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Increasing homeowners’ insulation activity in Germany: An empirically grounded agent-based model analysis

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Highlights

- A survey on homeowners’ decision-making processes regarding insulation was conducted.
- A model was developed to evaluate policies designed to increase insulation activity.
- Homeowners’ insulation decisions are largely unaffected by their financial resources.
- Homeowners’ attitudes affect their decision-making regarding wall insulation.
- Introducing a wall insulation obligation when ownership changes is recommended.

Abstract

In Germany, doubling today’s insulation rate of about 1% is an important element for reaching the government’s target of reducing the demand for energy in the housing sector by 80% by 2050. A survey among 275 private homeowners was conducted to better understand their insulation activity. The results were incorporated into an agent-based model, which was applied to evaluate new policy options. The results of the survey show that policies should focus on homeowners’ wall insulation activity. Homeowners’ decision-making processes regarding insulation are largely unaffected by their financial resources, which raises the question of the usefulness of financial incentives. In contrast, non-economic factors were found to have a statistically significant influence: in the year following a house ownership change, a comparatively large number of insulation projects are carried out. The probability of insulating walls can be predicted from knowing the homeowner’s age, attitude towards insulation, and the structural condition of the walls. The simulations indicate that information instruments lead to a comparatively small increase in the wall insulation rate, while obligating new homeowners to insulate the walls within the first year after moving in has the potential to increase the total insulation rate by up to 40%.

Keywords: Empirical study; Agent-based modeling; Private homeowners; Insulation activity; Policy design

1 Introduction

Improving the insulation of existing buildings plays an important role in Germany’s *Energiewende* (energy transition), as it is one of the key measures for reaching the government’s target of reducing the demand for energy in the housing sector by 80% by 2050. Private homeowners' activities in detached and terraced residential buildings cause about 50% of final energy demand in the housing sector (Bigalke et al., 2012). This particular group of residents’ motivations and barriers regarding installing insulation in their homes differ from those of landlords, whose tenants’ activities cause most of the other 50% of the total demand for energy in the housing sector. While landlords' decisions to insulate are predominantly based on economic considerations, private homeowners' decision-making regarding insulation is mainly determined by non-economic factors (Reed and Wilkinson, 2005; Stieß and Dunkelberg, 2012; Wilson et al., 2015).

The following presents Germany’s present policy mix for insulating existing buildings and discusses it in respect to its effectiveness. From this discussion, and the recommendations of previous research, the paper's objective is derived.

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1.1 Germany's building insulation policies

Germany's most important instruments for insulating existing buildings comprise regulatory and financial instruments, supplemented by information instruments. This mix of policies constitutes a basic scheme as presented by Vedung et al. (1998) in which governments either force us (regulations), pay us or have us pay (economic means), or persuade us (information) to undertake the desired action (see Fig. 1).

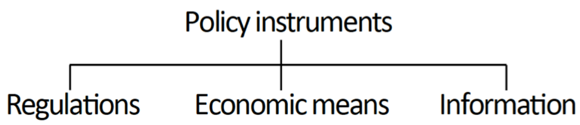

Fig. 1: A threefold typology of public policy instruments.

The main regulatory instrument in Germany is the Energy Conservation Act (*Energieeinparverordnung, EnEV*) (Galvin, 2010), which has governed energy efficiency building standards since 2002. If the building owner plans on renovating parts of the façade, roof or windows, the affected surfaces must afterwards comply with the prescribed minimum insulation standards (§ 9 Abs. 1 EnEV 2014). Insulation obligations, independent from actually planned renovation activities, only affect top floor ceilings of unheated and unused but accessible attics (§ 10 Abs. 3 EnEV 2014).

Low-interest loans and subsidies for insulation measures are provided by Germany's federal government subsidy institution, the *Kreditanstalt für Wiederaufbau,* KfW. The level of funding is based on the building's efficiency class achieved after being insulated (Weiss et al., 2012). Insulation measures must exceed the requirements set by EnEV by about 15-25% to have a chance of being funded by the KfW.

Novikova et al. (2011) identified two categories of information tools that support homeowners' decision-making regarding insulation. First, there are tools that inform them about the benefits of insulation, such as Energy Performance Certificates (ECPs), which encourage homeowners who are unaware of the benefits of insulation to consider it. ECPs became mandatory in the last EnEV update for houses and apartments which are rented out, sold or leased. Second, there are also tools that help homeowners to plan and invest in insulation by providing information about options and financial programs, such as energy audits and online information instruments.

This mix of policy instruments aims to increase the quality and quantity of insulation activities out by imposing energy efficiency building standards, providing low-interest loans and subsidies, and increasing homeowners' knowledge in this area. This portfolio of policies is often seen as fairly progressive (Eichhammer et al., 2011). However, a database representing the residential building stock demonstrates that the current insulation rate is rather low, around 1% between 2000 and 2008 (Diefenbach et al., 2010). With this low level of insulation activity, Germany is far from reaching its target of a 2% insulation rate (BMWi and BMU, 2010). Several studies indicate that the present mix of policy instruments is not very effective, nor are available resources to increase homeowners' insulation activity used efficiently: Galvin (2012) concluded in an evaluation of Germany's present policies on thermal insulation that policymaking tends to be informed by ideological, rather than practical, considerations and needs to better consider the actual shape and nature of the existing building stock. Weiss et al. (2012) argued that existing policy instruments have brought about only a little success because they do not adequately address the barriers in homeowners' decision-making. Friege and Chappin (2014) go further by pointing out that existing instruments underestimate the influence of non-economic motivations and barriers in homeowners' decision-making. While a major share of resources go into providing low-interest loans and subsidies, little attention is given to the main non-economic motivations and barriers. For instance, homeowners may have no time to address the topic or may believe that no (further) refurbishment is required. Furthermore, policies give insufficient consideration to the fact that situational factors play an important role in homeowners' insulation activity (Friege et al., 2016). Situational factors, such as the structural condition of the house, trigger renovation occasions, which are one of the main reasons why homeowners consider having insulation installed (Wilson et al., 2015).

1.2 Paper overview and objective

The design of more effective policy instruments needs to better consider the effect of non-economic factors. To move towards that, previous research explored how situational factors and social interaction influence homeowners' insulation activity by means of a simulation model (Friege et al., 2016). This paper draws on its authors' recommendation that an adequate evaluation of policy instruments that aim at increasing homeowners' insulation activity require their simulation model to be modified and calibrated on the basis of empirical research. Thus, the purpose of this paper is twofold:

1. To further increase the understanding and influence of factors involved in homeowners' decision-making regarding insulation by means of empirical research.
2. To incorporate these research results into a simulation model to evaluate new policy options aiming at an increase in homeowners' insulation activity.

The next section presents an empirical study carried out with 275 homeowners and puts forth conclusions towards designing the simulation model, followed by a description of the model. Afterwards, the simulation model is used to evaluate the effectiveness of the different policy options. The paper ends with a discussion on the validity of the model and a conclusion.

2 Empirical study

An empirical study was carried out to obtain data needed for modifying and calibrating the simulation model presented by Friege et al. (2016) with the purpose of making it usable for evaluating policy instruments that aim to increase homeowners' insulation activity. To serve this purpose, the empirical study was designed to gather accurate data regarding a) the composition of homeowners' individual characteristics and b) the homeowners' individual renovation activity. Due to the non-representativeness of the data on the aggregate level (e.g. age and income distribution among homeowners, see Appendix A), the model uses overall statistics on this level. Before presenting the findings and discussing its implications for the simulation model, it is important to outline the design of the survey.

2.1 Survey design

Data was collected through a nationwide online survey between July and October 2015. The link to the survey was communicated by distributing leaflets to homeowners, posting it in online forums, and placing references to it in newsletters. Of the 275 homeowners who participated in the survey, 198 to 232 responses could be used for the analysis, depending on the number of questions answered.

Composition of homeowners' individual characteristics

Information on the composition of homeowners' individual characteristics is necessary to increase the accuracy of how a homeowner's current situation is represented in the simulation model. This is highly relevant for the validity of the model results, because correlations between the condition of buildings and the socio-demographic, socio-economic, and psychological characteristics of homeowners would affect a homeowner's insulation activity. A correlation between building age and the homeowner's attitude towards insulation (the older the building, the more negative the attitude towards insulation), for example, would lower homeowners' insulation activity (assuming that the homeowners' attitudes influence their insulation decision). This is because fewer owners of old houses, which are often poorly insulated, would decide in favor of installing insulation. The following data was requested:

- House: Construction year; condition of building components at move in; renovation measures carried out
- Owner: Age; net household income; gender; lifestyle; information sources; number and (perceived) attitude of social contacts towards insulation, own attitude towards insulation[2]

2 The homeowner's attitude towards insulation comprises his or her opinion regarding the usefulness of insulation (economic and non-economic) raised with the help of eight Likert-scaled questions.

Homeowners' individual renovation activity

To allow for a more accurate simulation of homeowners' renovation decision processes, it is necessary to have data on homeowners' actual renovation activity. Combining this data with homeowners' personal characteristics can help to improve the understanding of homeowners' decision-making regarding renovations. Deriving general rules from the data can help to improve the accuracy of the model. In light of this, the survey also requested the following data:

- Year and type(s) of past renovation activities
- Year and type(s) of planned (future) renovation activities

Renovation activities were divided into measures that can be combined with insulation but do not improve it, such as renovating the roof or the façade[3], and measures that improve the insulation of the building envelope.

2.2 Findings

The following sections contain an overview of the main empirical findings regarding the composition of homeowners' characteristics and homeowners' renovation activity.

