

# Impact assessment of inhabitants on the economic potential of energy efficient refurbishment by means of a novel socio-technical multi-agent simulation



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## Abstract

**Purpose / Context** – Studies of building design and economic feasibility for energy-efficient refurbishments often utilise average temperatures for the heated space in a dwelling. As even small deviations have a significant impact on the resulting energy demand, an occupant-centred simulation is necessary for more precise evaluations and recommendations.

**Methodology / Approach** – An Agent-based model (ABM) with only two agent types was derived. On the one hand, the technical view is included by means of a *building agent* that resembles a multi-room building. On the other hand, individual *inhabitant agents* are able to interact with the *building agent* to make sure they feel comfortable with resulting climate conditions in the rooms they occupy. To model realistic behaviour, *inhabitant agents* are negotiating about temperature setpoints and change e.g. their level of clothing if necessary.

**Results** – It is possible to derive realistic demand situations from different types of household under consideration. Both resulting temperature levels and heat demand differ significantly from one household composition to the other. The insulation level of the building has an impact on these figures which has to be analysed in detail.

**Key Findings / Implications** – In fact, the reference temperatures given in current technical standards do not reflect the behaviour of occupants. Therefore, the potential for energy demand reductions and corresponding economic feasibility have to be considered on a more individual per-household basis.

**Originality** – The proposed agent model was designed from scratch and closes the gap between technical and social view in an integrated socio-technical perspective.

**Keywords** – Space heating, thermal comfort, socio-technical interaction, multi-agent simulation, agent-based modelling



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## 1. Introduction

Despite strong political efforts, numerous countries have to cope with a rate of modernisation that remains lower than expected. One issue for (German) home owners is that a change of the building hull often results in a legal liability to renovate to a higher level of energy refurbishment. However, a certain reference temperature must be used for the assessment of economic feasibility, which completely neglects the personal heating habits and preferences. As raising the heating set point by one degree leads to an increase in energy demand of roughly six percent, this is a high leverage for the actual energy consumption, and therefore is likely to have a big impact on investment decisions. To find the correct energy demand of residential buildings, simplified estimates for the annual energy consumption can be calculated by application of the formulas provided by the established standards. e.g. (DIN V 4108-6:2003-06). However, average setpoint temperatures have to be used throughout the year. Here, the link to the actual thermal sensation is clearly missing. Therefore, this paper will focus on small groups of inhabitants in residential situations and show the extent to which an individual's preference in thermal comfort leads to shifts in temperatures and heat demand. The shift of the estimated temperature setting in residential environments is quantified for different social compositions by introducing a new multi-agent simulation (MAS) approach. A sensitivity analysis is conducted to reveal effects of both personal factors and the building hull on temperature set points and the corresponding energy demand.

Main contributions are: 1) The developed MAS is capable of simulating social interactions of human beings concerning their thermal comfort, 2) the findings are validated by common standards for space heating, 3) the interplay of building hull and occupants' thermal preferences is analysed, and 4) findings show that the possible (economical) energy demand reductions for different social compositions vary significantly. The remainder of this paper is structured accordingly: After recapitulating the basics of Thermal Comfort, the MAS is derived according to the ODD protocol in section 2. Afterwards, the assumptions and model details are validated to then analyse the extent to which types of households drive the energy demand (section 3). Eventually, conclusion and outlook are given.

## 2. Methodology

The methodology presented in this paper builds on previous work of the same authors that deals with the detailed derivation of the mathematical background of personal thermal sensation (Hinker, Pohl, & Myrzik, 2015). To facilitate the understanding of the ABM, the findings will be presented in accordance with the extended ODD protocol (Grimm et al., 2010), which guides through the description of agents by first giving an *overview*, then showing the *design concepts* used, and eventually going into *details* of the implementation (hence the name ODD).

