Simulation-Supported Design Optimization of Atrium Buildings with Passive Cooling in Austria

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Abstract. This contribution reports on an ongoing research effort within the project Sim4DLG to reduce the energy and resource use in the building sector via design optimization of life cycle-oriented buildings in Austria. To reduce the heating demand and overheating risk in the cold and warm seasons respectively, a simulation-supported optimization strategy was pursued, resulting also in improved ratings in terms of the mandatory Austrian energy certificate. The application includes a range of different building types varying from stand-alone single-family houses to apartments in a multilevel building, using locally available ecological construction materials and renewable energy, with special focus on single-story atrium-style buildings. Natural ventilation scenarios were specifically explored to improve summertime thermal comfort conditions. The results are showing that the method can be used in a circular approach during the design process for reducing the overheating risk, while maintaining the passive house standard according to the Austrian energy certificate.

Keywords: Heating demand · Dynamic simulation · Sustainable buildings

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_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 K (K) above preindustrial level in context with the alarming greenhouse gas emissions [3].

In addition, 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.

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To encounter this demand, the study "Simulationsunterstützte Designoptimierung Lebenszyklus orientierter Gebäude" (Sim4DLG) aims at reducing the energy consumption through a design optimization 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 CO_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 [5]. To this end, a highly resource and energy-efficient building complex (see Fig. 1) is being built in the region of Böheimkirchen, Lower Austria, which is categorized as Cfb (warm tempered humid climate) [6].

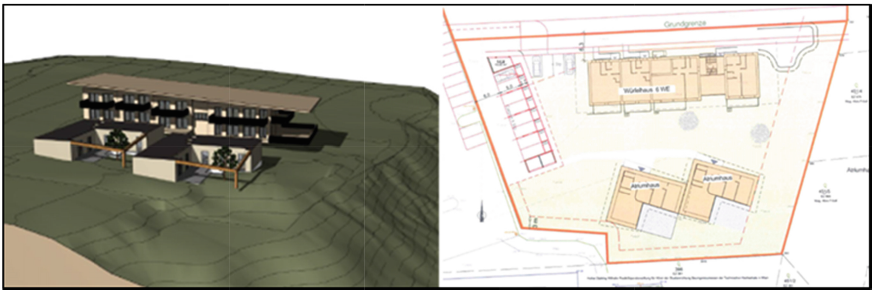

Fig. 1. Left: preliminary draft of the buildings; right: site plan with building compound and atrium-style houses (Arch. Scheicher)

The case study project includes six living units and a community area as well as two single-family houses, which will be realized in different construction styles.

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

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 utilization 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, deconstruction is 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 CO_2 balance of the building [8].

3 Design Optimization of the Atrium Buildings

This contribution presents an ongoing research effort of the project Sim4DLG addressing the design optimization of the atrium-style buildings regarding the reduction of energy and resource consumption as well as an increase of thermal comfort.

Proceeding from the results of the early stage optimization and the design planning [9], the single-family houses will be built in a load-bearing straw bale construction style using big bales with a clay layer on the inside and a lime layer on the outside. The usable floor space will be 107 m^2 containing nine thermal zones (see Fig. 2), namely three bedrooms (Bed1, Bed2, Bed3), a storage room (SR), an entrance hall (EH), a living-kitchen area (LK), a cloakroom (WC), a bathroom (Bath) and a room for installations (TR).

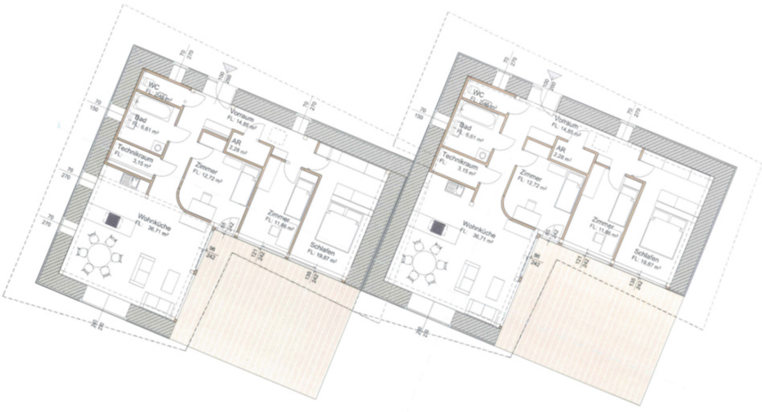

Fig. 2. Floor plan of the atrium-style buildings based on the planning design (Arch. Scheicher)

The buildings are connected for reducing the exterior surface of the building envelope, but vertically shifted in consequence of the building area's slope (see Fig. 3).