2.2.1 Composition of homeowners' individual characteristics

Analyzing the collected data reveals a number of correlations at the .01 significance level between different characteristics of homeowners (see Appendix A for details): the amount of time since homeowners moved into their houses positively correlates with the age of their houses as well as their own age. The houses' present wall insulation status negatively correlates with the age of the houses, but positively correlates with homeowners' income. A Mann-Whitney U test[4] shows that homeowners who already live in a house with wall insulation have more positive attitudes towards insulation than their counterparts without wall insulation ($W = 3718.5$, $n = 217$; $p = \leq .01$). The following figure shows homeowners' attitudes towards insulation divided into groups of homeowners who have their walls 'insulated' or 'not insulated'. Furthermore, homeowners' own attitudes towards insulation correlate with the (perceived) contacts' attitudes towards insulation. The second figure shows the difference between homeowners' own attitudes and the (perceived) contacts' attitudes towards insulation.

3 The term 'standard renovation measure' is later used to such activities that do not improve the insulation of the house.
4 The Mann-Whitney U test is used to test the hypothesis that two samples come from the same population.

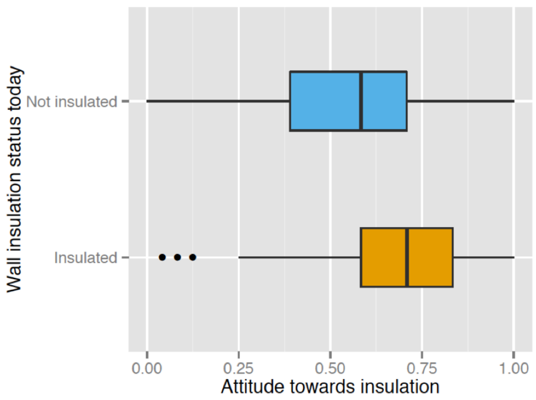

Fig. 2: Homeowners' attitudes towards insulation divided into groups of homeowners who have their walls 'insulated' and 'not insulated' (n = 198).

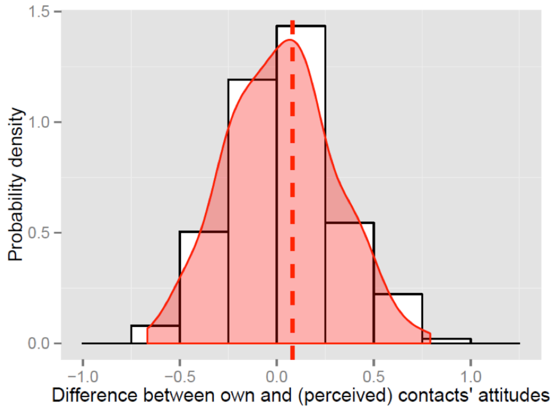

Fig. 3: Probability density of the difference between homeowners' own attitudes and the (perceived) contacts' attitudes towards insulation (n = 217).

Otte's lifestyle typology for Germany was used for assigning the respondents to nine different lifestyles (Otte, 2005). The typology is conceptualized along two dimensions: 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 their biographical perspective of living.

Various studies show that assigning persons to different lifestyles allows researchers to deduce their attitudes towards certain behaviors (Krebs et al., 2013; Schmid and Bruckner, 2011; Weber and Perrels, 2000). Therefore, a key hypothesis of the theoretical model of Friege et al. (2016) is that the homeowners' attitudes towards insulation differ between the lifestyles as described by Otte (2005). The following figures show that this could not be confirmed with the data raised. Performing the Mann-Whitney U test shows that only conservatives' (CONS) attitudes towards insulation differ statistically significant from the attitudes of the other lifestyles ($W = 2669$, $n = 230$; $p < .05$). The categories 'Traditional Workers' (WORK) and 'Entertainment Seekers' (ENTE) are represented by only two respondents in each case.

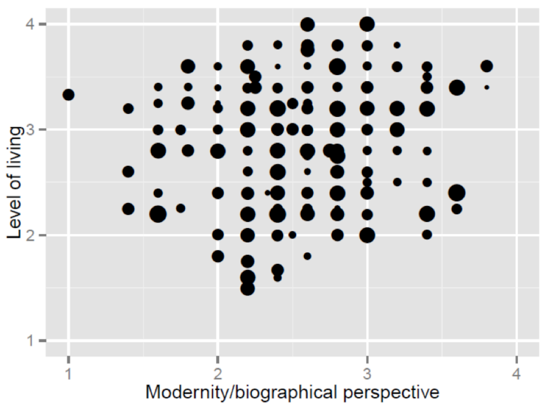

Fig. 4: Homeowners' attitudes towards insulation indicated by the size of the points by 'level of living' and 'modernity/biographical perspective' (n = 230).

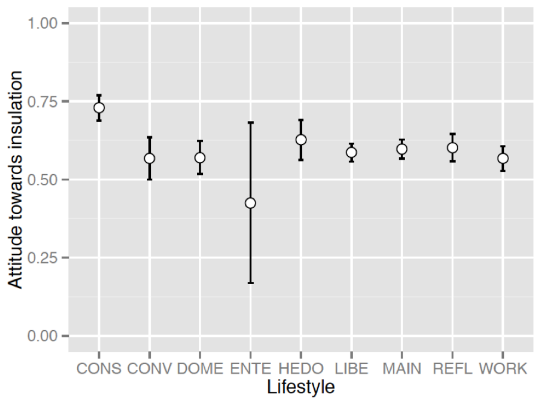

Fig. 5: Homeowners' attitudes towards insulation by lifestyle (n = 230). For an explanation of the abbreviations of the nine different lifestyles, see Appendix A.

It is possible to determine the current age of houses' walls and roofs by utilizing the point in time of the last renovation measure as well as the initial conditions. For the initial condition, participants were able to select 'very good', 'acceptable', and 'in need of renewal', which were translated to an age of 5, 15 and 31 years following Agethen et al. (2008). The ages of the walls (roofs) were found to be exponentially distributed with $\lambda = 0.066$ ($\lambda = 0.055$) (see Eq. 1). The condition of floors was not recorded.

$$f_\lambda = \begin{Bmatrix} \lambda \cdot exp(\lambda \cdot x) for x \geq 0 \\ 0 for x < 0 \end{Bmatrix} \text{Eq. 1}$$

2.2.2 Homeowners' individual renovation activity

Analyzing the data on homeowners' past and planned renovation activity reveals a number of factors influencing homeowners' renovation decision-making processes. These factors can be divided into an initiating occasion, triggering homeowners to start thinking about renovating their property (the renovation occasion) and homeowners' decision-making about what type of renovation to undertake (the renovation decision).

In total, the respondents' insulation activity is higher than that from the representative study of the IWU: in their study, the IWU calculated an average insulation rate of about 1% between the years 2000 to 2008 for all residential buildings in Germany (Diefenbach et al., 2010). The 10-year average insulation rate of the respondents, calculated using the same method, is 3.5%.

Renovation occasion

The results show that the probability of renovation measures being carried out is highest when homeowners move into a new building. To avoid a distortion of the data, only respondents who moved into a new building more than 10 years ago were included in the analysis. The results reveal the following: more than 30% of all insulation projects included in the analysis were carried out within the first year after moving in. In total, the relative frequency of insulation work carried out decreases with the total duration of occupancy (see Fig. 6). The same applies to the execution of the standard renovation measures of attic extension, roof renovation, façade painting, façade renovation, and cellar expansion.

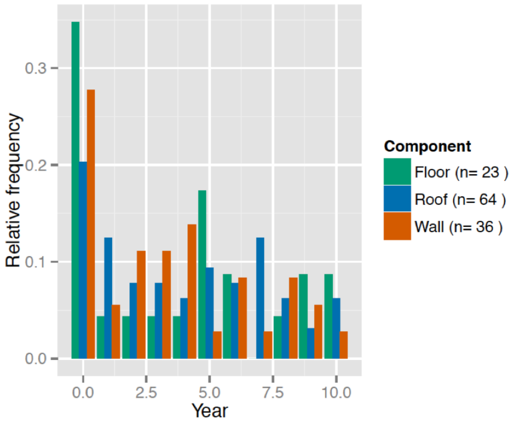

Fig. 6: Relative frequency of floor, roof and wall insulation projects carried out in the years after moving in for respondents who have lived in their house for more than 10 years (n = 123).

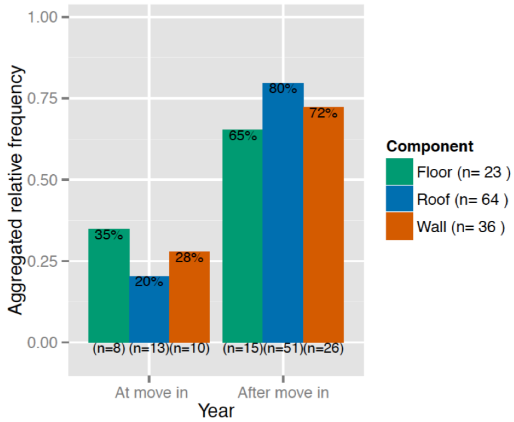

Fig. 7: Aggregated relative frequency of floor, roof and wall insulation projects carried out at move-in (year 0) and after move-in (year 1-10) of respondents who have lived in their house for more than 10 years (n = 123).

The homeowners' birth year and the year of moving in is used to estimate the probability that a homeowner will move into a new building depending on his/her current age. To calculate the probability, the share of homeowners who moved in at a given age, e.g. 40, is set in relation to the share of homeowners who had the possibility to move in at the age of 40. This share is determined by the number of homeowners who were a maximum of 40 years old when they moved into a new building and were older than 40 when the survey was conducted. This results in the following probabilities $p(\gamma_h)$ that a homeowner will move into a new building depending on the age category to which he/she belongs (γ_h).

