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Simulating the influence of socio-spatial structures on energy-efficient renovations

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Abstract—To meet climate protection targets it is suggested to increase the number of energy-efficient renovations. Homeowners are the main decision makers regarding renovations in their houses. It is hypothesized that socio-spatial structures affect the decision to renovate. Since it is crucial to consider all important aspects influencing the decision making of homeowners when designing policies to trigger higher energy-efficient renovation activity, we developed an agent-based model to examine the influence of socio-spatial structures on these decisions. The simulation results suggest that socio-spatial structures have a considerable effect on the type of renovation measures carried out. The distribution of socio-technical attributes, population density, social network properties, and residential segregation, affects the homeowners' decision to renovate. Additional research is needed to validate the model and make it applicable to evaluate policy instruments designed to promote the diffusion of energy-efficient renovations.

I. Introduction

Buildings are responsible for over one third of global greenhouse gas (GHG) emissions [1]. Despite the economic viability of many energy-efficient renovations (EERs) having a high potential to reduce greenhouse gas emissions and meet climate protection targets [2,3], the number of measures actually carried out is relatively low. In Germany, for example, the annual EER rate is less than one per cent [4]. Several climate protection scenarios at national, international and global level suggest an increase of the EER rate to meet climate protection targets [5–7]. It is the responsibility of the policy makers to introduce new or improve existing instruments to initiate and allow such transition to a climate-friendly building stock. Friege and Chappin (2014) point out that due to the decision-making processes of homeowners not yet sufficiently understood [8,9], present incentives lead to unsatisfactory results [10–12]. The authors conclude that a simulation model which maps the decision-making processes of homeowners is needed [13]. This paper presents an agent-based model (ABM), designed to investigate the influence of socio-spatial structures on EER decisions. The model is implemented in NetLogo v. 5.0.4 [14]. In the following we provide the theoretical background, present our research questions posed to facilitate the analysis and introduce the applied methodology.

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A. Theoretical background

A literature review on EER decisions of homeowners has shown that the economic viability of measures is only one motivating factor among others [13]. Wilson et al. (2013) even found that financial constrains do not prevent households from planning renovations, but they may make the decision more drawn out [15].

In order for individuals to perform EERs various wants and needs must be met [16]. Principal motivations of individuals to achieve energy efficiency are mentioned by Organ (2013): energy bill saving, increased comfort and reduced environmental impact [17]. Several studies indicate that the homeowners' social interaction influences their renovation decision-making processes [15–18]. According to Rogers (2010) communication of homophilous individuals (similar in certain attributes), which "usually belong to the same groups, live or work near each other, and are drawn by similar interests" [19], are likely to communicate more effective and more often. Wellmann (1996) shows that neighbors make up 23 per cent of a person's entire social network active ties while they are responsible for nearly two-fifth (38 per cent) of all contacts [20]. If one also takes into account that nearby houses are likely to be of the same type with similar renovation options, local socio-spatial structures possibly play a major role in homeowners' renovation decision to renovate.

B. Research questions

The following four research questions are posed to facilitate the analysis on how homeowners' social networks affected by local spatial structures influence the diffusion and in this way the share of EERs:

- Q_1: Does the population density and the density of social networks influence the diffusion of EERs?
- Q_2: Does the degree of homophily in neighborhoods influence the diffusion of EERs?
- Q_3: Does the distribution of socio-technical attributes amongst homeowners influence the diffusion of EERs?
- Q_4: Do the kind of renovations, most frequently carried out in the past, influence the diffusion of EERs?

C. Methodology

We developed an ABM to elaborate on our hypotheses. Establishing such a model requires the consideration of socio-demographic parameters, house type and condition, homeowners' interaction in social networks and several external framework conditions. One reason why we use this bottom-up methodology is its ability to capture complex emergent phenomena – in our case the diffusion of EERs. Homeowners' heterogeneity and social interactions can be modeled explicitly [21]: When transferring Rogers' theory of "Diffusion of innovations" [19] on our case, the likelihood that homeowners interact and that this triggers the adoption of EERs is dependent on baseline homophily and spatial proximity. Therefore, homeowners which share similar technical and socio-demographical attributes and live close to each other, have a higher possibility to communicate. Given the circumstance that homophilous individuals usually live near each other in houses that are likely to be of the same type, we expect a considerable diffusion rate of EERs in neighborhoods. Spatial structures, incomplete information and several other real-world phenomena influence the degree of homogeneity between homeowners and thus the diffusion of EERs. Holzhauer et al. (2013) state that spatial ABMs should consider "baseline homophily, i.e. the influence of local socio-demography on the composition of one's social network" and that "the probability of links (…) depends on geographical distance between potential partners" [22].

The structure of the present paper is as follows: Section 2 describes the creation and use of the spatial agent-based model. Section 3 presents the results. The paper closes with conclusions in Section 4.

