Simulation-supported shading design optimisation for a multi-storey building with passive cooling

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Abstract. This contribution reports on an ongoing research effort to reduce the heating demand and overheating risk in the cold and warm seasons respectively. A simulation-supported optimisation strategy for life cycle oriented buildings was pursued, resulting also in improved ratings in terms of the concurrently calculated mandatory Austrian energy certificate. Thereby, a range of different building types was considered, including a multi-storey building that uses locally available ecological construction materials and renewable energy. Apart from the heating demand of the building, the indoor environment for selected living units was specifically examined to avoid overheating risk and to increase the thermal comfort for the occupants. To reduce the indoor temperatures for different thermal zones, the dimensions of external shading elements were investigated. Likewise, natural ventilation scenarios were explored to improve summer-time thermal comfort conditions. The results suggest that by using properly dimensioned external fixed shading devices, especially in combination with natural ventilation, the indoor temperatures and also the thermal comfort can be improved significantly, while maintaining the passive house standard according to the Austrian energy certificate.

1. Introduction

A relatively large percentage of energy and resource consumption occurs in the building sector [1]. This concerns the production of building materials, the construction of buildings, but also the energy consumption during the use phase as well as the demand resulting from demolition and disposal of buildings or building parts at the end of their lifetime. To encounter this demand, the study “Simulationsunterstützte Designoptimierung Lebenszyklus orientierter Gebäude” (Sim4DLG) aims at reducing the energy consumption through a design optimisation of life cycle-oriented buildings by using dynamic simulations in addition to the mandatory energy certificate in Austria [2].

This part of the study is carried out in the framework of the European Union (EU) Life project “Life Cycle Habitation” (LCH), which targets the demonstration of innovative building concepts that significantly reduce CO\textsubscript{2} emissions, mitigate climate change and contain a minimum of grey energy over their entire life cycle to make energy-efficient settlements the standard of tomorrow in line with the EU 2020 objectives [3]. To this end, a highly resource and energy-efficient building complex is being built in the region of Böheimkirchen, Lower Austria, which is categorised as C\textsubscript{f}b (warm tempered humid climate) [4]. The case study project includes six living units and a community area as well as two single-family houses, which will be realised in different straw bale construction styles [5]. The concept of the buildings is based on energy-efficient building solutions (passive house components, improved household appliances, thermal insulation etc.) and on the maximum utilisation of regional renewable resources for building materials to reach a lower energy demand in production as well as shorter transport distances. In addition to this, buildings’ decommissioning is considered from the planning stage.
process on to promote recycling and composting after the use period. Therefore, straw bales have a key role in this project since they have been proven to be functional and show a very low primary energy intensity (PEI) as well as a positive effect on the CO₂ balance of the building [6].

2. Design optimisation

This contribution presents an ongoing research effort of the project Sim4DLG addressing the design optimisation of the building compound regarding the reduction of energy and resource consumption as well as an increase of the thermal comfort for the occupants.

Informed by the results of the early stage optimisation and the design planning, the building compound (Figure 1) will be realised in a 2-story non-load bearing straw bale construction in style of the neighbouring award-winning S-House [7] and consists of two living units in a town house style, a community area and 4 apartments with a total of 41 different thermal zones. Three living units are selected for a further design optimisation in specific. These are Top 2, Top 4 and Top 6, covering the town house style unit as well as one apartment in the ground floor (GF) and one in the upper floor (UF). This contribution is focusing on Top 2 with a total net living area of 106.7 m² on both floors and 8 thermal zones. These are an entrance hall (EH), a living-kitchen area (LK) and a cloakroom (WC) in the GF as well as a hallway (HW), three bedrooms (Bed1, Bed2, Bed3), and a bathroom (Bath) in the UF. The low U-value building elements (exterior wall=0.09 W/m²K; roof=0.07 W/m²K; floor=0.09 W/m²K; partition wall=0.11 W/m²K) are combined with triple layer windows using benchmark values (Ug=0.65 W/m²K; Uf=0.91 W/m²K; g-value=0.4) and an extended roof to improve the performance of the building. This concept will be completed with an innovative energy system based on locally available renewable energy sources for further reduction of the carbon footprint. The same system is used for all energy certificate calculations during this stage for a comparable evaluation of the results.

2.1. Methodology

The first performance indicator is the heating demand, while the second is the overheating, since the buildings are designed for passive cooling only and are not planned to have any air conditioning systems. And because these two key performance indicators may evolve in opposing directions, a parametric optimisation approach with EnergyPlus is used in combination with SketchUp and Openstudio in order to achieve improved models suitable for the buildings. For the concurrently calculated mandatory Austrian energy certificate the software GEQ by Zehentmayer is used. The simulation models are defined based on standard assumptions and calibrated according to calculation methods of the Austrian energy certificate with a standard heating set point (HSP) of 20 °C and a fixed air change rate (ACR) of 0.4 h⁻¹. According to the design of the buildings typical activities varying from sleeping to housecleaning in accordance with the ASHRAE standard are assumed for the occupants [8]. In the course of analysis and assessment of the indoor temperatures for each variant, an overheating of the building is to be avoided and the thermal comfort is to be improved.

