Supply chain dynamics in the UK construction industry and their impact on energy consumption in homes

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Abstract
Small and medium-sized enterprises (SMEs) are particularly important in the delivery of repair, maintenance and improvement (RMI) activity, especially in privately owned housing. The RMI market provides multiple opportunities for integration of energy efficiency improvements, and SMEs could have the scale and reach to influence energy demand at scale, through influencing the myriad individual decisions that are needed for each building project. This paper offers a contribution towards understanding why that potential is not being achieved and how a different perspective on the supply chains for renovation may offer ideas for changes in policy and practice to unlock that potential.

The paper sets out key aspects of how SMEs operate within their own networks and limitations to prepare the ground for a different analysis of the RMI system that could deliver energy retrofit in housing. The supply chain that supports SME RMI activity includes material design and supply, retail – including wholesale and merchants, training, maintenance and warranties/aftercare. There is also a strong local dimension to how the supply chain for renovation operates, encompassing both local policy or incentives, collaborative networks enfolding the SMEs and technical /design constraints and opportunities. By using the idea of a potential "co-evolving" set of systems, we offer a way of identifying new linkages and influences that might change the energy efficiency outcomes of refurbishment works.

Ideas for how the existing supply chain could be updated and amended include: How might product-service offerings to construction SMEs be changed to increase the likelihood of their adoption? What skills and capacities need to be developed at what points in the supply chain? What appear to be the most effective channels to share information about innovation? How might the perceived risks, and costs, of early adoption of innovations be reduced?

Introduction
Buildings continue to be a responsible for significant energy demand and associated carbon emissions - approximately 40 % of energy and 36 % of emissions across the EU. Levels of new build remain relatively low across Europe and in the UK; it is estimated that 80 % of our 2050 building stock is already with us (SDC, 2006) so the challenge to reduce energy demand must be met through renovation and refurbishment of existing buildings – also termed retrofit.

In the UK, improvements in building energy efficiency have stalled since 2012 (Committee on Climate Change, 2016) a change which has been attributed to a mixture of factors in the wider economy (reduced disposable income and varying energy prices) as well as inconsistent government policy (Rosenow & Eyre, 2016). While previous policy has led to improved energy efficiency and there has been a shallow decline in recent energy consumption from the residential sector, the scale of the challenge suggests that a new approach is required. Rather than setting up policy to deliver energy efficiency through individual measures (e.g. wall insulation, roof insulation), the challenge is to find ways in which mainstream renovation projects (which may not be primarily motivated by energy efficiency) can be delivered in such a way that appropriate interventions are taken to improve energy efficiency at the same time. For the energy efficiency community, this is a subtle but profound shift of focus. Instead of devising policy to insulate walls, say, the challenge is to identify where there are good opportunities to incorporate wall insulation into other works. Fitting a new kitchen or bathroom might be a good opportunity. This is not to deny the value of 'whole home' retrofits where they are possible, but the 'over time' approach allows for greater flexibility, greater market opportunity, and a level of technical ambition which may be only slightly lower than the most advanced standards (Fawcett 2014).

We encapsulate this shift by referring here to the market for repair, maintenance and improvement (RMI), which is a term commonly used in the construction industry. In contrast, terms like 'retrofit' have emerged in recent years in energy policy debates led by the energy research and policy community. By using RMI rather than retrofit, we consciously use the language of an incumbent sector with relatively little interest in energy issues but a huge degree of access to and influence on decisions on projects which alter the fabric of homes. RMI may include upgrades to existing building fabric or technology, and so our exploration of activity in this field includes the installation of micro-generation energy technologies as one element.

From a research perspective, this shift of focus from energy efficiency measures and policy towards the existing markets for renovation projects of all kinds has several important consequences. It requires investigation of how the system of building renovation functions, what motivates its actors and how the system might learn and change so that energy efficiency is automatically delivered through renovation. The systems of renovation for commercial and domestic buildings (homes) are distinct, with a very small overlap in terms of clients, technologies and contractors. This paper focuses on the latter.

Housing renovation is a highly fragmented system, reflecting the nature of home ownership. In countries like the UK the majority of homes are owned by their occupiers. In the UK, this means that renovation work must be commissioned by around 18 million clients, with a further 5 million homes rented from private landlords (ONS, 2015) in the next 3 decades. Even where individual owner occupation is lower, the numbers of individual clients are still huge.

Delivery of residential renovation work in turn relies on tens of thousands of small and medium-sized enterprises (SMEs) in the construction sector, usually micro-enterprises of 1–3 employees or self-employed workers operating as sole traders. Understanding of the importance of these individuals is starting to be explored and some of their characteristics are described below. The challenge of why these firms, who have been in existence for as long as construction has been an industry, do not already work to mainstream energy efficient outcomes in RMI is answered by observing that without the right policy framework, the market demand for low-energy renovation remains low; SMEs do not create market demand on their own. SMEs do have the scale and reach to undertake energy efficiency work within RMI, therefore policy needs to understand their practices better. Supportive policy that reflects the real behaviours of firms is an essential element of transforming the RMI market (Killip, 2013).