II. The agent-based model

A. Purpose

This paper addresses the poor understanding of how the composition of homeowners' social networks influenced by local spatial structures has an impact on the share of EERs in self-occupied houses. A comprehensive review on scientific literature and several project reports was carried out to obtain an initial insight into the socio-technical system [13]. The review was complemented by expert discussions and five initial semi-structured telephone interviews with homeowners regarding their decision making on EERs. These steps resulted in a system description suitable for the design of the model. Several concepts were identified to be important when modeling the diffusion of EERs: the socio-technical system, consisting of agents with their individual attributes (see Subsection B), the socio-spatial structure (see Subsection C), and interactions between agents within their social network further described in subsection D. Decision rules in our model are as much as possible based on literature but need empirical validation or rather modification in the follow up process (see Section IV). Our model has the potential to lead to a better understanding of how certain spatial structures influence the diffusion of EERs. This knowledge may be used to design policy instruments targeted at existing local spatial structures.

B. Socio-technical system

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 regarding investments in renovation measures. Even though households may consist of several individuals (parents, children etc.) we treat households as single entities. They are represented as homeowners containing several social and technical attributes.

Homeowners' technical attributes refer to characteristics of the house they live in. In accordance to our modeling purpose the house type and age are considered. These attributes have a low or even no influence on the type of performed renovation [23] but affect the renovation occasion, the spatial structure and the interaction between homeowners. We consider detached, semi-detached and terraced houses, the typical housing types of owner-occupiers.

Social attributes are grouped into socio-demographical and psychological characteristics. Socio-demographical attributes, mainly the homeowners' age, highly influence whether a renovation will be carried out. Comparatively high income also has a positive influence on the decision to renovate [23]. Psychological attributes such as stubbornness towards the opinion of other people or attitude towards energy efficiency, together with knowledge on EERs, highly influence the type of renovation measure carried out [23].

C. Spatial structure

The socio-spatial structure is based on the preference of people to move to a neighborhood of like-minded people, similar in certain socio-demographical and psychological attributes. Residential segregation leads to the physical separation of groups into different parts of the urban environment [24]. Due to incomplete information and heterogeneity of homeowners, a certain amount of diversity sustains within the neighborhood. Since houses are mostly build in complexes and therefore have a similar construction age and type, clustering is based on these values as well. Zhao et al. (2013) point out that the Euclidean distance function can be applied to measure the similarity between two data points, e.g. in social networks [25]. Accordingly, that function is used to determine the degree of homophily[1] between two homeowners (ΔH):

$$\Delta H = \sqrt{\left(\Delta T^2 + \Delta H_a^2 + \Delta A^2 + \Delta O_a^2 + \Delta I^2 + \Delta S^2\right)} \quad (1)$$

with socio-technical attributes given in Table I. For simplification purposes, it is assumed here that all attributes are of the same importance. Exploring the influence of different weighted socio-technical attributes on the simulation results is recommended for further work.

[1] Here, a low degree of homophily between two homeowners means that they are very much alike.

Setting up the socio-spatial and technical structure is done in three steps: 1) setup agents, 2) distribute agents at random, and 3) start simulation.

1) Homeowners are created and socio-technical attributes are assigned to them. The number of created homeowners is dependent on the desired density of homeowners on the grid. The socio-technical attributes are normally distributed with a mean of 0.5 and a standard deviation of 0.15, except for the types of houses (see Table I). The distribution of the different house type is based on a report by the German Federal Statistical office [26].

TABLE I: DISTRIBUTION OF SOCIO-TECHNICAL ATTRIBUTES

Attribute	Distribution	Description
House type [T]	60%	Detached houses
	27%	Semi-detached houses
	13%	Terraced houses
House age [H_a]	Normal distribution with $N(0.5, 0.15^2)$	Young to Old
Attitude [A]		Negative to Positive
Homeowner age [O_a]		Young to Old
Income [I]		Low to High
Stubbornness [S]		Low to Extreme

2) Homeowners are at first randomly distributed over the grid.

3) Each of the homeowners check the degree of homophily towards their neighbors within a predefined patch-radius on the grid with a size of 60 x 60 patches. If the average degree of homophily is below or at a certain threshold (tolerance), they remain where they are. The initial tolerance is set to zero. If the average degree of homophily is over their tolerance, they move to another place and slightly increase their tolerance. This artificial process to generate a spatial structure is repeated until all homeowners found a place to stay.

D. Social network

The composition of a homeowners' ego network is dependent on the likeliness (regarding socio-technical attributes) of other homeowners they come into contact with. The chance of contact is dependent on spatial proximity. The following function, adapted from Holzhauer et al. (2013) [22], is used to generate the social network. It describes the likelihood that two homeowners link:

$$p_{link} = \frac{\Delta H}{\Delta D^{\varepsilon}} \quad (2)$$

where ΔH is the degree of homophily between two homeowners (see Function 1), ΔD the distance between two homeowners and ε an auxiliary parameter to vary the likelihood for the occurrence of links between homeowners with a distance greater than one. Network ties based on this approach, represent a relationship between homeowners that may communicate and mutual influence each other [19]. Homeowners interact through their ego network by exchanging information on renovations they have carried out.

