Life-cycle oriented simulation-supported heating demand optimisation of buildings: An Austrian case study

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Abstract. This contribution reports on an ongoing research effort within the project Sim4DLG (FFG 853842) to optimise the performance of life cycle oriented buildings in Austria. For a reduction of the heating demand and overheating risk in the cold and warm seasons respectively, a simulation-supported optimisation strategy was pursued. This approach is applied to a range of different building types, varying from stand-alone single family houses to townhouses and apartments in a multi-storey building, which are to be constructed within the project Life Cycle Habitation (LIFE13 ENV/AT/000741). To avoid overheating risk in the buildings and to increase the thermal comfort, the dimensions of external shading devices were investigated, especially in combination with summer-time natural ventilation. Apart from the exploration of the indoor environment of each building type, the heating demands of the buildings were specifically examined. This includes a comparison of the building parameters and simulation procedures as well as an evaluation of the outcomes and deviations of the simulation results in relation to the concurrently calculated mandatory Austrian energy certificate. The simulation results suggest that this strategy has not only the potential to improve indoor conditions, but also to result in better ratings in terms of 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 and also the energy consumption during the use phase. With its high consumption of energy and thus mostly fossil fuels for the majority of processes, the building sector is with 10 % in Austria also one of the largest perpetrators of carbon dioxide (CO\textsubscript{2}) emissions [2].

The demand for improvements, new strategies and alternative solutions in the field of construction is also stated by the concluded Paris Agreement in 2015 with the goal of a global average temperature increase of below 2 kelvin (K) above preindustrial level in context with the alarming greenhouse gas emissions [3]. Furthermore, during the life cycle of buildings additional energy and resource consumption results 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 and an improvement of the planning processes themselves by using dynamic simulations in addition to the mandatory energy certificate in Austria [4].

2. Building project

This part of the study is carried out in the framework of the European Union (EU) Life project “Life Cycle Habitation” (LCH), which is targeting the demonstration of innovative building concepts that significantly reduce CO₂ 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 [5]. To this end, a highly resource and energy-efficient building complex (see Figure 1) is being built in the region of Böheimkirchen, Lower Austria, which is categorised as Cfb (warm tempered humid climate) [6].

![Figure 1. Design of the buildings (a), site plan with building compound and atrium-style houses (b).](image)

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 construction styles. The building compound will be designed as a two-story non-load bearing straw bale construction in style of the neighbouring award-winning S-House [7] and includes two row houses and four apartments, while the compact flat-roof buildings will be realised in a single-story atrium-style load-bearing straw bale construction.

The concept of the buildings is based on energy-efficient building solutions including the use of passive house components, improved household appliances, thermal insulation and on the maximum utilisation of regional renewable resources for building materials to reach a lower energy demand in production as well as by shorter transport distances. In addition to this, demolition and the separation of building materials are considered from the planning 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 buildings [8].

3. Methodology

This contribution presents an ongoing research effort of the project Sim4DLG addressing the design optimisation of the buildings regarding the reduction of the energy consumption and an increase of the thermal comfort, as well as an evaluation of the commuted results and deviations.

3.1. Design optimisation

Proceeding from the results of the early stage optimisation [9] and the design planning [10], the building compound consists of two living units in a town house style, a community area and four apartments with a total of 41 different thermal zones as well as two atrium-style houses with 9 thermal zones each. The net living area of all zones for all living units is approximately 710 m². Depending on the construction type, low U-value building elements (exterior walls = 0.06-0.09 W/m²K; roofs = 0.06-0.07 W/m²K; floors = 0.07-0.09 W/m²K; partition walls = 0.11 W/m²K) are combined with triple layer windows using typical benchmark values (Ug = 0.6 W/m²K; Uf = 0.9 W/m²K; g-value = 0.4) and an extended roof to improve the performance of the buildings.
The first performance indicator is the heating demand, while the second is the overheating, since the buildings are designed for passive cooling only and should not 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 (see Figure 2). 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. The atrium-style buildings and the living units in a town house style are designed as four person households with children, while the smaller apartments are foreseen to be used by two persons. It is assumed that the occupants are working or employed persons, or where applicable kids, which are usually not at home during the day, since professionals are covering with 4.26 of 8.79 million the largest group in Austria in 2017 [11]. According to the design of the buildings, typical activities varying from sleeping (72 W/person) to housecleaning (>207 W/person) and light exercises (>315 W/person) in accordance with the ASHRAE standard are assumed for the occupants [12]. For other internal gains caused by different devices in the living units, a standard electric equipment is to be considered [13], which is in accordance with the defined values of the ASHRAE standard, but slightly adapted in terms of an energy-efficient overall system.

