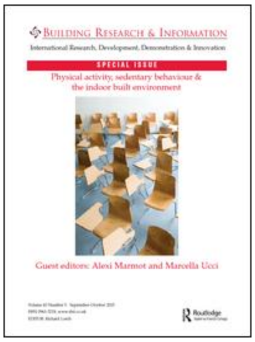

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Participatory system dynamics modelling for housing, energy and wellbeing interactions

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ABSTRACT
The built environment is a key target of decarbonization policies. However, such policies often have a narrow objective and narrow focus, resulting in 'policy-resistance' and unintended consequences. The literature attributes these unintended consequences to a narrow financial focus, adverse incentives, and inadequate handling of knowledge, skills, communication and feedback gaps, but it provides little advice on how these complex interactions can be captured. This paper illustrates the development and application of an integrated approach to address these complex interactions with regard to housing performance, energy, communal spaces and wellbeing. In particular, it explores the dynamics created by these relationships with simulation modelling in participatory settings, and with a diverse group of stakeholders. The simulation results suggest that monitoring is key to improve the performance of the housing stock besides energy efficiency; and investments in communal spaces positively affect the adoption of energy-efficiency measures and the wellbeing of residents. The evaluation results for participatory workshops show this approach was found useful by the stakeholders for supporting more integrated decision-making about housing. In future research, this approach can be implemented for policy problems in specific contexts.

KEYWORDS
energy efficiency; housing policy; public policy; simulation modelling; stakeholder participation; system dynamics; wellbeing

Introduction

Decarbonizing the built environment by decreasing its energy consumption has been a major goal of climate change policies in the UK. The residential sector is expected to make the largest contribution to total UK energy savings (40%) in 2020, and the second largest contribution in 2030 (30%) after the transport sector, and is expected to increase its contribution significantly in this 10-year period (DECC, 2015). Relevant interventions include the now-scrapped 'Green Deal' that aimed at stimulating the energy-efficiency refurbishment of existing buildings through the provision of loans and the national building regulations that set minimum energy efficiency requirements for new buildings (Nejat, Jomehzadeh, Taheri, Gohari, & Abd. Majid, 2015; Shrubsole, Macmillan, Davies, & May, 2014). For a more extensive review of home energy efficiency policies in the UK, see Mallaburn and Eyre (2014).

Besides reducing household consumption, energy-efficiency policies can potentially lead to considerable benefits for population health, *e.g.* increased thermal comfort and fuel poverty alleviation. Positive effects on occupants' physical and mental health have been investigated in several studies, based on self-reported health measurements (Gilbertson, Grimsley, Green, & Group, 2012; Gilbertson, Stevens, Stiell, & Thorogood, 2006), modelling studies (Hamilton et al., 2015; Wilkinson et al., 2009), or meta-analysis (Maidment, Jones, Webb, Hathway, & Gilbertson, 2014). However, if not implemented correctly, energy-efficiency interventions may result in negative unintended consequences, such as reduced indoor air quality, increased fuel poverty or a failure of the primary aim of the policy (Davies & Oreszczyn, 2012). Such consequences also manifest in economic, social and natural settings beyond the built environment. For instance, Gupta and Barnfield

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(2014) describe several unintended consequences related to occupant behaviour, such as the inappropriate operation of low-carbon systems or opening windows during heating, whereas Agbota (2014) reviews the adverse effects on the fabric and aesthetics of historic buildings. Shrubsole et al. (2014) provide a comprehensive overview of such unintended consequences affecting the built environment, population health and environment.

Energy-efficiency policies also encounter strong resistance, mainly in the adoption of policies for stimulating the refurbishment of the existing housing stock. This resistance is attributed to an inadequate design of incentives primarily due to a narrow, financial focus (James, 2012; Marchand, Koh, & Morris, 2015), or psychological and social barriers (James, 2012) such as lack of trust in the building industry (Weeks, Delalonde, & Preist, 2015). Furthermore, the performance gap in the construction industry's practice is another barrier to the success of energy-efficiency policies (Burman, Mumovic, & Kimpian, 2014; Oreszczyn & Lowe, 2010; Wingfield, Bell, Miles-Shenton, South, & Lowe, 2008). Causes of this gap include lack of knowledge and skills, ambiguity over responsibilities, lack of communication, and lack of feedback from post-occupancy to the design stage within the industry (van Dronkelaar, Dowson, Spataru, & Mumovic, 2016; Killip, Fawcett, & Janda, 2014; Menezes, Cripps, Bouchlaghem, & Buswell, 2012; Pan & Garmston, 2012).

These unintended consequences and policy resistance illustrate the complexity that extends beyond the fabric of the housing stock. To deal with this complexity, an integrated approach, systems thinking, is suggested for both research and decision-making (Davies & Oreszczyn, 2012; Shrubsole et al., 2014). This approach should accommodate both technical aspects (energy efficiency of the building fabric, indoor air quality *etc.*), as well as non-technical aspects (thermal comfort, occupant behaviour, health and wellbeing of occupants, and organizational challenges). Moreover, as Schweber and Leiringer (2012) conclude, current building and energy research is missing interpretivist approaches that can investigate the processes, understandings and motivations of stakeholders, which lead to observed problems and system behaviour. They suggest integrative approaches be used more intensively in building and energy research, especially in combination with systems modelling.

Systems modelling has been implemented in several studies to capture the complexity of household energy consumption and to estimate the future consumption values and related CO_2 emissions (Kesicki, 2012; Motawa & Oladokun, 2015; Natarajan, Padget, & Elliott, 2011). However, focusing only on emission reduction, these studies lack a multi-objective view; and empasizing only technical and economic aspects, they also lack a multidimensional view.

Macmillan et al. (2016) present a systems thinking and modelling study that adopts a multidimensional view and aims at investigating the links between housing, energy and wellbeing in the UK. Expanding the building and energy research to interpretivist approaches, their study follows a participatory system dynamics (SD) modelling methodology. It utilizes interviews and workshops in order to collect information from stakeholders and to facilitate their learning. The resulting qualitative SD model of Macmillan et al. is a diagrammatic representation of the complex relationships within and between seven themes: community connection, energy efficiency, fuel poverty, household crowding, housing affordability, land development and indoor air pollution. Following this qualitative model, Macmillan et al. point out that 'strategic small pieces of (quantitative) simulation modelling' (p. 33) would enable the testing of different assumptions, and of understanding the relative importance of different feedback mechanisms and the dynamic behaviour they generate over time.

The objective of the present paper is to combine such a quantitative simulation modelling study and an interpretivist approach carried out with the participatory SD modelling method in order to demonstrate a multi-objective and multidimensional view on the housing, energy and wellbeing aspects of the UK's housing stock. The development and use of this simulation model employed participatory tools through a series of stakeholder workshops. The purpose of the model is to serve as a virtual environment where model users can test various assumptions and explore future scenarios generated by the relationships between housing, energy and wellbeing. This paper discusses the modelling results and the participatory process of creating and using the model along with integrating different sectors and actors.

The paper is structured as follows. The next section elaborates on the participatory SD approach. This is followed by a brief description of the simulation model. The simulation results are then presented for particular scenarios. The penultimate section discusses the implications of this study for research and policy. The paper ends with conclusions and future research potential.

Methods

This study adopts an SD modelling approach to capture the complexity of the interactions between housing, energy and wellbeing in an integrated manner. This approach is well suited for better understanding of the causal mechanisms that generate the behaviour we see in different scenarios, and for conveying these insights to non-modellers. Furthermore, to address the need for more interpretivist approaches in building and energy research, a participatory modelling process has been opted for. This section first discusses the (participatory) SD method in general and then describes the process followed in this research in particular.

