Exploring homeowners' insulation activity
ODD protocol

[redacted]

In the following, the agent-based model is described by using the ODD (Overview, Design, concepts, Details) protocol (Grimm et al. 2010). A model overview is given in the subsections purpose, state variables and scales, and process overview and scheduling. In the following we describe different design concepts applied in the model such as emergence, sensing, and interaction. The model description closes with providing more details about the model including initialization and submodels.

1 Overview

1.1 Purpose

We built an agent-based model to foster the understanding of homeowners' decision-making processes with regard to having their houses insulated and to explore in what ways situational factors and social interaction influence their insulation activity.

1.2 State variables and scales

The actors in the socio-technical system are represented as agents in the model. The main actors we are looking at are owner-occupier households with decision-making power regarding investments in insulation. Even though households may consist of several individuals (parents, children etc.) we treat households as single entities. 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.

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 1). 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.

1 [redacted]

Table 1 Otte's lifestyle-typology, horizontal: modernity/biographical perspective, vertical: level of living.

High	Established Conservatives (CONS)	Established Liberals (LIBE)	Reflectives (REFL)
Middle	Conventionals (CONV)	Adaptive Mainstream (MAIN)	Hedonists (HEDO)
Low	Traditional Workers (WORK)	Domestically Centered (DOME)	Entertainment Seekers (ENTE)
	Traditional/biographically closed	**Partially modern/consolidated**	**Modern/biographically open**

Both, social and technical attributes are distributed amongst the homeowners based on empirical observations (see Table 2, 3, 4).

Temporal resolution of the model are monthly time steps. The simulations cover a time period of ten years.

Spatial resolution is a two-dimensional rectangular plane with site length 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. Each homeowner has a static position. The position is of importance since the probability of social interaction depends, inter alia, on the spatial proximity between two homeowners.

1.3 Process overview and scheduling

The initialization of the model consists of the procedures 'set houses', 'set owners', 'set homeowners', and 'set network'. The model consists of the sub-models 'When to start thinking about renovating' and 'Deciding about which type of renovation to undertake', which are called successively at each time step.

2 Design concepts

Basic principles in the model are derived from behavioral theories and literature on renovation decisions. Therefore, homeowners decide in favor of insulating their property if situational factors trigger a renovation occasion, and if attitude and perceived value of information result in positive perceived utility towards installing insulation (see Section 3.2).

Emergence occurs as diffusion of insulation activity. When particular characteristics of the individual (e.g. their attitude) or of the environment (e.g. degree of residential segregation) change, the observed insulation activity varies in complex ways. This leads to differing levels of insulation activity.

Adoption of the homeowners' attitudes towards insulation was not considered in the model. The time period between two specific renovation measures exceeds the simulated time period. Therefore, an adoption of the homeowners' attitude based on the renovation measure carried out, would not show any effect.

Objectives of homeowners drive their decision-making on insulation measures. Homeowners decide on adopting insulation if the sum of the homeowners' quantified attitude and perceived value of information on insulation is positive and vice versa.

Sensing of homeowners takes place through their interaction with other homeowners defined by the social network graph. Through the interaction with other homeowners, information on renovation is transferred and then assessed by the homeowners, based on the total number of network contacts and the time passed by since the network contacts carried out their last renovation measure. Both, the perceived value of information and homeowners' attitude towards insulations are considered in the decision-making. The structure of the social network depends on spatial proximity and the degree of homophily between two homeowners. The mechanisms by which agents obtain information are modeled explicitly.
Interaction happens through information exchange between those homeowners that share a tie in the social network. During the process of information exchange, the asked homeowner provides information on the renovation measure he/she carried out recently (adoption or non-adoption of insulation) and the time elapsed.
Stochasticity occurs in both, the model initialization and the sub-models. For details see below.
Observations made are homeowners' insulation activity. 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):

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

$N_{ro,ins}$, $N_{wa,ins}$, $N_{fl,ins}$, $N_{wi,ins}$ 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:

$$B = (25\% \cdot N_{ro,ba} + 50\% \cdot N_{wa,ba} + 12\% \cdot N_{fl,ba} + 13\% \cdot N_{wi,ba})/N_h \qquad (2)$$

$N_{ro,ba}$, $N_{wa,ba}$, $N_{fl,ba}$, $N_{wi,ba}$ 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.

3 Details

3.1 Initialization

Model initialization consists of three successive steps of creating and setting the houses, creating and setting the homeowners, and generating the social network. In the first initialization step, we aim to artificially reproduce a real-world building structure of detached and terraced houses. These house types are most common for owner-occupiers (Bigalke et al. 2012). Firstly, houses are created according to data on the German building stock (see Table 2).

