Adaptive Envelopes for Better Energy Efficiency and Enhanced Indoor Thermal Comfort

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Abstract. The increased use of renewable energy in the built environment is a key objective for sustainable development. While being a key priority for the future of energy use, renewable power generation is affected by local resource fluctuations, such as the amount of incoming solar radiation. Energy storage and increased energy efficiency will continue to gain importance in this context.

In cold and moderate climates, heating has traditionally accounted for the predominant part of energy use in buildings. In many parts of the world, heating remains fossil-fuel based to a significant extent. Due to a number of issues, including climate change, the proportion of heating energy has been steadily decreasing, while cooling loads have been on the rise. The use of electricity for heating and cooling has been increasing, partly related to an increased use of different types of heat pump technologies. Growing electricity use for cooling is increasingly seen in highly-insulated, low-infiltration, high energy-performance buildings, but also in other parts of the building stock.

High levels of insulation efficiently decrease heat losses during the heating season, but they also impair the removal of excess heat. This study explores how adaptive envelopes can be used to optimize the use of solar radiation during the heating season and enhance the removal of excess heat during the warm part of the year, depending on parameters including outdoor and indoor temperatures and the desired levels of thermal comfort. The IDA-ICE energy and indoor-climate simulation tool is used for exploring different adaptive envelope scenarios. It allows the calculation of heat flows through the walls, currently however without considering the impact of radiation on external walls. To compensate for this, a new approach is presented to simulating heat flows through different types of adaptive envelopes and wall constructions. This allows for a more detailed understanding of how adaptive envelopes allow incoming solar radiation in summer to be stored before it is transmitted to the main wall structure. Conversely, a more detailed analysis becomes possible of how accumulated heat can be released during the night by removing insulating layers of the wall, thus cooling the indoor environment.

Keywords. Adaptive building envelope, Building energy simulation
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1. Introduction

The (European) building sector uses 43 % of the European primary energy, out of which 66 % for space heating [1]. At 70%, the energy use for space heating in Germany is slightly higher [2]. To reach the goals of the European Climate Law to achieve net-zero greenhouse gas emissions (GHG) in the EU by 2050 [3], it is necessary to substantially reduce the energy use in building sector.

National frameworks such as the German Gebäude-Energien-Gesetz (GEG) and international frameworks such as the Energy Performance of Buildings Directive (EPBD) define criteria for the primary energy requirement of buildings and the permissible heat transmission through building envelopes for residential and non-residential buildings [4].

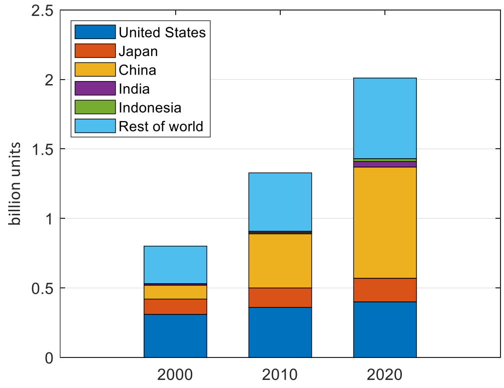

Figure 1 – Increase in the use of air conditioning units during 2000-2020 [5].

Adding to the challenge of efficient energy use, the cooling demand in buildings has been on the rise over the past two decades. This has been reflected by a commensurate increase in the number of air conditioning unit installed [5]. Figure 1 illustrates the world-wide growth in the use of air conditioning units.

The heating energy savings achieved in recent years in many parts of the world are being overshadowed by the an increasing use of cooling energy.

Parallel to stringent limitations on the amounts of energy used, strict requirements are setting the stage for an increased use of clean and renewable energies, as well as a rapid decrease and, eventually, avoidance of GHG emissions. Germany has decreed to no longer use nuclear power [6], emphasizing the need for an accelerated development and deployment of renewable energy technologies.

This study analyses the possibilities of managing variable heat loads in a residential building in Stuttgart by using adaptive building envelopes. The energy simulations were carried out with the IDA ICE software.