γ_h [a]	< 26	26-30	31-35	36-40	41-45	>45
$p(\gamma_h)$ [%/a]	5	10	10	6	4	1.5

Table 1: Probability (p) of a homeowner moving depending on his/her current age (γ_h).

Analyzing the cases where the relevant component was not insulated or only partly insulated at the time of moving in reveals that insulation is often combined with standard renovation measures such as roof renovation (87%), and façade renovation (77%) (see Fig. 8). In contrast, only 40% of all façade repainting work is combined with wall or floor insulation. The structural condition of the roof and the walls is related to the relative frequency that renovation measures are carried out (see Fig. 9). More than 60% of all components which were stated to be 'in need of renovation' at the time of moving in were renovated by the homeowners thereafter. Conclusively, a main occasion for insulation is poor structural conditions of the roof and/or the walls.

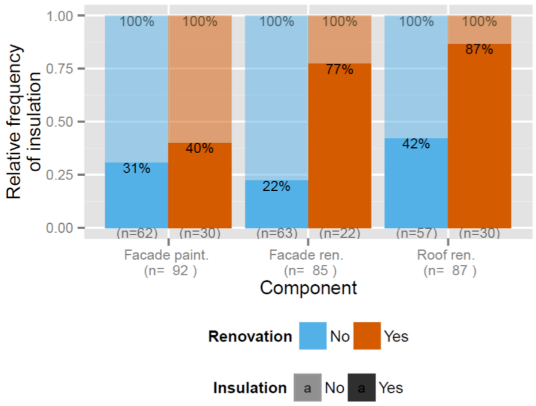

Fig. 8: Relative frequency of insulation for cases where the building components' condition at the time of moving in was 'acceptable' or 'in need of renovation' and the insulation status was 'not insulated'.

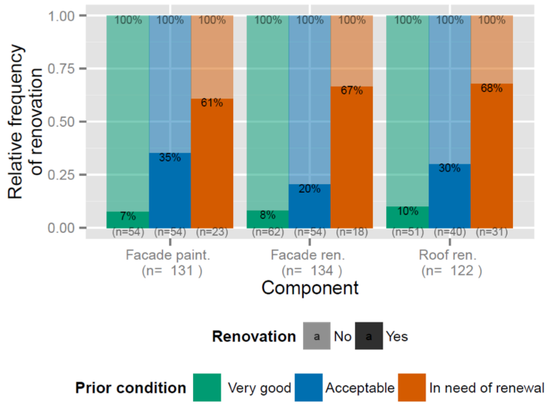

Fig. 9: Relative frequency of renovation of building components dependent on their condition at the time of moving in.

Renovation decision

When comparing the socio-technical characteristics of homeowners who decided in favor of carrying out insulation work with those who had the opportunity but did not have such work done, a few key factors stand out that affect homeowners' decision-making regarding wall insulation. In light of the results outlined in the previous section, it is possible to distinguish between the decision-making of homeowners who have just moved into a new building and the decision-making of homeowners in the years thereafter. Logistic regression models, which can be used to calculate the probability that wall insulation will be installed, were derived using a first subset of the data (training data set). A second subset of the data (test data set) was used to assess their predictive power.

To avoid the "curse of dimensionality" (Hastie et al., 2005), the maximum number of independent variables was set to four. This way, at least ten observations exist for each predictor, as Agresti (2002) suggests. The previous findings were used to make a preselection of possible independent variables used for fitting the logistic regression models. The following independent variables were selected: 'structural condition of the walls', 'age of homeowner at move in', 'homeowner's attitude towards insulation', and the 'homeowner's net household income'. The 'building's construction year' variable was excluded because it correlates with the 'structural condition of the wall'. Information on changes in a homeowner's attitude or income over time was not collected. Therefore, these variables were assumed to be constant over the considered period of ten years. The logistic regression models were fitted using 'lasso (least absolute shrinkage and selection operator) model selection', which has the advantage of producing "some coefficients that are exactly 0 and hence gives interpretable models" (Tibshirani 1996, p. 267). The algorithm is implemented in the R package glmnet (Friedman et al. 2010).

The probability equation, that a homeowner will insulate the walls ($\xi_w = 1$) after the first year (but within the first ten years) of moving into a new building ($t \neq 0$), was derived using a training data set comprising 92 homeowners without wall insulation, of which 27 insulated the walls within one of the years after moving in.

$$p(\xi_w = 1 | t \neq 0) = \frac{1}{10} \cdot \frac{1}{1+exp(3.15-0.07\cdot\gamma_{p,0}+1.15\cdot\phi_1-0.64\cdot\phi_3-0.84\cdot\alpha)} \quad \text{Eq. 2}$$

The homeowner's age at the time of moving in is $\gamma_{p,o}$. If the structural condition of the walls is 'very good' (renovated less than 5 years ago), ϕ_1 is 1 (otherwise 0). If the structural condition of the walls is 'in need of renovation (renovated more than 30 years ago), ϕ_3 is 1 (otherwise 0). The homeowner's attitude, scaled from 0 to 1, is denoted by α. The model shows that the structural condition of the walls highly affects a homeowner's decision to carry out insulation. Homeowners' net household income has no measurable effect on their wall insulation activity and thus does not appear in the logistic regression model. Furthermore, the probability of installing wall insulation increases with homeowner age and positive attitude. The probability equation, that a homeowner will insulate the walls ($\xi_w = 1$) at the time of moving in ($t = 0$) was derived using a training data set comprising 80 homeowners without wall insulation, of which 6 insulated the walls immediately after moving in.

$$p(\xi_w = 1|t = 0) = \frac{1}{1+exp(3.2-0.03\cdot\gamma_{p,0}-0.02\cdot\phi_1-2.16\cdot\phi_3-3.2\cdot\alpha)} \text{ Eq. 3}$$

Again, the wall insulation decision appears to be highly affected by the structural condition of the walls and homeowners' attitudes towards insulation. The quality of both logistic regression models is assessed by predicting homeowners' wall insulation decisions in the test data set and examining the total variance. The models' predictive power is shown in the table below. The first model ($t \neq 0$) correctly predicts 83%, the second model ($t = 0$) correctly predicts 86% of the wall insulation decisions made by the homeowners in the test data set. Since the second model ($t = 0$) was only trained with a relatively small number of homeowners who insulated the walls at the time of moving in, its apparently high predictive power must be interpreted with caution. The coefficients explain a share of at least 14% of null deviance in the first model ($t \neq 0$) and more than 42% cent in the second model ($t = 0$). Furthermore, the Receiver Operating Characteristic (ROC) curves show that the wall insulation decision models are strongly distinguishable from a random classification (see Appendix B). The areas under the curves are significantly greater than the areas under the diagonal line, underpinning the models' high quality.

	Years after move-in ($t \neq 0$)			**Within a year after move-in ($t = 0$)**		
Classification	**Predicted: 0**	**Predicted: 1**	**Correct**	**Predicted: 0**	**Predicted: 1**	**Correct**
Observed: 0	16	2	89%	15	3	83%
Observed: 1	2	3	60%	0	4	100%

Table 2: Accuracy of the logistic regression models for predicting homeowners' wall insulation decisions in the test data set ($n = 45$, 0 = no wall insulation, 1 = wall insulation).

For the insulation of the roof and the floor, it was not possible to fit a logistic regression model which explains more than 10% of the deviance. While the logistic regression models (see Appendix A) correctly predict 74% of the roof and floor insulation decisions, the ROC curves show that the decision models are largely insignificant (see Appendix B).

A descriptive evaluation of the data leads to the following insulation probabilities which can be adopted for buildings without roof or floor insulation: the probability for insulating the floor is 2% per year, the probability for insulating the roof is 3.5% if its condition is 'very good', 5.5% if its condition is 'acceptable', and 7.5% if its condition is 'in need of renovation'.

2.3 Recommendations for the simulation model

Composition of homeowners' individual characteristics

The results of the analysis reveal a strong relationship between homeowners' individual attitudes towards insulation and the perceived attitudes of social contacts towards insulation. However, it is difficult to say to what extent the real attitudes of the social network towards insulation deviates from the perceived attitudes. Furthermore, the data does not show to what extent homeowners' attitudes are influenced by the perceived attitudes of their social network or to what extent the homeowners merely choose social contacts with similar attitudes (network homophily).

For the simulation model, it is logical to assume network homophily with regard to homeowners' attitudes and an alignment of homeowners' attitudes with regard to the social impact of their network contacts over time. Holzhauer et al. (2013) show how to consider homophily when generating social networks for agent-based modeling. For modeling the social impact, the social impact theory from Latane (1981) can be used, as Friege et al. (2016) do as well.

Surprisingly, no statistically significant correlation between homeowners' lifestyles and attitudes towards insulation or the insulation status of their buildings was detected. It is arguable that this may be due to the fact that homeowners' attitudes towards insulation depend to a great extent on their specific situation, and therefore it is not possible to generalize them into groups of different lifestyles. In light of the results of the analysis of homeowners' renovation decision-making, which show that there is no statistically significant correlation between homeowners' affiliation to certain lifestyles and their decision to carry out insulation work, it is not necessary to include the lifestyle concept in the simulation model.

