Simulation-Assisted Monitoring-Based Performance Evaluation of a Historically Relevant Architectural Design

Matthias Schuss – TU Wien – matthias.schuss@tuwien.ac.at
Ulrich Pont – TU Wien – ulrich.pont.tuwien.ac.at
Mahnameh Taheri – TU Wien – mahnameh.taheri@tuwien.ac.at
Christoph Lindner – TU Wien – christoph.lindner@architektur2000.at
Ardeshir Mahdavi – TU Wien – amahdavi@tuwien.ac.at

Abstract

In this contribution, we describe ongoing research efforts to assess the performance of a number of buildings by the Austrian architect Konrad Frey, a pioneer of energy-efficient architecture. A number of his buildings, planned in the 1970s, adapted the principles of modern solar houses. These key projects are the subject of an ongoing nationally funded research project. Thereby, we deploy building simulation to assess the energy performance of one of his buildings (Kindergarten Pachern, located in Hart, close to Graz, Styria, completed in 1997). Moreover, the object was subjected to detailed performance monitoring. The building implements two design strategies: On the one hand, its envelope design is optimized for solar gains, on the other, the building is embedded in the local landscape's morphology, utilizing the benefits of reduced transmission losses via ground-adjacent building components. The building contains standard facilities for kindergarten usage (three group rooms, a gym, a kitchen, and sanitary facilities). The intensive monitoring phase started in summer 2016. The monitored data is expected to support the documentation of the building's actual performance. Moreover, a simulation model of the current state of the building will be calibrated via the collected data. Based on this calibrated model, previous states of the building (subtracting later adaptions) can be simulated. We thus can virtually reconstruct the building's originally intended state and assess its performance.

1. The Architect's Work

Konrad Frey was born in 1934 and is considered one of the pioneers in solar architecture in Austria and central Europe. Considered a key representative of the avangardistic *Graz School* of architecture (alongside with Günter Domenig, Helmut Richter, and others), Frey's work encompasses a wide range of different buildings and structures, spanning from social housing to private residences, schools, and office buildings. Konrad Frey's approaches to energy-efficient buildings date back to his study years in Graz and to his first office, which was created in London in the early 1970s (with Florian Beigel). His pioneering work regarding the integration of passive (and active) solar components is represented by his contribution to the "Sonnenhaus Österreich" (1976), and the planning of the Haus Fischer (see Fig. 1 and 2) in Grundlsee, Styria. However, Frey later admitted that he was disappointed by the output of the solar collector units in Haus Fischer, and conceptually changed his design approach.

Fig. 1 – External view Haus Fischer Grundlsee – Austria (Nextroom, 2016)

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Fig. 2 – Internal view of Haus Fischer, Grundlsee, Austria (Nextroom, 2016)

Fig. 3 – External view of Haus Zankl, Geneve, Switzerland (Wagner and Böck, 2013)

For the well-known Haus Zankel (Fig. 3), built from 1976 to 1985 in Geneve, Switzerland, he suggested to understand the building as a solar collector itself, rather than applying solar collector units to the façade. Haus Zankel provided an opportunity to test a number of concepts02653891
regarding solar house design thanks to Frey's very ambitious and adventurous client.

The related experiences resulted in multiple publications. For instance, one of the first handbooks for energy-efficient building designs published in Austria was co-authored by Konrad Frey (Wagner and Böck, 2013).

2. The Case Study Building

The Kindergarten Pachern in Graz, Styria was opened in 1997 and can be considered the rigorous further development of Frey's architectural approach to energy-efficient building design. The south-oriented parts (Fig. 4) of the complex's envelope allow both daylight and shortwave radiation to penetrate the building. Industrial rolling doors (Fig. 5) offer the opportunity to open a large part of the south façade in the summer season, creating thus a seamless transition from inside to outside.

Fig. 4 – External view of the Kindergarten Pachern Hart near Graz, Austria

Fig. 5 – South facing wall with the large garage-type rolling door (pictures by the authors)

The building design makes clever use of its location, as major parts of the building's envelope are embedded in the slope of the topography. The building appears well integrated in the surroundings. Moreover, the roof area can be used as playground, including a slide from the upper level to the ground level (Fig. 6).

