Increasing homeowners' insulation activity in Germany

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A theoretically and empirically grounded agent-based model analysis

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ABSTRACT

How is it possible to increase homeowners' insulation activity? Answering this question is key to successful policies regarding energy-efficient buildings worldwide. In Germany, doubling today's insulation rate of about 1% is an important element for reaching the government's target of an 80% reduction in energy demand in the building sector by 2050.

This thesis uses an agent-based model analysis to improve the understanding of homeowners' insulation activity and to explore new approaches aiming at its increase in Germany. Two agent-based models were developed and utilized. The first model was developed mainly based on insights derived from a structured literature review. The second emerged from the previous one, incorporating the results of an online survey conducted among 275 homeowners.

The results indicate that homeowners' economic means have little influence on their decision to install insulation. Instead, their insulation decision-making is mostly affected by situational factors and their attitudes towards insulation. Situational factors, such as the condition of the building, are important because they initiate homeowners' individual decision-making processes on insulation. The simulation results show that improving homeowners' attitudes about insulation by providing information has a comparatively low potential for increasing their insulation activity. Out of the policy options this thesis explored, the introduction of an obligation to insulate the walls within one year after change of house ownership was found to have the greatest impact on homeowners' insulation activity.

The research has been published in the scope of three peer-reviewed articles:

- Friege, Jonas, and Emile J. L. Chappin. "Modelling decisions on energy-efficient renovations: a review." *Renewable and Sustainable Energy Reviews* 39 (2014): 196-208.

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- Friege, Jonas. "Increasing homeowners' insulation activity in Germany: An empirically grounded agent-based model analysis." *Energy and Buildings* 128 (2016): 756-771.

1 INTRODUCTION

1.1 Statement of the problem

Homeowners'[1] insulation activity is central to this thesis. Its increase is one of the most promising approaches to tackling anthropogenic climate change and dealing with the depletion of fossil resources for countries located in the temperate climate zone (European Commission, 2010; Kemp, 2010; Taylor (Ed.), 2010). In the European Union's (EU) building sector, which is responsible for 40% of the EU's total final energy consumption (Balaras et al., 2007; IEA, 2013), 67% is for end-use space heating (Bosseboeuf, 2012). Improving buildings' insulation is noted to be the most effective way to reduce the energy needed for providing this energy service (Balaras et al., 2007; Enkvist et al., 2007). Installing insulation decreases the building envelope's heat losses and thus leads to a more efficient use of heating energy. Research shows that the total economic benefits of insulating existing buildings usually outweigh their costs (Chapman et al., 2009; Holm et al., 2016; Sterchele et al., 2016). Thus, for many homeowners, it pays to invest in insulation measures due to the reduction in energy costs amassed over the building's lifetime (Holm et al., 2015; Nauclér and Enkvist, 2009; Weizsäcker, 2010). Nevertheless, homeowners appear to be reluctant to take advantage of these opportunities in most European countries (Jakob, 2007; Organ et al., 2013; Tommerup and Svendsen, 2006; Zundel and Stieß, 2011).

About 50% of Germany's housing units are in single-family and two-family houses, the most common types for owner-occupier households. The space heating requirement of this particular group of actors account for about 11% of the country's final energy consumption (Bigalke et al., 2012). Compared to current levels, homeowners' insulation activity in Germany could be doubled and would still pay off in economic terms (Kleemann and Hansen, 2005). Doubling homeowners' insulation activity by 2020 is also one of the German government's main targets for reaching an 80% reduction in energy demand in the building sector by 2050 (Prognos et al., 2010). According to a statement by an expert commission, the building sector is not yet on track to reach this reduction target for energy demand (Löschel, 2016).

The Energy Performance of Buildings Directive of the European Parliament (Recast, 2010) requires national governments to introduce regulatory, financial, and information instruments to improve the energy performance of existing buildings. According to the directive, minimum energy performance requirements must be set in the event of major renovations and the replacement or retrofitting of building elements; Member States must also introduce energy performance certificates and compile lists of national financial measures to improve the energy efficiency of buildings. A 2014 status report

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1   Households who own the single-family or two-family house in which they also live in are referred to as "homeowners" throughout this text.

on the renovation strategies of selected EU countries concluded that considerable progress is still needed to be made in all Member States to follow the required transformation path for its existing building stock (Staniaszek et al., 2014). The mix of policy instruments implemented in Germany is often seen as fairly progressive (Eichhammer et al., 2011). Nevertheless, several studies indicate that they are not very effective, nor are the available resources to increase homeowners' insulation activity used efficiently (Galvin, 2012; Weiss et al., 2012).

The problem is that, in spite of the policy instruments put in place, the insulation rate[2] has remained around 1% (Diefenbach et al., 2010), whereas the German government's target is to reach 2% by 2020. Consequently, it is necessary to understand why present policies do not perform and to identify policies with the potential to reach the targeted increase in homeowners' insulation activity.

1.2 Insulation as an economic activity

Economic activities are actions that involve "the production, distribution and consumption of commodities" (Raich, 2005). Therefore, carrying out an insulation project, which involves the consumption of commodities such as insulation material and labor, is considered to be an economic activity. Concerned with the factors that determine economic activities, economics contributes a better understanding to homeowners' insulation activity.

Traditionally, economic systems are studied at two levels: the microlevel and the macrolevel. Microeconomics focuses on the economic behavior of individual agents, whereas macroeconomics studies aggregate processes in the economy. This thesis studies the insulation decision-making processes of individual homeowners (microlevel) in order to explore the effects of policy interventions on the overall level of insulation activity. It is not in the scope of this thesis to study the effects of an increased overall insulation activity on indicators such as GDP, unemployment, or inflation (macrolevel). Work in this field has already been conducted by Lutz and Meyer (2008). With their "PANTA RHEI" simulation model, the authors have estimated the employment effects of an increased overall insulation activity in Germany.

According to Bruun (2004), in the past it was not possible to adequately link the microlevel- and the macrolevel of economics unless very restrictive simplifications are made, such as in neoclassical economics.

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2   Weighted share of building elements being insulated each year.

1.2.1 Neoclassical economics

The following shows that the simplified economic viewpoint of neoclassical economics is not well suited for depicting homeowners' insulation decision-making and deriving policies aiming at an increase in their insulation activity. Neoclassical economics is consistent with rational choice theory, and utilizes constructions such as the "Homo Economicus" (Brzezicka and Wiśniewski, 2014). In neoclassical economics, it is often assumed that individuals' decision-making is based on full rationality, utility maximization, and perfect information (Weintraub, 2002).

According to these basic postulates of neoclassical economics, every homeowner would notice if the installation of insulation were to lead to an optimization of his or her own personal utility, and, in this case, act fully rationally by deciding in favor of having insulation installed. Financial incentives would only be required for insulation measures that do not lead to personal utility maximization. Information instruments would also not be required, due to the assumption of perfect information. Moreover, the introduction of insulation obligations would not be necessary, given the goal that only insulation measures that lead to personal utility maximization should be conducted.

Homeowners' currently low level of insulation activity indicates that their decision-making is not based on full rationality, utility maximization, and perfect information, but instead often emerges out of "bounded rationality", as understood by behavioral economics.

1.2.2 Behavioral economics

Behavioral economics aims to better predict the economic behavior of individual agents. It focuses "on the interrelations between economics and psychology" (Sent, 2004, p. 735) for increasing "the explanatory power of economics by providing it with more realistic psychological foundations" (Colin and George, 2004, p. 1). Behavioral economics is not a unified theory. It is instead a collection of tools or ideas (Wilkinson and Klaes, 2012), primarily concerned with the bounds of rationality of economic agents: according to the concept of "bounded rationality", a term coined by Herbert A. Simon, the rationality of individuals' decision-making is limited by the knowledge (or information) they have, the cognitive limitations of their minds, and the amount of time they have to make the decision (Simon, 1972). The work from Gigerenzer and Goldstein (1996) later built on Simon's concept. The authors proposed that the rationality of a decision depends on each individual's personal situation. People make the best possible use of limited knowledge, information-processing abilities, and time available by using heuristics that can lead to near-optimal inferences.

The way current building policies are designed shows that they are not solely based on neoclassical economics, as policymakers do not assume that people have full information. Moreover, financial instruments are accompanied by regulations,

indicating that it is not expected that all individuals decide based on utility maximization (Weintraub, 2002). Clearly, building policies seem to be based on more novel economic approaches such as those introduced above. Nevertheless, their low success rate shows that further steps are necessary. This thesis makes the argument that the design of more effective policy instruments aiming at an increase in homeowners' insulation activity requires adequately linking the microlevel and the macrolevel of economics. Only in this way will it be possible to understand how policy instruments influencing homeowners' individual decision-making processes on the microlevel can affect the aggregate level of insulation activity.

1.3   A complex adaptive systems perspective

Bruun (2004) states that linking the microlevel and the macrolevel is possible by taking the economy as a complex adaptive system, i.e. "a system where complexity arises because of the way a large number of agents interact" (Bruun, 2004, p. 1).

In complex adaptive systems, small changes can lead to surprisingly big effects, and vice versa. Complexity science, which is devoted to understanding, predicting, and influencing complex systems, can thus enable wiser decisions about policy interventions (Michalowski et al., 2009). In a changing and increasingly complex world, complexity science is becoming more and more relevant. Its emergence and evolution over the past decades has been catalyzed by major advances in computational technologies (Michalowski et al., 2009). Complexity science encompasses several theoretical frameworks and is highly interdisciplinary, including biologists, economists, sociologists, and many others to answer fundamental questions related to complex systems.

The following section argues why it is necessary to view homeowners' insulation activity from a complex adaptive socio-technical systems perspective: homeowners' insulation activity takes place in a socio-technical system. The physical infrastructure consists of a number of technological artifacts, such as the buildings' energy supply system or the insulation status of roof, walls, floor, and windows. In terms of a social system, the building energy infrastructure involves many actors, such as owner-occupier households, private and commercial landlords, craftsmen, and energy consultants. Both the social and the technical systems affect the economic activity of installing insulation on the part of homeowners. Homeowners influence each other's decision-making through interaction; their decision-making processes can be triggered by the condition of the structure itself or by their personal socio-demographic situation, and they adapt their behavior according to past experiences and a changing environment. Circumstances such as those stated above lead to a nonlinear development of the observed system, which must further be described as being both "complex" and "adaptive".

1.4 Agent-based modeling

1.4.1 The decision to use agent-based modeling

A complex adaptive systems perspective on insulation as an economic activity allows a choice among different complex system modeling tools for depicting homeowners' insulation activity in the context of this thesis. The decision to use agent-based modeling (ABM) is based on a comparative analysis of the suitability of different complex system modeling tools (see Table 1). For the analysis, this thesis utilizes an overview of modeling tools capable of representing decision making, behavior, and other complex dynamics provided by Heckbert et al. (2010).

Modeling tool	Description	Suitability
Equation-based	Equation-based models consist of a set of equations and are mostly applied to systems in which the dynamics are dominated by physical laws rather than information processing (Parunak et al., 1998). They are useful for characterizing relationships of complex systems and their aggregate attributes (Heckbert et al., 2010).	When deciding on insulation, homeowners mutually influence each other. Moreover, their decisions influence and are influenced by the condition of their houses. Since equation-based models cannot represent coherent or coordinated interactions, they are not well suited for depicting homeowners' insulation activity.
System dynamics	System dynamics models are characterized by causal feedback loops, and formalized through sets of differential equations (Borshchev and Filippov, 2004). Agents are typically aggregated, assuming that they are perfectly mixed and homogeneous (Rahmandad and Sterman, 2008). System dynamics models can be particularly useful for increasing the conceptual understanding of a system (Wakeland et al., 2004).	It is logical to assume that homeowners' decision-making processes can differ considerably dependent on their individual attributes and the condition of their buildings. Moreover, their geographical distribution might be relevant, because it can influence who they share information with. Since system dynamics models do not allow the representation of spatially distributed heterogeneous agents, they are not well suited for depicting homeowners' insulation activity.
Evolutionary computation	Evolutionary computation models are inspired by biological evolution for finding often closely approximate solutions to different kinds of optimization problems (Coello et al., 2007).	Homeowners autonomously modify and adapt their behavior based on past experiences and changing external influences. Since evolutionary computation models do not allow the representation of autonomous agents, they are not well suited for depicting homeowners' insulation activity.

Cellular automata	Cellular automata models consist of cells distributed on a grid of a specified shape that evolves through a number of time steps according to rules based on the states of neighboring cells (Weisstein, 2002).	Cellular automata models typically consist of cells with the same properties, and allow adaptive decision making only to a certain extent: the modeled agents (cells) typically make decisions based only on the states of their neighboring cells. Since a useful modeling tool calls for the possibility to represent heterogeneity and adaptive behavior (see above), cellular automata modeling is not well suited for depicting homeowners' insulation activity.
Agent-based	Agent-based models can consist of interacting autonomous entities (the agents), who possess dynamic behavior and heterogeneous characteristics. A detailed introduction to agent-based modeling is provided in Section 1.4.2.	In summary, a useful tool to model the target system calls for the possibility to represent dynamic feedbacks, to consider heterogeneity and geographical distribution, and to represent autonomous agents. Since agent-based modeling allows for the possibility to meet all these requirements, it is the method of choice for depicting homeowners' insulation activity.

Table 1: Comparative analysis of the suitability of different modeling tools.

The selection of ABM based on its suitability for modeling homeowners' insulation activity comes at the price of a number of drawbacks over the other complex system modeling tools. These include the need for detailed data due to the need to model the complex behavior of heterogeneous agents; good programming skills, as actual behavioral algorithms need to be coded; and a lot of computing power or time availability, since the individual behavior of hundreds of agents must be simulated simultaneously (Gençer and Ozel, 2010; Nikolić, 2010; Robertson, 2005). Furthermore, it may be more difficult to disseminate the simulation results, as ABM is a relatively novel approach, and is not yet considered mainstream.

1.4.2 An introduction to agent-based modeling

Agent-based modeling (ABM) is at the heart of complexity science (Castellani and Hafferty, 2009; Mills, 2010). It is a computational method that allows users to create, analyze, and experiment with models consisting of autonomous computational objects ("agents") that interact with their environment according to rules over space and time (Gilbert, 2008; Page, 2008). In this way, ABM can help researchers to improve their understanding of a system's behavior from the bottom up, and to assess transformation strategies (Bandini et al., 2009). The agents in this text are homeowners who interact with their building and their social network when deciding on insulation. In this thesis, the aim is to improve the understanding of homeowners' insulation activity (the system's behavior), and to assess policy options that attempt to increase the undertaking of insulation projects (an assessment of transformation strategies). This thesis uses

computer simulation because experiments in reality, which would consist of applying some treatment to an isolated system and observing what happens in comparison to an equivalent untreated system (the control), would be almost impossible, and are often ethically undesirable in social sciences (Gilbert, 2008). Four primary features of the method – the capability of modeling learning, networks, externalities, and heterogeneity – make it the method of choice for simulating the boundedly rational and socially influenced economic behavior of actors embedded in a complex socio-technical system (Page, 2008). The occurrence of interaction between agents and their environment makes the system "complex" – the agents' emergent behavior cannot be explained by analyzing the agents' behavior individually or by analyzing the aggregation of their individual states (An, 2012; Bonabeau, 2002).

1.4.3 Agent-based modeling in the social sciences

Agent-based modeling (ABM) in the social sciences has been used for purely theoretical purposes as well as in application-oriented research. Work by Epstein and Axtell (1996) is representative of agent-based theory building in social sciences. In their book, the authors show how the simple actions of individuals lead to sociocultural phenomena such as trade, wealth, and warfare. Epstein and Axtell achieved this by developing a program named "Sugarscape", which simulates the behavior of artificial people (agents) who are located in an artificial environment with a generalized resource (sugar).

The development of application-oriented ABMs in the social sciences is usually driven by major societal problems, such as the slow adoption of climate-friendly technologies and behavior. Global warming as a result of the slow reduction of the increase of greenhouse gas emissions is a major societal problem, as it is predicted to have a predominantly negative impact on a large number of individuals within our society. Thus, a great number of ABMs have been developed to tackle anthropogenic climate change. Case-specific policy advice for steering the transition towards the adoption of climate-friendly technologies and behavior demands sound knowledge of the sub-system concerned and the possibility of exploring the implications of any changes in basic conditions. The use of ABM allows researchers to meet both requirements. This has been demonstrated in the course of work steering the transition towards climate-friendly transportation (ElBanhawy et al., 2012; Ge and Polhill, 2016; Shafiei et al., 2012), energy production (Palmer et al., 2015; Sopha et al., 2011), and energy use (Chappin and Afman, 2013; Zhao, 2012), to name a few.

This work also aims to provide policy advice for managing the transition towards the adoption of a climate-friendly technology – the installation of thermal insulation in residential buildings. Insofar as installing insulation is an economic activity, its exploration belongs to a special stream of ABM, known as agent-based computational economics (ACE). ACE is the computational modeling of economic systems that are viewed as being both complex and adaptive. Viewing the economy as a complex

adaptive system gives ACE the "ability to combine micro- and macroeconomics and thus overcome one of the biggest hurdles of economics" (Bruun, 2004, p. 13). In ACE, economic systems are modeled as evolving systems of autonomous interacting agents (Tesfatsion, 2003). The resulting simulation models can be used for increasing the understanding of economic aggregates from the bottom up, such as (in the case of this thesis) the insulation activity of autonomous and interacting homeowners emerging from their individual decision-making processes on installing insulation.

1.5 Objectives and the research question

The main objective of this thesis is to *explore the potential of policy options designed to achieve the targeted increase in homeowners' insulation activity in Germany through an agent-based model analysis*. The policy options may be based on the basic scheme 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. In light of this, the agent-based model analysis must rest on a strong theoretical and empirical foundation. The role of the agent-based model analysis is threefold: to increase the understanding of homeowners' insulation activity, to guide the data collection process, and to evaluate the potential of policies aiming at an increase in homeowners' insulation activity. With regard to the latter, simulations are designed to result in quantitative insights, which allow a comparison of the potential of different policy options.

Ultimately, the results should 1) show why present policies do not deliver and 2) inform researchers and policymakers about policies that do have the potential to increase the number of insulation projects being undertaken.

The central research question is as follows:

> *How can the targeted increase in homeowners' insulation activity in Germany be achieved?*

The three sub-questions are:

1. What are the main factors influencing homeowners' decision-making processes on insulation?

2. In what way is it possible to model homeowners' decision-making processes and simulate their insulation activity?

3. What is the potential of policies designed to increase homeowners' insulation activity in Germany?

1.6 Outline

The workflow and structure of this thesis are depicted in Figure 1. Chapters 2 to 4, which have been published in the scope of three peer-reviewed articles, form the core of this work.
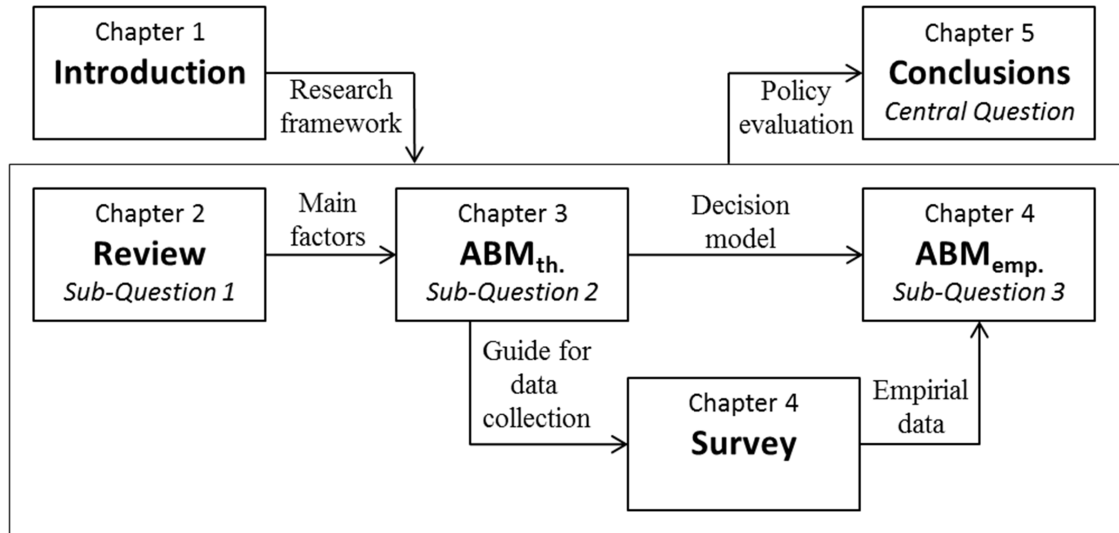
Fig. 1: Workflow and structure of this thesis.
Note: The arrows are labeled with each chapter's main input/output.

The theoretically grounded agent-based model (ABM$_{th.}$) (Chapter 3) is based on a systematic literature review (Chapter 2). The results of the ABM were used to guide the data collection carried out in the course of an online survey (Chapter 4). The results of this survey were then used to develop the empirically grounded agent-based model (ABM$_{emp.}$) (Chapter 4), which was applied to evaluate policy options that aim to increase homeowners' insulation activity. The thesis ends with a synthesis of the research (Chapter 5).

Chapter 2 explores the existing body of literature on energy-efficient renovations in a systematic literature review. To do this, a set of bibliometric methods was applied in order to identify papers at the research front and the intellectual base on energy-efficient renovation in four areas: technical options, understanding decisions, incentive instruments, and models and simulation. In the following, the papers identified by such methods were further reviewed to increase the understanding on homeowners' decisions to carry out domestic energy-efficient renovations.

Chapter 3 presents the theoretically grounded agent-based model (ABM$_{th.}$), primarily based on the results of the systematic literature review. This was used to foster the understanding of homeowners' decision-making processes regarding insulation, and to explore how situational factors, such as the structural condition of houses and social interaction, influence their insulation activity. Simulation experiments furthermore

allowed for the study of the influence of socio-spatial structures, such as residential segregation and population density, on the diffusion of renovation behavior among homeowners.