### 2.1 Thermal Comfort evaluations in thermal building simulations

Despite the advanced and standardised application of Thermal Comfort metrics (ASHRAE 55; ISO 7730:2005), one shortcoming is that only groups of people and their average sensation can be reflected, whereas typical constellations in the residential environment consist of few people. Finding a solution to this problem was the focus of the authors' previous contribution (Hinker et al., 2015), in which a personal Thermal Comfort model was derived from the PMV model. In the personal model a person rates the surrounding climate with his or her personal Thermal Sensation Vote (TSV) on the PMV-scale. The TSV is calculated in a similar manner as the PMV, except activity level and clothing insulation are subjective to the person. Additionally, the preferred thermal sensation ( $TSV_{pref}$ ) does not necessarily have to be zero and different people may show different sensitivities to thermal changes and also allow different deviations from their  $TSV_{pref}$  before regarding a climate as intolerably uncomfortable.

Consequently, the interaction of building and inhabitant has to be modelled in an integral concept with the right balance between level of detail and simplification. This can be satisfied by a thermal 3R2C model that allows the choice of arbitrary time step increments and reflects the thermal behaviour of buildings satisfactorily. However, to be most realistic concerning the resulting average heating temperature and resulting energy demands, multiple rooms have to be simulated. To this end, the simulation of one larger shoebox model is not a good compromise as heating habits differ for different types of rooms (Kane, Firth, & Lomas, 2015). Besides, presence of occupants in a room drives the energy demand, so the likeliness of heating many or even all rooms at the same time is low. In this study, the calculation kernel of VDI 6007 (VDI 6007) was used

## 2.2 Discussion of the novel multi-agent design according to extended ODD protocol

Agent-based models (ABM) or Multi-Agent Simulations (MAS) with related applications have been developed before (Bruse, 2007; Hauser, 2013; Wu, 2007). However, the concepts were not discussed in detail and many of the necessary information were missing. In the proposed design, one inhabitant is resembled by one agent that interacts with an arbitrary number of other inhabitant agents and the building agent. As the focus was laid on socio-technical interactions, and their consequences for the heating demand, the following thoughts were used to derive the model for the inhabitant agents:

- People implicitly know about the well-being of their relatives or housemates. It can be argued that the exact level of comfort is not easy to determine while situations with high discomfort (too hot or too cold) are obvious and can be identified by all household members. Having this in mind, it is assumed in this work that the thermal comfort of other persons can be estimated with a Gaussian error that decreases with the actual level of dissatisfaction.
- ISO 7730 defines three classes of thermal comfort which can indirectly be used to derive individual thermal preferences in both desired ideal temperature and acceptable deviation. These individualised preferences are assigned to people mostly randomly. Only babies, children and elderly people have a preconfigured bias towards higher temperatures.
- Thermostatic radiator valves (TRVs) can be used continuously, so any temperature from 8°C to 28°C is thinkable for off-the-shelf TRVs in theory. However, markings/indicators on TRVs propose a way of interaction that only makes use of certain steps. This was also acknowledged by literature. Consequently, only certain temperature setpoints are used in the simulation.

### 2.2.1 Purpose (Overview)

The impact of inhabitants with their individual preferences, sensitivities and habits shall be simulated in a context where they can interact with one another and with the building so that resulting average temperature levels and the heating demand can be derived for arbitrary building configurations (that is thermal properties) in a most realistic way.

### 2.2.2 Entities, state variables and scales (Overview)

Building agent: climatic environment by (indoor) ambient temperature  $T_{1,air}$  [°C], radiant temperature  $T_{1,rad}$  [°C], air velocity  $v_{1,air}$  [m/s] and relative humidity  $rh_1$  [%]. As air velocity and air humidity are not part of the 3R2C-model of the building, these parameters must be assumed constant. However, this is no drawback as e.g. ISO 7730 states that air humidity has almost no relevance for the resulting comfort, so it can be reduced to a constant 50%. The velocity can be considered to be within the required interval below 0.2 m/s without introducing relevant errors.

Inhabitant agent: Any inhabitant agent can interact with the building in the following ways: enter or exit the building, change rooms, change TRV setpoints in the current room. If more than one agent

