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Making the case for simulation: Unlocking carbon reduction through simulation of individual 'middle actor' behaviour

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Abstract

This paper makes the case for agent-based modelling as a route to unlocking the potential of existing buildings to reduce energy demand and contribute to achieving carbon reduction targets. Attention needs to be on rapid 'retrofitting' of existing buildings so that their net demand falls to near zero. The construction of a model to simulate this system requires significant innovation in data collection and handling. The need to focus on 'middle actors' in construction - specifically the tradesmen who carry out repair, maintenance and renovation - in order to reduce energy demand in existing buildings is described. Despite their apparent potential, middle actors have not been widely studied although qualitative researchers have begun to analyse their actions. The difficulty of analysing the collective impact of individual behaviours in this fragmented sector means that middle actors are overlooked in evidence-based policy development. After identifying this opportunity, the paper considers what modelling techniques are required to describe the possible effects of changes to middle actor behaviour across the construction industry. Having discussed the different types of data needed, the paper uses the 'overview, design, detail' approach by Grimm et al (2006), to describe how an agent-based model might be developed, using rule sets derived from middle actor data. Finally, the types of interventions that might be tested are outlined, indicating how policy and practice could be informed by the proposed modelling approach.

Keywords: energy retrofit; middle actors; construction; agent based modelling; spatial network modelling

1. Introduction

In developed countries there is a significant challenge is to reduce energy consumption in existing buildings in order to reduce energy costs and climate-changing carbon emissions. Around 80% of buildings that will be in use in 2050 are already built and in use (SDC 2006). Changing existing buildings so that they require less energy for their users to stay warm and well, a process termed "retrofitting", is therefore a priority. There has been significant research, into how and why households can change their energy behaviours, driven in part by the prospect of 'smart meters' providing much richer data describing energy use and the desire to understand the potential for that data to change energy demand. The potential to achieve energy demand reductions through ongoing building maintenance and renovation has also been explored, emphasising the need to understand where homeowners see the value of such action (Wilson et al. 2013). However, this paper focuses on how to understand the actions and impacts of a largely overlooked group of actors: the small construction firms and sole traders who implement repair, maintenance and renovation in homes. Finding a way to understand what influences the behaviours of individuals within this large, diverse group would be an important step in achieving significant reduction in carbon emissions from buildings

Currently there are two main approaches exploring the potential for energy demand reduction in homes. Sophisticated technical modelling considers the attributes of individual buildings, existing data on energy performance, the building stock in aggregate and changes to building fabric and appliances and can use epidemiological methods to estimate how low building energy demand can be pushed (e.g. for retrofit specifically, Hamilton et al. 2013, Hamilton et al. 2014) Another strand of work focuses on the individual building user or homeowner as a consumer and uses attributes of the individual to test the importance of various factors and assess the likelihood of energy demand changes. This research typically uses individual psychological framing and attributes (e.g. Abrahamse & Steg, 2009; Kleinschafer & Morrison, 2014) and focuses on how individuals conserve energy in their homes day to day, rather than exploring their propensity to incorporate low carbon measures into repair, maintenance or improvement to their homes. Studies which have explored how and why people undertake energy retrofit (e.g. Wilson et al, 2015; Haines & Mitchell 2014) are yet to scale up their findings to indicate how these factors might be introduced into policy and practice to achieve major reductions in energy consumption.

There is a need to (a) develop evidence for the potential impact of changes in policy and practice to ensure a much greater level of low carbon retrofit, and associated energy demand reductions, in owner-occupied homes, and (b) incorporate the behaviours of the middle actors – small construction firms – into analysis of how low carbon retrofit occurs. This implies a need to collide the technical modelling and psychological analyses and develop a new approach to modelling the domestic energy use system, where all relevant individual actors are represented.

One of the most tractable ways to understand how individuals will react to a situation or set of conditions is through simulation. Simulation allows systems to be recreated and scenarios to be run that allow theories to be both tested and generated. This approach also promotes new understanding of systems through the simulation of new policy interventions. For the problem that this paper focuses upon, such simulations would use existing building/housing conditions and current demography as the base case and then apply scenarios such as universal grant aid to householders, or a step change in the availability of skilled labour, or the mandating of specific technologies. There are several approaches available including microsimulation, choice models and agent-based modelling (ABM). Of these, ABM has rapidly risen in popularity in the last 10 years due to its flexibility and the ease with which individual behavioural rules can be constructed from both qualitative and quantitative data. Applications that focus on understanding behaviour can be found ranging from crime modelling (Malleson et al, 2013) to the spread of diseases such as cholera (Crooks and Wise, 2013). These applications show how ABM can be used to mimic both human decision making and how social networks can be used for the transfer of knowledge between individuals.