To reduce the indoor temperatures for different thermal zones, the dimensions of external shading devices are investigated [9]. A strong focus is therefore on the dimensions of the large, external fixed extending roof element on the south side of the building compound, while parameters of the transparent elements, which include the dimensions of the windows, are predefined by the overall architectural design.
design of the building and not modified in this optimisation stage. In addition, the effects caused by the balconies are investigated (Figure 2). The parametric optimisation variables of the roof and the balconies follow 0.1 m steps until a maximum depth of 3 m. The width of balconies follows fixed steps depending on the floorplan. In a first step, the selected living units are investigated separately, whereas in a second step combinations based on the prior results for the balconies are further explored, including combinations for a variation in a loggia style for which balconies are considered along the entire south wall, except for the community area.

Figure 2. Cross section (a), EnergyPlus geometry model for the building compound (b).

2.2. Heating and ventilation scenarios
In a second step during this optimisation phase, different heating and ventilation scenarios are applied to the optimised standard HSP building model in EnergyPlus to estimate the performance effect as well as the impact on the indoor climate and thermal comfort [10]. In the adapted HSP building model different temperature set points are considered, representing more common values for different thermal zones instead of the low standard assumption with a constant temperature of 20 °C. Accordingly, nighttime (between 11 pm and 7 am) setback temperatures are considered. The set points for the different thermal zones of Top 2 are shown in Table 1. Furthermore, for the standard HSP model, natural ventilation is considered for the summer period from 1st of May until 30th of September to investigate the overheating reduction possibilities for periods with indoor temperatures above 20 °C+1K. The low free cooling (FC) building model contains an intensive ventilation phase (3 h⁻¹) in morning and evening times as well as ventilation with tilted windows (1 h⁻¹) during occupancy at day and at night, while the high FC model includes also a higher night time ventilation (3 h⁻¹). It is assumed that natural ventilation is operated by occupants. To avoid an overcooling of the building during the night, a minimum indoor activation temperature of 19 °C is set for the high FC model, defined from the setback temperature for bedrooms of the adapted HSP building model plus 1 K.

Table 1. Adapted temperature set points.

| Temperatures | Bed1 | Bed2 | Bed3 | EH | HW | LK | WC | Bath |
|--------------|------|------|------|----|----|----|----|------|
| Set point [°C] | 18   | 20   | 20   | 22 | 22 | 22 | 22 | 24   |
| Setback [°C]  | 18   | 18   | 18   | 16 | 16 | 16 | 16 | 16   |

3. Results
3.1. Passive house standard
With the overall goal of achieving a reference climate heating demand (HWB_RK) of maximum 10.0 kWh.m⁻² according to the Austrian energy certificate, a parametric simulation was done in EnergyPlus with the above described building models and variables as well as combinations of these. The results are then compared regarding the two performance indicators heating demand and overheating of the building due to the indoor temperatures. The models show results between 7.9 and 9.7 kWh.m⁻² for the computed HWB_RK with the software GEQ. Because of the energy-efficient construction style and the compactness of the building with a surface-area to wall ratio (A/V) of 0.54 m⁻¹, all computed results for the models are under the threshold-value. Therefore, not only one but a range of improved models are suitable for the suggested building design depending on the different combination possibilities for the selected variables.
In a first step, the effect of the depth of the extending roof was explored for the selected living units, while also in case of Top 2 and Top 4 the depths and widths of the balconies were investigated. In general, a reduction of the indoor temperatures results due to an extension of the extended roof as well as an enlargement of the balconies. As a consequence of this shading effect, also the heating demand of the building is increased due to diminished solar gains. While the extension of the roof has a higher effect on the zones of the UF, the enlargement of balconies is mainly influencing the south-oriented zones in the GF. The suggested models show values of 2466 h for Top 2, 2318 h for Top 4 and 2404 h for Top 6, compared to the average values of 2501, 2544 and 2497 h as well as to the maximum values of 2555, 2668 and 2571 h considering all simulated variants.

In a next step the variables are combined for a further building optimisation. Based on the results, combinations, in which the depths of the roof and the balconies are extended in parallel including the appended balcony element for Top 2, are investigated in detail, but also variations with a maximum roof overhang of 3 m and an extension of the balcony depth with a step of 0.1 m. The suggested model with a computed HWB_RK of 9.1 kWh.m⁻², which is lower than the threshold value, display with 2356 h for Top 2, 2303 h for Top 4 and 2360 h for Top 6 reduced extent of time with indoor temperatures above 26 °C (Table 2). This results in 2586 h for the three living units altogether.