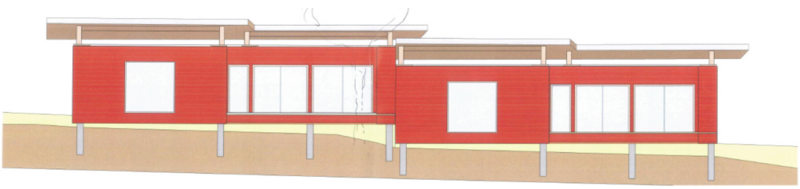

Fig. 3. South view of the atrium-style buildings (Arch. Scheicher)

The highly thermally insulating building envelope (wall = 0.06 W/m^2K; roof = 0.06 W/m^2K; floor = 0.07 W/m^2K) is combined with south-facing triple layer windows (Ug = 0.71 W/m^2K; Uf = 0.91 W/m^2K; g-value = 0.54) and an overhanging roof to improve the performance of the building. This concept will be completed with an innovative energy system based on locally available renewable energies for further reduction of the carbon footprint.

3.1 Methodology

The first performance indicator is the heating demand of the buildings. In order to optimize the performance of the buildings and in consequence also to achieve improved results for the mandatory Austrian energy certificate, a parametric design optimization approach is used, in particular for the architectural design of the buildings. Therefore, the whole building simulation tool EnergyPlus [10] is used in combination with SketchUp [11] and Openstudio [12] (see Fig. 4), while the software GEQ is used for the execution of the concurrently calculated Austrian energy certificate [13].

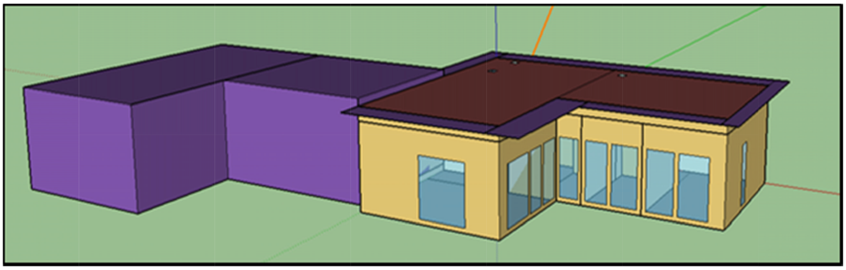

Fig. 4. EnergyPlus geometry model for the atrium-style building located to the east

The simulation model is defined based on standard assumptions and calibrated according to calculation methods of the Austrian energy certificate with a standard heating set point of 20 °C and a fixed air change rate (ACR) of 0.4 h^{-1}. According to the design of the building with three sleeping rooms, four occupants are assumed for the simulation with typical activities varying from sleeping to housecleaning in accordance with the ASHRAE standard [14].

Since the buildings don't have any air conditioning systems and are designed for passive cooling only, the second performance indicator is accordingly the overheating of the building. Due to an analysis and assessment of the indoor temperatures for each variant an overheating of the building should be avoided and the thermal comfort increased.

The variables for the parametric optimization of the windows are illustrated in the following Table 1. The windows facing the courtyard have fixed sizes because of structural reasons and are therefore excluded from the optimization process. The windows in the northwest corner of the buildings are replaced by solar tubes in the roof. An additional window in the northeast corner of the building is included in the simulations to examine the effect of a panoramic view of the surrounding countryside.

Table 1. Window width variables for parametric simulation

Building	EH-NNE [m]	Bed1-NNE [m]	Bed1-EES [m]	LK-SSW [m]	LK-WWN [m]
Atrium East	0.0–1.4	–	0.0–2.2	0.0–2.2	–
Atrium West	0.0–1.4	0.0–1.4	–	0.0–2.2	0.0–2.2

Table 2 is showing the parametric optimization variables for the overhang of the roof. A more detailed step of 0.1 m is used for the overhang, while the window width is dependent on the grid of the load-bearing straw bales measuring 0.8 m.