Within this paper, we make the case for integrating rich qualitative and quantitative data into a spatially explicit ABM in order to improve the understanding of individual behaviours and their consequences, with the need to reduce energy consumption in existing buildings as the area for applying this approach. In particular, we focus on representing the behaviour of "middle actors" (Janda and Parag, 2013), the builders, tradesmen and installers who implement retrofit actions. Whilst there is an increasing number of residential energy efficiency applications that use ABM (see Rai and Robinson, 2015; Sopha et al 2015; Moglia et al, 2017), these applications only focus on the consumer and do account for the middle actor. Middle actors are a crucial component within these systems operating in local markets and through spatially-constrained networks (Maby & Owen, 2015). Within this paper we outline how the use of an individual-based modelling approach such as ABM has the potential to reduce energy demand from existing buildings, and allows possible interventions to achieving carbon reduction targets to be rigorously assessed.

Section 2 further develops the rationale for the paper, describing the challenge of reducing energy consumption, and the ‘middle actors’ who are essential to an effective response to that challenge. Having argued that this is an important area of policy and practice to explore, Section 3 then describes how the principles of ABM make it a powerful tool to test interventions in the system of existing buildings, considers what datasets might be used to build models and discusses the challenges of calibrating and validating such models. Section 4 suggests how models might allow a range of interventions in policy and practice to be tested in order to develop an effective policy mix. Section 5 discusses the proposed approach, and shows how it might also be applicable to other aspects of the built environment and potentially, to other complex systems.

2. Context: Why is energy use in buildings important? Who and what affects levels of energy use?

Approximately one third of energy use in the UK can be attributed to buildings of which the largest proportion (more than 25% of final energy consumption in 2014) comes from residential buildings and home energy use (DECC 2015). The UK has committed to carbon reduction targets, underpinned by statute the Climate Change Act, 2008. Some sectors are more able to make carbon reductions than others and this is reflected in the variable sector targets to achieve the overall goal, with the effect that nearly all UK buildings need to be ‘zero carbon’ by 2050 (DECC, 2011). This presents a significant step-change from current practice, a change that can only be achieved by innovation across the whole system of energy and existing buildings.

In the UK, there are two main categories of housing: rented and owner-occupied, with private owner-occupied homes nearly two thirds of the total of UK residential properties (ONS, 2015). Rented accommodation is further divided into private rented (with many landlords, typically each managing a small number of properties) and social housing which is rent controlled and usually area-based, typically with large numbers of properties managed by each landlord. Social housing providers have made most retrofit progress, responding to pressures to improve tenant well-being through improving housing conditions as well as reducing domestic bills. These “registered social landlords” often own and manage thousands of homes and are thus able to achieve economies of scale through contracts which systematically improve building fabric (RE:NEW et al, 2015). The dominant focus has been “fabric first”, tackling issues of building envelope, insulation, double glazing and effective heating controls. The drivers, and rewards, as well as the means of delivery for low carbon renovation in owner-occupied homes are different to that in social (rented) housing. In private homes, action takes place in a single home, or even a single room, and is usually carried out by one of the thousands of small, local construction trade businesses – key ‘middle actors’.

One area of energy consumption research that has received considerable attention is individual occupant behaviour. As Janda (2011) comments “buildings don’t use energy, people do”. Occupant behaviour is increasingly well understood in terms of motivations and technical constraints (Wilson et al, 2015), habits (Marechal, 2010), and social practices (Shove, 2010).

There is tremendous scope to reduce the energy demand of existing buildings through work which is not currently defined as low carbon, but which could contribute to low carbon targets if low carbon practices were mainstreamed into construction. Approximately £11bn per year is spent by UK homeowners on repair, maintenance and improvement of existing properties – this includes renovation, upgrades and extensions (Maby & Owen, 2015). Homeowners' desired outcomes from renovation are likely to be linked to lifestyle improvements – more space, better organised to fit with residents' lifestyles (Maller et al., 2012). If repair or renovation activity delivered low carbon retrofit at the same time as the desired improvements in building function, using the existing investment in property, reductions in home energy consumption could be accelerated significantly.