Chapter 4 presents the results of an online survey among 275 homeowners conducted to increase the understanding of their insulation decision-making processes. The survey's results were incorporated into the empirically grounded agent-based model (ABM$_{emp.}$), which was applied to evaluate a number of policy options that aim to increase homeowners' insulation activity in Germany.

Chapter 5 gives an answer to the research question, discusses the main methodological challenges encountered in conducting the research, reflects on the thesis' main methods and research objective, and outlines some thoughts and plans for future research.

2 MODELING DECISIONS ON ENERGY-EFFICIENT RENOVATIONS

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Modeling decisions on energy-efficient renovations: A review

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ABSTRACT

The buildings sector accounts for more than 30% of global greenhouse gas emissions. Despite the well-known economic viability of many energy-efficient renovation measures which offer great potential for reducing greenhouse gas emissions and meeting climate protection targets, there is a relatively low level of implementation. We performed a citation network analysis in order to identify papers at the research front and intellectual base on energy-efficient renovation in four areas: technical options, understanding decisions, incentive instruments, and models and simulation. The literature was reviewed in order to understand what is needed to sufficiently increase the number of domestic energy-efficient renovations and to identify potential research gaps. Our findings show that the literature on energy-efficient renovation gained considerable momentum in the last decade, but lacks a deep understanding of the uncertainties surrounding economic aspects and noneconomic factors driving renovation decisions of homeowners. The analysis indicates that the (socio-economic) energy saving potential and profitability of energy-efficient renovation measures is lower than generally expected. It is suggested that this can be accounted for by the failure to understand and consider the underpinning influences of energy-consuming behaviour in calculations. Homeowners' decisions to renovate are shaped by an alliance of economic and noneconomic goals. Therefore, existing incentives, typically targeting the economic viability of measures, have brought little success. A deeper understanding of the decisions of homeowners is needed and we suggest that a simulation model which maps the decision-making processes of homeowners may result in refining existing instruments or developing new innovative mechanisms to tackle the situation.

Keywords: Energy efficiency; Renovation decision; Modeling; Incentive instruments; Bibliometrics; Citations

2.1 Motivation

The buildings sector is responsible for over one third of global greenhouse gas (GHG) emissions (IEA, 2013). Therefore, a critical focus on the building sector may be crucial for acting on climate change (Solomon et al., 2007). It is generally accepted that renewable energies and energy efficiency are important opportunities for mitigating GHG emissions (Firestone and Marnay, 2008; Panwar et al., 2011; Rahman and Khondaker, 2012). Renewable energy technologies replace fossil fuel-based technologies for energy production while energy efficiency measures reduce the energy used to provide the same level of energy service. The energy-efficient renovation (EER) of buildings may address both renewable energies (e.g. installation of a heating system based on renewable energies) and energy efficiency (e.g. improvement of the building shell). Environmental benefits resulting from EERs must be seen against their environmental impacts such as the production of insulation materials, their transportation, assembling and disposal at the end of their lifecycle. Asdrubali et al. (2013) state that such a comprehensive view is of particular importance with respect to

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Nearly Zero Energy Buildings, "for which there is a real risk of shifting the impacts from the operating phase to the construction and end of life phases" (Asdrubali et al., 2013). Xing et al. (2011) reviews technologies applied to reach zero carbon in existing buildings. EERs are economically viable in many cases and have great potential to reduce GHG emissions.

Several authors point out that there are profitable ways of reducing emissions in buildings (Nauclér and Enkvist, 2009; Tsagarakis et al., 2012; Verbeeck and Hens, 2005; Weizsäcker et al., 2009). Nauclér and Enkvist (2009) compared abatement costs, capital intensity and the abatement potential of different sectors worldwide projected until 2030 (see Fig. 2). The comparison shows that abatement measures in the building sector provide a comparatively high potential for reducing GHG emissions and at the same time have a large positive net profit (negative abatement costs) for the client. Nauclér and Enkvist (2009) state that upfront financing might be challenging because measures are relatively capital intensive.
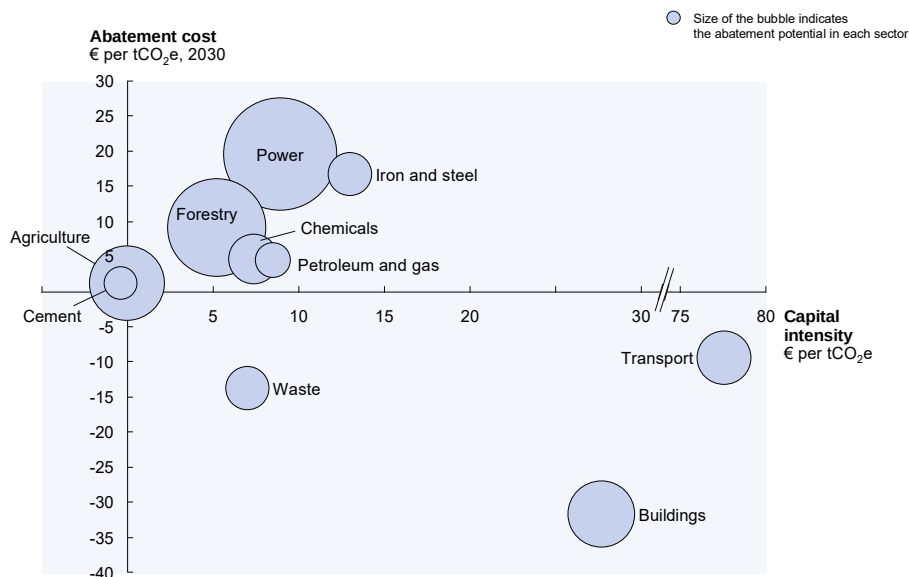
Fig. 2: Capital intensity and abatement cost across different sectors.
Source: Nauclér and Enkvist (2009).

A high potential for decreasing energy consumption at negative net cost by installing energy-efficient building elements is also acknowledged in the residential building stock of European Union (EU) Member States (Uihlein and Eder, 2010). Of the total final energy consumption at EU level in 2010, buildings represent about 40% (Balaras et al., 2007; Lechtenböhmer and Schüring, 2011) of which 67 is for end-use space heating (Bosseboeuf, 2012). Therefore EER measures to reduce GHG emissions are very important. This is encouraged by several climate protection scenarios at national, international and global level, which suggest an increase in EER adoption rates and evidence of more large-scale refurbishment of buildings (European Commission, 2010; Kemp, 2010; Taylor (Ed.), 2010). Baek et al. (2012) states that "existing residential

buildings are expected to play an important role in enabling countries to achieve their goals of reducing greenhouse gas emissions" (Baek and Park, 2012, p. 3946). This was also recognised by the EU, which introduced a Directive on Energy Performance of Buildings in 2002 (recast in 2010). The directive requires member states to introduce policies on building energy efficiency (EU, 2003).

In spite of recent encouraging trends, it is difficult to understand why there appears to be a reluctance to take advantage of these opportunities. In order to tackle this challenge one needs to identify and understand its root cause. A preliminary review of the scientific literature and several project reports was carried out to obtain an initial insight and understanding about the current state of research. Our findings from this review and expert discussions led us to formulate three hypotheses:

- Hypothesis I – Technical options and economic viability

  Technical options to decrease energy demand by EER measures are well understood (Lowe, 2007) and, in many cases, economically viable (Næss-Schmidt et al., 2012; Nauclér and Enkvist, 2009).

- Hypothesis II – Decision-making processes and incentive instruments

  Several incentive instruments are available to motivate homeowners to thermally upgrade their houses. The decision-making processes of homeowners are not sufficiently understood; Policy makers can only surmise the effect of instruments before implementing them, which leads to unsatisfactory results (Vrijders and Delem, 2010). Reviews of existing instruments are then conducted (Diefenbach et al., 2005), consuming a considerable amount of time and resources.

- Hypothesis III – Models and simulation

  Despite the fact that models are available that explore the decisions of homeowners regarding EERs (Stieß and Dunkelberg, 2012; Verhoog et al., 2013; Zavadskas et al., 2008), relevant factors and mechanisms to simulate the entire decision-making process are ignored.

A comprehensive review of scientific papers is conducted to evaluate these hypotheses. The following questions are posed to facilitate the analysis:

- What are the most important papers?

- What are the most important references used?

- What are their findings concerning our hypotheses?

In the following sections we elaborate on the methods used to map the research on EERs and identify the most important papers concerning our hypotheses. Results of the paper network analysis and a review of the most important papers is presented in Section 2.4. The paper closes with conclusions and recommendations.

2.2   Approaches to citation network analysis

The review was carried out using bibliometrics, which aims "to shed light on the process of written communication and of the nature and course of development of a discipline" (Pritchard, 1969, p. 348). We performed bibliographical analyses to explore the following core areas on EER relevant to our hypotheses: technical options, understanding decisions, incentive instruments, and models and simulation. Hypothesis II was examined by applying the analyses to two paper sets, one on: understanding the decision-making processes of homeowners and one on assessing the effectiveness of existing incentive instruments. The importance of papers within our core areas is operationalised by a citation network analysis.

There are different approaches for analysing the network of citations in a group of papers. The most important representations are a direct citation network, with co-citation coupling, an analysis of co-citations, and bibliographic coupling of the referencing documents (Small, 1973). They all create a network, linking documents, but what represents edges and nodes differ between the approaches. See Fig. 3 for an overview.
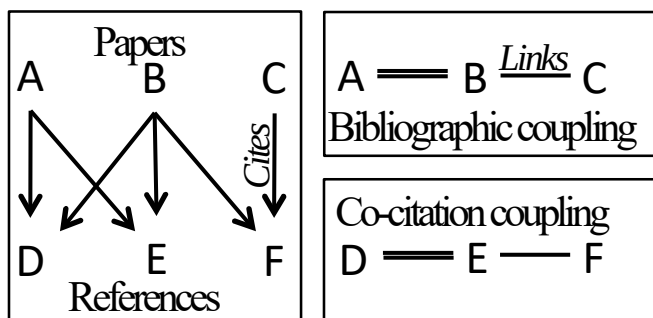
Fig. 3: Schematic overview of different approaches to citation network analysis.
Source: Adapted from Boyack and Klavans (2010).

A direct citation network shows the direct references between documents (A links to D and E, similar to the left picture in Fig. 3).

Co-citation coupling develops a cluster of cited documents, also called the "intellectual base" in bibliometrics (Persson, 1994). A relationship between two references is established if both are cited by another paper (i.e. a link between D and E, because both are cited by paper A in Fig. 3).

Small (1973)states that frequently co-cited papers, which are necessarily frequently cited individually as well, represent the key concepts, methods or experiments in a field. The patterns can than be used to map out in great detail the relationship between those key ideas. Osareh (1996) concludes that "in a specific field and period of time the most cited papers are the most useful or important papers, and also the most co-cited papers are the most related papers" (Osareh, 1996, p. 151). Cawkell and Newton (1976) point

out that by using co-citation as a part of the automatic clustering procedure, it is assumed that frequently cited papers are more important than less cited papers and that frequently co-cited papers are significant and related in subject to each other. A co-citation analysis is a variant of co-citation coupling, in which the shared references are also linked to the referencing document (D and E are both linked to A, next to the link between D and E).

Bibliographic coupling links two papers if they cite the same document and results in clusters of citing papers (Osareh, 1996) (i.e. a link between A and B, because both cite D in Fig. 3). In bibliometric terminology, a cluster of citing papers creates a research front, i.e. using similar parts of the intellectual base (Persson, 1994). Papers that share references are an indication that a probability exists (with unknown value) that they contain a related subject matter (Martyn, 1964). Jarneving (2007) confirms that bibliographic coupling can be used to link papers that have a similar research focus.

A study by Boyack and Klavans (2010) that compares the accuracies of different cluster solutions concludes that a direct citation network is by far the least accurate approach to map the research front. Bibliographic coupling "gave the most accurate solution, followed closely by co-citation analysis" (Boyack and Klavans, 2010, p. 7).

In our research we used bibliographic coupling and co-citation coupling to obtain a detailed view of the research front and intellectual base, and additionally performed a co-citation analysis. Data collection for the implementation of bibliographic coupling and co-citation coupling and analysis is described in the following section.

2.3   Data collection

A keyword-based search was performed in the Scopus scientific database. Falagas et al. (2008) state that Scopus covers a wider range of journals than other databases such as PubMed and Web of Science. Chappin and Ligtvoet (2014) note that it purportedly also encompasses more modern sources than further databases such as Web of Knowledge and Google Scholar. A preliminary literature search on energy efficiency, save energy, decrease energy consumption and renovation, retrofit and refurbishment resulted in a set of nearly 3,000 papers. By looking through the titles we found large numbers of papers undoubtedly not addressing our research area. Examples are retrofitting heat exchanger networks, applications of self-heat recuperation technology to crude oil distillation and a study of the interrelation between mean radiant temperature and room geometry. We chose to revise the search terms in order to acquire a more appropriate paper set. From the initial set, the keywords specified in the papers were listed and ranked. We used these keywords to increase the number of relevant papers and decreasing the number of irrelevant papers in the findings. In an iterative process we tried various combinations of highly ranked keywords to improve the focus of the search. With this approach we obtained a reasonable number (689) of papers addressing our research area. We found that it was crucial to add terms specifying the renovation object to remove irrelevant

papers. The following terms were used to obtain the final result: Energy efficiency, accompanied by save energy, as well as, residential/commercial building, home, house or dwelling, together with retrofit, renovation and refurbishment[4]. We recorded bibliographic data (authors, title, year, abstract, keywords, references) across 689 papers.

Within this set we looked for those papers that specifically address our four core areas (listed again below). We applied a similar iterative process, making use of the keywords from the papers to find appropriate search terms:

- Technical options: heat/thermal insulation, heating system

- Understanding decisions: motivation, barrier, decision process/making

- Incentive instruments: subsidy, regulation, incentive, energy tax, financial support

- Models and simulation: model, simulation

An overview of the most popular keywords for each of the subsets is provided in Table 2; it is shown that energy efficiency, energy utilization, buildings, energy conservation and retrofitting are popular across all sets. We realise that some intuitive keywords may not be present. One reasoning is that they do not make the four core areas distinct. An example of this latter are keywords regarding economic aspects. They are not used as search terms, but are present in the findings: keywords such as 'costs' or 'investments' are well established in the top keywords for all paper sets (see Table 2).

Because references were not provided for all papers, not all papers could be analysed (449 out of 689 papers were analysed). However, by including an analysis with co-citation coupling, which includes the references in the papers that could be analysed, the set of papers increased to almost 7,000. As a consequence, we are confident that the most important research is covered by our analysis.

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4 The search query used is: ((energy W/5 efficiency) OR (save energy)) AND ((residential W/5 building) OR (commercial W/5 building) OR dwelling OR home OR house) AND (retrofit OR renovation OR refurbishment). W/5 limits to search results that are less or equal than 5 words apart.

	Full paper set	**Technical options**	**Understanding decisions**	**Incentive Instruments**	**Models and simulation**
Popular keywords (number of different keywords)	1. energy efficiency 2. energy conservation 3. retrofitting 4. energy utilization 5. buildings ... 16. investments (4,277)	1. energy efficiency 2. heating 3. energy utilization 4. retrofitting 5. buildings ... 17. costs (1,305)	1. energy efficiency 2. retrofitting 3. buildings 4. energy utilization 5. decision making ... 7. investments (649)	1. energy efficiency 2. retrofitting 3. energy utilization 4. energy policy 5. carbon dioxide ... 9. investments (963)	1. energy efficiency 2. energy conservation 3. energy utilization 4. buildings 5. retrofitting ... 15. costs (1,807)
Analysed (% of total)	449 (65%)	98 (70%)	53 (93%)	85 (83%)	152 (76%)

Table 2: Popular keyword and number of analysed papers within the paper sets.

Note: Papers for which references could not be retrieved are omitted from the analysis. The first keyword related to economic aspects is included.

The data (see Appendix A) was processed by using the work of Chappin and Ligtvoet (2014). We adapted that work to link paper designations (Pattern of Author, Title, Year, Source title, Volume, Issue) and references based on the various approaches to citation network analysis (see Appendix A). Gephi (Bastian et al., 2008) was used to visualise and explore the paper networks.

2.4 Analysis of paper networks and key papers

In order to focus on our core areas, we analysed four subsets within our full set of 449 papers. These subsets are different in size and partially overlap, as shown in Fig. 4. The largest overlap occurs between the subsets of papers on 'Technical options' and 'Models and simulation' (41).
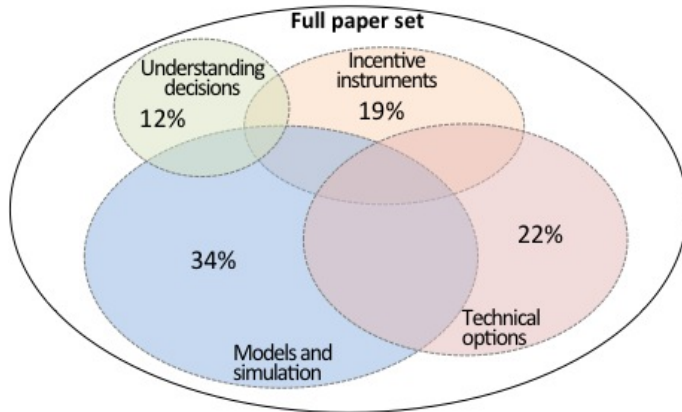
Fig. 4: Schematic overview of subset shares within the full paper set.

We identified several key papers and references by examining the bibliometric networks of the four subsets, using bibliographic coupling and co-citation coupling (see Appendix B). Our core areas includes 60% of the papers in the full paper set. The other papers were checked for relevant papers. Two papers (Vadodaria et al., 2010; Zundel and Stieß, 2011) were identified and added to the key paper analysis in the core area 'Understanding decisions'. The other paper do not explicitly concern our core areas, apart from peripheral issues, such as sound insulation of buildings, resource management in smart homes or indoor lighting facilities.

The purpose of the following sections is to present the outcome of bibliographic coupling (research front) and co-citation coupling (intellectual base) in detail and to interpret the results in order to evaluate our hypotheses. We start with presenting central research areas identified by a network analysis of the full paper set. Subsequently we give an overview of findings arising from the paper network analyses of the different subsets and explicitly work on our hypotheses. To this end, we focused on key papers, which are assumed to reflect the research front and intellectual base within our core areas. Since no further key papers were found through our co-citation analysis we abstained from presenting its outcomes.

2.4.1 Central research areas

The bibliometric networks were visualized and clustered[5]. Clusters were labelled by working through titles and abstracts of clustered papers. Fig. 5 illustrates the paper network of the full paper set resulting from bibliographic coupling (triggered by the number of shared references). It can be seen that Clusters 1-4 are strongly interconnected and they represent the four core areas, technical options, models and simulation, incentive instruments and understanding decisions. Clusters 5 through 8 are more separate and do not explicitly focus on our four areas.

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5   We used Gephi, an interactive visualisation and exploration platform for all kinds of networks. The data was imported (see Appendix A) and displayed according to the Yihan Hu Layout. Clusters are identified by using a heuristic method based on modularity optimisation (Blondel et al., 2008).

Within the densely connected clusters we found two central topics – economic assessment and behaviour (Clusters 1 and 2). One cluster focusing mainly on policies (Cluster 3) is strongly interconnected to the previous ones. This is not surprising as policies tend to influence behaviour by using incentive instruments. A smaller cluster (Cluster 4), tied to the others, refers to maximising energy savings by retrofits and optimising strategies for specific cases.

Most papers within Cluster 5 are case studies on the refurbishment of buildings in north China. Addressing economic issues keeps the cluster in the vicinity of the more interconnected clusters (1-4). Another cluster of papers on China (Cluster 6) addresses performance evaluations of refurbished buildings. Clusters on new approaches and statistical models (Clusters 7 and 8) are rather disconnected from the others. Their broad focus and methodology is quite detached, leading to the predominant use of a different intellectual base.

Surprisingly, we found three clusters referring to China and one to Ireland although neither of these countries were included as keywords in our keyword-based search. While subject areas of the subsets 'Models and simulation' (economic assessment, optimization, statistical models), 'Understanding decisions' (behaviour analyses, understanding behaviour, noneconomic benefits) and 'Incentive instruments' (policies) emerge, no cluster particularly focuses on 'Technical options'. Furthermore, we did not expect the formation of a cluster on new approaches and statistical models (Clusters 7 and 8). These were not addressed by our hypotheses, but seem to be important subject areas in our field as well. Because their methodology is quite distinct, they quote other sources and are therefore placed relatively far apart from the others.