is present in a room, their thermal comfort can be estimated with a certain error. Inhabitant agents can estimate the effect of any interaction with either the room or other inhabitants. More precisely, the effect of e.g. increasing/lowering temperatures or changing clothes on their own Thermal Comfort can be seen directly, while the effect on other agents' Thermal Comfort can at least be estimated. Hereby, agents act social, as their objective function also dictates to avoid an impairment of anyone's Thermal Comfort. Rooms are thermally simulated but do also have a specific function for the ABM, because they can either be used as *common rooms* or *bedrooms*. While common rooms are always shared, access to bedrooms may be restricted to some inhabitants. As in ISO 7730, the unit of measurement for the insulation level of clothing is [clo]. Inhabitants can change their clothing in discrete steps of 0.25 clo within {0.25, 1.25}, as this reflects typical combinations of clothing parts (ASHRAE 55). In case there should be more than one agent present and there is a conflict concerning the Thermal Comfort a hierarchy of inhabitants  $h$  is introduced as an elegant way to resolve them. An inhabitant of lower hierarchy will not change TRV-setpoints for his/her own sake if discomfort for a higher hierarchy inhabitant is anticipated. Changes of clothing are always permitted of course. Lower hierarchy inhabitants will also try to actively improve higher hierarchy inhabitants' comfort.

### 2.2.3 Process overview and scheduling (Overview)

The full process scheduling can be seen from the following Figure 1:

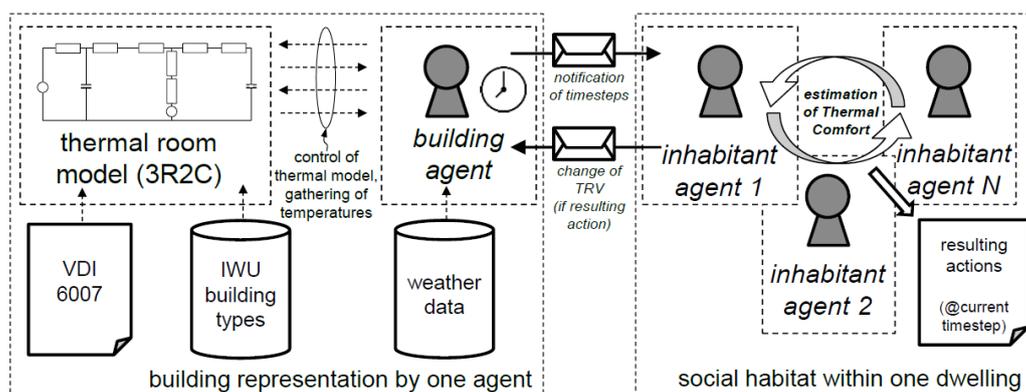


Figure 1 Involved agent types, interactions and data sources used for parametrisation

The building agent sends a message with the new time step to all inhabitant agents and waits for their messages concerning room and TRV changes. The simulation is advanced in time steps of 30 minutes, which preserves the transient behaviour of the building and enables a realistic number of adaptations and measures for the inhabitant agents. Shorter time steps (e.g. minute-wise) would lead to an unstable state where lots of measures could be conducted, which would make a penalty mechanism necessary. Each inhabitant agent undergoes a chain of behaviours to consider both their own and the Thermal Comfort of their roommates, which is structured in three different steps comprising 1) *perceive & poll*, to calculate own thermal sensation and estimate that of others, 2) *decide & negotiate*, to check which actions are possible and how they would influence others, and 3) *act & wait* to synchronise with the building agent, as discussed in (Hinker et al., 2015).

### 2.2.4 Design concepts

**Emergence:** By feeding each inhabitant agent of the simulation with (constant) thermal preferences, hierarchy levels, and a daily schedule of building occupancy, the sum of all inhabitant agents manipulates the temperature of one room at a time. Subsequently, together they form a power demand for heating that sums up in an unforeseeable manner by individual actions, so temperatures per room and the resulting energy demand are visible emergent outcomes.

**Interaction:** There are two coupling mechanisms involved. On the one hand, as the inhabitant agents know each other's Thermal Comfort (well enough) they act accordingly and proactively. On the other hand, there is a thermal interaction (heat conduction) between individual rooms.

**Stochasticity:** Hierarchy is kept constant over the course of one simulation and is assigned on a stochastic basis upon start, unless it is specifically declared. Occupancy throughout the day varies stochastically but only within pre-defined hourly time-frames. Metabolic activities vary stochastically when an inhabitant is awake.

**Observation:** the personal state of an inhabitant agent is available for clothing level, metabolic activity, and individualised thermal sensation in each time step. For all rooms in a simulated dwelling, the setpoint for the TRV and the resulting heating power are given for each time step as well.

