Managing overheating in buildings induced by climate change

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Abstract. Extended periods of drought, heavy rainfall and rapid changes between high and low outdoor temperature extremes have all been associated with global climate change. It is highly likely that a significant portion of climate change is anthropogenic. Large and rapid climatic changes have the potential to generate significant discomfort and even hazard to occupants. Well designed, constructed and managed buildings protect people from adverse climatic conditions and provide indoor spaces that foster well-being, health and productivity. Changing climatic conditions require innovative approaches to the design, building, management and use of comfortable and safe indoor environments. This study explores innovative approaches to reducing/avoiding climate-change-induced overheating in residential buildings in Northern Europe (Sweden and Germany), with a focus on managing heat loads during the summer season. Different approaches and measures are discussed, with relevance to building retrofitting and new construction. It is shown that the need for active cooling can be significantly reduced through good building design and smart climate control. Innovative insolation management devices are further shown to have the potential to reduce both winter heating and summer cooling loads. The study also explores the extent to which the intensity of urban heat islands can be reduced by addressing heat storage in the building structure. Innovative approaches to solar shading and heat protection are discussed as alternatives to heat load and indoor climate management.

1. Introduction

The building envelope as a link between the interior and exterior climate is an important factor that influences a building’s energy requirements. Depending on the envelope’s properties such as the heat transfer coefficient and the storage capacity it can influence indoor comfort, more precisely thermal comfort. A low heat transfer coefficient reduces the heat flow through the building envelope, which reduces heat loss in the wintertime and in the summertime. This property is favorable for the winter, while in the summer it can have a negative effect on indoor comfort. Additionally, with solar gains and internal loads, the thermal comfort in summer is compromised or can only be provided by additional energy use.

The final energy consumption in the building sector for space heating in Germany was approximately 30 per cent of total consumption in 2017. Guidelines in Europe – such as the Energy Performance of Building Directive (EPBD); in Sweden, such as the SBN; and in Germany the Energy
Saving Ordinance (EnEV) and the future Building Energy Act (GEG) – stipulate a reduction of heat losses in renovation and new constructions. These requirements include increasing the air tightness of the building (reduction of uncontrolled leakage) and optimising the heat transfer coefficient of the windows and building envelope. The result of specifications for the construction of new buildings or refurbishment is usually an inactive (fixed) building envelope. An inactive façade has a limited range of compensation of climatic influences, especially for the outside temperature. The range must be increased to provide an acceptable indoor climate; this is only achievable by building services systems [2].

The use of these systems leads to an additional energy use. The need to reduce energy use in the building sector leads to the question of whether buildings should be equipped with an adaptable envelope. There are numerous examples in nature where an envelope is adapted to the outside conditions. For animals, this ability is seasonal; for example, by changing the coat. Humans also adapt their clothing according to the outdoor conditions. This underlines the usefulness and confirms the use of an adaptable building envelope.

Studies on the topic of adaptable building envelopes have shown different approaches. In [3] the heat transfer coefficient is changed variably in a simulation and the effects were investigated. For this purpose, the properties of the building materials of individual building component layers were changed. In [4] a phase change material was used in a building envelope and investigated by simulation and laboratory set-up. [5] showed five different possibilities of an adaptable building envelope. In each of these possibilities, such as active vacuum thermal insulation, switchable insulation by mechanical contact, switchable insulation based on adherent particles, switchable insulation by embedded piping and switchable insulation by phase change materials, attempts were made to change the thermal transmittance. Dynamic insulation materials, presented in [6], showed a reduction potential of 17 per cent of the annual demand for heating and cooling energy. In [7] and [8], among other things, the heat transfer coefficient is switched to prevent or reduce the number of hours of overheating in the room. Although the thermal comfort in the interior is an important influencing variable, it has not been addressed in previous studies.

