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Exploring Homeowners' Insulation Activity

Abstract

Insulating existing buildings offers great potential for reducing greenhouse gas emissions and meeting Germany's climate protection targets. Previous research suggests that, since homeowners' decision-making processes are inadequately understood as yet, today's incentives aiming at increasing insulation activity lead to unsatisfactory results. We developed an agent-based model to foster the understanding of homeowners' decision-making processes regarding insulation and to explore how situational factors, such as the structural condition of houses and social interaction, influence their insulation activity. Simulation experiments allow us furthermore to study the influence of socio-spatial structures such as residential segregation and population density on the diffusion of renovation behavior among homeowners. Based on the insights gained, we derive recommendations for designing innovative policy instruments. We conclude that the success of particular policy instruments aiming at increasing homeowners' insulation activity in a specific region depends on the socio-spatial structure at hand, and that reducing financial constraints only has a relatively low potential for increasing Germany's insulation rate. Policy instruments should also target the fact that specific renovation occasions are used to undertake additional insulation activities, e.g. by incentivizing lenders and craftsmen to advise homeowners to have insulation installed.

Keywords:
Spatial Agent-Based Model, Decision-Making Process, Homeowners, Thermal Insulation, Situational Factors, Social Interaction

Introduction

1.1   Buildings account for more than 40 per cent of total final energy consumption and greenhouse gas emissions in the European Union (EU) (IEA 2013). Recent estimates suggest that existing buildings in the EU have an energy-saving potential of up to 80 per cent (Lechtenböhmer & Schüring 2011). Detached and terraced residential buildings, the most common types for owner-occupier households, offer the greatest potential for reducing energy use (Weiß & Dunkelberg 2010). Owner-occupier households in detached and terraced residential buildings, i.e. households who own the detached or terraced residential building in which they also live, are hereinafter referred to as "homeowners".

1.2   The most effective measure for reducing the energy consumed by existing buildings is to install or upgrade (thermal) insulation (Balaras et al. 2007; Enkvist et al. 2007). Empirical research shows that the total benefits of insulating existing buildings usually outweigh their costs (Chapman et al. 2009; Jakob 2006). Thus, for many homeowners, it pays to invest in insulation measures due to the reduction in energy costs amassed over their lifetime (Nauclér & Enkvist 2009; von Weizsäcker 2010). Nevertheless, homeowners appear to be reluctant to take advantage of these opportunities in most European countries, including Germany (Jakob 2007; Organ et al. 2013; Tommerup & Svendsen 2006; Zundel & Stieß 2011). A number of studies claim that an increase in insulation activity is required in order to achieve Germany's climate protection targets (Kirchner & Matthes 2009; Schlesinger et al. 2010). Results show that the number of households having insulation installed could be doubled in Germany compared to current levels, and would still pay off in economic terms (Kleemann et al. 2005). Even then, yet more households

could have insulation installed, which would pay off, because there is a considerable insulation backlog (share of building components with overaged or nonexistent insulation) (Diefenbach et al. 2010).

1.3   Existing policy instruments to increase insulation activity typically target the economic viability of insulation (Friege & Chappin 2014a). This is reasonable insofar as a homeowner's decision to insulate is indeed influenced by the economic viability of insulation. Other reasons, both those in favor and those against insulation, were identified in an earlier work by bibliographic analysis (Friege & Chappin 2014a) (see Table 1). Our analysis showed that one important reason for the poor success rate of existing policies is that the influence of noneconomic motivations and barriers is underestimated.

Table 1: Main economic and noneconomic motivations and barriers influencing homeowners' decisions to insulate. Adapted from Friege and Chappin (2014a).

	Motivations	**Barriers**
Economic	Homeowners may • expect a return on investment, an increase in the value of their home, and a reduction in energy bills and vulnerability to volatile prices.	Homeowners may • not have the necessary financial resources; • be unwilling to take out a (further) loan; • not be sure whether the investment will pay off.
Noneconomic	Homeowners may • expect an increase in thermal comfort, status, and resilience to climate change; • expect a reduction in energy demand, environmental impact, risk of future supply problems, and dependency on fossil fuels.	Homeowners may • think that no (further) refurbishment is needed; • have no time to deal with the issue; • not be interested in more upkeep than necessary; • be worried about the stress and mess that renovating creates.

1.4   Motivations and barriers to installing insulation differ among homeowners and are affected by situational factors and social interaction. For example, face-to-face interaction between homeowners and personal information can alter their expectations regarding the consequences of installing insulation (Zundel & Stieß 2011). Relevant situational factors can be the homeowner's socio-demographic situation or the structural condition of the house.

1.5   We argue that a better understanding of the effects arising from these factors can create a better understanding of homeowners' decision-making concerning insulation. This increase in knowledge could help policy-makers to design innovative policy instruments for increasing insulation activity. This leads us to pose the following research questions:

- In what ways do situational factors and social interaction influence the insulation activity of heterogeneous homeowners?
- How should policy instruments aiming at increasing homeowners' insulation activity be designed?

1.6   Research shows that agent-based modeling is particularly suitable for exploring dynamics of real-world systems which involve the interaction of individual entities (Bonabeau 2002; Gu et al. 2015; Putra et al. 2015; Rand et al. 2015). Since homeowners' insulation activity is, inter alia, influenced by social interaction (Ball et al. 1999; Xu et al. 2014), we develop an agent-based model for answering the questions posed above. In the third section we further introduce the methodology and describe the model. The model consists of autonomous interacting household agents going through multi-stage decision-making processes on whether or not to insulate their homes. Since social interaction affects the agents' decision-making, the model includes a social network with a composition that considers the agents' heterogeneity and spatial proximity.

1.7   We then present the results of the simulation experiments conducted to explore the influence of situational factors and social interaction on homeowners' insulation activity. The paper ends with a discussion and a conclusion. In the next section, we present the theoretical framework that serves as a basis for the model and that we developed based on behavioral theories and literature on insulation decisions.

The theoretical framework

2.1   In this section we present the theoretical framework developed to capture the centerpiece of the simulation model, homeowners' decision-making processes on whether or not to insulate their homes. The framework, depicted in Figure 1, shows that homeowners decide in favor of insulating their property (renovation activity) if situational factors trigger a renovation occasion, and if attitude and the perceived value of information result in positive perceived utility towards installing insulation. The elements of the framework will be further developed and described in greater detail below, based on behavioral theories
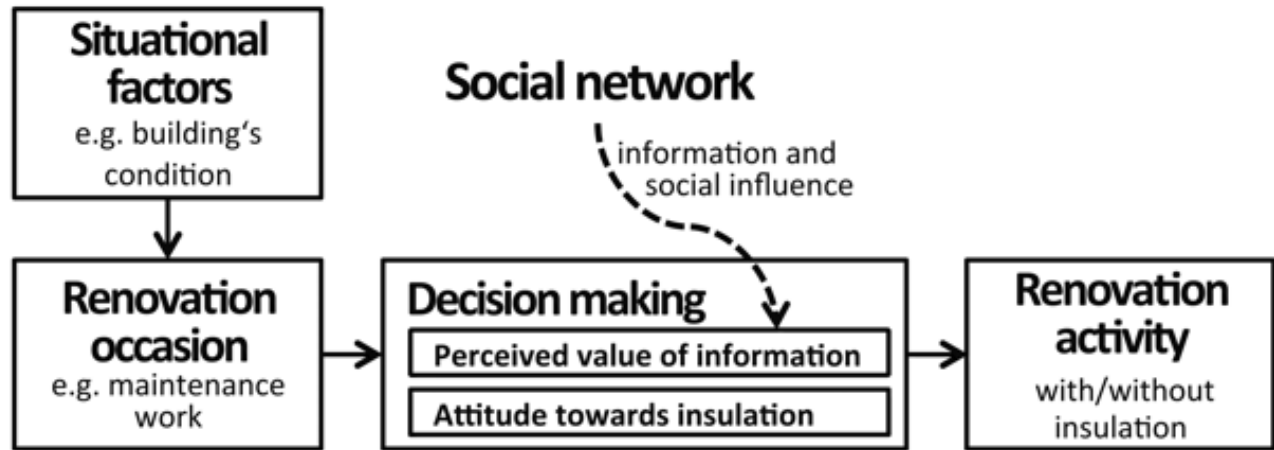
and literature on renovation decisions.

Figure 1. Theoretical framework for homeowners' decision-making processes on whether or not to insulate their homes.

2.2   Homeowners' decision-making on insulation is mainly triggered by situational factors such as the condition of the building or the homeowner's socio-demographic situation. Situational factors trigger the main renovation occasions, namely maintenance work, attic extension, and house purchase (Stieß & Dunkelberg 2012). Initially, these occasions lead to renovation measures that do not improve the insulation of the house, such as renewing the roof or the facade[1]. However, insulation is usually combined with such measures. Thus, renovation occasions represent a significant opportunity to install insulation (Wilson et al. 2013). Combining roof renewal with roof insulation or facade renewal with wall insulation is also less expensive than implementing the measures separately (Stolte 2011). Incorporating such a concept of facilitating conditions to model consumer action is in accordance with proposals by Ölander et al. (1995), who state that the opportunity to carry out an intention is a precondition for the performance of the specific behavior.