System dynamics (SD)

SD is a modelling methodology for analysing and understanding the behaviour of dynamic complex systems (Sterman, 2000). It originates from Jay Forrester's work (Forrester, 1961, 1968), which combined the concepts and tools of cybernetics, control engineering, organizational theory and information technology and applied them to long-term, dynamic socio-economic problems (Meadows, 1980). A main characteristic of the SD methodology is causal feedback thinking. This involves conceptualizing a system based on closed chains of these relations (Richardson, 1999). These closed chains, or 'feedback loops', together with the nonlinearity between its elements, create the complex dynamics of the system. By modelling the feedback loops and analysing the behaviour over time, a rich understanding of the system underlying a policy problem can be developed. Mathematically speaking, SD is based on integral equations, where variables that accumulate over time are represented by 'stocks' and the rates of change in these stocks are represented by 'flows'. Hence, simulating a model is equivalent to integrating the flow equations.

SD has long been used to address complex problems in the housing sector. Forrester's *Urban Dynamics* (1969) is one of the early renowned SD works that addresses urban growth and decay. Later SD works in the housing sector focus on the effects of urban development on the social housing market (Eskinasi, Rouwette, & Vennix, 2009) and the dynamics of housing markets (Eskinasi, Rouwette, & Vennix, 2011; Özbaş, Özgün, & Barlas, 2014) from a policy perspective. From an industrial perspective, the subjects addressed include: the building supply chain (Hong-Minh & Strohhecker, 2002), competitiveness in the construction industry (Gilkinson & Dangerfield, 2013; Peace, Dangerfield, Green, & Austin, 2010), project management (Park & Pena-Mora, 2003; Parvan, Rahmandad, & Haghani, 2015), and building design and operation (Thompson & Bank, 2010).

The SD approach has also been used for problems related to the decarbonization of the housing stock. These studies mostly focus on the diffusion of energy-efficiency measures in the existing housing stock and capture the core relations between the energy benefits and costs of energy-efficiency measures (Blumberga, Blumberga, Bazbauers, Zogla, & Laicane, 2014; Müller, Kaufmann-Hayoz, Schultheis, Schwaninger, & Ulli-Beer, 2013; Yücel, 2013). However, the interactions between this energy–economy subsystem and occupant wellbeing or other social factors have not yet been examined.

Participatory SD modelling is an approach that involves stakeholders, experts and clients in various phases of the modelling process. Group model building (GMB) is a specific participatory method that emphasizes the value of directly involving stakeholders in the model development *process*, in addition to the resultant simulation model (Forrester, 1985). In this way, model variables, causal relationships, parameter values and nonlinearities can be elicited from stakeholders with diverse backgrounds. This *process* enables the generation of a rich dynamic hypothesis, and supports model validation as well as shared learning (Vennix, 1996). Participatory sessions are usually structured with the help of GMB scripts (Scriptapedia, 2017). Scripts are best-practice examples for eliciting variables, causalities *etc.* that serve as building blocks for a workshop, including action and responsibility plans. Stakeholders have been involved in participatory SD studies on topics of energy transitions (de Gooyert, Rouwette, van Kranenburg, Freeman, & van Breen, 2016; Ulli-Beer et al., 2017), city resilience (Xing, Lannon, & Eames, 2014), residential energy efficiency (Elias, 2008), and social housing market dynamics (Eskinasi et al., 2009).

GMB has been structured and scrutinized over time and across several studies in order to enhance its benefits (Andersen, Richardson, & Vennix, 1997; Andersen, Vennix, Richardson, & Rouwette, 2007; Vennix, Andersen, Richardson, & Rohrbaugh, 1992). These benefits are twofold. First, GMB ensures that the model combines scientific and local expert knowledge about a system by representing a shared understanding of stakeholders (Andersen et al., 2007; Stave, 2010). Second, the benefits of GMB relate to 'meaning-making' by the stakeholders (Zimmermann, Black, Shrubsole, & Davies, 2015), which can be defined as an alignment process by which the stakeholders develop shared knowledge, understanding and meaning through mutual interactions (Zimmermann, 2017). Namely, GMB helps stakeholders in three aspects: (1) to understand a system's structure, *i.e.* the various components and the relationships between them, and behaviour resulting from these relationships; (2) to generate consensus about the causes of a problem or about a decision and commitment to it; and (3) to reduce conflict and build trust to each other (Andersen et al., 1997; Stave, 2010; Zagonel, 2002). As Stave (2010, p. 2766) states, a participatory approach can generate 'shared ownership of the analysis, problem, system description, and solutions or a shared understanding of the trade-offs among different decisions'. In other words, it can guide not only model-building but also the conceptualization and policy-testing stages of a modelling study. Following this view, this study adopts a participatory approach in several stages of SD modelling, as the next section describes.

Participatory SD approach

This study explores the dynamics created by the relationships between housing, energy and wellbeing. It builds upon earlier participatory SD work (Macmillan, Davies, & Bobrova, 2014; Macmillan et al., 2016), which included a diverse set of stakeholders and developed comprehensive causal maps of interconnections between housing, energy and wellbeing. Based on the understanding obtained from these causal maps, and by collaborating with the same stakeholders, this research moves towards simulation modelling in key areas that relate to the fragmentation of the built environment beyond qualitative causal maps but still with a participatory approach. In other words, the novelty of this research, compared with the causal maps developed in the previous part of the project for understanding the system, is the quantitative simulation model developed and used in participatory settings. For an overview of the entire project, see the Housing, Energy and Wellbeing (HEW) Project website (HEW Website, 2016), particularly under 'Group Model Building Workshops', 'Workshop 4' and 'Interactive Simulation Environment'.[1] Figure 1 illustrates the process followed in this study, which incorporates participatory elements in model conceptualization, development and use, as detailed below.

Model conceptualization based on interviews

In order to obtain information about the barriers and stimulants of integrated decision-making in the housing, energy and wellbeing domain, semi-structured interviews were conducted with 17 interviewees from central and local government ($n = 5$), industry ($n = 5$), non-governmental organizations (NGOs) and social landlords ($n = 3$), community groups ($n = 2$), and academia ($n = 2$). Several of these stakeholders are at the same time Greater London residents. The interviews took place around four main questions about: (1) the role of the interviewees; (2) the nature and mission of their organization; (3) their organizational experience with fragmentation or integration in relation to the built environment and housing at the local level; and (4) the personal and organizational delivery framework. The authors analysed the textual data from the transcribed interviews and developed causal maps for the industry, community and policy dimensions, described in more detail by Eker and Zimmermann (2016a, 2016b).

Group model-building (GMB) workshops

Three GMB workshops were conducted with small groups of participants in March and April 2016 on the challenges arising with regards to housing, energy and wellbeing outcomes, due to the lack of multi-objective and multidimensional perspectives. Each workshop addressed a different dimension of the problem: industry

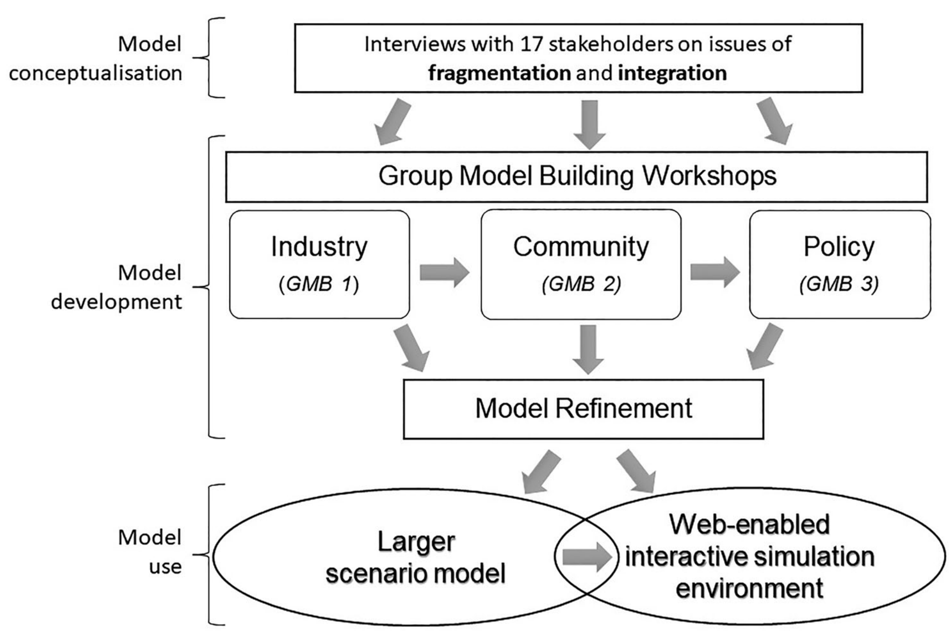

Figure 1. The participatory system dynamics modelling process of the Housing, Energy and Wellbeing project.