Homeowners' individual renovation activity

The results of the data analysis provide insight on homeowners' decision processes regarding renovations and allow for the derivation of two logistic regression models which can be implemented in the simulation model to estimate the probability of wall insulation projects being carried out. Since the goal is to use the simulation model to assess the influence of policies on homeowners' insulation activity, it is worthwhile limiting the model to wall insulation activity for the following reasons: first, the data did not allow the derivation of applicable logistic regression models for homeowners' roof and floor insulation decisions. Therefore, the number of simulated roof and floor insulation projects would not be affected by any variables which could be influenced by possible policies. Second, insulating the walls constitutes 55% of the total energy-saving potential of insulating existing buildings (Diefenbach et al., 2010), yet such insulation activities are not a priority for homeowners under cost-benefit considerations (Verbeeck and Hens, 2005). Furthermore, the data shows that roof insulation activity is already comparatively high, although roof insulation only makes up 30% of the total energy-saving potential. The low floor insulation rate is problematic, but floor insulation only makes up 15% of the total energy-saving potential of installing insulation (Diefenbach et al., 2010). Thus, developing and using a simulation model on homeowners' wall insulation activity is both possible through using the data available and particularly useful for tapping into the energy-saving potential of existing buildings.

3 The agent-based model

Based on the findings and recommendations from the empirical study, the following section describes an agent-based model (ABM) developed to evaluate new policy options that aim to increase homeowners' insulation activity. The model is an adaptation and extension of an existing ABM presented by Friege et al. (2016). In their study, the authors pointed out that if using such a model, additional empirical research is required to adequately evaluate the effectiveness of specific policy instruments that aim to increase homeowners' insulation activity. ABM is a widely used technique for modeling systems of autonomous interacting agents and is particularly suitable for capturing emergent phenomena arising from interacting agents, such as homeowners' insulation activity influenced by their social contacts (An, 2012; Bonabeau, 2002). In other words, ABM is the method of choice for conducting a comparative analysis of different policies that aim to increase homeowners' insulation activity.

The following lays out the model's main procedures: initialization, which includes setting up the techno-spatial structure; distributing the homeowners among the houses and establishing the social network; and the simulation of homeowners' decision-making processes.

The model is implemented in NetLogo v.5.1.0 (Wilensky and Evanston, 1999).

3.1 Model initialization

3.1.1 Spatial structure

To limit the number of independent variables and make the model as realistic as possible, geospatial information system (GIS) data on the location of houses in a section of the city of Bottrop (district of Batenbrock) was used to set up the spatial structure. Bottrop is a city in west Germany located in the Ruhr Area, a highly industrialized region. The data provided includes information on each building's construction year, as represented by different shades of color in Figure 10. This is an advantage for setting up the model because it is possible to estimate the probable condition of the wall insulation of the structures by knowing their construction year (Diefenbach et al., 2010). In total, the area includes 2,435 residential buildings. 82% of the buildings were built before 1979, which is higher than the German average of 65% (Diefenbach et al., 2010).

Fig. 10: Distribution of houses in Bottrop, Germany. Color shades of the dots represent the houses' age from old (dark) to new (bright).

3.1.2 Socio-technical characteristics

To calculate the condition of the wall insulation of the buildings, representative data from the IWU regarding the percentages of insulated walls per construction year was used (see Table 3).

Construction year	<1918	1918-1948	1918-1948	1958-1968	1969-1978	1979-1983	1984-1994	1995-2001	2002-2006
Walls insulated when built [%]	3.1	1.8	2.9	7.4	25.4	33.3	41.4	57.4	54.0
Walls insulated later [%]	32.0	28.4	30.1	28.3	16.4	13.4	5.9	3.3	10.3
Wall insulated total [%]	35.1	30.2	33.0	35.7	41.8	46.7	47.3	60.7	64.3

Table 3: Share of houses with 'walls insulated when built' and 'walls insulated later' by construction year category in the German building stock (Diefenbach et al., 2010).

The age of the walls is set according to an exponential distribution with $\lambda = 0.066$, which was found to best fit the data obtained (see Section 2.2.1), considering that the age of the walls cannot exceed the age of the structure. Since the surveyed age distribution of homeowners is not representative, a representative distribution from the UBA ($n = 604$), where the average age of a homeowner is 50.41 ± 14.7 years, was used to set the homeowners' age. Homeowner period of occupancy is uniformly distributed, considering that it cannot exceed the homeowner's age or the age of the building. The next characteristic implemented into the model is homeowners' own attitudes towards insulation (α), scaled from 0 (negative) to 1 (positive). Homeowners' attitudes towards insulation, mirrored at 0.5 (α_m) (see Eq. 4), can be determined by two Weibull distributions for the two groups of homeowners with 'insulated' and 'not insulated' walls, with the following values:

- Group 'Insulated': $f(\alpha_m \mid \xi_w = 1)$: $k_1 = 1.498$, $\lambda_1 = 0.353$
- Group 'Not insulated: $f(\alpha_m \mid \xi_w = 0)$: $k_0 = 1.947$, $\lambda_0 = 0.501$

With the probability density functions, the mirrored values for homeowner attitudes (α_m) can be calculated. ξ_w indicates the wall insulation status, k is the shape parameter, and λ is the scale parameter for the distribution. The resulting mirrored attitude must be adapted as follows, because the Weibull distribution is left-skewed while the attitude distribution is right-skewed:

$\alpha = (-\alpha_m) + 1$ Eq. 4

3.1.3 The social network

The social network is ought to represent a relationship where homeowners influence each other's attitudes towards insulation by talking to each other about renovation. Rogers (2010) states that sharing information occurs most frequently among homophilous individuals - individuals who are alike. Moreover, homophilous individuals are likely to have more influence on one another (McPherson et al., 2001). Thus, homophily must be taken into consideration when creating the social network for a simulation model. To do so, an algorithm developed by Holzhauer et al. (2013) was adapted. Their algorithm takes into account that the probability of interaction also depends on the geographical distance between two potential partners. To set up the social network, each homeowner in the model undergoes the following procedures: first, the number of network contacts is defined through random drawing from a gamma-distribution with alpha 1.8 and lambda 0.27 based on the results of the empirical analysis, where the median number of network contacts is five ($Q_1 = 3$, $Q_3 = 10$). Second, the following equation is used to estimate the probability that a homeowner X comes into contact with another homeowner Y.

$p_{xy}(\Delta O, \Delta\alpha, \Delta E) = \frac{1}{1+\Delta O^2+\Delta\alpha^2+\Delta E^2}$ Eq. 5

In the equation, the age difference (ΔO) and the attitude difference between two homeowners (Δα) (scaled from 0 to 100) to the power of two are used to calculate the degree of heterophily between two homeowners. This determination is based on other studies which show that networks are homogeneous by age (Burt, 1991; Hagestad and Uhlenberg, 2005) and the findings of the empirical analysis, which shows a strong correlation between the homeowners' own attitudes and their network contacts' attitudes towards insulation. The probability for homeowners to get the chance to talk to each other about building renovation decreases with geographical distance by a power of two (ΔE^2) between them: Manturuk et al. (2010) has demonstrated that the geographical distance plays a key role in social networks among homeowners. The distance is measured from the center of one property to another. If a homeowner comes into contact with another homeowner, they establish a relationship under the condition that his/her maximum number of network contacts (see above) has not yet been reached.

3.2 Model operation

Based on the results of the empirical analysis, crucial actions were derived which are suitable to simulate homeowners' wall insulation behavior. In each time step, representing a period of one month, each homeowner goes through a number of consecutive steps, for which an overview is provided in Figure 11.

First, a homeowner's decision to move into a new building depends on his/her age as depicted by Table 1 in Section 2.2.1. If a homeowner moves into a new building, the homeowner is reinitialized, following the relevant initialization procedures described in Section 3.1. The new homeowner's period of occupancy is set to zero. If the homeowner does not move into a new building, the homeowner's attitude towards insulation is updated once a year and after the decision on insulating the walls, based on the (perceived) attitudes of network contacts; according to Latane (1981), the influence of social network contacts depends on the effectiveness of communication, the closeness in time and space, and the number of people in the social network.

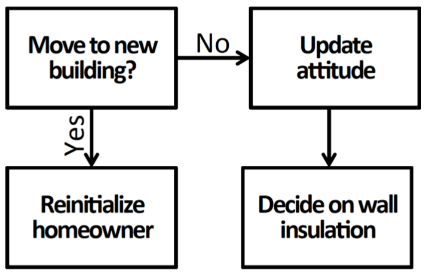

Fig. 11: Main steps for simulating homeowners' wall insulation behavior.

The algorithm used to build the social network takes into consideration the geographical distance between homeowners (closeness in space). Furthermore, the network ties represent relationships where homeowners can influence each other's decision-making (effectiveness of communication). This is achieved by considering the degree of homophily between two homeowners when creating the social network (see Section 3.1.3). The remaining two factors, 'closeness in time' and 'number of people in the social network', were incorporated in the equation to estimate the (perceived) social impact (I); this is then incorporated into a more complex equation reflecting how it affects a homeowner's attitude (A_t) as follows:

$$A_t = 0.5 \cdot (A_{t-1} + I) = 0.5 \cdot \left(A_{t-1} + \begin{Bmatrix} \sum_{i=1}^{N} \left(\frac{\xi_{w,i}}{1+T_i[a]} \right) \div \sum_{i=1}^{N} \left(\frac{1}{1+T_i[a]} \right) for N > 0 \\ A_{t-1} for N = 0 \end{Bmatrix} \right) \text{ Eq. 6}$$

The updated attitude (A_t) is the average of the previous attitude (A_{t-1}) and the perceived social impact (I). The time that has elapsed since network contacts last decided on wall insulation (T_i) is used to capture 'closeness in time'. If the homeowner has not yet decided about wall insulation during the simulated time period, the age of the wall insulation or of the walls (if no wall insulation is installed) is used. Thus, the perceived social impact received through network contacts decreases with the time that has elapsed since the last wall renovation or insulation measure was carried out. Furthermore, Latane's (1981) finding is adopted that the social impact by individual contacts decreases as the number of total network contacts (N) increases. $\xi_{w,i}$ is 0 if the network contact has no wall insulation installed and 1 if the network contact's walls are insulated. In this way, it is possible to take into account that the social impact can be either positive or negative. After updating the attitude towards insulation, a homeowner decides on insulating the wall, according to the probability equations introduced in Section 2.2.2.