2. State of the art

2.1 Key previous research

A number of studies of adaptive building envelopes have been conducted [7], documenting different approaches to achieving variable thermal resistance to building envelopes.

Two main approaches can be distinguished, as shown in Figure 2, Switchable Insulation Systems (SIS) and Dynamic Insulation Materials (DIM) [8]. The difference between the two methods is that in SIS-systems, insulation may be used or removed to modify thermal resistance. The insulation layer can be made of one material or may be formed by air-gaps separated by thin materials. DIM-systems consist of a mixture of different materials, allowing them to dynamically adjust their insulating properties. Variable heat transfer resistance is used to manage heat flow, based on outdoor conditions and conditions in a room, a zone, or an entire building.

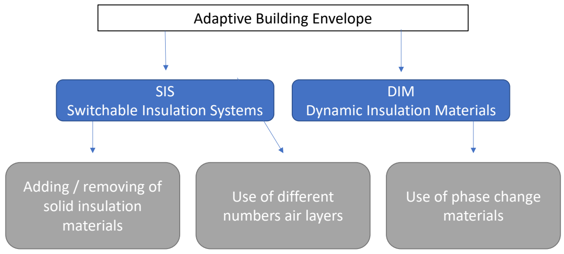

Figure 2 – Overview of adaptive building envelope systems.

That leads to the advantage of reducing heat loss in the cold season and the combination reducing heat input or provide heat loss to the outside in the warm season.

One example where SIS were simulated shown in [9]. Initially using a zone of a non-residential building, with an uninsulated and insulated building envelope, simulated with IDA-ICE. With Matlab the results were combined and differentiated according to various variables. Dependeing on the conditions in the zone, the building envelope was adapted. A reduction of the total energy demand up to 15 % was determined compared to the use of insulation throughout. In [10] switchable insulation was applied using several film layers. By using d different number of layers, the thermal resistance value is changed. The results show a reduction of 29 % of the total energy demand for heating and cooling.

In [11] a SIS was applied to a zone in a residential building. By removing and adding insulation layers, two different thermal resistance values were achieved for the wall. The study was carried out as a simulation for case studies in Sweden and Germany, with the overall result that the total energy demand could be deceased compared to using static insulated building envelopes.

2.2 Physical background

A detailed investigation of the transmission heat losses from buildings requires an analysis of the heat transfer through the individual layers of the building envelope, including conduction, radiation and convection. In buildings, heat transfer typically occurs through air change (mechanical or natural ventilation) and heat transmission through the building envelope. In the simulation described here, the heat transfer through air change is assumed to be constant. The heat conduction is described locally by the heat flux density $\dot{q}$, which depends on the temperature (T) gradient:

$$\dot{q} = -\lambda \, grad \, T \qquad (1.1)$$

Here, λ represents the local value of the thermal conductivity. Assuming constant thermal conductivity λ_l and a constant temperature gradient for a temperature difference ΔT, the heat flow along the x-direction perpendicular through a wall (or a layer of thickness Δx for the one-dimensional case), can be expressed as:

$$\dot{q}_l = -\lambda_l \frac{\Delta T}{\Delta x} \qquad (1.2)$$

Multiplying equation (1.2) by the area A, leads to (Fourier's law):

$$\dot{Q}_l = -\lambda_l A \frac{\Delta T}{\Delta x} \qquad (1.3)$$

where $\dot{Q}_l$ is the the heat [W] transmitted through a solid wall or layer with thickness Δx, across which a temperature difference ΔT exists for the period of time under consideration. The thermal conductivity and temperature gradient are considered to be constant over time and across the wall or layer thickness [12].