The importance of the builder and installer in achieving low carbon buildings through renovation and improvement is starting to be recognised (Owen et al, 2014; Owen & Mitchell, 2015; Killip, 2013). Small and medium enterprises (SMEs) of less than 50 people, as well as sole traders and micro-enterprises (three people or less) are the main agents for RMI work in private homes. This is not a small group of actors. UK estimates based on 2014 data are that there are around 330,000 (around 1% of employment) people working in 120,000 small firms in the residential property areas of the construction industry and, of these, around two thirds of these are sole traders (Maby & Owen, 2015). Importantly for the proposals in this paper, most of these small firms operate over a limited spatial extent. Understanding the individual builder or installer who carries out RMI work, together with the drivers and consequences of their behaviour, is a crucial piece in the retrofit picture and a vital, overlooked element of achieving carbon emission and energy consumption reduction.

3. Why agent-based modelling?

Having established the importance of the behaviours of individuals in small construction small firms for energy use in buildings, and the need to understand the cumulative impact of the behaviours of these individuals, we turn now to considering how agent-based modelling (ABM) is an appropriate tool to respond to that need. At the very core of ABM is the individual. Through ABM, individuals are ‘created’ and assigned unique behaviour and relationships. Typically, behaviour is derived from in-depth analysis of both quantitative and qualitative data sets. A ‘population’ of agents can be entirely homogeneous i.e. each agent exhibits the same characteristics and behaviour, or each agent can be unique. This ‘bottom-up’ representation allows new knowledge and behaviours to emerge from interactions between the agents (see Crooks and Heppenstall, 2012 for a detailed introduction). An attractive aspect of ABM is its ability to represent individuals and their relationships across different spatial scales, giving them the ability to learn, evolve, and make decisions adaptively in both space and time. Through representing individual decision-making and interactions, the researcher can examine the consequences of a range of different policy options and potential changes to practice, driven by individual decisions and interactions that have been informed and shaped through their social (and professional) networks. As Batty (2012) remarks, use of ABMs therefore gives rise to a more heterogeneous approach that could reflect the richness and diversity of reality.

Figure 1 shows the structure of a simple ABM. Here an agent (in this case a builder) is given ‘life-stage’ attributes of age, sex, wealth and education. This is drawn from quantitative data such as the UK Census. Any number of characteristics could be used depending on the application, as well as any appropriate data set. Attitudes or behavioural characteristics are drawn from more qualitative data sources, such as surveys or interviews. Bringing together these seemingly disparate data sources results in a more holistic view of the individual, and their likely decisions, than previous methods have been able to achieve. Agents can also be potentially linked together through their social networks (if data is available) thereby allowing knowledge to diffuse through those networks.

FIGURE ONE HERE

Figure 1: Schematic illustrating how agent attributes and behaviour can be constructed from different types of data.

Within the literature there are numerous examples of ABM simulating a small aspect of human behaviour. These range from simulating the behaviour of how pedestrians move through time and space (Torrens, 2012); urban residential choice (Huang, 2014); susceptibility to disease e.g. cholera (Augustijn-Beckers et al, 2011) and human behaviour in reaction to a natural disaster (Crooks and Wise, 2013). As noted earlier, ABM is starting to emerge as a popular tool for simulating the uptake of different residential energy efficiency measures by consumers (see Rai and Robinson, 2015 and Sopha et al 2015). Moglia et al. (2017) performed a comprehensive review of the use of ABM within this area; whilst every application focused on simulating consumers, middle actors were entirely absent. What these applications do show is that the success of using ABM's to simulate individual behaviour is highly reliant on the availability of individual-level data not only for constructing the agent's rule set, but also for calibrating and validating their resulting behaviour and actions. Fortunately for researchers we are now in the midst of a ‘digital era’ with an abundance of “big data” potentially at our disposal. Much of this data is available at the individual level. “Big data” includes large established data sets such as census, construction industry data collated by national government through the Office of National Statistics (UK), planning application data and VAT returns as well as new datasets such as mobile phone records, ‘smart’ energy meter outputs, travel-card data and loyalty card data, including the types of data collected by builders’ merchants. By careful mining of these data sets, we are able to drill below the level of large aggregate datasets to detailed individual behavioural data that provides a richer picture of activities and effects.

4. Proposals for model design

In the following section, a description of the model is given based on the Overview, Design concepts and Details (ODD) protocol by Grimm et al. (2006). As we are making the case for this approach as a valid response to a real-world problem (energy consumption in buildings), this is a conceptual model and we present only those details that are important for constructing the model. These details are presented for the purpose of showing the utility of ABM in simulating interactions and behaviours within this research area.