### 2.2.5 Initialisation (Details)

The first time step of the simulation is defined to be at midnight of September 1<sup>st</sup>, which is the start of the heating period in the given climate. The simulation thus ends after 273 simulated days at midnight of May 1<sup>st</sup>. Initially, all inhabitants are situated in their corresponding bedrooms and in a sleeping state (not actively influencing their environment). Also, TRVs in all rooms are set to three, which equals a setpoint of 20°C. As the capacities utilised in the 3R2C-model are not precharged for the simulation, the impact of weather and new setpoints is effectively reduced for the very first time steps.

## 3. Validation and results

After the depiction of an exemplary day's simulation outcome, the validation of the model by comparison with calculations from a standard is conducted. Afterwards, the specific meaning of the social compositions in the context of further simulations are discussed from two different socio-technical perspectives, which is an occupancy centered life-cycle assessment for buildings and the meaning of energy-related refurbishments.

### 3.1 Interaction of inhabitants and building

To show the general functionality of the MAS, the course of a regular winter day of one inhabitant agent is discussed (cf. Figure 2).

The agent wakes up in room 1 at time step 18 (9:00am) and immediately rates the surrounding climate as too cold. It estimates the effect of possible actions it could take to counter this and determines that its level of clothing of 0.25 clo is inadequate for the current temperature. Thus, it puts on more clothes, resulting in a clothing level of 1.25. 30 minutes later it still feels too cold. As its clothing level is already at the maximum, the only other option is an increase in TRV-setpoints. It increases the TRV-setpoint to 3.5, resulting in a room temperature of roughly 23°C, which the agent considers comfortable. For the next 10 time steps no changes are necessary. Then, the agent enters room 3. Luckily, his room mate (not shown) already reduced the TRV-setpoint in this room from 5 to 2.5 one hour earlier so room 3 is at a comfortable temperature level now. After another time step the agent leaves the building and returns in time step 40, entering room 2. After three time steps in this room, it feels uncomfortably hot, since its activity level increased from 1.07 met to 1.67 met. The agent therefore decreases the TRV-setpoint in this room to 2, resulting in a room temperature of comfortable 22.9°C. After this, the agent changes rooms two more times, without breaching its comfort zone and eventually goes to sleep in room 1 at time step 46 (11:30pm).

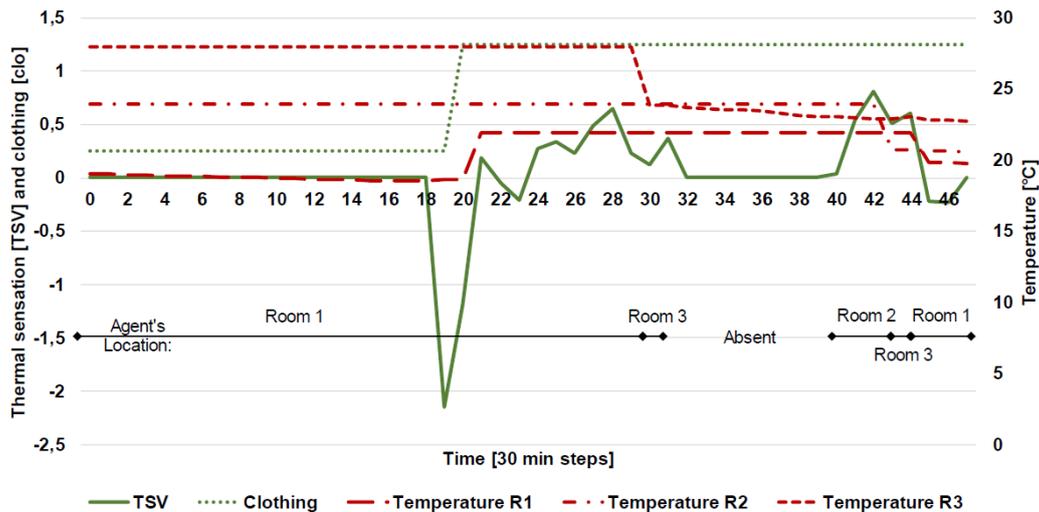


Figure 2 Interactions of one inhabitant agent with the individual rooms of a building