E. Decision-making process

After setting up the spatial structure and generating the social network, it is time to implement the homeowners' decision making behavior. According to Wilson et al. (2013) homeowners run through three different stages in their decision-making process: 1) thinking about renovations in general terms, 2) planning a concrete renovation, and 3) executing renovations. In the following, the decision making of homeowners is described by looking at the different stages in detail. Before that, there has to be an occasion triggering the homeowners to start thinking about renovations.

When to start thinking about renovations

About half of a representative sample of 1,028 homeowners were not considering a renovation [15].

The precondition for homeowners to start thinking about renovations is that they did not think about or actually renovated their building for more than a year (cool-down). Homeowners start to think about renovating their property when the opportunity or need arises to do so. Stieß and Dunkelberg (2012) [27] list three occasions, 1) purchase of a building, 2) extensions/alterations and 3) maintenance which can trigger an EER. According to Stieß and Dunkelberg (2012) such particular situations are associated with a buildings' condition and homeowners' socio-demographic situation/phases of life. Since no precise data regarding the probability of occurrence of different occasions dependent on homeowners' age (purchase and extension/alteration of a building) or on house age and condition (maintenance) were found, the dependencies were based on suggestions derived from literature [28,29].

- Purchase of a building: After associating a normally distributed random number $N(0.35, 0.1^2)$ to each homeowner, it is checked whether their age attribute is equal to this number (accuracy of one decimal place). If this situation arises, the purchase occurs with a possibility of 30 per cent
- Extensions/alterations: Same procedure as for the occasion above. The linked numbers are normally distributed with $N(0.40, 0.15^2)$
- Maintenance: The third renovation occasion occurs with a probability of $(0.9 + 0.1 \times H_a) \times 30\%$

Therefore very young and very old homeowners are less likely to purchase a building or extend/alter it. Maintenance is more likely to occur in older buildings.

Thinking about renovations

Thinking about a renovation in general terms includes the exchange of information between homeowners. Stieß et al. (2010) found that 60 per cent of questioned renovators do not carry out comprehensive EER measures because they believe their house to be in a good energetic condition [23]. This significant finding was implemented in the model by only giving 40 per cent of the homeowners the knowledge that a comprehensive EER may be a useful option for their house. “Informed” homeowners were chosen based on characteristics of two different types of renovators given by Stieß et al. (2010), persuaded energy savers and open-minded skeptics: medium to high income and attitude, rather old houses, not middle-aged, low and quite high stubbornness. A homeowner, who is not in possession of such information, adopts it if:

$$\frac{N_I}{N} \geq S \qquad (3)$$

where N_I is the number of “informed” network contacts, N of all homeowners’ network contacts and S is the homeowners’ stubbornness. Furthermore homeowners can adopt the information through other channels such as media or energy consulting and repress or forget the information.

The previously mentioned circumstance that 60 per cent of renovators believe their house to be in a good energetic condition is stated to be the second most important barrier to prevent homeowners from carrying out a comprehensive EER [23]. Since it was not necessary to distinguish between simple and comprehensive EERs to address our research questions, we decided to abstain from doing so in the presentation of the results (see Section III). The distinction will become relevant in further research.

Planning renovations

Homeowners concretely planning a renovation decide whether to carry out a measure to increase the energy efficiency of their building in addition to a pure amenity renovation. The focus is set on this matter due to the findings of several reports on EER decisions:

- Efficiency measures are rarely done alone, they are commonly bundled with amenity-only measures [15]
- Since amenity-only measures dominate market activity, would-be amenity renovators “represent a largely unexploited opportunity to introduce efficiency measures into homeowners’ decisions to renovate” [15]
- EER measures are more profitable if carried out additionally to amenity-only measures [30]

We adopted the approach for “a multiparameter model for innovation uptake” by McCullen et al. (2013) [31] to describe the adoption of EER measures subject to individual homeowner's characteristics. Thus the decision to additionally carry out an EER measure is “determined by the perceived usefulness, or *utility*, to the individual” [18]. The homeowner adopts the measure, when this utility outweighs the barriers, or *threshold*, to adoption. The total utility U for an individual homeowner is the sum of (additional) personal P_{Be} and social benefits S_{Be} [32]:

$$U = P_{Be} + S_{Be} \qquad (4)$$

In addition to the social motivation, Organ (2013) mentions three further motivations to perform an EER: reducing energy bills; increase comfort; and reducing environmental impact [17].