Cluster	Topics
1a	Economic assessment, Ireland
1b	Economic assessment, China
2a	Behaviour analyses
2b	Understanding behaviour
2c	Non-economic benefits
3	Policies
4	Optimisation
5	Case studies, China
6	Performance evaluations, China
7	New approaches
8	Statistical models
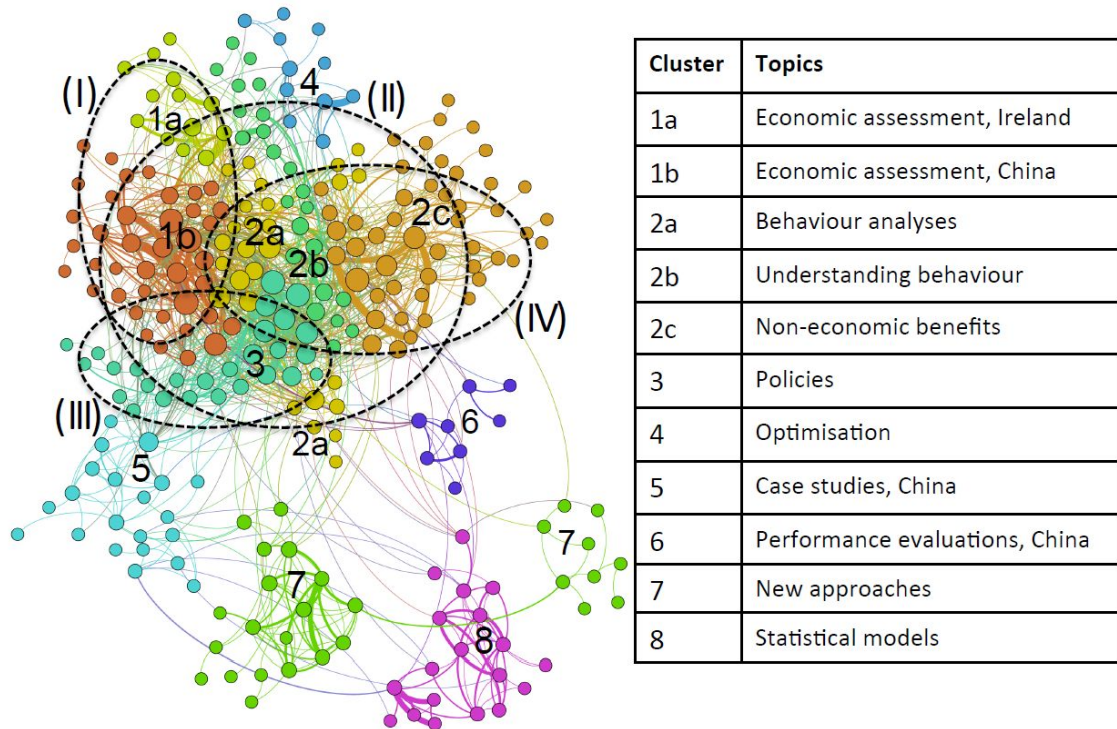
Fig. 5: Paper network of the full set resulting from bibliographic coupling.

Note: Nodes represent papers and links represent shared references between papers. Larger nodes have more shared references. Approximate location of subsets are indicated with: (I) Technical options, (II) Models and simulation, (III) Incentive Instruments and (IV) Understanding decisions. Colors indicate the listed clustered topics (1-8).

The network analysis of the full paper set gives an overview of the main topics within our research area. We analysed the paper networks of the different subsets in order to obtain a deeper understanding of the research structure and central discussion topics. Main clusters were labelled for that purpose. Subsequently we reviewed the identified key papers.

2.4.2 Technical options

The research front on 'Technical options' contains clusters on North China and the United Kingdom (see Fig. 6). No relation was noticed amongst the papers in the other clusters.
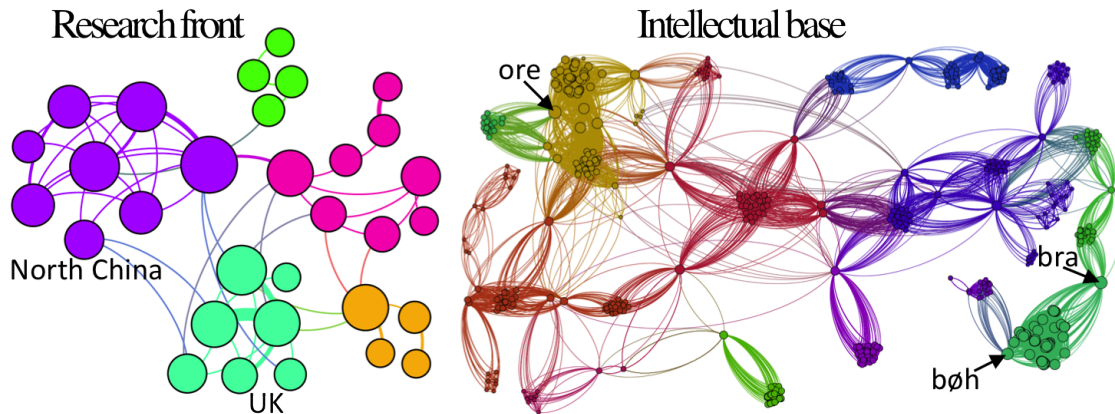
Fig. 6: Paper networks in subset 'Technical options'.

Note: On the left, the research front is the result of a bibliographic coupling analysis (similar to Fig. 5). On the right, co-citation coupling visualises the intellectual base. A node is a reference that is cited together with other references. The more often it is cited with other references in the set, the larger the node. Two references are linked if they are cited together. Three key references are indicated: ore(Oreszczyn et al., 2006), bra(Branco et al., 2004), bøh(Bøhm and Danig, 2004).

Studying the most important papers from the research front reveals that there are several options for decreasing energy consumption through EER. The authors' main purpose is to evaluate the effects of EERs in terms of energy saving, emission reduction and economic viability. The importance of this topic is underlined by the fact that it is addressed by most of the key papers, of which the analysed technical options and their effects are summarised in Table 3.

Paper	Region	Technical options	Effects
Bojić et al. (2012)	Serbia	Insulation of external wall; lowering of ceiling; thermal insulation of ceiling	Of these, the best single refurbishment measure (in terms of energy savings, investment and investment return) is thermal insulation of the external wall.
Hong et al. (2006)	UK	Cavity wall and loft insulation; introduction of gas central heating system	Cavity wall and loft insulation can reduce the space heating fuel consumption by more than 10%. The introduction of a gas central heating system has no significant impact in reducing fuel consumption.
Chen et al. (2013)	North China	Retrofit of space heating system, roof, wall, windows	Measures are cost effective except window and wall retrofit, which are not economic to conduct separately.
Liu et al. (2013)	North China	Retrofit of external wall, windows, indoor heating system	External wall retrofit makes the largest contribution to energy conservation followed by external window retrofit.
Lloyd et al. (2008)	New Zealand	Retrofit of external walls, windows, floor, ceiling	The average indoor temperature was higher. A small reduction in energy consumption was also found.

Anastaselos et al. (2011)	Germany	Use of radiative heating system	Infrared heating systems can be combined with renewable energies to enhance the building's overall environmental efficiency and significantly improve the thermal comfort.

Table 3: Technical options and their effects as presented in the key papers obtained by bibliographic coupling in the core area 'Technical options'.

As expected from the paper network analysis, most of the identified key papers can be assigned to northern China and the UK. Others present findings from studies in New Zealand, Germany and Serbia. Research activities focus on two types of EER, i.e. thermal insulation and retrofitting space heating systems. Thermal insulation measures include the insulation of external walls and ceiling and window retrofits. Despite the fact that retrofitting space heating systems may include the switch to renewable energies such as biomass (pellet stove), ambient and geothermal energy (heating pump) or solar energy (solar thermal system), none of the identified key papers discuss these options in detail. The research focus appears to be on thermal insulation rather than space heating systems or especially space heating systems based on renewable energies. It was found that energy saving, emission reduction and economic viability of EER measures is dependent on different aspects such as

- the type of measure/combination of different measures being carried out;

- the heating behaviour before and after the implementation of measure(s);

- the location (energy prices, climate, etc.);

- the type and current state of the building.

Key references in the intellectual base (displayed in Fig. 6) are from two approaches. The first contains reviews and surveys; the other discusses the results of case studies. Authors of the highest rated reference carried out a survey to "quantify the extent to which variation in indoor temperatures is explained by dwelling and household characteristics" (Oreszczyn et al., 2006, p. 245). It was found that temperatures are influenced by property characteristics (age, construction, thermal efficiency) and also by the household number of people and the age of the head of the household. Two other references present the survey results on domestic dwelling temperatures (which is important to assess the value of various energy conservation measures) (Hunt and Gidman, 1982) and on the English house condition (Moore et al., 2000). The English house condition survey is a continuous national survey that "collects information about people's housing circumstances and the condition and energy efficiency of housing in England" (DCLG, 2013, p. 1). This survey is highly rated in all other subsets as well (see Appendix B). The second field contains case studies. Branco et al. (2004) examines the difference between the calculated and actual heat consumption of buildings. The authors state that a major difference occurs when the real conditions of utilisation are not taken into account in the calculations. Bøhm and Danig (2004) discuss results from monitoring the heating system and the loading circuit for the production of domestic hot

water (Bøhm and Danig, 2004). The authors suggest to provide tools to help users to analyse the energy consumption of their buildings. Apart from pure data sources, mainly literature from two topic areas is used for current studies on the economic viability of EER measures:

- Literature on indoor temperatures;
- Literature on the difference between actual and calculated energy savings or heat demand

The second topic area is also addressed by papers on the research front (Chen et al., 2013; Liu and Guo, 2013). The analysis shows that the retrofit of the space heating system, roof, wall and windows are commonly applied renovation measures, which are, in many cases, economically viable. There are indications that measures conducted together have a higher chance to be economically viable. Research also focuses on thermal comfort and the difference between actual and calculated energy savings or heat demand after the implementation of EER measures. Thus, the actual (socio-economic) energy saving potential and profitability of EER measures is lower than generally expected.

2.4.3 Understanding decisions

Two main clusters were found in the research front on 'Understanding decisions', namely implementation approaches and residents' decision context (see Fig. 7).
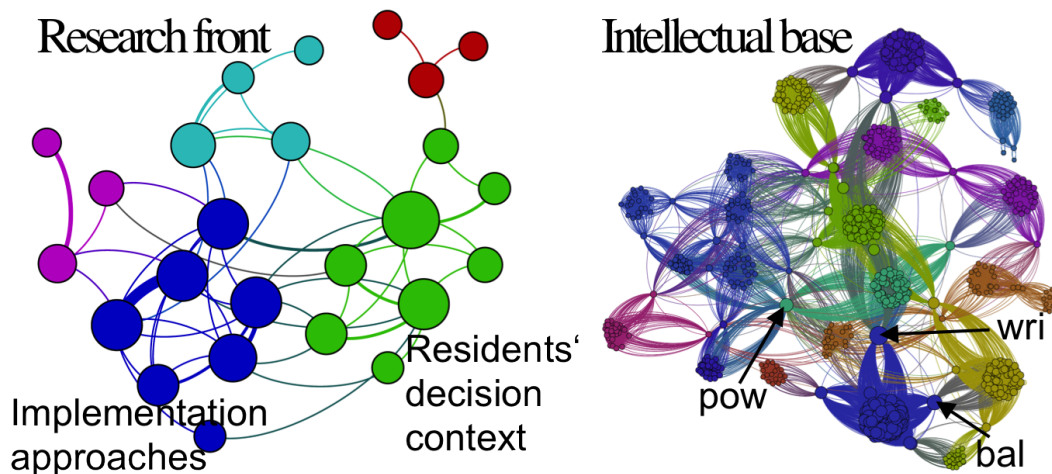
Fig. 7: Paper networks in subset 'Understanding decisions'.
Note: Three key references are indicated: pow(Power, 2008), wri(Wright, 2008), bal(Balaras et al., 2007).

The first cluster works on the residents' decision context. Decisions about EERs are dependent on residents' motivations and, prior to this, barriers, legislative constraints, demographic developments, and so on. Table 4 presents the main motivations and barriers found by Organ et al. (2013) and Zundel and Stieß (2011).

	Motivations	Barriers
Economic	An EER • pays back; • increases the home's value; • reduces energy bills and vulnerability against volatile prices.	Homeowners may • not have the necessary financial resources; • be unwilling to raise a (further) loan; • not be sure, whether the investment will pay off.
Noneconomic	An EER • increases thermal comfort, convenience, status, resilience against climate change; • reduces energy demand, environmental impact, risk for future supply problems, and dependency on fossil fuels.	Homeowners may • have the opinion that no (further) refurbishment is needed; • have no time to deal with that topic; • be not interested to do more upkeep than necessary; • be worried that a renovation causes much dirt and stress.

Table 4: Main motivations and barriers regarding EERs as presented in the key papers obtained by bibliographic coupling in the core area 'Understanding decisions'.

Beside the detection of motivations and barriers it is important to understand the homeowners' decision-making processes. Zundel and Stieß (2011) point out that homeowners not only consider the additional costs of technical measures to estimate their profitability and do not solely regard their refurbishment as an investment. The authors argue that "refurbishments are the outcome of a broader decision which is shaped by an alliance of economic and noneconomic motives and goals" (Zundel and Stieß, 2011, p. 91). Crilly et al. (2012) conclude that a comprehensive understanding of the whole process is essential to make informed decisions on the EER of homes. It is inadequate to focus on just one of the various motivations to perform an EER. Vadodaria et al. (2010) point out that "irrespective of cost factors, the perceived benefits and aspirational appeal of carbon-reducing technologies need to outweigh the cost associated with disruption from the perspective of the householder" (Vadodaria et al., 2010, p. 1). The second cluster focuses on approaches to integrate energy efficiency measures in refurbishments and claim that an improvement of policy instruments is necessary to trigger activity. Konstantinou and Knaack (2011, 2013) propose a set of different refurbishment options systematically organised in a "toolbox". By defining the impact of different possible choices, the decision-making process about refurbishments is supported and incorporated into the aim of integrating energy efficiency into refurbishment strategies (Konstantinou and Knaack, 2011, 2013). The other key papers were also identified in the core area 'Incentive Instruments'. Since they provide greater insights concerning this matter, we present their main findings in the corresponding section. Key references cover a wide range of topics such as presented in Table 5. Contrary to our expectations, the intellectual base contains no prominent literature on

decision making. This indicates that there is no shared basis on decision making addressing this issue. Rather, the intellectual base covers the topic in general. This was confirmed by a scan through the other references in the intellectual base.

Paper	Subject matter	Main conclusions
Power (2008)	Demolish or refurbish older housing?	Refurbishment of older housing induces major social, economic and environmental benefits and is preferable to demolition.
Tommerup and Svendsen (2006)	Energy saving potential of EERs in Denmark	Energy performance upgrades offer a great (profitable) energy saving potential within the residential building stock.
Balaras et al. (2007)	Priorities for EERs in the EU	The most effective measure in terms of energy savings is the insulation of external walls.
Wright (2008)	Factors influencing energy use	Energy use in dwellings is influenced by a complex interaction between built form, location, energy-using equipment, occupants and the affordability of fuel.

Table 5: Main conclusions of key references in the intellectual base obtained by co-citation coupling in the core area 'Understanding decisions'.

Our review of the research front shows that decisions on EERs are affected by several economic and noneconomic motivations and barriers. Researchers still intend to gain a deeper understanding of the decision-making processes of homeowners regarding EERs. The intellectual base indicates that the research on understanding the decisions is in its infancy, because there is limited underpinning of decision making regarding EERs.

2.4.4 Incentive Instruments

Clusters from the research front on 'Incentive instruments' form around papers from two main authors, Ray Galvin (University of East Anglia, UK) and Jinlong Ouyang (Sichuan University, China) (see Fig. 8).
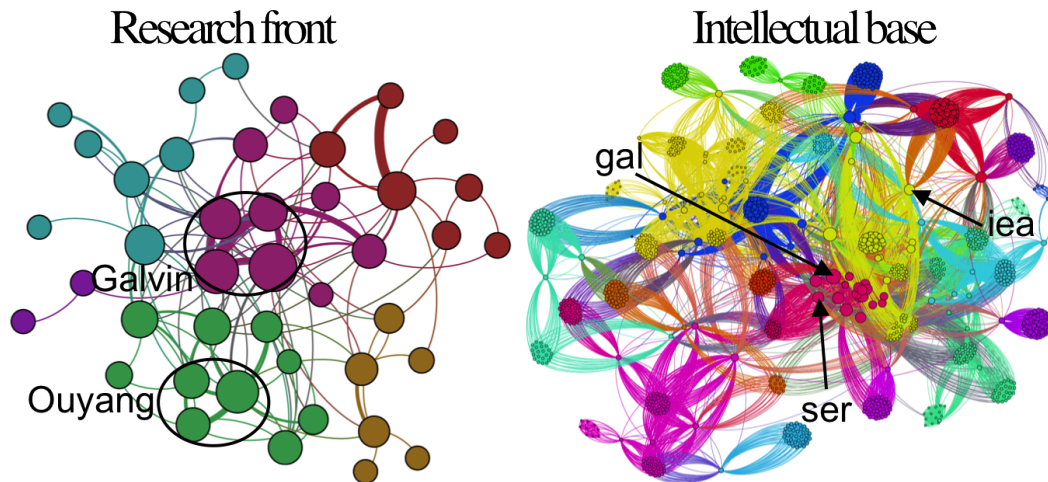
Fig. 8: Paper networks in subset 'Incentive instruments'.

Note: Three key references are indicated: gal(Galvin, 2010), ser(De T'Serclaes, 2007), iea(Bradley and Peccoud, 2008).

Identified key papers and references evaluate existing incentive instruments and give recommendations for the future. Table 6 presents the authors' assessment of existing incentive instruments.

Paper	Region	Incentive Instrument	Evaluation
Weiss et al. (2012)	Germany	Regulatory instruments; subsidy programmes; communicative instruments	These, for Germany most important measures for motivating homeowners to pursue energy-efficient retrofitting, have brought only little success. Existing instruments do not adequately address the barriers in homeowners' decision making.
Galvin (2010)	Germany	Progressive regulation for higher renovation standards; subsidies only for projects that go beyond a minimum standard	These policies may not work out well in the future. Costs of renovating to high standards rise exponentially while the amount of additional energy saved rises only a small amount.
Watts et al. (2011)	England and Wales	Energy Performance Certificates	Energy Performance Certificates are a mandatory requirement for all dwellings sold or rented in the region, but have had little impact on decision making or price negotiation so far.
Grösche and Vance (2009)	Germany	Programs that provide subsidy for retrofits	The effectiveness of these programs may be undermined by free-riders, i.e. house owners receiving the subsidy which would also have renovated without the subsidy.

De T'Serclaes (2007) and Bradley and Peccoud (2008)	EU, USA, Japan	Policy packages which seek to address multiple financial barriers at the same time	Such policies are likely to be quite effective.

Table 6: Evaluation of existing incentive instruments as presented in the key papers and references obtained by bibliographic and co-citation coupling in the core area 'Incentive Instruments'.

Several inventive instruments such as regulations or subsidies are applied to trigger more EER activity. The authors point out that they have brought only little success so far and attempt to understand why that is the case. One explanation that the literature provides, is that they do not adequately address the barriers in homeowners' decision making. We have made a structured overview of the recommendations regarding incentive instruments from the key papers and references. They can be clustered around three approaches: either they intend to enforce existing instruments, to increase the economic viability of measures, or to introduce new approaches (see Table 7).

Approach	Recommendation
Enforcement of existing instruments	• Introduce random audits to improve the implementation and enforcement of existing regulatory standards and to make better use of refurbishment opportunities (Weiss et al., 2012); • Better communicate the benefits of financial aid mechanisms for improving energy efficiency (Watts et al., 2011)
Increase of economic viability	• Increase energy prices and provide subsidies for renovating aging residential buildings (in China) (Ouyang et al., 2011); • Expand financial support instruments targeted at home-owners willing to achieve a high standard of energy efficiency as well as those meeting lower standards (Weiss et al., 2012); • Governments need to create more favourable conditions for energy efficiency investments (Bradley and Peccoud, 2008)
Introduction of new approaches	• Emphasise on reasons for EERs measures other than economic viability (Galvin and Sunikka-Blank, 2013); • Take into account other reasons for low levels of renovation activity (e.g. costs) and individual-based explanations of behaviour (e.g. no motivation) and carry out in-depth analyses into social practises of households (Moloney et al., 2008); • Increase awareness of co-benefits and cost dynamics of energy efficiency investments of decision makers in the real estate sector, politics and administrations (Jakob, 2006); • Consider social criteria (Weiss et al., 2012); • Introduce Public-Private-People Partnership (4P) into redevelopment processes. 4P can lead to a situation where EER is affordable and people can choose between several renovation and finance options (Kuronen et al., 2011)

Table 7: Recommendations of identified key papers and references regarding incentive instruments obtained by bibliographic and co-citation coupling in the core area 'Incentive Instruments'.

The first two sets of approaches aim to improve existing incentive instruments by increasing implementation rates, expanding their scope and by changing the economic context in which they take place. The last set contributes approaches that mainly address noneconomic motivations and barriers. The literature also suggests that additional research is needed that addresses policy design that incorporates relevant noneconomic factors in the decision making of homeowners. As hypothesised, several instruments are available to motivate homeowners to improve the insulation of their homes, but their success rate is rather low. Confirming Section 2.4.4's findings, the literature suggests that the success of policies depends on how homeowners' decision making is taken into account.

2.4.5 Models and simulation

In the research front on 'Models and simulation' we found a cluster on statistical models as well as strongly interconnected clusters on behaviour and economic viability (see Fig. 9).
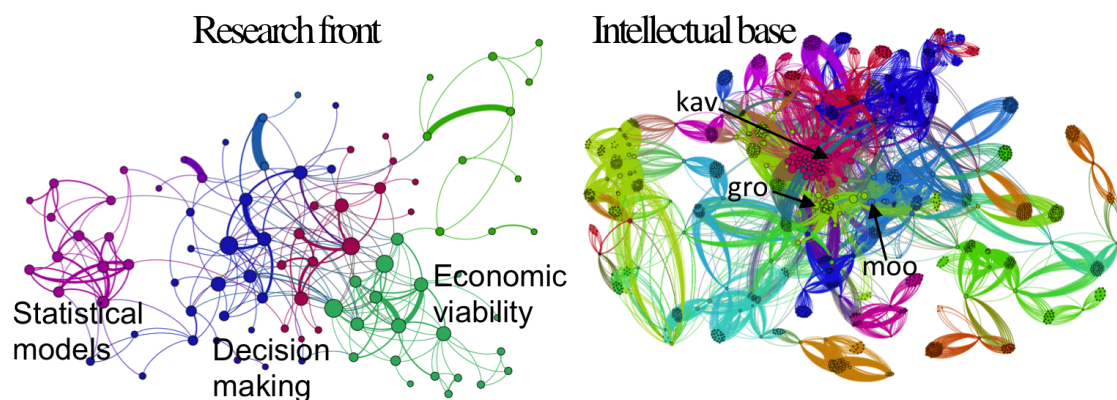
Fig. 9: Paper networks in subset 'Models and simulation'.
Note: Three key references are indicated: kav(Kavgic et al., 2010), gro(Grösche and Vance, 2009), moo(Moore et al., 2000).