Overview

Purpose: The purpose of the model is to experiment with the behaviour of middle actors in order to gain a better understanding of the cumulative effects of the decisions of the agents i.e. what emerges from the interactions. Through this we can uncover which factors influence installers to include low energy techniques in their work in the repair, maintenance and improvement of existing homes. The aim of the ABM would be to answer research questions such as

- To what extent can changing middle actor behaviour contribute to achieving reductions in carbon emissions from the existing building stock? or
- What factors affect the effectiveness of policy interventions in changing middle actor behaviour and energy demand reduction?

As with any model, simplifications and assumptions have been made to distill the complexities of the system into a tractable problem to be modelled (Batty and Torrens, 2005).

State variable and scales

The model will focus predominantly on the uptake of retrofitting within a population of buildings and occupiers. To gain a greater understanding of the role that the construction worker or installer – the middle actor - plays within this system, 'softer' factors such as experience and reputation are incorporated.

Figure 2 diagrammatically represents the structure of the system to be simulated in terms of agents and networks (relationships). There are five types of agent that will be represented within the model: the *installer*, *building*, *householder (customer)*, *householder (non-customer)* and *supply merchant*. Buildings have fixed locations and are allocated to householders. All agents are instantiated with different attributes that contribute towards their heterogeneity. Agents differ in their personal characteristics (e.g. age, sex, or type of building), social ties (e.g. householders who have experienced retrofit, installers have different links to supply merchants) and goals and priorities (see section on Goal Selection below).

FIGURE TWO HERE

Figure 2: Schematic representation of the networks and agents to be represented in the model. A represents a household agent (customer); B a household agent (**non**-customer) and C a house agent. Other agents are the installers and suppliers. Networks to be accounted for are represented by the dashed lines.

Behaviourally, agents are purpose-orientated. They determine a specific activity (goal) at a given time, depending on their priorities, and move towards it. This model is spatially explicit, relationships and access to resources are constrained by space. For example, a small firm or sole trader installer based in a location will typically work on jobs within one hour's drive of the base location, with this range varying slightly depending on the cost of fuel and personal circumstances such as the need to be able to collect children from school (Maby & Owen, 2015). Equally, the small construction firm will usually rely on a merchant who will offer free delivery of materials within some radius of the merchant's retail location.

Householders (non-customer) who have not engaged with retrofitting have a propensity to take this up based on their building type, socio-economic factors (education, income) and whether any of their connections have had positive of experience retrofitting. This positive experience for householders (customers) is based on the one of the capacities of the installer. This is an essential part of the model, innovative in how softer qualitative factors such as experience and competence are incorporated into the installer agent. The level of different 'capacities' of the installer agent is the main driver of uptake of whether low carbon considerations feature in retrofitting activity within the system. The capacities of an installer in terms of their motivation to delivery low carbon retrofit, their technical ability to do so, and their ability to adapt the solutions they offer in light of a household's needs and constraints are all important variables that affect whether or not a repair, maintenance or improvement project becomes a low carbon retrofit fit project (Owen et al, 2014). The installer's capacities will shape and filter both the options presented to the householder client, and the way in which the project is delivered, with an impact on final energy consumption by the household after the project is complete. For example, an installer who has a low 'low carbon' motivation may believe that cost is the only consideration for a potential householder client and if the installer also has a low level of adaptability they may not identify other prompts that suggest a client is interested in factors other than cost.

The other important component of this model is the environment which needs to cover a sufficiently large area to capture the installer–supplier networks, the networks of complementary trades which need to collaborate to deliver a retrofit project, and the social networks which are important in generating work for installers together. There are four important types of network that need to be considered as shown in Figure 2 above (Owen, 2015). *Intra-trade networks* are those between firms who might compete for similar work; these networks are important in setting the local norms for performance of a building after work has been carried out. *Inter-trade networks* are those where different specialists routinely undertake projects together for example, a builder will often have a preferred electrician, heating engineer, plasterer and roofer. *Social networks* are vitally important for the small construction firm in winning work. Again, the norms and expectations of a social network in a particular area will set the standards for how much low carbon retrofit is part of standard practice. The *supply chain network* in an area can enable or constrain low carbon retrofit by choosing whether or not to stock relevant materials and technologies. Each of these networks is, in turn influenced by further networks at different spatial scales. For example, the local builders' merchant that is the focus of the local supply chain network may be part of a national chain where stocking decisions are made based on non-local criteria such as supplier discounts or credit practices. At the heart of all these different networks is the individual. Their behaviour can have a significant impact on that of others, most pertinently in this work, the likelihood of low energy retrofitting in a given property.