Accordingly, the personal benefit P_{Be} is a combination of financial, comfort and environmental benefits:

$$P_{Be} = \alpha \left(F_{Be} + C_{Be} + E_{Be} \right) \qquad (5)$$

where α is a weighting for the personal benefit, F_{Be} represents the financial benefit, C_{Be} is the comfort benefit and E_{Be} is the environmental benefit. The perceived financial, comfort and environmental benefits are dependent on the individual homeowners’ attributes (see Table I):

$$F_{Be} = 1 - I + H_a \qquad (6)$$

$$C_{Be} = O_a \qquad (7)$$

$$E_{Be} = A \qquad (8)$$

So the perceived financial benefit F_{Be} decreases with increasing income and increases with increasing house age. The comfort benefit C_{Be}, namely thermal comfort, air quality and noise protection [33], is expected to be more important for older homeowners who are assumed to spend more time in their building than younger homeowners. Furthermore, homeowners with a positive attitude towards energy efficiency perceive a higher environmental benefit E_{Be} by reducing their environmental impact via an EER than homeowners who do not care about this matter. However, the degree of the different dependencies needs to be adjusted based on empirical data (see Section IV).

According to McCullen et al. (2013) the individual social benefit S_{Be} can be split into both the direct influence from a homeowners’ ego network D_{Be} and the influence from society in general G_{Be} [34]. w_D and w_G are weightings for the social benefits.

$$S_{Be} = w_D \cdot D_{Be} + w_G \cdot G_{Be} \qquad (9)$$

$$D_{Be} = \frac{(1-S) \cdot (N_{M2} - N_{M1})}{N} \qquad (10)$$

$$G_{Be} = \frac{(1-S) \cdot (O_{M2} - O_{M1})}{O} \qquad (11)$$

where N_{M2} represents homeowners’ network contacts which have already carried out a mixed (amenity-only and efficiency) renovation measure and N_{M1} are the network contacts to those where the last renovation measure carried out was an amenity-only measure. O_{M2} and O_{M1} are homeowners within the model to whom the last renovation measure carried out was amenity-only or mixed respectively. O stands for the number of all homeowners within the network. As can be seen the social benefit of performing a mixed renovation measure is only positive if more mixed measures other than amenity-only measures in the homeowners network or the society in general have been carried out. The degree of influence again is dependent on each homeowners own stubbornness towards the opinion of others.

The threshold to adopting the innovation consists of perceived financial F_{Ba}, socio-demographical S_{Ba} and technical barriers. Since there is no distinction drawn between different types of EER measures, the model lacks to map specific technical barriers. Technical barriers are partly considered by taking into account a necessary cool-down before a renovation occasion can trigger homeowners to think about renovations as introduced above. Homeowner's individual threshold θ is calculated as shown below:

$$\theta = F_{Ba} + S_{Ba} = 1 - A + O_a \qquad (12)$$

The financial barrier is therefore expected to decline with a more positive attitude towards energy efficiency and increase with the homeowner's age. Homeowners with a positive attitude towards energy efficiency are more likely to raise a credit for or spend the money they have on energy efficiency measures instead of spending it for something else. Stieß et al. (2010) found that the circumstance that most homeowners are unwilling to raise a (further) credit [23], is the most important barrier preventing EERs.

The socio-demographical barrier is high for elderly homeowners because they may not live long enough to experience the EER to pay back. This is especially the case if the homeowners do not have relatives who could inherit their property. Elderly homeowners are also expected to be more irritated by additional noise and dirt caused by the renovation. A homeowner decides whether to carry out a mixed renovation measure instead of an amenity-only renovation measure if the utility U outweighs the threshold θ.

Executing renovations

Finally, homeowners actually carry out the renovation they decided on. The time they spend on this and the other stages was estimated based on a survey carried out by Wilson (2012)[15].

III. Results

The aim of the model is to understand whether the composition of homeowners' ego networks influenced by local spatial structures has an impact on the diffusion of EERs in self-occupied houses. By means of a reference scenario (see Subsection A) various socio-spatial structures and parameters relevant in the decision-making process on EER activities were simulated (see Subsection B and C). Subsection D elaborates on the significance of the simulation results. Since the parameter variations result in different spatial structures, we were able to address our research questions (see Section IV).

A. Reference scenario

We develop a reference scenario to investigate the impact of various socio-spatial structures and parameters relevant in the decision making process on the share of mixed renovations (F_m). It is pointed out here that time frame and renovation dynamics over time are of secondary importance since the model is not developed to predict possible future states but to reconstruct potential present situations. Of particular interest is the share of mixed renovations after reaching a steady level. Therefore, the simulations are run up to a certain degree of stabilization of the share of mixed renovations. The parameters for the reference scenario are designed to sketch the present situation: At a cool-down time of one year, the shares of homeowners within the different decision stages stagnate at values found by the survey of Wilson et al. (2013)[15]. Therefore, the period of time before homeowners start thinking about renovations again (after their last decision-making process) is set to one year. α, the weighting for the personal benefit, is set to 1.4. At this value, the mean personal benefit of all homeowners towards mixed renovations is below the mean threshold. The other parameters for the reference scenario were estimated by the authors considering the results of several simulation runs with different parameter combinations. The following table (Table II) gives an overview of all relevant reference scenario parameters.

