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Quantifying energy-saving measures in office buildings by simulation in 2D cross sections

Andreas Witzig, Camilo Tello, Franziska Schranz, Johannes Bruderer, Matthias Haase

Zurich University of Applied Sciences, Switzerland

Abstract. A methodology is presented to analyse the thermal behaviour of buildings with the goal to quantify energy saving measures. The solid structure of the building is modelled with finite elements to fully account for its ability to store energy and to accurately predict heat loss through thermal bridges. Air flow in the rooms is approximated by a lumped element model with three dynamical nodes per room. The dynamic model also contains the control algorithm for the HVAC system and predicts the net primary energy consumption for heating and cooling of the building for any time period. The new simulation scheme has the advantage to avoid U-values and thermal bridge coefficients and instead use well-known physical material parameters. It has the potential to use 2D and 3D geometries with appropriate automatic processing from BIM models. Simulations are validated by comparison to IDA ICE and temperature measurement. This work aims to discuss novel approaches to disseminating building simulation more widely.

1. Introduction

When implementing energy-saving measures it is a challenge to predict its effectiveness and to guarantee indoor comfort. Physics-based dynamical simulation would be a good basis for facility management to make decisions and to optimize HVAC systems. However, proper analysis of the building physics by means of today's software tools is often too elaborate for this aim. Comprehensive modeling of heat storage by the building structure and heat loss through thermal bridges also still requires expert knowledge and is applied only selectively, if at all.

The reason why building simulation is too costly for a widespread application in facility management is that translating the information from building plans into the physical model cannot be done automatically yet. The process includes tasks like identifying walls from complex geometries and estimating heat loss parameters.

A lot of effort has already been put into supporting architectural building design to better integrate building simulation [1] early on with a focus on energy savings [2]. This was reflected in the development of simulation models in the early design phase [3]. The performance of the building design was optimized, and the focus was put on developing design options and their relative differences in performance [4]. To meet the world-wide sustainability goals, the existing building stock needs appropriate transformation of energy systems. The user and operation manager starts to play a major role and thus needs new methods and tools [5]. Computer power intensive finite elements simulation was done focusing on specific building elements like ground slabs [6], or boreholes [7], or fenestration [8]. On the other hand, more and more approaches were published that focus on whole building performance including building fabric, complex fenestration, HVAC systems and controls [9; 10]. Some recent work also highlights the value of simulation models for energy system optimization [11].

There are two megatrends that make a new approach look promising:

1. Building information modeling (BIM) has greatly advanced in the last few years. The digital representation of a building is now ready to contain a variety of parameters and a full 3D model.
2. Computational power has immensely increased since the design of our state-of-the-art tools for building simulation.

Many attempts have been made to integrate energy simulation into the BIM workflow [12; 13]. This work proposes a finite-element discretization for the building structure. It uses a simulation domain that is closer to the BIM representation and relies on physical material parameters. The approach has the potential to reduce the effort for the translation from BIM to the simulation model. It aims at providing detailed information about the thermal-electric interactions in buildings taking the thermal capacity into account. In our current version, we apply 2D numerical simulation of the concrete structure in order to save computational resources. This will prove the concept of getting more insights into the interactions between building fabric and energy flows in buildings. In the long-term vision, 3D simulations will simplify the process at the cost of additional computational power required for the thermal analysis.

In addition to the heat flow in the solid structures, radiation between the walls is properly accounted for resulting in more precise surface temperatures. Air flow in the rooms is approximated by a lumped element model with three dynamical nodes per room. This is in contrast to full 3D fluid dynamics simulations which has both the drawback of extremely high CPU usage as well as a requirement for more knowledge of the occupancy and the user behavior [14].

The dynamic model also contains the control algorithm for the HVAC system and predicts the net primary energy consumption for heating and cooling of the building for any time period. Variants of energy saving measures can be compared and evaluated on a yearly basis with the use of a stochastic model for the outside weather conditions and the user behavior. Besides the physical parameters which are interesting for engineers, the results also contain a cost analysis that is relevant for the owner or manager of the building.

2. Multiphysics model for indoor climate

The building structure consists of solid materials and air volumes. The furniture is neglected in the current model. Also, the water-bearing elements such as heating pipes or the supply and exhaust shafts for ventilation are not represented in detail.