The main conclusions of the key papers are presented in Table 8. By examining the abstracts of the most important papers from the research front, we identified two clusters of models, which is in line with the results of our paper network analysis (see Fig. 9). The first group focuses on economic viability whilst the second contains models addressing homeowners' decision making regarding EER measures.

Paper	Cluster	Subject matter	Main conclusions
Amstalden et al. (2007)	Economic viability	Assumed future energy prices	Present Swiss policy pushes investments for energy-efficient retrofitting to profitability. Assumed future energy prices are very important for the predicted investment profitability.
Galvin and Sunikka-Blank (2012)	Economic viability	Fuel price elasticity of demand	The inclusion of fuel price elasticity of demand into models lowers the net present value and lengthens the payback time of retrofit measures. CO2 saved over the technical lifetime is lower than anticipated.
Ouyang et al. (2009)	Economic viability	In fact and simulated energy demand	There is a great discrepancy between in fact and in thermal simulation of heating and cool loads. Therefore, the investigation of the factual energy consumption of the subject building is very important to predict accurately the energy-saving effects and financial benefits of measures.
Ouyang et al. (2011)	Economic viability	Life cycle cost	Building energy retrofits in China would lead to less energy consumption meant less environmental load and would reduce the tight pressure from the international environmental organizations. Occupants would enjoy a more comfortable indoor environment and avoid energy costs.
Organ et al. (2013)	Decision making	Homeowners' motivations	Differing internal factors, contexts and the dynamic nature of owner-occupier motivation have to be taken into account to shape national and local policy and information campaigns.
Charlier and Risch (2012)	Decision making	Environmental public policy measures	The effectiveness of a policy is stronger if it is combined with another. However, the redundancies of policies can lead to inefficiency.

Table 8: Main conclusions of the identified key papers obtained by bibliographic coupling in the core area 'Models and simulation'.

Models in the cluster on economic viability explore different factors that influence the estimated economic viability of EERs. The authors point out that some of the factors, such as assumed future energy prices, price elasticity, and the difference between expected and realised energy demand, are crucial in the analysis of EERs, for instance in terms of sensitivity of the models' outcomes.

Two key papers address homeowners' decision making. Organ et al. (2013) present a motivation model for EERs in owner-occupied housing; Charlier and Risch (2012) consider a variety of household investment decisions. Other top rated papers, that focus on behaviour, analyse the influence of future energy price expectations and the role of environmental concern (Achtnicht, 2010; Alberini et al., 2013; Urban and Ščasný, 2012). None of the identified papers provides a model of the process of EER decision making of homeowners. Various reviews prominently underpin the models and simulations (Kavgic et al., 2010; Sanders and Phillipson, 2006; Sorrell et al., 2009;

Train, 1985). These reviews are not on decision making regarding EER measures, but on building stock models, rebound effects, discount rates, and differences between measured and theoretical energy savings. In addition, the intellectual base contains papers on homeowners' behaviour, examining determinants of heating expenditures and the willingness to pay for energy saving measures and energy conservation (Banfi et al., 2008; Grösche and Vance, 2009; Rehdanz, 2007).

2.5   Conclusions

We analysed a set of 449 peer-reviewed articles and conference proceedings on energy-efficient renovations (EER) as well as their ~7,000 references in order to identify the obstacles involved in increasing the adoption of EER measures and what has been done to address the problem so far. We conclude that the literature on energy-efficient renovation gained considerable momentum in the last decade, but lacks a deep understanding of the uncertainties surrounding economic aspects and noneconomic factors driving renovation decisions of homeowners.

We have performed a keyword analysis to identify appropriate terms for papers in the field, visualised and analysed the networks of the research front and intellectual base. We have shown that bibliographic coupling can be used to identify clusters of papers with a related subject matter within the topic of EER in buildings. Clusters form around specific topics (e.g. behaviour or economic viability), geographical areas (i.e. China, Ireland and the UK), methodologies (e.g. statistical models), despite the fact that none of these were included as keywords in our keyword-based search. We studied key papers of four core areas to evaluate our hypotheses (see Section 2.1) on technical options, understanding decisions, incentive instruments, and models and simulation.

Hypothesis I – Technical options and economic viability

The literature indicates that the (socio-economical) energy saving potential and profitability of EER measures is lower than generally expected. Nevertheless, the key papers evaluating the effects of EER options on energy savings, investment return and thermal comfort confirm that EER options are cost effective in most cases. Some indicate that measures conducted together have a higher chance to be economically viable (Bojić et al., 2012; Chen et al., 2013). There is considerable attention for the difference between expected and realised energy savings or heat consumption. This effect leads to underestimates of renovation's pay back times. One reason for this bias is the fact that heat consumption levels also depend on energy expenditures, leading to less energy consumption in poorly insulated and higher energy consumption in thermally refurbished houses than predicted.

Hypothesis II – Decision-making processes and incentive instruments

Individuals perform EERs if various wants and needs are met (Zundel and Stieß, 2011): the homeowners' decision to renovate is shaped by an alliance of economic and noneconomic goals such as reducing energy bills, raising comfort, and reducing their environmental impact (Organ et al., 2013). The research on understanding the decisions regarding EERs is just emerging, which is, in our analysis, illustrated by the way in which the research is grounded. Numerous papers focus on the evaluation of incentive instruments that motivate homeowners to thermally refurbish their homes and give recommendations for making improvements. The literature shows that existing instruments have brought only little success and recommend to enhance existing instruments and to consider new approaches that take into account the decision-making processes of homeowners.

Hypothesis III – Models and simulation

The literature focuses on modelling the economic viability of renovations and the potential for energy savings and $CO2$ reduction. However, some of the factors that influence the estimated economic viability of EERs are not taken into account, which leads to biased results, overestimating the merit of EERs. In addition, noneconomic factors are typically ignored. None of the key papers in this area present models of the process of heterogeneous individual homeowners' decision-making regarding EERs.

Clusters

Our analysis led to unexpected findings in the way in which clusters appear in the citation networks. One surprise is a cluster on statistical models which emerged in both the network analysis of the full paper set as well as the subsets. This finding suggests the existence of another research front, and should be taken into consideration when focusing on questions addressing related issues. Another is the focus on geographical areas, which indicates that both the intellectual base as well as the research front may well be specific to regions. This indicates that there are ample opportunities for research on EERs bridging cultures.

Modelling motivations for renovations

The analysis resulted in an overview of the motivations for homeowners to do renovations. Economic aspects are found throughout the literature. A variety of other motivations could be further explored. An approach for future research is to use simulation which maps the decision-making process of homeowners on EERs for their homes, exploring heterogeneity, perceived economical and noneconomical motivations and barriers, and social impacts in different socio-spatial structures. The main factors that influence the current low take up rates in EER may be elucidated with such a model. Additionally, it may result in refining existing instruments or developing new innovative instruments that would address the problem. This could save a considerable amount of time and resources needed to meet climate protection targets.

We are aware that, as with any analysis, the data used will not cover everything there is to say about EERs in buildings. We aimed at a broad analysis by including a relatively large number of papers and explored both their content and structure. We have identified the most important papers within this field of research and analysed them, which corresponds to the methodology described by Allen et al. (2009), who state that tools linking expert peer reviews with quantitative indicators, such as citation analysis, are useful when attempting to assess the importance of research papers. We hope that our analysis leads to a better understanding of the literature on EERs, that it may enable cross-fertilisation of research, and, at the end of the day, that it may inspire the development of appropriate policies that enable us to reach ambitious climate protection targets.

3 EXPLORING HOMEOWNERS' INSULATION ACTIVITY

Exploring homeowners' insulation activity

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ABSTRACT

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

Keywords: Spatial agent-based model, Decision-making process, Homeowners, Thermal insulation, Situational factors, Social interaction

3.1 Introduction

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

The most effective measure for reducing the energy consumed by existing buildings is to install or upgrade (thermal) insulation (Balaras et al., 2007; Enkvist et al., 2007). Empirical research shows that the total benefits of insulating existing buildings usually outweigh their costs (Chapman et al., 2009; Jakob, 2006). Thus, for many homeowners, it pays to invest in insulation measures due to the reduction in energy costs amassed over their lifetime (Nauclér and Enkvist, 2009; Weizsäcker, 2010). Nevertheless, homeowners appear to be reluctant to take advantage of these opportunities in most European countries, including Germany (Jakob, 2007; Organ et al., 2013; Tommerup

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and Svendsen, 2006; Zundel and Stieß, 2011). A number of studies claim that an increase in insulation activity is required in order to achieve Germany's climate protection targets (Kirchner et al., 2009; Prognos et al., 2010). Results show that the number of households having insulation installed could be doubled in Germany compared to current levels, and would still pay off in economic terms (Kleemann and Hansen, 2005). Even then, yet more households could have insulation installed, which would pay off, because there is a considerable insulation backlog (share of building components with overaged or nonexistent insulation) (Diefenbach et al., 2010).

Existing policy instruments to increase insulation activity typically target the economic viability of insulation (Friege and Chappin, 2014a). This is reasonable insofar as a homeowner's decision to insulate is indeed influenced by the economic viability of insulation. Other reasons, both those in favor and those against insulation, were identified in an earlier work by bibliographic analysis (Friege and Chappin, 2014a) (see Table 9). Our analysis showed that one important reason for the poor success rate of existing policies is that the influence of noneconomic motivations and barriers is underestimated.

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

Table 9: Main economic and noneconomic motivations and barriers influencing homeowners' decisions to insulate.
Source: Adapted from Friege and Chappin (2014a).

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

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

- In what ways do situational factors and social interaction influence the insulation activity of heterogeneous homeowners?

- How should policy instruments aiming at increasing homeowners' insulation activity be designed?

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

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

3.2 The theoretical framework

In this section we present the theoretical framework developed to capture the centerpiece of the simulation model, homeowners' decision-making processes on whether or not to insulate their homes. The framework, depicted in Fig. 10, shows that homeowners decide in favor of insulating their property (renovation activity) if situational factors trigger a renovation occasion, and if attitude and the perceived value of information result in positive perceived utility towards installing insulation. The elements of the framework will be further developed and described in greater detail below, based on behavioral theories and literature on renovation decisions.
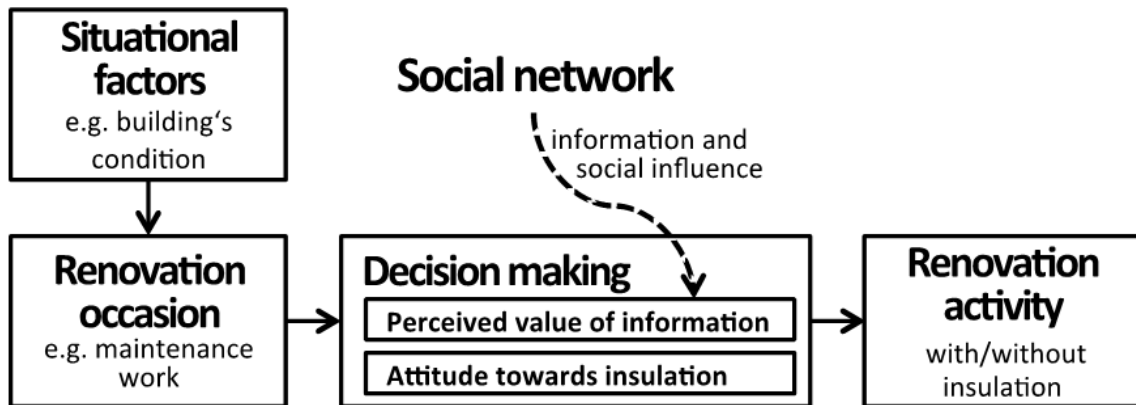
Fig. 10: Theoretical framework for homeowners' insulation decision-making processes.

Homeowners' decision-making on insulation is mainly triggered by situational factors such as the condition of the building or the homeowner's socio-demographic situation. Situational factors trigger the main renovation occasions, namely maintenance work, attic extension, and house purchase (Stieß and Dunkelberg, 2012). Initially, these occasions lead to renovation measures that do not improve the insulation of the house, such as renewing the roof or the façade[7]. However, insulation is usually combined with such measures. Thus, renovation occasions represent a significant opportunity to install insulation (Wilson et al., 2013). Combining roof renewal with roof insulation or façade renewal with wall insulation is also less expensive than implementing the measures separately (Stolte et al., 2012). Incorporating such a concept of facilitating conditions to model consumer action is in accordance with proposals by Ölander and ThØgersen (1995), who state that the opportunity to carry out an intention is a precondition for the performance of the specific behavior.

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

Social interaction becomes relevant for homeowners' decision-making because the installation of insulation requires specialized information and skills, and homeowners "are not usually trained in construction and technology and thus must find ways to cope with the need for expert knowledge" (Stieß and Dunkelberg, 2012, p. 252). Stieß and Dunkelberg (2012) found that homeowners' main and most important source of information on insulation is their own social network. This view is supported by

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

McMichael and Shipworth (2013), who suggest that information received on energy-reducing innovations has a stronger impact on the decision to adopt such measures if verified by personal contacts (McMichael and Shipworth, 2013). In his theory of 'social impact', Latane (1981) showed that the perceived value of information received through social networks differs depending on the effectiveness of communication, the closeness in time and space, and the number of people in the social network. By incorporating the concept of the perceived value of information into our framework, we take into account the influence of social interaction on homeowners' decisions to insulate.

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

3.3   The agent-based model

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

Several scientists have successfully used ABM to model systems comprising autonomous interacting entities such as, in our case, homeowners (An, 2012; Bonabeau, 2002). The studies show that ABM enables emergent phenomena to be captured, in our case homeowners' insulation activity arising from their interaction. Homeowners mutually influence each other's decisions due to social interaction. Thus, homeowners' insulation activity cannot be explained by analyzing their decision-making individually or by analyzing the aggregation of their individual states. In addition, the agent-based approach enables homeowners' multistage decision-making processes to be modeled influenced by their individual situation. We thus consider ABM to be suitable for exploring homeowners' insulation activity.

First, we describe the homeowners' characteristics, which serve as input for the ABM as depicted in Fig. 11. Additional input are a number of parameters such as the assumed population density. The influence of population density on homeowners' insulation activity and the development of the condition of a building is explored in the simulation experiments. We then describe the main model procedures: the initialization, which

includes creating the spatial structure and establishing the social network, and the actual simulation of homeowners' decision-making processes. Finally, we describe the different insulation activity indicators used later to present the results of the simulation experiments.
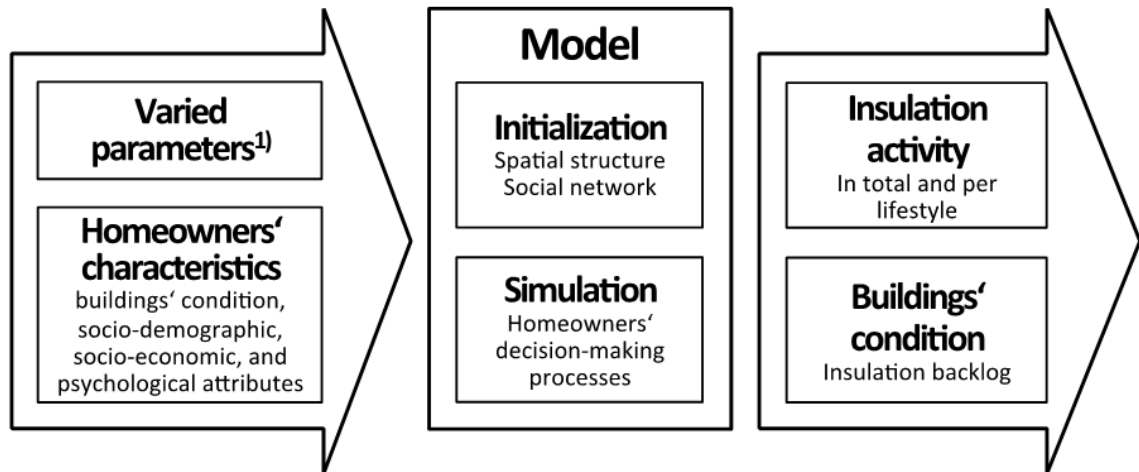
Fig. 11: Overview of model input, processes and output.
[1] Parameters used to vary basic assumptions such as the population density or residential segregation in the simulation experiments.

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

3.3.1 Homeowners' characteristics

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

To capture homeowners' socio-demographic and psychological heterogeneity, we draw on Otte's lifestyle typology for Germany (Otte, 2008). The typology is conceptualized along two dimensions and comprises nine different lifestyles (see Table 10). The hierarchical dimension 'level of living' relates to individuals' economic and cultural resources. The temporal dimension 'modernity/biographical perspective' relates to individuals' values (traditional vs. modern) and biographical perspective of living.

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

Homeowners of the different lifestyles differ regarding their attitude towards insulation, age and income. Homeowners' attitudes towards insulation, expressed in quantitative terms (from -0.5 very negative to +0.5 very positive) per lifestyle, was estimated by the authors based on the study "potentials for sustainable living in Germany" (Rückert-John, 2012). The study describes the attitude adopted by the prevailing lifestyles towards climate and environmental protection activities such as installing insulation. The study additionally provides information on the homeowners' age and household net income distribution per lifestyle as presented in Table 10. For the shares of homeowners per lifestyle we use data collected in the city of Essen (Linnebach et al., 2014). It was not possible to use the national survey because it provides only data on the shares per lifestyle of the whole population. Since the population group 'homeowners' have, on average, a higher 'level of living', their distribution among lifestyles does not match the rest of the population.

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

Table 10: Otte's lifestyle typology.
Note: Horizontal: modernity/biographical perspective, vertical: level of living. The numbers in the square brackets indicate: the share of homeowners of the different lifestyles in per cent, their age in years, their net income in euros per month, and their attitude towards insulation ranging from -0.5 very negative to +0.5 very positive.
Source: Rückert-John et al. (2012), Linnebach et al. (2014).

3.3.2 Socio-spatial structure

For our model, we create an artificial socio-spatial structure that resembles the building and social structure of real-world urban areas. It consists of spatially distributed houses and their homeowners located in the same position as their houses. Each homeowner occupies one patch on a two-dimensional rectangular plane with side lengths of 60 continuous units. One unit represents the lateral length of one homeowner's property. Considering that properties in western Germany have an average area of 610 square meters (statista, 2009), the modeled area corresponds to approximately 2.25 square kilometers. Parameter D is used to define the population density, which is the number of

homeowners in relation to the total number of patches. Houses of a similar construction year and type are typically located close to each other (Ottens, 2012). For this reason, in the model houses are spatially clustered based on these values. During the clustering process, houses are initially randomly distributed over the grid. The following equation is then used to calculate the probability (P_C) that a house will remain at the chosen location. These steps are repeated until all houses are set. Throughout the initializations of the simulation experiments, they follow the same course of action.

$$P_C = \frac{N_C}{N} \quad \text{Eq. 1}$$

N_C is the number of houses built in the same construction year category (see Table 11) in the direct neighborhood; N is the total number of houses in the direct neighborhood. Table 11 provides an overview of the share of detached and terraced houses and their insulation status by construction year category, as provided by the 'Institut Wohnen und Umwelt' (IWU) (Diefenbach et al., 2010). In IWU's building typology, building phases of similar construction methods are used to classify housing units of different construction years into same construction year categories. The typology is a standard to classify buildings in Germany and thus ensures that our simulation results are comparable to other studies focusing on building insulation. The share of houses with 'next-generation' insulating glazing (triple-glazed windows) was virtually zero at the end of 2006 (VFF and BF, 2014).

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

Table 11: Share of detached and terraced housing units and insulated building components by construction year category in the German building stock.
Source: Diefenbach et al. (2010).

The socio-spatial structure of an urban area is additionally based on the preference of similar[9] lifestyle groups for the same residential areas. For example, upper class residential areas are in higher demand among individuals with high economic and cultural resources (dimension 'level of living'). This results in residential segregation, the physical separation of groups into different parts of the urban environment (Massey and Denton, 1988). The degree of residential segregation can be captured by dissimilarity indices, which indicate the evenness with which two groups of people are

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

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

$$S_X = \sum_{i=1}^{N_R} (1 - I_{XYi})/N_R \quad \text{Eq. 2}$$

N_R is the number of other homeowners in a given radius R. A large radius leads to a high level of residential segregation, and vice versa (see Table 12). In order to facilitate interpretation of later simulations, we then refer to R as the 'level of residential segregation'. I_{XY} are dissimilarity indices between lifestyle X and lifestyle Y for which the data is provided by Otte (2008) (see Appendix D). Once each homeowner's level of satisfaction has been calculated, those with a satisfaction level of 1 remain at their chosen location. The remaining homeowners first leave the grid and then randomly choose a new house. Each round, the level of satisfaction needed for homeowners to remain falls by 0.001. This procedure, inspired by the famous Schelling model, finishes as soon as all homeowners have found a satisfactory place to reside.