(GMB 1), community (GMB 2) and policy (GMB 3). The participants were selected from the stakeholders of the project. The participants of each workshop were diverse, as is recommended for reasons of representation, legitimacy and if the goal is to obtain a holistic view of an issue (Antunes, Stave, Videira, & Santos, 2015; Vennix, 1996). For instance, the participants of the policy workshop were not only from local or central policy organizations but also from academia, industry and NGOs. Therefore, having this diversity within each group helped capture different views on the subject and facilitated the discussion of these differences by the stakeholders towards a mutually agreed model representation.

The team sizes were three, five and seven for the industry, community and policy workshops respectively. Although there is no ideal team size stated in the literature for such modelling sessions, the authors found such small groups appropriate for a fruitful discussion where different views are captured, yet no one is inhibited. Most participants had been interviewed previously in the project or had participated in previous stakeholder workshops. Therefore, they had an introductory knowledge of the project and SD.

Each workshop lasted approximately three hours and involved two main parts. Participants were first provided with a list of concepts related to the session's topic, derived from the previous interviews, which hung on a wall. Following a clarification of these concepts, the participants were asked if they would like to suggest additional concepts. Then, each participant was asked to distribute a certain number of 'dots' to the concepts according to their importance and relevance for the model scope. This confirmatory and disconfirmatory allocation exercise helped us delineate the problem context and model scope.

The second part focused on structure elicitation, initiated by discussing the results of dot allocation, and explaining a 'concept model'. These small and simple simulation models originated from the causal maps we derived from the interviews. Each concept model focused on a core problem element, but deliberately lacked detail. The purpose of using a concept model (Richardson, 2006) was to familiarize the participants with SD modelling, to confirm and disconfirm our thinking around the modelled issue, and to stimulate and structure the discussion when it suspended or diverted. Based on the concept model, structure elicitation in each session resulted in a mix of stock-flow and causal-loop diagrams mostly at a qualitative level. Yet, in some cases quantitative information, such as nonlinear functions and parameter values, was also obtained. Towards the end of each workshop, participants were explicitly asked about connections to the other two problem dimensions of industry, community or policy, so that the interlinkages between the workshops, and the simulation model, could be identified.

Facilitation is an important element of effective group processes (Andersen et al., 2007). In each of the three workshops, the same three facilitators were present. One facilitator moderated the dot-allocation exercise and contributed to shaping the structure elicitation. Another facilitator primarily led the structure elicitation by moderating the discussion and drawing the suggested model structure on a white board, whereas the third facilitator recorded the emerging model structure on a modelling software and occasionally asked clarification questions. The software used for model development and simulations was Vensim DSS (Ventana, 2009).

After each workshop, a visualization of the developed model structure and a brief explanation about it were sent to the participants to ensure that the model represents their knowledge and view as discussed in the workshop. No objections were received to the model structures at this step.

Model refinement

As mentioned above, the product of the GMB sessions was mostly qualitative. The workshops did not impose a high degree of formalism in model co-development due to time limitations and the desire not to obstruct an emergent discussion. Therefore, the model structures obtained from onsite development required an offsite refinement and quantification by the facilitators to be useable as formal simulation models.

Model refinement included (1) linking the three structures obtained from the workshops; (2) eliminating double-counting of any effect or model element if it was discussed with different terms in multiple workshops; (3) ensuring a consistent model scope and level of resolution, even though this required some model elements to be removed; and (4) formulating the model equations and quantifying the parameters. In addition to the data acquired in the workshops, the authors quantified the model with longitudinal data obtained from governmental sources,[2] parametric data from the literature, and qualitative data obtained in the previous workshops of the project about the reference behaviour of particular model variables. The model itself is not specific to a geographical scope and represents a generic problem, yet the data used corresponded to Greater London for quantification, because this was a context relevant for many of our stakeholders and a useful first step. This refinement and quantification process was iterative, ensuring that the model was consistent both internally and externally with the data and expert view.

Model use: larger scenario model

The final model covers industry, community and policy aspects of the housing, energy and wellbeing problem with respect to the quantity, energy efficiency and overall building performance of the housing stock, and wellbeing of occupants related to building performance and communal spaces. The purpose of this model is to uncover interactions across sectors and facilitate the exploration of internally consistent scenarios and system understanding, rather than serving as a decision-support tool directly.

The elements of this model and its results were presented in a stakeholder workshop held in June 2016 with 16 stakeholders (also referred as the 'Large Workshop'). The participants represented local and national government, NGOs, industry and academia. Strategic pieces of model structure and simulation results were chosen to present, which are also presented in the next two sections below. The model stimulated an engaging and fruitful discussion among the participants. The section below discusses the reaction of participants to the model and scenarios in more detail.

Model use: interactive simulation environment

The model that resulted from the GMB sessions and refinement was deemed too large and, thus, not very convenient for stakeholders to experiment with simulations and grasp the implications of complex relations and feedback loops in the system. Therefore, the model was simplified through a semi-formal procedure in order to reach a version that is small enough to be used as an interactive simulation environment, yet comprehensive enough to cover the core feedback mechanisms between housing, energy and wellbeing.

The simplification procedure used here was similar to those of Saysel and Barlas (2006) and Kopainsky, Pedercini, Davidsen, and Alessi (2010). It mostly depended on the insights obtained previously in the project. Several mechanisms were aggregated and abstracted to have a lower model resolution, and the relationships that do not relate to the core feedback mechanisms were removed. Despite a narrower scope, the output of the simplified model is similar to that of the original model for the variables they contain in common.

The simplified model was used in the background of a web-based interactive simulation environment named HEW-WISE,[3] which was introduced in the June 2016 workshop. In a two-phase group process, the participant subgroups were asked to determine a unanimous investment strategy. Namely, each group was asked to allocate a certain built environment budget into energy efficiency, communal spaces and monitoring of construction projects. These interactive simulation sessions were reported to provide engagement and extra insights to the problem of low housing, energy and wellbeing outcomes. Carnohan, Zimmermann, and Rouwette (2016) discuss the impact of these interactive simulation sessions and GMB workshops on stakeholder engagement, learning and communication in more detail.

