Applied Mechanics and Materials
ISSN: 1662-7482, Vol. 887, pp 353-360
doi:10.4028/www.scientific.net/AMM.887.353

Submitted: 2017-06-08
Revised: 2017-07-25
Accepted: 2017-07-25
Online: 2019-01-25

Simulation-Supported Early Stage Design Optimisation for a Case Study of Life Cycle Oriented Buildings

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Keywords: Heating demand, dynamic simulation, energy-efficiency, sustainable building, energy certificate

Abstract. To reduce the energy and resource consumption in the building sector this study is focusing on a design optimisation of life cycle oriented buildings. In order to optimise the performance of the buildings and in consequence also to achieve improved results for the mandatory Austrian energy certificate a simulation-based rapid design approach is used for the early stage design phase of the buildings, in particular for the architectural design of the buildings.
Methods like the Window to Wall Ratio, at the very beginning of the design process, a parametric simulation with EnergyPlus or a more detailed optimisation approach with GenOpt are integrated in this study applied to example buildings. The results are showing that the method can be used in a circular approach for improving the heating demand of the Austrian energy certificate for this case study by more than 25 % compared to the preliminary design.

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.

Energy for space heating and increasingly for space cooling is needed especially for buildings of low energetic standard. Furthermore, energy for domestic hot water and appliances (such as kitchen appliances, washing machine, light sources and other electrical equipment) is required. 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.

With its high consumption of energy and thus mostly fossil fuels for the majority of processes, the building sector is also one of the largest perpetrators of CO_2 emissions. In addition, it produces construction waste as a consequence of demolition or remodelling of buildings as well as at the construction site (packaging, plastic pipes, clippings of insulation materials etc.), which is difficult to recycle or dispose of. The aspects of deconstruction, recycling and disposal were particularly focused in Austria due to a massive increase of building waste in the last years [2]. Although, according to the "Federal Waste Management Plan 2011" by the Ministry of Life [3], the total amount of waste decreased by 500,000 t to 53,543,000 t, waste from the building sector still accounts for 12.7 % of total waste in Austria (6,870,000 t). A prognosis for 2016 foresees an increase to 7,395,000 t.

The demand for alternative solutions is also stated by a recently introduced supplementary document in addition to the waste framework directive 2008/98/EG, which supports the goal of a minimum recycling rate of 70 % of non-hazardous construction and demolition waste until 2020 [4]. This document also includes duties for the demolition of buildings approved after the 1st of January 2016 regarding the separation of materials to prepare for the re-use of high-quality recycling materials.

Beyond that, the concluded Paris Agreement in 2015 with the goal of a global average temperature increase of below 2 K above preindustrial level in context with the alarming greenhouse gas emissions is supporting the demand for improvements and new strategies in the field of construction [5].

To encounter this demand, the study "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 [6].

In a first step a simulation-based rapid design approach is used for the early-stage design phase. This part of the study is carried out in the framework of the EU Life project "Life Cycle Habitation", 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 [7]. To this end, a highly resource and energy-efficient building compound is being built in Böheimkirchen, Lower Austria.

Building Concept

Preliminary Design. The case study project, as shown in the preliminary draft and the site plan (Fig. 1), consists of a building compound, which includes 6 living units and a community area, as well as 2 single-family houses. The building compound will be designed as a 2-storey non-load-bearing straw bale construction in style of the neighbouring award winning S-House [8] and includes 2 row houses with a usable floor space of 107 m² each and 4 apartments with sizes between 55 and 90 m². The single-family houses, which have a usable floor space of approximately 107 m² as well, will be realised as compact flat-roof buildings in a 1-storey atrium-style load-bearing straw bale construction. Including the community area, in total building units with a usable floor surface of approximately 710 m² will be constructed in an optimised and energy-efficient way.

Figure 1: *Left: site plan with building compound ("Gebäudeverbund") and single-family houses ("Atriumhaus"); right: preliminary draft of the buildings (Arch. Scheicher)*

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, 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 PEI as well as a positive effect for the CO_2 balance of the building [9]. For this project 2 different types of wood-straw bale construction will be realised. The first variant, for the building compound, consists of prefabricated non-load-bearing straw bale modules, which will be attached to a wooden structure. The second variant, for the atrium houses, will be a load-bearing straw bale construction made of big bales with a clay layer on the inside and a lime layer on the outside. Triple layer windows and an overhanging roof improve the performance of the building envelopes. This concept will be completed with an innovative energy system based on locally available renewable energies for further reduction of the carbon footprint.