Table 12 shows how the level of residential segregation and the population density affects socio-spatial structures. In the left panel, the level of residential segregation is lower than in the right panel, visible in the stronger clustering of homeowners of identical lifestyle groups, indicated by identical shades of color. The population density is higher in the bottom panel than in the top one.
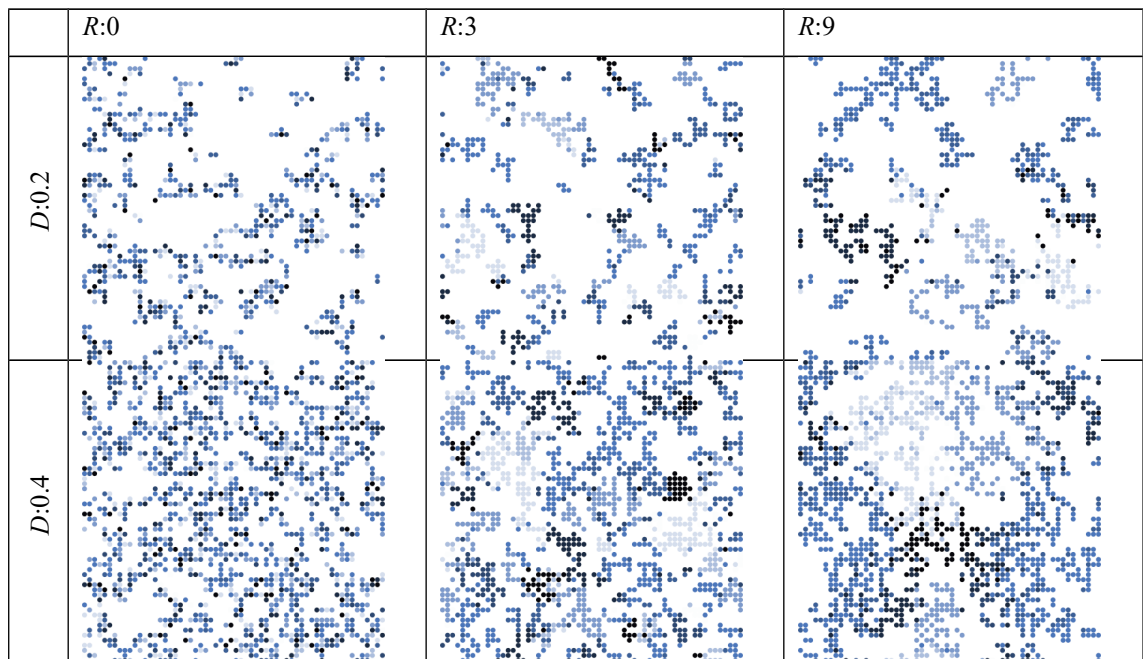
Table 12: Examples of socio-spatial structures of different levels of residential segregation (R) and population density (D).
Note: The different shades of color represent homeowners of different lifestyle groups.

3.3.3 Social network

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

$$P_{XY} = \frac{A_{XY}}{\Delta E^2} \quad \text{Eq. 3}$$

A_{XY} is the likelihood that homeowners of lifestyles X and Y will link if they come into contact with each other. Values for A_{XY} are provided by Otte (2008) (see Appendix D). Low values in Table 28 stand for a low probability that two homeowners link if they come into contact with each other, such as in the case of conservative and entertainment seeking lifestyles. The empirically based likelihoods are employed to consider that the effectiveness of communication depends on who is communicating with each other. The probability that two homeowners will come into contact with each other decreases quadratically with the distance (ΔE) between them. The distance from one homeowner to another is measured from the center of one property to another. For adjacent properties, this is the side length of one patch corresponding to approximately 25 meters in the real world. The average number of links per homeowner generated this way is between two and four. This range is consistent with results of a survey in which data was collected on the number of relationships in a city through which households exchange their views and opinions on heating-related topics (Jensen et al., 2015).

3.3.4 Homeowners' decision-making processes

The theoretical framework shows that two events are of utmost importance when sketching the decision-making process of homeowners with regard to insulating their houses. First, there has to be an initiating occasion when homeowners start thinking about renovating their property. Homeowners then have to decide what type of renovation they wish to undertake. Table 13 provides an overview of the main elements of homeowners' decision-making processes concerning renovation. The table shows that a homeowner starts thinking about renovating, for example, if the structural condition of

the house requires maintenance such as painting the façade. If the house does not have wall insulation, then painting the façade is an ideal opportunity for simultaneously installing wall insulation. We further consider that the decision regarding the type of renovation to undertake is delayed by financial constraints (Wilson et al., 2013).

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

Table 13: Inventory of situational factors, occasions and renovation activities.
[1] Rather than standard glazing

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

When to start thinking about renovating

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

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

$$T_h[a] = F \cdot T_a[a] \cdot \frac{I_a[€/a]}{I_h[€/a]} \quad \text{Eq. 4}$$

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

Deciding about which type of renovation to undertake

In this step, homeowners decide whether or not to insulate their houses as presented in Table 13. A precondition that insulation measures are considered is that either the lifetime of existing insulation has expired or no insulation has yet been installed. The decision then depends on 1) the perceived value of information and 2) homeowners' attitudes towards insulation. A homeowner will therefore decide to have insulation installed if its perceived utility becomes positive. Perceived utility is defined by the sum of the homeowner's individual attitude towards insulation and the perceived value of information.

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

$$I_h = \frac{W}{N} \sum_{i=1}^{N} \frac{F_i[a]}{T_i[a]} N^{0.6} \quad \text{Eq. 5}$$

The time that has elapsed since network contacts last renovated (T_i) is used to capture 'closeness in time'. Thus, the perceived value of information received through individual network contacts decreases with the time that has elapsed since they last renovated. Further, we adopt Latane's (1981) finding that the perceived value of

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

Insulation activity indicators

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

$$I_{1a} = \left(0.25\,N_{ro,ins} + 0.5\,N_{wa,ins} + 0.12\,N_{fl,ins} + 0.13\,N_{wi,ins}\right)/N_h \quad \text{Eq. 6}$$

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

$$B = \left(0.25\,N_{ro,ba} + 0.5\,N_{wa,ba} + 0.12\,N_{fl,ba} + 0.13\,N_{wi,ba}\right)/N_h \quad \text{Eq. 7}$$

$N_{ro,ba}$, $N_{wa,ba}$, $N_{fl,ba}$, $N_{wi,ba}$ is the number of houses where the roof, wall and floor insulation and insulating glazing is outdated or nonexistent. The weightings are identical to those used to calculate the insulation rate. The insulation backlog represents the remaining energy-saving potential that can be achieved by installing insulation. An insulation backlog of 30 per cent, for example, means that only two-thirds of the present energy-saving potential that can be achieved by installing insulation is exhausted.

3.4 Experimental design and model results

During the simulation experiments we explored how homeowners' insulation activity varies between socio-spatial structures. Further, we explored homeowners' insulation activity over time. In order to ensure that the analysis was comprehensive, we selected parameters for variation that influence the main elements of homeowners' decision-making processes, identified by developing the theoretical framework of the model. In

the following, we introduce the setting of the experiments including their setup, execution and design, and provide an overview of the experiments conducted. Subsequently, we present and discuss the results of the simulation experiments.

3.4.1 Experimental design

Setup and execution

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

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

Experiments

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

- The 'population density' (D) was varied from 20 per cent (rural area) to 40 per cent (urban area). In the densely populated city of Munich, for instance, the area

taken up by buildings and (related) open spaces makes up 44 per cent of the whole area (Kizlauskas, 2011).

- The 'level of residential segregation' (*R*) was varied from 0 (no residential segregation) to 10 (high level of residential segregation). When R is 10, there is virtually no mixing between homeowners of different lifestyles (see Table 12).

- The 'average attitude towards insulation' (*A*) was varied from -0.5 to +0.5. The simulation results (see Fig. 12) show that there is virtually no insulation activity below an average attitude of -0.4. Above +0.4, the range of possible results remained unchanged.

- The parameter 'weighting of information received' (*W*) was varied from 0 (information received has no impact on the decision to insulate) to 10. At a value of 10, homeowners' perceived value of information typically ranged from -10 to +10. Since the second parameter that influences the decision to insulate – the attitude towards insulation – ranged from -1 to +1 (taking into account the variation of the average attitude), giving *W* a value of 10 significantly enhanced the assumed impact of the information received about the decision whether or not to insulate.

- The 'impact of financial constraints' (*F*) on the length of time between thinking about renovating and taking action was varied from 0 (no impact) to 10. Giving *F* a value of 10 delayed homeowners' decisions to renovate by five years on average.

In order to explore the influence that different parameter combinations have on homeowners' insulation activity, we ran simulations, tracked the annual insulation rate, and calculated its average over ten years (I_{10a}). The use of a ten-year average for the insulation rate was found to be sufficient for exploring the parameter space. Homeowners' insulation activity over time was explored in the context of the more detailed analysis. As with the other simulation experiments, the simulation was repeated 50 times for each combination of parameter settings so as to be able to analyze the variety of outcomes. For the analysis, we determine the median[10] of the 50 different outcomes. By determining the median outcome of experiments with ten repetitions, we found that they differed too much to be able to draw statistically verified conclusions. In contrast, the median outcome of experiments with 100 repetitions was found to be similar. Fig. 12 shows the simulation results of applying LHS.

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10   We use the median rather than the average to account for a distribution of the simulation results that is not necessarily symmetrical.
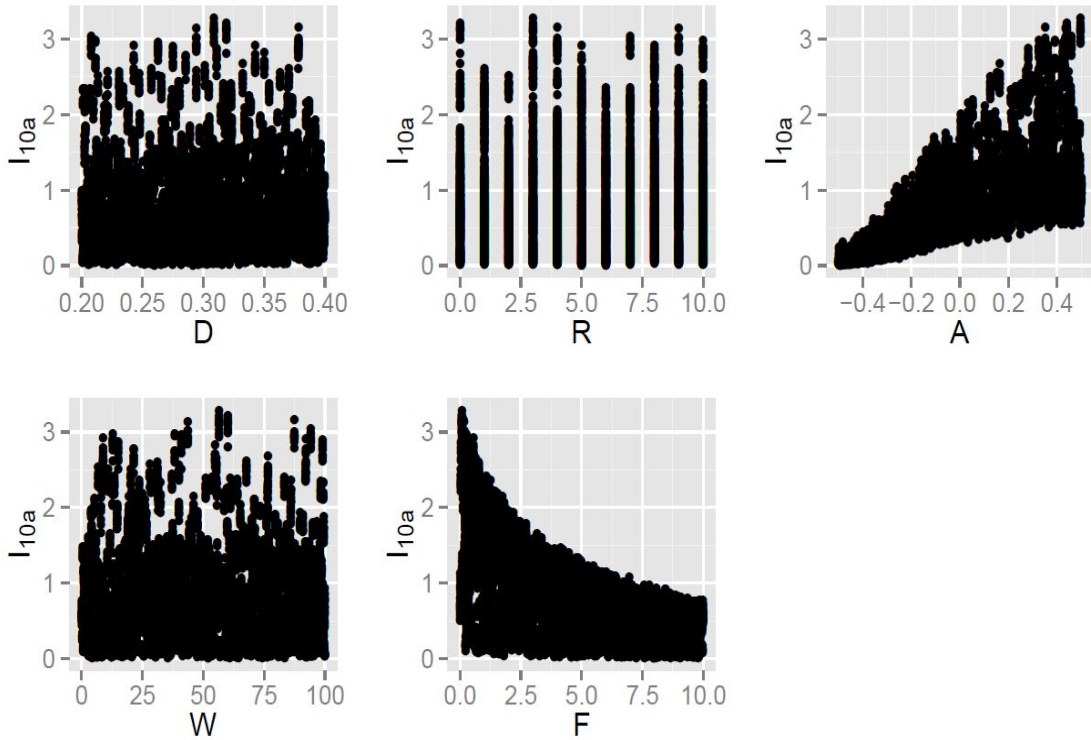
Fig. 12: Simulation results of applying the Latin Hypercube Sample (LHS).
Note: The vertical axis represents the ten-year average of the median of insulation rates (I_{10a}) depending on variations of the different parameters.

The simulation results of applying LHS were used to design the experiments as described below. An overview of the design of the experiments is given in Table 14. The preliminary results revealed a correlation[11] between insulation activity and average attitude (A). In addition, the same average attitude can lead to different results (range of over 2 percentage points). Consequently, the average attitude was varied throughout the experiments. Fig. 12 shows that the impact of financial constraints (F) can limit the average insulation rate. In the first experiment (1), we explored the role of financial constraints in more detail by capturing the development of the annual insulation rate (I_{1a}) over time while varying the impact of financial constraints. Since we expected the insulation backlog (B) to be responsible for the partly high ten-year average insulation rate of over 3 per cent, its development was also captured. We adopted this approach because we expected the delay effects of financial constraints to become most visible when seen from a temporal perspective. In the second experiment (2), we explored whether homeowners' insulation activity varies between different socio-spatial structures. In our model, the socio-spatial structures varied in terms of 'population density' (P) and the 'level of residential segregation' (R).

We then refined the analysis and additionally investigated insulation activity among homeowners of different lifestyles (2.1) and the influence of different levels of social

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11   corr(A,I_{10a})=0.70, p-value < 2.2e-16

impact affected by the 'weighting of information received' (*W*) (2.2). In order to make it easier to analyze the results of the second simulation experiment, we determined the ten-year average of the median of the insulation rates captured (I_{10a}, $I_{10a,s}$).

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

Table 14: Design of simulation experiments.

3.4.2 Insulation activity over time

We explored insulation activity over time in order to examine the effect of financial constraints on homeowners' insulation activity and to determine whether the insulation backlog (*B*) is the factor that led to the partly high ten-year average insulation rate of over 3 per cent. Fig. 13 shows the development of the annual insulation rate and the insulation backlog over time. The impact of financial constraints (*F*) was varied from 0.1 to 10. The average attitude (*A*) was varied from -0.3 to +0.3, depicted by the color of the lines.
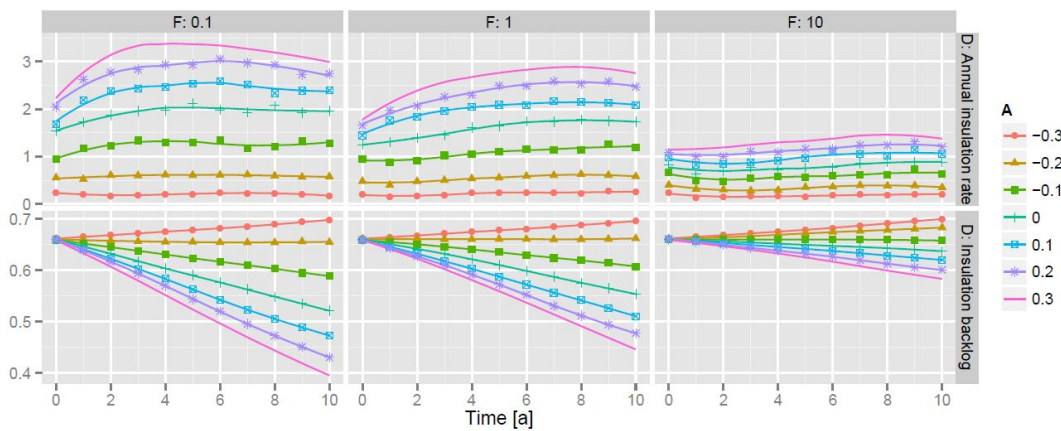
Fig. 13: Insulation backlog and annual insulation rate over a ten-year period for different levels of average attitude (A) and varying impact of financial constraints (F).

The simulation results show that a considerably high insulation rate is possible by reducing the insulation backlog. The fact that a large portion of insulation installed will reach its respective lifetime over the next few years (see Fig. 14) caused an increase in the insulation rate during the first years of the simulation period in all cases. The simulations further show that changing the impact of financial constraints has a greater effect at high levels of average attitude, which result in a high share of decisions in favor of insulation. Here, reducing the influence of financial constraints led to more insulation measures being undertaken in a shorter period of time. Accordingly, this

resulted in a faster depletion of the insulation backlog.

However, the simulation results show that reducing or increasing the impact of financial constraints at a low insulation rate of about 1 per cent (with an average attitude of about -0.1), the current rate in Germany, has only a minor impact on homeowners' insulation activity.
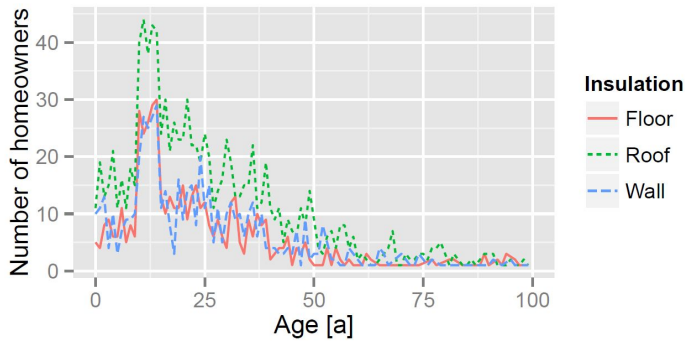
Fig. 14: Exemplary age distribution of insulation installed by 1,440 homeowners (*D*:0.4) at the start of the simulation.

3.4.3 Insulation activity in different socio-spatial structures

In the second experiment, we recorded the ten-year average of the median of insulation rates in different socio-spatial structures and the values of average attitude (*A*), as presented in Fig. 15.
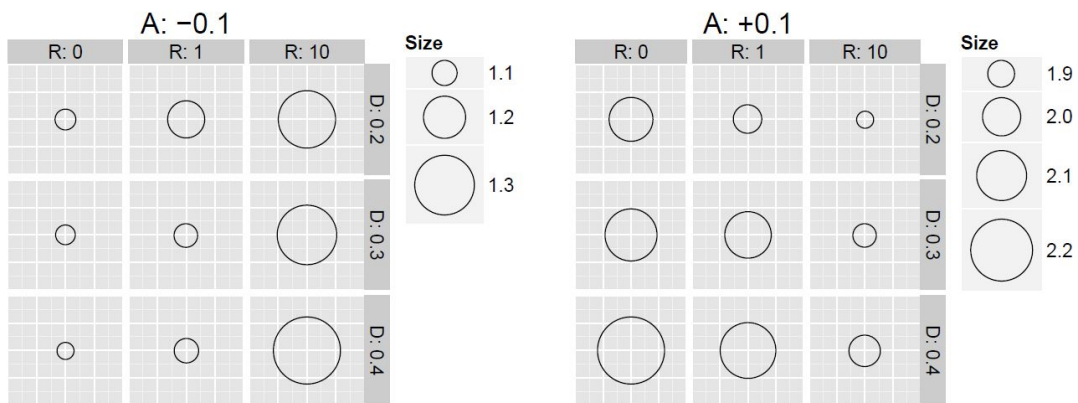
Fig. 15: Insulation activity in socio-spatial structures.
Note: The size of the dots represents the ten-year average of the median of insulations rates (I_{10a}).

The simulation results show that socio-spatial structures influence homeowners' insulation activity. We found that a low level of residential segregation (low value for *R*) facilitated the diffusion of the dominant renovation behavior. The dominant renovation behavior was defined as the kind of decision (in favor of or against insulation) taken by the majority of homeowners. With an average attitude of +0.1, the dominant renovation behavior was to decide in favor of having insulation installed. This behavior was

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reinforced at a low level of residential segregation, as is apparent in the figure from the comparatively high levels of insulation activity. Here, the ten-year average of the median of insulation rates (I_{10a}) is around 1 per cent at a low level of residential segregation (R:0) but reaches 1.3 per cent at high level of residential segregation (R:10). With an average attitude of -0.1, the dominant renovation behavior was to reject the idea of having insulation installed. This behavior was reinforced at a low level of residential segregation, as is apparent in the figure from the comparatively low levels of insulation activity. At a high level of residential segregation, a reinforcement of the dominant (negative) renovation behavior was almost absent. We argue that this is because a high level of residential segregation leads to the formation of clusters of homeowners with a similar attitude, which are less prone to the impact of network contacts with opposing attitudes. This results in a greater heterogeneity of renovation behavior in the modeled environment.

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

Lifestyle groups

In order to analyze the effect of socio-spatial structures on homeowners' insulation activity in greater detail, we further recorded lifestyle-specific insulation rates. Fig. 16 presents the results of the simulations we ran.
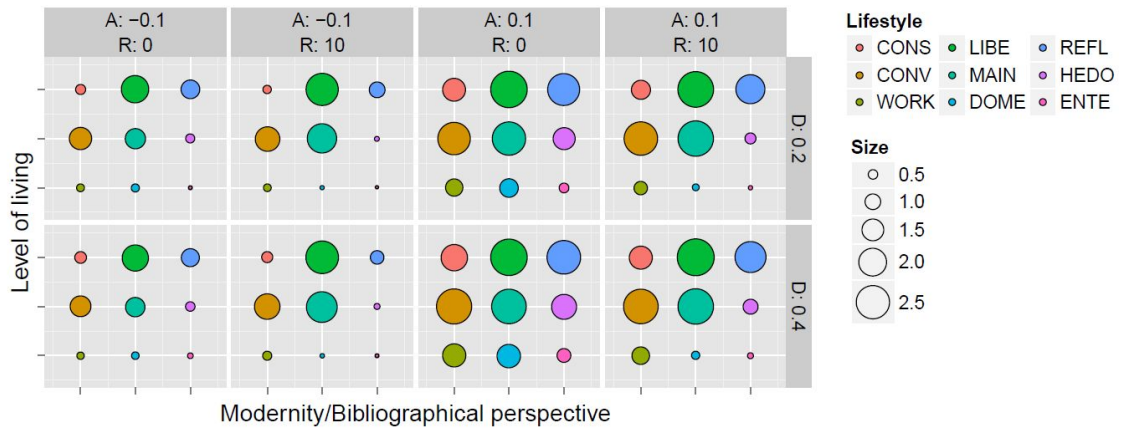
Fig. 16 Diffusion of insulation activity among lifestyles.

Note: The size of the colored dots represents the ten-year average of the median of lifestyle-specific insulation rates ($I_{10a,s}$). The dots are shown in the same order as the legend sequence. For an explanation of the abbreviations of the nine different lifestyles, see Table 10.