### Table 2. Time (number of hours) with indoor temperatures > 26 °C for optimised standard HSP models.

| Bed1 | Bed2 | Bed3 | SR | EH | HW | LK | WC | Bath | All Zones |
|------|------|------|----|----|----|----|----|------|-----------|
| Top 2 | 1967 | 2318 | 1575 | - | 836 | 1228 | 1409 | 1085 | 1323 | 2356 |
| Top 4 | 2027 | - | - | 1416 | 1488 | - | 2137 | - | 1704 | 2303 |
| Top 6 | 2165 | - | - | 1313 | 1412 | - | 2016 | - | 1602 | 2360 |

### 3.2. Heating and ventilation scenarios

Continuing from the suggested building model, the above-mentioned heating and ventilation scenarios to estimate the performance effect and the impact on the indoor climate are described in more detail in the following section. Table 3 summarises the impact on the indoor climate of Top 2 due to the sum of hours of the indoor temperatures above 26 °C, while Table 4 provides an overview for the combined living units within the building compound including the calculated heating intensities by EnergyPlus.

### Table 3. Scenario results of the suggested building model for the optimised living unit Top 2.

| Hours with temperatures > 26 °C for all zones per living unit | Standard HSP [h] | Adapted HSP [h] | Low FC [h] | High FC [h] |
|---------------------------------------------------------------|------------------|----------------|------------|-------------|
| Top 2 All year                                               | 2356             | 2461           | 1366       | 608         |
| Top 2 summer period                                         | 2043             | 2056           | 1053       | 295         |

The results show in general similar tendencies for the selected living units. The Standard HSP scenario for Top 2 with a constant heating temperature set point of 20 °C is displayed in Figure 3. Especially during the summer season with a warmer outdoor environment and higher solar radiation also the number of hours of the indoor temperatures above 26 °C increases. The occasionally occurring high values during hot periods of single days in spring and autumn, especially for the south oriented rooms in the UF, rise due to the mechanical shading system, which is only operated during summer in this building model.
The adapted HSP scenarios, which represent more common temperature set points show wider temperature variations than the standard HSP scenarios, because of the different temperature set point values (Figure 3). These reflect the increased daytime temperatures for selected zones such as the bathroom, but also reduced night time temperatures.

In contrast, due to the application of natural ventilation in the standard HSP model in the summer period, a significant reduction of the indoor temperatures can be achieved. The integrated natural ventilation results in case of the low FC building model (Figure 4) in a 42.0 % reduction down to 1366 h for the period of a whole year, while for the summer time a reduction of 48.5 % to 1053 h can be achieved (Table 3).

Examining the calculated heating demand in EnergyPlus of the entire building for the different heating and ventilation scenarios, the adapted HSP scenario shows with 21.13 kWh.m⁻² an increase of 5.06 kWh.m⁻² in comparison to the standard HSP scenario (Table 4). Comparing the total number of indoor temperatures above 26 °C for the three selected zones together, the adapted HSP also show a slight increase from 2586 to 2634 h for the entire year and from 2170 to 2172 h for the summer period only. As with the individual living units, the combined living units results show a significant reduction of the indoor temperatures above 26 °C due to the application of natural ventilation in the standard HSP model. A 32.8 % decrease down to 1739 h and of 39.0 % down to 1323 can be achieved for the low FC.
model and of 67.1 % down to 851 h and of 79.1 % down to 436 h for the high FC model for the entire year and for the summer months respectively.

**Table 4.** Scenario results for the suggested building model of the compound.

| Scenario               | EnergyPlus heating intensity compound [kWh.m²] | Hours with temperatures > 26 °C for all zones of Top 2, 4, 6 All year [h] | Summer period [h] |
|------------------------|-----------------------------------------------|------------------------------------------------------------------------|------------------|
| Standard HSP model     | 16.07                                         | 2586                                                                   | 2170             |
| Adapted HSP model      | 21.13                                         | 2634                                                                   | 2172             |
| Low FC model           | 16.05                                         | 1739                                                                   | 1323             |
| High FC model          | 16.12                                         | 851                                                                    | 436              |

4. Discussion

This contribution highlights some of the optimisation results of the ongoing research study for a building project in Austria. In this optimisation approach, it is shown that dynamic simulation tools can be used for buildings’ design optimisation to increase the thermal comfort for the occupants. This is achieved by investigating the indoor temperatures and indoor air overheating prevention. Considering an optimisation of the single living units separately from the overall design of the building compound, models with large roof extensions and balconies on the south-façade of the building are suggested to reduce overheating risk. Simultaneously, passive house standards can be met as per energy certificate results. Specifically, deployment of night-time natural ventilation during summer time can be shown to significantly reduce the risk of overheating.

5. Conclusion

The presented study showed that an accurate design of shading elements can reduce indoor air temperatures, while maintaining a low heating demand. Furthermore, overheating risk during summer time could be reduced significantly by a proper operation of the windows for passive cooling.

In the next step, this approach will be reapplied to the building's final design and data of the selected building products and elements. After the construction, a comprehensive building monitoring will be conducted during the initial occupancy phase to validate the simulated results.

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