Despite numerous studies on adaptable building envelopes, there are few examples of them being implemented in practice. Considered over the entire life cycle of a building, complex component designs can lead to problems during deconstruction (recycling). With increasing complexity of the construction, the possibility of individual components failing increases. This can result in additional costs, which is why the decision was ultimately made against an adaptable building envelope [5]. Thus, there is still a need for solutions that can be applied on a broad scale at an acceptable cost/benefit balance.

2. Simulation methodology

2.1. Scope of the investigation

This study investigated the application of an adaptable building envelope of a residential building in Stockholm (Sweden) and in Potsdam (Germany). The aim was to keep the interior climate (the interior temperature) as comfortable as possible by varying the heat transfer coefficient by applying and removing the insulation (switchable insulation by mechanical contact). Thus, the supportive use of building services equipment should be prevented as long as possible. For this purpose, different compositions of the building envelope were simulated and evaluated using the simulation tool IDA-ICE. For different zones (interiors) with different types of building envelope, the time periods in which acceptable conditions were present in the zone could be identified. To reduce the energy demand, the different types of the building envelope were combined with each other to provide acceptable conditions as long as possible without energy input. The different types of building envelope were then compared and the potential for reducing energy use was determined.
2.2. Design of building envelopes

In this study, two different types of building envelope were examined for Sweden and Germany, respectively. In the further course of the study, they were used in combination. Envelope type A has the higher heat transfer coefficient. It stands for buildings in Sweden that have been erected within the framework of [9] and in Germany within the framework of the Thermal Insulation Ordinance 1982/84 [10]. Envelope type B has a lower heat transfer coefficient. It stands for buildings in Sweden that were constructed in Sweden since 2019 and in Germany within the framework of the Building Energy Act. Table 1 summarises the respective layer structures, with details of the building material properties.

| Table 1. Overview of design and properties envelope, type A (slightly insulated), type B (insulated) |
|---------------------------------------------------------------|
| **Type A** | **Sweden** | **Germany** |
| | [m] | [W/mK] | [kg/m³] | [Wh/kgK] | [m] | [W/mK] | [kg/m³] | [Wh/kgK] |
| Wood | 0.015 | 0.140 | 500 | 2300 | Plaster | 0.010 | 0.380 | 1000 | 1000 |
| Insulation | 0.130 | 0.050 | 350 | 1470 | Brick | 0.250 | 0.560 | 1200 | 1000 |
| Insulation | 0.040 | 0.170 | 350 | 1470 | Insulation | 0.050 | 0.045 | 200 | 1450 |
| Wood | 0.015 | 0.140 | 500 | 2300 | Plaster | 0.010 | 1.000 | 1800 | 1000 |
| Wood | 0.015 | 0.140 | 500 | 2300 | 0.301 | W/m²K | | |

| **Type B** | **Sweden** | **Germany** |
|---------------------------------------------------------------|
| | [m] | [W/mK] | [kg/m³] | [Wh/kgK] | [m] | [W/mK] | [kg/m³] | [Wh/kgK] |
| Wood | 0.015 | 0.140 | 500 | 2300 | Plaster | 0.010 | 0.380 | 1000 | 1000 |
| Insulation | 0.130 | 0.050 | 350 | 1470 | Brick | 0.250 | 0.560 | 1200 | 1000 |
| Insulation | 0.040 | 0.170 | 350 | 1470 | Insulation | 0.050 | 0.045 | 200 | 1450 |
| Wood | 0.015 | 0.140 | 500 | 2300 | Plaster | 0.010 | 1.000 | 1800 | 1000 |
| Wood | 0.015 | 0.140 | 500 | 2300 | 0.090 | W/m²K | | |
| Insulation | 0.100 | 0.045 | 350 | 1470 | 0.045 | W/m²K | | |
| Wood | 0.015 | 0.140 | 500 | 2300 | 0.174 | W/m²K | | |

Four zones were modelled for each building envelope type (A and B). For each type, one zone was created to the north, one to the east, etc. The structure of the internal wall surfaces consists of only one layer. If zones without neighbouring zones are used in IDA-ICE, they are considered adiabatic; in this case, a heat flow is only considered between the interior and exterior.