### 3.2 Validation

External input first of all includes weather data which includes short- and longwave radiation, and ambient temperatures in the desired timely resolution. For the evaluations in this paper *Test Reference Year* (TRY) data for Essen, Germany is used in 30-Minute-resolution. Besides, the building model with its thermal properties has to be defined. Normally, the strongest influence has to be expected from the thermal conductivities of walls and windows, so they have to be chosen with care. For cold climates, realistic infiltration rates have to be set as well, because even if the windows are assumed to be closed, air exchange through gaps (so called gap ventilation) is always present in reality. Here, thermal conductivities of type-E and type-H buildings from German IWU typology (Institut Wohnen und Umwelt GmbH) are used in the context of both single family and multi-family houses. The ventilation rate is assumed to be at a constant rate of 0.6/h.

The validation of the behaviour of specific inhabitant agents is generally difficult as it would make extensive measured data in hundreds of dwellings necessary. However, it is possible to examine the emergent behaviour of the entire simulation with regards to plausibility and compare it to different (field) studies. The following validation is based on findings from (VDI 4655) and exemplary for the other validation examples which are not shown here. The input data for the evaluation is set up to be similar to the field studies the results are being compared to. While conductable for any building, all of the studies' samples make use of typical thermal conductivity values for both single family houses (SFH) as well as multi-family houses (MFH) are used from the TABULA study (Institut Wohnen und Umwelt GmbH). The amount of inhabitants per dwelling ranges from one through five and five different types of inhabitants are simulated: working, non-working, retired, child and baby. The daily schedule of each inhabitant type, i.e. time spent working, at home, leisure and sleeping, is set up in accordance to (Statistisches Bundesamt, 2015). The amount of inhabitants per dwelling and inhabitant compositions resemble the German average (Statistisches Bundesamt, 2013) as this is assumed to be similar to the field study household types. The occupants' thermal preferences vary. According factors are assigned to the occupants with a Gaussian distribution but with a small bias for retirees, children and babies towards higher TSV-preferences in comparison to working or non-working occupants (Kelly et al., 2013). The hierarchy levels are randomly distributed among inhabitants, except for babies, who always receive the highest hierarchy level of 0 (a maximum of one baby per household is allowed). For each household a typical heating period from September through May is simulated as only temperatures and heat loads in this period are of interest.

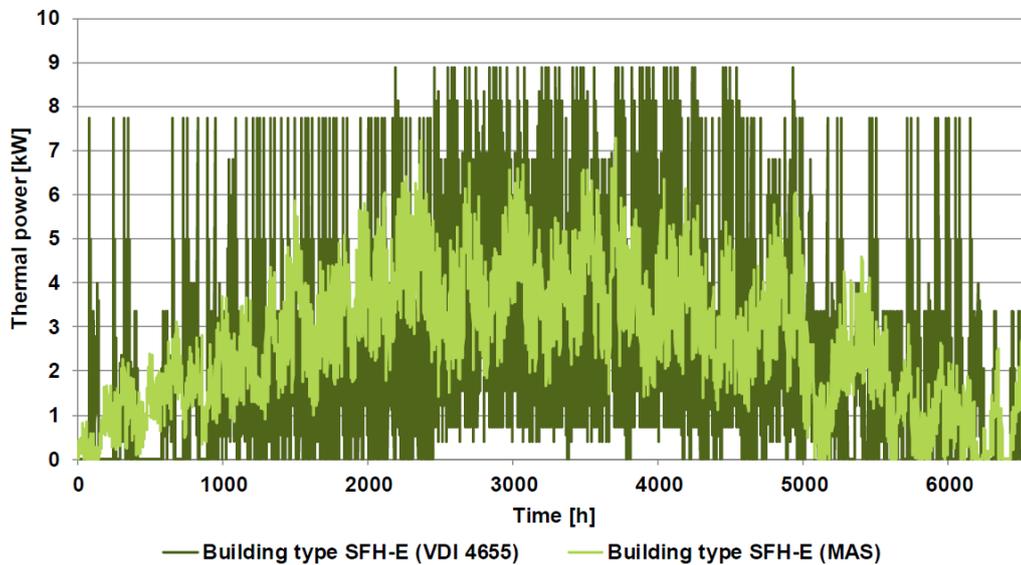


Figure 3 Comparison of the simulation reference and resulting heat demand from MAS