Fig. 6 – Plan of the building site (Google maps 2016, modified)

The interior layout includes three large group rooms (Fig. 7) and a gym on the south side. Sanitary rooms, cloak room, a kitchen, and an office are mainly illuminated by skyligths and a small ligth shaft.

Fig. 7 – Internal view of a group room at the Kindergarten Pachern Hart near Graz, Austria

3. Performance Monitoring

A detailed monitoring of the indoor conditions started at the beginning of summer 2016. The data acquisition focuses on air temperature, humidity, and carbon dioxide concentration in the three group rooms, the gym, and the corridor. To capture occupancy patterns, two motion detection sensors were installed in each group room. The state of windows and doors were recorded with contact sensors (Fig. 9).

All sensors are standard wireless energy independent sensors equipped with EnOcean transmitters. An Arduino YUN based data logger recorded the collected sensor data locally and forwarded it via UMTS-Modem to our central monitoring data repository (Schuss et al., 2016, for more details on the general monitoring strategy and configuration). In addition, local external weather conditions were recorded with a wireless weather station directly from the flat roof (Fig. 8). Additional details on sensors are given in Table 1.

Table 1 – Deployed monitoring devices

Device	Range / Accuracy
Davis Vantage Pro2 Wireless Weather station	Temperature: -40 to +65 °C ± 0.5 °C Humidity: 0 to 100 % ± 3 % Solar radiation: 0 to 1800 W ± 5 % Wind speed: 1 to 67 m/s ± 1 m/s or ± 5 % Wind direction: 0 to 360° ± 4°
Pressac CO_2, Temperature and Humidity Sensor	Temperature: 0 to 51 °C ± 0.5 °C Humidity: 0 to 100 % ± 5 % CO_2: 0 to 2550 ppm ± 125 ppm
Thermokon SR-MDS Solar	Occupancy / Motion: 0 / 1 Light level: 0 to 510 lx
Thermokon SRW01 Window contact	Status: 0/1

Fig. 8 – Wireless local weather station

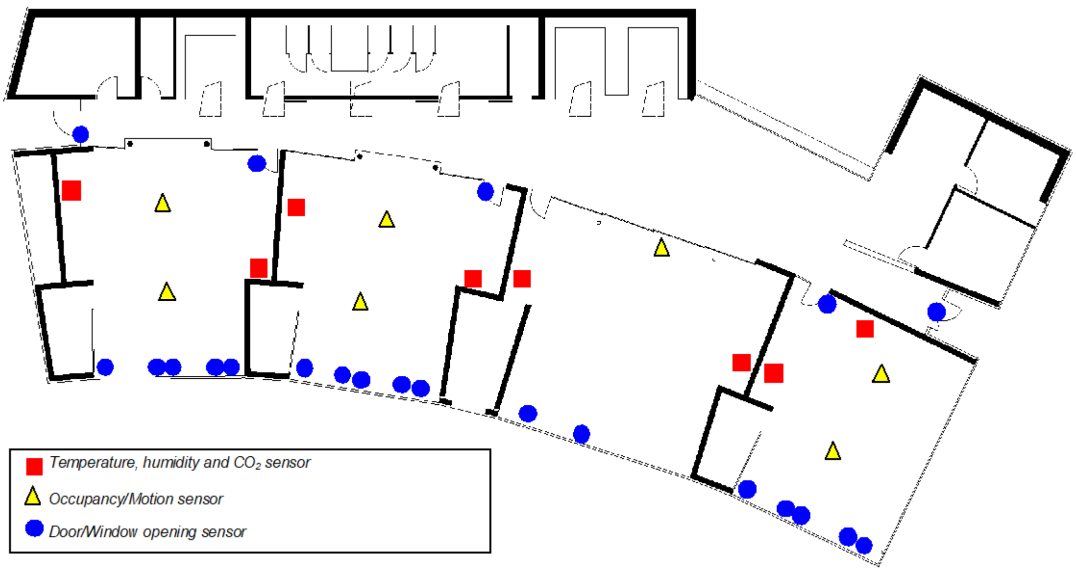

Fig. 9 – Floor map with locations of the performance monitoring sensors installed at the Kindergarten Pachern Hart near Graz, Austria

4. Performance Simulation

An initial thermal model of the building was developed based on construction plans and site visits. EnergyPlus (2016) was selected as simulation tool. Generated and calibration of simulation models are expected to help explore the influence of adaptions in the building and its usage on building's actual performance.

