Simulation-based optimization of energy performance with focus on sustainable building services engineering

Daniel Kierdorf[1], Farzan Banihashemi[1], Hannes Harter[1], Michael Vollmer[1], Werner Lang[1]

[1]Institute of Energy Efficient and Sustainable Design and Building, Technical University of Munich, Arcisstr. 21, 80333 Munich, Germany

daniel.kierdorf@tum.de

Abstract. The aim of this study is to compare and validate a building energy simulation model of a university building with monitored data. In addition, different building services engineering concepts are compared with each other regarding their ecological life cycle-based performance using Life Cycle Assessment (LCA) methods. Optimizing these performances regarding sustainability indicators plays an essential role in realizing a climate-neutral building stock. A university building from the 90s, which consists of almost 900 thermal zones, is used as a case study. Detailed heating consumption data are available for the inspected building and are compared to the simulation results. Different energy supply concepts are first subjected to conducting LCA and then to a detailed energy performance simulation. This paper presents a procedure that enables decision-makers to examine building services engineering issues and to derive conclusions in a time-saving manner regarding appropriate sustainable actions. The focus on sustainable energy supply systems is an essential milestone for the realization of climate-neutral building stocks. The scientific innovation is in the detailed reproduction of the existing building and the comparison between simulation data and real-time data as well as an innovative and experimental approach to building and Heating, ventilation, and air conditioning (HVAC) system simulation.

1. Introduction

To counteract climate change, Germany has set itself the goal of being climate neutral by 2050. To achieve this goal, the building sector plays an essential role, as it is responsible for about one-third of final energy consumption, about 40% of energy-related global CO_2 emissions, and about and 45% of total waste generation. [1] [2]

Through the use of Building Energy Simulations (BES) and optimization as well as the application of LCA, buildings can be designed and implemented in a more energy-efficient and sustainable way. Parameter studies can be used to identify influential parameters and optimize efficient system operation.

In order to be able to carry out a holistic consideration (from the construction phase along with the use phase to the disposal phase), ecological data are integrated into the parametric planning and design process. In order to demonstrate the potential of this approach, an existing campus building is modeled and simulated using the simulation software IDA ICE.

It has already been shown that the energy performance gap between simulation and reality is minimal. Other plant concepts considered suggest that the focus on the sustainability of the plant concepts can contribute to a significant increase in the efficiency of the building.

This research aims to create a BES model that corresponds to the actual monitored building. In addition, a sustainable energy supply concept is going to be implemented into the BES model to optimize the energy consumption of the building. This study shows how existing buildings can be optimized for a climate-neutral building stock and how alternative energy supply systems focusing on sustainability can be planned and implemented in a time-saving manner.

2. Comparison between the actual building and the BES model

The investigated university building is located in Munich. The campus building was built in 1996 and corresponded to state of the art of its construction time regarding the building envelope as well as the building services. The heat supply is based on a connection to the district heating network of the state capital Munich. The average heating energy demand for the years 2017 - 2019 is 2,275.12 MWh/a. The building has a net floor area of 67,220 m². This results in a specific heating energy demand of 33.85 kWh/m²yr.

The simulation model consists of almost 900 thermal zones with 14 different usages (e.g., offices, laboratories, lecture halls). The boundary conditions of the BES model are set based on the zone usage and according to DIN 18599-10 [3]. This standard focuses on the calculation of the usable, final, and primary energy demand for heating, cooling, ventilation, domestic hot water, and lighting of buildings by using energy balances. DIN 18599-10 defines the presence times of occupants, full usage hours, air exchange rates, and internal loads based on different types of usages.

The investigated university building is complex and consists of too many thermal zones for performing parametric runs and numerical optimizations in a time saving manner. Hence, to reduce the computational complexity, in a first step a detailed BES was modelled. Afterwards, the detailed model was simplified with Model Order Reduction (MOR) techniques. A MOR based on time series clustering with the clustering algorithm k-means was conducted. The MOR groups similar behaving zones based on the simulation results of the original model, for instance, indoor air temperature, operative temperature, and the hourly energy load of each thermal zone. The dimension of the simulation results was reduced through an autoencoder to perform the time series clustering. The MOR significantly reduces the simulation time. The Reduced Order Model (ROM) was validated by comparing the simulation results with the detailed model. The ROM is utilized for the simulations and optimizations in the next step.

The simulated specific heating energy demand of the reduced model is 29.46 kWh/m²yr and is 12.97% lower than the monitored data for the year 2019. The deviation is relatively low and can be due the assumptions based on the DIN standard, which derives from reality. Therefore, the BES model can be used as a digital replica of the existing building for further considerations.