2.1. Basic Physics: Thermal conduction in solids and radiative equilibrium wall-ceiling-floor

Heat transfer and heat storage are calculated with a spatial resolution. For this purpose, the heat flux $\vec{q}(\vec{r},t)$ and the temperature $\vartheta(\vec{r},t)$ are modeled as time-dependent field quantities by

$$\rho(\vec{r})c_{\mathrm{p}}(\vec{r}) \cdot \frac{\partial\vartheta(\vec{r},t)}{\partial t} + \nabla \cdot \vec{q}(\vec{r},t) = Q_{\mathrm{src}}(\vec{r},t) \tag{1}$$

$$\vec{q}(\vec{r},t) = -\lambda(\vec{r})\,\nabla\vartheta(\vec{r},t) \tag{2}$$

The variable $Q_{\mathrm{src}}(\vec{r},t)$ represents heat sources. Material parameters are listed in Table 1. In the interior spaces, there is also heat exchange via long-wave electromagnetic radiation. Since surface temperatures are in a narrow temperature band, the equation can be linearized. The surface-to-surface radiation model generates a heat source term Q_{rad} in each element j with contributions from the emitted radiosity J_{em} from all neighbouring elements i in the same room.

$$Q_{\mathrm{rad}}(\vec{r}_j,t) = \varepsilon_j\, A_j \left(\sum\nolimits_i F_{ij} \cdot A_i \cdot J_{\mathrm{em}}(\vec{r}_i) - e_{\mathrm{b}}(\bar{\vartheta},t)\right) \tag{3}$$

with surface emissivity ε_j, blackbody hemispherical total emissive power $e_{\mathrm{b}}(\bar{\vartheta})$ and average room temperature $\bar{\vartheta}$, finite element surfaces A_i and view factors F_{ij} [8]. Wavelength dependency of the radiative properties has been set to constant and a hemicube radiation pattern has been chosen.

2.2. Compact model for heat transfer and heat storage in air domains

A lumped thermal system model is applied to non-locally couple the finite element domains [8]. With three dynamical nodes per room, one at the bottom, in the middle, and one at the ceiling, it is possible to account for the air temperature with very few additional degrees of freedom and at the same time provide an accurate temperature distribution at the boundaries of the domains with solid material.

Figure 1 depicts the complete model with 2D finite element solution in the coloured domains and the compact model in the air domains. The compact model is built with the symbols known from electric circuits with parameter values summarized in Table 2.

2.3. Stratification in air domains

Temperature differences in the lower, middle and upper air regions in one room can lead to natural convection. Two thermal power flux terms are introduced, $P_1(t)$ from the lower to the middle and $P_2(t)$ from the middle to the upper node. The stratification process is modelled with a constant power flux in case that warm air is below cold air. For warm air laying on top of cold air, this power is zero since the air layers are stable. Since the physical processes of natural convection are not represented in detail, the stratification model is the most uncertain of all applied models and needs to be calibrated with measurement. However, the advantage of this model is to avoid the discretization of the air domain and to numerically solve the dynamics of air movement.

2.4. Boundary conditions and HVAC system modelling

The temperatures and heat flux densities in the finite element domain are tightly coupled to the temperatures in the lumped element nodes. The heat power fluxes $P_k(t)$ into node k of the compact model is a sum over all elements i from the adjacent finite elements.

$$P_k(t) = \sum_i h_i \cdot (\vartheta_i - \vartheta_k) \cdot A_i$$

where h_i is the heat transfer coefficient listed in Table 2, ϑ_i is the temperature in the finite element, ϑ_k is the temperature in the compact model node k and A_i is the finite element surface area.

Solar irradiation and heat from people or electronic equipment in the rooms are implemented as shown as time dependent heat sources. The time-domain simulation is well-suited to account for their stochastic nature. Power to or from the HVAC system is modeled likewise as a power source or sink in the compact model. In the dynamic simulation, the HVAC control strategy needs also being implemented in order to get realistic temperature curves.

Table 1. Material parameters used in the simulation study.