Specifically, in this paper we explore the dynamics of supply chains in the UK's residential RMI industry. Given that supply chains are an important influence on what gets specified and installed in RMI projects, any attempt to steer those projects towards greater energy efficiency needs to engage with supply chains. Energy policy researchers may take the view that clear, well-designed policy will be sufficient to motivate these actors to embrace energy efficiency. Such policy needs to have a better understanding of the dynamics of supply chains in the mainstream construction sector to design policy which enables ambitious levels of residential renovation in the context of energy and climate change.

The conventional linear representation of a supply chain comprises manufacturers, feeding wholesalers, feeding retailers and ending with the customer. In the context of building renovation, these supply chain actors might be more closely defined as material and equipment manufacturers, trade suppliers (builders' and plumbers' merchants), the construction firm who deploys the materials or installers the equipment, and the building user. The skills and knowledge of installer firms are also important considerations, so vocational education and training (VET) need to be considered as part of the supply chain.

Our analysis concentrates on how five sets of actors – institutions, manufacturers, wholesalers, construction firms and building users – relate to each other and what flows between these actors in terms of money, knowledge (and people), as well as decision making influence. This paper proposes a theoretical framing for such analysis, based on emerging findings from qualitative research with a range of supply chain network actors.

Our approach is aligned with the concept of 'middle actors' (Parag & Janda, 2014), which recognises the important role of organisations with links to end-users (e.g. through service delivery) and policy-makers (e.g. through lobbying) rather than "intermediaries" often identified in discussions of innovation. Intermediaries are conventionally seen in innovation studies as actors within the process of innovation who broker, bridge, exchange information, or organise 'superstructure' (Howells, 2006) or as standard-setting third parties who intervene in the decisions of others whether or not to adopt a new innovation (Mantel and Rosegger, 1987). Rogers (2003) identified intermediaries as 'change agents' who had influence on the adoption of innovative products, and also on the speed of their diffusion. The roles of intermediaries can also include 'gatekeepers', such as industry associations, and retailers, both being actors who are in positions to select other actors for transition activities (Loorbach, 2010) as well as to choose technological innovations for product markets (Belz, 2004). In all these cases, intermediaries have the potential to suppress innovations, as well as to promote them.

Middle actors, by contrast, are active and influential in the development of markets and policy, serving their own goals and motivations, which may (but may not) align with the goals and motivations of policy and consumers. This conception is important because it opens up a set of research questions about understanding middle actors better, not merely treating them as passive delivery agents who respond (predictably and uncritically) to policy 'push' and consumer 'pull'. In RMI, middle actors shape and allow or constrain the degree of energy efficiency delivered through renovation. For these reasons, the term 'middle actor' represents agents in the RMI system more accurately than the term 'intermediary'.

The construction supply chain often represented in a linear way from materials supplier, to wholesaler, to installer/builder, to energy end user but this oversimplifies a messier reality, with many feedback loops, unevenly distributed power and influence over decisions such as materials selection, mixed motivations and varying indicators of success or performance. As we start to analyse the dynamics of the supply chain, new ideas emerge for how the system might encourage energy efficiency in RMI, working towards energy efficiency as a default outcome.

To support a different way of thinking about interactions in a supply chain network, we use the framing of co-evolving systems (Kallis & Norgaard, 2010). Systems are considered co-evolving if they influence each other through processes of variation, inheritance (transmission), and selection. Coevolution has been used explain how systemic barriers have prevented the adoption of carbon-saving technologies in energy fuel systems (Unruh, 2000) and how sustainability standards have varied, been selected and transmitted in different country contexts (Manning et al., 2012). In the RMI context, we are interested in variations, or innovations, in products or processes, for more energy efficient outcomes, which might arise from one system, and are subject to selection processes and mechanisms from other systems. Such an innovation then can either become a variation that is used and retained in future projects, or selected out, leading to a reduction in variety.

Potential for energy efficiency in household renovation

Motivations for renovation are likely to be something other than energy reduction per se (Wilson et al, 2015). Homeowners are likely to be renovating or extending in order to improve the usable space of a home, or to reconfigure how that space is used (Hand et al. 2007, Maller et al. 2012). This is not to deny the contribution that might be made by more ambitious 'whole home' projects, including innovative approaches such as energiesprong. However, the market opportunity for whole-home projects is smaller than it is for room-by-room projects. In fact, we argue that the best way to capture as much potential as possible is to think in terms of 'project-by-project', including projects at all scales from individual rooms to whole homes and extending to projects at neighbourhood or city scale, as this aligns with how the construction industry operates.

In addition to the technical challenge of achieving design intent, there is the socio-technical challenge of integrating energy demand considerations into the design and planned activity at all! Similarly, where renovation is an upgrade to an existing functional space like a kitchen or a bathroom, the challenge is to mainstream energy reduction into works being carried out for non-energy reasons.