2.3   If a renovation occasion occurs, attitude and the perceived value of information (see below) influence the homeowner's decision to combine standard renovation measures with insulation. Various theories contend that the attitude towards a particular behavior influences a person's decision-making (Fishbein & Ajzen 1975; Guagnano et al. 1995; Ölander et al. 1995). Since empirical studies exploring homeowners' decision-making regarding installing insulation in their homes suggest the same findings (Stieß & Dunkelberg 2012; Wilson et al. 2013), we incorporated the 'attitude' concept into our framework.

2.4   Social interaction becomes relevant for homeowners' decision-making because the installation of insulation requires specialized information and skills, and homeowners "are not usually trained in construction and technology and thus must find ways to cope with the need for expert knowledge" (Stieß & Dunkelberg 2012, p. 252). Stieß and Dunkelberg (2012) found that homeowners' main and most important source of information on insulation is their own social network (Stieß & Dunkelberg 2012). This view is supported by McMichael and Shipworth (2013), who suggest that information received on energy-reducing innovations has a stronger impact on the decision to adopt such measures if verified by personal contacts (McMichael & Shipworth 2013). In his theory of 'social impact', Latane (1981) showed that the perceived value of information received through social networks differs depending on the effectiveness of communication, the closeness in time and space, and the number of people in the social network. By incorporating the concept of the perceived value of information into our framework, we take into account the influence of social interaction on homeowners' decisions to insulate.

2.5   If attitude and the perceived value of information result in positive perceived utility towards installing insulation, we assume that homeowners decide in its favor. This assumption is consistent with the provisions of different integrative theories of consumer behavior. In accordance with Stern (2000), homeowners' decision-making on insulation is a "function of the organism and its environment". As suggested by Ölander et al. (1995), the target behavior requires task knowledge, the opportunity, and a sufficient amount of motivation to be executed. The motivation – opportunity – ability (MOA) framework from Ölander et al. (1995) only differs in so far from our approach that they incorporate both habit and task knowledge in their 'ability' concept. Because installing insulation is not a habitual behavior (Bartiaux et al. 2011), the habit component was not used in our framework.

The agent-based model

3.1   The theoretical framework shows that homeowners' decision-making concerning insulation is triggered by situational factors and influenced by social interaction. We use the technique of agent-based modeling (ABM) to explore how situational factors and social interaction influence homeowners' insulation activity.

3.2   Several scientists have successfully used ABM to model systems comprising autonomous interacting entities such as, in our case, homeowners (An 2012; Bonabeau 2002). The studies show that ABM enables emergent phenomena to be captured, in our case homeowners' insulation activity arising from their interaction. Homeowners mutually influence each other's decisions due to social interaction. Thus, homeowners' insulation activity cannot be explained by analyzing their decision-making

individually or by analyzing the aggregation of their individual states. In addition, the agent-based approach enables homeowners' multistage decision-making processes to be modeled influenced by their individual situation. We thus consider ABM to be suitable for exploring homeowners' insulation activity.

3.3   First, we describe the homeowners' characteristics, which serve as input for the ABM as depicted in Figure 2. Additional input are a number of parameters such as the assumed population density. The influence of population density on homeowners' insulation activity and the development of the condition of a building is explored in the simulation experiments. We then describe the main model procedures: the initialization, which includes creating the spatial structure and establishing the social network, and the actual simulation of homeowners' decision-making processes. Finally, we describe the different insulation activity indicators used later to present the results of the simulation experiments.
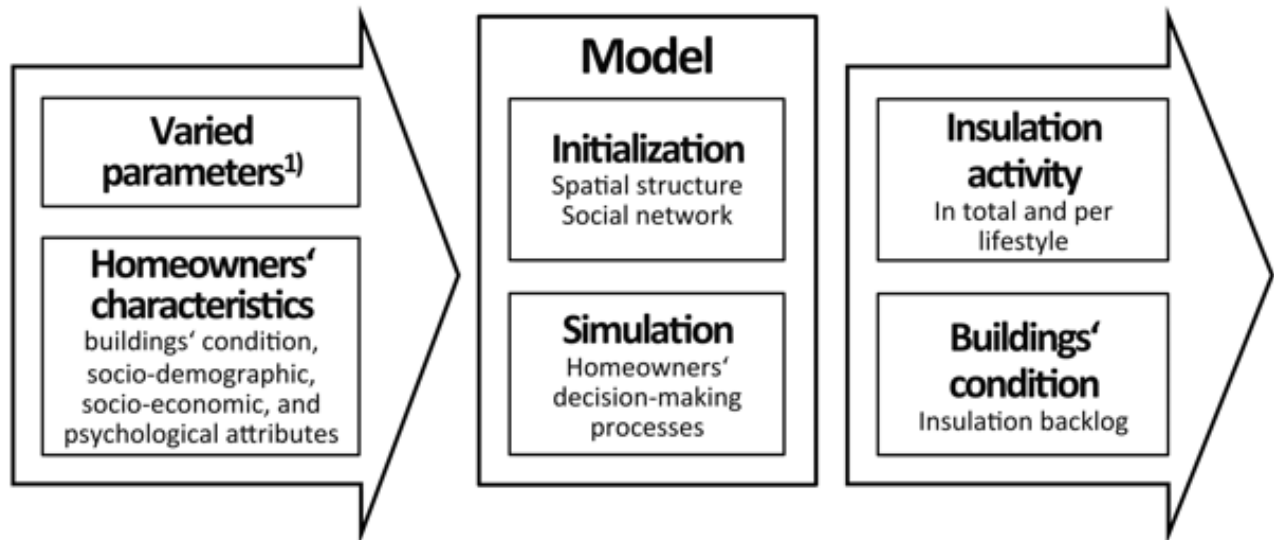

Figure 2. Overview of model input, processes and output. 1) Parameters used to vary basic assumptions such as the population density or residential segregation in the simulation experiments.

3.4   The model code and an 'ODD' protocol (Grimm et al. 2010) can be retrieved from www.openabm.org/model/4419. The model is implemented in NetLogo v.5.1.0 (Wilensky 1999).

Homeowners' characteristics

3.5   The agents in the model are owner-occupier households with decision-making power regarding investments in renovation. They are represented as homeowners in the model containing several social and technical characteristics. Relevant technical characteristics are: the type and age of their house; the age and lifetime of insulation, roofing, wall paint, exterior rendering, and the heating system. The lifetime of modeled building components are normally distributed (see Appendix B, Table 8). The age of the building components is calculated as the difference between the house age and a multiple of the components' lifetime[2].

3.6   To capture homeowners' socio-demographic and psychological heterogeneity, we draw on Otte's lifestyle typology for Germany (Otte 2008). The typology is conceptualized along two dimensions and comprises nine different lifestyles (see Table 2). The hierarchical dimension 'level of living' relates to individuals' economic and cultural resources. The temporal dimension 'modernity/biographical perspective' relates to individuals' values (traditional vs. modern) and biographical perspective of living. Homeowners of the different lifestyles differ regarding their attitude towards insulation, age and income. Homeowners' attitudes towards insulation, expressed in quantitative terms (from −0.5 very negative to +0.5 very positive) per lifestyle, was estimated by the authors based on the study "potentials for sustainable living in Germany" (Rückert-John et al. 2013). The study describes the attitude adopted by the prevailing lifestyles towards climate and environmental protection activities such as installing insulation. The study additionally provides information on the homeowners' age and household net income distribution per lifestyle as presented in Table 2. For the shares of homeowners per lifestyle we use data collected in the city of Essen (Linnebach et al. 2014). It was not possible to use the national survey because it provides only data on the shares per lifestyle of the whole population. Since the population group 'homeowners' have, on average, a higher 'level of living', their distribution among lifestyles does not match the rest of the population.

Table 2: Otte's lifestyle typology, horizontal: modernity/biographical perspective, vertical: level of living. The numbers in the square brackets indicate: the share of homeowners of the different lifestyles in per cent, their age in years, their net income in euros per month, and their attitude towards insulation ranging from −0.5 very negative to +0.5 very positive. The data was provided by Rückert-John et al. (2013) and Linnebach et al. (2014).