Model

In this section, key components and structures of the large model are described, with emphasis placed on those that

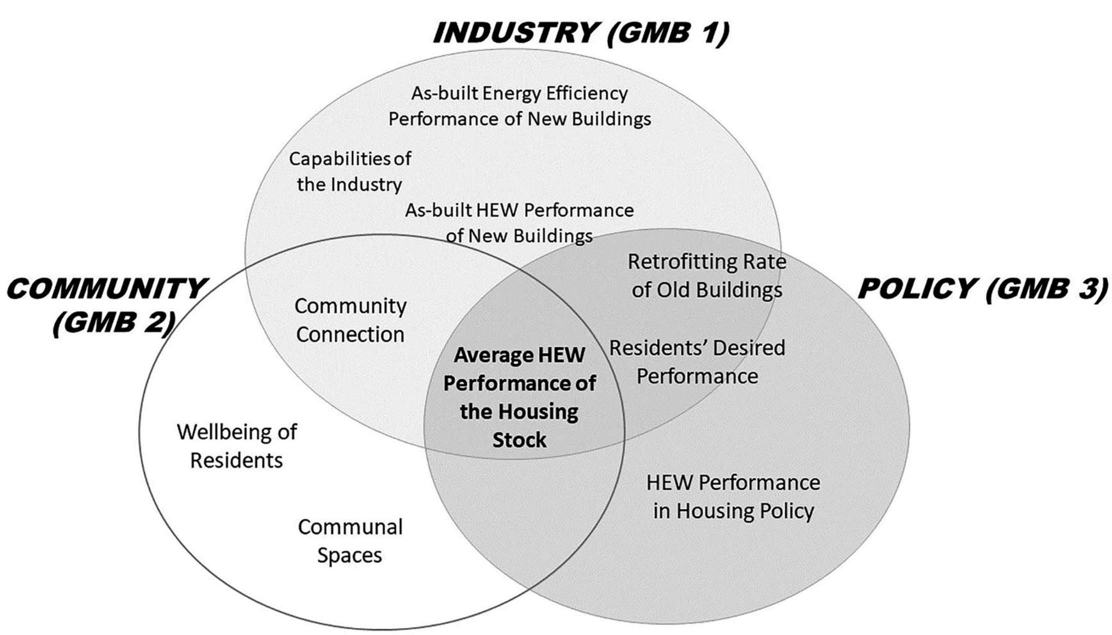

Figure 2. Overview of the model components and the workshops in which they were developed.

are important to understand the simulation behaviour of scenarios explored in the next section. Figure 2 illustrates an overview of the model and indicates in which workshop the main variables were identified and formulated. The industry segment captures the industry practice and performance gaps in construction and retrofitting; the community segment includes the interrelations between occupants' physical and emotional wellbeing, community connection and communal spaces; and the policy segment focuses on the design and adaptation of policies as well as their uptake in terms of housing retrofit. Intersections in Figure 2 show the model elements that were developed jointly in multiple workshops since they relate to multiple aspects.

HEW performance

The variable *As-built HEW* (*Housing, Energy and Wellbeing) Performance* lies at the centre of the model and in the intersection of three workshops. 'HEW performance' is an abstract term we defined in collaboration with the stakeholders, which takes normalized values between 0 and 1. It refers to how well the built environment meets multiple demands of occupants as a space comfortable to live in, affordable to heat/cool and well-integrated with the surrounding environment. For example, it covers the concepts of thermal comfort, indoor air quality and layout. With this broad scope, 'HEW performance' differs from 'energy efficiency', which relates only to the energy efficiency of the building fabric.

The paper models the *Average HEW Performance* (also *Energy Efficiency*) *of the Housing Stock* of the housing stock as the weighted average of the HEW performance (also energy efficiency) of the old, new and retrofitted houses. Therefore, both the performance values and the share of each group in the housing stock are used to formulate this variable. Below, the *Average HEW Performance of the Housing Stock* is discussed in detail, and the quality and quantity mechanisms affecting it. In order to capture the quality aspect via performance gaps that emerge in new buildings between the design and construction stage, the model differentiates between *Designed* and *As-built HEW Performance of New Buildings*. To capture the quantity of energy efficient houses, the model includes the *As-built HEW Performance of New Buildings* and *Retrofitting Rate* of old houses.

Figure 3 captures the causal relationships affecting the *As-built HEW Performance of New Buildings*. It represents HEW performance as a three-stage process from *HEW Performance in Housing Policy*, to what architects specify in the *Designed HEW Performance of New Buildings*, and to how well industry implements design in the *As-built HEW Performance of New Buildings* depending on the *Capabilities of the Industry*. *As-built HEW Performance of New Buildings* is also determined by *As-built Energy Efficiency Performance of New Buildings*. It increases as energy efficiency increases, but not proportionately, because the unintended consequences of energy-efficiency measures, such as interior dampness, imply a HEW performance lower than it could be. *Capabilities of the Industry* positively affect both *As-built HEW Performance* and *Energy Efficiency of New Buildings* since they play an important role in proper implementation of the design performance and integrated construction to prevent the unintended consequences of energy efficiency measures. *Capabilities of the Industry* increase as house builders do rework to improve low *As-built HEW Performance of New Buildings*. However, an increasing *HEW Performance* requires less rework, therefore it negatively affects *Capabilities of the Industry*, forming the 'balancing feedback loops of HEW and energy capabilities'.

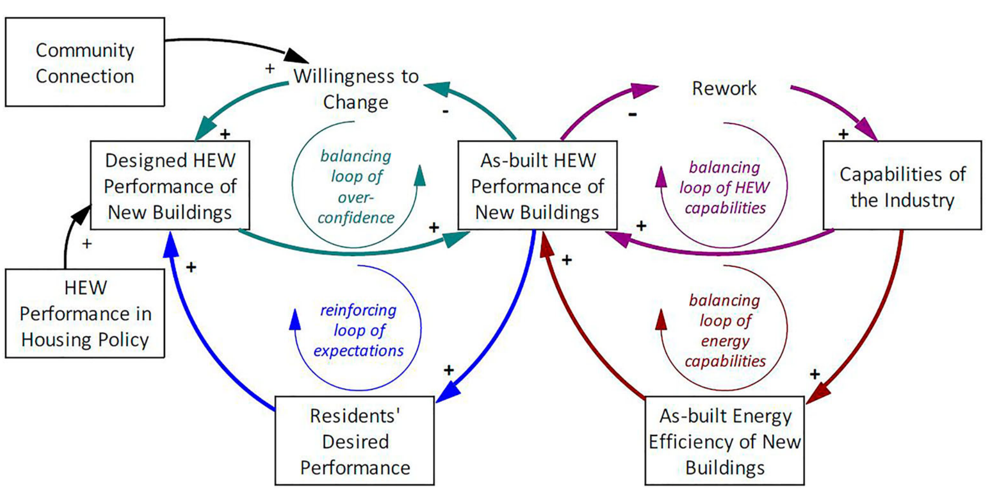

Figure 3. Causal loop diagram (see note 3) for the *Designed* and *As-built HEW Performance*.

The two main drivers of the *Designed HEW Performance of New Buildings* are *Residents' Desired Performance* (which indicates residents' expectations and needs from their houses), and *HEW Performance in Housing Policy* (which indicates the minimum performance level set by building regulations and other housing and energy policies). The eventual *Designed HEW Performance of New Buildings* depends on to what extent these two drivers are taken into account by designers. The relation between design and as-built performance is governed by the 'balancing loop of overconfidence', which implies that as the as-built performance increases, the designers become more confident with the outcome of their work and less willing to change their designs for higher energy efficiency and HEW performance. This willingness is affected by the feedback they receive from residents, which is more intense when *Community Connection* is high. Figure 3 also depicts the 'reinforcing loop of expectations', meaning that *Residents' Desired Performance* increases as the as-built performance increases, which further stimulates the design performance.