Overlaying these motivations are the particular windows of opportunity to renovate, linked to major changes in how people use their homes. Moving into a new home is a specific opportunity to change fabric before habits, particularly thermal comfort habits, are formed. Life events such as the arrival of a new child are also an opportunity to change patterns of energy use when so much is also changing in other areas of household behaviours.

There are technical risks associated with taking an opportunistic approach and incorporating energy considerations into RMI work, as a key consideration in the energy impact of any building renovation is how different building elements interplay. While recognising such risks, we suggest they can be mitigated if there is someone on-site who understands the risks and makes decisions accordingly, as well as the RMI team supporting their customers, the building occupants to use their homes in ways which are consistent with its fabric and technology (Fawcett and Killip, 2014). This reinforces the need to think about how to enhance the capacity of middle actors in RMI to ensure energy efficiency.

Characteristics of UK firms working in household renovation

The majority of construction firms working in the UK RMI market are classified as Small or Medium Enterprises (SMEs). SMEs are typically defined as firms employing less than 250 people, although some definitions also refer to total annual turnover. In practice, most construction firms in the UK RMI market are much smaller than this, making up a networked constellation of sole traders and micro-enterprises employing three people or less. The dominance of SMEs and micro-enterprises has important implications for policy and engagement. From a policy perspective, these firms are hard to reach, being both short of time and disinclined to engage in policy debates which take them away from 'real work' (i.e. activity for which they can be paid). The presence of so many small firms in the RMI market means that the market response to policy is very fragmented.

Killip (2013) found that SME construction firms can be open to innovation (including unfamiliar requests for energy efficient outcomes) in the right circumstances. Key factors are sufficient extra time and money for the project, and a sympathetic client who is able to make (and stick to) decisions, whilst also being able to compromise and discuss issues as they arise. The availability of products locally on the same day (or within a few days) is also important, and supply chains create very real constraints on what installer firms work with, feel comfortable with, and will recommend to clients. Maby and Owen (2015) found a similar level of importance in the reliance on product availability as well as interdependence between small firms making a whole network vulnerable to a specification that changes or a client who refuses to pay, both of which reduce the desire to innovate or take risks in methods and products.

SME firms and microenterprises operate in flexible networks with a high degree of trust and shared reputational risk between them. Delivery of renovation work, as distinct from the design of renovation work, will usually require multiple sets of trade skills (general builder, plumber, heating engineer, electrician, joiner, plasterer and so on) and yet most firms will specialise in one trade. Their ability to deliver projects is linked to their networks of contacts and flexibility of response: the 'lead' contractor (i.e. the one first called in by a prospective client) may vary from project to project, and each firm will typically have preferred collaborators to whom they sub-contract aspects of the work, with different trade skills and levels of accreditation. Skill areas are not always tightly defined, when working on a task, a sub-contractor may be able to support another trade in order for the overall job to progress. Tradespeople are likely to be working on more than one job at the same time, moving between parallel tasks as programmes allow. Thus, a 'lead' contractor may need to make several enquiries before finding sub-contractors to work with on any given project. And, from one project to the next, the role of 'lead' and sub-contractor may be reversed.

These networks are generated in at least four ways with different types of relationships leading to different actions for collaboration, learning and competition: inter-trade, intra-trade, supply chain and client-based (Owen 2015). They appear to very stable over time. It is not unusual for several generations to be involved in a network delivering work as skills are passed on in families. A tradesperson will be loyal to a particular merchant or wholesaler for decades, trusting their commercial terms to be fair and the products they supply to be of a quality which helps the tradesperson complete the job and satisfy their customers.

This is important because a critical factor in the operation of these networks is their mutual reliance to ensure a positive reputation with existing and potential clients. Small construction firms operating locally to their base report that reputation, and "word of mouth" are essential factors in winning new work, and in winning the kind of work that they want to do, ideally without going through a tendering process (Maby & Owen 2015). The firm's reputation is closely aligned with the issue of "trust" in tradespeople which has been identified as a vital element in whether energy efficiency is actually delivered (Mallaband et al, 2013).

A firm's positive reputation with a customer is derived from at least three sources. First, the experience of the installation from the homeowner's perspective. Homeowner clients may judge the quality of work by how well the tradespeople tidied up after themselves, and generally how they respected the home, even though it was their place of work. A builder who supplies and uses their own vacuum cleaner and mop is signalling, to a home owning RMI customer, that they undertake quality work (Owen et al., 2012; 2014). Second, how well the installation functions once the construction firm leaves, in terms of delivering the comfort and, potentially, reduced bills that the customer expects. This is particularly noticeable with a technology unfamiliar to the customer –such as a heat pump. There is evidence that even if the function is not immediately of the standard expected, a responsive follow up and delivery of customer service in terms of answering queries and revisiting site can underpin trust in the firm and repeat business (Owen et al, 2012). Third, and closely linked to the previous two, the visual and surface appearance of completed RMI works are judged to be a proxy for performance (Fylan et al, 2016).

