conclusions section assesses the lessons drawn from the cross-comparison in terms of what the co-evolutionary framework adds to the meta-analysis; and in terms of how well the previous studies map onto the pre-defined categories.

Summary of previous studies

The four studies varied in scope but, taken together, they represent a wealth of information about many individual projects, firms and innovations (Table 1).

Table 1 Summary of previous studies used in this analysis

Study	Projects	Firms	Key innovations
S1 French co-operative	A start-up aiming to do 35 retrofits in its first year	Co-operative of small firms with centralised technical and marketing functions	Guaranteed energy performance contracts; extensive technical monitoring and feedback; contractualised occupant behaviour
S2 UK Housing Association	36 homes retrofitted	One firm involved – most workers were directly employed, not contractors	Multi-skilling, team incentives based on project completion, not task completion
S3 Local authority heat pump programme	80 rural homes equipped with air source heat pumps (over 3 years)	Project management outsourced to large consultancy by local authority. Heat pump installation delivered by sub contracted small firm.	Novel technology (air source heat pumps) installed as part of a package of welfare measures, for environmental and social benefits
S4 Whole-home advanced retrofit (Retrofit for the Future competition)	119 dwellings retrofitted, of which 26 were studied in detail (over 2 years)	Projects were led by a business, Housing Association or Council. Multiple firms involved: specialist consultants, surveyors, architects, engineers, contractors, sub-contractors.	Ambitious design standards requiring integrated technical solutions of low-carbon combined systems

The descriptions given here are necessarily brief and very selective - more detail is available in the original studies cited. This is an 'information-oriented' sample (Flyvbjerg, 2006), focused on that sub-set of RMI activity where low-energy housing retrofit is a key goal; it is not intended to be representative of the wider RMI market. The analysis of studies S1-S4 reflects a variety of economic contexts, clients, purposes and delivery models, and explores common themes. The studies are:

S1. A French co-operative of construction firms offering guaranteed energy performance. Building users affect energy consumption through their occupancy, use of technology, and personal preferences (e.g. for providing comfort). In this innovative business model, households undergoing renovation works are required to describe their household (using variables such as numbers of people, typical hours at home) and their habits (e.g. frequency and length of showers, preferred indoor temperatures) in the contract. In return, the co-operative of firms guarantee that their design and workmanship will achieve a quantified level of energy consumption. If the guaranteed consumption is exceeded and the household's contracted occupancy and behaviour has not changed, then the contracting firms undertake to re-do or re-commission their installations of technology and materials. However, if the residents' behaviour and use of the building differs significantly from the contract, then a revision is needed to the contract and the expected (modelled) energy performance. This might happen, for example, where a relative comes to live with the household for several months. An array of environmental sensors in refurbished homes provides 'live' data, which the co-operative monitors through a centralised technical support function. Data anomalies prompt alerts, which are designed to allow for early identification and remedy of potential problems. A zero-interest loan scheme backed by the French government was a source of up-front capital (see Killip et al., 2014).

S2. A UK housing association (social landlord) with a directly employed labour force (the building workers are employees rather than contractors) undertook ambitious low-energy renovations on an estate of 36 quasi-identical properties. Despite the appeal of achieving economies of scale by doing all 36 simultaneously, the work was tackled in nine batches of four, largely because four properties were empty at the outset, and the phased programme would cause minimal disruption to tenants. The project was late and over budget after the first four, but an iterative learning process among the project team led to major savings, and the thirty-sixth property was finished ahead of schedule and under budget. A team bonus scheme incentivised the labour force to take responsibility for collaborative problem-solving, and to undertake tasks which might normally be outside their trade job description. A tight-knit management team of three people, located in a temporary site office, provided effective supervision of the work and communication with tenants (see Killip et al., 2014).

S3. A UK local authority working with other public sector agencies across several policy areas (notably energy and social care), funded and installed air source heat pumps for space heating in the homes of private home owners off the mains gas grid. The programme used one installation contractor and two heat pump products. In this rural area, many of the homeowners were elderly or receiving welfare benefits and financial support from the state and at risk of fuel poverty. This group of homeowners were not the usual early adopters of innovative heating technology. While many homeowners were delighted with the new, low cost and reliable heating, there were also problems associated with the lack of familiarity with the technology and the challenges of commissioning, leading to 'incorrect' user behaviour. An unusually cold period of winter weather after the first round of installations also caused one of the brand of heat pumps to fail (see Owen et al, 2012).