The convective heat transfer (Figure 3) from a wall or a solid layer to a convective layer is also described by a heat flux density $\dot{q}_{l,n}$. It depends on the difference ΔT_n between the temperature of the solid surface $T_{s,n}$ and the temperature of the fluid T_n as well as on the heat transfer coefficient. Equation (1.4) describes the relationship:

$$\dot{q}_{l,n} = -\alpha \left(T_{s,n} - T_n\right) = -\alpha \, \Delta T \qquad (1.4)$$

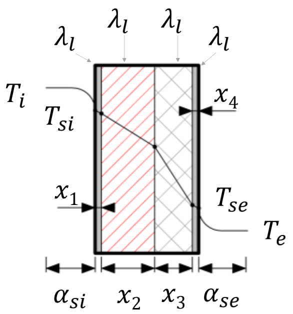

Figure 3 – Schematic representation of the temperature profile in a wall from the inside to the outside through different material layers. The layers of convective heat transfer are represented by their heat transfer coefficients $\boldsymbol{\alpha_{si}}$ and $\boldsymbol{\alpha_{se}}$, respectively.

If one looks again at an area A of the wall or a solid layer, then multiplying equation (1.4) by A results in a relationship (1.5) between the transferred power per unit area A from wall or solid layer to the fluid, non-stationary medium:

$$\dot{Q}_{l,n} = -\alpha A \left(T_{s,n} - T_n\right) = -\alpha A \Delta T_n \qquad (1.5)$$

The direction of the fluid flow must be taken into account for the heat transfer coefficient. For this reason, a distinction is made for the building envelope between the heat transfer coefficient α_{si} for inside and α_{se} for outside. In the case $T_i > T_e$, there is a falling fluid flow on the inside, while an ascending fluid flow is present on the outside. In the case $T_i < T_e$ there is an ascending fluid flow in the zone (inside) and a falling fluid flow on the outside [12]. For this reason, a fixed value, e.g. according to DIN 4108-2, can be used for stationary calculations. The current convective heat transfer value is continuously calculated for simulations. The entire heat flow through the wall is ultimately made up of several heat flows as per above. The temperature for the individual wall layers is unknown. These can be eliminated. By repositioning a heat transfer coefficient k for example for a complex overall strucutre according to equation (1.6) can be derived [13, 14].

$$k = \frac{1}{\alpha_{si} + \sum_{j=1}^{N} \frac{\Delta x_j}{\lambda_j} + \alpha_{se}} \qquad (1.6)$$

The wall structure consists of N directly connected solid layers and is covered with a fluid layer (air) on the outside and inside. When using IDA ICE, the wall layer thicknesses Δx_j are used in the simulation as fixed parameters. They cannot be changed during the simulation. Changing the heat transfer coefficient to the value 0 is not possible and leads to a numerical error. For this reason, in the version of IDA ICE used, the heat transfer coefficient cannot be changed during the simulation which poses a shortcoming.

3. Modelling Approach

3.1 Model properties

For the research, a zone model of a residential building is used. The construction period of the building is between 1950 and 1960. For this period, a typical thermal resistance value for the building envelope is $k = 1.4\, W/m^2K$ [15]. A typical thermal resistance value for windows with double glazing is assumed as $k = 2.7\, W/m^2K$. As a part of an energy renovation, the use of insulation results in a lower thermal resistance value of $k = 0.20\, W/m^2K$. Furthermore, the windows are replaced with better windows with a thermal resistance value of $k = 1.3\, W/m^2K$. The new values of the building envelope and the window meet the requirements of the Building Energy Act [3]. Additionally, for the window an external blind is used after the energy renovation. A summary of the details of the building envelope and the window are shown in Table 1.

Table 1 – Summary details of the IDA ICE Zone model.

Name	Value	Unit
Wall surface	14.5	m^2
Window surface	2.50	m^2
Wall k-Value	0.20	W/m^2K
Window k-Value	1.30	W/m^2K

The schedule for heating and cooling setpoints is set to reflect conditions in a residential building (Table 2). During the daytime a lower setpoint is used. From the evening to morning and for the weekend, a higher setpoint is used. Occupancy (two persons) is scheduled as shown in Table 3. On weekends, the occupants are assumed to be present all day. The air exchange rate is assumed as 0.4 h-1, a ventilation system is not used. No schedule is considered for window opening.