The contractual arrangements of these networks vary from job to job (Maby & Owen, 2015). Equally, who takes on the project management and co-ordination role also varies – this is sometimes the client, sometimes an architect (if they are used), sometimes the general builder and occasionally one of the specific tradespeople, particularly where their trade is driving the project e.g. a heating engineer might co-ordinate the installation of a heat pump. Thus many different actors across the network are, at different times, responsible for the reputation, and therefore future work, of others in that network.

An important aspect of being able to support innovation in RMI is understanding how the capacity of these small firms might be changed through learning. Formal learning, i.e. training, for these firms varies across European countries depending on the tradition of guilds and how this has informed vocational education (Brockman et al, 2008). In the UK formal education for construction workers is often minimal: there was a steady decline at the end of the twentieth century in both the technical content of training and the numbers of youth trainees, whilst the number of self-employed construction workers (for whom training is not compulsory) increased (Clarke and Wall 2000). There are exceptions, notably for those trades which require certification of their qualifications or their work on safety or insurance liability grounds. This applies to gas engineers, electricians and window installations (which may be a subset of joinery). There is extensive informal learning in these small firms. Informal learning happens through trusted parts of the individual's network i.e. other tradespeople, and suppliers. On a particular project, an architect may trigger learning through what they specify and therefore what the contractor has to deliver. Similarly, a client may also trigger learning if they are driving a particular set of outcomes from the project they are paying for. Wade et al (2016) found that in formal networks and the social capital developed through links in the supply chain network is an important route for learning about new products and process improvements for domestic heat installations.

Connected to how people learn, and to how technology allows or prevents individuals trying out new technologies, products or processes, it is worth considering the nature of innovation in housing RMI. Delivering low carbon retrofit at scale will certainly require innovation in both the technologies designed, supplied and installed, and in the processes of renovation undertaken on site. Innovation is often considered as a new approach which needs to be diffused through a community of potential users and models of innovation have their roots in agricultural extension programmes (Rogers, 2003).

While most small firms would not consider themselves 'green' entrepreneurs (Gibbs & O'Neill, 2014), or innovators, in the context of household renovation, each new job requires innovation. For a construction worker on a renovation project, problem solving is a continuous process where materials and processes need to be adapted in order to achieve the outcomes required in a bespoke context. Once they have been occupied, even identically designed homes become unique in the way they are used and the way they perform in terms of energy consumption (Gram-Hanssen, 2014).

The RMI supply chain network – a co-evolutionary framework

The conventional linear understanding of the supply chain does not reflect the many connections and feedback loops involved in RMI. Using models of business co-evolution as an inspiration (Foxon, 2011), we conceptualise a more interconnected supply network, illustrated in Figure 1. This network illustrates the range of possible influences between the network and further research is needed to allow this conceptual model to be developed and to recognise that relationships may not exist, or may be of different strengths. Here, each system has the potential to be a "middle actor" (Parag & Janda, 2014), not only transmitting information but shaping and informing action by other actors.