4 Policy design

This next section explores new policy options deduced from literature and the empirical findings, and describes their implementation into the model. The strategy of simulating them with the model is also presented. The deduced policy options aim for a better allocation of the resources available for increasing homeowners' insulation activity. In this context, it is essential to consider a homeowner's specific situation. Research shows that, in most cases, it pays to invest in insulation measures due to the reduction in energy costs amassed over their lifetime (Nauclér and Enkvist, 2009). Combining standard renovation measures such as roof renovation or façade renovation with the installation of insulation significantly reduces their break-even period, related time requirement, and effort (Uihlein and Eder, 2010). Therefore, renovation occasions which trigger standard renovation measures represent a prime opportunity to introduce insulation measures into the homeowners' decision to renovate. According to Stieß and Dunkelberg (2012), prime opportunities are overdue maintenance work and change of house ownership. Since this is consistent with the findings of the empirical research, the suggested policies aim to take advantage of these two opportunities.

4.1 Introducing a change of house ownership insulation obligation

The results of the empirical study show that influencing homeowners' insulation decisions through economic means is unlikely to be very effective. From the two remaining instruments, regulation and providing information, regulation is particularly suitable for connection to the change of house ownership occasion: one option is to obligate homeowners to insulate the walls within one year after moving in. For the following reasons, this option is preferable over other approaches:

- Homeowners can include the knowledge about the obligation into their decision to move into a new building.
- Since the transfer of house ownership is officially recorded, the obligation is easy to enforce.
- The obligation lowers the market value of houses without wall insulation.

The policy is implemented in the simulation model by forcing homeowners who moved into a house without wall insulation one year ago and did not insulate the walls within this period to insulate the walls. This way, only the policy's additional effect on homeowners' wall insulation activity is recorded.

4.2 Improving homeowners’ disposition to insulation

Since homeowners’ attitudes regarding insulation play a role in their wall insulation decision-making, various strategies can be used to positively influence homeowners’ attitudes towards insulation and thus increase their wall insulation activity. Possible occasions include conversations with craftsmen or energy consultants about upcoming renovations or during the meeting with the bank when a homeowner applies for a mortgage.

Who should be targeted by the policy?

Private homeowners are a specific demographic in terms of characteristics such as age, family size, education and income. In addition to designing policies focused on people with those specific characteristics, it might be reasonable to promote insulation to owners of old houses in particular. Targeting owners of old houses might be a good strategy because old houses are more likely to be in need of renovation. Additionally, old houses are more likely to be poorly insulated due to lower efficiency standards in the past. As a result, fewer homeowners need to be contacted to come across one who could find an occasion to insulate his or her building compared to randomly targeting homeowners. On the other hand, randomly targeting owners of houses results in a higher penetration of the social network and might therefore result in higher insulation activity due to greater network effects.

Should the policy be short-termed or extended for a prolonged period?

Any pre-defined time horizon of a policy should influence overall activity, in this case for increasing wall insulation activity. Latane’s (1981) social impact theory teaches us that communication about recent events leaves a stronger impression than communication about events which lie far in the past. Thus, network effects caused by a short-term policy might fizzle out after it has come to an end, which could result in a decrease in homeowners’ insulation activity back to former levels. On the other hand, more homeowners can be reached in a shorter period of time, which can lead to multiplying network effects.

Should the policy’s capability be distributed among many or few?

This question arises due to homeowners’ heterogeneous attitudes towards installing insulation. Therefore, some house buyers may already plan on installing insulation without external intervention, some may need a little encouragement, and some may require a massive amount of persuasion. In the model, it is assumed that policymakers are unable to know the specific attitudes of individual homeowners. Therefore, each target person is approached using the same amount of effort. But should the policy campaign target a few homeowners with great effort or many homeowners with little effort? Each strategy has advantages and disadvantages: targeting a few homeowners with great effort has the advantage of also convincing some of those with a very negative attitude towards insulation - whose network contacts have a below-average attitude as well. On the other hand, targeting many homeowners with little effort increases the overall attitude to a greater extent, because less effort is wasted on homeowners who already have a very positive attitude towards insulation.

What is the potential effect of harnessing homeowners’ social networks?

Aside from harnessing the existing network, there is the option of increasing the spread of positive attitudes towards insulation through the social network to increase the overall insulation activity. One example of this strategy is the distribution of recommend-a-friend vouchers to homeowners who have decided on installing insulation, which gives them a reward for ‘spreading the word’. If they pass vouchers to other homeowners in their social network, this would affect the recipients in different ways: first, the recipient would receive personalized information about installing insulation, learn about the process, funding sources, and obstacles to overcome. Second, the recipient would notice his or her friend’s (positive) attitude towards insulation, influencing his or her own thinking about the topic. Finally, the recipient would be able to use the voucher for whatever service it provides. But how should the policy’s effort be divided between directly targeting house buyers and targeting their social network contacts through instruments such as recommend-a-friend vouchers?

How well-endowed should the policy be?

The greater the resources of the policy, the higher homeowners' wall insulation activity will be. But does doubling the resources result in a doubling of the increase of homeowners' wall insulation activity? And if not, how much resources should be allocated to the policy to achieve the best cost-benefit ratio?

How is the policy implemented in the simulation model?

The following table provides an overview of how the different elements of the policy were implemented in the agent-based model.

Research question	**Parameter**	**Value**	**Description**
Who should be targeted by the policy?	target-group	old, random	Defines whether old houses (built before 1978) or randomly selected houses are targeted by the policy.
Should the policy be short-term or extended for a prolonged period?	time-frame	1, 5	Defines the time frame (in years) within which the policy takes effect. The probability that a homeowner of the target group will be reached by the policy is adapted accordingly (see Eq. 7).
Should the policy's capability be distributed among many or few?	points-per	0.25, 0.5, 0.75	Defines the number of points which are provided to the target group. A score of 0.25 points corresponds to an increase in the homeowners' attitudes towards insulation of one category.
What is the potential effect of harnessing homeowners' social networks?	harn-netw	true, false	Defines whether targeted homeowners score an additional number of points which they pass on to other homeowners who do not have their walls insulated and have been living in their house for more than one year.
How well-endowed should the policy be?	share-pol	0.2, 0.4, 0.6	Defines the share of homeowners reached when providing 0.25 points to each homeowner.

Table 4: Overview of how the policy is implemented in the simulation model.

Since there is no data on the precise effect of different instruments, such as on-site consultation on homeowners' individual attitudes towards insulation, the instrument's effect is implemented in the model directly. The effect is quantified through the extent to which a homeowner's attitude is improved. For example, a new policy, valued at 25 points, allows the model to improve the attitude of 100 homeowners by a value of 0.25 points. An increase of 0.25 points in attitude equals the increase of one attitude category as used in the survey. In the survey, the attitude towards insulation was queried using a four-category scale from 'very negative' to 'very positive'. Thus, the model is incapable of answering the question of which instrument is most suitable for convincing an individual homeowner to carry out an insulation project. Nevertheless, assigning each policy design the same number of points allows to compare the combined effect of the different strategies presented in the table above. During simulation, the distribution of the points, which increase homeowners' attitudes towards insulation, is carried out in the following manner:

1. The total amount of points is designed to last for providing different shares of homeowners (X) with points at a value of 0.25. With an increasing number of points provided to each homeowner, fewer homeowners are reached.
2. The total amount of points is split equally into 'direct points' and 'network points', if the policy is designed to harness homeowners' social networks.

3. For defining the probability (p) that a homeowner who belongs to the target group will receive points, the following equation is used:

$$p(N, N_T, T, P, S) = \frac{X \cdot N}{12 \cdot T[a] \cdot \left(\frac{P}{0.25}\right) \cdot N_T \cdot \left(\frac{1}{S}\right)} \text{ Eq. 7}$$

Where N is the total number of homeowners, N_T the number of homeowners in the target group, X the share of homeowners that can be reached when providing 0.25 points to each homeowner, T the time period of the policy (in years), P the number of points provided to each homeowner, and S the share of points which are directly used (the rest go into harnessing homeowners' social networks).

4. If the policy is set to harness homeowners' social networks, each homeowner receives additional points to the value of P, which are shared with one other homeowner in his/her social network, who does not have insulated walls.

5 Results and discussion

According to the model's design, the simulations span ten years, with 120 time steps, each representing a month. In the simulation experiments, the simulation was repeated 100 times for each combination of parameter settings so as to be able to analyze the variety of outcomes. Homeowners' wall insulation activity is measured through the ten-year average of the annual wall insulation rate. An annual wall insulation rate of 2% in the model corresponds to the walls of 49 structures being insulated each year.

First, homeowners' wall insulation activity is explored without considering the introduction of policies (P_0). This serves as a reference scenario and enables the model's validity to be assessed. Second, the model was used to assess the different policies introduced before (P_1, P_2). Table 5 gives an overview of the simulation results.