Process overview and scheduling

The way in which the model treats time in the simulation will follow multiple tracks. We suggest starting with a timeframe associated with individual properties. A household's propensity to decide to undertake a retrofit project is divided into two categories. Every ten years, the propensity to undertake major retrofit, such as building additional space, or converting a loft or basement, or installing a completely new heating system, is evaluated. This reflects what is known about the duration of owner-occupier tenure in the UK, and the frequency of life-events which trigger demand for major changes in how space at home is configured (such as birth of a child). Within this ten year cycle, every six months the household's propensity to undertake smaller retrofit work, such as replacing windows, improving insulation, upgrading elements of kitchens/bathrooms, is also evaluated. At each evaluation point, a positive decision to start retrofit activity will be informed by a variety of factors including the house's age, location and type, and the household's age, level of education, income and interest in low carbon issues. Finally, the decision to undertake a retrofit project may also be influenced by whether the householder and an installer both participate in the same local, social networks. These social connections lead to trust between individuals, which is a factor in retrofit decision making (Haines and Mitchell, 2014).

Once the decision is made to undertake a retrofit project, large or small, then the decision-making timescale switches to something much more rapid. Typically, the decisions that affect how much reduction in energy demand is actually achieved from the retrofit activity are taken on a daily basis. Thus the propensity to achieve low carbon outcomes from a project will be evaluated each day, and will be determined based on the householder's characteristics, the installer's characteristics (notably their technical capacity and their degree of low carbon motivation), as well as the price and stock availability of materials in the local supply chain nodes.

Design concepts

Observation and Sensing

There are several options for examining model output, ranging from the number of houses that take up retrofit through spend on low carbon retrofit to potential carbon saving. Of primary interest to policymakers is the level of carbon reduction achieved alongside a measure of economic activity in the construction sector. Confidence in the findings of these models is crucial for uptake in policy – while approaches for calibration, verification and validation are not specifically addressed within this paper, any legitimate ABM would address all these issues rigorously using range of methods from AI and spatial statistics.

For a given set of postcodes encompassing a given number of properties of a known size and value (i.e. data sourced from a combination of land registry data and housing statistics) the amount (£) of RMI activity that would take place in a year in that area can be estimated. This baseline RMI activity would probably maintain the level of energy demand in an area, maybe decrease it slightly through some efficiency gains in building fabric. By running the model with changing characteristics in the different agents, reflecting different policy approaches, the differing levels of low carbon outcomes, varying from that baseline, could be simulated.

An important aspect of this model is the external influence on householder behaviour. Capturing and representing the experience of the social network connections of the agents is critical. For example, if a neighbour or friend has a positive retrofit experience, this can increase the propensity for retrofitting in that area, and vice versa.

Details

Initialisation

The initialisation of this type of model relies on detailed geo-demographic and spatial information of the study area (see Rai and Robinson, 2015; Moglia et al, 2017). Parameter values will primarily be drawn from analysis on established data sets or data collated through fieldwork with a synthetic population constructed using microsimulation. Linking in the softer qualitative data at this stage to create specific behavioural rules is a key innovative element of the proposed approach. As highlighted above, defining a study area that encompasses the right number of spatial and social networks is critical. As UK evidence suggests that small firm installers typically work within an area defined by a travel-to-work distance (Maby & Owen, 2015) a small, spatially well defined, town would be most suitable to pilot this approach.

The use of a well-defined spatial area for this type follows the successful work of Rai and Robinson (2015) examining the adoption of residential solar Photo-Voltaic (PV) systems in Austin, Texas (US). Here individual agents (consumers only and not middle actors) were intiailised with city-wide survey data, with attributes such as financial resources, attitudes and social influence included. Social influences occurred over a small-world network structure representing the local peer-network, with the distance between houses considered when assigning the networks. This information was drawn from surveys and this form of data collection could be replicated for simulating the different networks that middle actors and consumers operate.

Inputs/Data

While the case for spatial ABM may be convincing, the issue of whether the data can be gathered that would allow the model to be constructed also has to be examined. In a recent review of ABM and uptake of residential energy efficiency technologies, Moglia et al (2017) highlight a lack of empirical evidence as the biggest barrier of work within this area.