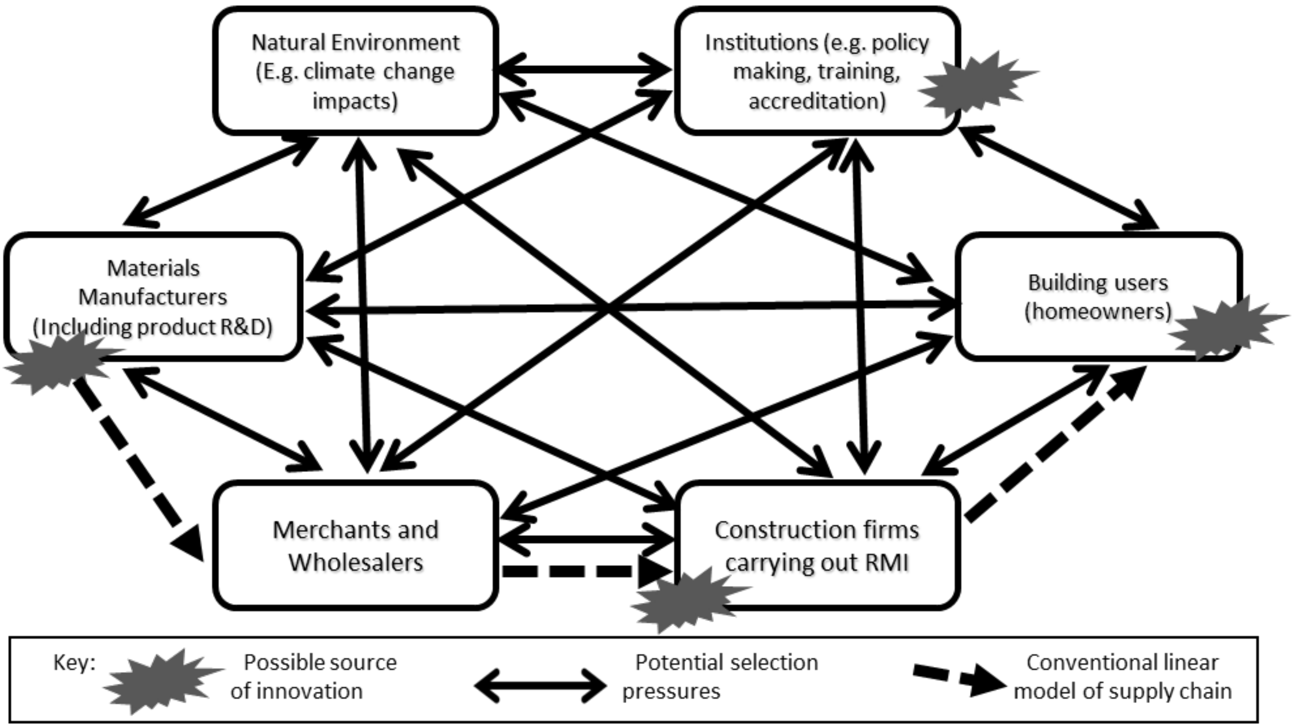

Figure 1. The (co)evolutionary elements of the RMI system.

We have extended the co-evolutionary framing for energy transitions developed by Foxon (2011). The mapping of five co-evolving systems would include construction firms as the technology users, in the sense that the construction firm deploys the technology during RMI work, but would exclude the occupier or consumer of the renovated space. As there are undoubtedly renovation projects which deliver energy retrofit because of customer demand, we have added the building occupier, who will also be the renovation customer in owner-occupied properties, into our mapping of the supply chain network. In fact, in the current market, successful customer-led renovation projects have involved many kinds of innovation, but one common element is that the customers have had to commit significant time and effort to learning in order to get key decisions right and manage contractors effectively – including at times ignoring incorrect or misleading advice from contractors (Fawcett & Killip, 2014).

This evolutionary – and possibly co-evolutionary - model allows us to include institutions; in the case of renovation, the training (VET), regulation and policy forces who also play a role in shaping supply chain activity. Even though VET is not primarily concerned with product sales, the manufacturers and distributors of products take account of skills and knowledge of installers in relation to investment decisions and business strategy. Gleeson (2016) argues that one reason why gas boilers continue to dominate the residential market for space and water heating is because technical design and specification issues are embodied in the technology, leaving the installer with largely practical tasks for installation (such as making watertight connections between pipes). In contrast, the successful installation of heat pumps is more critically dependent on the installers' underpinning knowledge of a building's specific heat loss, and flow rates and temperatures of the heat pump and heat emitters. Equally, regulation may set a new performance standard that will then drive innovation in other elements of the system. These examples illustrate how thinking about the elements of each system as 'middle actors', as well as bringing together the different systems as a co-evolving network, highlights different influences on RMI delivery, and how well that delivery supports energy efficient outcomes.

The co-evolutionary model of the supply network therefore includes the four systems of the conventional linear supply chain – manufacturer, wholesaler, construction firm and customer -, the institutions outlined above, plus a sixth component – the natural environment. This sixth component is different in kind to the others, in that it is not a social construct. Nonetheless, it is important in influencing the context in which the five social groups affect RMI activity: climate policy is strongly influenced by scientific evidence of climate change, while the responses of supply chain actors to climate-driven policy can be many and varied: they may be sceptical or convinced about climate change; they may be alive to the economic opportunities of new work in their sector, or resistant to change which they perceive as a threat to a profitable status quo;, physical conditions such as climate might influence the type and function of products developed, the materials used in construction products, and how the infrastructure of supply operates.

It is not clear whether these elements of the system are co-evolving, in terms of influencing each other through variation, selection and inheritance (Kallis & Norgaard, 2010), but they do appear to be co-dependent in commercial terms and there is evidence that information and knowledge, and therefore the potential for innovation, flows between these actors. To emphasise the point above, innovation in renovation might mean the use of new materials, the use of new technologies that passively reduce energy use, or technologies that actively manage and reduce demand, or increase renewable generation.

As an example of how the supply chain network allows or constrains innovation, a local builders' merchant will stock insulation materials for which they know there is local demand. They may agree to stock new materials from an existing manufacturer supplier, potentially on a trial basis if the commercial terms are favourable e.g. allowing for 'sale or return'. What a merchant holds in stock is important because a sole trader or small firm will often only go into a merchant to obtain materials the day before or on the day he plans to carry out the work. Domestic renovation jobs do not have the space or working capital to allow all materials to be purchased and held on site until needed. So 'just in time' purchase is a necessary strategy to avoid cash flow problems; work may not be invoiced until a job, or a stage of a job, is complete. Thus what might appear a 'hand to mouth' approach avoiding strategic planning is in fact a pragmatic business strategy. Therefore, if an architect or project manager specifies a new material or a product that requires a different installation technique, that specification will only be fulfilled if the builders' merchant has the material in stock, or if the builder is willing to place an order in advance so that the material comes into stock 'just in time', and if the merchant can also supply or access the knowledge and support to help the builder use the new material effectively.