Retrofitting rate

Besides the performance levels, the quantity of high-performance housing drives the *Average HEW Performance* (and *Energy Efficiency*) *of the Housing Stock*. Following that, the *Retrofitting Rate* of old houses has drawn close attention in both the industry and policy workshops since it indicates the transformation level of the old and low-performing housing stock and the success level of market-based energy-efficiency policies. The model structure elicited in the workshops for retrofitting is similar to the diffusion models used earlier (Müller et al., 2013; Yücel, 2013) with respect to two feedback loops shown in Figure 4. The 'reinforcing loop of visibility' represents how more people retrofit their houses as more houses are retrofitted and become visible in their neighbourhoods. Counteracting this reinforcing mechanism, the 'balancing loop of market saturation' indicates that as the *Retrofitting Rate* increases, fewer houses are left in demand of retrofitting, hence the *Retrofitting Rate* declines.

In addition to this core structure, the model emphasizes the importance of residents' *Trust in the Industry* for undertaking retrofit projects, and *Community Connection* affecting trust and visibility, represented by the 'reinforcing loop of trust'. The number of households who intend to retrofit depends on their *Trust in the Industry*, *i.e.* whether the industry can successfully and affordably deliver a high performance to them. *Trust* depends on the population-level perception of the HEW performance, which is named *Perceived Compliance*, and this perception is affected by *Community Connection* which provides a stronger word-of-mouth effect as it gets higher. The loop is closed by the link between the *Retrofitting Rate* and the compliance of *Average HEW Performance of the Housing Stock* with *Residents' Desired Performance.*

Wellbeing and community

Figure 5 illustrates the community sub-model. As a key outcome indicator in this study, *Wellbeing of Residents*

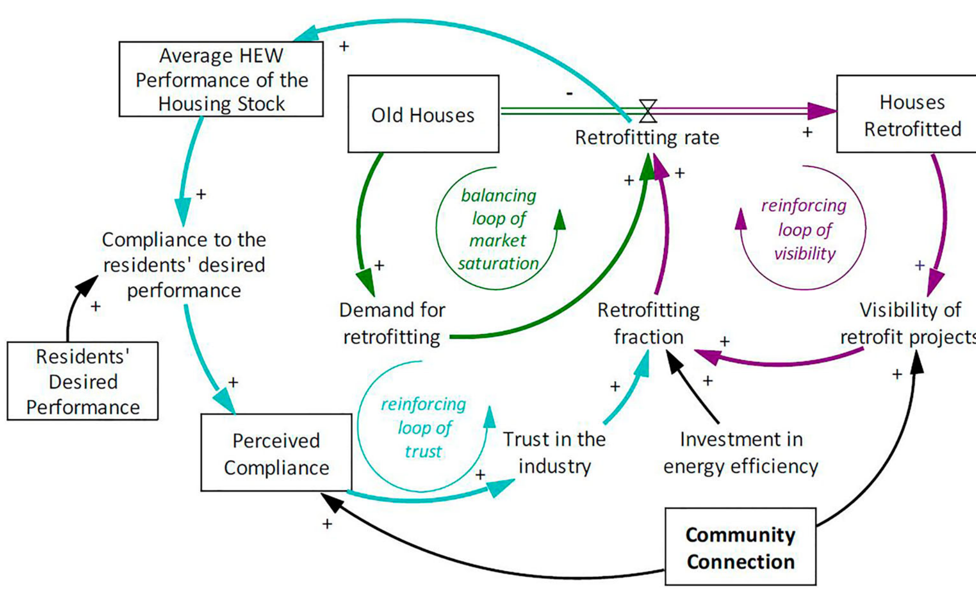

Figure 4. Stock-flow diagram for the retrofitting rate of old houses.

refers to the physical, emotional and mental wellbeing of residents related to their houses and the communal environment in which they live. Although wellbeing depends on many more factors, three major factors are identified within this study's scope: (1) the availability of *Communal Spaces*, *e.g.* green spaces, libraries and pubs, where people can relax and socialize; (2) the extent of *Community Connection* in their neighbourhoods so that they feel socially integrated; and (3) the *Average HEW Performance of the Housing Stock*, which affects their physical and mental health through factors such as thermal comfort, indoor air quality and space.

Communal Spaces primarily depend on the funding available to maintain and improve these spaces in both size and quality. The funding for *Communal Spaces* increases if used more extensively by the public, and their use increases as their availability increases. This reinforcing mechanism is represented by the loop of 'communal space creation'. The 'reinforcing loop of community formation' describes how more connected residents make greater *Use of Communal Spaces*, and how this fosters greater *Community Connection* between them. *Community Connection* is also affected by the *Average HEW Performance of the Housing Stock* because it allows residents to feel more at home, secure and at ease so that they can establish strong relationships within their community.

Validity of the model

All models are simplified representations of reality. Therefore, they are wrong by definition, yet they may be useful for particular purposes (Box, 1979; Sterman, 2002). The validity of a model is assessed according to the purpose for which it is developed (Barlas, 1996). This model's purpose was to serve as a virtual environment where model users can test various assumptions and explore internally consistent future scenarios. Therefore, its validity is assessed not based on the precision expected from forecasting models, but rather on its usefulness to generate credible dynamics, understanding and insights.

Regarding the simulation dynamics' credibility, we first verified that the model equations are dimensionally consistent, and then conducted a number of formal validation tests such as extreme conditions test, sensitivity analyses and behaviour reproduction proposed by Barlas (1996). This testing process was iterative, meaning that the model was revised if the tests did not yield satisfactory results until such results were obtained. Sensitivity analyses confirmed that the model variables are sensitive to the model parameters and functions only to an extent that is expected in real life. Behaviour reproduction tests showed that the model can produce behaviour patterns similar to the historical data once the past conditions (initial values) are met correctly.

Figures 6 and 7 show a comparison of the model output (line 1) and the historical data (line 2) in the period between 2005 and 2015 for *As-built Energy Efficiency Performance of New Buildings* and *Post-occupancy HEW Performance* respectively.[4] The model output does not fully fit the data, *i.e.* it does not match with the short-term oscillations in *Post-occupancy HEW Performance*, nor does it stagnate as early as does the data for *As-built Energy Efficiency Performance of New Buildings*. However, it closely reproduces the main pattern of data, hence can be told to produce plausible dynamics in this particular instance of the past conditions.

Moreover, being based on expert knowledge collected in the workshops brings credibility to the model in terms of addressing the relevant and salient aspects of the problem. The model's usefulness to address such aspects has been confirmed by the stakeholders when they were asked to answer validity-related questions in the evaluation questionnaires after the workshops. These

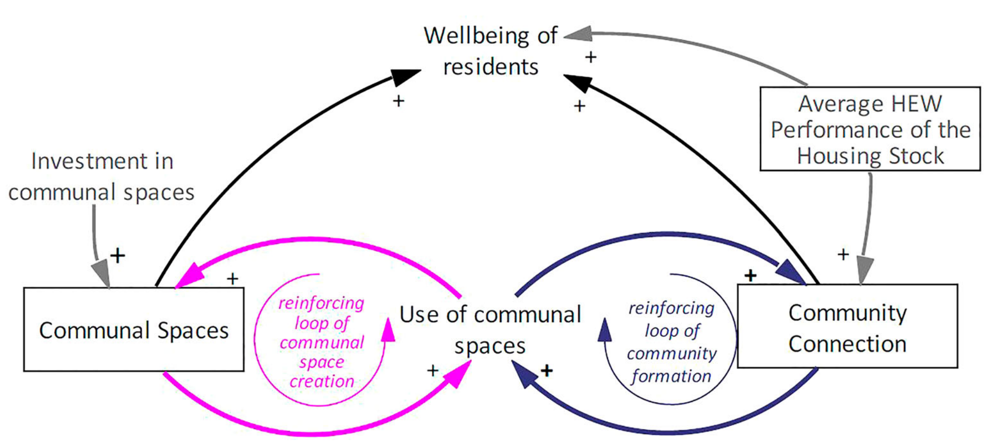

Figure 5. Causal loop diagram for Wellbeing, Communal Spaces and Community Connection.