Table 1 presents the different types of data which would need to be collected, to construct an ABM of the building retrofit system, focusing on the behaviours and influence of installers and builders. These data would draw on multiple sources and exist in a variety of formats. Through careful linkage of disparate data types, a detailed picture of individuals and their behaviour could be constructed. Data is assigned to five types of agent: installer, building, household (customer), household (non-customer) and supplier. These agents were chosen on the basis of research examining different aspects of the retrofit process (Killip, 2013; Owen et al, 2014; Owen, 2015; Wade & Shipworth, 2016; Wilson et al, 2013; Wilson et al, 2015). Details of these different agents are presented in the following sections.

Agent	Characteristics	Data source and type
Installer	Base location	VAT registrations or local survey
	Distance travelled for work	Individual data collection / interviews
	Type of trade (e.g. general builder, heating engineer, electrician…)	Local survey
	Number of links to - Other trades - Competitors - Potential customers - suppliers	Individual data collection / interviews
	Preference for using - other trades - suppliers - technologies	Individual data collection / interviews

	Characteristics in terms of capacities (Owen et al 2014) e.g. - motivation - technical competence - adaptability	Individual data collection / interviews
	Financial revenue – related to number of houses worked on and number of measures implemented	Simple economic model based on typical local hourly fee rates and standard costs of measures installed.
Building (home)	Pre-retrofit energy consumption (or energy rating)	English housing condition survey, validated by local sample.
	Location	Postcode data
	Value	Land registry data
	Building type	English housing condition survey
Household (retrofit customer)	Income	Census
	Age	Census
	Level of education	Census
	Interest in retrofit	Survey data, Energy Savings trust monitoring data
Household (not a customer)	Income	Census

current retrofit customer)	Age	Census
	Level of education	Interview / survey data collection via supply chain hubs
	Interest in retrofit	Survey data, Energy Savings trust monitoring data
Supplier (merchant)	Location	Local postcode data
	Range and turnover in retrofit technologies	Local data collection.
	Customer account data	

Table 1: Agent types and corresponding data sets that will be used to build behaviour/rule sets.

Each different dataset will have a set of constraints associated with it. For example, there is extensive data describing the UK building stock although this is fragmented and based on sample interviews and inspections (CLG, 2016). Spatial analysis of this data helps us to understand current patterns of energy demand in buildings, but sheds little light on what drives that demand, and how reductions in energy use might be achieved (Ravetz, 2008). For datasets held by merchants describing patterns of buying behaviour, there are certainly issues of commercial confidentiality. Datasets will also have specific requirements for manipulation before they can be used effectively in a model. The rich qualitative data that provides potential rule sets for middle actor behaviour will apply to only the individual who supplied that data. These rule sets will need to be applied using a probability distribution which triangulates with other datasets and a wider sample in order to generate the characteristics of the population in the model.

Goal selection

Embodying agents with decision-making is notoriously difficult (An, 2012; Kennedy, 2012). Related work has used a variety of different approaches for construction of individual rule sets. Rai and Robinson (2015) used a Theory of Planned Behaviour, Sopha et al (2015) used the Consumat meta-model for decision-making whilst Carrillo-Hermosilla (2006), impeded by a lack of empirical data, formed rule sets based on literature and judgement. There is also a parallel body of work emerging that uses cognitive frameworks to handle individual behaviour (see Crooks, Heppenstall and Malleson, 2018 for a discussion); one of the most promising is the PECS framework (Schmidt, 2002). This has been successfully implemented to simulate the motivations and movements of burglars within a city (Malleson et al, 2013). These are all valid approaches for deriving and constructing rules sets; the differences in approach highlights an important consideration: each system has its own unique attributes and characteristics (influenced by both social and spatial factors), and the purpose of the research clearly influences the approach taken; capturing the unique qualities of the individual driving forces is key. Our approach, which will shape how the rule sets will be informed is to use a combination of using industry expertise and qualitative data to distill the behaviour down into the simplest possible rules that retain the main goals and purpose of this work.

Goal selection: installers – the primary aim of the installer is focused around profit optimisation, not maximisation, relatively few SMEs in the construction industry are growth orientated (Maby & Owen, 2015) as well as retaining customer good will. Satisfied customers offer repeat work or connect to further work through social networks due to ‘word of mouth’. This means that for the installer, there is no need to expend resources on winning work. Additional goals might include keeping turnover below the VAT threshold to avoid additional activities of financial reporting and accountancy costs. For these small businesses, minimising stock held and working capital is likely to be key.

Goal selection: suppliers – the goals of the suppliers will be driven by profit maximisation (to achieve this, they will select particular sets of products and suppliers / manufacturers that they believe match local market conditions including level of activity, type of building stock etc.). For the suppliers, a key of their profit maximisation strategy will be managing stock carefully.