	Established Conservatives (CONS) [5.7; 50 to 65; >3,000; -0.25]	Established Liberals (LIBE) [15.9; 50 to 65; >3,000; +0.5]	Reflectives (REFL) [6.9; 30 to 65; >3,000; +0.25]
High	Established Conservatives (CONS) [5.7; 50 to 65; >3,000; -0.25]	Established Liberals (LIBE) [15.9; 50 to 65; >3,000; +0.5]	Reflectives (REFL) [6.9; 30 to 65; >3,000; +0.25]
Middle	Conventionals (CONV) [9.9; 50 to 65; 2,000 to 3,000; +0.25]	Adaptive Mainstream (MAIN) [26.9; 30 to 49; 2,000 to 3,000; +0.25]	Hedonists (HEDO) [10.0; <29 to 65; 1,000 to > 3,000; +0.25]
Low	Traditional Workers (WORK) [6.6; >65; 1,000 to 2,000; +0.25]	Domestically Centered (DOME) [14.7; <29; 1,000 to 2,000; -0.25]	Entertainment Seekers (ENTE) [3.4; <29; 1,000 to 2,000; -0.5]
	Traditional/biographically closed	**Partially modern/consolidated**	**Modern/biographically open**

Socio-spatial structure

3.7   For our model, we create an artificial socio-spatial structure that resembles the building and social structure of real-world urban areas. It consists of spatially distributed houses and their homeowners located in the same position as their houses. Each homeowner occupies one patch on a two-dimensional rectangular plane with side lengths of 60 continuous units. One unit represents the lateral length of one homeowner's property. Considering that properties in western Germany have an average area of 610 square meters (statista 2009), the modeled area corresponds to approximately 2.25 square kilometers. Parameter D is used to define the population density, which is the number of homeowners in relation to the total number of patches. Houses of a similar construction year and type are typically located close to each other (Ottens 2012). For this reason, in the model houses are spatially clustered based on these values. During the clustering process, houses are initially randomly distributed over the grid. The following equation is then used to calculate the probability (P_C) that a house will remain at the chosen location. These steps are repeated until all houses are set. Throughout the initializations of the simulation experiments, they follow the same course of action.

$$P_C = \frac{N_C}{N} \qquad\qquad (1)$$

3.8   NC is the number of houses built in the same construction year category (see Table 3) in the direct neighborhood; N is the total number of houses in the direct neighborhood. Table 3 provides an overview of the share of detached and terraced houses and their insulation status by construction year category, as provided by the 'Institut Wohnen und Umwelt' (IWU) (Diefenbach et al. 2010). In IWU's building typology, building phases of similar construction methods are used to classify housing units of different construction years into same construction year categories. The typology is a standard to classify buildings in Germany and thus ensures that our simulation results are comparable to other studies focusing on building insulation. The share of houses with 'next-generation' insulating glazing (triple-glazed windows) was virtually zero at the end of 2006 (VFF & BF 2014).

Table 3: Share of detached and terraced housing units and insulated building components by construction year category in the German building stock (Diefenbach et al. 2010).

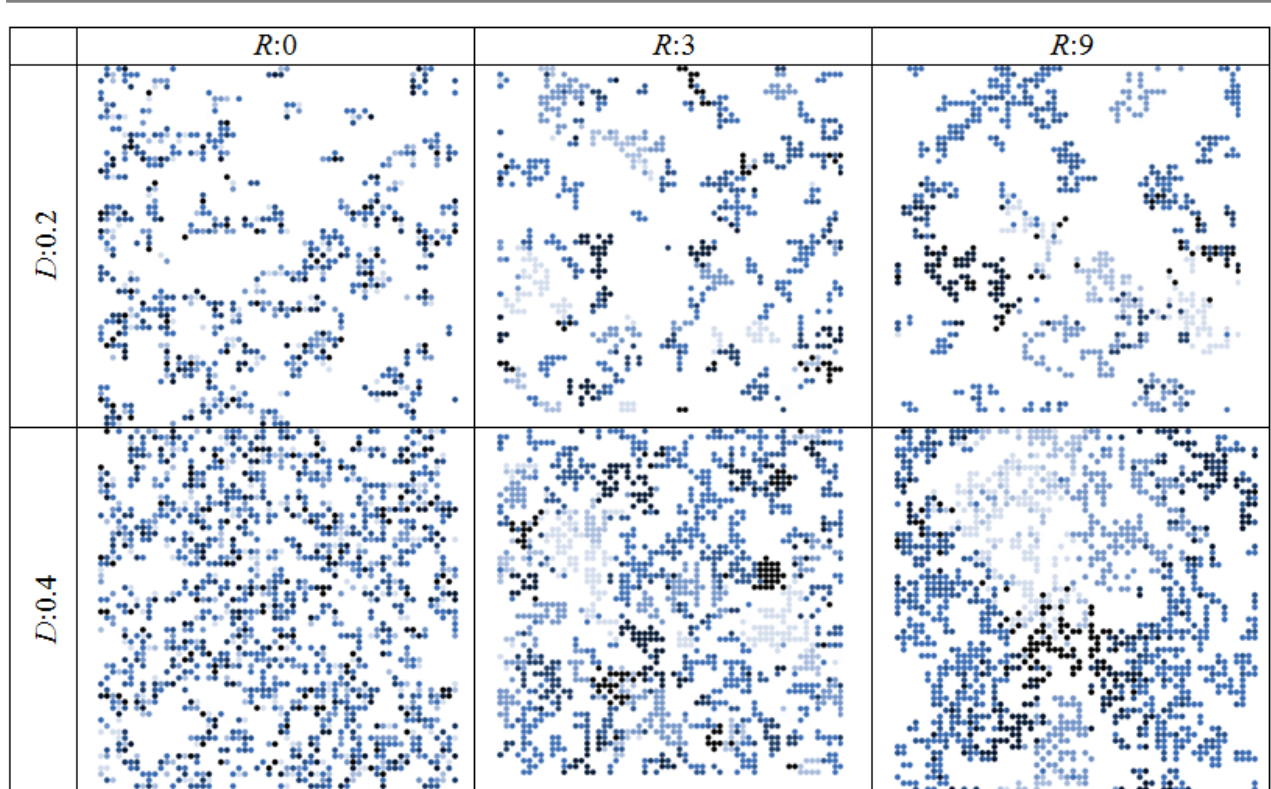| Construction year	<1918	1918-1948	1949-1957	1958-1968	1969-1978	1979-1983	1984-1994	1995-2001	2002-2006
Housing units [%]	14.7	12.4	11.4	14.0	12.7	6.1	12.4	12.1	4.0
Wall insulated [%]	35.1	30.3	33.0	35.7	41.9	46.8	47.0	60.7	64.3
Roof insulated [%]	59.0	60.3	69.2	71.2	81.6	85.2	92.3	96.6	97.4
Floor insulated [%]	22.9	17.4	20.8	21.0	37.7	41.2	61.7	75.4	83.9

3.9   The socio-spatial structure of an urban area is additionally based on the preference of similar[3] lifestyle groups for the same residential areas. For example, upper class residential areas are in higher demand among individuals with high economic and cultural resources (dimension 'level of living'). This results in residential segregation, the physical separation of groups into different parts of the urban environment (Massey & Denton 1988). The degree of residential segregation can be captured by dissimilarity indices, which indicate the evenness with which two groups of people are distributed across subareas of an entity. During our model initialization, homeowners are initially randomly distributed among the houses. Next, we use the following equation to calculate lifestyle X homeowners' satisfaction with their surroundings. The level of satisfaction (S_X) ranges from 0

(dissatisfaction) to 1 (maximum satisfaction).

$$S_X = \sum_{i=1}^{N_R} (1 - I_{XY_i}) \Big/ N_R \qquad (2)$$

3.10 N_R is the number of other homeowners in a given radius R. A large radius leads to a high level of residential segregation, and vice versa (see Table 4). In order to facilitate interpretation of later simulations, we then refer to R as the 'level of residential segregation'. I_{XY} are dissimilarity indices between lifestyle X and lifestyle Y for which the data is provided by Otte (2008) (see Appendix B, Table 9). Once each homeowner's level of satisfaction has been calculated, those with a satisfaction level of 1 remain at their chosen location. The remaining homeowners first leave the grid and then randomly choose a new house. Each round, the level of satisfaction needed for homeowners to remain falls by 0.001. This procedure, inspired by the famous Schelling model, finishes as soon as all homeowners have found a satisfactory place to reside.

3.11   Table 4 shows how the level of residential segregation and the population density affects socio-spatial structures. In the left panel, the level of residential segregation is lower than in the right panel, visible in the stronger clustering of homeowners of identical lifestyle groups, indicated by identical shades of color. The population density is higher in the bottom panel than in the top one.

Table 4: Examples of socio-spatial structures of different levels of residential segregation (R) and population density (D). The different shades of color represent homeowners of different lifestyle groups.

Social network

3.12   Once the socio-spatial structure has been arranged, the social network is established. The theoretical framework suggests that network ties in the model need to represent a relationship where homeowners influence each other's decision-making by sharing information on renovation. Rogers (2010) states that sharing information occurs most frequently among homophilous individuals. He defines homophily as "the degree to which pairs of individuals who interact are similar in certain attributes, such as beliefs, education, social status, and the like" (Rogers 2010, p. 18). Holzhauer et al. (2013) show how to consider homophily when generating social networks for agent-based modeling. Their algorithm considers that the probability of linking also depends on the geographical distance between potential partners. We adapted the algorithm from Holzhauer et al. (2013) to generate the social network. Otte's lifestyle concept is used to capture the degree of homophily between two individuals. Thus, the likelihood (P_{XY}) that a homeowner of lifestyle X links with another homeowner of lifestyle Y is described as follows:

$$P_{XY} = \frac{A_{XY}}{\Delta E^2} \qquad (3)$$

3.13 A_{XY} is the likelihood that homeowners of lifestyles X and Y will link if they come into contact with each other. Values for A_{XY} are provided by Otte (2008) (see Appendix B, Table 10). Low values in Table 10 stand for a low probability that two homeowners link if they come into contact with each other, such as in the case of conservative and entertainment seeking lifestyles. The empirically based likelihoods are employed to consider that the effectiveness of communication depends on who is communicating with each other. The probability that two homeowners will come into contact with each other decreases quadratically with the distance (ΔE) between them. The distance from one homeowner to another is measured from the center of one property to another. For adjacent properties, this is the side length of one patch corresponding to approximately 25 meters in the real world. The average number of links per homeowner generated this way is between two and four. This range is consistent with results of a survey in which data was collected on the number of relationships in a city through which households exchange their views and opinions on heating-related topics (Jensen et al. 2014).