2.3. Versions

In the study, various parameters such as window shading, heating and cooling, and the application of internal loads were changed systematically. The following settings and sources were used:

- The set point for heating is 20 °C, for cooling is 26 °C, controlled to the operating temperature. Heating and cooling is done by an element under the window.
- Windows are equipped with an external shading, which is used depending on the solar radiation (closing on the building envelope from a solar radiation of 200 W/m²).
- The air tightness of the building is set to 3.0 h⁻¹ [12]. No ventilation system is used.
- The windows will be designed with light insulation for the zone and the same insulation for the zone according to current specifications.
- Persons receive a schedule for the presence of a residential zone. If the presence is active, two persons are in the zone.
- The lighting also receives a schedule for the presence of a residential zone. The maximum power of the lighting in the zone is 40 W, a complete conversion into heat is assumed.
- Two devices are used in the zone, one device (WLAN router) is used continuously with 15 W, and a second device (TV set) is used with 35 W according to a schedule for living.
The weather data used for the years 2010, 2013 and 2035 for Germany and the year 2013 for Sweden are taken from ASHRAE database (IWEC 2.0).

The zones in Section 2.4. were examined in the different versions by simulation. Table 2 lists the variants that have been found to be relevant for the investigations. Version 3 and 4 are used only for model evaluation.

| Version 1 | Version 2 | Version 3 | Version 4 | Version 5 |
|------------------|------------------|------------------|------------------|------------------|
| Window shading no | Window shading yes | Window shading yes | Window shading yes | Window shading yes |
| Heating no | Heating no | Heating yes | Heating yes | Heating yes |
| Cooling no | Cooling no | Cooling no | Cooling no | Cooling yes |
| Internal loads no | Internal loads no | Internal loads no | Internal loads no | Internal loads yes |
| Determining the course of indoor temperature | Effect of window shading on the indoor temperature | Determination of the heating energy demand | Determination of the heating energy demand with internal loads | Determination of the heating and cooling energy demand |

2.4. Adaptive building envelope

By actively adjusting the building envelope, the energy used for cooling and heating should be reduced. In this study, adaptive means the use of the open (Figure 1 left) or closed (Figure 1 right) building envelope. This adjustment was used to optimise the total energy demand. The optimisation is achieved by adjusting the building envelope according to the demand. The energy input is used to achieve and maintain a specified indoor temperature (changes according to the outdoor temperature) or to achieve and maintain a specified PMV range. Therefore, two approaches are investigated. At first, the change of the building envelope dependent on the outside temperature, and second, dependent on the PMV.

2.4.1. Adaptation of the building envelope according to outside temperature, time of measurement and interval of adjustment. The combination between the both types of building envelopes is based on the following parameters: outside temperature, time of temperature measurement and the interval of adjustment use of building envelope type A (BET-A) or building envelope type B (BET-B). The aim of the investigation is to determine which setting requires the lowest energy demand and the number of hours per year that the building envelope type is used.

![Figure 1: The two states of the building envelope (wall construction case Sweden). Left: the additional insulation is stowed on the side; the building envelope has a heat transfer coefficient of 0.30 W/m²K. Right: the additional insulation is positioned in front of the building envelope; the building envelope has a heat transfer coefficient of 0.17 W/m²K.](image-url)
2.4.2. *Adaption of the building envelope according to predicted mean vote (PMV).* The combination of the building envelope type depending on the PMV is based on a case differentiation. The simulated PMV value of the zone is verified every hour and the building envelope type is set to BET-A or BET-B based on the PMV. A decision matrix is made according to a PMV greater than 1.0 (slightly warm) and a PMV less than -1.0 (slightly cold). This matrix divides the results into nine cases. For example, Case 1 tests whether the PMV value of the BET-A and of the BET-B zone is smaller than the set point. If this condition occurs, the BET-B building envelope should be used. For Case 7, in both zones the PMV value is too warm, so the building envelope type should be A. The other cases define six conditions that are more possible.