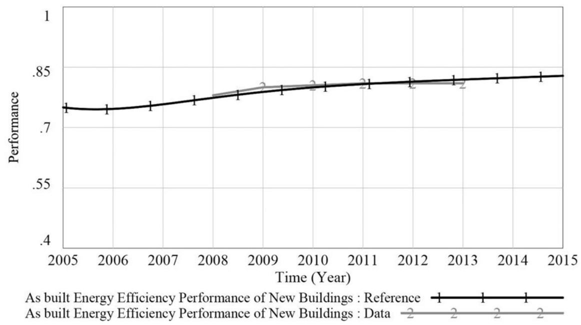

Figure 6. Comparison of model output with the data for *As-built Energy Efficiency Performance of New Buildings*.
Data source: DECC (2015).

questionnaires included scope-related questions about the usefulness of including a particular concept in the model, such as 'HEW performance' or 'community connection', and general questions about the ability of the model to capture the problem and its outputs. Table 1 lists such questions and the average response given to them in each workshop. According to these responses, the authors cannot claim that stakeholders unanimously agree on the validity of the model, yet they are highly positive on average, contributing to establishing the validity of the model. It must be noted that these conclusions are limited to the responses given to the questionnaires, and only a portion of participants (9 out of 16) completed the questionnaire in the Large Workshop.

Simulation results

This section presents the simulation results of four different scenarios. The first corresponds to the reference simulation without policy interventions. The second includes intense monitoring of the construction process of new buildings so that the industry properly complies with building regulations and the as-built HEW performance does not diverge much from the design performance.[5] In the third scenario, energy-efficiency retrofitting of old houses is incentivized financially in a

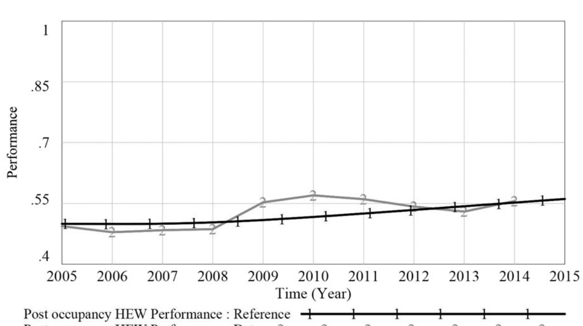

Figure 7. Comparison of model output with the data for *Post-occupancy HEW Performance*.
Data source: DCLG (2016).

Table 1. Feedback response by the stakeholders about the validity of the model.

	Average response given in the workshops			
Questions	**GMB 1 (3)[a]**	**GMB 2 (5)**	**GMB 3 (7)**	**Large Workshop (9)**
Most of the variables in the model are well defined, and could be understood by others in my field	3.00	4.00	4.00	4.00
The structure of the model does NOT represent the problem as I see it	2.33	1.75	1.83	2.22
The simulation results do NOT capture the problem as I see it	2.33	2.00	2.17	2.44
The important issues or problem areas that needed attention were investigated	4.00	4.40	4.67	4.11

Notes: A value of 1 corresponds to 'complete disagreement' and a 5 corresponds to 'complete agreement'.
[a]Numbers in parentheses next to the workshop headings indicate how many participants responded to the questionnaires.
GMB = group model building.

short period between 2016 and 2019, similar to the market-based energy-efficiency policies that were active between 2013 and 2016 in the UK. The last scenario relates to the community dimension of the model scope and explores the implications of regular investments in the maintenance and growth of communal spaces. Table 2 lists these four scenarios and their primary targets and summarizes their major assumptions.

The influence of these scenarios is considered below for a number of variables representing the major policy criteria. Table 3 summarizes the simulation results by scoring each scenario in terms of its impact on each variable of interest, where the score of the reference scenario is 0. This scoring is based on an ordinal scale and it is only an indicative comparison of the scenarios. The dynamic effects of scenarios will be discussed in more detail below for each variable.

Figure 8 shows the behaviour of *As-built HEW Performance of New Buildings* over time in three scenarios in the period 2005–55. *As-built HEW Performance of New Buildings* was assumed to be a variable between 0 and 1. It increases over time in the reference simulation (line 1), yet with a slowing increase. This increase is attributed to the goal of catching *HEW Performance in Housing Policy* and *Residents' Desired Performance*, which are increasing over time, too, due to the reinforcing loop of expectations. As for the slowing increase, it is attributed to the balancing loop of capabilities and overconfidence discussed above in the section entitled 'Model'. Monitoring leads to a significant rapid increase in *As-built HEW Performance of New Buildings* (line 2) from 2016 on, yet the improvement it creates compared

Table 2. Summary of the scenario components.

Scenario	Primary target	Assumptions
Reference	–	• A certain fraction (90%) of the new buildings are assumed to be approved for commissioning without performance checks • There is no incentive on retrofitting, therefore the market is left to its own dynamics • Investment in communal spaces is at a relatively low value that varies according to the *Use of Communal Spaces*
Monitoring	HEW (Housing, Energy and Wellbeing) performance of new buildings	• New buildings are approved according to their actual compliance with *HEW Performance in Housing Policy* • Increase in *As-built HEW Performance of New Buildings* by rework is higher, since the builders are more careful • Increase in *As-built HEW Performance of New Buildings* is proportional to *As-built Energy Efficiency* performance • *Design Performance* is linked to *Post-Occupancy HEW Performance*, indicating that designers are better informed about the consequences of their work
Retrofitting	Energy retrofitting rate of old houses	• The normal value of *Retrofitting Fraction* (without the effect of *Trust*) is tripled gradually in a three-year period between 2016 and 2019, and then reduced
Communal spaces	Area of the communal spaces	• A constant annual investment in communal spaces is ensured continuously for 2016–55

with the reference scenario lessens over time due to the balancing feedback loops of capabilities and overconfidence mentioned above. In the communal spaces scenario (line 3), *As-built HEW Performance of New Buildings* takes slightly lower values than the reference scenario. This is due to delays in the design process caused by a stronger *Community Connection*, *e.g.* the community holding up plans with which they are not satisfied.

The four scenarios result in different dynamic behaviour for the refurbishment of the old housing stock, as shown by the number of *Houses Retrofitted* in Figure 9. In the reference scenario (line 1), most of the old households, which are initially 2.6 million, implement a retrofitting measure by 2055. Yet, this happens mostly in the last decades of the simulation horizon. The increase in the *As-built HEW performance of New Buildings* in the monitoring scenario (line 2) only slightly increases the overall number of *Houses Retrofitted* due to the relatively small fraction of new buildings in London. A similar yet larger improvement is observed in the communal spaces scenario (line 4), attributed to the influence of *Community Connection* on the *Visibility of Retrofit Projects*. In both scenarios, the old housing stock is refurbished more quickly than in the reference simulation. In the retrofitting scenario (line 3) where housing refurbishment is incentivized directly, such an increase in *Houses Retrofitted* is observed earlier, following the introduction of financial incentives in 2016–19.

The speeding effect of retrofitting incentives on the number of *Houses Retrofitted* is reflected in the *Average Energy Efficiency Performance of the Housing Stock*, as can be seen in Figure 10. Due to the increasing number of more energy-efficient houses, the *Average Energy Efficiency Performance of the Housing Stock* increases more quickly in the retrofitting scenario (line 3) than other scenarios. However, despite an almost-full retrofitting of the old housing stock by 2055, the entire housing stock does not reach a full energy-efficiency level. This

Table 3. Summary of the simulation results for each scenario and five key variables.