Table 2 – Daily schedule details of the IDA ICE zone model for heating and cooling.

	Value	Unit
Heating setpoint:		
06:00 a.m. – 06:00 p.m.	18	°C
06:00 p.m. – 06:00 a.m.	21	°C
Cooling setpoint:		
06:00 a.m. – 06:00 p.m.	27	°C
06:00 p.m. – 06:00 a.m.	25	°C

For the annual simulation in IDA-ICE, internal loads are considered, as shown in Table 3 and Table 4. The tables account for occupants (internal loads 1) and other devices (internal loads 2).

Table 3 – Internal loads (1) of the IDA ICE zone model.

	Value
Zone occupancy	(Monday – Friday)
Person 1 (75W)	00:00 a.m. – 07:00 a.m
	03:00 p.m. – 12:00 a.m.
Person 2 (75W)	00:00 a.m. – 07:00 a.m.
	05:00 p.m. – 12:00 a.m.
	(Saturday – Sunday)
Both persons	00:00 a.m. – 12:00 a.m.

Table 4 shows the operating schedules for lighting and other equipment.

Table 4 - Internal loads (2) of the IDA ICE zone model.

	Value
Zone lighting	(mon. – sun.) 50 W
	06:00 a.m. – 08:00 a.m.
	15:00 p.m. – 23:00 p.m.
Zone equipment	(mon. – fri.) 150 W
	06:00 a.m. – 08:00 a.m.
	15:00 p.m. – 23:00 p.m.
	(sat. – sun.) 150 W
	08:00 a.m. – 11:00 a.m.
	14:00 p.m. – 23:00 p.m.

3.2 Control strategy

In this simulation study, the control strategy is based on the temperatures shown in Figure 4. These include the air temperature in the zone T_i, the surface temperature of the external wall T_{se}, as well as the outdoor air temperature of the air otuside T_e. Whetever an insulated wall is used depends on different boundary conditions, see below. Is any of the two conditions described below TRUE, the temperature T_{se} is transferred to position T'_{se} (Figure 4). Is none of the conditions TRUE, no temperature transfer is applied. In that case, a temperature between $T_{l,2}$ and $T_{l,3}$ will occur at position T'_{se}.

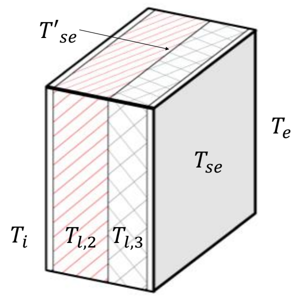

Figure 4 – Schematic representation of the wall structure showing the temperatures on which the control strategy is based.

If air exchange and lighting are neglected, the following control strategy conditions can be set for heating/cooling:

$$con_1 = \begin{Bmatrix} 1;\ T_e \leq 15, T_{se} \geq 22 \\ 0;\ T_i > 22 \end{Bmatrix}$$

$$con_2 = \begin{Bmatrix} 1; T_{se} \leq 24, T_i > 24 \\ 0;\ T_i < 20 \end{Bmatrix}$$

Condition 1 (con_1) leads to heating. The outside temperature will be set to T_e 15 °C. If the outside temperature is lower than the setpoint, the heating of the zone is allowed. In Germany, 15 °C is often used as heating limit temperature. If the outside surface temperature $T_{s,e}$ is higher than 22°C, a heat flow into the zone will occur. In order to prevent overheating of the zone, at an inside temperature $T_{i\ a}$ above 22 °C the condition 1 goes to FALSE and heating is stopped.

Condition 2 (con_2) leads to cooling. If the indoor temperature T_i is greater than 24 °C and at the same time the wall surface temperature T_{se} less than 24 °C, a heat flow from the zone to the outside will occur. If either or both conditions (con_1) or (con_2) are TRUE, an enhanced insulation of the building envelope is not necessary. Through an extension in IDA-ICE, the insulation command will be bypassed. If none of the conditions is TRUE, the control stops functioning, the and the heat flow is allowed to pass through the temperature control layer.