To reduce the indoor temperatures for the different thermal zones, the dimensions of external shading devices are investigated [14]. A strong focus is therefore on the dimensions of the large, external fixed extending roof elements for depths between 0.0 m to 1.5 m (for the atrium-style buildings) and between 0.0 m to 3.0 m (for the building compound) with 0.1 m steps. The balconies and the sizes of the transparent elements are also modified in this optimisation, if not predefined by the architectural overall design of the buildings. 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 increased.

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

In the next step three different heating and ventilation scenarios are applied to the suggested optimised standard HSP building model in EnergyPlus. First, different temperature set points are considered, which represent more common values for the different thermal zones instead of the low standard assumption with a constant temperature of 20 °C. These are varying from setback temperatures of 16 °C during night times up to 24 °C for the bathroom in the adapted HSP building model [15]. Second, 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. This low free cooling (FC) building model contains intensive ventilation (3 h⁻¹) in the morning and evening as well as ventilation with tilted windows (1 h⁻¹) during attendance times of the occupants. Third, the high FC model includes also a higher night time ventilation (3 h⁻¹).

3.2. Evaluation of heating demands and deviations
Continuing from the suggestions of the design optimisation to avoid the overheating risk in the buildings, the design is further adapted for the building permit application. This concerns mainly the window parameters and dimensions of the shading elements. In contrast to the design optimisation, product specific values of passive house suitable wood frames and triple layer glazing are used for the window
constructions (Ug = 0.47 W/m²K; Uf = 0.91 W/m²K; g-value = 0.52) instead of the previously applied benchmark values.

The calculated heating demands of the buildings for EnergyPlus and GEQ are then compared and analysed in detail, especially regarding deviations caused by the transmitted solar radiation through transparent building elements.

The goal of this section is not to compare the different calculation methods for EnergyPlus und GEQ step by step, which are described in detail in the EnergyPlus Engineering Reference [16] and in the ÖNORM B8110-5 [17], but to give a basic guideline for the effects on the computed results. Therefore, the differences of the transmitted solar radiation between the selected programs are investigated for the project location of Böheimkirchen, Lower Austria.

In a first step, the results of a sample window with a transparent surface of 5 m² for both programs are examined regarding the effects of a differing window size, varying orientation due to a clockwise rotation with a step of 22.5° for a total of 16 different directions as well as concerning a lateral shading caused by the building itself in case of the atrium-style buildings and a window overhang. The window overhang includes variations for a length from 0.0 m to 3.0 m with a step of 0.5 m for shading elements attached directly above the window and with heights of 0.33 m as foreseen in the design of the building compound for the ground floor and of 0.98 m as with the atrium-style buildings.

Second, the influencing parameters of the orientation, the window overhang and the lateral shading are also applied for the adapted building designs containing all window elements and the effects of these are evaluated altogether. For an appropriate comparison of the results no mechanic shading devices are applied in the EnergyPlus model, which are actually foreseen in the building design. The lengths of the overhangs for the adapted designs of the buildings and the corresponding window directions are displayed in the following Table 1.

| Overhang  | N  | NNE | E  | EES-1 | EES-2 | S  | SSW-1 | SSW-2 | W  |
|-----------|----|-----|----|-------|-------|----|-------|-------|----|
| Compound  | 2.0| -   | 4.5| -     | 3.0   | -  | -     | -     | 2.8|
| Atrium East| - | 1.3 | -  | 0.7   | 1.5   | -  | 1.0   | 1.2   | -  |
| Atrium West| - | 1.3 | -  | -     | 1.5   | -  | 1.0   | 1.2   | -  |

The results are then compared regarding the transmitted solar radiation for one m² of the transparent surface for the period of one year (kWh/m²a) and regarding the total transmitted solar radiation of the sample window for each month (kWh) to show the tendency throughout the year.

4. Results

The results of the design optimisation for the different building types as well as the findings of the evaluation for the deviations of the heating demands are described in the following sections.