To validate that heating power is consumed in a realistic manner and that different energetic standards of buildings result in different energy consumptions, the average simulated heating power of each building type is compared to the building type's heating load calculation according to (VDI 4655), which is used as a reference. While the heating load of single realisations may of course differ from the standard calculation due to the occupants' individual behaviour, the average heating consumption across all simulations of one building type should be similar to the aforementioned reference calculation. This comparison is depicted for building type SFH-E in Figure 3. Depending on the simulated building type, average deviations are within a range of  $\pm 20\%$ . However, up to  $\pm 30\%$  are explainable if the occupants' behaviour is accounted for (Sunikka-Blank & Galvin, 2012).

Besides, the underlying stochastic distributions for (VDI 4655) calculations are based on a low sample size, which is another factor to be considered.

### 3.3 Interaction of building hull, situation of family, and occupant behaviour

With the socio-technical focus of this work in mind, the preferences of social compositions shall be evaluated, so the interplay of individual inhabitants becomes clear and explanations for deviations of the heating demand of individual household can be derived. As stated above, occupancy, bias towards higher/lower preferred temperatures, and a sensitivity can be modelled for individuals, who then form the household composition within one dwelling. Four such exemplary compositions were defined as follows: A "typical" family undergoes a stereotypical development in the following four stages: A newly founded family including a newborn makes it necessary that one parent stays at home (I). The stay-at-home parent is able to go to work again after the child has grown old enough (II). The child is old enough to serve his/her apprenticeship and is employed afterwards, which means that the occupancy is comparable to the full-time working parents (III). The child stays with the retired parents (IV). The number of family members is thus kept constant throughout the simulation.

For the evaluation N=40 simulations were conducted for each of the four compositions. As the output is stochastic by design (cf. section 2.2.4), box-whisker-plots are used to show characteristics of the resulting temperatures and heat demands. The following Figure 4 shows the average temperatures in the simulated SFH-H building:

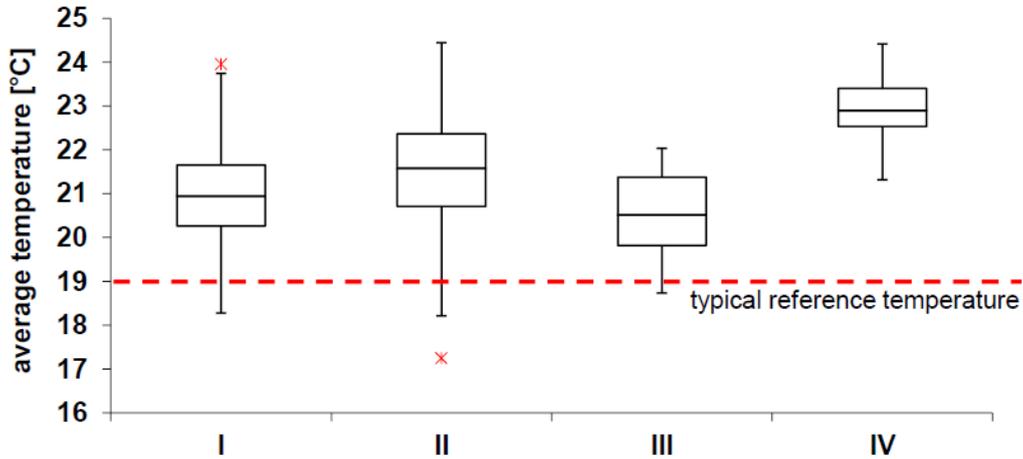


Figure 4 Box-plots for average temperatures of the four social compositions (building type H)

The resulting temperatures are rather high in comparison with the reference temperature. First of all, there is a big variety of possible temperature levels, and it is even possible that households achieve to stay below the reference temperature with their average temperature, so it might be more appropriate to change assumed temperatures for economic considerations depending on real occupancy and preferences. Secondly, since occupants do not use window blinds and ventilation, the results are skewed towards higher temperatures due to high levels of insolation at the beginning and end of the heating period, so there is room for improvement.