Material	Mass density $\rho(\vec{r})$ in $\mathrm{kg/m^3}$	Thermal conductivity $\lambda(\vec{r})$ in $\mathrm{W/(m \cdot K)}$	Specific heat capacity $c_\mathrm{p}(\vec{r})$ in $\mathrm{J/(kg \cdot K)}$
Concrete	2300	1.15	880
Pavement	1000	1	800
Insulation	200	0.04	1000
Window frames	1380	0.15	900
Quarz glass	2200	0.05	1000
Average for window	1500	0.0264	1000

Table 2. Heat transfer coefficients in $\mathrm{W/(m^2 \cdot K)}$

h_{ceiling}	4.0
h_{wall}	2.5
h_{floor}	2.0

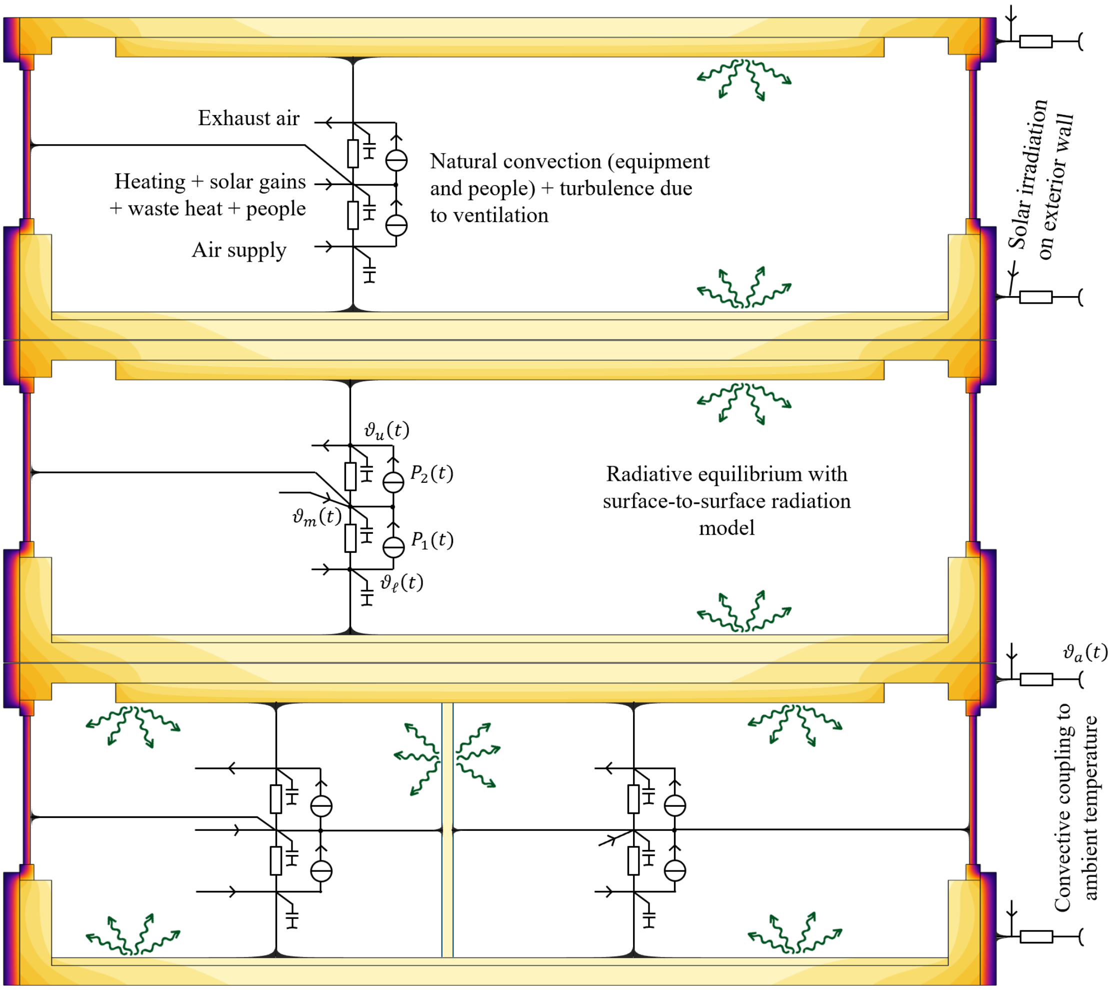

Figure 1. Schematic representation of the simulation model for the case of a building with three floors. Resistors and capacitors represent the heat flux and heat storage in the air domains. Radiative equilibrium is enforced with a surface-to-surface radiation model connecting the boundary elements for each room. A simple model for natural convection is implemented in the power terms $P_1(t)$ and $P_2(t)$. Additional power terms are introduced to represent the HVAC system.