Table 2. Overhang depth variables for parametric simulation

Building	NNE [m]	EES-1 [m]	EES-2 [m]	SSW-1 [m]	SSW-2 [m]
Atrium East	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5	0.5–1.5
Atrium West	0.5–1.5	–	0.5–1.5	0.5–1.5	0.5–1.5

3.2 Heating and Ventilation Scenarios

In a second step, different heating and ventilation scenarios are applied to the optimized standard heating set point (HSP) building model in EnergyPlus to estimate the performance effect as well as the impact on the indoor climate respectively on the thermal comfort [15].

In the adapted heating set point building model 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. Accordingly also setback temperatures for night times between 11 pm and 7 am are considered. The set points for the different thermal zones are shown in Table 3.

Table 3. Adapted temperature set points

Temperatures	Bed1	Bed2	Bed3	SR	EH	LK	WC	Bath	TR
Set point [°C]	18	20	20	5	22	22	22	24	5
Setback [°C]	18	18	18	5	16	16	16	16	5

Furthermore, for the standard heating set point model natural ventilation is considered for the summer period from 1st of May until 30th of September to investigate the overheating reduction possibilities. The low free cooling building model contains a rush airing (ACR = 3 h^{-1}) in morning and evening times as well as ventilation with tilted windows (ACR = 1 h^{-1}) during the night, while the high free cooling model includes also a higher night time ventilation (ACR = 3 h^{-1}). It is assumed that the natural ventilation is operated by the occupants. To avoid an overcooling of the building during the night, a minimum indoor activation temperature of 19 °C is set, defined from the setback temperature for sleeping environments of the adapted heating set point building model plus 1 K.

4 Results

4.1 Passive House Standard

With the overall goal of achieving a heating demand HWB_RK of maximum 15.0 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 are showing results between 14.1 and 16.3 kWh * m^{-2} for the concurrently computed heating demand HWB_RK with the software GEQ. Variants with a HWB_RK above 15.0 kWh * m^{-2} are excluded. Especially variants with additional north-facing windows are exceeding this value. Therefore a model with huge south-facing windows for high solar gains (see Table 4) and large overhangs to prevent overheating (see Table 5) is suggested.

Table 4. Optimization results for window width variables

Building	EH-NNE [m]	Bed1-NNE [m]	Bed1-EES [m]	LK-SSW [m]	LK-WWN [m]
Atrium East	0.0	–	0.6	2.2	–
Atrium West	0.0	0.0	–	2.2	0.0

The suggested model with a computed reference climate heating demand (HWB_RK) of 15.0 kWh*m^{-2}, which is within the threshold value, is showing with 1851 and 1901 the smallest numbers of hours for indoor temperatures above 26 °C (see Table 6), compared to the average value of 1975 h and the maximum of 2227 h considering all simulated variants.

4.2 Heating and Ventilation Scenarios

In the following section the above-mentioned heating and ventilation scenarios to estimate the performance effect and the impact on the indoor climate are described in more detail. An overview of both atrium-style buildings is given in Table 7. This includes the calculated heating intensities by EnergyPlus as well as the sum of hours of the indoor temperature above 26 °C for the entire year and for the summer season only.

Table 5. Optimization results for overhang depth variables

Building	NNE [m]	EES-1 [m]	EES-2 [m]	SSW-1 [m]	SSW-2 [m]
Atrium East	1.0–1.5	0.7	1.5	1.0	1.2
Atrium West	1.3–1.5	–	1.5	1.0	1.3

Table 6. Time with indoor temperatures >26 °C for optimized standard HSP model

Building	Bed1 [h]	Bed2 [h]	Bed3 [h]	SR [h]	EH [h]	LK [h]	WC [h]	Bath [h]	Zones 1–8 [h]
Atrium East	1287	1602	1318	865	715	1786	382	976	1901
Atrium West	935	1527	1265	761	628	1748	347	940	1851

Table 7. Scenario results for building model with heating demand HWB_RK of 15.0 kWh * m^{-2}

