Simulation-based Optimization of thermal Comfort in a heritage Manor House

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Key Innovations
- Holistic building-in-building concept
- Digital twin model approach incl. calibration with high resolution measurement data
- Monitoring and simulation of heritage buildings
- Low-ex heat supply in heritage buildings
- Models of construction elements with variable internal distances and thicknesses

Practical Implications
This paper gives an overview about the application of new simulation approaches and IOT-methods for the preservation of heritage buildings. Due to the individual designs and constructive elements of such buildings, accurate and high-resolution measurement data is required to calibrate the associated simulation models. This in turn increases the technical effort substantially.

Introduction
High investments costs and technical expertise are required when preserving heritage buildings. This is mainly due to the use of unique materials and the unique designs of such buildings. Such a preservation is only feasible if the buildings remain in daily use.

To address these challenges, a new architectural approach proposes a building-in-building concept which unifies modern building uses and the heritage building construction. This approach considers the integration of a closed inner shell within the remains of historic buildings using timber construction materials.

![Figure 1: Manor house with timber interior construction](image)

Besides minor, necessary renovation for the preservation of the building structure, the existing construction of the historic building remains almost untouched. The new interior construction uses both sustainable building materials and allows for future building use according to modern standards. A simple direct-electric heating system in combination with a PV system on the rooftop increases thermal comfort and energy efficiency. This innovative building-in-building concept can thus ultimately help in preserving historic buildings by reducing required efforts in expertise and costs.

The reconstructed building consists of three building parts (A, B, C) with two storeys each. It is mainly used for residential purposes. Indoor thermal comfort is thus a high priority in system design. A holistic monitoring system incl. high-resolution temperature sensors and power meters provides data for concept testing and evaluation. The monitoring of the building showed that the installed direct-electric ceiling heating surfaces were not able to provide sufficient heat during the first occupied winter period. Furthermore, the building showed significantly higher power consumption than expected.

Simulation models should therefore help to identify suitable retrofit measures. The use of simulation models to evaluate thermal comfort in heritage buildings is a common approach in building engineering (c.f. Bonora et al., 2019). Special emphasis is put on the different construction elements, such as walls and floors due to their different materials as well as variable internal distances and thicknesses. However, coupled models of unique building physics and modern building technology incl. calibration represent a new engineering approach.

Methods
To address these challenges, the modelling process used a hybrid (digital) twin approach (c.f. Chinesta et al., 2018). The internal building control system therefore provided measurement data (i.e. one-wire sensors) of the average thermal conditions in all building parts and floors, with a temporal resolution of 5 minutes. The indoor air temperature and humidity could thus be accurately evaluated in detail for the considered test period from the end of October to December.

As this building still served as a prototype for the new architectural approach for heritage buildings, other meters were also installed to provide high resolution and accurate measurement data. A three-phase, four-quadrant meter with Modbus connectivity measures power consumption, voltages and current in each phase of the electric power supply system. A stand-alone weather station provides additional data of outdoor temperature, solar irradiation
and local wind conditions. These measurements shall be necessary in a second project phase to control and evaluate local renewable energy share by the planned photovoltaic systems on the rooftop.

The implemented simulation model uses the Modelica-based simulation library Green City in SimulationX which provides models for both building physics and HVAC system simulation. The use of Modelica’s multi-domain simulation approach allows the substitution of different model parts with measured data and vice versa. It is thus predestined to analyse and optimize building, control and HVAC system behaviour using a Digital Twin model approach (c.f. Vering et. al., 2019).

Results

The implemented simulation model consists of eight connected room models including a brief description of occupancy (i.e. inner loads based on power measurement and average personal presence). Ventilation losses are modelled using a window opening regime that depends on the simulated indoor air quality. The weather conditions are based on the measurement data during the considered test period.

![Figure 2: Simulation results vs. measurement data](image)

After calibration, the simulated indoor temperature remained within a 3% tolerance band when compared to the measured data during the considered period. Simulated total electricity consumption, including direct-electric heating and occupant energy use, was less than 9% higher than corresponding measurements.

With this sufficient accuracy, the model was then simulated using weather conditions and building use data for a local reference year to evaluate following retrofit measures:

1. Improvement of insulation by applying insulation material into the intermediate spaces
2. Integration of ventilation with high-efficiency heat recovery

(3) Integration of an air-to-air heat pump

The improvement of the insulation resulted in significant improvements of the thermal comfort during most of the reference year. This significantly increased energetic efficiency of the building results in a total energy consumption reduction of about 26%. The simulation however showed some time-periods in which the heat supply during times with cold outdoor temperatures, was not sufficient.

The additional integration of a ventilation system with heat recovery (i.e. air ducts were already preinstalled) helps to additionally improve the thermal comfort during cold winter times, especially in the upper floors, but does not result in additional lower electricity consumption (i.e. additional savings are compensated by additional consumption). Only the integration of an additional air-to-air heat pump as an additional heat supply system provides an adequate thermal comfort (in 99% of the year) and higher energy consumption reduction (about 57%).

After further testing and evaluation of this study, suitable insulation material (SLS20F) was applied into the intermediate spaces according to solution (1).

Conclusion

The presented simulation approach combines the strengths of both dynamic building performance simulation and building monitoring into a holistic engineering approach. It is thus a role model for all complex building retrofit analyses as well as for more advanced applications of building performance simulation in other sectors (c.f. Rodemann and Unger, 2018).

References