Table 2 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	1948-1957	1958-1968	1969-1978	1979-1983	1984-1994	1995-2001	2002-2006
Detached housing units [%]	14.0	10.7	10.2	12.1	9.9	5.0	10.9	10.6	3.6
Terraced housing units [%]	0.8	1.7	1.2	1.9	2.8	1.1	1.5	1.5	0.4
Wall insulated when built [%]	3.1	1.8	2.9	7.4	25.4	33.3	41.4	57.4	54.0
Wall insulated later [%]	32.0	28.4	30.1	28.3	16.4	13.4	5.9	3.3	10.3
Roof insulated when built [%]	4.4	6.3	9.0	14.7	42.5	52.0	71.9	91.0	87.5
Roof insulated later [%]	54.7	54.1	60.1	56.5	39.1	33.2	20.3	5.6	9.9
Floor insulated when built [%]	3.1	4.4	6.2	10.5	32.1	35.1	58.9	73.2	81.6
Floor insulated later [%]	19.7	13.0	14.7	10.5	5.5	6.2	2.7	2.2	2.3

Since the actual useful life of buildings' elements depends on a variety of factors, it is subject of intensive research (Bahr & Lennerts 2010; Kalusche 2004; Ritter 2011). Due to the possible delay of performing maintenance, we chose comparatively low life expectancies. According to Kleemann and Hansen (2005), the lifetime of building's elements is normally distributed. At installation of building's elements their lifetime is determined according to the distributions presented in Table 3. The present age of building's elements is randomly distributed amongst the houses considering the matter that it can not exceed the age of the building or its own lifetime. The number of houses is determined by the product of population density and size of the grid.

Table 3 Lifetime of building elements. 1) With more than 95% of the values within the lifetime boundaries provided by Agethen (2008).

Building elements	Lifetime [a]	Distribution1)
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	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)

Secondly, houses of the different construction years are successively set and arranged on the grid. 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.

$$P_C = \frac{N_C}{N} \qquad (3)$$

N_C is the number of houses built in the same construction year category (see Table 2) in the direct neighborhood; N is the total number of houses in the direct neighborhood.

In the second initialization step, homeowners are created and distributed among the houses. Homeowners of the different lifestyles differ regarding their attitude towards insulation, age and income (see Table 4).

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 4. 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 4 Social-demographical and psychological characteristics of homeowners based on Rückert-John et al. (2013) and Linnebach et al. (2014)

Lifestyle	Age	Income	Attitude	Share [%]
Established Conservatives	50-65	>3,000	-0.25	5.7
Conventionals	50-65	2,000-3,000	0.25	9.9
Traditional Workers	>65	1,000-2,000	0.25	6.6
Established Liberals	50-65	>3,000	0.5	15.9
Adaptive Mainstream	30-49	2,000-3,000	0.25	26.9
Domestically Centered	<29	<2,000	-0.25	14.7
Reflectives	30-65	>3,000	0.25	6.9
Hedonists	every	every	0.25	10.0
Entertainment Seekers	<29	1,000-2,000	-0.5	3.4

The socio-spatial structure of an urban area is additionally based on the preference of similar[2] 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

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

indices, for which the data is provided by Otte (2008) (see Table 5). They indicate the evenness with which two groups of people are distributed across subareas of an entity.

Table 5 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 1.

[%]	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

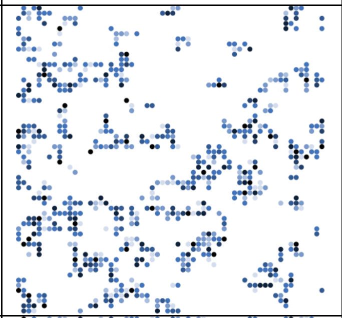
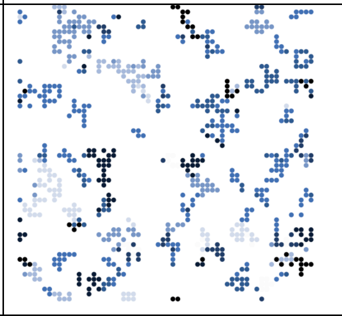
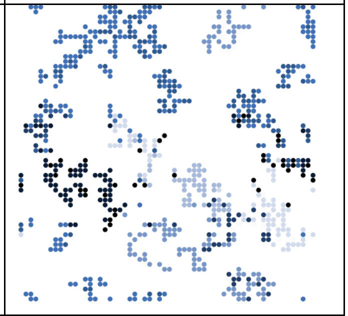
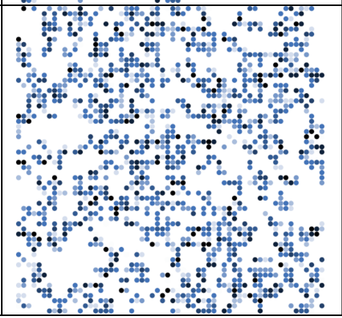
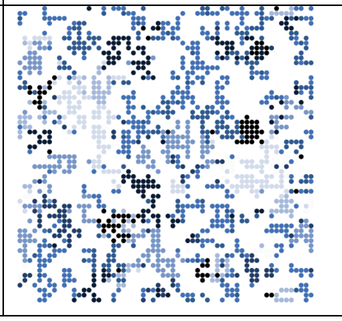
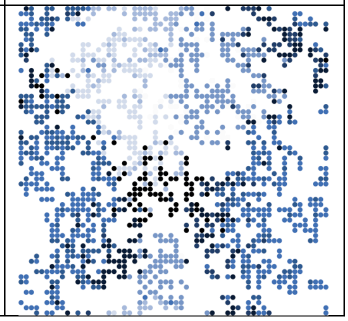
During our model initialization, homeowners are initially randomly distributed among the houses. Next, we use the following equation to calculate lifestyle X homeowners' satisfaction with their surroundings. The level of satisfaction (S_X) ranges from 0 (dissatisfaction) to 1 (maximum satisfaction).