3. Methodology

The methodology is based on strategies for increasing the energy efficiency of complex public properties with a focus on university properties. The methods build on the findings of a previous research project called HoEff-CIM [4]. In addition, the building service systems are subjected to a sustainability assessment using LCA in order to identify the most sensible and sustainable energy supply concepts possible.

The methodical approach is divided into two main parts. The first part deals with the identification of sustainable energy supply concepts. Established supply concepts are evaluated and compared from a sustainability point of view. In a second step, the resulting concept is transferred into the BES model. With the help of parameter studies and optimization procedures, the simulation results are compared with the actual building, and the corresponding savings potential is shown.

3.1. Sustainability assessment of energy supply systems

Nowadays, there is a multitude of energy-efficient building technology systems. However, these are rarely put into a sustainable context. Based on this idea, different supply concepts are evaluated in terms of sustainability using LCA. Through this, it is shown which systems have a low impact on our ecosystem in addition to high energy efficiency.

An analysis of all current energy supply systems is made with regard to their theoretical and general suitability for climate neutrality. This includes data on efficiency but also LCA data that consider the whole life cycle of system components. Data from the current standardization as well as from the German LCA database Ökobaudat are used. [5] [6] [7] [8] [9]

The systems are evaluated according to the following criteria:

1. Feasibility: It is necessary to weigh up whether an energy supply concept for a building is fundamentally feasible. This is a knock-out criterion. If a supply concept is not fundamentally feasible, it is not considered further (e.g., ground collectors in inner-city areas because there is not enough space available)
2. Efficiency: The efficiency of the individual systems is compared in an appendix of characteristic values. These include: Efficiency, annual utilization factor, seasonal performance factor, coefficient of performance, energy efficiency ratio, and seasonal energy efficiency ratio
3. Resource use: The resource use for the life cycle phases A1-A3 (manufacturing phase or production), B6 (energy use during use), and C3 (waste treatment) is considered
4. Environmental impact: The environmental impact is considered for the life cycle phase A1-A3 (manufacturing phase or production), B6 (energy input during use) and C3 (waste treatment) using the indicator Global Warming Potential (GWP) [CO_2-eq.], total primary energy demand from non-renewable energy sources (PENRT) and renewable energy sources (PERT). These calculations are based on the Ökobaudat data set.

In addition to the standard variants (e.g., gas condensing boilers, oil boilers), variants with a focus on renewable energies (e.g., heat pumps) are included in the analysis. The following system concepts are considered in this analysis: boiler (oil, natural gas, biomass), heat pump (ground source, brine/water, ground collector, air), combined heat, and power plant.

The first evaluation criterion is the theoretical feasibility of the system concept. For instance, since an extremely large amount of biomass is required in this building scale, biomass concepts are not considered. The situation is similar for system concepts based on ground collectors. These are unrealistic in this order of magnitude and are also not investigated. In addition, it is an existing building and the implementation of geothermal exchanges below the building (e.g. borehole heat exchangers or energy piles) are difficult to hardly feasible.

The second evaluation criterion looks at the efficiency of the plant concepts. Here, air-source heat pumps and combined heat and power plants are not considered further due to their lower efficiency.

The third and fourth assessment steps are the use of resources and the environmental impacts within the life cycle (phases A1-A3, B6, and C3 - see list above). At this point, the ground source heat pump (or geothermal heat pump, heat pump connected to a dynamic aquifer) performs best, as it has the lowest primary energy demand and at the same time the highest renewable primary energy demand. The GWP also performs best compared to the other variants. Since the ground source heat pump was identified as the most suitable and sustainable system in this evaluation matrix, it will be transferred to the simulation model in the next step. Since the building has large roof areas, solar thermal collectors for hot water production are also considered. These are not considered in the sustainability assessment.

3.2. Building energy simulation and optimization

BES is used to identify potential savings in new and existing buildings. For this process, a building and plant concept must be mapped in as detailed as possible. The object of investigation with the corresponding plant technology is simulated using the simulation software IDA ICE (www.equa.de).

For the initial situation of the simulation, standard components (sensible thermal storage tank for hot and cold water, solar thermal flat plate collectors, one water-to-water heat pump each for heating and cooling) are used within the simulation software. The dimensioning and design of the initial situation corresponds to the recognized rules of technology and standardization (German and international standardization).

Within the model, parameters are set to perform parameter studies and optimization procedures. The parameters considered are solar thermal area, heat pump capacity (heating and cooling), thermal storage volume (hot and cold).