The risks that different supply chain actors are willing, or able, to take to introduce energy retrofit and innovation into renovation projects is connected to their financial size and resilience. The smallest firms may choose to operate below the threshold for value added tax (in the UK, this threshold was a turnover of approximately €95,000 in 2016/17). This can mean that renovation clients are asked to purchase materials directly from merchants, preventing the value of those materials appearing on the small firm's financial accounts and enabling them to stay below the taxation threshold. For domestic customers, using a contractor who is not VAT-registered offers a price reward. Using a VAT-registered firm automatically increases prices by 20 % (in the UK) and while a commercial, VAT-registered, customer can claim back the VAT, a domestic customer cannot.

Place and location

Supply chain analysis often focuses on flows of material and finance but in the case of building renovation, and specifically domestic building refurbishment and renovation, the geographic distribution (and learning?) of the supply chain needs to be understood. Place and location-specific responses are important in building renovation. This has several dimensions including technical requirements, trade relationships, customer networks and local policy.

By technical requirements, we mean the distinctive materials, technologies that might be characteristic of a particular location. For example, a style of dormer roof which requires particularly careful insulation detailing might be a common occurrence across an estate built by a particular developer. Or there may be aspects of vernacular architecture associate with the character of places, such as the dominance of solid masonry walls in buildings built before 1900 which mean that a particular cladding product has an extensive local market. The skills in the construction firms working in this geographic area will tend to reflect learning from previous jobs and therefore reflect the needs of that local built distinctiveness. At the same time, care must be taken not to suggest that there are no transferable elements between different locales, because of the distinctiveness of local building styles and materials.

Local distinctiveness of form and materials may be closely linked to the local policy context and potentially the funding available to undertake renovation work. Planning authorities covering rural areas with stone houses valued for heritage and cultural value may only allow renovation works which conserve or enhance the visual quality of that built environment. A planning authority in a university city may be particularly concerned with the techniques and opportunities for renovation in house of multiple occupation, tenanted by students. The city of Leeds has a unique challenge in its 30,000 remaining Victorian back-to-back terraces, where a mid-terrace home has three party walls with neighbouring homes.

In other cases, the local policy context may not be driven by building type but by other goals. The UK local authority of Kirklees (a mixed urban-rural area in the post-industrial north of England, with an ethnically diverse population of 400,000 in 171,000 homes) drove an ambitious programme to insulate every home in the borough homes, regardless of household income, over three years from 2007–10. This area-focused programme came from local political drivers, windfall income from the share of sales in the local airport, and the opportunity to achieve environmental, economic and social goals by creating sufficient market to generate jobs in insulation installation (Owen, 2013).

The localised nature of the supply chain and relationships is illustrated by the pivotal role of the local builders' and plumbers' merchants, as outlined above. While a local depot may be part of a regional or national chain, the relationships between local firms and the individual staff who work in those depots can be highly stable over time and appear to be a vital link in how new ideas, and knowledge of changing customer expectations and requirements, flow in the supply chain/network. There are also national, on-line merchants, often offering rapid free delivery, but these appear to be selected for known products only, where there is a cost advantage to using them. When new items are required, most small firms prefer to deal with the local merchants who they have known and been advised by for a long time.

Finally, small firms gain a large proportion of their business through referrals and customer networks, which tend to be locally based. Customer networks may be based in neighbourhoods, or around key social assets (such as a school or a church), or around other shared interests (e.g. a sports club), each of which will have a limited spatial reach.

Opportunities to alter household renovation supply chain dynamics

By examining each of the linkages between the six groups of actors in the household renovation supply chain/network, ideas for how to change the dynamics of those linkages emerge. Here' the idea of "middle actors" helps us see possible relationships which are not clearly visible in a linear supply chain. In making such possible relationships visible, we also open up the possibility of changing the way in which those relationships function, and thus altering the outcomes or impacts of the network delivering RMI activity.

While there are 15 potential linkages, each of which might theoretically have influence in both directions, that possible list of 30 relationships along which innovation might diffuse can be quickly reduced by a pragmatic assessment of where innovations might arise and therefore which linkages might apply selection pressures and enable or constrain the transmission of that innovation. Table 1 sets out the linkages being explored as the first stage of mapping the selection pressures affecting the diffusion of energy innovation in RMI. This subset then helps us focus on which relationships might be altered in order to achieve more energy efficiency outcomes from RMI, and leads, for example, to the opportunities outlined in Table 1.

The four opportunities below are not proposed as an exhaustive set of solutions, rather they illustrate how focusing on a particular linkage and thinking about what is important about that connection in terms of allowing an innovation to reach a RMI project, and then be repeated in a future project, allows new ideas to reconfigure the supply chain network to emerge.