Location and Climate. The case study buildings are located in Böheimkirchen, Lower Austria. The exact coordinates of the construction site are latitude at 48.19°, longitude at 15.75° and an average altitude of 245 m. With average monthly air temperatures between 0.2 and 20.9 °C and average monthly relative humidities between 62 and 79 % Böheimkirchen has a temperate climate [10]. According to the Köppen-Geiger classification the north-eastern region of Austria is categorised as Cfb (warm tempered humid climate) with the warmest month lower than 22 °C in average and four or more months above 10 °C in average [11]. The annual precipitation is in total approximately 670 mm, while the monthly values are varying between 30 and 80 mm. The annual average mean irradiance of global radiation horizontal is 134 W/m² for Böheimkirchen according to the Meteonorm climate data.

Methods

In order to optimise the performance of the buildings and in consequence also to achieve improved results for the mandatory Austrian energy certificate a simulation-based rapid design approach is used for the early stage design phase of the buildings, in particular for the architectural design of the buildings. In this approach the whole building simulation tool EnergyPlus [12] by the U.S. Department of Energy is used in combination with SketchUp [13], Openstudio [14] and GenOpt [15] for different optimisation methods, while the software GEQ by Zehentmayer Software GmbH is used for the execution of the concurrently calculated Austrian energy certificate [16].

For the time being, the study is focusing on the optimisation and analysis of the atrium-style compact flat-roof buildings based on the preliminary design.

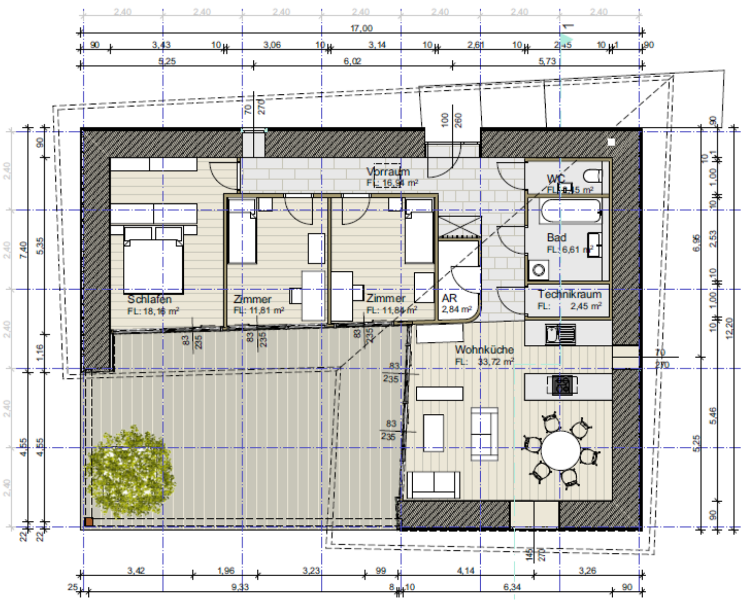

Figure 2: *Floor plan of the atrium-style building based on the preliminary design (Arch. Scheicher)*

There is a variety of options how a building can be improved even with these preselected tools, but the biggest effects during the early stage design phase can be achieved in general by improving the building shape, the orientation of the building, the type of thermal insulation, the size and position of the transparent building elements as well as by appropriate shading [17].

Methods like the Window to Wall Ratio at the very beginning of the design process, a parametric simulation with EnergyPlus or a more detailed optimisation approach with GenOpt are integrated in this study:

Window to Wall Ratio. In the first optimisation approach the general ratio of transparent to opaque building elements of the preliminary draft is analysed in order to change the sizes of the south and east oriented windows, which are facing the courtyard. A simple and easy-to-handle tool to do so is the Open Studio User Scripts Extension "Set Window To Wall Ratio", which can be used while creating the geometry of the building in SketchUp instead of drawing the windows manually.