4.1. Heating and ventilation scenarios

With the overall goal of achieving a reference climate heating demand (HWB_RK) of maximum 15.0 kWh/m²a for the atrium-style buildings and 10.0 kWh/m²a for the building compound 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 those. The results are then compared in view of the two performance indicators heating demand and overheating of the building due to the indoor temperatures.

The models show results between 14.1 kWh/m²a and 16.3 kWh/m²a for the concurrently computed heating demand HWB_RK for the atrium-style buildings and results between 7.9 kWh/m²a and 9.7 kWh/m²a for the building compound with the software GEQ. Variants with a HWB_RK above 15.0 kWh/m²a are excluded. In general, models with large south-facing windows (for high solar gains) and large overhangs (to prevent overheating) are proposed.
The suggested models for the atrium-style buildings with a computed HWB_RK of 15.0 kWh/m²a, which is under the threshold value, show with 1851 h and 1901 h the smallest number of hours for indoor temperatures above 26 °C for all zones of the buildings (see Table 2), compared to the average value of 1975 h and the maximum of 2227 h considering all simulated variants. The suggested model for the building compound with a HWB_RK of 9.1 kWh/m²a shows with 2586 h the smallest number of hours for indoor temperatures above 26 °C.

Table 2. Scenario results for the suggested building models.

| Scenario                     | EnergyPlus heating intensity [kWh/m²a] | Hours with temperatures > 26 °C |
|------------------------------|---------------------------------------|---------------------------------|
|                              | All year                               | Summer period                   |
|------------------------------|---------------------------------------|---------------------------------|
| Standard HSP compound        | 16.07                                 | 2586 h                          |
| Adapted HSP compound         | 21.13                                 | 2634 h                          |
| Low FC compound              | 16.05                                 | 1739 h                          |
| High FC compound             | 16.12                                 | 851 h                           |
| Standard HSP Atrium East     | 16.64                                 | 1901 h                          |
| Adapted HSP Atrium East      | 23.90                                 | 1938 h                          |
| Low FC Atrium East           | 16.60                                 | 922 h                           |
| High FC Atrium East          | 16.73                                 | 344 h                           |
| Standard HSP Atrium West     | 16.65                                 | 1851 h                          |
| Adapted HSP Atrium West      | 24.03                                 | 1894 h                          |
| Low FC Atrium West           | 16.62                                 | 879 h                           |
| High FC Atrium West          | 16.63                                 | 410 h                           |

The results for the applied heating and ventilation scenarios of each building are likewise displayed in Table 2 and show similar tendencies. While there is an increase for the heating demands as well as for the numbers of hours for the indoor temperatures above 26 °C for the adapted HSP scenarios, the numbers of hours with temperatures above 26 °C could been reduced significantly due to the application of natural ventilation during the summer time by 30 to 40 % for the low FC building models and by up to 80 % for the high FC building models.

To achieve low heating demands for the building models, which are defined based on standard assumptions and calibrated according to calculation methods of the mandatory Austrian energy certificate, large south-oriented windows are required for high solar gains in winter time, while in contrary large shading elements for these windows and the application of natural ventilation can contribute to avoid overheating of the buildings in summer time.

4.2. Effects of shading elements

In this section different software results regarding the heating demands of the adapted building designs for the building permit application are compared. Based on the different calculation methods of each program, varying results are expected but with similar tendencies for the different building types [18]. The results are displayed in Table 3 and show significant differences. For an appropriate comparison of the results and the transmitted solar radiations for the buildings and site, the location climate heating demand (HWB_SK) is used instead of the HWB_RK, which defined the overall goal for the design optimisation.

While the calculated heating demands of the Atrium East and West buildings show the same tendencies with lower values of 15.57 kWh/m²a and 15.58 kWh/m²a for EnergyPlus in relation to GEQ with values of 17.01 kWh/m²a and 16.94 kWh/m²a, the heating demand of the building compound with 15.26 kWh/m²a for EP is higher compared to 11.78 kWh/m²a for GEQ. The results therefore not only show deviations between the calculation programs, but also deviations between different building types within the same software. A first evaluation of the results suggests that these values are strongly dependent on the transmitted solar radiation through the transparent building elements (see also Table 3).
Table 3. Heating demands and transmitted solar radiations for the adapted building designs.