3.3 Model validation

A multiple-step simulation model was developed using a temperature layer where the temperature T'_{se} is controlled, see Figure 4. The individual steps are shown in Figure 5. In the first step a standard model (level 0) was built in IDA-ICE. In the second step (level 1) the model was converted into an advanced level model, were the individual modulescould be changed. Thus, the temperature layer consists of a space heating element, becoming separate from the heating and cooling supply elements. At the second level, the temperature calculation is developed for the case "without control", followed by a temperature calculation "with control" at the third level. At the last level, level 4, the control is actively used throughout the simulation.

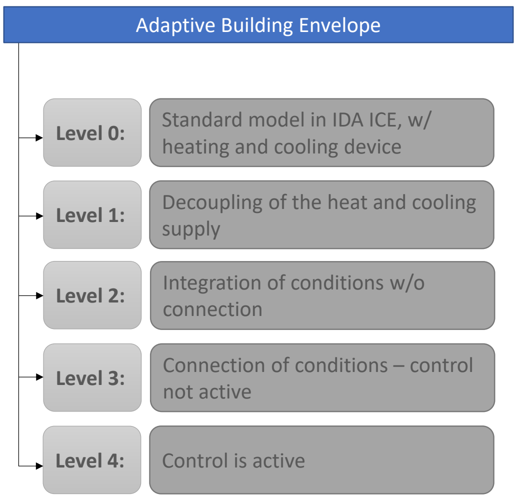

Figure 5 – Overview of the model development.

After completing every individual level, a test simulation was performed. The results of each test simulation, shown in Table 5, were evaluated for plausibility. The calculated energy demands are shown in Table 5 indicating fluctuations between the different simulation levels. Between level 0 and level 1, changes in the hydraulic system were made, and slight variations in the calculated values are understandable. Differences in water volumes can lead to additional result variations.

Table 5 – Energy demand of IDA ICE zone model for different extension levels.

Extension Level	Heating [kWh]	Cooling [kWh]
Level 0	54	520
Level 1	58	510
Level 2	54	521
Level 3	60	484
Level 4	64	91

Between level 1 and level 2 only calculations were inserted, the resulting variations are difficult to explain. The same results as in level 1 would be expected. Since the deviation is less than 10 % (for heating 7 %, for cooling 2 %), the model will continue to be used further.

Between level 2 und level 3, the comparison and calculation algorithm are linked to the model. The differences in calculated energy demand can be attributed in part to transitional phases when the condition of the control system changed. These transitional phases are shown in Figure 6.

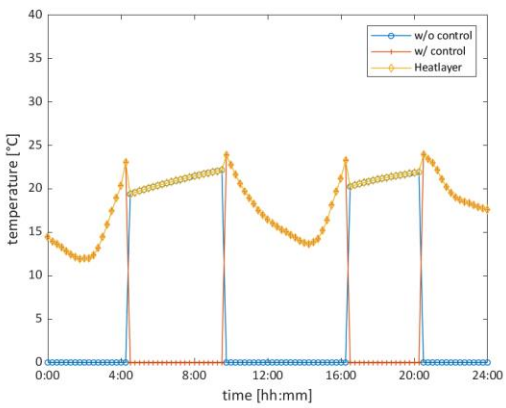

Figure 6 – Heat layer temperature (yellow), for the simulation cases with (red) and without (blue) control.

Figure 6 illustrates the temperature variation of the temperature layer T'_{se} as affected by control. Control was either active (w/ control) or not active (w/o control). The model was designed such that transition phases occurred during the simulation when the control mode was switched between the mode (w/ control) and the mode (w/o control). The change between the control modes was implemented through a dedicated additional algorithm which generated the output signal. As shown in Figure 6, the transition phases were completed within 30 min. The output interval for the simulation was therefore set to 30 min.