S4. The UK *Retrofit for the Future* programme (RfF) was an innovation competition run by the government's Technology Strategy Board (since renamed Innovate UK). It was a set of trials for a 'whole-house' approach in social housing, integrating innovative low-carbon measures and systems. A budget of up to £150 000 was awarded to each of the 86 projects covering 119 low-rise houses in the programme, with the aim of achieving an 80% reduction targets in CO_2 emissions. In many respects, RfF played the role of an experimental 'living-lab' in which new technologies were combined to test their performance. In many cases there was a significant gap between design expectation and monitored performance. Where monitoring results were close to the design expectation, the common feature was a very high attention to detail and quality at every stage: from design to procurement, commissioning, installation, monitoring, handover to residents and aftercare support. The combinations of multiple low carbon systems and measures to comply with Passivhaus[2] standards raised difficulties in sourcing products and materials locally in combination with cutting edge technologies/materials from international supply chains. Project delays and cost over-runs were associated with discontinuity of personnel during and after project completion, whereas projects which retained the same people throughout had better outcomes. It was also difficult to find a sufficiently skilled workforce for high performance installation and aftercare support (Topouzi 2015).

[2] Passivhaus is a building energy performance standard, originating in Germany, which is a world leader in terms of the ambition of its standards and the technical thoroughness of the design methods. See http://www.passivehouse.com/

Having summarised each previous study briefly, some highlights are shown for comparison in Table 2.

Table 2 Comparison of previous study highlights using the systems classification of the co-evolutionary framework

ID	Ecosystems	Institutions	User practices	Business strategies	Technologies
S1	Climate change mitigation mediated through national targets	Zero-interest 'eco' loan scheme provides access to capital	Contractualised energy-consuming behaviour	Co-operative structure; technical monitoring; performance guarantees	Monitoring and communication technologies essential to business model;
S2	Climate change mitigation mediated through national targets	The desire to avoid decanting tenants led to batching; opportunities for learning	Customisable to meet resident preferences (to an extent); enthusiasm; rebound effect	Directly employed labour; team bonus scheme; on-site management team	Wall insulation proved difficult and slow to install
S3	Climate policy and targets; Technology effectiveness (heat pumps failed in cold winter)	Multiple agencies (social care, fire prevention, housing, public health) led to multiple project objectives	Deliberate under-heating to save money; unfamiliarity with heat pump technology;	Manufacturers and vertical integration of supply chains	Performance of heat pumps depends on ambient temperature, low heat loss and good quality installation
S4	Climate change mitigation mediated through national targets	Passivhaus standard; strong focus on technology and design	Users experienced renovation as a constraint on practice; feeling like guinea pigs; lack of control	Largely shaped by RfF competition rules. Key issues: monitoring of in-use performance; quality assurance based on user feedback; and aftercare service.	New technology combinations often failed to work well; failure to take account of pre-existing building led to unintended problems

A co-evolutionary analysis of previous studies

Across the four studies S1-S4, factors enabling or constraining innovation can be found in all five co-evolving systems. The Ecosystems system is rather different from the other four in that it is expressed primarily as a policy goal. It is nonetheless present in all four studies, as the existence of policy is an important influence on innovation in the other systems. Among the other four systems, co-evolution is observed in all four studies: causal links and interdependencies are multiple and reciprocal. Our findings explore the processes that support such co-evolution and therefore support the spread of innovation.