Homeowners' decision-making processes

3.14 The theoretical framework shows that two events are of utmost importance when sketching the decision-making process of homeowners with regard to insulating their houses. First, there has to be an initiating occasion when homeowners start thinking about renovating their property. Homeowners then have to decide what type of renovation they wish to undertake. Table 5 provides an overview of the main elements of homeowners' decision-making processes concerning renovation. The table shows that a homeowner starts thinking about renovating, for example, if the structural condition of the house requires maintenance such as painting the facade. If the house does not have wall insulation, then painting the facade is an ideal opportunity for simultaneously installing wall insulation. We further consider that the decision regarding the type of renovation to undertake is delayed by financial constraints (Wilson et al. 2013).

Table 5: Inventory of situational factors, occasions and renovation activities. [1] Rather than standard glazing

When to start thinking about renovating			Deciding about which type of renovation to undertake	
Situational factors		Occasions	Standard renovation	Combinable insulation
Structural condition of house	Financial constraints	Maintenance	Standard glazing	Insulating glazing[1]
			Exterior rendering	Wall insulation
			Facade painting	
			Roof renewal	Roof insulation
			Heating system renewal and queuing standard renovations	Queuing (combinable) insulation
		Attic extension	Roof renewal	Roof insulation
Socio-demographic situation		House purchase	Queuing standard renovations	Queuing (combinable) insulation
			Basement extension	Floor insulation

3.15 We now describe how the two events 'When to start thinking about renovating' and 'Deciding about which type of renovation to undertake' were implemented into the model. In the model, a decision-making process can be triggered in each tick, which represents one month.

When to start thinking about renovating

3.16 Homeowners start to think about renovating their property when a renovation occasion occurs. Stieß and Dunkelberg (2012) list three main occasions: 1) purchase of a building, 2) extensions/alterations and 3) maintenance/repair. According to Stieß and Dunkelberg (2012), such particular situations are associated with the condition of a building and the homeowner's socio-demographic situation/phase of life. Data on average occupancy periods was used to estimate the distribution of points in the homeowners' lifetime when they purchase new buildings (DCLG 2010). Homeowners contemplate extending the attic if more space is required due to an addition to the family, which is affected by the homeowners' age. It is assumed that a basement extension is only considered if no other measures are carried out after the house purchase. Maintenance/repair is required when the building components reach the end of their lifetime. For this purpose the advancing age of buildings components over time is considered by the model.

3.17 We assume that renovation occasions always lead to the associated renovation activities. In particular, financial constraints do

not fully hamper renovation activities, but merely delay them. Thus, the period between thinking about renovating and undertaking the measures is prolonged due to financial constraints (Wilson et al. 2013). The following equation is used to determine the period between these two events, measured in years (T_h):

$$T_f[a] = F \cdot T_a[a] \cdot \frac{I_a[=\Box a]}{I_h[=\Box a]} \qquad (4)$$

3.18   The average length of time taken by homeowners o think about renovating before taking action (T_a) was estimated to be 0.5 years, based on findings by Wilson et al. (2013). I_h is each homeowner's net income, and I_a is the average net income of all homeowners (approximately € 39,600 per year). The impact of financial constraints on the period between thinking about renovating and taking action is varied by applying parameter F.

Deciding about which type of renovation to undertake

3.19   In this step, homeowners decide whether or not to insulate their houses as presented in Table 5. A precondition that insulation measures are considered is that either the lifetime of existing insulation has expired or no insulation has yet been installed. The decision then depends on 1) the perceived value of information and 2) homeowners' attitudes towards insulation. A homeowner will therefore decide to have insulation installed if its perceived utility becomes positive. Perceived utility is defined by the sum of the homeowner's individual attitude towards insulation and the perceived value of information.

3.20   The perceived value of information received through social networks depends on the effectiveness of communication, the closeness in time and space, and the number of people in the social network (Latane 1981). The factors 'closeness in space' and 'effective communication' are already taken into account in the algorithm used to establish the social network. Thus, the composition of the social network considers the geographical distance between homeowners and network ties represent relationships where homeowners can influence each other's decision-making. The remaining two factors, 'closeness in time' and 'number of people in the social network', were incorporated in a calculation of the perceived value of information (I_h) (see Equation 5).

$$I_h = \frac{W}{N} \cdot \sum_{i=1}^{N} \frac{F_i[a]}{T_i[a]} \cdot N^{0.6} \qquad (5)$$

3.21   The time that has elapsed since network contacts last renovated (T_i) is used to capture 'closeness in time'. Thus, the perceived value of information received through individual network contacts decreases with the time that has elapsed since they last renovated. Further, we adopt Latane's (1981) finding that the perceived value of information provided by individual contacts decreases in line with an increasing total number of network contacts (N) by employing an exponent of 0.6. In the absence of more accurate data, the specific value of 0.6 was estimated by the authors based on experimental findings from Latane (1981). F_i is −1 if the network contact's perceived utility is negative and +1 if the network contact's perceived utility is positive. In this way, we consider that the information received can be in favor of or against having insulation installed. W is a weighting factor for information received, used later in the simulation experiments. For W to equal one, the homeowner's perceived value of information attains a value of 2.3 if four out of four network contacts had insulation installed within the last year. Typically, values range between −1 and +1.

Insulation activity indicators

3.22   The annual insulation rate (I_{1a}) is a widely used dimension to track insulation activity (Lechtenböhmer & Schüring 2011; Olonscheck et al. 2011; Weiss et al. 2012). It is calculated as follows (Diefenbach et al. 2010):

$$I_{1a} = (25\% \cdot N_{ro,ins} + 50\% \cdot N_{wa,ins} + 12\% \cdot N_{fl,ins} + 13\% \cdot N_{wi,ins})/N_h \quad (6)$$

3.23 $N_{ro,ins}$, $N_{wa,ins}$, $N_{fl,ins}$, $N_{wi,ins}$ is the number of houses where roof, wall and floor insulation and insulating glazing were installed over a one-year period. N_h is the total number of houses. Diefenbach et al. (2010) set the weightings of the measures (percentages in the equation) according to their contribution to resulting energy savings. The annual insulation rate is our main indicator for tracking homeowners' insulation activity. It is calculated considering all homeowners in the model. We also capture lifestyle-specific insulation rates ($I_{1a,s}$). Further, we track the development of the insulation condition of buildings by means of the insulation backlog (share of building components with outdated or nonexistent insulation). The insulation backlog (B) is calculated as follows:

$$B = (25\% \cdot N_{ro,ba} + 50\% \cdot N_{wa,ba} + 12\% \cdot N_{fl,ba} + 13\% \cdot N_{wi,ba})/N_h \quad (7)$$

3.24 $N_{ro,ba}$, $N_{wa,ba}$, $N_{fl,ba}$, $N_{wi,ba}$ is the number of houses where the roof, wall and floor insulation and insulating glazing is

outdated or nonexistent. The weightings are identical to those used to calculate the insulation rate. The insulation backlog represents the remaining energy-saving potential that can be achieved by installing insulation. An insulation backlog of 30 per cent, for example, means that only two-thirds of the present energy-saving potential that can be achieved by installing insulation is exhausted.

Experimental design and model results

4.1 During the simulation experiments we explored how homeowners' insulation activity varies between socio-spatial structures. Further, we explored homeowners' insulation activity over time. In order to ensure that the analysis was comprehensive, we selected parameters for variation that influence the main elements of homeowners' decision-making processes, identified by developing the theoretical framework of the model. In the following, we introduce the setting of the experiments including their setup, execution and design, and provide an overview of the experiments conducted. Subsequently, we present and discuss the results of the simulation experiments.

Experimental design

Setup and execution

4.2 The simulation experiments were conducted as follows: during model initialization, 1) an artificial socio-spatial structure was created, 2) a social network was established, and 3) a preparatory simulation phase was executed. This preparatory simulation phase was necessary because agents' perceived utility is mutually dependent and cannot be consistently defined up-front. The formation of perceived utility resulted in a significant fluctuation of homeowners' insulation activity during the first steps of the model. We therefore ran the model until the distribution of homeowners' perceived utility to have insulation installed had settled. After this preparatory simulation phase, the homeowners' socio-technical attributes were set back to the base year, while retaining the distribution of perceived utility.