OPPORTUNITY 1: MOVE FROM PRODUCT OFFERINGS TO PRODUCT-SERVICE OFFERINGS

This opportunity arises from considering the linkages from manufacturer to merchant and on to the construction firm, influenced by policy making institutions. This supply chain innovation changes the nature of what the product manufacturer design and supplies, and what the wholesaler offers e.g. a shift from selling a material to selling a service that delivers a warmer home. This would also mean moving away from costs based on quantities of material or equipment, towards costs based on the services offered e.g. paying to have a warm home maintained, rather than paying for the capital cost of a domestic boiler. This would mean incorporating maintenance and aftercare into the 'product' design and could lead to significant changes in the cost structure of the construction/retrofit industry. Intermediary merchants often provide many of these advisory services to support innovation, and moving towards a cost model based on service might allow the value of that advice to be realised in financial terms. This has the knock on effect of encouraging long term commitment to a customer base, as revenue streams are connected to ongoing relationships. While service offering could be developed to be supported through a merchant's depot or on-line, there is a case for at least some of these service offerings to be location-specific, reflecting both the networks of support and the particular types of buildings found in an area.

OPPORTUNITY 2: DERISK NEW PRODUCTS FOR SMALL FIRMS

This opportunity arises from considering the linkages between construction firm and building user (the firm's client) as influenced by policy, manufacturers and merchants and changing decision making for the construction firm in terms of trying new products. By changing the financial and technical support wrapped around a product, the risks feared by a small firm can be reduced. Specifically, SMEs often fear the financial risks associated with installing new equipment or trying new techniques, which may require additional SME labour, and therefore costs, reflecting the time taken to learn a new technique, or the time to test, install and commission new equipment. The financial risks of increased labour costs, which cannot necessarily be charged to the customer without appearing uncompetitive, are compounded by the risks to reputation and therefore to future workstreams if a new product or technique does not deliver the outcome the customer wanted. If this learning time was subsidised through the supply network, then these risks would be reduced. A technology supplier or wholesaler might underwrite additional time costs for learning, for example, as part of their product.

This approach is distinct from public procurement, where the public sector subsidises learning time through commissioning the installation of an innovation. In our suggestion, the costs of learning are part of the product's marketing costs, subsidised by the supplier (although the cost of the subsidy may be reflected in the cost of the material or service over the longer term). The subsidy need only be applied for the first few installations by a particular contractor. Risk might even be transformed to incentive if the subsidy rewarded rapid learning and trialling of new ideas. Again, this approach might benefit from being

Table 1. Prioritising linkages in the RMI supply network.

Innovation source	Linkages where selection criteria appear most likely to affect innovation diffusion	Linkages where impact on innovation diffusion appears to be weaker; lower priority to analyse
Manufacturers e.g. new product design and development	Builders merchants Construction firms Building users Institutions (policy, accreditation) Natural Environment	
Construction firms e.g. on the job innovation to fix a particular problem	Builders' merchants Customers Institutions (training) Manufacturers	Natural environment
Institutions e.g. policy makers driving innovation by setting outcome standards	Manufacturers Building users Construction firms	Natural environment Homeowners
Building users / homeowners e.g. demanding non-standard outputs	Construction firms Institutions	Natural environment Manufacturers Merchants

targeted on locations where the housing stock had particular technical challenges to be overcome. A similar suggestion was made by heating engineers charged with installing air source heat pumps in rural areas off the gas network as part of an area-based programme to reduce fuel poverty and carbon emissions (Owen et al, 2012). In that case, the heat pump manufacturers were seen as the people with the greatest incentive to increase the capacity of local firms to install their products and the perception of those products varied depending on the initial, and ongoing, support and training offered by the manufacturer to the installers.

OPPORTUNITY 3: PRESENT AND OFFER INNOVATION IN WAYS, WHICH ALIGN WITH MICROENTERPRISE PRIORITIES

This opportunity arises from considering the linkages between construction firms to the building users and to the merchants and changes how products (and services) are designed and what product support is provided. Product design is often driven by technical innovation (what a new material or manufacturing technique can deliver) or regulatory requirements. An example of technical innovation would be promoting a new form of glazing based on changes to float glass chemistry, which changed its thermal properties. An example of regulatory requirements would be the step change to condensing boilers in the UK, driven largely by changes to building regulations (Banks, 2001). If, however, product design started with what the building user wanted (thermal comfort, visual appeal, low cost, flexibility, minimal disruption from installation) and, critically, what the installer wants (reliability, ease of installation, compatibility with other building products and existing infrastructure, compatibility with existing skills and knowledge), then innovation might become appealing, rather than a challenge, and uptake would increase accordingly. In the UK, the slow adoption (admittedly for new build) of pre-fabricated insulated panels for construction illustrates the potential. Once a builder has tried using this technique, which means overcoming the barriers of learning about a new supply chain, they can become advocates for it, if there is a demand from the next client, or if the builder can see an opportunity to deploy the innovation to the client's advantage and increase the builder's precious resource, reputation. The construction techniques used are familiar, the labour cost savings by reduced time on site are significant (labour cots are usually a higher proportion of a construction project than material costs, in domestic work), and the quality of the final built product is appreciated by customers.