Policy	Description	Wall insulation rate [%/a]
P_0	No policy intervention (reference scenario)	1.39 ± 0.11
P_1	Introducing an obligation to insulate when house ownership changes	Δ 0.79 ± 0.13
P_2	Improving homeowners' attitudes towards insulation	Δ 0.02 to 0.11

Table 5: Ten-year average of the annual wall insulation rate without policy intervention (P_0) and the increase achieved through policy intervention (P_1, P_2).

5.1 Reference scenario

Without policy intervention, the simulation model results in a ten-year average wall insulation rate of 2.35 ± 0.08%. Over time, homeowners' insulation activity decreases because fewer houses are in need of insulation. The decision on refurbishing existing insulation was not simulated. In their representative study, the IWU calculated an average wall insulation rate of 1.2% between 2000 and 2008 for all residential buildings in Germany (Diefenbach et al., 2010). In Germany, more walls have insulation (42% instead 37%), which has an adverse effect on homeowners' wall insulation activity and explains the higher activity in the simulated area to some extent. However, the greater part of the deviation between the simulation findings and the representative study from IWU results from the generally higher renovation activity of the homeowners taking part in the survey (see Section 2.2.2), whose activity was used to derive the decision-making models. Therefore, the simulation model was calibrated by reducing the frequency at which the homeowners make a renovation decision by 50%. After calibration, the homeowners wall insulation rate is 1.39 ± 0.11%. The following section utilizes this calibrated model to evaluate the policies.

5.2 Policy evaluation

5.2.1 Introducing an obligation to insulate when house ownership changes

The following section uses the agent-based model to evaluate the potential of exploiting the occasion of renovation following an ownership change by introducing an obligation to insulate walls at that time. To do so, the results of 100 simulation runs to determine the 10-year average wall insulation rates with or without applying the insulation requirement were compared with each other: these results show that the insulation obligation increases homeowners' wall insulation rates by 0.79 ± 0.13 percentage points. The difference between the two groups of simulation results (with/without obligation) was found to be statistically significant as determined by one-way ANOVA ($F(1,198) = 3,960$; $p < .001$).

5.2.2 Improving homeowners' attitudes towards insulation

Next, the model is used to assess the impact of a policy increasing the homeowners' attitudes towards insulation. The total potential of increasing homeowners' wall insulation activity through the approach used in this paper can be calculated by providing each homeowner with 0.75 policy points at the start of the simulation. The comparison of 100 simulations with/without providing this amount of policy points to each homeowner reveals the policy's maximum potential, which is an average increase in homeowners' ten-year average wall insulation activity of 0.11 ± 0.18 percentage points. The difference between the two groups of simulation results (with/without policy) was found to be statistically significant as determined by one-way ANOVA ($F(1,198) = 38.31$; $p < .001$).

Assigning the policy enough points to reach 20%, 40% or 60% of all homeowners results in an increase of 0.022, 0.031 and 0.046 percentage points in the ten-year average of homeowners' wall insulation rates. Continuing only with the case where 40% of all homeowners can be reached reveals that directing 0.25 points to each homeowner is more efficient than 0.5 or 0.75 points. The difference between the three groups of simulation results (0.25: 0.05, 0.5: 0.04, and 0.75: 0.03 percentage points) was found to be statistically significant as determined by one-way ANOVA ($F(2,2397) = 6.85$; $p < .01$). Targeting owners of old houses seems to be advantageous over targeting owners of houses randomly (increase of 0.057 percentage points instead of 0.052). However, the difference is not statistically significant.

With regard to the length of the time frame, a shorter period leads to a statistically significant higher increase in the wall insulation rate (1 year: 0.063 percentage points, 5 years: 0.046 percentage points). Assigning half of the resources to harnessing the social network, leads to a significantly lower increase in the wall insulation rate (with harnessing social network: 0.056 percentage points, without harnessing social network: 0.07 percentage points).

5.3 Model validity

The agent-based model developed here represents the further development of a model presented in the Journal of Artificial Societies and Social Simulation (Friege et al., 2016). This entailed conducting an empirical study among 275 homeowners and incorporating its results into the agent-based model. The model was limited to the simulation of homeowners' wall insulation activity, for which logistic regression models were derived from empirical data from the survey. However, this collected data was not sufficient to make any predictions regarding roof and floor insulation activities on the part of homeowners.

As far as possible, overall statistics were used for modeling the composition of the population. However, it was necessary to use the empirical data when dealing with the distribution of homeowners' attitudes towards insulation. To minimize the bias resulting from non-response behavior, the fact that homeowners' attitudes towards insulation correlates with the wall insulation status of their home was utilized. Calculating two attitude distributions, one from homeowners with wall insulation and one from homeowners without wall insulation, and using these distributions for setting up the agent-based model, took care of the fact that the respondents' average attitude towards insulation is most likely more positive than the average attitude of the general population. This distortion is indicated by the share of respondents who have their walls insulated, which is 20 percentage points above the share of the general population (42%) (Diefenbach et al., 2010).

One weakness of the model is that the simulation of homeowners' decision-making (the logistic regression models) is based on the assumption that homeowners' attitudes towards insulation do not change depending on the type of decision made. To eliminate this error, time series data would be needed on homeowners' attitudes before and after deciding on insulation. In reality, based on the principle of cognitive dissonance, it is to be expected that a decision in favor of or against installing insulation which is not in accordance with one's own attitude is rationalized by modifying attitudes afterwards. Over the course of the empirical study, an attempt was made to minimize the resulting bias by assessing homeowners' attitudes towards insulation through a number of different questions related to thermal insulation.

6 Conclusions

6.1 Understanding homeowners' decision-making regarding insulation

The empirical analysis of homeowners' insulation decision-making reveals that the decision to insulate the walls can be explained to a great extent by means of a few variables. These are: period of occupancy, the structural condition of the walls, attitudes towards insulation, and the homeowner's age. The analysis indicates that knowing these variables is sufficient for correctly predicting about 80% of homeowners' wall insulation decisions. Nevertheless, there was insufficient data to determine key decision variables regarding decisions about insulating the roof or the floor. Furthermore, the data shows that roof insulation activities are already comparatively high, even though roof insulation only accounts for 30% of the total energy-saving potential of installing insulation. The low rate of floor insulation is problematic, but only accounts for 15% of the total energy-saving potential. Thus, policies should focus on homeowners' wall insulation activities, as 55% of the total energy-saving potential of installing insulation occurs here.

As suggested by Friege and Chappin (2014), the data confirms that homeowners' income plays no decisive role in their decision to carry out insulation projects. This is demonstrated by the fact that there is no statistically significant difference between the income of homeowners who carried out insulation work and those who had the opportunity to carry out insulation work but decided against it. Furthermore, the study shows that the majority of homeowners pursue a high standard of living and have an above-average net household income. These findings are consistent with other studies (Linnebach et al., 2014; Rückert-John, 2012) and could be a reason why financial issues were found to play an insignificant role in homeowners' decision-making regarding insulation. Of course, this can be much different for landlords' decision-making in this regard.

Surprisingly, no statistically significant correlation was found between the homeowners' adoption of a particular lifestyle and their attitudes towards insulation. This observation differs significantly from other studies which show that people's environmental concerns or attitudes towards climate change varies among different lifestyles (Rückert-John, 2012). Consequently, defining target groups for increasing homeowners' insulation activity is very challenging: it is necessary to identify those homeowners which have not insulated yet, but nevertheless have a positive attitude towards insulation. This is particularly difficult because the majority of homeowners with a positive attitude towards insulation live in houses where the walls are already insulated.

Exploiting the right moment is important for tapping into the potential for homeowners to insulate. Since standard renovation measures are often combined with insulation, it is recommended to provide information on standard renovation measures together with information on combinable insulation projects. The same applies to the change of house ownership when an above-average number of insulation projects are carried out. Since younger people move more often but insulate their home significantly less often, there is a need for policy instruments which particularly focus on younger age groups.

Finally, the data shows a strong relationship between the (perceived) attitude of one's social network and one's own attitude or decision to insulate the walls. Other studies on energy-relevant investment decisions have generated similar results (Bollinger and Gillingham, 2012). Indeed, social influences are often underestimated and may play a greater role than self-reported measurements suggest (Cialdini, 2005). The possible implications of harnessing homeowners' social networks to increase their insulation activity were tested by means of the simulation model.

6.2 Increasing homeowners' insulation activity in Germany

This final section details some conclusions that can be drawn regarding the three options policymakers have to increase homeowners' insulation activity: information, economic means and regulations.

6.2.1 Information

The simulation results show that increasing homeowners' wall insulation activity by improving their attitudes towards insulation by providing information is a difficult undertaking. The total potential of this approach is about a 7% increase in the wall insulation rate handled by homeowners themselves (an increase from 1.4 to 1.5%). Simulating various strategies to implement the policy shows that it is more advantageous to run a short and intense campaign than to extend it over a prolonged period, and to target many homeowners with low effort rather than target a few homeowners with major effort. Targeting old houses in particular or harnessing homeowners' social networks were not found to have statistically significant greater impacts on homeowners' wall insulation activity. In sum, improving homeowners' attitudes towards insulation through policy instruments does not seem to be a promising option for increasing homeowners' wall insulation activity to the extent needed to meet Germany's climate protection targets.