3. Simulation results for various examples

Simulations are done with Comsol Multiphysics [15] on a relatively coarse mesh as shown in Figure 2. The space is 2.4 m high, 5 m wide with windows on each side and has a partition wall separating it into two rooms. Sunshine is only assumed in the right room (heading south). Periodic boundary conditions are imposed at the top and at the bottom of the simulation domain for simplicity

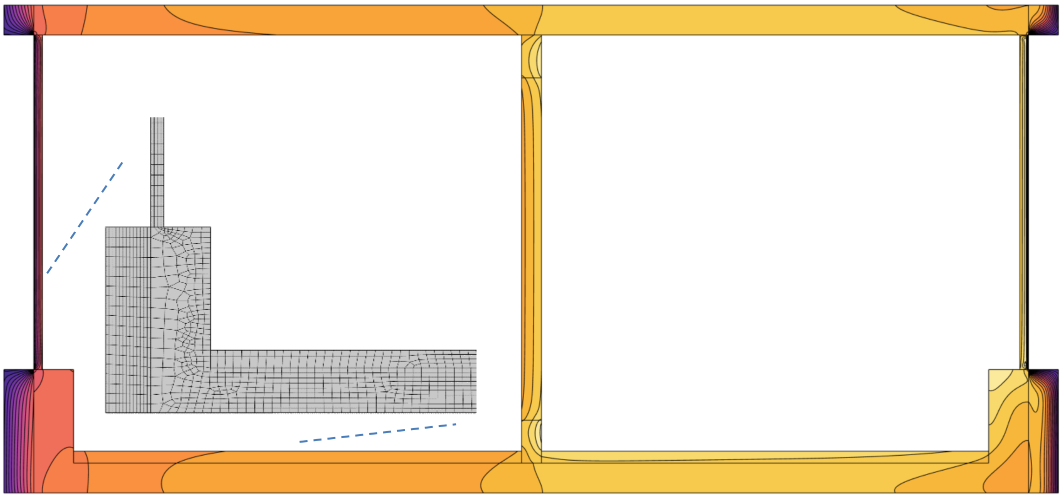

Figure 2. Simulation detail for a structure with two rooms in the evening after a sunny day. Solar irradiation was mainly present in the room heading south (right). Neither of the rooms has the heating turned on. The simulation results show that the room heading north (left) has a lower temperature. Inlet: finite-element mesh.

Simulations first solve for a stationary solution which is the initial condition for the transient study. Solar radiation, outside temperature and thermal loads from people and electronic equipment are an input to the model. Material parameters are summarized in Tables 1 and 2. The coloured areas in Figure 2 shows the temperature profile ranging from yellow (23°C room temperature) to dark blue (ambient temperature $\vartheta_a(t_0) = 4\,°C$). The HVAC system has turned off and no automatic sunlight shading is assumed.