Table II: Reference scenario parameters

Parameter	**Value**
Socio-spatial structure	
Population density [P_d]	40%
Search radius of homeowners [R]	3
Distribution of socio-technical attributes [D]	See Table I
Likeliness parameter for links [ε]	3
Initial share of amenity-only renovations [J_a]	0%
Initial share of mixed renovations [J_m]	0%
Decision making	
Weighting of personal benefit [α]	1.4
Weighting of direct social benefit [w_D]	1
Weighting of benefit for society in general [w_G]	0.5

The influence of different socio-spatial structures (see Subsection B) and decision making parameters (see Subsection C) on the share of mixed renovations was tested by changing only one parameter at once while keeping the others constant. Since the model outcomes differ in each run, each parameter constellation was run a hundred times in order to be stochastically sure about the outcomes.

B. Socio-spatial structure

The following section introduces the framework used for the analysis, presents the simulation results and gives some visualization examples of different socio-spatial structures.

Analysis framework

A sensibility analysis was carried out to investigate the impact of different socio-spatial structures on the dissemination of mixed renovations after 120 ticks:

- Population density (P_d): 10% - 70% (10%/step)
- Search radius of homeowners (R): 1- 4 (1/step)
- Distribution of socio-technical attributes (D): Normal or uniform distribution of socio-technical attributes
- Likeliness parameter for links (ε): 2 – 4 (0.5/step)

Additionally, the initial share of renovations carried out before starting the simulation was varied:

- Initial share of amenity-only renovations (J_a): 0% - 100% (10%/step)
- Initial share of mixed renovations (J_m): 0% - 100% (10%/step)

Population and network density

The population density and the network density (affected by the likeliness for the occurrence of links) were found to have a major influence on the mean final share of mixed renovations in the reference scenario. The final share of mixed renovations decreases with increasing population density and increasing likeliness for the occurrence of links (the likeliness increases with a decreasing likeliness parameter for links) (see Fig 1). These patterns emerge since a low population density and a low likeliness for the occurrence of links leads to low network densities.

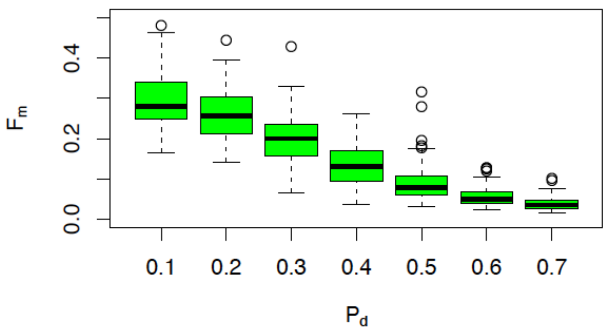


Fig 1: Final share of mixed renovations (F_m) dependent on the population density (P_d)

Here, clusters of homeowners with a positive perceived personal benefit towards mixed renovations are not as much affected by the generally negative perceived personal benefit as at high social network densities (see Fig 2). A population density of 10 per cent represents 360 homeowners on the grid with a size of 60 x 60 patches.

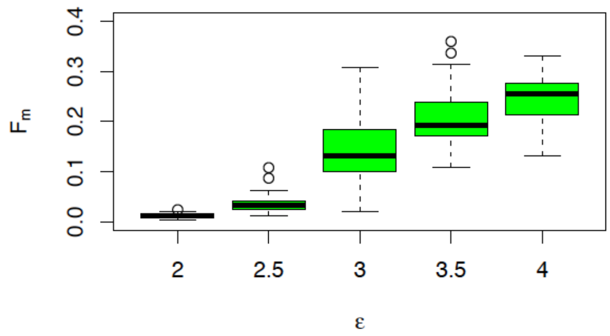


Fig 2: Final share of mixed renovations (F_m) dependent on the likeliness parameter for links (ε)

Size of clusters

The search radius has an effect on the size of clusters in the model, since homeowners consider the degree of homophily towards neighbors in a larger radius. Larger clusters have a positive influence on the final share of mixed renovations (see Fig 3). This is the case since larger clusters of homeowners with mixed renovations are better equipped against direct social pressure than smaller clusters. A search radius of more than one leads to cluster sizes which make it easier to resist against exogenous social pressure.

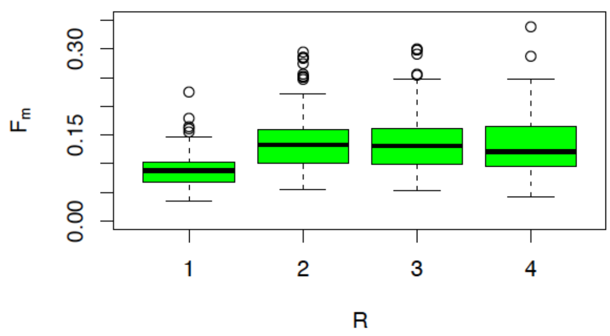


Fig 3: Final share of mixed renovations (F_m) dependent on the search radius (R)

Accordingly, when considering an initial share of mixed renovations of 50 per cent, the final share of mixed renovations is smaller if the clusters are larger (see Fig 4).