OPPORTUNITY 4: ALIGN MERCHANT'S DECISION MAKING ON PRODUCT SELECTION AND ENERGY EFFICIENT RENOVATION

This opportunity arises from considering the selection pressures that the builders' merchant applies in deciding what to make available to the construction firm (the potential innovator). If merchants make different decisions on what they stock that will change what local construction firms are able to deploy. Timely availability of building materials is essential to a cost effective renovation project. Thus what a merchant chooses to hold in stock, and the criteria they use in making that selection, are critical to the range of materials that are used. There may be opportunities to alter the merchants' selection criteria – e.g. number of lines or stock units held, profit margin, supplier payment terms or the availability of 'sale or return' - which mean that energy efficiency renovation materials are the default costing and purchasing decision. Selection criteria that could change might include the number of product lines held, the profit margin on each line, availability of materials on a call-off basis from suppliers, 'shelf life' of materials, payment terms offered by suppliers, and other factors concerned with the history and experience of working with a supplier.

Discussion and conclusions

Building energy use remains a major component of energy demand and associated carbon emissions. Existing buildings need to be retrofitted to near zero carbon standards within the next few decades if international commitments and targets on energy use and carbon emissions are to be met. The focus on end user energy demand in housing is not enough and we need to look beyond the building occupier to the construction supply chain actors who shape what that occupier can or cannot do. The importance of middle actors is starting to be recognised, as they offer potential for change in both incremental and deep retrofit work. Reducing building energy consumption will not happen without engaging the army of small firms and sole traders who work on individual home renovation projects, and, in turn the supply chain network who informs what that army of construction workers does. Renovation work is carried out supported by a supply chain network with many more connections and feedback loops than is suggested by the conventional characterisation of a supply chain as a linear flow of goods and services in exchange for money. In particular, location-specific or location-distinctive responses and interventions are needed in order to reflect the particular characteristics of how innovation is shaped in a given area, depending on building characteristics, social capital, customer/supplier demography, energy availability and other socio-technical factors. By focussing on the motivations and critical success factors for different supply chain actors, opportunities to reshape the supply chain start to emerge. This paper has suggested four such opportunities not as a comprehensive list of possibilities, but as ideas to stimulate further debate.

Two emerging themes will likely be of particular interest to policy makers and energy researchers. Firstly, the fragmentation of the RMI market is a key challenge, and one that cannot be ignored. This is observed when policy introduces new accreditation requirements as a way of improving quality of work and providing some consumer protection. The need for training and accreditation is viewed as an administrative burden, which many firms will seek to avoid. A few firms then take on that burden because it gives them a niche role, which other (non-accredited) firms will pay for. Policy may need to find new ways of steering the industry towards more coordinated outcomes, and here the focus of attention should be on the gaps or 'interfaces' between different firms, different projects and different types of actors in the supply chain network. Given that a fragmented industry response (to fragmented consumer demand) is the reality of the sector, the challenge is to coordinate activity effectively. It seems likely that this will mean a coordination of policy efforts in government departments, notably between those responsible for energy efficiency and those responsible for innovation, education and training.

Secondly, by focusing on the incumbents in the RMI sector, this paper shows that policy for energy efficiency is too narrowly framed at the moment. It has neglected consideration of the selection pressures that RMI actors face, which arise from suppliers, building users and institutions. It is couched almost exclusively in terms of technical and economic potential, with too little attention being paid to delivery of good-quality interventions on the ground and at the scale required to meet energy and climate policy goals. Broadening the frame to take account of supply chain dynamics will involve the energy efficiency community in new fields, engaging with unfamiliar stakeholders, and getting to grips with issues which may seem only indirectly relevant to the policy goals of energy retrofit of housing. Our contention is that this broadening of the frame is key to the development of successful future policy.

In relation to analytical tools and academic theory, the coevolutionary framework outlined in this paper takes forward Parag and Janda's model of middle actors as active and influential stakeholders, and presents the supply chain for an entire industry as a constellation of many such middle actors. Studying the patterns of influence among many different middle actors is a challenge for research: it requires considerable time to engage, and the practical impossibility of engaging more than superficially with a small subset of possible stakeholders has to be acknowledged. At the same time, the study of a supply chain suggests that the work goes beyond the realm of individual case studies, and is perhaps perceived (rightly or wrongly) as being more generalisable. We do not make the claim of generalisable conclusions ourselves, and yet our interaction with both innovators and incumbents provides a contextual richness which descriptions of individual innovations sometimes lack. Equally, one attraction of working with a wide range of supply chain actors is that the research activity itself may catalyse contacts, discussions and actions among our research subjects which would not otherwise have happened.

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