3. Results

3.1. Temperature

The results of the course of the indoor temperature are compared to the outdoor temperature. The comparison generates a field of all occurring temperatures over the duration of one year (8760 hours). The following figures show how often the zone temperature falls below the target temperature for heating (20 °C). If the temperature falls below this value, the zone is “too cold”. Furthermore, you can see for the zone how often the set point temperature for cooling (26 °C) is exceeded. If the set point is exceeded, it is “too warm” in the zone. In the range of the upper and lower set point value, the temperature status in the zone is “ok”. Temperatures inside the south-oriented zone in Sweden: variation 1 (image left) without shading and variation 2 (image right) with shading, for the zone with BET-A (blue plus) and the zone with BET-B (red square).

Figure 2: Temperatures inside the south oriented zone in Germany, variation 1 (image left) without window shading and variation 2 (image right) with window shading, the BET-A in blue (plus) and the BET-B in red (squares).

Figure 2 presents – for versions 1 and 2 in the simulation (Table 2) – the ranges that can be reached by the indoor temperature as a function of the outdoor temperature. The temperature ranges are shown for the zone with BET-A and the BET-B without window shading (left illustration in each case) and the zone with the BET-A and the BET-B with window shading (right illustration in each case). For both locations – Sweden and Germany – the zone with the type A building envelope can cool down more than the zone with the type B building envelope. This effect will help to reduce the cooling energy demand in the further course of the investigations. Furthermore, the use of shading for the window shows a reduction of overheating (temperatures in the zone above 27 °C). However, depending on the shading control system used, the use of shading can also lead to an increase in heating energy demand, as can be seen from the lower temperatures achieved in the zones.
3.2. Energy demand

In this section, the results of the energy demand are presented and evaluated. The zone heating and zone cooling is done in the simulation of version 5 (Table 2). The heating and cooling energy demand for the South zone (see Figure 3) is grouped by the year and into the zone with BET-A and BET-B. Figure 3 shows the heating and cooling energy demand for the South zone in the years 2010, 2013 and 2035 (forecast). The illustration is divided into the zone with the BET-A and the zone with the BET-B for simulation version 5 (Table 2) in Sweden and Germany. The lower average annual temperatures in Sweden compared to Germany leads to a higher heating demand in Sweden than in Germany, despite better heat transfer coefficients in the former. Furthermore, it can be seen that the improvement of the heat transfer coefficient in Sweden from 0.301 W/m²K to 0.174 W/m²K and the improvement of the heat transfer coefficient in Germany from 0.567 W/m²K to 0.266 W/m²K, in the simulation leads to a complete avoidance of the heating energy demand. The complete reduction results from the combination of the improvement of the heat transfer coefficient and the consideration of internal loads.

In order to more easily compare the energy demand between room heating and room cooling, the efficiency of both systems is taken into account. Figure 3 shows the energy requirements for space heating with a COP of 1.0 (electrical) and for space cooling with a COP of 3.0 (electrical). The figure shows that even with the BET-A, according to the SBN75 and WSchV'82/84 specifications, there is already a cooling requirement that exceeds the heating energy requirement. Thus, when using the building envelope with an even lower heat transfer coefficient, the cooling load is even higher.

According to Figure 3, for heating and cooling (Sweden 2013, left image) in the type A zone, 301 kWh are required, compared to 267 kWh for heating and cooling in the zone of type B. In relation to the type A zone, the energy requirement is reduced by 11.3 per cent by improving the heat transfer coefficient. For the future scenario, with the data of the forecast weather file for the year 2035, the energy demand is reduced by 15.8 per cent. Due to the internal loads, a minimum of energy remains to provide thermal comfort. Further improvement of the heat transfer coefficient will not significantly reduce this energy demand. Due to the higher average temperatures in Germany, a different result is expected for 2013. According to Figure 2, for heating and cooling in the zone of type A 281 kWh are required, while 253 kWh are required in zone type B. In relation to the zone of type A, the energy requirement is reduced by 10 per cent. For the future scenario, with the data of the forecast weather file for the year 2035, the energy demand increases by 17 per cent due to the cooling loads. The obstruction of heat flow through the insulation in the building envelope by the better heat transfer coefficient prevents the possibility of natural cooling of the zone. Further improvement of the heat transfer coefficient is not recommended.
3.3. Results of the application of an adaptive building envelope in Sweden