4.3 The simulation spanned ten years, with 120 time steps, each representing a month. Although insulation is a long-term investment, we argue that the simulated period of ten years is sufficient. In order to explore homeowners' present insulation activity, therefore, it was not necessary to look far into the future. However, the period had to be long enough to ensure that a statistically relevant number of renovations were conducted by homeowners from each lifestyle group. This condition had to be met in all simulation experiments. A period of five years was found to be too short due to the delaying effect that financial constraints have on homeowners' insulation activity, explored in one of the simulation experiments. More than 50 per cent of homeowners renovated at least once over a ten-year period. This includes standard renovation measures such as renewing the roof or the facade, and partial insulation measures such as insulating the wall or the floor only.

Experiments

4.4 In order to determine suitable parameter ranges and parameter combinations for our experiments, we used Latin Hypercube Sampling (LHS), "a statistical technique that guarantees uniform sampling with the desired granularity of the scenario space given in a Y dimensional parameter space and with a limit of X experiments" (van Dam et al. 2012, p. 110). For our purpose, LHS considers the five global parameters and finds where in the parameter space the predifined number of 1,000 experiments should be performed to get the most representative subset of the space. In line with suggestions by Werker and Brenner (2004), we specified wide parameter ranges for LHS:

- The 'population density' (D) was varied from 20 per cent (rural area) to 40 per cent (urban area). In the densely populated city of Munich, for instance, the area taken up by buildings and (related) open spaces makes up 44 per cent of the whole area (Kizlauskas 2011).
- The 'level of residential segregation' (R) was varied from 0 (no residential segregation) to 10 (high level of residential segregation). When R is 10, there is virtually no mixing between homeowners of different lifestyles (see Table 4).
- The 'average attitude towards insulation' (A) was varied from −0.5 to +0.5. The simulation results (see Fig. 3) show that there is virtually no insulation activity below an average attitude of −0.4. Above +0.4, the range of possible results remained unchanged.
- The parameter 'weighting of information received' (W) was varied from 0 (information received has no impact on the decision to insulate) to 10. At a value of 10, homeowners' perceived value of information typically ranged from −10 to +10. Since the second parameter that influences the decision to insulate – the attitude towards insulation – ranged from −1 to +1 (taking into account the variation of the average attitude), giving W a value of 10 significantly enhanced the assumed impact of the information received about the decision whether or not to insulate.
- The 'impact of financial constraints' (F) on the length of time between thinking about renovating and taking action was varied from 0 (no impact) to 10. Giving F a value of 10 delayed homeowners' decisions to renovate by five years on average.

4.5   In order to explore the influence that different parameter combinations have on homeowners' insulation activity, we ran simulations, tracked the annual insulation rate, and calculated its average over ten years (I_{10a}). The use of a ten-year average for the insulation rate was found to be sufficient for exploring the parameter space. Homeowners' insulation activity over time was explored in the context of the more detailed analysis. As with the other simulation experiments, the simulation was repeated 50 times for each combination of parameter settings so as to be able to analyze the variety of outcomes. For the analysis, we determine the median[4] of the 50 different outcomes. By determining the median outcome of experiments with ten repetitions, we found that they differed too much to be able to draw statistically verified conclusions. In contrast, the median outcome of experiments with 100 repetitions was found to be similar. Figure 3 shows the simulation results of applying LHS.
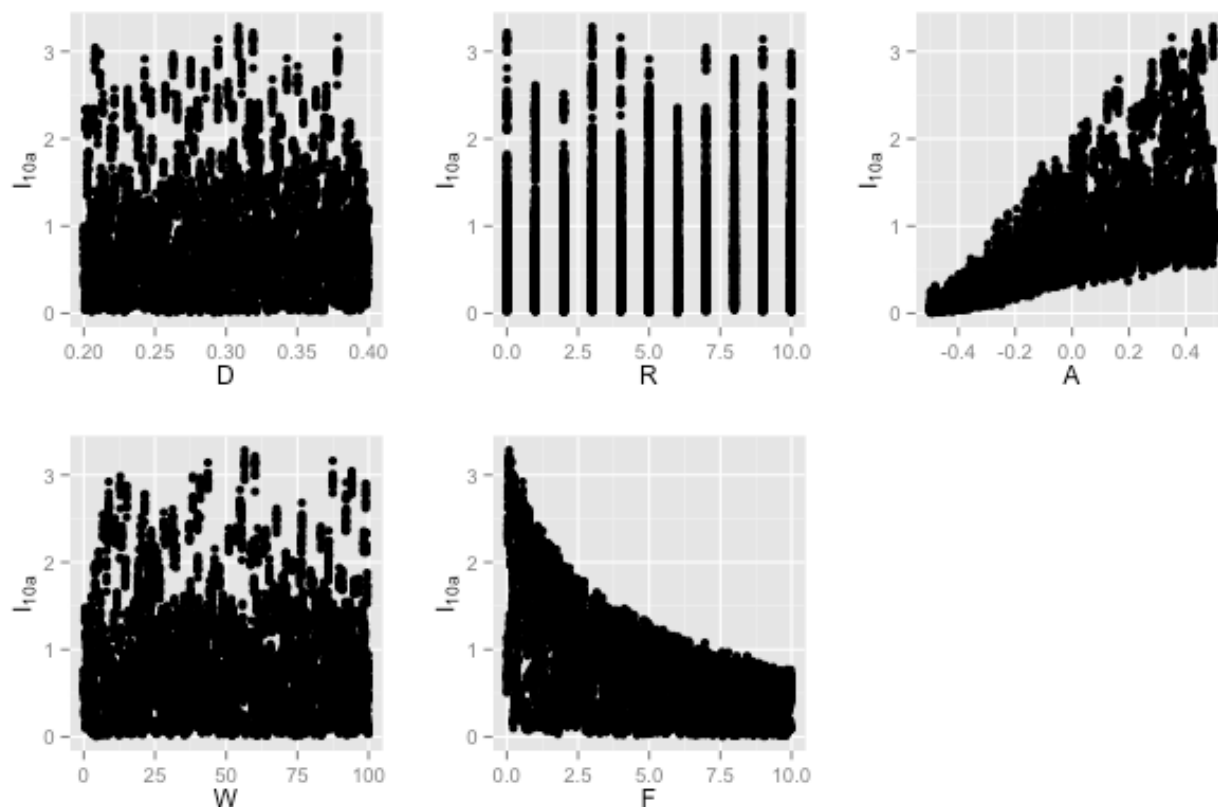

Figure 3. Simulation results of applying the Latin Hypercube Sample (LHS). The vertical axis represents the ten-year average of the median of insulation rates (I_{10a}) depending on variations of the different parameters.

4.6   The simulation results of applying LHS were used to design the experiments as described below. An overview of the design of the experiments is given in Table 6. The preliminary results revealed a correlation[5] between insulation activity and average attitude (A). In addition, the same average attitude can lead to different results (range of over 2 percentage points). Consequently, the average attitude was varied throughout the experiments. Figure 3 shows that the impact of financial constraints (F) can limit the average insulation rate. In the first experiment (1), we explored the role of financial constraints in more detail by capturing the development of the annual insulation rate (I_{1a}) over time while varying the impact of financial constraints. Since we expected the insulation backlog (B) to be responsible for the partly high ten-year average insulation rate of over 3 per cent, its development was also captured. We adopted this approach because we expected the delay effects of financial constraints to become most visible when seen from a temporal perspective. In the second experiment (2), we explored whether homeowners' insulation activity varies between different socio-spatial structures. In our model, the socio-spatial structures varied in terms of 'population density' (P) and the 'level of residential segregation' (R).

4.7   We then refined the analysis and additionally investigated insulation activity among homeowners of different lifestyles (2.1) and the influence of different levels of social impact affected by the 'weighting of information received' (W) (2.2). In order to make it easier to analyze the results of the second simulation experiment, we determined the ten-year average of the median of the insulation rates captured (I_{10a}, $I_{10a,s}$).

Table 6: Design of simulation experiments.