Here, the choice of the appropriate optimization algorithm is an essential factor to achieve the greatest reduction of the objective function [10]. Optimization algorithms that require a smooth function without gaps may fail on a discontinuous objective function and not determine the desired optimum. [11]. If the complexity of the optimization problem increases (e.g. due to number of objective functions), the probability of a discontinuous objective function also increases. For this reason, an objective function is chosen that pursues a reduction of the heating energy demand. The optimization is done in two steps. In a first step, the proximity of a global optimum is identified using a stochastic optimization method (PSO - Particle Swarm Optimization). A deterministic optimization based on this starts at the endpoint of the stochastic optimization and yields the real numerical optimum of the objective function. For this purpose, a Hooke-Jeeves algorithm is used. [12] [13]

4. Results

The results are divided into two parts. The first part considers the simulation and optimization results. The second part deals with the comparison between the real building and the simulation model.

4.1. Building energy simulation and optimization results

Two optimization procedures were carried out with regard to the absolute energy demand and the heating energy demand. As an example, the correlations within the simulation data are shown on the basis of the absolute energy demand in Figure 1. The lower the correlation between two parameters, the lower the determined correlation coefficient (blue plot). As the correlation between the parameters increases, the correlation coefficient increases (red plot). The considered parameters are sensible thermal storage hot (WATER-VOLUME-W), sensible thermal storage cold (WATER-VOLUME-C), area of solar thermal collectors (AREA_SOL), power consumption of heat pump for heating (P_H), power consumption of heat pump for cooling (P_C).

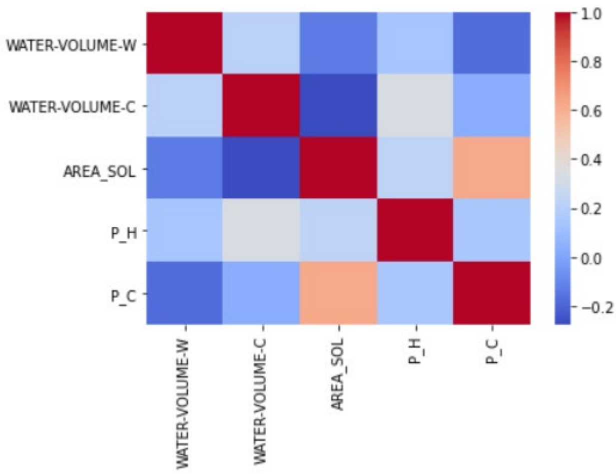

Figure 1. Heat map of Correlations between parameters set in the simulation model

The objective function of the optimization pursues the goal of a low heating energy demand. These simulations revealed that there is a significant correlation between the surface area of the solar thermal collectors (AREA_SOL) and the heat pump performance for cooling (P_C). No significant correlation was found between the other parameters investigated. Figure 2 shows the correlation between these two parameters. Further simulations showed that a greater solar thermal surface area causes a lower heating energy demand, respectively, a lower electrical energy demand caused by heat-pump systems. Since an increase in the solar thermal collector area leads to higher power consumption of the cooling heat pump, a suitable optimum is identified within this scope.

4.2. Comparison between the real building and the simulation model

The specific heating energy demand can be reduced to 17.43 kWh/m²a after optimization of the plant technology. Thus, the investigations show that a theoretical energy saving of the heating energy demand of 51.5% can be realized. In relation to the building as a whole, this results in a saving of 1,103.48 MWh/yr for the whole building. These savings are only related to the plant and building technology. In further investigations, the building construction must also be included in the building optimization in order to identify further savings potential.

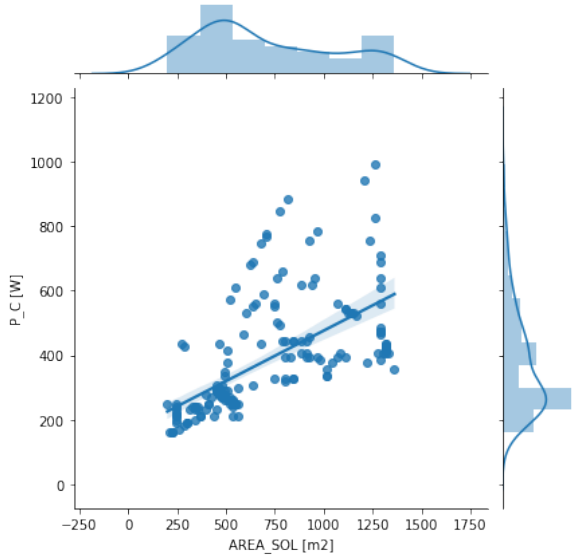

Figure 2. Correlations between the solar thermal surface area (AREA_SOL) and the power consumption of the cooling heat pump (P_C)

The study shows that an almost climate neutral building operation can be realized. The most remarkable result to merge from the data is that the presented method can support decision makers to identify the main key performance indicators for a climate neutral building operation. These findings thus need to be interpreted with caution and do not replace detailed design and planning for buildings.