Variation

The four previous studies show different types of variation arising from different systems. In the French co-operative (S1), variation is in the innovative business model, which assembled multiple firms and used monitoring and communication technology as well as building products and technologies to increase energy efficiency and reduce CO_2 emissions. The business model also entrained changes to user practices, formalised through the notion of contractual patterns of occupancy and behaviour. In the case of the 36 retrofits by a housing association (S2), the source of variation was the housing association itself, which held multiple roles: construction client; landlord; employer of construction workers and site managers. The phasing of the renovations in nine batches of four was serendipitous, as it created a context for learning. In the case of the heat pump programme (S3), the variation arose in the technologies system i.e. innovation was in the type of heating system chosen by the project partners and it brought with it changes in user practices. No previous heat pump installations were known in the area. Finally, the government-fund RfF programme (S4) provides an example of variation in technologies and design being led by policy, and mediated through a process defined by engineering logic; a field-trial of the most ambitious renovation design standard, designed to explore technical limits and monitor performance without normal budgetary constraints.

Selection pressures

The minority of RfF renovations (S4) that did meet the targets set, had project teams which remained constant, suggesting that this in itself may be important in allowing an innovation to be channelled to a desired outcome. It is not immediately clear why continuity of personnel is important, but it may well be connected to the inherent complexity and novelty of whole-house, low-carbon retrofit. Where there is hand-over of responsibility from one person to another, the need for communication and shared understanding may not be met: the purpose and reasoning for design and installation details may not be obvious to a newcomer. The 'devil in the detail' is very likely to be lost where responsibility is fragmented; or where skills and knowledge are insufficient; or where communication is inadequate or incomplete.

In the French study (S1), concerted efforts were made to achieve low-energy renovations in two villages a few kilometres apart, but there was only interest and wide take-up in one village. This was attributed to the role of the village mayor, who was both a well-respected community leader and a passionate advocate of the low-energy project. His role in persuading his neighbours to allow the project team into their homes and his support for the overall project may well have been instrumental in securing so many renovations in this one village.

In the heat pump programme (S3), user acceptance of the novel heat pump technology was highly influenced by the experience of the homeowner during installation and commissioning. If the installer treated the home with care and respect, and they took the time, immediately upon commissioning and at intervals afterwards, to explain the operation of the heating system, users were much more likely to operate the heating systems in ways that achieved the desired reductions in energy demand.

Transmission

There is evidence of transmission in the social housing programme (S2), with learning from each earlier phase of four feeding in to fewer wrong turns in later phases, producing a quicker and more confident programme of work, and increasing labour productivity. This last point is worth emphasising, since there was a clear convergence of two issues on this project: the objective of achieving low-energy outcomes; and the effective management of the workforce (including the high degree of responsibility taken by the workforce for finding solutions). One manager on this project reported that an unexpected effect of the novel project management was a decision to reduce the amount of time allocated to certain tasks (e.g. fitting a new kitchen). Increasing labour productivity was not the original purpose of the renovations, but labour productivity was increased as a consequence of the innovative practices and processes used. What seems to have happened after the 36-house project is that the expectation of increased productivity has been transmitted as a requirement for future projects but the low-energy standards have not.

In S3, the technologies could not initially be installed by local contractors, paralleling S4 where challenging performance standards could not be met by local tradespeople. In S4, sourcing expertise from outside the local area, and then deliberately engaging in knowledge sharing or capacity building activities brought new competences into the local renovation supply chains.

Discussion

The secondary analysis of previous studies involving some element of innovation in retrofit offers two different types of insight. This section first considers how using the co-evolutionary framework provides useful insights into the structure of the RMI system. The second part of the discussion outlines where the co-evolutionary framework requires some amendments to reflect RMI accurately.

Analysing the four studies using the co-evolutionary framework proves effective in terms of classifying the features of the process which progressed innovation from a variation of product or process in one of the systems, to potentially becoming a wider systemic change. Using the framework helps to ensure that innovations are understood in the context of who produces them and what relationships with other systems are influential.

Common themes from our examples of selection pressures that might be affecting the widespread transmission of innovation are: phased working to allow a team to share learning and experiment with variations to their previous practices; strong coordination; monitoring/feedback loops; renovation as a repeat service offer (i.e. tying customers in to a service provider); commitment to quality of finished work and customer care. What is notable in each of these themes is the vital importance of connections between systems and communicating the purpose, effect and means of each innovation. For example, monitoring and feedback mechanisms deployed during a project (connecting the *technologies* and *user practices* systems in the co-evolutionary framework) underpin learning and create the stimulus for a project team to vary their practice and reflect on the impact of that change. Considering how the *business strategies* system might connect to other systems through innovation in business models highlights interesting connections with both *technologie*s and with *user practices*, for example by introducing feedback mechanisms from one stage to another, or through vertical integration of more than one aspect of: technology manufacture, distribution, installation, after-sales service, and monitoring.