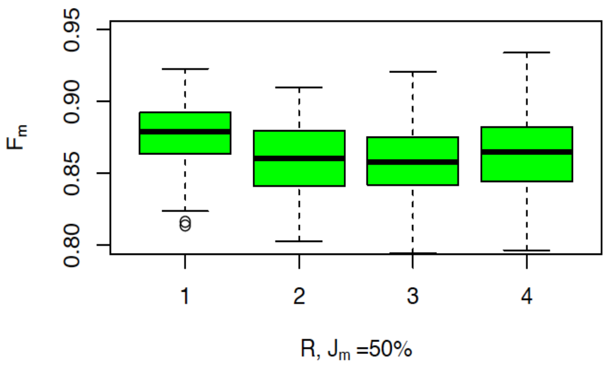


Fig 4: Final share of mixed renovations (F_m) dependent on the search radius (R) considering an initial share of mixed renovations (J_m) of 50 per cent.

Distribution of socio-technical parameters

How socio-technical parameters were distributed amongst homeowners was found to have a major effect on the final share of mixed renovations. A normal distribution of homeowners attributes leads to a higher share of mixed renovations compared to a uniform distribution if the average benefit of performing an EER is positive (at α=1.6, see Fig 5). If the average benefit (at α=1.4) is negative, the uniform distribution leads to a higher share of mixed renovations. Since more homeowners have a medium utility and threshold when their attributes are normally distributed, the marginal utility of increasing the personal benefit based on a medium personal benefit (at α=1.5) is higher compared to uniformly distributed attributes.

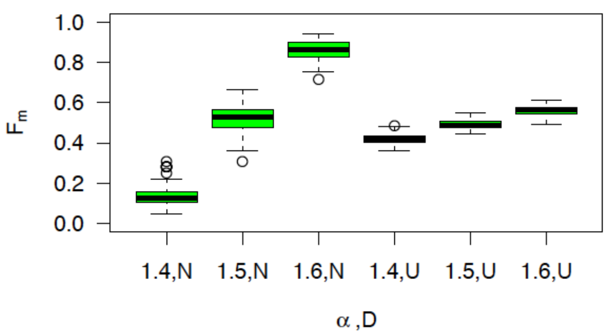


Fig 5: Final share of mixed renovations (F_m) dependent on the distribution (normal|uniform) of homeowners and different weightings of the personal benefit (α)

The greater diversity of attributes at uniformly distributed socio-technical parameters furthermore demands homeowners to be more tolerant in order to find a favorable neighborhood.

Path dependency

A share of already performed mixed, or amenity-only, renovation measures before starting the simulation highly influences the results (see Fig 6 and 7). Given the initial shares of performed mixed or amenity-only renovation measures, this is not surprising since the social benefit is not neutral at initialization of the model. This imbalance leads to a higher final share of mixed renovations at a high initial share of mixed renovations compared to a high initial share of amenity-only renovations.

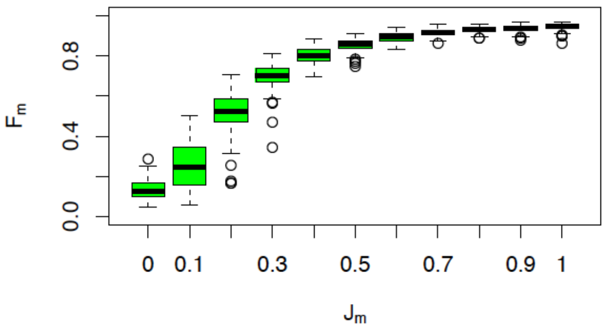


Fig 6: Final share of mixed renovations (F_m) dependent on the initial share of mixed renovations (J_m)

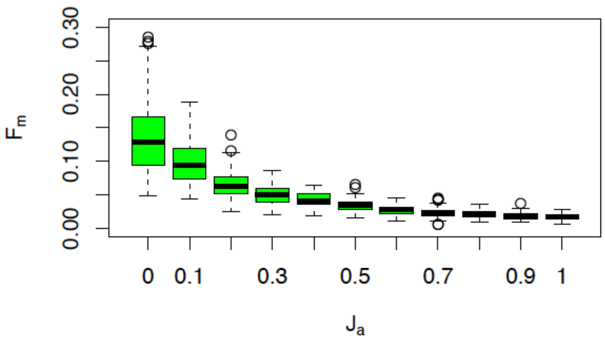
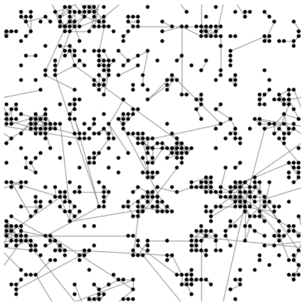
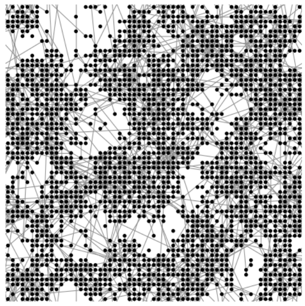
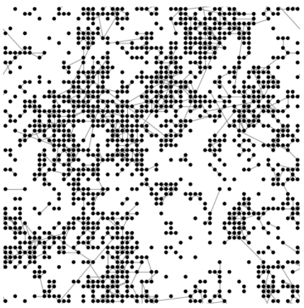
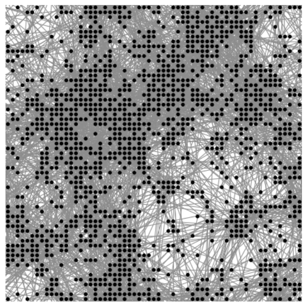
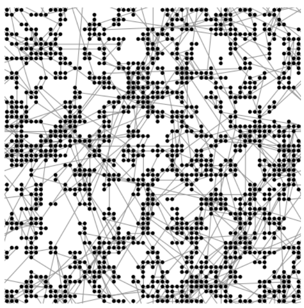
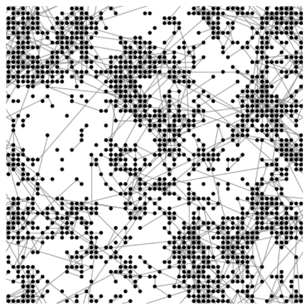