Fig. 10 illustrates the complex geometry of the EnergyPlus model (visualized by OpenStudio plugin for SketchUp). The energy model of the building involves five monitored zones, including three group rooms, a gym, and the corridor (Table 2. Thus, performance indicators such as mean air temperature in each zone can be calculated. Moreover, four non-monitored zones are also included in the EnergyPlus model.

Table 2 – Studied thermal zones

Zone	Area [m²]	Volume [m³]
Group room 1	77.5	124.4
Group room 2	76.2	220.7
Gym	96.7	280.5
Group room 3	81.4	223.6
Corridor	170.4	460.0

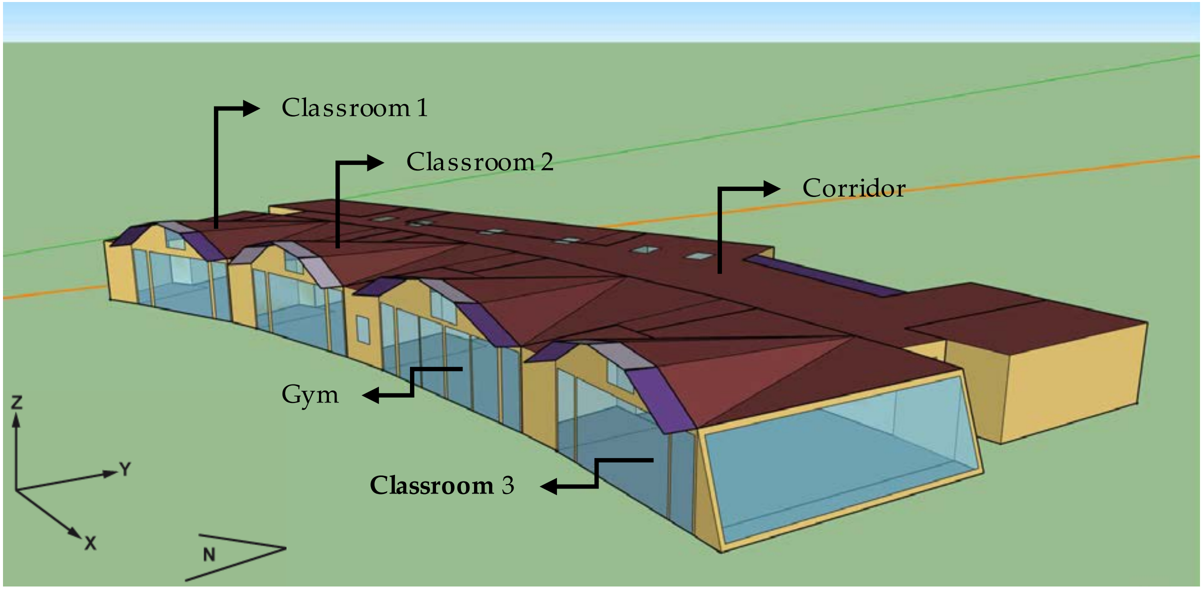

Fig. 10 – EnergyPlus model geometry for the kindergarten building

4.1 Thermal Properties of the Construction

Besides the geometrical modelling, the thermal properties of the constitutive materials were set according to the real existing setup. Table 3 summarizes information on the thickness and the estimated U-Value of the different opaque elements. Layer structure and solar transmittance of the transparent building elements are listed in Table 3.

4.2 Operation Schedules

In the initial model, occupancy schedules were defined for the rooms considering the working hours of the kindergarten and each group room. Moreover, lighting was modelled in the initial model based the installed power and the daily occupied hours.

In order to define the schedules in the calibrated models, sensor data (occupancy, windows) was used to generate more accurate operation schedules. The observed data was integrated via csv-files and assigned to the related variables such as state of windows (open/closed), occupancy (absence/presence), and lights (on/off).