	Scenarios			
Variables	Reference	Monitoring	Retrofitting	Communal spaces
As-built HEW Performance of New Buildings	0	+	0	–
Houses Retrofitted	0	+	+ + +	+ +
Average Energy Efficiency Performance of the Housing Stock	0	+	+ +	+
Average HEW Performance of the Housing Stock	0	+ +	+	+
Wellbeing of Residents	0	+ +	+	+ + +

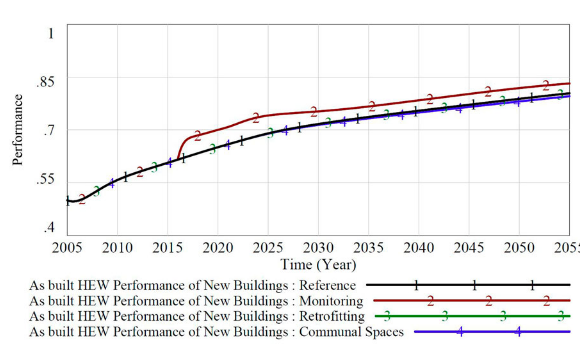

Figure 8. Simulation results for *As-built HEW Performance of New Buildings* in four scenarios.

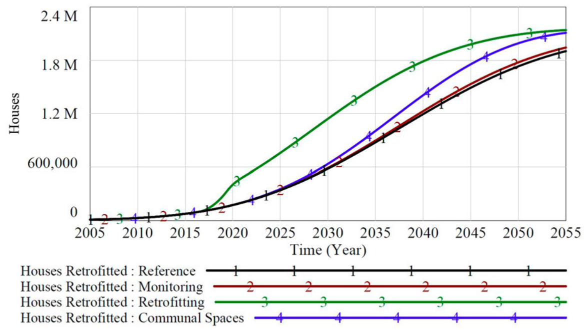

Figure 9. Simulation results for *Houses Retrofitted* in four scenarios.

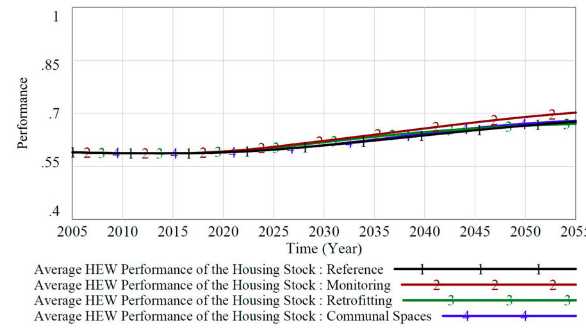

Figure 11. Simulation results for *Average HEW Performance of the Housing Stock* in four scenarios.

is due to the quality of retrofit and new buildings, which is related to a relatively low *As-built Energy Efficiency of New Buildings*. Furthermore, in the long term, the monitoring and communal spaces scenarios (lines 2 and 4) result in values as high as the retrofitting scenario. Monitoring helps to ensure a high-quality level for newly built houses besides the quantity of retrofitted houses, and a higher community connection facilitates the growth of retrofitting. Therefore, this outcome can be interpreted as a necessity to support financial incentives with monitoring and/or communal space policies in order to obtain a more energy-efficient housing stock in the long term.

As Figure 11 shows, *Average HEW Performance of the Housing Stock* does not increase as much as the energy efficiency of it (Figure 10) and the HEW performance of new buildings (Figure 8). Still, it slowly grows in the early decades, then accelerates and saturates. Due to a higher number of *Houses Retrofitted* in the retrofitting (line 3) and communal spaces (line 4) scenarios, *Average HEW Performance of the Housing Stock* is also higher in these scenarios than the reference scenario (line 1) in the first few decades. However, the increasing trend ceases in the long term, around values even lower than those in the reference case due to a lower inflow of retrofitted houses in the long term in the retrofitting scenario once retrofitting incentives cease. The housing stock has the highest HEW performance values in the monitoring scenario (line 2), where *As-built HEW Performance of New Buildings* is proportional to the *As-built Energy Efficiency Performance of New Buildings*. This finding indicates the importance of enhancing the performance level of new and retrofitted buildings besides the quantity of them in order to increase the performance level of the entire housing stock.

In terms of *Wellbeing of Residents*, the reference, monitoring and retrofitting scenarios (lines 1, 2 and 3) do not demonstrate considerable differences, as shown in Figure 12. In these scenarios, *Wellbeing of Residents* declines until around 2030 due to declining *Communal Spaces* and *Community Connection*. The increasing effect of *Average HEW Performance of the Housing Stock* can be seen only after that time, yet this is a slight change. Relatively, the improvement in the monitoring and retrofitting scenarios compared with the reference case is quite small. However, in the communal spaces scenario (line 4), *Wellbeing of Residents* increases considerably as opposed to its decline in the other two scenarios. The reason for this favourable increase in wellbeing is the direct effect of increasing *Communal Spaces* and *Community Connection*. Therefore, this finding can be interpreted as the necessity to consider communal spaces in the housing policy in order to improve the wellbeing of residents, in addition to policies targeting the built environment.

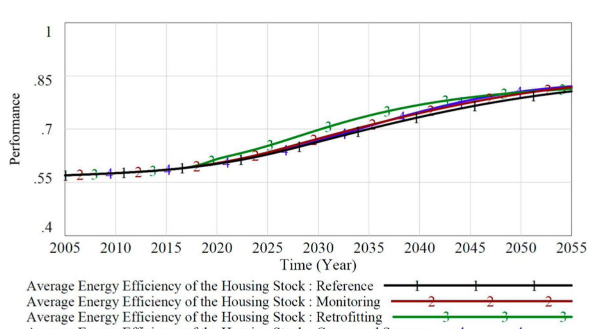

Figure 10. Simulation results for *Average Energy Efficiency Performance of the Housing Stock* in four scenarios.

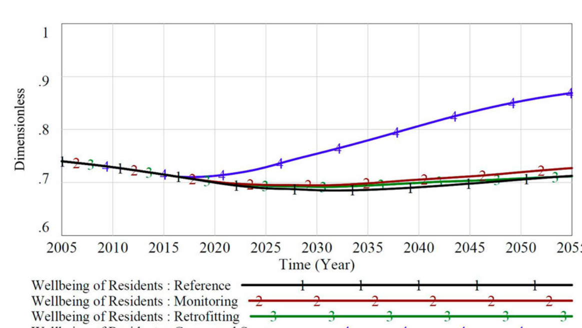

Figure 12. Simulation results for *Wellbeing of Residents* in four scenarios.

Discussion

This study was a response to the calls for an integrated approach for both research and decision-making in the built environment (Davies & Oreszczyn, 2012; Schweber & Leiringer, 2012). This section considers the implications and limitations of this study as an integrated approach for built environment-related research and decision-making in light of simulation results and our observations during the process.

Implications for policy

This study aimed to understand the relative importance of different feedback mechanisms and the dynamic behaviour they generate, and to inform the policy debate about these. Simulation analyses suggest that monitoring is key to increasing HEW performance proportional to energy efficiency and to closing the performance gaps in the industry, *i.e.* between design and as-built performance. However, this increase in HEW performance is still subject to stagnation due to balancing feedback loops related to the capabilities of builders and willingness of designers to change. Therefore, for an ongoing increase in HEW performance, the effect of these balancing mechanisms needs to be mitigated.

Another policy-relevant conclusion of this study is that energy efficiency or HEW performance of the housing stock may not be the most important factor to enhance residents' wellbeing. Wellbeing can be better improved if communal spaces are increased in unison with energy efficiency and HEW performance increases. Improving communal spaces also leads to better community connection, which not only enhances wellbeing but also boosts the adoption of energy-efficiency measures through word-of-mouth mechanisms. Therefore, a combination of policies contributes to reaching multiple policy objectives in a balanced way.