Scenario	EnergyPlus heating intensity	Hours with temperatures >26 °C for zones 1–8	
	[kWh * m^{-2}]	All year [h]	Summer period [h]
Standard HSP Atrium East	16.64	1901	1689
Adapted HSP Atrium East	23.90	1938	1692
Low free cooling Atrium East	16.60	922	709
High free Cooling Atrium East	16.73	344	133
Standard HSP Atrium West	16.65	1851	1657
Adapted HSP Atrium West	24.03	1894	1666
Low free cooling Atrium West	16.62	879	684
High free cooling Atrium West	16.63	410	215

The indoor temperatures of the Atrium East building for the standard heating set point scenario with a temperature set point of 20 °C are illustrated in Fig. 5 for the different thermal zones, while the ones for the adapted heating set point scenario with more common temperature set point values are displayed in Fig. 6.

The HSP model shows wider variations depending on the selected set point values with a reduced night time temperature of 16 °C and increased daytime temperatures for selected zones. As a result, the computed heating intensities in EnergyPlus would increase by 7.26 kWh * m^{-2} for the east and by 7.38 kWh * m^{-2} for the west building model and the total number of indoor temperatures above 26 °C would also increase slightly.

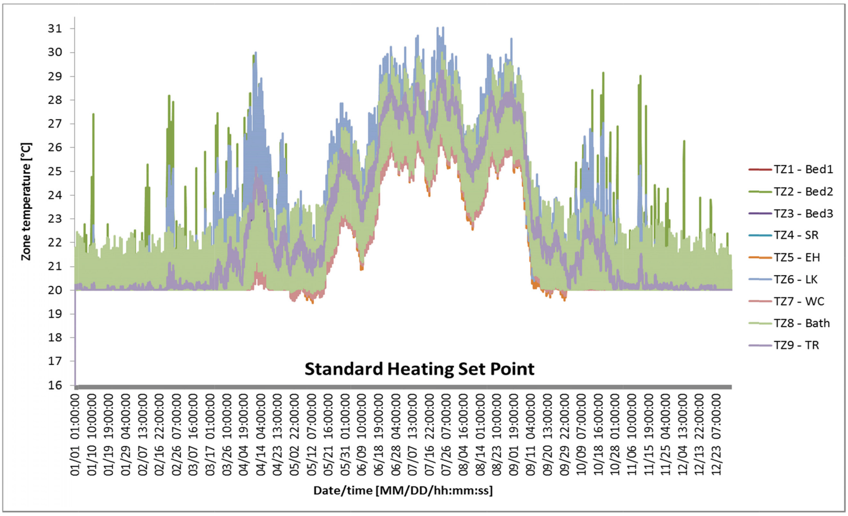

Fig. 5. Indoor air temperatures for the Standard HSP model of the Atrium East building

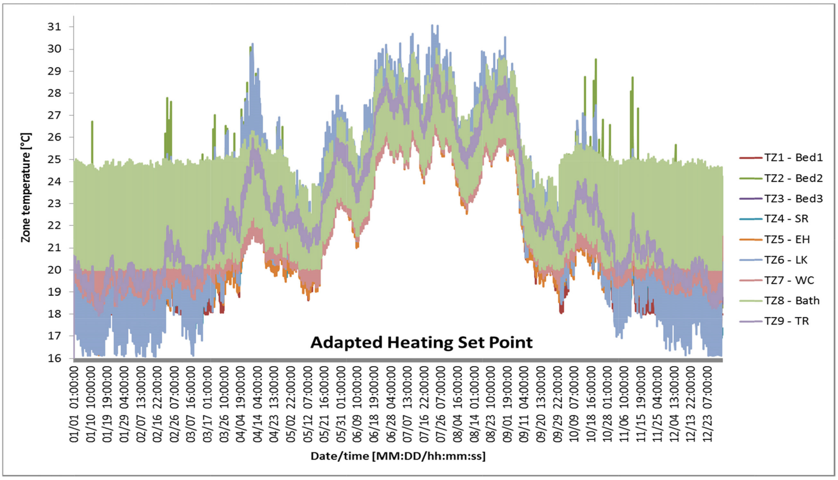

Fig. 6. Indoor air temperatures for the adapted HSP model of the Atrium East building

In contrast, due to the application of natural ventilation in the standard heating set point model in the summer period, a significant reduction of the indoor temperatures can be achieved.