Another example is that when after care service is provided (connecting the *business strategies* and *user practices* systems in the co-evolutionary framework) this forces a change in business strategy in order to find ways of generating the revenue that makes after care service viable. A third example is when local or national policies and targets (the institutions system in the co-evolutionary framework) connect to *business strategies* and *technologies* and create a pathway for innovation.

The context of innovation is important, and there are aspects of the existing RMI sector and the nature of its work that are pertinent. Every building is different. Even seemingly identical buildings will have different occupants, and the physical buildings themselves quickly accrete physical changes in response to changing needs (Brand 1995). As a result, the builders and tradespeople working on a site are necessarily engaged in frequent acts of practical problem-solving, connecting the *user practices*, *institutions* and *technologies* systems. Each renovation project is bespoke in the detail of practical execution. Existing structural or material limitations and defects may not be visible until a project is underway, and the builder or tradesperson must find creative solutions which will respond to challenges as they arise. However, the way in which problems are solved, i.e. the ways in which potential innovations are selected, do not automatically lead to low carbon outcomes for the final performance of the building. Despite superficial similarities, this innovation in project execution is not the same as bricolage (Baker & Nelson 2005). Where bricolage refers to the combination of available resources to meet new opportunities, the practical problem-solving of RMI is concerned with the process of discovering that things do not (or cannot) work as designed, and having to find a work-round. It is the process of combining available resources to satisfy the aims of an under-specified original task.

Moving to the second area of learning from our analysis, the co-evolutionary framework does not capture certain characteristics of the retrofit domain very well. For example, it is difficult to reflect the fragmentation of the RMI sector as an attribute of the business strategies system, although we know that such fragmentation makes it more difficult for innovations to be transmitted to other RMI projects. Equally, the length of supply chains is a barrier to innovation diffusion, but does not fit neatly into a co-evolutionary analysis. The question of resource use is not prominent in the co-evolutionary framework, and yet the consumption of energy (and other finite resources) is arguably more salient to local actors in the built environment than planetary ecosystems.

Applying the co-evolutionary framework to the RMI sector undertaking low carbon renovation is helpful in revealing the ways in which barriers to innovation lie in the connections between different systems. However, we found limitations in representing the RMI effectively through the five co-evolving systems. Specifically, those who deploy the technologies (installers) and those who use those technologies once installed in buildings (building users) can be considered as separate, linked, systems. The building trades (installers) also demonstrate the attributes of the *business strategies* system, their actions shaped by the need to maintain reputation through a perception in their clients of high quality or cost effective work. These installers are a distinct element of the *business strategies* system compared to the technology manufacturers, or the retailers and merchants who connect the manufacturers and installers. This implies that in order to support innovation that will enable lower energy consumption in buildings, we need to understand the behaviours of RMI installers as users of innovation. They are part of a web of connections and interactions that allow innovation to move between projects or be inherited. Similarly, within the institutions system we find aspects of business behaviours, technology standards and user expectations and norms.

Innovation may take place in different co-evolving systems, notably for RMI in technologies, business strategies, and user practices. Acknowledging these multiple sources of innovation increases the potential for innovation to be transmitted and for low carbon outcomes to be achieved. Established models of innovation diffusion focus on technological innovation or process innovation (Rogers, 2003); a co-evolutionary framing identifies more sources of innovation, and more possible routes of diffusion, or transmission. In essence, it allows for greater complexity. This may be a positive thing, for example where new opportunities are identified for innovations in businesses' strategies, and for overcoming institutional structural forces that can present barriers to innovation being selected. But positive outcomes are not guaranteed: identifying complexity is not the same as navigating a successful path through the many possibilities that arise.