4. Results

4.1 Building energy demand

Figure 7 shows the simulated annual building heating and cooling energy demand. It shows a typical energy use for a building with an optimized building envelope for a low heating energy requirement. Due to the insulation, there is a short period in which the building needs to be heated (dec-feb) and another short period in the transition period in which there is only slight heating or cooling demand (mar, oct-nov). During the rest of the year there is a need for cooling (apr-sep). According to Table 6, the modelled zone has a heating energy demand of 60 kWh and a cooling energy demand of 484 kWh.

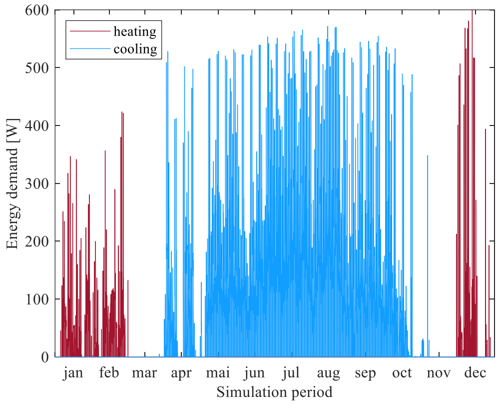

Figure 7 – Annual energy demand for heating and cooling without adaptive building envelope.

Table 6 – Overview of annual energy demand for heating and cooling with and without adaptive building envelope (abe). Cooling energy demand assuming COP=3.0.

	Heating [kWh]	Cooling [kWh]	Cooling^{COP} [kWh]
w/ abe	64.4	91.0	30.3
w/o abe	60.0	484.0	161.0

Figure 8 shows the annual heating and cooling energy demand building energy demand with active use of the adaptive building envelope. No significant change in the heating energy demand was found compared with when no ABE is used. According to Table 6, the heating energy demand without ABE increased by only 7 %, from 60 kWh to 64.4 kWh. However, a significant reduction in cooling energy demand for cooling could be observed when ABE is used. The period in which the zone needs to be cooled could be reduced by around 3 months. According to Table 6, the cooling energy demand with ABE decreased by 81 %, from 484 kWh to 91 kWh.

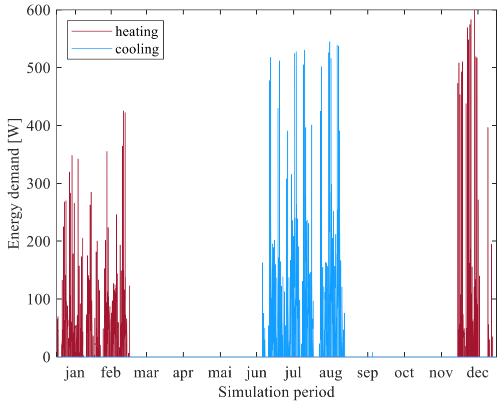

Figure 8 – Annual Energy Demand for Heating and cooling with adaptive building envelope (ABE).

For the total energy demand for heating and cooling of the modelled zone, the result shows a reduction from 544 kWh to 155.4 kWh with ABE, corresponding to 71 %.

4.2 Frequency of application of the adaptive building envelope

Figure 9 shows the frequency of condition (con_1) and condition (con_2), see section 3. The logging of the Simulation results were logged in 30-min intervals resulting in a total of $1.752\ x\ 10^4$ values on which the data in Figure 9 are based. Data are presented separately for the time intervals 7:00 a.m. to 7:00 p.m. and 7:00 p.m. to 7:00 a.m.

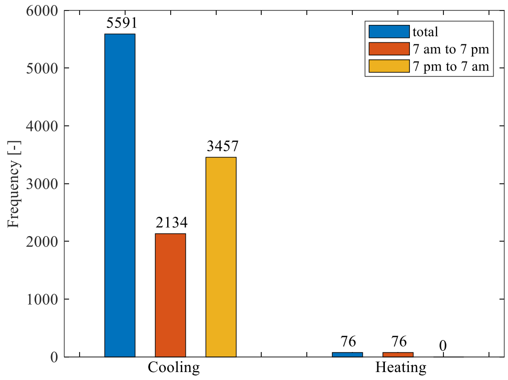

Figure 9 – Annual frequency of adaptive building envelope use, during the day (orange), the night (yellow) and overall (blue).