This results in a decrease of 51.5% to 922 h for the low free cooling model of Atrium East and of 52.5% to 879 h for Atrium West considering the timespan of the entire year, while for the summer period reductions of 58.7% to 684 h and of 58.0% to 709 h can be achieved (see Fig. 7).

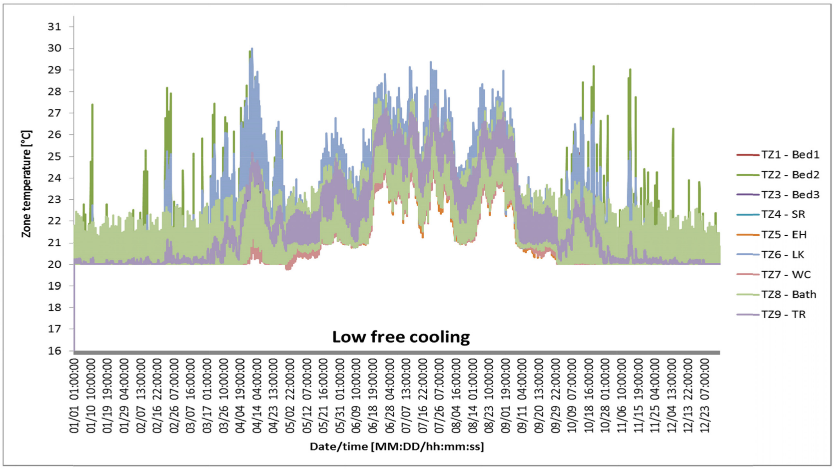

Fig. 7. Indoor air temperatures for the low free cooling model of the Atrium East building

For the high free cooling model even reductions by 81.9% to 344 h for Atrium East and by 77.8% to 410 h are possible for the whole timeframe, caused by the higher ACR especially during the night, whereas in the summer period decreases by 92.1% to 133 h and by 87.9% to 215 h are achievable (see Fig. 8).

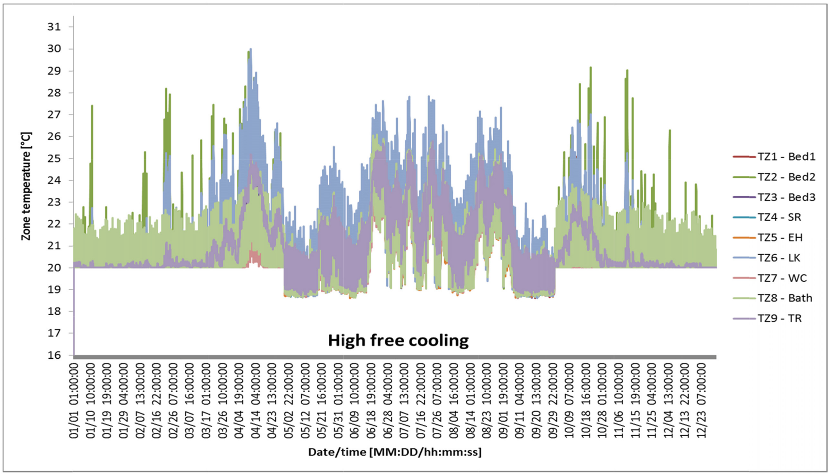

Fig. 8. Indoor air temperatures for the high free cooling model of the Atrium East building

5 Discussion

This contribution is highlighting some of the optimization results of the ongoing research study regarding the atrium-style buildings of the project Life Cycle Habitation in Austria. In this circular optimization approach proceeding from the preliminary design, it is shown that dynamic simulation tools can be used for a design optimization of the buildings to increase the thermal comfort for the occupants by investigating the indoor temperatures and therefore preventing an overheating of the buildings, while at the same time improved results for the concurrently calculated energy certificate can be achieved. In addition, especially by use of natural ventilation at night during summer time, the risk of overheating can be reduced significantly.

6 Conclusion

The presented study showed that an accurate design of the building openings and shading elements can reduce indoor air temperatures in the atrium-style case study buildings while maintaining a low heating demand. Furthermore, the 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 applied to the living units of the two-story building. After construction a comprehensive building monitoring will be executed during a trial living phase to validate the simulated results.

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