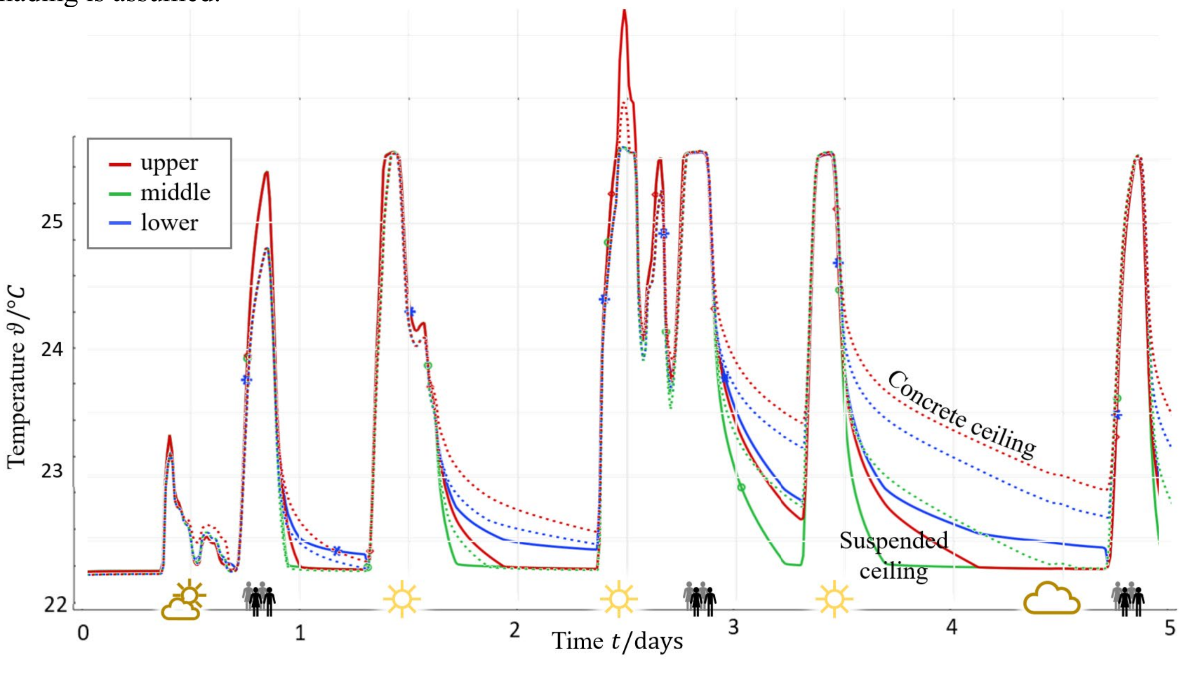

Figure 3. Comparison between different building concepts, one with concrete ceiling (dotted line) and another with suspended ceiling (solid line). Realistic user behaviour and weather data is used as an input. Weather and people symbols are shown to allow an interpretation of the stochastic nature of the input. It is clearly visible that a concrete ceiling significantly balances out thermal loads.

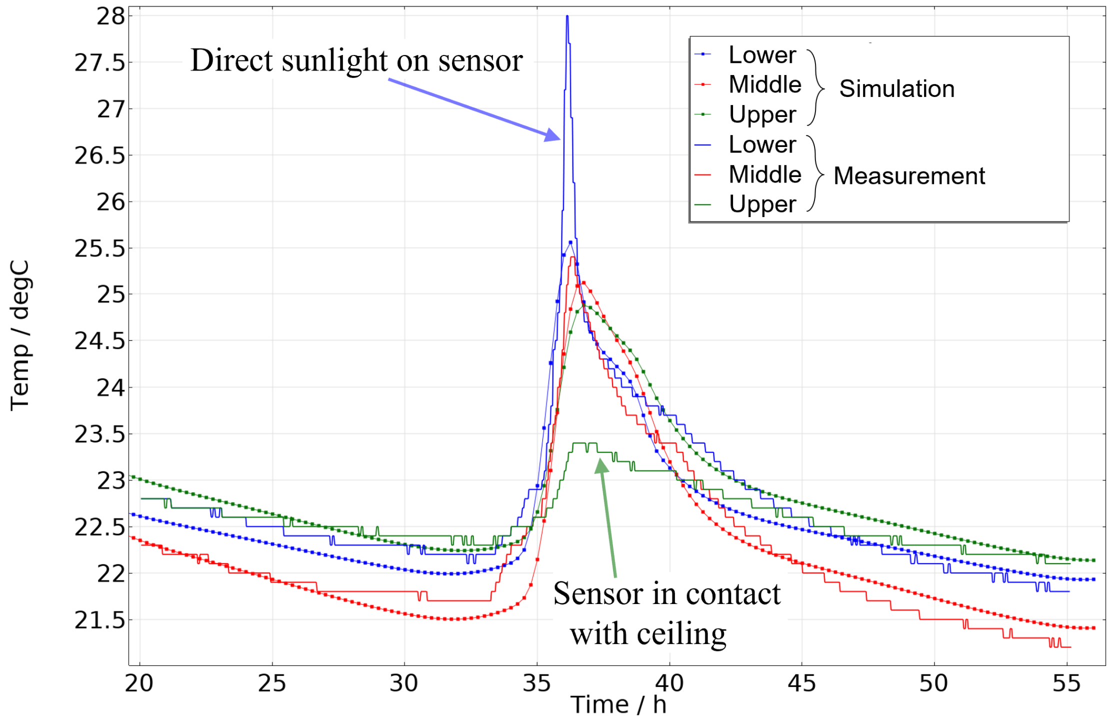

Figure 4. Validation of the lumped thermal system components by comparison of measurement and simulation. The sensor data show significant overshooting in the short time of the day where sunlight is directly shining on the sensor. This effect has not been accounted for in the simulation model.

It is important to see that thermal loss trough the building shell is calculated accurately with the full dynamics of the building structure including the thermal storage capability of the building structure. Solar irradiation on the south façade does contribute to the heat balance of the building (although it is minimal in the presented example because the outer layer of the wall is insulating). It is not necessary to introduce U-values as parameters and thermal bridges are naturally solved with adequate precision.

For a second simulation study, a simple HVAC control model has been implemented which heats with a constant power if the room temperature falls below a given lower threshold and cools if it is above an upper limit. Time domain results in Figure 3 for five consecutive days with various amount of sunlight and heating by people. Two different variants of the building structure have been compared, one with suspended ceiling and one with an open concrete ceiling. It is clearly visible that the concrete ceiling has the capability to store energy in the range of one day.