It is remarkable that the adaptive building envelope for heating only needs to be used for 36 hours per year. The time range is only during the day, which is plausible because only during the day there is the possibility of increasing the surface temperature of the building envelope through solar radiation.

In the cooling mode, the control of the adaptive building envelope is active for 2796 hours. At 61.8 % of total time, the ABE is mainly used during the night. Thus, the key goal of cooling the building through night cooling, is achieved. In addition, the natural cooling of the building can be used during 1067 daytime hours.

4.3 Indoor thermal comfort

The thermal comfort is determined for time intervals when occupants are present in the zone. The duration (number of hours) of occupant dissatisfaction is shown for the simulation time of 8760 hours. The change is examined using three simulation scenarios.

- (1) Zone without cooling,
- (2) Zone with cooling, without adaptive building envelope,
- (3) Zone with cooling and with adaptive building envelope.

Table 7 shows the results of the three simulation scenarios. Scenario 1 shows the longest duration of occupant dissatisfaction due to the high temperatures in the zone.

Table 7 – Comparison of hours of occupant dissatisfaction depending on the scenario used.

Scenario	Heating [kWh]	Cooling [kWh]	Hours of dis-satisfaction [h]
(1)	51.0	0	6735
(2)	60.0	484.0	1129
(3)	64.4	91.0	871

In scenario 2, the number of hours of dissatisfaction can be reduced by 83 % by using the cooling device, but an additional cooling demand of the zone of 484.0 kWh is required. In scenario 3, the number of hours of dissatisfied occupants is reduced by a further 4 % compared to scenario 2, with a reduction of cooling enegery demang by 81%. A positive effect of ABE use was thus also obtained on simulated perceived thermal comfort.

5. Conclusions

In this study, the application of an adaptive building envelope as a switchable insulation system (SIS) was investigated by simulating a zone in Stuttgart with IDA-ICE software. For the simulation, an outer wall of an existing residential building, from the construction period between 1950-1960, underwent an energy refurbishment in order to implement current national requirements as defined in German Gebäude-Energie-Gesetz (GEG).

The effects of the adaptive building envelope were analysed for two alternatives: the building envelope is either considered to be uninsulated, having an overall wall k-value of 1.40 W/m²K, or insulated with a k-value of 0.20 W/m²K. This switch cannot be achieved with the current BDF-wall model in IDA-ICE. A temperature change was therefore assumed between the outer surface of the outer wall and the surface between the insulation and the load-bearing masonry. Thus, the insulation's influence on simulated heat flow can be bypassed. The simulation results showed a reduction in cooling energy demand of 81 % by applying ABE. The heating energy demand was found to increase by approximately 7 %. The calculated increase in annual heating energy (7 %) is caused by computational aspects of the control strategy simulation, where a temperature spread in the order of +0.25 K to -0.25 K needed to be introduced to avoid numerical errors.

Overall, ABE use reduced the energy demand for heating and cooling of the zone by 71 % compared to using static insulation. This indicates the significant potential of using ABE toward achieving substantial energy savings in the building sector.

In energy-refurbished buildings there remains a risk of zone overheating. Cooling devices can, of course, be used to prevent overheating and reduce the incidence and duration of occupant dissatisfaction. However, active cooling energy use increases the overall energy use. Instead, ABEs can be used to reduce occupant dissatisfaction while using significantly less energy.

Buildings are usually built for a period of use longer than 50 years. An adaptive building envelope shell is not permanently connected to the building (glued to the supporting structure) but is attached in front of it in a moveable way. Therefore, it has the advantage of being easier to recycle when the building is dismantled. There is no need for a complex separation. Furthermore, national and international requirements for the thermal permeability of the building envelope are currently changing at a significantly shorter interval than the usage time. An adaptive building envelope can be replaced more easily than a fixed insulation connected to the structure contributing to a sustainable development.

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