Fig 7: Final share of mixed renovations (F_m) dependent on the initial share of amenity-only renovations (J_a)

Visualization of different socio-spatial structures

Table III gives some visualization examples of different socio-spatial structures: low and high population and network density, and small and large clusters. Each figure is labelled with the parameter modified in comparison to the reference scenario.

TABLE III: VISUALIZATION OF DIFFERENT SOCIO-SPATIAL STRUCTURES

 Population density (P_d): 20%	 Population density (P_d): 60%
 Likeliness parameter for links (ε): 4	 Likeliness parameter for links (ε): 2
 Search radius of homeowners (R): 1	 Search radius of homeowners (R): 4

C. Decision making

The following section introduces the framework used for the analysis and presents the results of varying decision making parameters.

Analysis framework

Apart from analyzing the influence of several setup parameter variations on the results, we also looked at different decision making parameter variations. Besides varying the personal benefit of installing a mixed renovation measure, the perceived social benefit was modified. w_D represents the weighting for the direct benefit from a homeowners' ego network and w_G the weighting for the benefit of society in general. The following parameter variations were used in the analysis:

- Weighting of personal benefit (α): 1 – 2 (0.05/step)
- Weighting of direct social benefit (w_D): 0 – 1.5 (0.25/step)
- Weighting of benefit for society in general (w_G): 0 – 1.5 (0.25/step)

Personal benefit

The weighting of the personal benefit (α) has a high influence on the final share of mixed renovations (see Fig 8). The share of mixed renovations varies between 2 per cent and nearly 96 per cent at a range of α between 1.2 and 1.8.

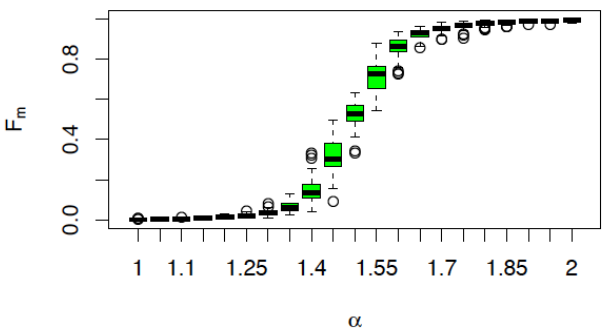


Fig 8: Final share of mixed renovations (F_m) dependent on the weighting of the personal benefit (α)

Direct social benefit and benefit from society in general

Since the reference scenario (w_D=1, w_G=0.5) results in a low share of mixed renovations (about 20 per cent), homeowners are confronted with a high social pressure to perform amenity-only renovations. Consequentially, the final share of mixed renovations decreases with an increased weighting of the influence from society in general (see Fig 10). Surprisingly, this is not the case looking at the weighting of the direct social benefit (see Fig 9). Here, the final share of mixed renovations decreases up to a weighting of 0.5 and increases afterwards. After analyzing the outcome of several simulations in detail, we suggest that this behavior emerges due to the circumstance that clusters of homeowners who performed mixed renovations hold together more strongly if the weighting of the direct social benefit is above a certain level. The clusters mentioned above have more links amongst each other than with the outside world.