5. Discussion and Conclusion

A comparison of different energy supply systems was carried out by means of sustainable issues. In addition, a sustainable plant concept was then transferred to a thermal simulation model for optimization. We applied common optimization methods in building simulation and identified a suitable optimum for a real existing building. This gives the potential to save 51,5% of heating energy during the operation of the building. Our work clearly has some limitations. Despite this, we believe our work could be a framework for the implementation of sustainable energy supply systems. However, a more careful and detailed analysis must be carried out during the design, planning, and implementation phase of buildings. The main purpose of the presented method is to check in advance the decisive criteria from a sustainable point of view in order to implement life cycle-based sustainable buildings.

The presented approach can help property managers/operators and stakeholders to respond to increasing requirements regarding climate-neutral building operations. Through the implementation of CO_2 pricing, energy savings are directly reflected in taxes.

Within the scope of this study, we have considered the plant technology of a building from the point of view of sustainability and energy efficiency. Such an approach must become more important in the planning and design of future buildings in order not to miss the goal of a climate-neutral building stock.

In order to realize a holistically optimized building in terms of climate neutrality, aspects of the use of renewable energies must also be taken into account. This must be given more attention in future studies.

User behavior must also be increasingly included in these considerations, since the building user plays a key role in the operation of energy-efficient buildings. Only through sustainable user behavior can a building be operated in a climate-neutral manner.

6. Acknowledgments

This publication is part of the NuData Campus Project which is funded by the German Federal Ministry for Economic Affairs and Energy. Within this project, several energy supply systems will be investigated in more detail. For more information, please refer to www.nudata.de. The project partners are: University of Applied Sciences Munich and the Technical University of Munich.

References

[1] Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU), Hrsg., Klimaschutzschutzplan 2050: Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung, S.6-15 (2016)

[2] Bundesministerium für Wirtschaft und Energie (BMWi), Hrsg., Energieeffizienzstrategie Gebäude: Wege zu einem nahezu klimaneutralen Gebäudebestand (Kurzfassung), S.2f (2015)Another reference

[3] DIN V 18599-10:2018-09 Energy efficiency of buildings - Calculation of the net, final and primary energy demand for heating, cooling, ventilation, domestic hot water and lighting - Part 10: Boundary conditions of use, climatic data

[4] Dotzler, C., Botzler, S., Kierdorf, D., & Lang, W. (2018). Methods for optimising energy efficiency and renovation processes of complex public properties. Energy and Buildings, 164, 254–265. https://doi.org/10.1016/j.enbuild.2017.12.060

[5] DIN EN 15804:2020-03 Sustainability of construction works - Environmental product declarations - Core rules for the product category of construction products; German version EN 15804:2012+A2:2019

[6] DIN EN 15978:2012-10 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method; German version EN 15978:2011

[7] DIN EN ISO 14040:2021-02 Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006 + Amd 1:2020); German version EN ISO 14040:2006 + A1:2020

[8] DIN EN ISO 14044:2021-02 Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020); German version EN ISO 14044:2006 + A1:2018 + A2:2020

[9] Federal Ministry of the Interior, Building and Community. (2020). ÖKOBAUDAT: Sustainable Construction Information Portal

[10] A. T. Nguyen und S. Reiter, "Passive designs and strategies for low-cost housing using simulation-based optimization and different thermal comfort criteria", Journal of Building Performance Simulation, Jg. 7, Nr. 1, S. 68–81, 2013

[11] M. Wetter und J. Wright, "A comparison of deterministic and probabilistic optimization algorithms for nonsmooth simulation-based optimization", Building and Environment, Jg. 39, Nr. 8, S. 989–999, 2004

[12] M. Ferrara, E. Fabrizio, J. Virgone und M. Filippi, "A simulation-based optimization method or cost-optimal analysis of nearly Zero Energy Buildings", Energy and Buildings, Jg. 84, S. 442–457, 2014

[13] M. Hamdy, A.-T. Nguyen und J. L. Hensen, "A performance comparison of multiobjective optimization algorithms for solving nearly-zero-energy-building design problems", Energy and Buildings, Jg. 121, S. 57–71, 2016