$$S_X = \sum_{i=1}^{N_R} (1 - I_{XY_i}) \Big/ N_R \qquad (4)$$

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 6). 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 finishes as soon as all homeowners have found a satisfactory place to reside.

Table 6 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 6 Examples of socio-spatial structures of different levels of residential segregation (*R*) and population density (*D*). The different color shades represent homeowners of different lifestyle groups.

	R:0	*R*:3	*R*:9
D:0.2			
D:0.4			

Once the socio-spatial structure has been arranged the social network is established. Network ties in the model 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 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:

$$P_{XY} = \frac{A_{XY}}{\Delta E^2} \qquad (5)$$

A_{XY} is the likelihood that homeowners of lifestyles *X* and *Y* link if they come into contact with each other. Values for A_{XY} are provided by Otte (2008) (see Table 7). Since the data from the network analysis is based on a sample of 2,757 people which have network contacts outside this group, the horizontal values distinguish from the vertical values.

Table 7 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 1.

[%]	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

The probability that two homeowners come into contact with each other decreases quadratic with the distance (ΔE) between them. The distance from one homeowner to another is measured from the center of one property area 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).

3.2 Submodels

Two events are of main importance when sketching the decision-making process of homeowners regarding 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 8 provides an overview of the main elements of homeowners' decision-making processes concerning renovation. According to the table, 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 8 Inventory of situational factors, occasions and renovation activities. 1) Rather than standard glazing

<table>
<tr><th colspan="3">When to start thinking about renovating</th><th colspan="2">Deciding about which type of renovation to undertake</th></tr>
<tr><th colspan="2">Situational factors</th><th>Occasions</th><th>Standard renovation</th><th>Combinable insulation</th></tr>
<tr><td rowspan="5">Structural condition of house</td><td rowspan="8">Financial constraints</td><td rowspan="5">Maintenance</td><td>Standard glazing</td><td>Insulating glazing 1)</td></tr>
<tr><td>Exterior rendering</td><td rowspan="2">Wall insulation</td></tr>
<tr><td>Facade painting</td></tr>
<tr><td>Roof renewal</td><td>Roof insulation</td></tr>
<tr><td>Heating system renewal and queuing standard renovations</td><td>Queuing (combinable) insulation</td></tr>
<tr><td rowspan="3">Socio-demographic situation</td><td>Attic extension</td><td>Roof renewal</td><td>Roof insulation</td></tr>
<tr><td rowspan="2">House purchase</td><td>Queuing standard renovations</td><td>Queuing (combinable) insulation</td></tr>
<tr><td>Basement extension</td><td>Floor insulation</td></tr>
</table>

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.

3.2.1 When to start thinking about renovating

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. The probability that homeowners think about extending their attic (P_a) therefore depends on their age (A_h):

$$P_a = 1 - \frac{|A_h - 35|}{100} \qquad (6)$$

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. Then it is considered with the following probability (P_m):

$$P_m = 1 - \frac{|A_h - 60|}{100} \qquad (7)$$

A deviation from the age 35 (in the case of attic extensions) and 60 (in case of maintenance measures) leads to a reduction of the probability to think about renovation measures. Assumptions regarding the probability of the occurrence of attic extension and maintenance, are led by findings of Stieß et al. (2010) and Littlewood and Munro (1996).

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):

$$T_h[a] = F \cdot T_a[a] \cdot \frac{I_a[€/a]}{I_h[€/a]} \qquad (8)$$

The average length of time taken by homeowners to 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.

3.2.2 Deciding about which type of renovation to undertake

In this step, homeowners decide whether or not to insulate their houses as presented in Table 8. 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.

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 9).

$$I_h = \frac{W}{N} \cdot \sum_{i=1}^{N} \frac{F_i[a]}{T_i[a]} \cdot N^{0.6} \qquad (9)$$

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.

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