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

Social impact

Within the different socio-spatial structures, we further distinguished between different 'weightings of information received' (W) in order to investigate the effect they have on homeowners' insulation activity. In the simulation experiments, we varied the average attitude (A) in single steps (+0.1 per step) from -0.4 to +0.4 and parameter W within a range from 0 to 10 (0,1,10) (see Video 3 in Appendix C). Fig. 17 shows the simulation results for an average attitude of -0.2 and -0.3, which are of particular interest for our analysis.
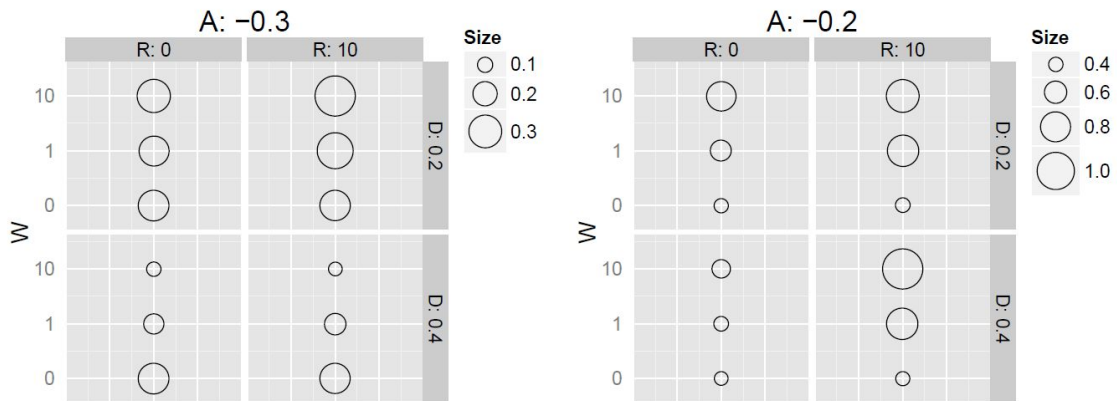
Fig. 17: Importance of social interaction.

Note: The size and color of the dots represent the ten-year average of the median of insulations rates (I_{10a}).

High values for W were found to enforce the particular effects that socio-spatial structures have on homeowners' insulation activity. A high weighting of information received led to a stronger separation between adopters and rejecters of insulation. If the specific socio-spatial structure had a positive effect on homeowners' insulation activity, e.g. with a high residential segregation and a negative average attitude, the effect was enforced by a stronger separation between adopters and rejecters of insulation (see Table 15). Thus, additional contacts within adopters' networks are also convinced into insulating their homes.

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

The fact that the insulation rate in Germany is above the point where socio-spatial structures have no influence on homeowners' insulation activity (at the 'neutral point', the insulation rate is around 0.3-0.4 per cent) indicates that the conditions for a diffusion of insulation activity may vary substantially between regions with different socio-spatial structures.
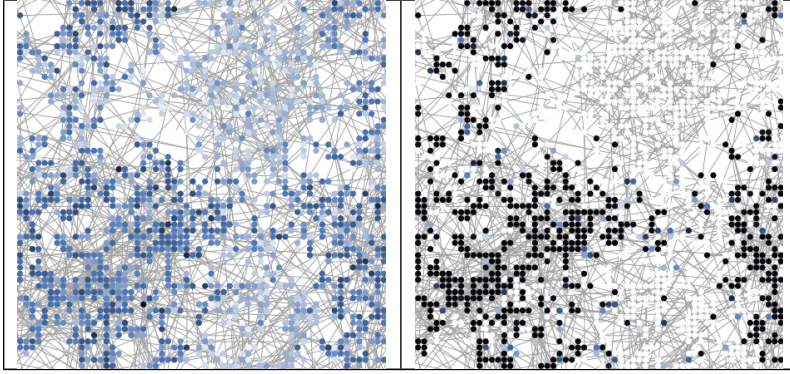
Table 15: Exemplary illustration of homeowners' perceived utility of having insulation installed.
Note: The different 'weightings of information received' (*W*) (left *W*:0, right *W*:10) are indicated by different shades of color. The darker (brighter) the dots, the higher (lower) the homeowners' perceived utility. In this example, the share of homeowners with a perceived utility greater than zero is 31 per cent (43 per cent) for *W*:0 (*W*:10).

3.5 Discussion and conclusion

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

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

3.5.1 Model validity

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

3.5.2 Situational factors

Situational factors play an important role in homeowners' insulation activity, because they trigger renovation occasions, which were identified as a requirement for homeowners to undertake standard renovation measures and consider insulating their homes. Consequently, homeowners' insulation activity is potentially higher in areas with many buildings in need of renovation and insulation, an active housing market (short occupancy periods), and a low level of financial constraints (e.g. due to a high average income). Out of these situational factors, policies may address the impact of financial constraints, e.g. by offering subsidies for renovation, as is the case in existing policy instruments. However, our simulations indicate that reducing financial constraints only has a small potential to increase Germany's insulation rate above its current level of 1 per cent, although Germany's insulation backlog would allow an insulation rate of up to 3 per cent for a limited period of time.

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

3.5.3 Social interaction

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

In conclusion, the success of policy instruments aiming at increasing homeowners' insulation activity in a specific region may be highly dependent on the existing socio-spatial structure. Thus, we recommend considering the local situation before carrying out information campaigns, on-site consultation of homeowners, or other spatially delimited measures. Since social network contacts have a strong influence on homeowners' decision-making with regard to insulation, harnessing social networks to promote the installation of insulation is a promising option for increasing homeowners'

insulation activity. Relevant measures could include money-back vouchers for adopters, which they pass on to other homeowners or open house events for neighbors of homeowners who recently had their houses insulated.

3.5.4 Future research

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

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

4 INCREASING HOMEOWNERS' INSULATION ACTIVITY IN GERMANY

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

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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, noneconomic 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

4.1 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 noneconomic 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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4.1.1 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. 18).

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              Policy instruments
        ┌────────────┼────────────┐
   Regulations   Economic means   Information
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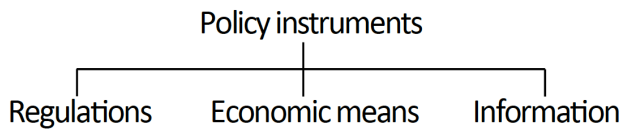
Fig. 18: A threefold typology of public policy instruments.

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 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 (2014a) go further by pointing out that existing instruments underestimate the influence of noneconomic 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 noneconomic 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).

4.1.2 Paper overview and objective

The design of more effective policy instruments needs to better consider the effect of noneconomic 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.

4.2 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 E), 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.

4.2.1 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[13]

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13 The homeowner's attitude towards insulation comprises his or her opinion regarding the usefulness of insulation (economic and noneconomic) 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[14], and measures that improve the insulation of the building envelope.

4.2.2 Findings

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

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 E 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[15] 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 = ≤ .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.

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14 The term 'standard renovation measure' is later used to such activities that do not improve the insulation of the house.

15 The Mann-Whitney U test is used to test the hypothesis that two samples come from the same population.
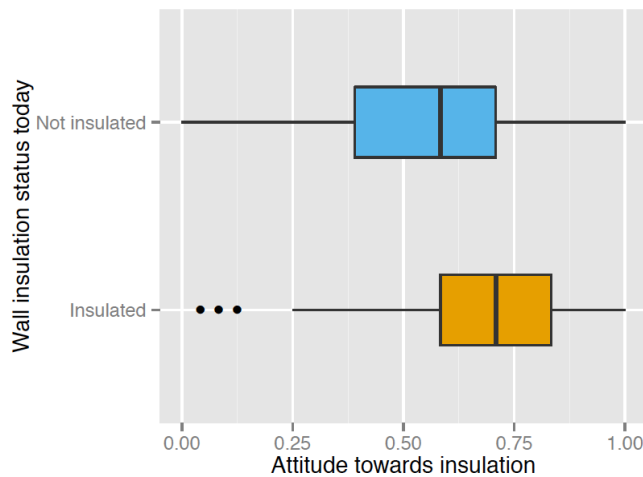
Fig. 19: Homeowners' attitudes towards insulation (n = 198) divided into groups of homeowners who have their walls 'insulated' and 'not insulated'.
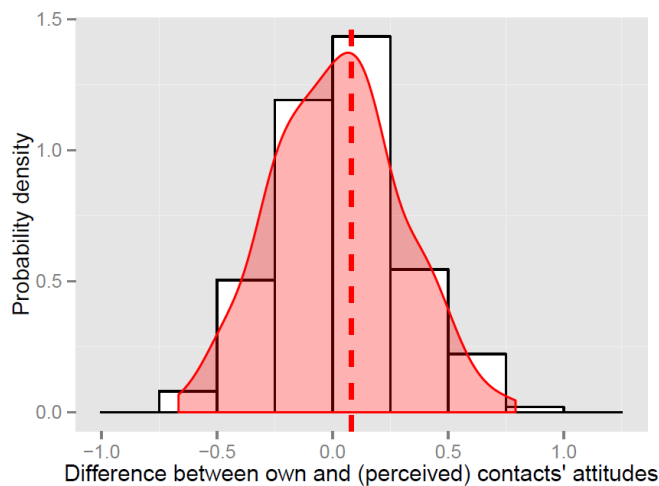
Fig. 20: Probability density of the difference between homeowners' own attitudes and the (perceived) contacts' attitudes towards insulation (n = 217).

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.
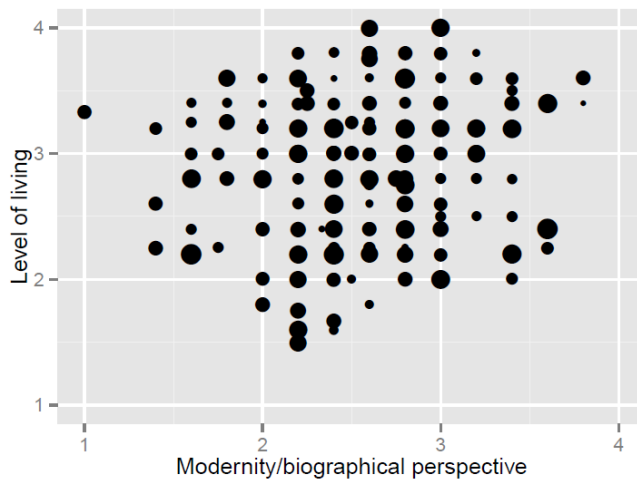
Fig. 21: Homeowners' attitudes towards insulation (n = 230) indicated by the size of the points by 'level of living' and 'modernity/biographical perspective'.
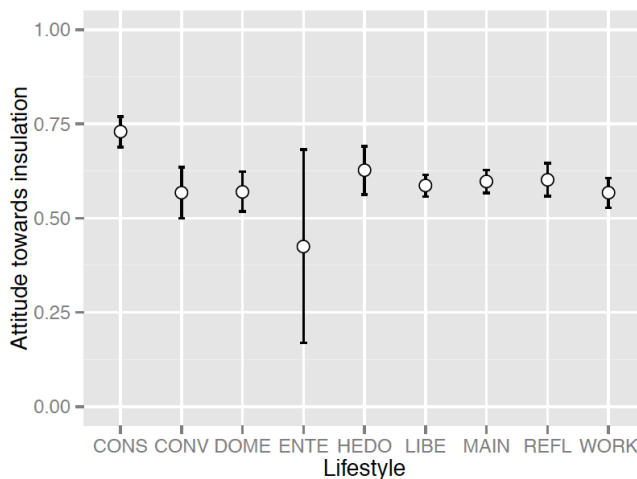
Fig. 22: Homeowners' attitudes towards insulation by lifestyle (n = 230).

Note: For an explanation of the abbreviations of the nine different lifestyles, see Table 10.

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. 8). The condition of floors was not recorded.

$$f_\lambda = \left\{ \begin{matrix} \lambda \cdot \exp(\lambda \cdot x) \ for \ x \geq 0 \\ 0 \ for \ x < 0 \end{matrix} \right\} \ Eq. \ 8$$

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. 23). The same applies to the execution of the standard renovation measures of attic extension, roof renovation, façade painting, façade renovation, and cellar expansion.
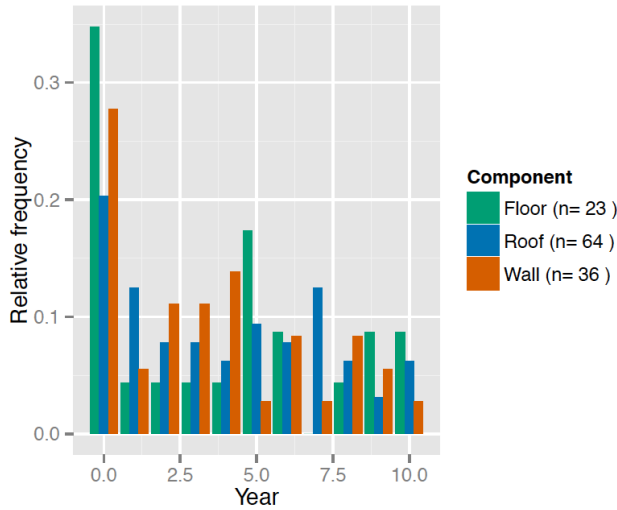
Fig. 23: Frequency of insulation projects carried out (n = 123) in the years after moving in for respondents who have lived in their house for more than 10 years.
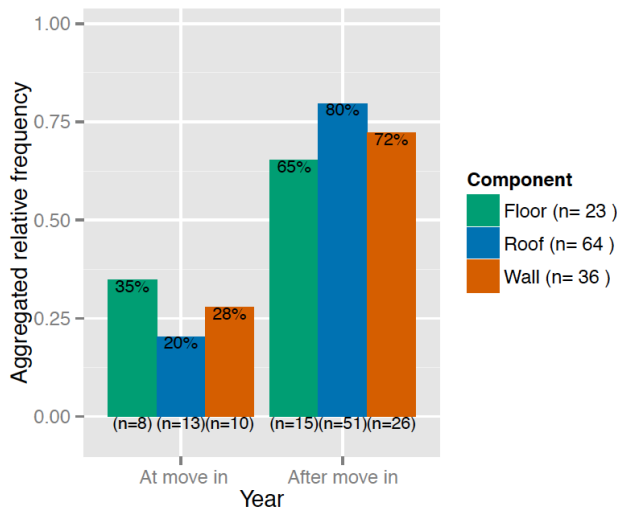
Fig. 24: Aggregated frequency of insulation projects carried out at move-in and after move-in of respondents who have lived in their house for more than 10 years (n = 123).

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 16: 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. 25). 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. 26). 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.
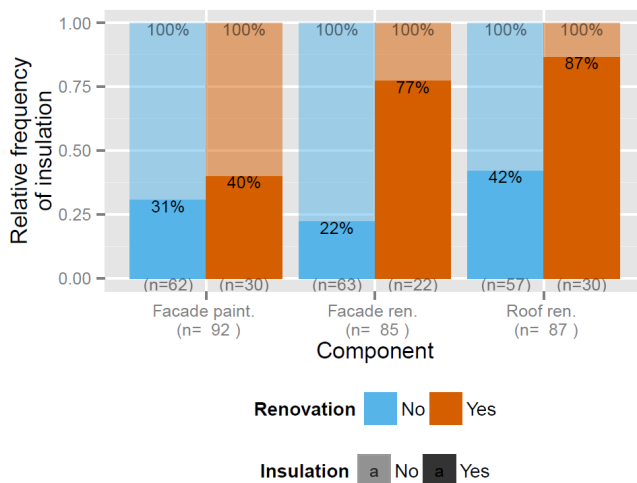
Fig. 25: Relative frequency of insulation for cases where the building components' condition at the time of moving in was 'acceptable' or 'in need of renovation' and the insulation status was 'not insulated'.
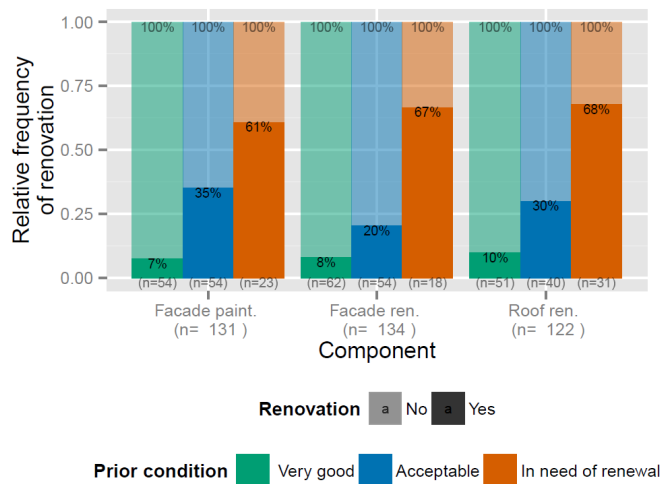
Fig. 26: Relative frequency of renovation dependent on the building components' condition at the time of moving in.

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"

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(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.

$$p(\xi_w = 1 | t \neq 0) = \frac{1}{10} \cdot \frac{1}{1 + \exp(3.15 - 0.07 \cdot \gamma_{p,0} + 1.15 \cdot \phi_1 - 0.64 \cdot \phi_3 - 0.84 \cdot \alpha)} \quad \text{Eq. 9}$$

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.

$$p(\xi_w = 1 | t = 0) = \frac{1}{1 + \exp(3.2 - 0.03 \cdot \gamma_{p,0} - 0.02 \cdot \phi_1 - 2.16 \cdot \phi_3 - 3.2 \cdot \alpha)} \quad \text{Eq. 10}$$

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 F). 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 ≠ 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 17: Accuracy of the logistic regression models for predicting homeowners' wall insulation decisions in the test data set (n = 45).

Note: 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 E) correctly predict 74% of the roof and floor insulation decisions, the ROC curves show that the decision models are largely insignificant (see Appendix F).

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'.

4.2.3 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.

4.3   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).

4.3.1 Model initialization

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 27. 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. 27: Distribution of houses in Bottrop, Germany.
Note: Color shades of the dots represent the houses' age from old (dark) to new (bright).

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 18).

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 18: Share of houses with 'walls insulated when built' and 'walls insulated later' by construction year category in the German building stock.
Source: 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 4.2.2), 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. 11), 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:

$$\alpha = (-\alpha_m) + 1 \quad \text{Eq. 11}$$

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 (Q1 = 3, Q3 = 10). Second, the following equation is used to estimate the probability that a homeowner X comes into contact with another homeowner Y.

$$p_{xy}(\varDelta O, \varDelta \alpha, \varDelta E) = \frac{1}{1 + \varDelta O^2 + \varDelta \alpha^2 + \varDelta E^2} \quad \text{Eq. 12}$$

In the equation, the age difference (ΔO) and the attitude difference between two homeowners ($\Delta \alpha$) (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.

4.3.2 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 28.

First, a homeowner's decision to move into a new building depends on his/her age as depicted by Table 16. If a homeowner moves into a new building, the homeowner is reinitialized, following the relevant initialization procedures. 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.
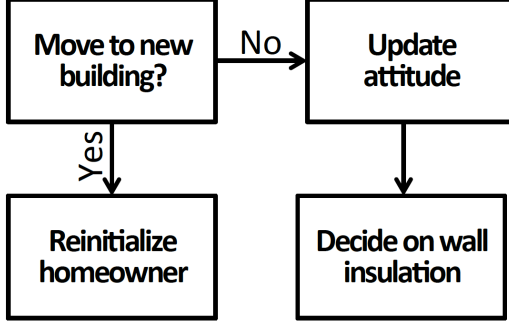
Fig. 28: Main steps for simulating homeowners' wall insulation behavior.

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 4.2.3). 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 (At) as follows:

$$A_t = 0.5 \cdot (A_{t-1} + I) = 0.5 \cdot \left(A_{t-1} + \begin{cases} \left(\sum_{i=1}^{N} \left(\dfrac{\xi_{w,i}}{1 + T_i[a]} \right) \div \sum_{i=1}^{N} \left(\dfrac{1}{1 + T_i[a]} \right) \right) \, for \, N > 0 \\ A_{t-1} \, for \, N = 0 \end{cases} \right) \quad \text{Eq. 13}$$

The updated attitude (At) is the average of the previous attitude (At-1) and the perceived social impact (I). The time that has elapsed since network contacts last decided on wall insulation (Ti) 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 4.2.2.

4.4 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

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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.

4.4.1 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.

4.4.2 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 in 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. 14).
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 19: 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:

$$p(N, N_T, T, P, S) = \frac{X \cdot N}{12 \cdot T[a] \cdot (\frac{P}{0.25}) \cdot N_T \cdot (\frac{1}{S})} \quad \text{Eq. 14}$$

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.

4.5 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 20 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	$\Delta\, 0.79 \pm 0.13$
P_2	Improving homeowners' attitudes towards insulation	$\Delta\, 0.02$ to 0.11

Table 20: Ten-year average of the annual wall insulation rate with/without policy intervention.

4.5.1 Reference scenario

Without policy intervention, the simulation model results in a ten-year average wall insulation rate of $2.35 \pm 0.08\%$. 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, 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 $1.39 \pm 0.11\%$. The following section utilizes this calibrated model to evaluate the policies.

4.5.2 Policy evaluation

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 ($F(1,198) = 3,960$; $p < .001$).

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).

4.5.3 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.

4.6 Conclusions

4.6.1 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 (2014a), 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.

4.6.2 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.

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.

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" (I. 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)

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% considered as necessary 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.

5 CONCLUSIONS AND DISCUSSION

Increasing homeowners' insulation activity is one way for countries located in the temperate climate zone to tackle anthropogenic climate change and to deal with the depletion of fossil resources. This thesis presented two agent-based models (ABMs) on homeowners' insulation activity. The first model was developed based on insights gained in a structured literature review. The second emerged from the previous one, incorporating the results of an online survey. The purpose of developing and using these simulation models was to improve the understanding of homeowners' insulation decision-making processes, and to explore new approaches that aim to increase their insulation activity in Germany.

This final chapter gives an answer to the research question, discusses the main methodological challenges encountered when conducting the research, reflects on the thesis' main methods and research objective, and outlines some thoughts and plans for future research.