6.2.2 Economic means

The results of the empirical analysis indicate that homeowners' economic means have only very little influence on their decision to insulate. This applies to their net household income as well as to their standard of living. Other authors' results of recent research have reached similar conclusions on the relatively minor role of economic factors in homeowners' decision-making processes on insulation:

- Pettifor et al. (2015) found "that non-renovators were no more likely than renovators to be facing financial constraints suggesting monetary concerns are unlikely to account for why they were not renovating" (Pettifor et al., 2015, p. 171).
- Stieß et al. (2009) concluded that critical barriers for installing insulation "can hardly be overcome by financial incentives alone" (Stieß et al., 2009, p. 1827).
- Wilson et al. (2013) stated that "financial constraints do not act as a barrier to renovation decisions or strengthening intentions. They may, however, lengthen the time spent deciding" (Wilson et al., 2013, p. 7).

6.2.3 Regulations

Ultimately, tightening regulatory instruments seems to be the best way to sufficiently increase homeowners' insulation activity. One recommendation would therefore be to introduce a requirement to insulate walls after a change of house ownership. This would make use of the window of opportunity posed by a change of house ownership, because many homeowners take advantage of this occasion to conduct extensive renovations anyway. Homeowners who plan on moving into a new building can include the knowledge about the wall insulation obligation into their purchase decision. It is expected that this would result in a decreasing market value of houses without wall insulation (corresponding to the associated expense). Furthermore, the transfer of house ownership is officially recorded, which means that the obligation to insulate the walls is easy to enforce. Exemptions should apply to listed buildings. In order to increase the social acceptance of such a policy, it could be complemented by low-interest loans and/or grants.

The potential of increasing homeowners' wall insulation activity through the suggested measure corresponds to the number of homeowners who move into a house without wall insulation and do not decide in favor of insulating the walls on their own accord. In the simulation model presented in this paper, an obligation would increase homeowners' average ten-year wall insulation rate by 0.79 ± 0.13 percentage points. Using the calculation method from the IWU (Diefenbach et al., 2010), this would correspond to a total increase in homeowners' insulation activity of about 40% in Germany.

This does not yet correspond to doubling today's insulation rate of about 1% needed to achieve the German government's target of an 80% reduction in energy demand in the housing sector by 2050, but it would contribute a major step towards that goal.

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Appendix A – the empirical study

A.1 Data overview

The collected data was compared to representative data sets using Pearson's chi-squared test of goodness of fit to assess its usability for the model. The main socio-demographic and socio-economic characteristics of homeowners collected were age and net household income. The following figures show the homeowners' ages and their net household income distribution from the collected data (FRI) in comparison to data gathered in the course of a representative study published by Germany's Federal Environmental Agency (UBA) (Rückert-John, 2012).

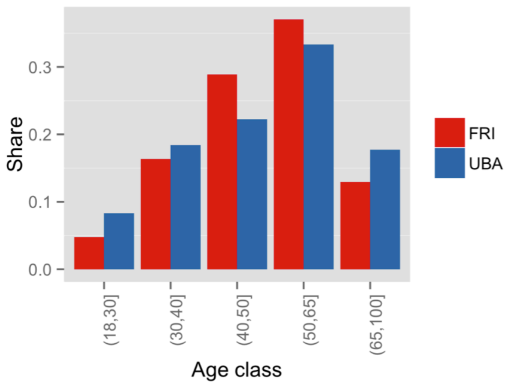

Fig. A.1: Homeowners' age distribution in author's own study (FRI: n = 232) and representative study (UBA: n = 604).

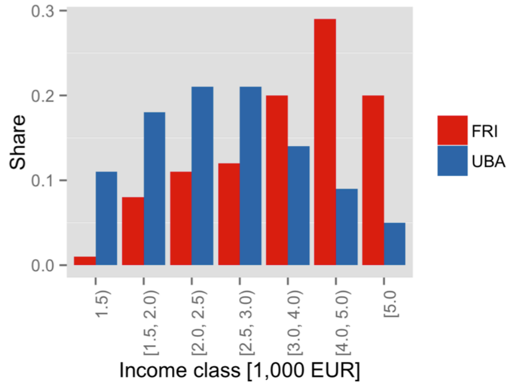

Fig. A.2: Homeowners' household net income distribution in author's own study (FRI: n = 214) and representative study (UBA: n = 604).

The figures show that homeowners between 40 and 60 years old and homeowners with an above-average net household income are overrepresented in the data. According to the results of Pearson's chi-squared test of goodness of fit, the null hypothesis that the raised age and income distributions provide a good match to the representative distributions must be rejected at .05 level of significance.

The following figures compare the share and distribution of lifestyle typologies in both the self-conducted study (FRI) and the study introduced above (UBA). Pearson's chi-squared test of goodness of fit reveals that the raised data is not representative at .05 level of significance.

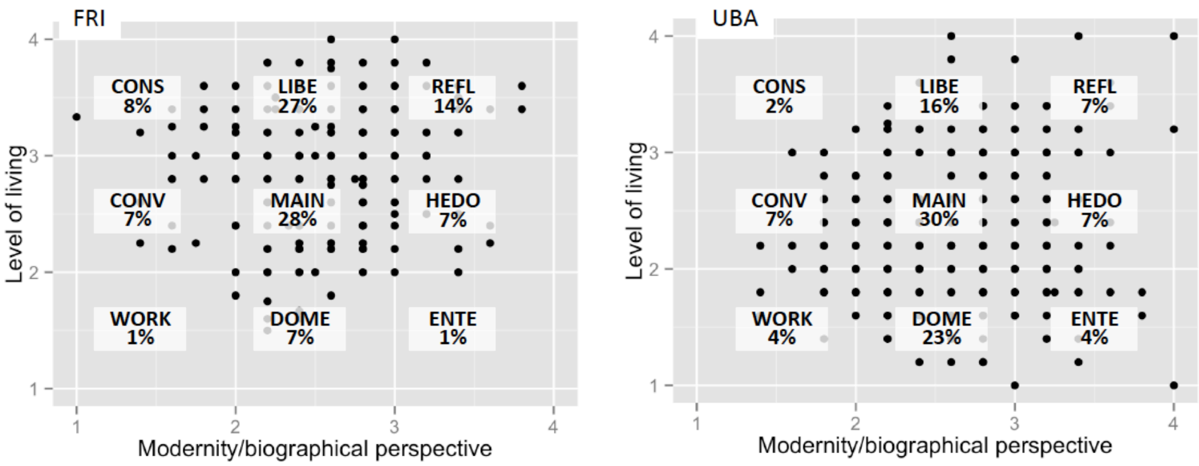

Fig. A.3: Lifestyle distribution in author's own study (FRI: n = 227) and representative study (UBA: n = 406) with CONS = Established Conservatives, CONV = Conventionals, TRA = Traditional Workers, LIBE = Established Liberals, MAIN = Adaptive Mainstream, DOME = Domestically Centered, REFL = Reflectives, HEDO = Hedonists, ENTE = Entertainment Seekers.

The conditions of homeowners' buildings were captured by their construction year, the insulation status at move-in, and the insulation measures carried out up to the present day. A building typology developed by the *Institut Wohnen und Umwelt* (IWU) (Diefenbach et al., 2010), using building phases of similar construction methods for classifying housing units of different construction years into the same construction year categories, was used to depict the survey data. The following figures show the share of homeowners who have a house in the particular construction year category and the average insulation status of the houses. To quantify the average insulation status, a method introduced by Diefenbach et al. (2010) was applied. The following equation, with $N_{ro,ins}$, $N_{wa,ins}$, $N_{fl,ins}$ being the numbers of houses with existing roof, wall and floor installation, and N_h being the total number of houses, was used to calculate a weighted insulation status for each construction class. The weightings of the installed insulation projects (percentages in the equation) are defined according to their contribution to resulting energy savings.

$$I_{stat} = (55 \cdot N_{wa,ins} + 30 \cdot N_{ro,ins} + 15 \cdot N_{fl,ins})/N_h$$

Again, the data collected for the present study was compared to that of a representative study carried out by the IWU in 2009/2010.

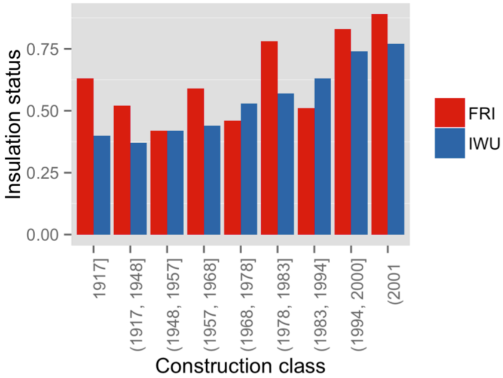

Fig. A.4: Distribution of detached and terraced residential buildings by construction class according to author's own study (FRI: n = 218) and representative study (IWU: n = 4,850).

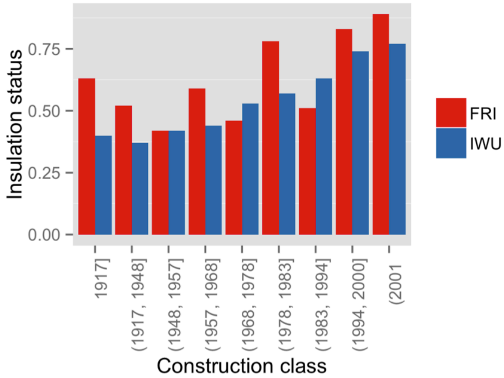

Fig. A.5: Distribution of detached and terraced residential buildings' insulation status per construction class according to author's own study (FRI: n = 218) and representative study (IWU: n = 4,850).

The figures show that the basic conditions revealed by the IWU also appear in data collected for the present study: 1) more than 50% of the buildings were constructed before 1978 – before Germany's first Heat Insulation Ordinance for new buildings was introduced (Förster et al., 1980); 2) new buildings are better insulated. Pearson's chi-squared test of goodness of fit reveals that the shares of respondents who have a house in the particular construction class is not representative at the .05 level of significance.