Table 3 –Opaque building elements

Building element	Thickness [m]	U-Value [W m^{-2} K^{-1}]
Outside wall – Type 1	0.37	0.493
Outside wall – Type 2	0.47	0.164
Outside wall – Type 3	0.38	0.460
Inside wall – Type 1	0.14	0.224
Inside wall – Type 2	0.30	4.226
Floor – Type 1	0.56	0.317
Floor – Type 2	0.47	0.313
Green roof – Type 1	0.76	0.211
Green roof – Type 2	0.48	0.218
Flat roof	0.46	0.227
Outside door	0.10	0.497
Inside door	0.02	3.864

Table 4 – Transparent building elements

Building element	Layers	Solar transmittance [-]
Window type 1	Clear glass Air Clear glass	0.781
Window type 2	Coated glass Air Coated glass	0.165

4.3 Local Weather Data

For the initial model we obtained hourly weather data from the EnergyPlus weather file database for the closest city to the case study, namely the city of Graz, Austria. For more accurate simulations, we generated a local weather file based on the measured values from our locally installed weather station. An exported data set for an entire year together with our measured data from the weather station was used to create an hourly data import file for Meteonorm (2016) and to process the generation of an EPW-file for EnergyPlus.

4.4 Simulation Results

Fig.s 11 to 14 illustrate the simulated indoor air temperatures (in the group rooms 1 to 3 as well as in the gym) based on the previously mentioned tree models together with the corresponding monitored values for the later part of August 2016.

For a comparison between the simulated and measured room air temperatures in August 2016, values for the following statistics were calculated (Table 5): Mean Bias Error (MBE), Root Mean Square Error (RMSE), and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)).

The initial model simulation results (with general operational schedules based on working hours, maximum internal gains, and the Graz weather file) showed significant deviations from the monitored results and displayed a strong trend toward overheating. A second variation with a weather file based on the local measurements further increased this overestimation of indoor temperatures: The local data involved comparatively higher outdoor temperatures and radiation values.

The third set of simulations used more realistic operation patterns (lower internal gains and different ventilation rates) and resulted in a significantly higher agreement with the measured values. However, the group room 1 shows, even for the calibrated model, significantly higher temperatures as compared to the measurements. The inaccurate modelling of the surrounding trees and external canvas blind could explain this circumstance. Further model improvements, especially for the autumn and winter period, are to be implemented in the near future. As in this case the building will not be operated in the free-running mode, additional sensors will be required for model calibration (e.g., surface temperature probes for radiators for the calculation of thermal energy magnitudes introduced in the spaces).

The resulting final calibrated model of the building will be used to generate different virtual variants of the building to account for the past adaptions. The results are expected to explain how the initial design concept and the related performance could have been influenced by such adaptations. For instance, a cross ventilation possibility was an important part of the original design. Adaptations during the construction phase and the actual use patterns, however, significantly reduce the natural cooling possibility in summer. A virtual building setup and simulations using a calibrated model can document (possibly validate) this original design intention for the provision of thermal comfort via passive cooling.

Table 5 – Simulation errors (room air temperature), expressed in terms of the statistics values (four rooms, three simulation models)

Model		Group room			
		1	2	3	4
Initial model EPW Graz	MBE [%]	8.1	1	-3.5	-2.5
	RMSE [K]	2.7	2.1	2.4	3.1
	CV(RMSE) [%]	11.4	8.9	9.5	12.1
Initial model EPW Hart	MBE [%]	16.0	8.6	4.3	5.3
	RMSE [K]	4.2	2.9	2.0	2.8
	CV(RMSE) [%]	18.0	11.7	8.1	10.9
Calibrated model	MBE [%]	8.5	1.8	0.17	-2.2
	RMSE [K]	2.7	1.8	1.6	2.3
	CV(RMSE) [%]	11.3	7.4	6.4	8.7