The simulation model developed in this study is based on expert knowledge and reliable data, yet it cannot be considered as a complete decision support tool. This is mainly because the model was not intended to have such a detailed and contextual focus that is required for a decision support tool, as previously discussed. Still, stakeholders consider the model as a useful tool for providing policy-relevant insights, broadening their views and enhancing their understanding. These features help in designing more inclusive and effective policies with credible and legitimate information and insights provided to the policy design debate. For example, the positive effects of improving communal spaces in the simulation can be used as an argument for a continuous investment in London's Green Belt, its parks, pubs and other communal spaces. The co-benefits created by monitoring of industry provide reasons to increase the testing of building and energy performance. Furthermore, this study creates opportunities to identify knowledge gaps and to develop models that can be used as decision support tools for specific problems.

Implications for research

This study followed the participatory SD modelling method for this interdisciplinary project. The authors' experience has shown that this method is useful to integrate many social, technical and economic phenomena from various disciplines. The model co-developed with stakeholders was able to capture this interdisciplinarity, with interrelated social, technical and economic components such as community connection, energy efficiency, 'HEW performance' and the demand for energy-efficiency retrofitting.

The method was found useful also in bringing together the diverse stakeholder knowledge and views from various disciplines. When the participants of the large workshop were asked to rate the 'usefulness of this kind of modelling approach for supporting more integrated decision-making about housing' on a scale from 1 to 4, where 1 corresponds to 'not useful at all' and 4 corresponds to 'extremely useful', the average response was 3.67. Several stakeholders reported comments that support this outcome, such as 'I have gained a much better understanding of the complexity and interacting nature of HEW interventions' and 'I am really supportive of the systems approach and have been inspired by how you have used it to bring stakeholders together to do this.'

Based on individual questions asked in the evaluation questionnaires, this high usefulness rating is attributed to increased insight about the problem, and to consensus building among the participants in both the model development and interactive simulation sessions. Moreover, these sessions are reported to be more useful than normal meetings in generating insight and better communication, yet not necessarily in a quicker way. The participants also reported that this approach would not be easily followed by all persons in their home organizations, implying the difficulty of establishing such an integrated approach within organizations. For a more detailed discussion about the contribution of these sessions to learning, understanding, engagement and communication, see Carnohan et al. (2016).

A large majority of the stakeholders acknowledged that a quantified model was highly beneficial. However, one participant raised a concern about quantification and found the discussion around assumptions and relations more important. The present authors agree that a discussion on assumptions and relations is highly useful in revealing and understanding the diversity of stakeholder values and knowledge. Yet, simulation modelling combines this diversity systematically, links the current relationships to future dynamics and allows assumption testing. Therefore, it further contributes to an informed debate by providing focus and insight about the long-term dynamics and the implications of various assumptions and decisions.

Stakeholders also commented on the model scope. It was acknowledged that the study extends to multiple dimensions, yet they suggested the inclusion of additional factors, such as business models and financial aspects of energy-efficiency policies, or resourcing of low-income housing. Also, the content and results of the model were found rather general and abstract. The authors consider these comments relate to the aim of this study, which was not addressing a particular policy with elaborate modelling, but rather developing an integrated approach and disseminating systems thinking among stakeholders. Therefore, the model remained at a general and abstract level as a natural consequence. However, as a result of the stakeholder platform and understanding established in this study, the authors have started contextual and practical implementations for particular policy problems in follow-up studies.

This study was conducted in the context of the UK's housing and energy-efficiency policies, with stakeholders representing the organizations and institutions based in the UK, and with data belonging to the UK, particularly London. However, many of the relationships between housing, home energy efficiency and wellbeing of residents are universal, and the problems arising from overlooking these relationships are common in many countries. Therefore, a similar modelling approach can be implemented at the national level or in an international context, too. Such studies focusing on different countries need to take the differences in regulations and market structures into account.

Conclusions

This paper presented the application of an integrated approach for housing, energy and wellbeing, considering multiple policy objectives and multiple aspects of the problem simultaneously. This integrated approach is comprised of a positivist dimension, on the one hand, which systematically investigates the governing socio-economic and technical mechanisms and explores future dynamics these mechanisms lead to with a quantitative simulation model. On the other hand, it involves an interpretivist dimension which actively considers the interests and motives of stakeholders, brings their knowledge and expertise to research and enhances their understanding of the system in an integrated way. This interpretivist dimension was realized with participatory modelling, which involved stakeholder engagement both in model development and use. The process of model development, the resulting simulation model and experimentation with it were reported to be useful by the stakeholders who participated in the workshops. Through observing the usefulness of the approach in these workshops, a government department initiated a participatory SD project with us on their policy questions.

Two major points can be addressed in future studies. First, although the participatory SD modelling approach was deemed useful by several organizations and led to follow-up studies, several participants reported that the penetration of such an integrated approach within their organizations would be difficult. Since participation in our research project allowed participants to see the power of a participatory SD approach, an increased participation by organizational members in participatory modelling could be most beneficial for triggering a similar organizational project and for implementing such thinking directly in organizations. In addition, tools and techniques of participatory modelling can be made more accessible to increase its acceptance in organizations. Second, having been initiated with the aim to build a stakeholder platform for integrated decision-making in the housing sector, our project had a rather broad focus; hence, the resulting simulation model and analysis are partially acontextual. In future studies, similar integrated approaches can be implemented for a particular policy problem, such as analysing system-wide benefits and shortcomings of a policy, comparing two policies on a wide spectrum of social, environmental and economic criteria, exploring a wider variety of scenarios, or fostering understanding about the interlinkages between policy areas and policy complementarity. The follow-up project we implemented with external partners moved exactly in this direction. Such customized and contextual projects can not only help solve a particular policy problem, but also reach a wider stakeholder group from each relevant organization for an increased acceptance of integrated approaches.

Notes

1. The Web-enabled Interactive Simulation Environment (HEW-WISE) is a simplified version of the larger model used for scenario analyses of about 25% in size, fully transparent and ready for use. It allows the running of selected scenarios with similar results, but does not provide numerical identity to the larger model. It can be publicly accessed at both: https://www.ucl.ac.uk/bartlett/environmental-design/research/hew-integrated-

decision-making-about-housing-energy-and-wellbeing and http://www.systo.org/hew_wise.html/. The simulation environment allows the testing of various decision options, presents the simplified model, briefly describes it, and allows scenario testing and even changing the model assumptions.
2. This is based on the English Housing Survey (EHS) and Housebuilding Statistics released by the Department for Communities and Local Government (DCLG), and Energy Efficiency Statistics and Green Deal and ECO Statistics released by the Department of Energy and Climate Change (DECC).
3. In causal-loop diagrams, causal links are depicted by an arrow between two variables, with a sign indicating the polarity of this relation. A positive (negative) causality means that a change in the cause variable affects the effect variable in the same (opposite) direction. A closed chain of links forms a feedback loop, and the polarity of a loop is determined by multiplying the polarities of individual links. A single positive feedback loop (reinforcing loop) creates an exponential behaviour, whereas a single negative (balancing) feedback loop creates an asymptotic change. Variables indicated by a box are accumulations that only change with delay.
4. The best available data are used to approximate these variables. *As-built Energy Efficiency Performance of New Buildings* is matched with the 'Mean SAP Score of New Buildings' provided in the Energy Efficiency Statistics. *Post-occupancy HEW Performance* is matched with the responses given to the question: 'How satisfied are you with your accommodation?' asked in the EHS. Namely, the percentage of respondents who were 'very satisfied' is used as an indicator of *Post-occupancy HEW Performance*.
5. In this scenario, monitoring is aligned with the certification (approval) of the buildings before commissioning, and it targets only new dwellings. The reason for excluding retrofitted houses is the current implementation in the UK, where retrofitting projects require approval only under certain conditions, *i.e.* if they lead to a structural change. We envision future research to include monitoring scenarios of retrofit projects, too.

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