In order to see if there is an interaction between building hull and occupants, all simulations were repeated another 40 times with a second building type (type E instead of H, cf. Figure 5). Heating demand and assumed financial potential of a family in each stage are analysed now to show the discrepancy between the need and the financial possibility for refurbishment.

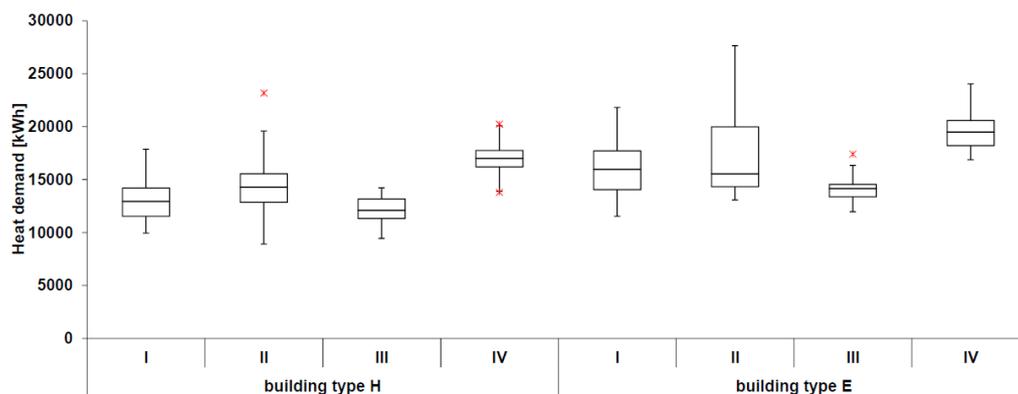


Figure 5 Box-plots for heat demand of different household compositions and buildings

The heating demand clearly differs from stage to stage: First, in stage (I), the heating demand is relatively low and so is the financial potential of the household since only one inhabitant is employed and they also have to take care of a newborn. In stage (II) the heating demand is more unpredictable, since both parents spend a lot of time at work causing the heating demand to strongly depend on how the child uses the heating system. The overall household income is now higher than before since two people are working. In stage (III) the heating demand reaches its minimum, since all three inhabitants spend most of their daily time at work. At the same time, the financial potential of the household is at its peak, due to the triple income of the inhabitants. In stage (IV), the heating demand suddenly increases because the parents spend a lot of time at home and have increased thermal preferences, while the child still spends most of its time at work. But at this point, the income of the household is much lower than before since there is only one income source present. This course of events shows a possible explanation for the low modernisation rate today. The perceived need for a modernisation (i.e. the heating demand) is at imbalance with a household's financial potential for undergoing such a modernisation. At the stage of its highest overall income, a family has the lowest heating demand and therefore may not want to pay for such an investment. However, in the next stage of their lives, the heating demand sharply rises, but now the family might not have the financial potential to modernise their home anymore. Figure 5 also includes two different building types with significantly different thermal insulation properties, which allows to qualitatively assess the financial impact of an energy efficient refurbishment.

#### 4. Conclusion and outlook

In this paper, a novel simulation environment was developed, which enables the evaluation of interactions between inhabitants themselves and the buildings occupied by them. This contribution builds on a mathematical description of the reasoning processes of individuals which was derived in previous work. The modelling of the necessary thermal simulation as a multi-room equivalent circuit model was argued in the socio-technical context, and a full description of important pillars of the developed MAS was explained in accordance with the extended ODD protocol. Furthermore, the general applicability of this approach was proven by a comparison of different studies with stochastic outcomes of the developed simulation. While smaller deviations from reference values remain, the results are promising and show that modelling from a bottom-up perspective helps to find realistic ranges of temperatures and heat demand. The results also show that there is a big influence of the individual preference for temperature levels. While one person alone could just change a setpoint at will, a group of people works in a different way and leads to different results as they have to cope with the needs of others. By explicitly simulating household compositions in their timely occurrence, the economic potential of refurbishment in cold climates becomes especially clear. Ongoing work deals with the reproduction of power peaks as they appear in reality. To this end, a more complex model of the heating system has to be implemented and calibrated. Besides, more light shall be shed on the the economic potential and reasoning process to show policy makers to what extent they can steer and support the advancement of the building stock to reduce carbon emissions.

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