Using a co-evolutionary framing may also help in widening the scope of policy development supporting ambitious ambition reduction goals. The scale of the climate challenge and of energy consumption in buildings means the RMI sector cannot be ignored, but policy so far has not been effective in engaging with this complex sector. In this analysis, the co-evolutionary framework has allowed us to record influential connections and make selection pressures visible, bringing often overlooked actors into focus.

Conclusions

The challenge of transforming existing buildings so that they are responsible for minimal carbon emissions, and provide affordable, comfortable environments for their users, is huge. It is a challenge that requires system-wide innovation. Using a co-evolutionary framework helps shift the focus away from incremental improvements in individual behaviours or specific technologies, and supports an analysis that identifies the processes which allow or constrain innovation to achieve transformation at scale.

By applying a co-evolutionary perspective, several facets of domestic renovation are revealed, where previously some of them were hidden. It emphasises the role of supply chains, designers and installers, while still taking account of the homeowner/building occupier and the technological aspects (which have been the focus of much building energy use research to date). The co-evolutionary framework holds the promise of being useful here, not only in framing the issue as a set of co-evolving systems, but also in giving equal status to the five systems. Most work to date has focused on innovators at the level of the firm, but little has been done to explore the role of supply chain actors (manufacturers, distributors), government agencies or departments. Research which systematically identifies connections between co-evolving systems and the selection pressures that such actors apply to innovation could provide a much more extensive menu of policy levers. However, describing the possible policy levers is not enough: transmission of an innovation between systems and projects is a necessary but not sufficient condition for transition and system wide change. A handful of observations of transmission in action does not necessarily translate into transformational change at system level. For the RMI sector to be able to rise to the climate challenge, there needs to be a policy focus on how the selection pressures might be influenced to favour low carbon outcomes on a much larger scale.

The lessons for policy need to be approached with a degree of caution. There is a risk that the co-evolutionary approach might be seen as opening policy up to an unworkable and unnecessary degree of complexity in tackling real-world problems at multiple levels. However, the art of successful policy design lies in framing rules in such a way that businesses and citizen-consumers can negotiate the detail in order to achieve multiple objectives, including (from the policy viewpoint) the energy and climate policy goals. Historically, policy for residential energy efficiency has not followed this logic, but has instead focused on the installation of individual 'measures'. Raising the profile of the systems that are less prominent (in policy thinking) could help to re-frame future policy work.

This paper reflects an attempt to find a theoretical framing for empirical observations and engagement activities, which is neither too simplistic nor over-complicated. On the evidence presented here, the co-evolutionary framework strikes a good balance. It needs to be tailored and interpreted to the specific context of inquiry, but that is preferable to the quixotic pursuit of a perfect theory of everything. This analysis suggests that co-evolutionary framing is most useful when the five co-evolving systems can be flexibly defined to reflect the nuances of the problem being considered. In this example, key actors in the supply and installation of RMI works that could lead to low carbon outcomes have attributes of both *user practices* and *business strategies*. This seems related to the fact that building renovation is a project-based industry, in which multiple members of a project team use multiple technologies in non-trivial combinations to deliver changes to a pre-existing building, in order to meet changing user needs. Renovation is a different type of activity to product manufacture, where the physical environment of a factory and the control by one firm make quality control more easily manageable and outcomes more predictable. For retrofit, we have found that quality assurance relies on fastidious attention to detail, technical knowledge, and good team-working. How generalisable these findings are – for example, to other project-based industries – is a promising topic for future research.

A final note that the authors would like to highlight is concerned with the challenges of undertaking theoretically robust but practically grounded research. All co-authors of this paper have experience as both practitioners and researchers. The initial development of this paper was driven by a problem focus, specifically what needed to be done to support innovation and enable massive improvement in the energy performance of existing buildings? Despite the usefulness in providing a conceptual framework and highlighting system behaviours at work, the co-evolutionary approach says nothing about methodologies that might be appropriate to effect change in those systems. Nor does it provide an explicit way of flagging up system-wide properties (such as industry fragmentation), which might hinder (or help) innovation. Without the ability to identify responsive tactics, innovation is stifled and the status quo remains. In straddling the practice-theory divide, we are still engaged in an iterative process of conversation with actors in the institutions, businesses, technologies and users.

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