For this method it has to be taken into account that the results in EnergyPlus can differ, even if the transparent surface area is the same, due to varying solar gains caused by the diverging shape and arrangement of the fenestration surfaces. Such differences are shown in Fig. 3.

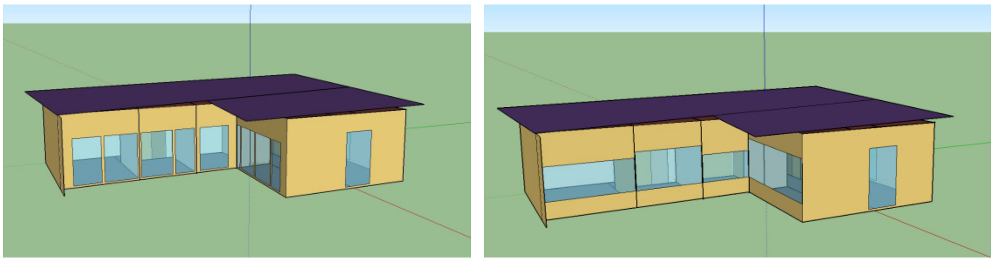

Figure 3: *Window to Wall Ratio application for the same transparent surface area: Left: preliminary design; right: Window to Wall Ratio function*

Orientation. In the second approach the parametric modelling function of EnergyPlus is used for identifying the optimal orientation of the current building model. The simulation can be performed for example with a clockwise rotation of a defined step starting from the north axis until a complete turn of 360°. If the simulation is to be compared with the energy certificate calculation, it has to be taken into account that the direction of the building can only be selected from a maximum of 16 points of the compass.

Detailed Window Optimisation. In the third approach EnergyPlus is used in combination with GenOpt for a detailed window optimisation to achieve a minimum heating and cooling demand for selected thermal zones of the building. This method can be used for example for improving the size and general position of the elements, but also for supporting the selection of materials and appropriate shading like an overhanging roof or the operation of a mechanical shading device [18].

Results

The starting point for the optimisation process is the energy certificate of the preliminary design (see Fig. 2). Since the final concept for the housing technology is not selected at this early design stage, an envisaged concept is used for all energy certificate calculations during this stage for a comparable evaluation of the results. This concept includes solar collectors in combination with district heating from cogeneration, an efficient heating system with a heat recovery of 90 % and a floor heating system for higher comfort. Due to the use of big straw bales for the atrium houses, the building elements show outstanding thermal properties with U-values of 0.060 W/m²K for the exterior wall, 0.068 W/m²K for the baseplate and 0.064 W/m²K for the roof construction. They are supplemented with ecological solid wood frames and triple glazing components for the windows selected from the Austrian Baubook database [19].

The results for the preliminary design with an orientation to the north and an A/V of 0.82 show a value of 20.1 kWh/(m²a) for the heating demand including heat recovery (HBW_{RK}) according to the Austrian energy certificate (see Table 1, preliminary design).

Applying the methods for optimisation of the building in the early design stage may happen in a more linear approach, but can also take place in multiple phases, depending on the specific design or e.g. in case of an alternative building geometry or boundary.

Phase 1. A first and rapid analysis method of the general preliminary design is the Window to Wall Ratio, which can also be combined with a slight rotation of the building according to different orientations of the houses using the parallel simulation method.

For the EnergyPlus simulation the materials and constructions of the opaque building elements were used according to the energy certificate of the preliminary draft, while for the fenestration surfaces a simplified triple glazing construction from the EnergyPlus database without frame was applied. Beyond that, objects for occupancy, people activity and infiltration were used in the model including an HVAC system for all zones except storeroom (AR) and technical room (TR) with a heating temperature set point of 20 °C.

This first analysis shows that the comparatively large window surfaces of the preliminary draft result in the lowest heating energy demand, as does the maximum applied rotation of 20° starting from north orientation.

In a next step, EnergyPlus in combination with GenOpt is used for optimising the sizes of the south and west oriented windows in the sleeping and living rooms. The goal is a minimum heating demand for the selected zones with a constant heating set point of 20 °C and a constant cooling set point of 40 °C for all zones, since there should be no active cooling device in the building.