4. Parameter calibration and model validation

The physical parameters used in the thermal conduction and storage in solids are well-known since they are fundamental material parameters. Some of the lumped element components can also be derived from physics, such as the heat transfer between different air layers, or the storage capacity of the air volumes.

Comparison to measurement data has shown that the temperature sensors and in particular their placement bears the largest uncertainty. Figure 4 shows the measurement curve of three sensors compared to the simulation data. It can be seen (no surprise), that direct sunlight on the sensor results in a peak that is not predicted by the numerical model. Furthermore, the sensor for the upper air zone has been directly attached to the concrete ceiling which shaves the temperature peak in comparison to the prediction of the simulation. In order to simplify the model, average materials have been chosen for the window area (see Table 1). This parameter together with the heat transfer coefficient between the middle air node and the window have been recognized to cause the middle temperature (red curve in Figure 4) to be lower than the bottom and the top air volumes.

When comparing with other simulation tools, the difference from 2D to 3D is the biggest deviation. For validation purposes, in consequence, a 3D simulation domain is used. IDA ICE [16] is chosen as a reference tool. 3D simulations with Comsol currently require 16 GB of main memory and 1h of CPU time for a simulation of two days. A detailed sensitivity analysis of the model parameters and a systematic calibration procedure is in preparation and will be addressed in a separate publication.

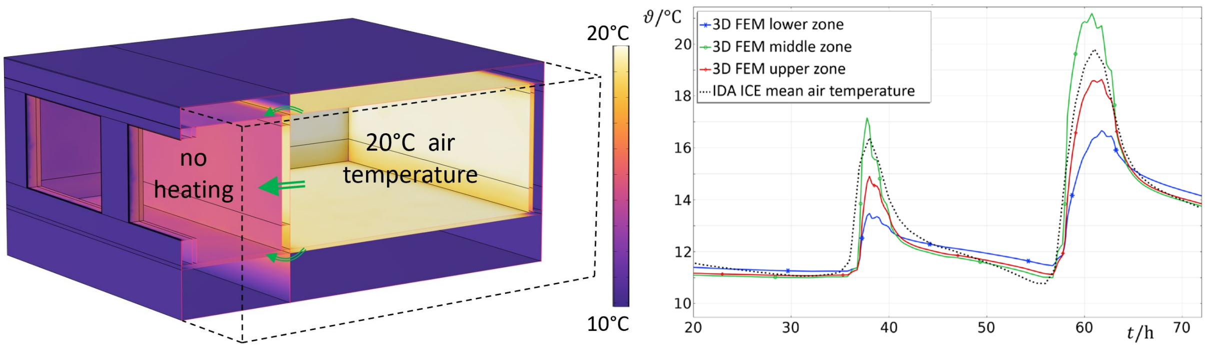

Figure 5. Validation of the 3D FEM simulation model by comparison with an established building simulation. Left: Comsol simulation results, geometry according to ASHRAE Standard 140, Case 960 [17]. Green arrows depict the heat transfer at night. Right: Comparison between 3D FEM and IDA ICE simulation. Very good agreement between the two simulations have been achieved by modifying the heat conductivity of the separation wall in IDA ICE to account for horizontal heat transport in ceiling, floor, and side walls.

5. Conclusion and outlook

An approach to building energy simulation is presented which uses a well-defined set of physical material parameters and a geometric description of the building. The goal is to explore ways to enable facility management to predict energy (and money) saving potential and optimize energy-saving measures. Current advances in building information modeling allow proper geometry processing and complexity reduction. BIM databases will eventually contain all required physical material parameters. Consequently, the building simulation will be substantially simplified.

Secondly, the approach has the ambition to carefully model the concrete structure of the building with its capability of energy storage and with thermal bridges. Some building designs make use of this effect [18; 19] and the construction projects have proven that the concept keeps its promise. It has been shown in Figure 2 that the proposed simulation method supports these innovative designs and could also be applied in the energy management strategy of existing buildings.

Further investigations will explore the setup of 3D simulation structures and the necessary mathematical treatment to speed up transient simulations. On the application side, concrete field tests will be done in equipping buildings with a large number of sensors, collect their data in a digital twin and perform a comprehensive comparison between simulation and measurement. This will help to define use cases in existing buildings for a better management of the building. In addition, this work supports the development of advanced energy management strategies based on passive and active thermal energy storage and electricity grid services.

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