The results of the analysis further indicate how insulated building components are distributed among houses. The likelihood that all components (roof, wall and floor) are insulated is under 40%, even for houses built after 2001. The chance of coming across a building where solely the wall is insulated is less than 2% across all construction classes.

	Before 1918	**1918-1948**	**1949-1957**	**1958-1968**	**1969-1978**	**1979-1983**	**1984-1994**	**1995-2001**	**After 2001**
$p(I_{wa})$	1.0%	0.9%	0.9%	1.0%	1.2%	1.3%	1.3%	1.7%	1.7%
$p(I_{fl})$	0.8%	0.6%	0.7%	0.7%	1.3%	1.4%	2.1%	2.5%	2.7%
$p(I_{ro})$	14.5%	14.9%	17.0%	17.5%	20.1%	21.0%	22.7%	23.0%	22.2%
$p(I_{wa} \cap I_{fl})$	0.8%	0.6%	0.7%	0.7%	1.3%	1.4%	2.1%	2.5%	2.7%
$p(I_{wa} \cap I_{ro})$	13.4%	13.7%	15.7%	16.1%	18.5%	19.3%	20.9%	21.2%	20.4%
$p(I_{fl} \cap I_{ro})$	4.0%	3.0%	3.6%	3.7%	6.5%	7.2%	10.7%	12.7%	13.5%
$p(I_{wa} \cap I_{ro} \cap I_{fl})$	21.6%	18.7%	20.4%	22.0%	25.8%	28.8%	29.0%	36.3%	36.7%

Table A.1: Probability of insulation combinations by construction class (n = 218) with I_{wa} = wall insulation, I_{fl} = floor insulation, I_{ro} = roof insulation.

A.2 Statistically significant correlations

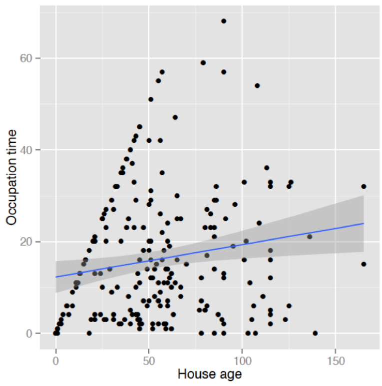

Fig. A.6: Correlation between occupation time and house age

(r = .17, p = ≤ .01, n = 219).

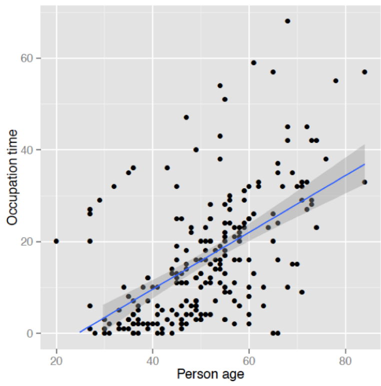

Fig. A.7: Correlation between occupation time and person age

(r = 0.55, p = ≤ .001, n = 232).

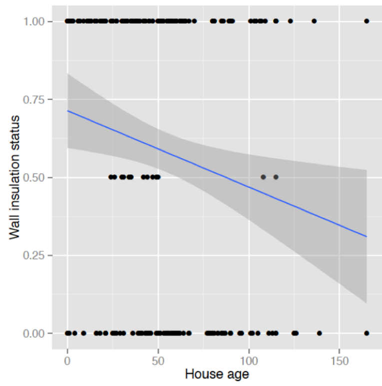

Fig. A.8: Correlation between wall insulation status and house age

(r = -0.17, p = ≤ .01, n = 219).

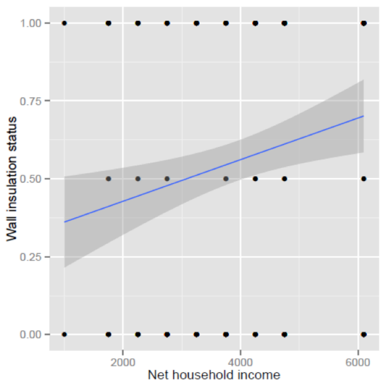

Fig. A.9: Correlation between wall insulation status and net household income

(r = 0.20, p = ≤ .01, n = 214).

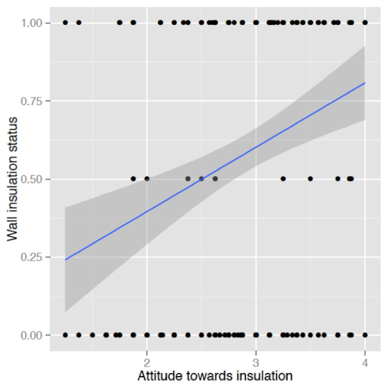

Fig. A.10: Correlation between wall insulation status and attitude towards insulation

(r = 0.28, p = ≤ .001, n = 228).

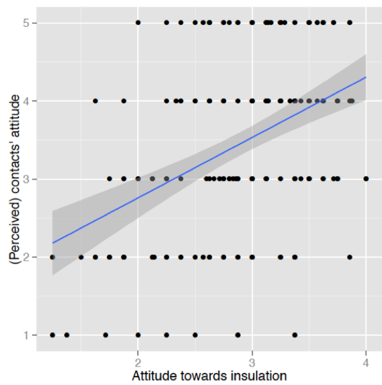

Fig. A.11: Correlation between (perceived) contacts' attitude and attitude towards insulation

(r = 0.43, p = ≤ .001, n = 198).

A.3 Roof and floor insulation decision

The following shows the probability equation that a homeowner will insulate the roof (ξ_w=1) within a period of 10 years after moving in.

$$p(\xi_r = 1) = \frac{1}{1+exp(1.21-0.06\cdot\gamma_{p,0}+1.12\cdot\phi_1-0.23\cdot\phi_3)} \text{ Eq. A.2}$$

The homeowner's age at the time of moving in is $\gamma_{p,o}$. If the structural condition of the roof is 'very good' (renovated less than 5 years ago), ϕ_1 is 1 (otherwise 0). If the structural condition of the roof is 'in need of renewal' (renovated more than 30 years ago), ϕ_3 is 1 (otherwise 0). The following shows the probability equation that a homeowner will insulate the floor (ξ_f=1) within a period of 10 years after moving in.

$$p(\xi_f = 1) = \frac{1}{1+exp(0.41-1.7\cdot t_1)} \text{ Eq. A.3}$$

If the homeowner moved in less than one year ago, t_1 is 0 (otherwise 1). The probability equations for the homeowners' roof and floor insulation decisions were not implemented into the agent-based model because they do not explain more than 10% of the deviance. Moreover, the ROC curves (see Appendix B) show that they are largely insignificant.

Appendix B - ROC curves

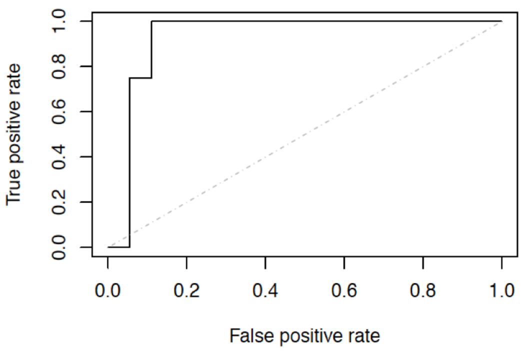

Fig. B.1: ROC curve for first wall insulation decision regression model (t = 0).

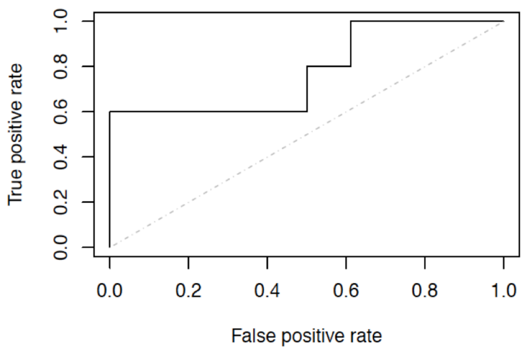

Fig. B.2: ROC curve for second wall insulation decision regression model (t ≠ 0).

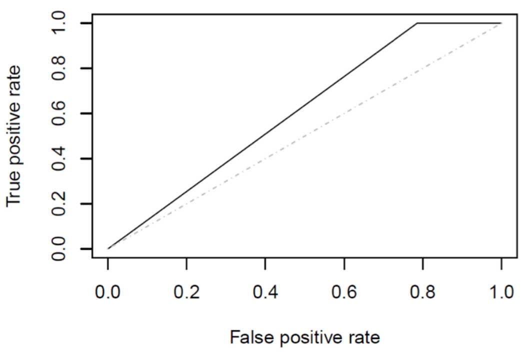

Fig. B.3: ROC curve for floor insulation decision regression model.

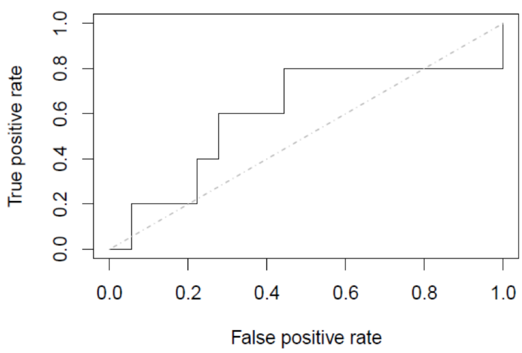

Fig. B.4: ROC curve for roof insulation decision regression model.