The result of the optimisation suggests an increase of the transparent surfaces in the thermal zones which are situated along the building envelope, while the windows in the 2 thermal zones which are situated in the centre of the building and are therefore surrounded by conditioned zones should be slightly reduced. This results in a total reduction of the transparent surfaces by 1.39 m².

The HWB_{RK} of the energy certificate is only slightly increased to 20.3 kWh/(m²a) after the optimisation (see Table 1, final phase 1), in general because the energy certificate software only takes into account the whole building envelope with the general orientation of the transparent surfaces, independent of the different thermal zones. Due to the reduced surfaces also the solar gains are less.

Phase 2. In a next step the general floor plan of the atrium buildings was changed because of modified building product dimensions and to be able to use the brick construction method for the load-bearing straw bale walls to achieve a higher stability. A more compact energy-efficient variation was selected with a slightly bigger gross floor area (GFA) and an A/V of 0.8 due to a modified distribution of the rooms. As a side effect also the sizes and locations of the windows were slightly changed. The HWB_{RK} for the initial design of phase 2 was reduced to 18.6 kWh/(m²a) (see Table 1, initial phase 2).

As the development of the building design progresses, further elements are added which make a more detailed EnergyPlus simulation possible, such as lights and other internal gains as well as more appropriate window constructions including frames by selecting materials from the international glass data base (IGDB) by using the window creator program window 7.4.

The sizes of the fenestrian surfaces were improved same as in phase 1. In the next step the parametric modeling function of EnergyPlus was used for optimising the orientation of the current building model. The simulation was performed with a clockwise rotation step of 2.5° starting from the north axis until 90°. The lowest heating demand for this model was simulated at a rotation of 75°.

Through a further extension of the south oriented transparent building elements the solar gains can be increased and as a result the heating demand for the building according to the Austrian energy certificate can be further reduced. But it has to be noted that the cooling demand is not considered for residential buildings in the mandatory energy certificate and that there are almost no shading devices in the current model so far. This results in a high risk of overheating of the building during hot periods in summer. Accordingly the EnergyPlus model is simulated with a theoretical cooling set point of 30 °C together with an optimisation of the window sizes and an optimisation of the window overhang for appropriate shading especially for the south oriented windows.

The optimisation is also reflected in the calculation result of the Austrian energy certificate with an HWB_{RK} of 16.8 kWh/(m²a) (see Table 1, interim phase 2).

As a consequence of the optimisation results the design of the roof was modified. The roof overhang for the south east and south west oriented windows facing the courtyard is extended to prevent overheating (see Fig. 4).

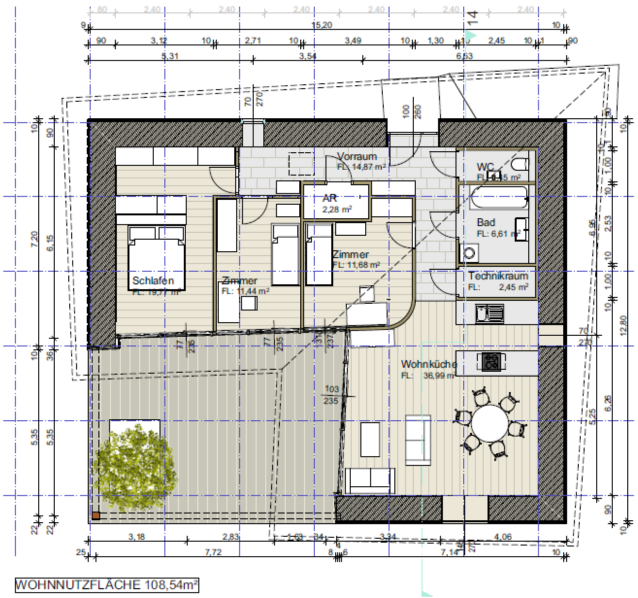

Figure 4: *Optimised temporary floor plan (Arch. Scheicher)*

In a further step of improving the building another shading element is necessary in addition to the overhang, for example either natural shading by the surrounding, which cannot be guaranteed at the moment, or a mechanical shading device like external shades.

GenOpt was therefore also used to define the operation set point of external shades to reduce the heating load. Since the average radiation capacity for the location is 137 W/m² the simulation was executed for a range between 125 and 175 W/m².