| Building type/element | EP – heating intensity [kWh/a] | GEQ – HWB [kW/m²] | EP – transmitted solar radiation [kWh/m²a] | GEQ – transmitted solar radiation [kWh/m²a] |
|-----------------------|--------------------------------|--------------------|---------------------------------------------|---------------------------------------------|
| Compound [kWh/a]      | 10407.41                       | 9203.00            | 23761.67                                    | 39981.20                                    |
| Floor/window [m²]     | 682.08                         | 781.00             | 155.00                                      | 155.00                                      |
| [kWh/m²a]             | 15.26                          | 11.78              | 153.30                                      | 257.94                                      |
| Atrium East [kWh/a]   | 2076.08                        | 2598.00            | 5504.06                                     | 5394.70                                     |
| Floor/window [m²]     | 133.31                         | 152.69             | 31.60                                       | 31.60                                       |
| [kWh/m²a]             | 15.57                          | 17.01              | 174.18                                      | 170.72                                      |
| Atrium West [kWh/a]   | 2076.99                        | 2586.00            | 5146.62                                     | 5008.70                                     |
| Floor/window [m²]     | 133.31                         | 152.69             | 29.44                                       | 29.44                                       |
| [kWh/m²a]             | 15.58                          | 16.94              | 174.82                                      | 170.13                                      |

4.2.1. Sample window. To investigate the reasons causing these significant differences of the transmitted solar radiations between the building types and software, first the effects on a south-oriented sample window with sizes of 1.0 m², 5.0 m² and 10.0 m² are compared using the same properties without additional shading elements for both programs. The results suggest that there is a general difference of 239.8 kWh/m²a for EnergyPlus to 382.4 kWh/m²a for GEQ, because of varying climate data sources, a difference of 37% independent of the window size.

Next, the 5.0 m² sample window is examined regarding varying orientation due to a clockwise rotation with a step of 22.5° for a total of 16 different directions. The results for the total annual transmitted solar radiation show, accordingly to the prior findings, for all variations higher values for the software GEQ than for EnergyPlus, but with a varying difference (see Figure 3, a). The biggest gap with 142 kWh/m²a between the results is for the south-facing sample window, while the smallest difference is with 92 kWh/m²a for the north-facing window direction.

This behaviour is also reflected in the results for the monthly transmitted solar radiation of the sample window for a clockwise building rotation between 0° and 180° (see Figure 3, b). It is important to mention that the results for GEQ are mirrored along the north-south axis while the results for EnergyPlus are slightly varying.

![Figure 3. Sample window with varying orientation, no shading: Transmitted solar radiation in kWh/m²a (a) and kWh (b).](image)

The causes for the diverging effects of the transmitted solar radiation are subsequently examined in more detail in view of the application of shading elements, in particular a window overhang as well as a lateral shading caused by the building itself in case of the atrium-style buildings.
The results for the transmitted solar radiation of the south-oriented sample window with an overhang are displayed in Figure 4. Similar to the previous investigations the results for GEQ are in general higher than the ones for EnergyPlus. The difference between the values decreases from 142 kWh/m²a to 68 kWh/m²a with an extension of a directly above the window attached overhang shading to a maximum depth of 3.0 m. Due to the use of shading elements, which are attached higher above the window elements than foreseen in the final building design, also the transmitted solar radiation increases, but with a similar tendency.

Comparing the monthly transmitted solar radiations, Figure 4 shows that with an increased length of the overhang shading element for EnergyPlus also the differences between the variants decrease. Long shading elements between 2.5 m and 3.0 m almost show with an average difference of less than 5 kWh/m²a similar low values for each month throughout the year compared to shorter elements with more than 20 kWh/m²a, while for GEQ the general tendency with an average difference of approximately 25 kWh/m²a remains almost the same.

Figure 4. Sample window with varying overhang shading: Transmitted solar radiation in kWh/m²a (a) and kWh (b).

The results for the transmitted solar radiation of the sample window concerning a lateral shading caused by the building itself in case of the atrium-style buildings are displayed in Figure 5. A south-oriented position for the sample window is selected facing the courtyard with a distance of 4.1 m to the shade producing wall element with a length of 5.8 m.

Figure 5. Sample window with lateral shading and varying orientation: Transmitted solar radiation in kWh/m²a (a) and kWh (b).