Simulation experiments	Parameters varied	Indicators captured
(1) Insulation activity over time	A, F	I_{1a}, B
(2) Insulation activity in different socio-spatial structures	A, D, R	I_{10a}
(2.1) Lifestyle groups	A, D, R	$I_{10a,s}$
(2.2) Social impact	A, D, R, W	I_{10a}

Insulation activity over time

4.8   We explored insulation activity over time in order to examine the effect of financial constraints on homeowners' insulation activity and to determine whether the insulation backlog (B) is the factor that led to the partly high ten-year average insulation rate of over 3 per cent. Figure 4 shows the development of the annual insulation rate and the insulation backlog over time. The impact of financial constraints (F) was varied from 0.1 to 10. The average attitude (A) was varied from −0.3 to +0.3, depicted by the color of the lines.
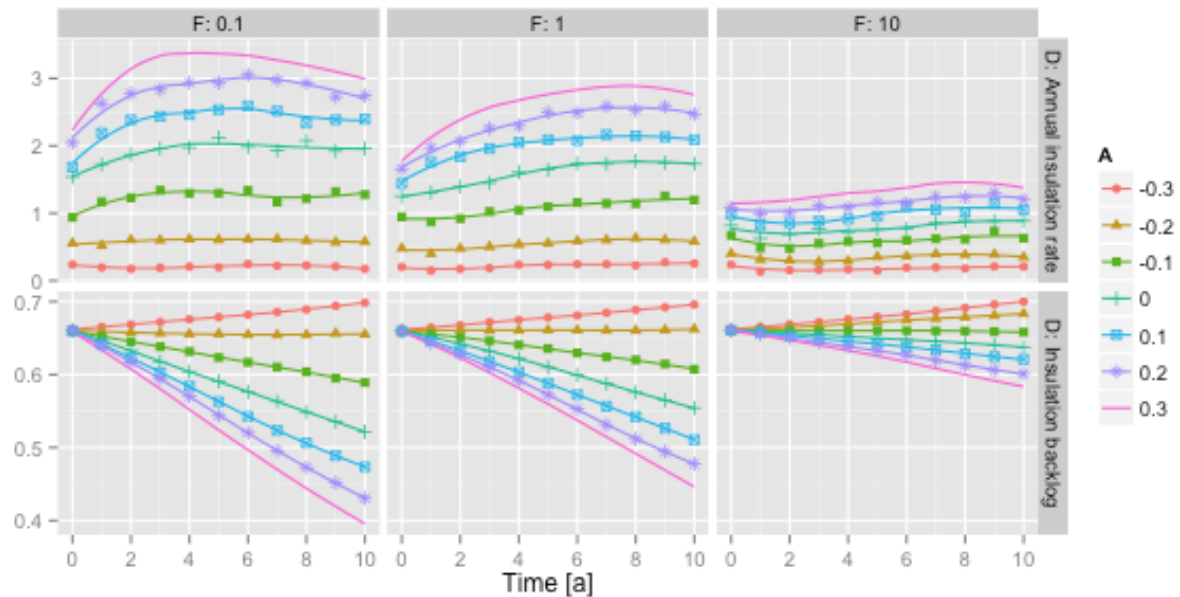

Figure 4. Insulation backlog and annual insulation rate over a ten-year period for different levels of average attitude (A) and varying impact of financial constraints (F).

4.9   The simulation results show that a considerably high insulation rate is possible by reducing the insulation backlog. The fact that a large portion of insulation installed will reach its respective lifetime over the next few years (see Fig. 5) caused an increase in the insulation rate during the first years of the simulation period in all cases. The simulations further show that changing the impact of financial constraints has a greater effect at high levels of average attitude, which result in a high share of decisions in favor of insulation. Here, reducing the influence of financial constraints led to more insulation measures being undertaken in a shorter period of time. Accordingly, this resulted in a faster depletion of the insulation backlog.

4.10   However, the simulation results show that reducing or increasing the impact of financial constraints at a low insulation rate of about 1 per cent (with an average attitude of about −0.1), the current rate in Germany, has only a minor impact on homeowners' insulation activity.
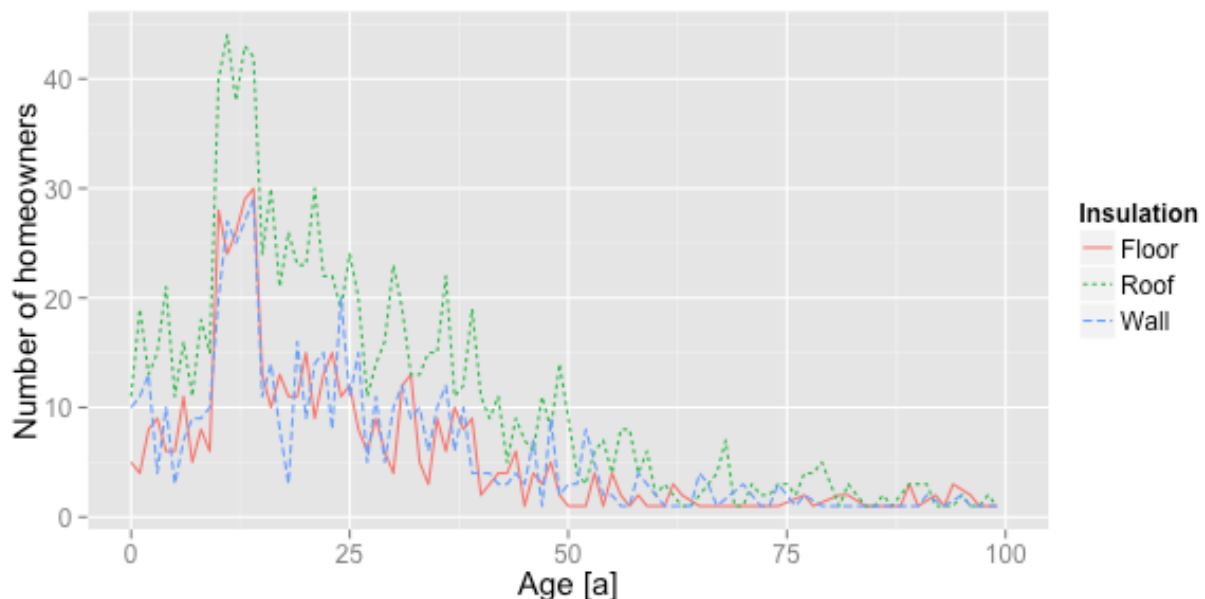

Figure 5. Exemplary age distribution of insulation installed by 1,440 homeowners (D:0.4) at the start of the simulation.

Insulation activity in different socio-spatial structures

4.11   In the second experiment, we recorded the ten-year average of the median of insulation rates in different socio-spatial structures and the values of average attitude (A), as presented in Figure 6.
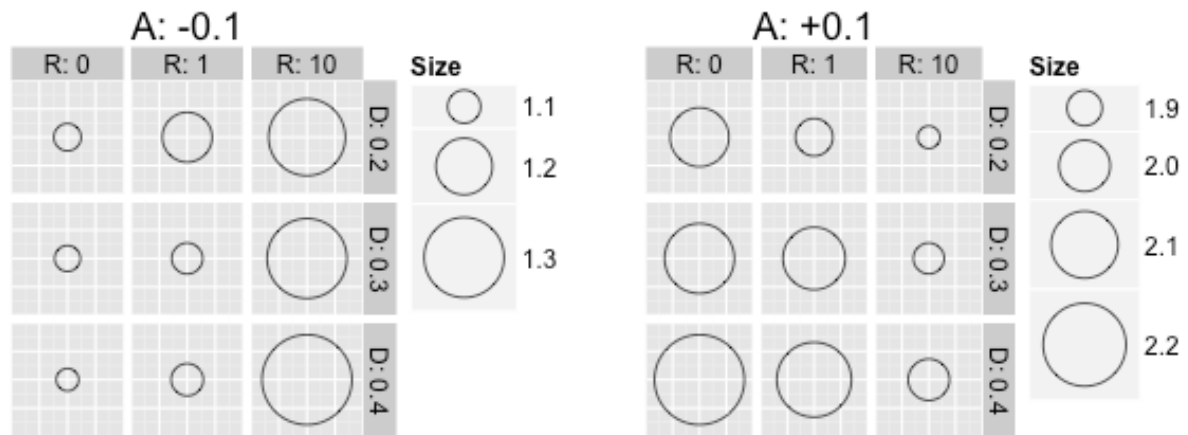

Figure 6. Insulation activity in socio-spatial structures. The size of the dots represents the ten-year average of the median of insulations rates (I_{10a}).

4.12   The simulation results show that socio-spatial structures influence homeowners' insulation activity. We found that a low level of residential segregation (low value for R) facilitated the diffusion of the dominant renovation behavior. The dominant renovation behavior was defined as the kind of decision (in favor of or against insulation) taken by the majority of homeowners. With an average attitude of +0.1, the dominant renovation behavior was to decide in favor of having insulation installed. This behavior was reinforced at a low level of residential segregation, as is apparent in the figure from the comparatively high levels of insulation activity. Here, the ten-year average of the median of insulation rates (I_{10a}) is around 1 per cent at a low level of residential segregation (R:0) but reaches 1.3 per cent at high level of residential segregation (R:10). With an average attitude of −0.1, the dominant renovation behavior was to reject the idea of having insulation installed. This behavior was reinforced at a low level of residential segregation, as is apparent in the figure from the comparatively low levels of insulation activity. At a high level of residential segregation, a reinforcement of the dominant (negative) renovation behavior was almost absent. We argue that this is because a high level of residential segregation leads to the formation of clusters of homeowners with a similar attitude, which are less prone to the impact of network contacts with opposing attitudes. This results in a greater heterogeneity of renovation behavior in the modeled environment.

4.13   A high population density (high value for D) leads to a network structure where the average number of contacts per homeowner is higher than in the case of a low population density. As a result, homeowners who live in areas with a high population density are influenced by social interaction to a greater extent (cf. Equation 5). In addition, the high network density facilitates the diffusion of the dominant renovation behavior. As a consequence, we noticed that increasing population densities led to increasing levels of insulation activity in line with increased average attitude. This phenomena became more apparent in Video 1 in Appendix A by varying the average attitude in single steps (+0.1 per step) from −0.4 to +0.4. With an average attitude of −0.4, the highest level of insulation activity was obtained with a low population density of 0.2; with an average attitude of +0.4, it was obtained with a high population density of 0.4.