5.1 An answer to the research question

The central research question is as follows: *How can the targeted increase in homeowners' insulation activity in Germany be achieved?* The following summarizes this thesis' conclusions along with the three research sub-questions posed in the introduction, and closes with an answer to the central research question.

5.1.1 What are the main factors influencing homeowners' decision-making processes on insulation?

Conclusion 1: The systematic literature review and the online survey, which included an analysis of 449 peer-reviewed articles as well as their ~7,000 references and questioning 275 homeowners, revealed that their decision making about insulation is mostly affected by situational factors and their attitudes towards insulation. The analyses further revealed that homeowners' financial resources play only a minor role in their decision to carry out insulation projects.

Situational factors, such as the structural condition of the house or the homeowner's socio-demographic situation, are important because they initiate homeowners' decision-making processes on insulation. Attitudes influencing homeowners' decision making on insulation can consist of positive and negative elements. Expecting a return on investment, an increase in the value of their home, and reductions in both energy bills and vulnerability to volatile prices all improve a homeowner's attitude towards insulation. This also applies to expecting increases in thermal comfort, status, and resilience to climate change; reductions in energy demand, environmental impact, and

risk of future supply problems; and dependency on fossil fuels. Being unwilling to take out a (further) loan or not being sure whether the investment will pay off has a negative effect on a homeowner's attitude towards insulation. This is also the case when a homeowner thinks that no (further) refurbishment is needed, is not interested in more maintenance than necessary, or is worried about the stress and mess that renovation creates. How the points posed above contribute to the formation of the homeowners' personal attitudes towards insulation depends on their knowledge, affected by their social network.

The analyses of the data acquired showed that homeowners' household net income and standard of living play a minor role in their decision to carry out insulation projects. In the data of the online survey, 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. These findings are contrary to prevailing expectations, apparent in the existing instruments' focus on financial incentives. However, other empirical studies which have taken a closer look at the influence of homeowners' financial resources on their decision to carry out insulation have reached similar conclusions (Pettifor et al., 2015; Stieß et al., 2009; Wilson et al., 2013).

5.1.2 In what way is it possible to model homeowners' decision-making processes and simulate their insulation activity?

Conclusion 2: In the model of homeowners' decision-making processes on insulation, situational factors served as a trigger for renovation occasions, because they were identified as a main requirement for homeowners to begin to consider insulation. The final decision to insulate is affected by their socially influenced attitudes towards insulation. As a result, simulating the overall insulation activity takes into consideration that homeowners interact with each other and their environment; this aspect is made possible through applying the method of agent-based modeling (ABM).

The development of the theoretically grounded ABM involved the preparation of a model depicting the main stages individual homeowners go through when deciding on insulation. Coupling existing theories on consumer behavior with the findings of the systematic literature review resulted in the following main stages:

1. Trigger: Homeowners' renovation decision-making processes are most commonly initiated by situational factors, such as the condition of the building or the homeowner's socio-demographic situation. Those factors can trigger renovation occasions, such as maintenance work, an attic extension, and a house purchase, which can in turn motivate the undertaking of standard renovation measures that do not improve the insulation of the house, such as refurbishing the roof or the façade (referred to as a "standard renovation measure").

2. Decision: Standard renovation measures present a major opportunity to also decide on improving the building's insulation. At this point in time, the decision to install insulation is furthermore affected by the homeowner's attitudes towards insulation, which are influenced by his/her own social network.

The influence of one's social network on his/her decision to insulate was modeled for this thesis by utilizing the social impact theory by Latane (1981). According to this theory, the influence of social network contacts depends on the effectiveness of communication, the proximity in time and space, and the number of people in the social network. The theoretically grounded agent-based model analysis showed that a low level of residential segregation facilitates the diffusion of the dominant renovation behavior, i.e. the decision (in favor of or against insulation) made by the majority of homeowners is reinforced. Such reinforcement is virtually absent at high levels of residential segregation. Furthermore, high population densities also facilitate the diffusion of the dominant renovation behavior. The degree to which social interaction influences homeowners' individual decision making determines how strong the effects of socio-spatial structures are on the diffusion of the dominant renovation behavior.

Both the theoretically grounded ABM ($ABM_{th.}$) and the resultant empirically grounded ABM (ABM_{emp}) could be used to simulate homeowners' insulation activity. The models' main differences are depicted in the following table. For a comprehensive description of the models, see Section 3.3 ($ABM_{th.}$) and Section 4.3 (ABM_{emp}).

	$ABM_{th.}$	$ABM_{emp.}$
Purpose	To explore in what ways situational factors and social interaction influence homeowners' insulation activity	To evaluate different policy options that aim to increase homeowners' insulation activity
Spatial structure	Artificially created, but resembles the structure of real-world urban areas	Based on real-world GIS data from Bottrop Batenbrock
Technical attributes	Age and status of roof, wall, floor insulation, roofing, windows, heating system, exterior rendering, façade painting	Construction year of building, age of wall, and status of its insulation
Social attributes	Lifestyle, income, age, attitude, network contacts	Period of occupancy, age, attitude, network contacts
Decision process	Based on a theoretical framework derived from the literature review	Based on the regression model derived from the empirical data

Table 21: Main differences between the theoretically ($ABM_{th.}$) and empirically grounded ($ABM_{emp.}$) agent-based models developed in this thesis.

5.1.3 What is the potential of policies designed to increase homeowners' insulation activity in Germany?

Conclusion 3: Of the policy options under study that aim to increase homeowners' insulation activity in Germany, the potential of regulatory instruments was found to be higher compared to the potential of financial incentives and providing information. Introducing an obligation to insulate the walls within one year after change of house ownership has the potential to increase homeowners' overall insulation activity by about 40%.

To come to this conclusion, the knowledge generated by the prior analyses was extended by the development of an empirically grounded agent-based model, which allowed an exploration of the potential effects of policy options designed to increase homeowners' insulation activity in Germany.

Regulatory instruments

The potential of increasing homeowners' wall insulation activity through obligating new homeowners to insulate the walls within the first year after moving in corresponds to the number of homeowners who move into a house without wall insulation and do not decide in favor of insulating the walls of their own accord. The empirically grounded simulation model shows that such obligation would lead to a significant increase in homeowners' average ten-year wall insulation rate. Using a calculation method from the Institut Wohnen und Umwelt (Diefenbach et al., 2010), the increase correspond to a total increase in homeowners' insulation activity of about 40% in Germany.

Financial incentives

The results of the empirical analysis as well as the systematic literature review showed that homeowners' economic means have little influence on their decision to install insulation. This applies to their net household income as well as to their standard of living. Other authors have reached similar conclusions on the relatively minor role of economic factors in homeowners' decision-making processes on insulation (Pettifor et al., 2015; Stieß et al., 2009; Wilson et al., 2013). It should be noted that the conclusions of the other authors are based on empirical data collected before the current period of low interest rates, which lowers the barrier to obtaining a loan for carrying out insulation. It can be assumed that the impact of financial incentives on homeowners' insulation activity has decreased even further in recent years.

Providing information

The simulations show that improving homeowners' attitudes towards insulation by providing information leads to an increase in their insulation activity. According to the simulation results of the empirically grounded ABM presented in Section 4.5.2, the potential for this approach is about a 7% increase in the wall insulation rate. Simulating various strategies to implement this policy shows that it is more advantageous to run a

short and intense campaign rather than to extend it over a prolonged period, and to target many homeowners with low effort rather than targeting 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. More sophisticated information instruments, such as multi-stage on-site energy consultations, may also be promising approaches for increasing homeowners' insulation activity. In the scope of this thesis, they have not been modeled due to the lack of detailed empirical data.

5.1.4 How can the targeted increase in homeowners' insulation activity in Germany be achieved?

Overall conclusion: Even with the further tightening of regulatory instruments, it appears difficult to reach the German government's target of doubling homeowners' insulation activity by 2020.

Of all the options analyzed, the largest increase in homeowners' insulation activity of about 40% was found to result from the introduction of an obligation to insulate the walls within one year after change of house ownership. Making use of the window of opportunity that a change of house ownership provides has been suggested in various studies (Stieß et al., 2010; Wilson et al., 2015). Stieß et al. (2015) have developed guidelines for potential house buyers that provide them with information on the opportunity to install insulation. In the scope of this thesis, this approach has been followed and translated into an obligation for homeowners to insulate the walls after change of house ownership.

There are number of arguments in favor of introducing such obligation apart from the large increase in homeowners' insulation activity: the frequent coupling of insulation projects with renovation measures that do not improve the building's insulation (referred to as "standard renovation measures"), triggered by externally unavoidable occasions, suggests that it would be beneficial to tailor the design of policy instruments to such occasions. Joint work on insulation and standard renovation measures has many advantages: it significantly reduces the break-even period of insulations, and reduces associated time and efforts on the part of the homeowner (Uihlein and Eder, 2010). That these aspects were recognized by policymakers in Germany is evidenced by a previously introduced obligation to insulate those wall surfaces where extensive renovations are being carried out. Regarding this, so far the main problem has been the difficulties to enforce such obligations. Since the transfer of house ownership is officially recorded, an obligation to insulate the walls would be less challenging to enforce. Furthermore, it is expected that the introduction of an insulation obligation would lead to a lower market value of houses without wall insulation (corresponding to the associated expense), which puts houses with wall insulation in a better position.

5.2 Methodological challenges encountered

5.2.1 Data utility

How to cope with subjectivity when deciding on which literature to use

Obtaining data from literature on energy-efficient renovation, representative for the current state of science, was challenging due to the great deal of publications in this area of research, and the demand for objectivity regarding the decision on which sources should be included in the review. By applying the method of citation network analysis, it was possible to identify papers at the research front and intellectual base out of a relatively large body of literature (449 peer-reviewed articles and their almost 7,000 references). The content and structure of the papers identified was analyzed among four areas: technical options, understanding decisions, incentive instruments, and models and simulation. The approach used in this work corresponds to the methodology described by Allen et al. (2009), who point out that tools linking expert peer reviews with quantitative indicators, such as citation analysis, are useful when attempting to assess the importance of research papers.

However, as with any analysis, the data used here does not cover everything there is to say about energy-efficient renovation in buildings. This became more obvious when exploring homeowners' insulation activity by using the agent-based model based on the results of the literature review; the need for more detailed empirical data became clear when the time came to assess policy options that were designed to increase homeowners' insulation activity.

How to deal with the non-representativeness of the empirical study

Obtaining empirical data on homeowners' decision-making processes on insulation that would be suitable for an ABM (which itself was eventually used to assess policy options) was challenging due to the limited amount of resources available to conduct the survey. This required creativity in conducting the survey and harnessing the results. To gather detailed empirical data on homeowners' insulation decision-making processes, this study conducted an online survey. At first, the link to the survey was only communicated by distributing leaflets to homeowners. Due to the poor cost-benefit ratio of that measure (response rate below 1%), the link was further posted in online forums and referred to in newsletters. The additional dissemination activities resulted in a total response of 275 completed questionnaires.

Due to the non-representativeness of some data on the aggregate level (e.g. age distribution among homeowners), this data was not further used. From the aggregate level, only the empirical data on homeowners' attitudes towards insulation was used. To minimize the bias resulting from non-response behavior, the fact that homeowners' attitudes towards insulation correlate with the wall insulation status of their homes 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 empirically based ABM, 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.

Data on insulation decisions from individual homeowners was used to derive logistic regression models to estimate how often a homeowner would decide in favor of or against installing insulation. The logistic regression models 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. While the collected data was not sufficient to make safe predictions regarding roof and floor insulation decisions on the part of homeowners, it provided for estimating homeowners' wall insulation decisions with an accuracy of 80%. Accordingly, only the logistic regression models on homeowners' wall insulation decision were used for the empirically grounded ABM.

5.2.2 Model validity

How to limit the models' uncertainty

Every model is a representation of a part of reality, which causes uncertainty regarding their validity. Uncertainty regarding the validity of a model's simulation results can increase with the model's level of complexity, since more parameters and equations are needed to describe it. In keeping with the phrase "model a problem, not a system", one way of keeping it simple and thus limiting uncertainty is to develop the model according to its purpose as discussed in the second subsection. In addition, the study attempted to limit potential uncertainties arising from 1) the prediction of future conditions, and 2) the representation of social impacts.

1) Predicting future conditions with a model based on existing knowledge naturally results in a certain level of uncertainty. The level of uncertainty increases with the considered time period in the future, because real-world systems are highly complex, and develop dynamically depending on a wide range of different factors. This circumstance led to the establishment of the scientific discipline of scenario analysis, the goal of which is to project the development of systems under various conditions. The experiments conducted in the scope of the ABM analysis showed that a simulated time period of ten years was sufficient to produce a statistically relevant number of renovation decisions. By limiting the considered time period to ten years, it is argued that changing conditions, such as demographic change or the development of energy prices, have a low influence on homeowners' insulation activity. The decision to exclude these parameters limits the model's complexity and thus its uncertainty.

2) Agent-based modeling allows users to represent interaction between agents and their environment. Based on the insights of other studies (McMichael and Shipworth, 2013;

Stieß and Dunkelberg, 2012), the ABMs presented here focus on interaction among homeowners. In the ABMs, homeowners interact by exchanging information on insulation and socially influencing each other. For this reason, it made sense to apply Latane's (1981) social impact theory. A sensitivity analysis was carried out to explore the potential influence of social interaction on homeowners' insulation activity. The simulation results led to further investigations of this issue in the scope of the empirical study. The results from the empirical study also show 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 their real attitudes towards insulation deviate from perceived attitudes. Goel et al. (2010) have indicated that the perceived attitude of social network contacts is in between the subject's own and the network contacts' real 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 homeowners merely choose social contacts with similar attitudes (network homophily). Both factors suggest that the impact of social network contacts is actually lower than reported in the scope of the empirical study. Whereas network homophily was considered in the model, it was not possible to quantify the deviation between the contacts' real and perceived attitude. Nevertheless, a correct representation of the deviation between the contacts' real and perceived attitude would only strengthen the conclusion that policy instruments harnessing the social network of homeowners are not well suited to sufficiently increasing homeowners' insulation activity.

How to ensure that the models are fit for purpose

Various scholars have pointed out the importance of how well a model is fit for purpose as a central element for its validation (Chappin and Dijkema, 2010; Chilcott et al., 2010; Zang et al., 2008). The process depicted below, describing the search for feedback at every stage of model development, facilitated the process of fitting the models to their purpose, thus providing a sufficient reply to the research question as presented in Section 5.1. During the early stages of its development, the first model was presented and discussed at the Social Simulation Conference 2014 in Barcelona (Friege and Chappin, 2014b). In addition, the structural design of the model and the consistency of the preliminary simulation results were validated at a workshop with building insulation and consumer behavior experts. The model's methodological accuracy was ensured through a double-blind peer review, which included disclosure of the program code and the submission of an "ODD" (Overview, Design concepts, and Details) protocol (Grimm et al., 2010) of the model. The "ODD" protocol provides a framework for describing ABMs with the purpose of making them more understandable and complete. The results of the second model, which emerged from the previous one, were presented to and discussed with representatives dealing with activities designed to increase the energy efficiency of buildings in their city.

5.3 Reflections and future research

The following section reflects on the main methods applied during the course of conducting the research and the goal of doubling homeowners' insulation activity as a means for achieving Germany's climate protection targets. The second part of this chapter outlines some thoughts and plans for future research.

5.3.1 Reflections on research methods

Bibliometrics

This study used a set of bibliometric methods to analyze a set of 449 peer-reviewed articles and conference proceedings on energy-efficient renovations as well as their ~7,000 references. Identified papers at the research front and intellectual base were reviewed to form a base of knowledge on energy-efficient renovation (see Chapter 2). A number of advantages and disadvantages become apparent when reflecting back on the bibliometric methods used.

Applying the bibliometric methods of co-citation and bibliographic coupling showed that they are suitable in terms of objectively assessing the importance of a great volume of literature. In comparison, an exclusively manual assessment would have been both subjective and relatively time-consuming. However, to apply these bibliometric methods, it was necessary to develop specific algorithms and combine various software tools to process the data. Since not all steps can be automated, the amount of work necessary is still directly related to the amount of literature taken into account. Nevertheless, applying such bibliometric methods in future work will require less time, since it can build on scripts that have already been developed. With respect to results, it is important to note that using bibliometrics may be a good introduction into a selected area of research. Subsequent work showed that an increased focus on a specific issue may still require some additional manual literature selection. Because the amount of literature decreases as the focus of research is narrowed down, this is not a major concern.

Agent-based modeling

Agent-based modeling (ABM) was the main research method applied in this thesis (see Chapters 3 and 4). The development and utilization of two ABMs, based on insights from a structured literature review (see above) and the results of an online survey (see below), allows for reflection on the method's weaknesses and limitations as well as its strengths and capabilities.

The experience gained from this study shows that ABM can be used to increase system understanding, to guide data collection, and to challenge the robustness of prevailing concepts of thought. One main strength of ABM lies in the fact that it allows for a very straightforward representation of the system under investigation. ABMs consist of

discrete entities (agents) that interact with each other and their environment, and act based on rules assigned to them. Experience gained over the course of presenting the models showed that the modeling paradigm is easily understood by stakeholders, which facilitated communicating the simulation model and its results. Being able to represent a system in a very straightforward manner further facilitated model development. Developing the ABMs required a number of sequential steps starting with problem formulation, system identification, concept formalization, model formalization, and software implementation (van Dam et al., 2012). Following these steps contributed to an increased understanding of the system and guided the process of data collection. The conclusions drawn by this thesis furthermore showed that ABM can challenge the robustness of prevailing concepts of thought when it gives quantitative insights on previously theoretically grounded hypotheses, e.g. regarding the effectiveness of different types of policy intervention aiming at an increase in homeowners' insulation activity.

The process of developing and using ABMs in the scope of this thesis also revealed a number of weaknesses and limitations associated with (computer) modeling in general and ABM in particular. In general, model complexity seems to increase exponentially with every additional parameter introduced into the model. Based on conversations with other modelers involved in large modeling projects, increasing complexity is a significant issue with regard to model transparency, which is necessary for users to understand the assumptions, relationships, and data that shape the model (Martinez-Moyano, 2012). The unguided use of a relatively non-transparent model in particular can lead to erroneous conclusions with potentially dire consequences. In the field of ABM, modelers have developed various strategies to address this issue. The probably most widely known instrument to increase the transparency of an ABM is using the ODD protocol as introduced earlier. ABM suffers from two particular problems that limit its usability – its relatively high requirement for empirical data, and the difficulty to represent social interaction. One main strength of ABM, its ability to represent the interaction between agents, can at the same time be a reason for great levels of uncertainty. Hypotheses regarding the impact of social interaction have been found to be particularly hard to validate with empirical data (see following section). Building the ABMs revealed that their inherently detailed structure resulted in a rather high data requirement. To build a realistic model, it is necessary to describe its elements in great detail, including each agent's decision-making processes.

Online surveying

An online survey was conducted following completion of the work on the theoretically grounded ABM. The results of the survey were incorporated into the empirically grounded ABM (see Chapter 4). When reflecting back on this course of action, one might wonder whether it was necessary to build an ABM before gathering the empirical data. In fact, building a theoretically grounded ABM first was beneficial, as it helped to understand the model's data requirements in advance, and thereby to find a smart design

for the questionnaire. Nevertheless, experienced modelers might be able to skip this step of theoretically grounded modeling and to go straight to data collection or recognize that the existing data is sufficient to build an ABM that is fit for purpose.

One main limitation of the survey method selected is the resulting uncertainty surrounding the actual effects of social interaction and the potential change over time of those household attributes that were identified to be decision-relevant. In general, the second aspect can be resolved by carrying out a panel study, where the participants are surveyed before and after making renovation decisions. Considering the low level of insulation activity, obtaining useful data in this way would have been too expensive and time-consuming. Regarding the actual effects of social interaction on a specific decision, there was no suitable approach available with the potential to eliminate the reporting bias. This was found to be a disadvantage for ABM, because it led to the need for theory-based assumptions regarding the validity of the data. A more general disadvantage of gathering empirical data through surveying is non-response behavior, which makes it difficult to obtain a representative sample of the target population. However, it can be noted that non-representative data can still be of use, provided that the conclusions that are drawn come with a careful discussion.

5.3.2 Reflections on the research objective

The central objective of this thesis was *to explore the potential of policy options designed to achieve the targeted increase in homeowners' insulation activity in Germany through an agent-based model analysis*. The German government's target of reaching a 2% insulation rate originates from a study in which the authors presume that almost every standard renovation measure conducted after 2020 is combined with the installation of insulation (Prognos et al., 2010). The authors argue that, in this way, only the additional costs for insulation need to be taken into account, making it economically viable in most cases (Feist, 2005; Holm et al., 2015). Because economic factors were found to play only a minor role in homeowners' decision making on insulation, it is necessary to question the goal of doubling homeowners' insulation activity. With the exception of regulatory instruments, policy measures were found to have a relatively low potential for increasing homeowners' insulation activity. The conclusion was that doubling homeowners' insulation activity is likely to be difficult. But, is it really necessary to double the level of insulation activity among homeowners in Germany?

The growing share of renewable energies, especially in the electricity mix, combined with the advancing electrification of heat supply (e.g. heat pumps) as well as future supply with renewable natural gas, will lead to a reduction of CO_2 emissions saved by insulating buildings. In addition, the use of more efficient heating systems and the implementation of local heat supply concepts can lead to a substantial reduction of final energy demand and the corresponding CO_2 emissions without insulating buildings. Therefore, it is necessary to constantly reflect on the costs and benefits of present

policies fostering insulation. Furthermore, increasing so-called "energy sufficiency" (restriction and reduction of the consumption of useful energy) in households can take the pressure off the goal of doubling the insulation rate by 2020. The increasing demand of living space per capita especially counteracts efficiency gains through improved insulation. Between 2003 and 2015, the demand of living space per capita increased by 14% (destatis, 2016). This increase is caused by a number of factors, such as higher standards of living and an increase in single and two-person households. Accordingly, the development of measures that aim to stop or reverse this trend can help to reduce energy demand in the building sector more quickly.