This section describes how the energy demand for heating and cooling was determined depending on the heat transfer coefficient of the building envelope. While the improvement of the heat transfer coefficient has completely reduced the demand for heating energy, the improvement of the heat transfer coefficient leads to a higher demand for cooling energy. By adaption (the combining of the two variants of the BET), both the higher demand for cooling energy and the demand for heating energy should be reduced. The combination depends on the parameters, limit temperature, time of temperature measurement, and frequency of temperature measurement, as well as the PMV.

The limit temperature is a fixed comparison value to the outside temperature and is used to decide which type of BET will be used. If the outdoor temperature is below the limit temperature, the BET-B is used. If the value is above the limit temperature, the BET-A is used. The first series of tests is carried out with a fixed limit temperature of 10 °C. The adjustment of the building envelope occurs once a day and the time of measurement is varied from 0:00 a.m. to 11:00 p.m., hourly. In the investigation, the optimum result is achieved with the measurement time at 1 p.m. (see Figure 4, the COP of the systems was taken into account). The comparison of the results shows that the application of both types of building envelopes over the year can reduce the energy demand for heating and cooling by up to 26.0 per cent compared to the building envelope with permanent increased heat transfer coefficient. For the calculated case, the BET-B was used for 50.4 per cent of the year (4416 hours), while the BET-A was used for the remaining 49.6 per cent of the year.

The second series of tests is carried out with a variable limit temperature of 0 °C to 20 °C with an interval of 2 °C. The adjustment of the building envelope is carried out once a day with a fixed measuring time at 1 p.m. In the second series of tests, the optimum result is achieved with a limit temperature between 4 °C and 6 °C. As shown in Figure 4 (left), the total energy demand (a COP of 3.0 was taken in account) amounts to 174 kWh. Compared to BET-B energy demand, a further decrease up to 35 per cent can be achieved. In summary, the lowest energy demand for heating and cooling, for the model in Sweden, is determined at a limit temperature of 4 °C, the measurement time at 1 p.m. and the possible adaption of the BET once a day.

The calculated energy requirements are often exceeded in the real use of the building. One reason for this can be that the thermal comfort in the interior is not given, which means that an intervention by the user is necessary. This intervention is usually less efficient in the use of energy. Therefore, in adaption of the adjustment of the BET is carried out in dependence of the existing PMV. The limit value for the PMV ‘too cold’ was set to -0.7, while the limit value of the PMV for ‘too warm’ was set to 0.7. These values were chosen because the set operative temperature for heating (20 °C) and for
cooling (26 °C) during the simulation already led to a PMV interval of -1.0 to 1.0. The adaption of the application of the building envelope according to the PMV results in a heating energy demand of 18 kWh and a cooling energy demand of 479 kWh. After adjustment via the COP, the total energy requirement for the year 2013 is 178 kWh, which is close to that of the combination.

3.4. Results of the application of an adaptive building envelope in Germany

The calculations for the study in Germany are the same as for the study in Sweden. In the first series of tests, a fixed limit temperature of 10 °C was used. An adjustment of the BET occurred once a day, the measurement time varied from 0:00 a.m. to 11:00 p.m., hourly. In the test, the optimum result is achieved with the measurement time at 4 p.m. Taking into account the COP of 1.0 for heating and 3.0 for cooling (both measures are electrical), the following results were obtained. The comparison of the calculations shows that, by applying both types of BET over the year, the reduction of energy demand for heating and cooling by up to 20.7% is higher than the permanent increase of the heat transfer coefficient. For the calculated example, the BET-B was used for 41.9 per cent of the year (3672 hours). For the remaining 58.1 per cent, the BET-A was used.