Lifestyle groups

4.14   In order to analyze the effect of socio-spatial structures on homeowners' insulation activity in greater detail, we further recorded lifestyle-specific insulation rates. Figure 7 presents the results of the simulations we ran.
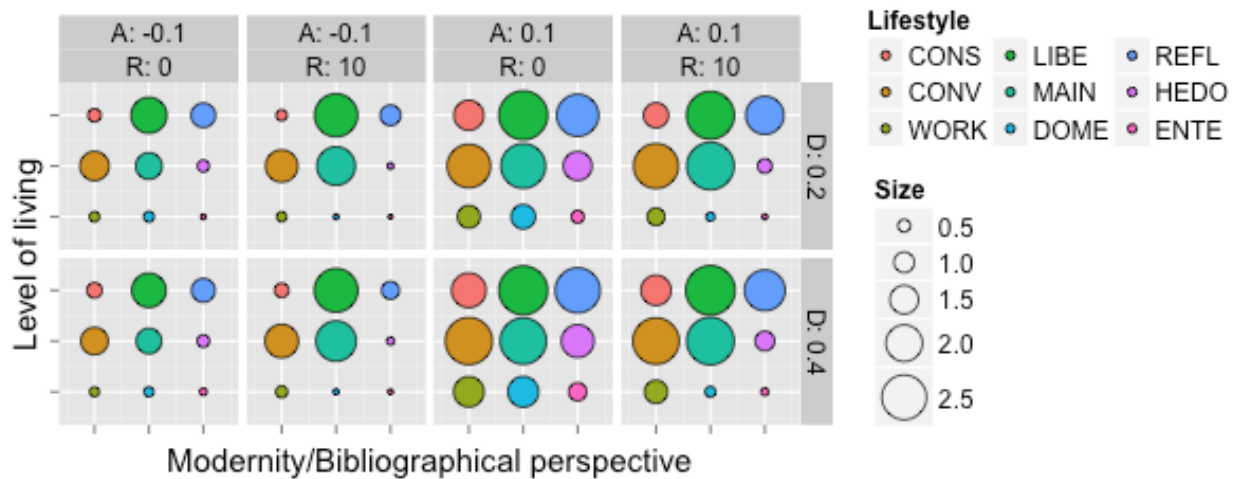
Figure 7. Diffusion of insulation activity among lifestyles. The size of the colored dots represents the ten-year average of the median of lifestyle-specific insulation rates ($I_{10a,s}$). The dots are shown in the same order as the legend sequence. For an explanation of the abbreviations of the nine different lifestyles, see Table 2.

4.15   By determining standard deviations between the nine lifestyle-specific insulation rates for the same parameter combinations, we found that they decrease as the level of residential segregation decreases (lower values for R). This confirmed the previous finding that a low level of residential segregation facilitates the diffusion of the dominant renovation behavior between homeowners of different lifestyles, and vice versa. A low level of residential segregation enables lifestyles such as Established Conservatives, Traditional Workers, Domestically Centered, Hedonists, and Entertainment Seekers to build network contacts to lifestyles with a more positive attitude towards insulation such as Conventionals, Established Liberals, Adaptive Mainstream, and Reflectives. Consequently, in cases of a positive average attitude, more homeowners decide to have insulation installed. If the average attitude is negative, the same effect leads to a lower level of insulation activity. The simulation results further indicate that a higher population density induces a greater diffusion of the dominant renovation behavior. This phenomena became more apparent in Video 2 in Appendix A by varying the average attitude in single steps (+0.1 per step) from −0.4 to +0.4.

Social impact

4.16   Within the different socio-spatial structures, we further distinguished between different 'weightings of information received' (W) in order to investigate the effect they have on homeowners' insulation activity. In the simulation experiments, we varied the average attitude (A) in single steps (+0.1 per step) from −0.4 to +0.4 and parameter W within a range from 0 to 10 (0,1,10) (see Video 3 in Appendix A). Figure 8 shows the simulation results for an average attitude of −0.2 and −0.3, which are of particular interest for our analysis.
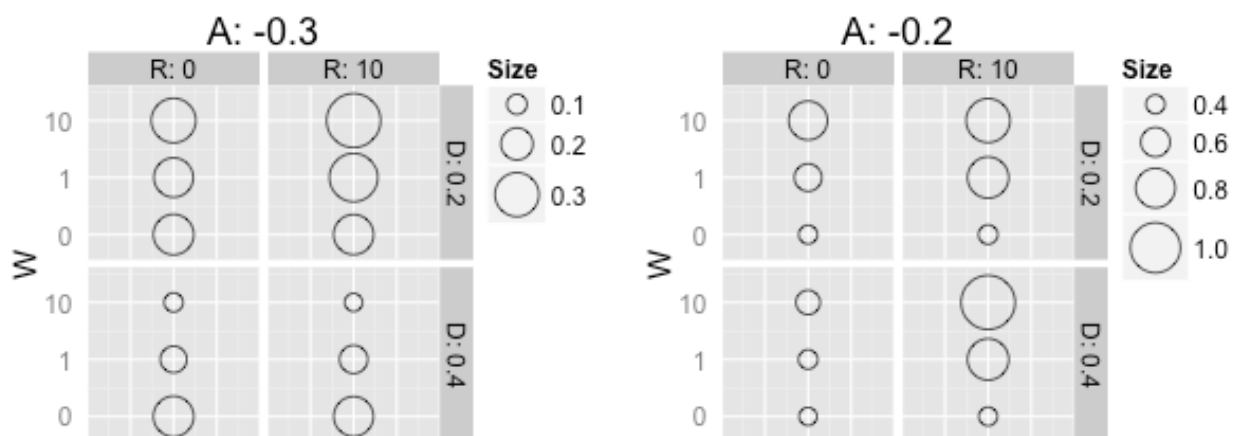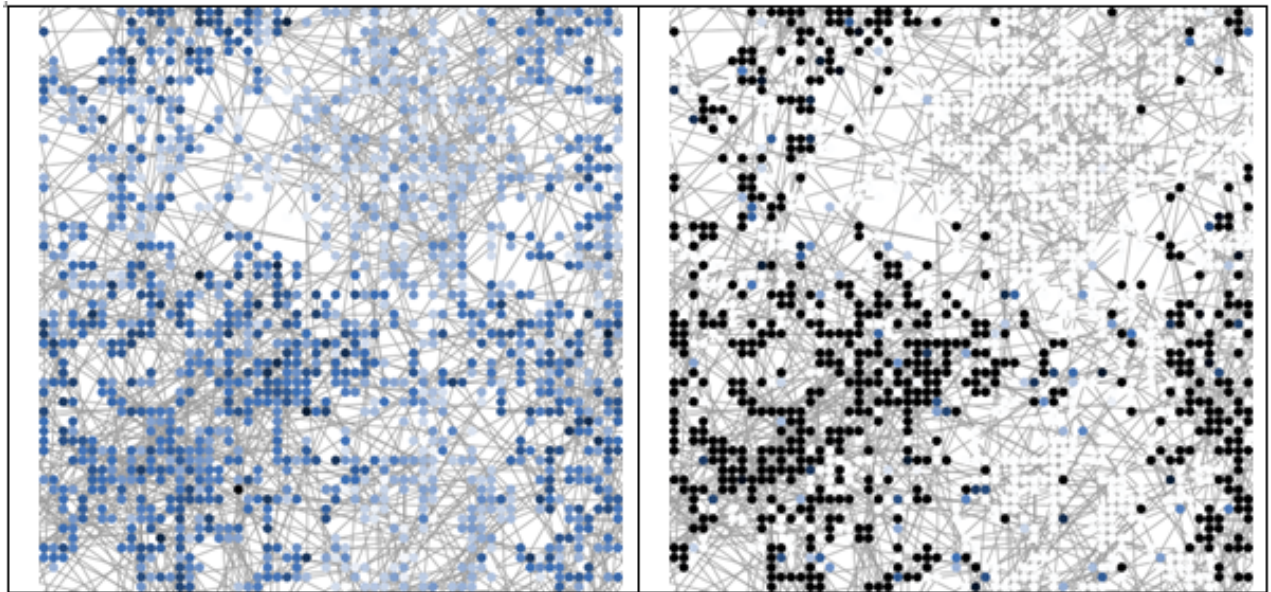

Figure 8. Importance of social interaction. The size and color of the dots represent the ten-year average of the median of insulations rates (I_{10a}).

4.17   High values for W were found to enforce the particular effects that socio-spatial structures have on homeowners' insulation activity. A high weighting of information received led to a stronger separation between adopters and rejecters of insulation. If the specific socio-spatial structure had a positive effect on homeowners' insulation activity, e.g. with a high residential segregation and a negative average attitude, the effect was enforced by a stronger separation between adopters and rejecters of insulation (see Table 7). Thus, additional contacts within adopters' networks are also convinced into insulating their homes.