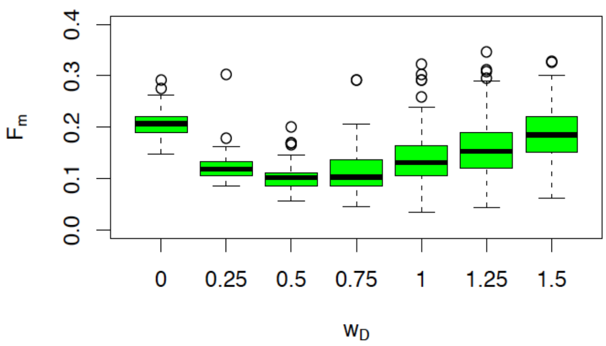


Fig 9: Final share of mixed renovations (F_m) dependent on the weighting of the direct social benefit (w_D)

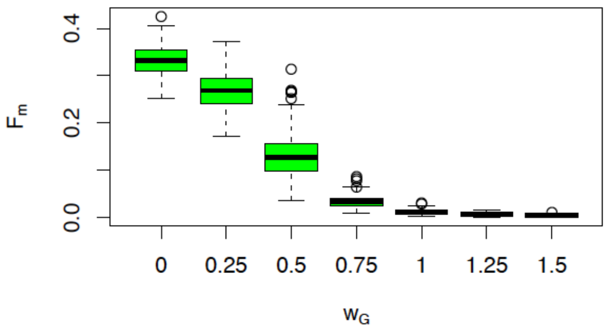


Fig 10: Final share of mixed renovations (F_m) dependent on the weighting of the influence from the society in general (w_G)

D. Analysis of Variance

An analysis of variance (ANOVA) of the simulation results was carried out to test the null hypothesis that data from all groups (different population densities, different likeliness parameters for links, etc.) have equal means. The one-way ANOVA (performed in R [35]) returns a p-value that takes into account the variance, the mean expression difference and the sample size. The p-value is a measure of how likely it is to get the spot data if no real difference existed. A low p-value indicates that the chance is very low [36]. Since the p-value is lower than 0.05 (confidence level of 95%) in every analyzed case, the difference in group expression data is significant. Therefore the null hypothesis of equal means in the groups is rejected.

IV. Conclusions

This paper presents a literature based ABM examining the influence of socio-spatial structures on energy-efficient renovation (EER) decisions. An analysis of variance (ANOVA) showed that the influence of parameter variations on the number of EERs in combination with amenity-only renovations (mixed renovations) is of significance in every analyzed case. The following conclusions regarding the posed research questions are complemented by an outlook on further work.

A. Socio-spatial structure

The influence of different socio-spatial structures on the number of mixed renovations was analyzed by using a spatial ABM.

We found that the population density and the network density have an influence on the share of mixed renovations (Q_1). A low population density and a low likeliness for the occurrence of links leads to low network densities where clusters of homeowners with a positive perceived personal benefit towards mixed renovations are not as much affected by the generally negative perceived personal benefit as at high social network densities.

The simulation results further show that homeowners in homogeneous neigborhoods (large clusters) are less likely to impose their own opinion (Q_2). In the reference scenario, the average benefit to perform a mixed renovation measure is negative. Here, spatial structures with larger clusters lead to higher shares of mixed renovations. This is the case since larger clusters of homeowners with mixed renovations are better equipped against direct social pressure than smaller clusters.

The distribution of homeowners' socio-technical attributes affects the number of mixed renovations carried out (Q_3). Since more homeowners have a medium perceived utility and threshold when their attributes are normally distributed, the marginal utility of increasing the personal benefit based on a medium personal benefit (A=1.5) is higher compared to uniformly distributed attributes.

Initial shares of amenity-only or mixed renovations affect the future type of renovations carried out (Q_4). An initial share of renovations not including energy efficiency improvements, leads to a lower number of renovations including EER measures.

B. Decision making

The influence of relevant decision making parameters on the number of mixed renovations was analyzed as well. The final share of mixed renovations increases if homeowners have a greater personal benefit to do so. An increased weighting of the influence from society leads to less mixed renovations measures carried out since the majority of homeowners do not perceive mixed renovations to be beneficial compared to amenity-only measures in the reference scenario. In case the direct social benefits become more important for the homeowners, clusters of homeowners who performed mixed renovations hold together more strongly when the weighting of the direct social benefit is above a certain level. This results in a higher final share of mixed renovations in the reference scenario.

C. Further work

Assumptions on agent's behavior in the presented model are, inter alia, derived from a comprehensive literature review [13]. Nonetheless the model as a whole needs validation in order to assess accuracy of the experimental outcomes and to prove that the model answers the research question posed. Traditional validation techniques consist of comparing experimental results and real-word data [37]. Due to the exploratory design of the model it must be examined whether this technique is applicable to our case. Other validation techniques such as face validation through expert consultation or literature validation [37] might be more appropriate: Nikolic et al. (2013) state that the validation through expert consultation "is the most commonly used validation approach in agent-based modeling" [21]. Performing an expert validation would include workshops with larger groups of experts or interviews with individuals, systematically going through the model. Besides deriving modeling assumptions from literature, studying academic literature may also serve to validate the model as a whole. Accordingly, the confidence in the outcomes of the model can be increased by comparing these with both theoretical research and other models. The involvement of potential users and stakeholders in the model specification, design, testing and use could be considered to support the development of the ABM [38].

We also aim to extend the model to evaluate policy instruments designed to harness social networks to promote the diffusion of EERs. Collecting further data on homeowners' ego networks and decision-making processes and implementing it in the ABM will lead to a better representation of the real-world system.

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