The second series of tests was carried out with a variable limit value of 0 °C to 20 °C in an interval of 2 °C. The adjustment of the BET was carried out once a day, with a fixed measuring time at 4 p.m. The optimum result was achieved with a limit temperature between 4 °C and 10 °C. For the total energy demand for heating and cooling (the COP 3.0 for cooling was taken into account), 191 to 194 kWh will be required (Figure 5). The result is in the range of the first series of tests; no further variation of the limit temperature takes place.

Additionally, it is determined how often the adaptation of the BET must be carried out in order to achieve an energy demand reduction. Two scenarios are carried out: the first had a possible adjustment of the BET at 4 a.m. and 4 p.m., the second at 4 a.m., 10 a.m., 4 p.m. and 10 p.m. The calculations do not show any additional energy demand reduction. In summary, the lowest energy demand for heating and cooling, for the model in Germany, is determined at a temperature set point of 10 °C, the measurement time at 4 p.m., and the possible adaptation of the BET once a day.

Figure 5: Results of the adaption of the BET for Germany in 2013 (left) and the year (2035 - future scenario; right). Also shown are the PPD for the case ‘too cold’ (light red) and for the case ‘too warm’ (light blue). Further details are the energy demand for heating (red) and for cooling (blue), the number of hours using the BET-A (light grey) and BET-B (dark grey).

An adaption of the BET in accordance with the PMV is also carried out for the location of Germany. The energy demand of the zone was 5.0 kWh for heating and 190.0 kWh for cooling (a COP 3.0 for cooling was considered). Thus, the adaption according to the PMV leads to a similar energy demand result as well as the adaption after a limit temperature.
4. Conclusions
This paper has demonstrated the heating and cooling demand, depending on the used building envelope type (BET) A or B, for a zone in Sweden (Stockholm) and Germany (Potsdam). The BET-A is constructed to the Swedish construction standard (SBN75) and the German the Energy Saving Ordinance (EnEV). It has the higher heat transmission coefficient of both envelope types used in the study. The BET-B was constructed in adherence to actual guidelines in both countries. Zones with different orientations and BET were designed and simulated, by using IDA-ICE. Insulating a building by looking only at its energy requirements for heating could mean that this requirement would be completely eliminated. However, this also means that there is a permanent need for energy for cooling if a comfortable indoor climate has to be maintained. Further insulation of buildings to reduce the heating requirement prevents passive cooling by transmission through the building envelope. By a combined application of two types of building envelopes, with different heat transfer coefficients in this study, the total energy demand for heating and cooling could be reduced by up to 30 per cent.

The potential of the reduction depends on the location of the building, the difference in the respective heat transfer coefficients, the type of use of the building and the management of the building envelope to achieve an optimal indoor climate. In the present study, zones facing north, east, south and west were investigated. From these investigations, the results of the south zone were presented in this paper and the potentials were determined and evaluated. For the south zone, overheating caused by internal loads in the zone was determined by simulation. The application of a future scenario, through a weather file for the year 2035 from ASHRAE, shows an increase in the risk of overheating. The application of two types of building envelopes can also help to reduce the number of hours of overheating. It is further emphasised that, in the scenarios studied, the building envelope with a lower heat transfer coefficient only had to be applied for 42 per cent of the annual hours in order to reduce the energy required for heating. The investigations show that an adaptive (active) building envelope can help to reduce the energy consumption of the building and consequently for the urban scale as well. The reduction can be applied to both heating and cooling requirements. It is possible to extrapolate the results from own zone to one building up to an urban scale. To provide the optimised energy demand, each building façade orientation needs its own control device. In addition, the adapted building envelope type is a system that can be used in existing buildings as well as new buildings to reduce the heating and cooling energy demand.

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