4.18   The enforcing effect of W enabled us to identify the point from which an effect on insulation activity emerges from specific socio-spatial structures. The 'neutral point', where W had virtually no influence on homeowners' insulation activity, was found to be between parameter combinations A:−0.2, R:0, D:0.4 and A:−0.3, R:0, D:0.2. In all of the other parameter combinations, W either led to a decrease (e.g. at A:−0.3, R:0, D:0.4) or an increase (e.g. at A:−0.2, R:10, D:0.4) in homeowners' insulation activity.

4.19   The fact that the insulation rate in Germany is above the point where socio-spatial structures have no influence on homeowners' insulation activity (at the 'neutral point', the insulation rate is in the range of 0.3 and 0.4 per cent) indicates that the conditions for a diffusion of insulation activity may vary substantially between regions with different socio-spatial structures.

Table 7: Exemplary illustration of homeowners' perceived utility of having insulation installed for different 'weightings of information received' (W) (left W:0, right W:10) indicated by different shades of color. The darker (brighter) the dots, the higher (lower) the homeowners' perceived utility. In this example, the share of homeowners with a perceived utility greater than zero is 31 per cent (43 per cent) for W:0 (W:10).

Discussion and conclusion

5.1   In this paper, we developed a theoretical framework to capture homeowners' decision-making processes with regard to having their houses insulated, and translated it into an agent-based model (ABM) to explore how situational factors and social interaction influence their insulation activity.

5.2   In this section, we discuss the validity of the model and, based on the simulation results, provide recommendations for designing innovative policy instruments that acknowledge the important role played by the aforementioned factors in homeowners' renovation decisions. Further, we propose avenues for future research.

Model validity

5.3   At an early stage of its development, the model was presented and discussed at the SSC 2014 in Barcelona (Friege & Chappin 2014b). In addition, the structural design of the model and the consistency of the preliminary simulation results were validated at a workshop with building insulation and consumer behavior experts. The design of the model was based on insights gained from a bibliographic analysis (Friege & Chappin 2014a), empirical findings on homeowners' decision-making concerning insulation, and insights from consumer behavior literature. In order to ensure a realistic representation of real-world conditions, we used empirical data on the structural condition of houses in Germany and homeowners' socio-demographic situation. Uncertain parameters were varied in simulation experiments to evaluate the impact they have on the results. For a number of parameter combinations, the model reproduced Germany's present annual insulation rate of about 1 per cent, leading us to place even greater confidence in the overall validity of the model.

Situational factors

5.4   Situational factors play an important role in homeowners' insulation activity, because they trigger renovation occasions, which were identified as a requirement for homeowners to undertake standard renovation measures and consider insulating their homes. Consequently, homeowners' insulation activity is potentially higher in areas with many buildings in need of renovation and insulation, an active housing market (short occupancy periods), and a low level of financial constraints (e.g. due to a high

average income). Out of these situational factors, policies may address the impact of financial constraints, e.g. by offering subsidies for renovation, as is the case in existing policy instruments. However, our simulations indicate that reducing financial constraints only has a small potential to increase Germany's insulation rate above its current level of 1 per cent, although Germany's insulation backlog would allow an insulation rate of up to 3 per cent for a limited period of time.

5.5   In order to increase the number of households having insulation installed, additional instruments are required to encourage homeowners to include insulation in the renovation process. Such instruments should focus on the times when occasions occur and should raise awareness of the benefits of insulating homes. This could be achieved, for example, by incentivizing lenders and craftsmen to advise homeowners on having insulation installed.

Social interaction

5.6   The simulation experiments show that the socio-spatial structure is relevant for the diversity of insulation activities among homeowners of different lifestyles. We found that a low level of residential segregation facilitates the diffusion of the dominant renovation behavior, i.e. the decision (in favor of or against insulation) made by the majority of homeowners is reinforced. Such reinforcement is virtually absent at high levels of residential segregation. These findings are consistent with the work by Choi et al. (2010), who compared the diffusion of innovations in a highly cliquish network and a network with more random bridges (Choi et al. 2010). Further, high population densities also facilitate the diffusion of the dominant renovation behavior. The degree of influence of social interaction on homeowners' individual decision-making determines how strong these effects of socio-spatial structures are on the diffusion of the dominant renovation behavior.

5.7   In conclusion, the success of policy instruments aiming at increasing homeowners' insulation activity in a specific region may be highly dependent on the existing socio-spatial structure. Thus, we recommend considering the local situation before carrying out information campaigns, on-site consultation of homeowners, or other spatially delimited measures. Since social network contacts have a strong influence on homeowners' decision-making with regard to insulation, harnessing social networks to promote the installation of insulation is a promising option for increasing homeowners' insulation activity. Relevant measures could include money-back vouchers for adopters, which they pass on to other homeowners or open house events for neighbors of homeowners who recently had their houses insulated.

Future research

5.8   The results of the simulation experiments enable general recommendations to be derived for the design of innovative policy instruments. However, the results indicate that homeowners' insulation activity depends largely on their attitude towards insulation and the impact of social interaction on their decision to insulate, which were varied throughout the experiments due to insufficient data. In order to adequately evaluate the effectiveness of specific policy instruments aiming at increasing homeowners' insulation activity using agent-based modeling, therefore, the distribution of homeowners' attitudes towards insulation and the impact social interaction has on the individual's decision to insulate must be calibrated by conducting empirical research. Due to our finding that local socio-spatial structures can influence homeowners' insulation activity, we further recommend implementing more specific socio-spatial structures when aiming to evaluate specific policy instruments.

5.9   Finally, we hope that our work leads to a better understanding of homeowners' decision-making regarding having their houses insulated, and that it encourages the development of more effective policies aiming at stimulating insulation activity, as required to meet climate protection targets.

Notes

[1]The term 'standard renovation measure' is later used to refer to such measures that do not improve the insulation of the house.

[2]If, for example, the house age is 110 years and a component's lifetime is 50 years, the age of the component is assumed to be 110 minus two times 50 years.

[3]Here, similarity means close to each other in Otte's two-dimensional lifestyle typology.

[4]We use the median rather than the average to account for a distribution of the simulation results that is not necessarily symmetrical.

$^5\mathrm{corr}(A, I_{10a}) = 0.70$, p-value < 2.2e–16

Appendix A: Supplementary results

Video1

Video 1. Insulation activity among socio-spatial structures. The size and color of the dots represent the median of the average insulation rate over a ten-year period (I_{10a}). When playing the video, the average attitude (A) is varied from −0.4 to 0.4

Video 2

Video 2. Diffusion of renovation behavior among lifestyles. The size of the dots represents the median of the lifestyle-specific insulation rate over a ten-year period ($I_{10a,s}$). When playing the video, the average attitude (A) is varied from −0.4 to 0.4.

Video 3

Video 3. Importance of social interaction. The size and color of the dots represent the median of the average insulation rate over a ten-year period (I_{10a}). When playing the video, the average attitude (A) is varied from −0.4 to 0.4.

Appendix B: Supplementary data

Table 8: Lifetime of building elements. [1] With more than 95 per cent of the values within the lifetime boundaries provided by Agethen et al. (2008).

Building elements	Lifetime [a]	Distribution[1]
Roof insulation	30-50	N(40,5)
Wall insulation	30-50	N(40,5)
Floor insulation	30-50	N(40,5)
Roofing	40-60	N(50,5)
Windows[2]	20-40	N(30,5)
Heating system	15-25	N(20,2.5)
Exterior rendering	35-65	N(50,7.5)
Facade painting	10-20	N(15,2.5)

Table 9: Dissimilarity indices (I_{XY}) for the different lifestyles provided by Otte (2008). For an explanation of the abbreviations of the nine different lifestyles, see Table 2.

[%]	CONS	CONV	WORK	LIBE	MAIN	DOME	REFL	HEDO	ENTE
CONS	0	13	15	9	13	20	12	15	22
CONV	13	0	12	10	10	14	23	20	20
WORK	15	12	0	13	8	12	20	11	8
LIBE	9	10	13	0	6	19	13	12	20
MAIN	13	10	8	6	0	19	19	13	14
DOME	20	14	12	19	19	0	24	15	12
REFL	12	23	20	13	19	24	0	14	26
HEDO	15	20	11	12	13	15	14	0	12
ENTE	22	20	8	20	14	12	26	12	0

Table 10: Values A_{XY} used to generate the social network provided by Otte (2008). For an explanation of the abbreviations of the nine different lifestyles, see Table 2.

[%]	CONS	CONV	WORK	LIBE	MAIN	DOME	REFL	HEDO	ENTE
CONS	23	3	10	26	8	3	21	5	3
CONV	13	18	13	17	27	4	4	4	1
WORK	0	24	24	4	16	22	0	4	7
LIBE	11	8	2	23	18	4	17	14	2
MAIN	4	11	5	11	26	11	9	17	6
DOME	1	14	16	5	17	25	1	10	11
REFL	6	1	0	15	11	4	28	31	4
HEDO	2	4	2	7	20	7	11	34	15
ENTE	0	1	3	1	16	21	7	23	28

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