The optimisation of the operation for the set point of the shades in combination with the overhanging roof shows that on the one hand the depths of the roof shading should be reduced in order to increase the solar gains for the south east and south west oriented windows, while on the other hand the operation set point for the shades should be raised in the upper range to prevent overheating only during hot periods. A further reduction of the HWB_{RK} to 15.6 kWh/(m²a) was possible through this combined optimisation approach (see Table 1, final phase 2).

Phase 3. In a final design approach the atrium houses are relocated and connected in order to decrease the exterior wall surface for a further reduction of the heating demand (see Fig. 5). As a consequence the buildings are not anymore identical and have deviating A/V values (see also Table 6). Furthermore the eastern building still has a window facing north east, while the western building has a comparable window facing south west.

The combined optimisation approach applied in phase 2 for the window sizes, depth of the overhang roof and the operation of the external shades is then repeated in this optimisation phase 3 for each thermal zone of the 2 buildings. The optimisation results show similar but slightly deviating values, which are then modified in oder to unify and simplify the construction as well as the operation of the buildings.

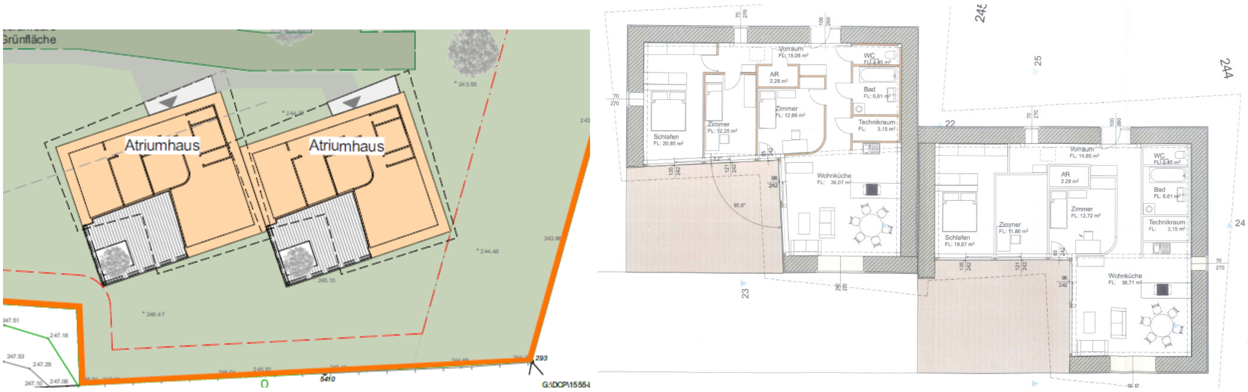

Figure 5: *Connected buildings of phase 3: Left: site plan; right: floor plan*

In total the heating energy demand for the energy certificate was decreased from 20.1 kWh/(m²a) to 14.2 (see Table 1, final phase 3 east) and 13.9 kWh/(m²a) during this simulation-supported early stage design phase (see Table 1, final phase 3 west).

Table 1: *Energy certificate results*

Model	Orientation	GFA [m²]	A/V [1/m]	lc [m]	HWB rk [kWh/(m²a)]	EP heating and cooling intensity [kWh/(m²a)]
Preliminary design	N	148	0.82	1.22	20.1	45.22
Final phase 1	N	148	0.82	1.22	20.3	45.19
Initial phase 2	N	152	0.8	1.25	18.6	41.97
Interim phase 2	ONO	152	0.8	1.25	16.8	38.66
Final phase 2	ONO	152	0.8	1.25	15.6	35.31
Final phase 3 east	ONO	152	0.76	1.32	14.2	34.75
Final phase 3 west	ONO	152	0.75	1.33	13.9	34.22

Conclusion

At this early stage of a design process there is in general not enough information available for performing a detailed simulation of the whole building. This is the reason why during the entire process simplified models are used, which are getting more precise during the process. Therefore the optimisation results of EnergyPlus cannot be compared directly with the concurrently executed energy certificate, but they can be used to show a tendency for improving the results in a circular approach during the designing process towards an energy-efficient building.

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