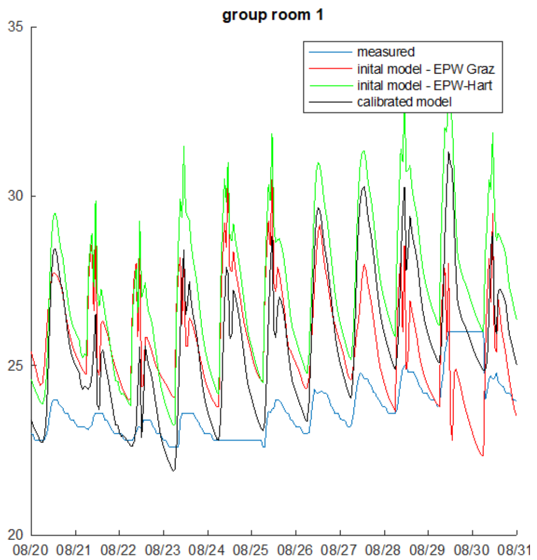

Fig. 11 – Trend of measured and simulated room temperature in group room1

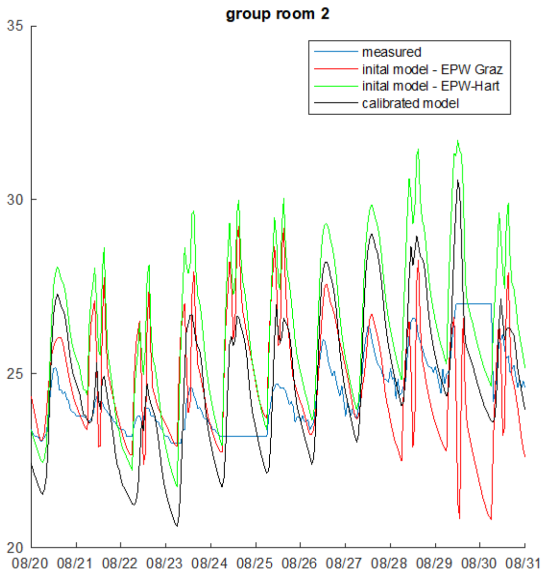

Fig. 12 – Trend of measured and simulated room temperature in group room2

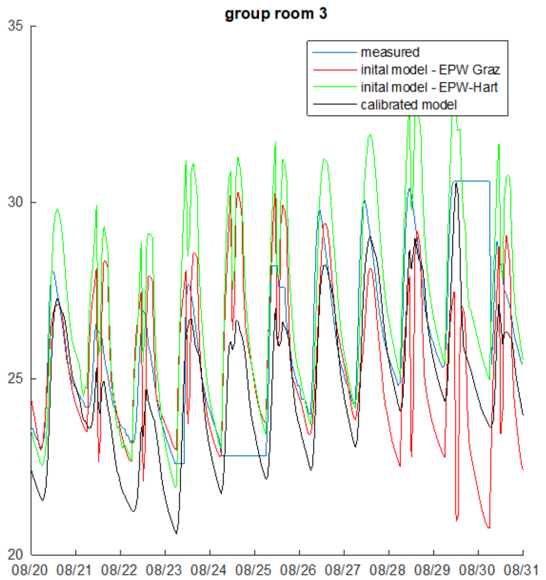

Fig. 13 – Trend of measured and simulated room temperature in the gym

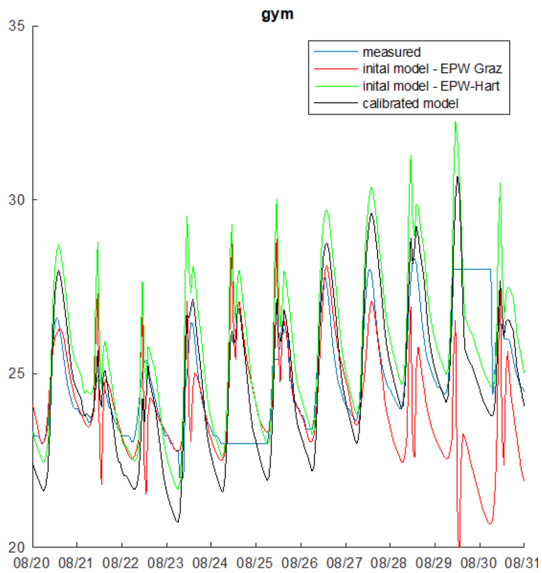

Fig. 14 – Trend of measured and simulated room temperature in group room3

5. Conclusion

The present paper illustrates the use of monitored data to generate a more accurate simulation model compared to standard design assumptions for operational schedules and external climate. The differences in the mean room temperature derived by simulation and measured values highlight the importance of realistic operation schedules and internal gains. The calibrated models will be used to virtually reconstruct the building in accordance with the architects original design intentions. The effectiveness of the underlying design strategies in view of energy and environmental performance could thus be objectively examined.

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