Goal selection: householders (customers and non-customers)– for these agents, the primary motivation is to achieve wellbeing goals such as increased usable space, improved aesthetic or comfort from home and affordable warmth (Shove, 2010; Maller et al, 2012). A secondary motivation is to improve the energy efficiency of how they use the building (and this may have a proxy of a motivation to reduce energy costs). Previous research has attempted to model household energy and pro-environmental behaviours through the Theory of Planned Behaviour (Ajzen, 1991) and its variants, including the Triandis model which was adopted by UK energy policymakers for a period (POST, 2012). Other researchers have used a value-belief-norm model (Stern, 2000) in order to incorporate the values that individual consumers hold into an understanding of when particular consumer behaviours are activated. These frameworks all fall in the broad category of ‘expectancy value models’ where a set of antecedents lead to action, which appears to be an area which aligns with the needs of the modelling approach proposed here.

Goal selection: building – The UK government has the aim to be zero carbon by 2050. The main goal of the building is therefore to be net zero carbon emissions 'in use'. The level of carbon footprint that each building has will be calculated based on factors drawn from type of house, materials and type of retrofit. The main goal of the buildings is to increase energy efficiency of fabric and increase renewable energy generation.

4. What interventions could be simulated and tested by an ABM?

To inform model development, and to provide some motivation for overcoming the challenges of constructing a model which can simulate effectively individual behaviours and system outcomes from the complex system of building repair, maintenance and renovation, it us useful to explore the potential value of such a model in developing and testing scenarios. We present here three ideas for interventions in repair, maintenance and renovation activity which might be simulated if an ABM model was constructed using data representing the populations of households, tradesmen and property types in a specified area. These illustrations of how the model might be used to simulate and test policy changes provides a final element in our justification of the usefulness of the proposed modelling approach.

a) A known barrier to introducing low carbon considerations into building renovation is the reluctance of small firms to innovate because of the high risks to their income and reputation that they face if the innovation does not work as planned and requires additional commissioning work or rework (Maby & Owen, 2015). If the costs associated with this risk were carried by the technology or materials provider i.e. they underwrote the tradesperson's additional time when first installing an innovation, then that barrier might be eroded. This could be simulated by changing – in the model - the costs and the distribution of the costs of low energy technology, including installation. This means that different levels of subsidy could be tested to understand the level of subsidy that was most cost effective in achieving carbon reduction goals and property improvement outcomes.

b) As well as the potential additional costs incurred by tradespeople in installing new technologies or using energy saving techniques, the tradespeople's own lack of experience, confidence and knowledge is a barrier to them undertaking work with the financial implications described in (a). An ABM could run a simulation with a variety of skills attributes (and accreditations) for the local population of tradespeople. If skills are upgraded in a specific trade, or a specific technology, or in a project process such as team communication, which has the most impact on tradespeople's income and on the energy consumption of buildings in the area modelled?

c) The two factors outlined above – financial risk and technical knowledge for the tradesperson – are also reflected in customer reluctance to trust tradespeople to deliver cost effective work that meets the household's aims. As identified in the 'Process Overview' section above, trust in installers is known to be a vital element of enabling low carbon retrofit work to be accepted by householders (Haines & Mitchell, 2014) and for low carbon issues to be considered at all (Sleeth-Keppler et al. 2017). Accreditation is seen by policymakers as a simple way to signal that a firm or person will deliver to expected standards and therefore increase trust. However, accreditation is usually seen as an administrative burden with little benefit in terms of winning work by the tradespeople in small firms (Maby & Owen 2015). Different types of accreditation for different skillsets or geographies could be simulated and the combination which leads to changes in renovation work done and carbon emissions reduced could be identified.

5. Discussion and Conclusions

Slow progress towards carbon reduction targets suggests that the focus to date on technological measures and on energy consumer behaviours are not enough to achieve statutory carbon reduction goals.

Policy and practice need to reflect the complexity of the retrofit systems in particular, recognising the influence of key actors such as the small construction firm, and also allowing for localised policy mixes. What works well in one town or city may not be easily transferred to another area where housing stock, demography, social networks and supply chain configurations are different.