The commuted results for the total annual transmitted solar radiation for EnergyPlus show with an average difference of 8 kWh/m²a lower values compared to the sample window without any lateral
shading impact, but the general tendency of the results remains the same. However, the results for GEQ show significant deviations. First, the results for GEQ are also mirrored along the north-south axis as with the sample window without any shading, caused by the use of simplified shading factors for each window element independent of the buildings actual shape. The fact that the sample window should be shaded from different directions with a varying impact, taking the path of the sun as well as the rotation of the building into account, is not considered in this calculation method. Second, the lateral shading has a comparable high impact on the south-oriented directions from south-south-east to south-south-west resulting in lower total annual solar radiation values than for EnergyPlus. This behaviour is also reflected in the results for the monthly transmitted solar radiation of the variants (see Figure 5, b). The main difference especially occurs in the summer time between April and September, when the results for GEQ of the south-oriented variants decrease below the values for EnergyPlus.

4.2.2. Adapted building design. Proceeding from the evaluation of the sample window regarding the influencing parameters of the orientation, the window overhang and the lateral shading, the adapted building designs of the atrium-style buildings and the building compound are also examined in more detail.

The results for the transmitted solar radiation of the adapted building designs are displayed in Figure 6. Especially the tendencies of the atrium-style building with a lateral shading for a rotation of 22.5° (see Figure 5, b) are evident. With more than 60 % of the transparent surfaces facing south-south-west, the values of the transmitted solar radiations are with 174 kWh/m²a for EnergyPlus higher compared to 170 kWh/m²a for GEQ (see Table 3). A simulation without a window overhang results even in a bigger difference of 209 kWh/m²a for EnergyPlus compared to 192 kWh/m²a for GEQ. Additional shading effects in EnergyPlus from overhangs not only to the windows directly below but also to other transparent surfaces especially in the corner of the atrium courtyard, influence the results. This effect in EnergyPlus, which is not automatically considered in GEQ, leads to a slightly higher transmitted solar radiation and in further consequence to a lower heating demand for the atrium-style buildings with EnergyPlus compared to GEQ (see Table 3).

The results for the adapted design of the building compound likewise reflects the prior findings for the sample window (see Figure 6, b). With the buildings original orientation (building rotation of 0°) and without any lateral shading, because of the rectangular building shape, the total transmitted solar radiation is with 39981 kWh/a for GEQ clearly above the calculated value of 23761 kWh/a for EnergyPlus, resulting in 257 kWh/m²a and 153 kWh/m²a (see Table 3).

Figure 6. Transmitted solar radiation for the adapted designs of Atrium East (a) and building compound (b).

5. Discussion
This contribution highlights some of the optimisation results of the ongoing research study for a building project in Austria. It is shown that dynamic simulation tools can be used to optimise the design of buildings and in further consequence also to increase the thermal comfort for the occupants due to the
evaluation of indoor temperatures, while achieving results within the range of the passive house standard for the concurrently calculated Austrian energy certificate. In addition, the use of natural ventilation at night times can help to reduce the risk of overheating during summer.

Comparing the results, differences for the heating demands are identified caused by calculation methods and sources of climate data between the software. The general tendency of the deviations is, however, similar. This applies for the investigated external shading devices apart from effects attributable to south-oriented transparent surfaces of non-rectangular buildings or other objects causing a lateral shading. In these cases, a divergent transmitted solar radiation results in varying calculated heating demands, which has to be considered when applying the proposed optimisation approach.

6. Conclusion
The presented study showed that an optimised building design can lead to an increased thermal comfort for the occupants, while maintaining a low heating demand of the buildings. Nevertheless, it has to be considered that there are deviations regarding the transmitted solar radiations and therefore also for the heating demands depending on the type of shading element – especially for non-rectangular buildings.

Future research efforts involve the reapplication of the procedure to the final design of the buildings, including data pertaining to the definitive version of the selected building products and elements. After the construction stage, a comprehensive building monitoring will be conducted during a trial occupancy phase to validate the simulated results.

Appendices

| Table 4. List of abbreviations. |
|--------------------------------|
| **Abbreviation** | **Definition** |
| ACR             | Air change rate         |
| Cfb             | Warm tempered humid climate |
| CO$_2$          | Carbon dioxide          |
| EU              | European Union          |
| FC              | Free cooling            |
| HSP             | Heating set point       |
| HWB_RK          | Reference climate heating demand |
| HWB_SK          | Location climate heating demand |
| K               | Kelvin                   |
| LCH             | Life Cycle Habitation   |
| PEI             | Primary energy intensity|
| Sim4DLG         | Simulationsunterstützte Designoptimierung Lebenszyklus orientierter Gebäude |

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