In summary, a holistic approach is needed for governing the transition towards a carbon neutral building stock, which has to combine renewable energies, energy efficiency, and energy sufficiency.

5.3.3 Thoughts and plans for future research

Landlords' insulation activity

The insulation activity by landlords, the second main group with the decision-making power to invest in insulation measures in Germany, was not covered in the scope of this thesis. Brechling and Smith (1994) have indicated that their insulation activity must be explored separately. They state that landlords will only make "investments if they can recoup the benefit through subsequent higher rents" (Brechling and Smith, 1994, p. 55) as they do not benefit directly from a reduction in energy bills due to improved energy efficiency. This lack of alignment between the interests of landlords and tenants thus appears to be one of the greatest barriers hindering insulation projects in rented properties (Ástmarsson et al., 2013). The central question is whether the implementation of more effective financial instruments or a further tightening of regulatory instruments have the potential to double landlords' insulation activity.

Energy refurbishment at city neighborhood level

A higher-level approach to decreasing the CO_2 emissions in buildings is to consider whole city neighborhoods for energy refurbishment. In this way, the supply of electricity and heat can become more climate-friendly and be made available at lower cost compared to the single-unit approach. One example of an energy refurbishment measure at the neighborhood level is the construction of a local heat network fed by heat produced by solar thermal power plants, heat pumps, or combined heat and power units. Benefits may arise from lower specific costs for installed power capacity due to the construction of larger power units and a higher power plant utilization rate.

Despite its benefits, the implementation of such measures is not yet mainstream. Most initiatives do not extend past the development of potential studies and concepts for implementation (Erhart et al., 2013; Messari-Becker, 2014; Stephan, 2014). Additional research is needed to identify and overcome the main barriers hindering the broad implementation of energy refurbishment measures at neighborhood level.

Resource impact of insulation

The use of energy and resources in the scope of the life cycle of insulation materials (i.e. energy for production, the supply chain, and the disposal of insulation materials) also needs to be considered when assessing the overall ecological gains of carrying out insulation projects. At the moment, we are in the process of conducting a study combining life cycle assessments, household energy models, and agent-based models to calculate the resource implications of homeowners' insulation decisions. Preliminary results show that, in the long run, the installation of insulation saves both energy and resources.

Given the recent negative press coverage of insulation in the German media landscape, research such as this is necessary because it can contribute to a high-quality debate on policies fostering increases in homeowners' insulation activity.

APPENDICES

A - Data preparation (Chapter 2)

Tool to standardise different data formats

In order to create a look-up table - a tool for automatically standardising the format of the same bibliographic information in a reproducible way - a list of the different paper designations was uploaded to and processed using Google Refine. Next, two columns from the list were created entitled "original" and "preferred". Within the "preferred" column, different clustering methods were applied to find groups of (often slightly) different patterns used for the same bibliographic information. Since it is likely that this method can also cluster false positives all suggestions to merge potentially identical bibliographic information had to be checked manually (see Table 22).

Values in Cluster	New Cell Value
1) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) j build phys, 33, pp. 125-154" 2) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) journal of buildings physics, 33 (2), pp. 125-154"	1) and 2) "corrado, v. uncertainty and sensitivity analysis for building energy rating (2009) journal of building physics, 33 (2), pp. 125-154"

Table 22: Example for clustering using Google Refine.

Since our main interest was the content of papers and their references, regardless of the specific circumstances of their publication, we also merged the following bibliographic information:

- Different publication statuses, for example: conference proceedings, submitted, in press, published, updated edition;

- Different parts, chapters, section of pages;

- Reports, balances, reviews, statistics from different years.

The resulting table of "original" and "preferred" patterns of bibliographic information was used to prepare the data for the analyses. For this purpose, another script was used at different stages within the implementation of the citation network analysis. In the first step, the script deletes rows within the table where the patterns of both columns (original and preferred) look alike. After performing this step, the look-up table is ready, containing 1,095 rows in our case. Hereafter, the script loads the data from the file to be processed and looks up the patterns of the 'original' column and replaces them with the patterns of the 'preferred' column from the look-up table.

The procedure described above is necessary because Gephi (used to visualise and explore the paper networks) only recognises the occurrence of equal paper designations and references if the patterns are exactly the same.

Scripts to implement citation analyses

Bibliographic coupling

Before we were able to couple papers using the same references, it was necessary to accomplish two prior steps: 1) generation of an edge list of direct citations; and 2) use of the look-up table to standardise the format of same bibliographic information. The script used to produce an edge list of direct citations takes the references of the different papers and places them separately into a column next to the duplicated paper designation. The script to process the look-up table (see Appendix A) is then used to standardise the format of same bibliographic information within that list. Finally, the script that couples papers with the same references was executed. The script initially creates a separate list of references and deletes duplicates. Afterwards, it reads the list line by line and looks for equal patterns within the edge list of direct citations. If an equal pattern is found, the pattern aside (the paper designations) is copied to a temporary file. The temporary file later contains one or more (if a reference is cited by more than one paper) paper designations. Finally, a double loop is used to combine and add each combination of these patterns to the final edge list.

Co-citation coupling and analysis

For co-citation analysis, editing the data started with splitting the complete file into files organised according to the pattern of bibliographic information. In these files a loop with different steps was executed:

1. Store the paper designation in one file and a list with the references in another;

2. Separately link the (duplicated) paper designation to the paper references and store them in an edge list;

3. Finally extend the edge list through a list of all possible combinations of the references, using a double loop.

Besides performing the complete co-citation analysis, results of co-citation coupling were collected. For co-citation coupling, the combinations of references were not linked to the paper designations. After performing this procedure for all patterns of bibliographic information, the script for the look-up table was executed to standardise their format.

B - Complementary results (Chapter 2)

Overview on key papers and references

The following table gives an overview on the several key papers and references identified by examining the different subsets. Some were identified through bibliographic coupling as well as co-citation coupling within our different subsets (see Table 23 and Table 24, first row).

Bibliographic Coupling			
Technical options	Understanding decisions	Incentive instruments	Models and simulation
(Chen et al., 2013)	(Power, 2008) (Organ et al., 2013) (Watts et al., 2011) (Kuronen et al., 2011) (Weiss et al., 2012)	(Watts et al., 2011) (Kuronen et al., 2011) (Galvin, 2010) (Grösche and Vance, 2009) (Weiss et al., 2012)	(Chen et al., 2013) (Organ et al., 2013) (Amstalden et al., 2007) (Grösche and Vance, 2009)
(Bojić et al., 2012) (Hong et al., 2006) (Liu and Guo, 2013) (Lloyd et al., 2008) (Anastaselos et al., 2011)	(Zundel and Stieß, 2011) (Vadodaria et al., 2010) (Crilly et al., 2012) (Konstantinou and Knaack, 2011, 2013)	(Ouyang et al., 2011) (Galvin and Sunikka-Blank, 2013) (Moloney et al., 2008)	(Galvin and Sunikka-Blank, 2012) (Ouyang et al., 2009) (Charlier and Risch, 2012)

Table 23: Key papers in different subsets identified by bibliographic coupling.

Co-citation Coupling			
Technical options	Understanding decisions	Incentive instruments	Models and simulation
(Moore et al., 2000)	(Power, 2008) (Moore et al., 2000) (Amstalden et al., 2007) (Kavgic et al., 2010)	(Galvin, 2010) (Moore et al., 2000)	(Moore et al., 2000) (Grösche and Vance, 2009) (Kavgic et al., 2010)
(Oreszczyn et al., 2006) (Branco et al., 2004) (Bøhm and Danig, 2004) (Hunt and Gidman, 1982)	(Wright, 2008) (Balaras et al., 2007) (Tommerup and Svendsen, 2006) (Miguez et al., 2006) (Pérez-Lombard et al., 2009)	(De T'Serclaes, 2007) (Bradley and Peccoud, 2008) (Jakob, 2006) (Hens et al., 2010) (Milne, 2000) (Martin and Watson, 2006)	(Banfi et al., 2008) (Sanders and Phillipson, 2006) (Sorrell et al., 2009) (Train, 1985) (Rehdanz, 2007)

Table 24: Key papers in different subsets identified by co-citation coupling.

Most overlaps occurred between the subsets 'Understanding decisions' / 'Incentive instruments' and 'Understanding decisions' / 'Models and simulation'. This is not surprising because research on modelling and incentive instruments also requires knowledge of homeowner motivations, their decision-making processes and possible barriers.

Most related papers

After listing the links between papers at the research front by thickness, it was not surprising to find that authors reuse their references. An analysis showed that 80% of the papers which share more than 5 references have at least one same author. For the top 3 most related papers, see Table 25.

Node I	weight	Node II
Clinch et al. (2001), modelling improvements in domestic energy efficiency, environmental modelling and software	16	Clinch et al. (2001), cost benefit analysis of domestic energy efficiency, energy policy
Sunnika and Galvin (2012),introducing the prebound effect: the gap between performance and actual energy consumption, building research and information	15	Galvin and Sunikka (2012), including fuel price elasticity of demand in net present value and payback time calculations of thermal retrofits: case study of German dwellings, energy and buildings
Theodoridou et al. (2011), statistical analysis of the Greek residential building stock, energy and buildings	15	Theodoridou et al. (2011), assessment of retrofitting measures and solar systems' potential in urban areas using geographical information systems: application to a Mediterranean city, renewable and sustainable energy reviews

Table 25: Top three most related papers.
Note: Bibliographic coupling, full paper set.

Through co-citation coupling we expanded our analysis to the intellectual base, identifying the key references from almost 7,000 different references – including 'grey literature' not covered by Scopus. A detailed analysis of the links between two references revealed that frequently co-cited references are mainly recurring works such as data books and surveys of different years.

C - Supplementary results (Chapter 3)

https://youtu.be/4o8qBN8FFCw

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

https://youtu.be/1GgGObhVjhY

Video 2 Diffusion of renovation behavior among lifestyles. The size of the dots represents the median of the lifestyle-specific insulation rate over a ten-year period (I10a,s). When playing the video, the average attitude (A) is varied from -0.4 to 0.4.

https://youtu.be/nwTY5KWp1JE

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

D - Supplementary data (Chapter 3)

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

Table 26: Lifetime of building elements.
[1] With more than 95% of the values within the lifetime boundaries provided by Agethen et al. (2008).

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

Table 27: Dissimilarity indices (I_{XY}) for the different lifestyles.
Note: For an explanation of the abbreviations of the nine different lifestyles, see Table 10.
Source: Provided by Otte (2008).

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

**Table 28: Values A_{XY} used to generate the social network.**
Note: For an explanation of the abbreviations of the nine different lifestyles, see Table 10.
Source: Provided by Otte (2008).

E - The empirical study (Chapter 4)

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).
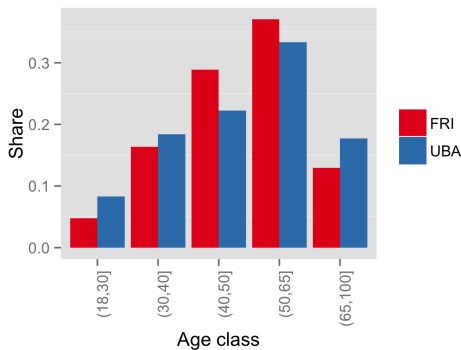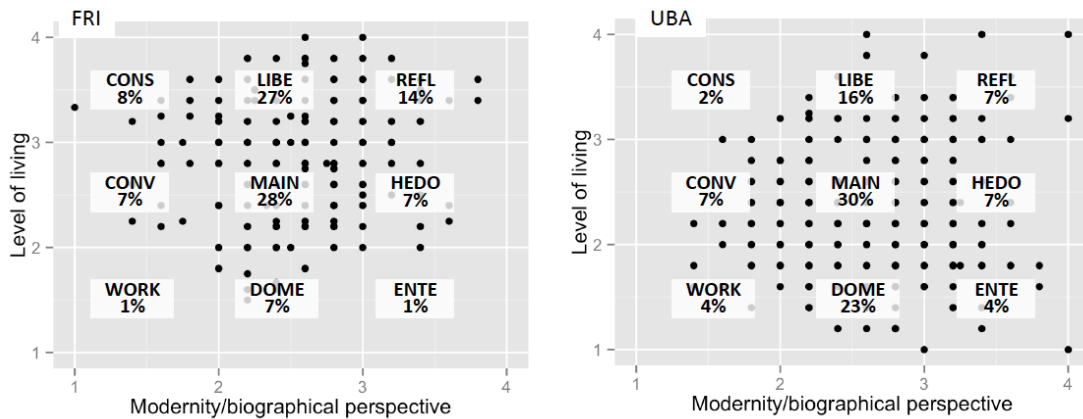

Fig. 29: Homeowners' age distribution in author's own study (FRI: n = 232) and representative study (UBA: n = 604).
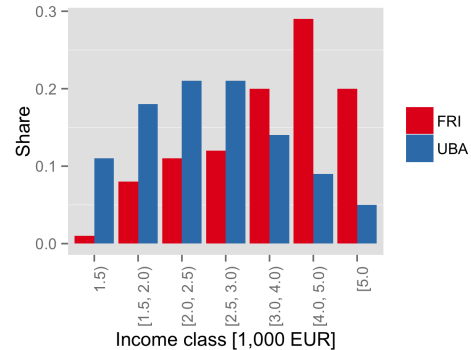
Fig. 30: Homeowners' household net income distribution in author's own study (FRI: n = 214) and representative study (UBA: n = 604).

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. 31: Lifestyle distribution in author's own study (FRI: n = 227) and representative study (UBA: n = 406)

Note: 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 Nro,ins, Nwa,ins, Nfl,ins being the numbers of houses with existing roof, wall and floor installation, and Nh 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.

$$I_{stat} = \left(55 \cdot N_{wa,ins} + 30 \cdot N_{ro,ins} + 15 \cdot N_{fl,ins}\right)/N_h \quad \text{Eq. 15}$$

Again, the data collected for the present study was compared to that of a representative study carried out by the IWU in 2009/2010.
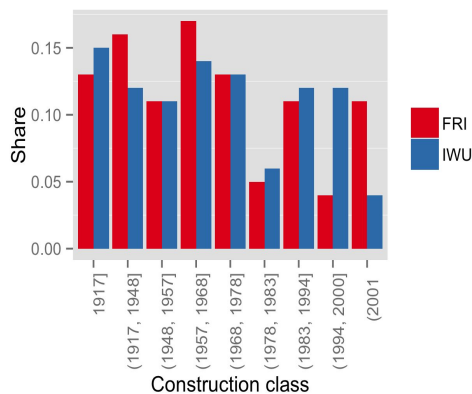
Fig. 32: Distribution of buildings by construction class according to author's own study (FRI: n = 218) and representative study (IWU: n = 4,850).
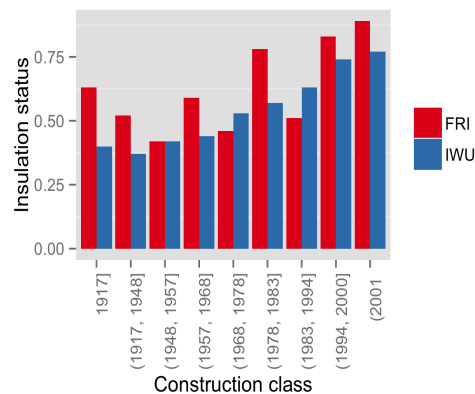
Fig. 33: Distribution of buildings' insulation by construction class according to author's own study (FRI: n = 218) and representative study (IWU: n = 4,850).

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 29: Probability of insulation combinations by construction class (n = 218).

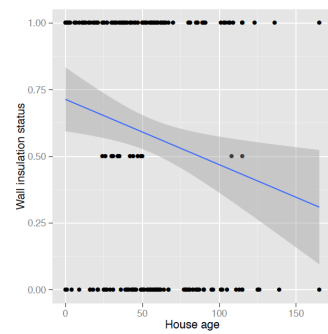Note: I_{wa} = wall insulation, I_{fl} = floor insulation, I_{ro} = roof insulation.

Statistically significant correlations
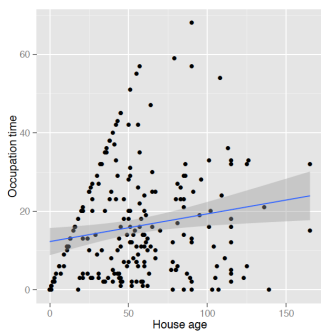
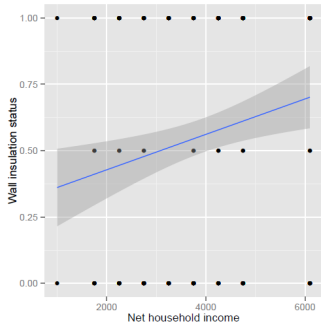**Fig. 34: Correlation between occupation time and house age.**
(r = .17, p = ≤ .01, n = 219).
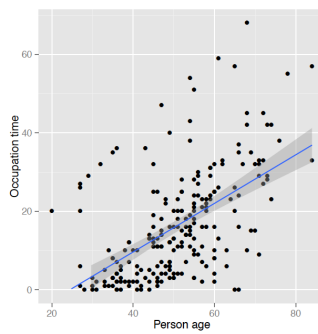
Fig. 35: Correlation between occupation time and person age.
(r = 0.55, p = ≤ .001, n = 232).
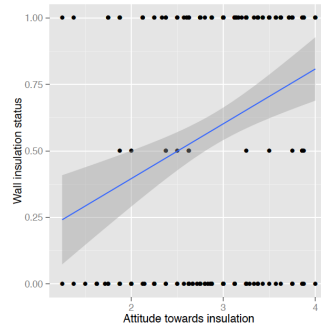
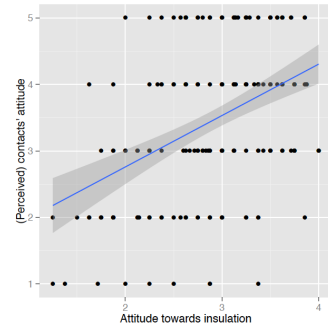**Fig. 36: Correlation between wall insulation status and house age.**
(r = -0.17, p = ≤ .01, n = 219).

Fig. 37: Correlation between wall insulation status and net household income.
(r = 0.20, p = ≤ .01, n = 214).

Fig. 38: Correlation between wall insulation status and attitude.
(r = 0.28, p = ≤ .001, n = 228).

Fig. 39: Correlation between (perceived) contacts' attitude and attitude.
(r = 0.43, p = ≤ .001, n = 198).

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.

$$p(\xi_r=1)=\frac{1}{1+\exp(1.21-0.06\cdot\gamma_{p,0}+1.12\cdot\phi_1-0.23\cdot\phi_3)} \quad \text{Eq. 16}$$

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.

$$p(\xi_f=1)=\frac{1}{1+\exp(0.41-1.7\cdot t_1)} \quad \text{Eq. 17}$$

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 F) show that they are largely insignificant.

F - ROC curves (Chapter 4)
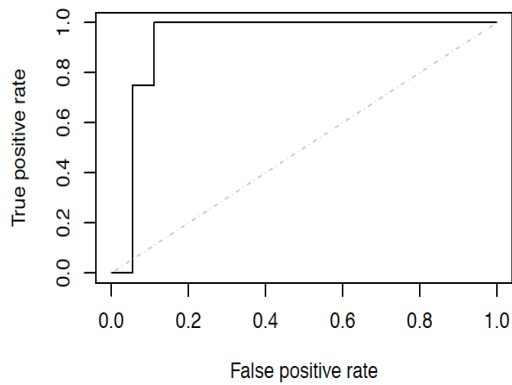
Fig. 40: ROC curve for wall insulation decision regression model I (t = 0).
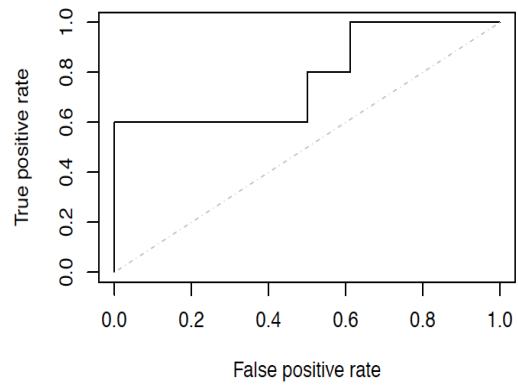
Fig. 41: ROC curve for wall insulation decision regression model II (t ≠ 0).

Fig. 42: ROC curve for floor insulation decision regression model.

Fig. 43: ROC curve for roof insulation decision regression model.

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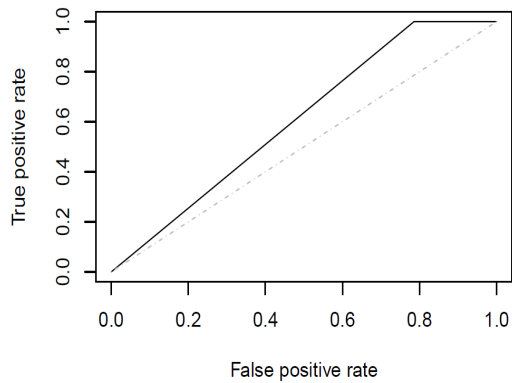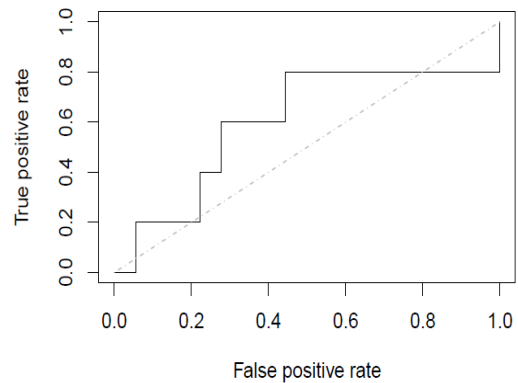
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