While, in the UK, there is extensive technical modelling to understand what retrofit actions are feasible in buildings, and there is also significant research into understanding householder behaviours, there is currently no modelling which takes account of the influence of the key middle actors, installers and builders who implement building repair, maintenance and renovation which could result in reducing energy demand from existing buildings

Simulations need to be able to reflect a variety of timescales. Whilst it varies reflecting economic cycles, the typical length of private household occupation in the UK is at least ten years (ONS, 2011) with key points for changing the property fabric (and therefore household energy use) coming at the point of moving in and then with subsequent changes in household size and age. The opportunity to change household behaviours has been documented in terms of travel behaviours (Schafer et al, 2012) and drivers for household retrofit are often associated with a desire to change how a property's space is used following, for example, the arrival of a new child, or changes in intergenerational living (Hand et al, 2007; Maller et al., 2012). Thus the specific temporal windows to make low carbon retrofit changes to a home will be limited. In addition, building repair or renovation projects are themselves time bound. Small scale repair and maintenance work may be specified and implemented within a few weeks, drawing on existing reserves of installer knowledge and likely to use materials and products easily accessed through known sourcing routes. Larger projects such as extensions or reconfigurations may have a more iterative process of design and installation, potentially allowing for more learning about low carbon options as the project develops. The amount of learning, for both the client/homeowner and the installer, will be constrained by the other goals in play, such as cost limitations, and the existing reserves of knowledge capital and how these can be changed through training and development.

The spatial considerations in designing the models which will run useful and effective scenarios are also complex. We argue here for a model which represents a localised systems, covering an urban neighbourhood or small town (in the UK, a population of 15 – 20 000) which appears to be the scale at which the installers' networks operate and intersect with the social networks which generate business and the inter-trade networks which allow projects to be delivered. This would allow the agents in a model to be assigned distinctive attributes that reflect an area's physical and economic geography as well as its demography.

In this paper we set out what is needed to allow spatial network modelling of construction industry actors in order to generate appropriate and effective mixes of policy and interventions. We suggest that ABM, with rule sets informed by rich and qualitative data describing practices and social/professional networks, would allow innovative policy and interventions to be assessed.

Whilst ABM is flourishing as a discipline, many of the applications abound in the research literature have rule sets (behaviour) that are powered through quantitative data sets. The nature of these data sets are beginning to change with the advent of 'big data', but there are still few examples that derive rule sets from both qualitative and quantitative data – an issue highlighted by the recent review of Mogala et al (2017). The incorporation of qualitative data is essential to increase the realism of the representation of behaviour within these models. However, constructing rules from these types of data presents its own set of challenges namely how do we accurately translate qualitative information into more quantitative rules that the agents can operate without losing the essence of the behaviour? One possible avenue worth investigating is that of fuzzy logic (see Al-Ahmadi et al, 2009 for an example) a method that can bring a notion of randomness/indecision into the operation of the rules and has not been used in this area before.

Embedding fuzzy logic within ABM would represent a step forward in methodological innovation, however the proposed approach would also promote other methodological innovations driven by the availability of new individual levels of data. These include developing robust methods for identifying different types of processes (behaviour) emerging at different spatial and temporal scales. One of the areas where ABM is particularly open to criticism is that of calibration and validation – here big data can help in developing new approaches that build a strong level of confidence in the results of the ABM. It is this lack of robustness in the evaluation of ABMs that is one of the central reasons that ABMs have made very little impression within the policy arena. Reducing energy consumption and associated carbon emissions is an important policy area – and with rigorous calibration and validation, this approach could be an important example in how ABM can support an effective evidence base for policy.

For this type of work to be successful, expertise needs to be drawn from a number of disciplines. The qualitative researcher needs the expert modeller to expand the reach and impact of their small-scale data sets, the expert modeller needs the qualitative researcher to give the rule sets richness and validity that makes the model more effectively representative of the complex system bring described.

In addition, there are other policy areas where supply chains are fragmented, relationships are complex, motivations are mixed but a change in system outcomes is required. One example is promoting active travel (walking and cycling) which is dependent on both physical infrastructure, system norms, individual equipment, as well as individual decisions based on habits and perceptions. Another example might be the desire to change agricultural practices to encourage more sustainable outcomes rather than optimising a system for production in the short term. In this case, the key actors (farmers) take seasonal decisions based on a complex set of social, financial, technical and learning factors. A third area is educational attainment, given the importance of networks of learners, teachers, parents and peers and the impact of neighbourhood effects and demography.

In conclusion, this paper suggests that trialling ABMs including middle actors in the construction industry could reveal policy and practice opportunities which will support low cost changes to our building stock, ensuring we meet carbon targets. Successful exploration of this area could provide a template to transfer to other intractable areas of policy development.

Could understanding key individuals – the installers and builders who work in homes - be the key to unlocking not only the potential of carbon reduction from retrofit, but also the potential of ABM to simulate complex systems where we need to make system changes?

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