

Predicting Thermal Losses in a Low-Energy Building

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Abstract

Energy management of small-scale renewable energy systems (microgrid) requires control of the energy consumption. Commercial buildings are sized using energy consumption criteria from the building standards. The energy consumption of a building depends on a number of dynamic factors, including thermal loss, building climate control, and building utilization. This paper presents a simple model for predicting the thermal loss of a building. The basic simulation module is a single room model where the outer walls and windows are exposed to the ambient conditions without sun influx. We model the thermal loss based on building design data and validate the model using operational data for an actual low-energy building. The model prediction accuracy is within $\pm 1^\circ\text{C}$ for up to 7 days when predicting thermal losses in the building construction.

Keywords: energy management, powerhouse, thermal loss prediction, Matlab

1 Introduction

A powerhouse is a building that produces more electric power than it consumes during the building lifecycle, including construction and decommissioning/disposal. Sustainability conscious real estate asset owners are interested in the concept and Norway has seen a rise in the construction of powerhouses in the past 4-5 years.

Powerhouses have large solar PV systems installed at the roof. At its maximum, the solar PV systems generate significantly more energy than consumed by the building at any time. In addition, the maximum power production occurs in the summer season when the heating demand is at its yearly minimum. Heating is the main energy consumer of commercial buildings. Thermal losses drive the heating demand. In our research, we explore models for predicting thermal losses in a low-energy building. The model will be used as part of a digital twin of the building's energy system. Our overall goal is to develop practices for energy management of powerhouses.

The digital twin is a dynamic virtual model of a system that incorporates business, contextual, and sensor data from physical systems into the virtual system model (Madni et al., 2019). A true digital twin is different from other models because it includes the specific instance(s) that reflects the characteristics of the physical twin, in real time. Madni et al. (2019) sees the digital twin as promising technology, particularly in the

building and real estate industries, because of real time access to system data that are essential for energy management (Madni et al., 2019).

Research papers suggest different approaches for assessing thermal performance of buildings. (Kildsgaard et al., 2013; Makaka, 2015; Rohdin et al., 2014) are relevant examples for low-energy buildings and passive houses. Both physical models and machine learning models are available in literature. Mendes et al. (2001) give a first principle (physical model) of the thermal loss. In the digital twin, we need a model that integrates the virtual and physical world. We need to base our model on simple approaches because calculation speed will be an issue due to the large amount of data in the system and the need for real time monitoring and prediction.

Lie (2019) defines the hybrid model as a combination model. A hybrid, data driven model improves the fit between an imperfect physics-based model and (inherently limited) experimental data. The hybrid model is particularly interesting for digital twin applications. To ensure fast response of the digital twin, it is essential that the model is as simple as possible.

This paper outlines a simple, first principle based model for calculating the thermal losses of a low-energy building. The model predicts the energy losses from the building when exposed to varying ambient conditions. We base our model on the design assumptions of the building and we validate the model using operational data from the building. We ask in our research how well a simple energy balance model can predict the thermal losses of a real building if we base the model on the design parameters of the building.

2 Vestsiden Middle School Case

We use Vestsiden middle school in Kongsberg as our case. Kongsberg Kommunale Eiendom (KKE) completed the building construction in August 2019. The school is a low-energy house. Power and heat is supplied through geothermal heat and solar power systems. The national electric grid connects to the building. Solar power is produced by 1054 solar PV panels installed at the roof. Excess energy is stored in a battery and consumed at night. KKE plans to install an electrolyzer and hydrogen storage system for seasonal storage. A fuel cell will generate electric power from the hydrogen during winter. There are currently no guidelines for dimensioning and operation of a hydrogen loop in a hybrid renewable energy system for buildings (Bredesen, 2019).

2.1 Construction Standards

The design of commercial buildings in Norway comply with NS-EN ISO 52000 (energy performance standard) and NS3701 (passive house standard). The standards allow for assessment of the power demand of a building. The designers use the standards to assess if the building design complies with the regulations. The standards provide a specification basis for the products and construction elements.

Special purpose simulation programs assist the building designers in the calculation of energy consumption of the building at various ambient conditions throughout a typical year (SIMIEN, 2020).

The construction company adjusts the heat loops and ventilation flow rate so that the as-built building complies with the design intent. The building constructor sets the water valves and ventilation dampers during commissioning.

2.2 Real Time Measurements

The Supervisory Control and Data Acquisition System (SCADA) monitors and controls the building in multiple zones. More than one thousand instruments are installed in the building. The data sample rate depends on the PLC, and is typically 1 minute. At a minimum, the controller measures air temperature, carbon dioxide level, and ventilation flow rate in each zone. The SCADA system sends the data to a database located at USN Campus Kongsberg.

We measured the actual air temperature in the room and the ambient temperature during the months of March and April 2020. The four weeks from 18th of March to 16th of April 2020 are particularly interesting. Due to the 2020 pandemic, the school was in lockdown and there were no people in the building during this time.

3 Design Basis and Assumptions

To predict the thermal losses and verify with actual room temperature measurements, we need to understand the energy balance of the building. The outside air temperature and the radiation from the sun affect the building, Figure 1. The basic simulation module is a single room model where the outer walls and windows are exposed to the ambient conditions.

We do not consider the effect of solar energy influx in this work. The room used for model verification is facing North-West with the horizon at 315 degrees.

Multiple effects influence the energy balance at a given time. Figure 2 shows a sketch of the contributors to the energy balance of a room. We combine the most relevant thermodynamic processes in our model: a) thermal losses of walls, windows and roof, b) thermal mass of furniture, and c) heat flow contributed through air ventilation, floor-heating, radiator heating, and people (users).

3.1 Walls, Windows, and Roof

The energy performance standard governs the building design. We use the same approach in our model and we use the overall heat transfer coefficient, U-factor, and heat storage capacities applied in the building design. The data are available from the building owner. With this approach, we do not need the building construction details like the composite wall design or insulation material. Using the design basis allows us a direct comparison with the design basis.

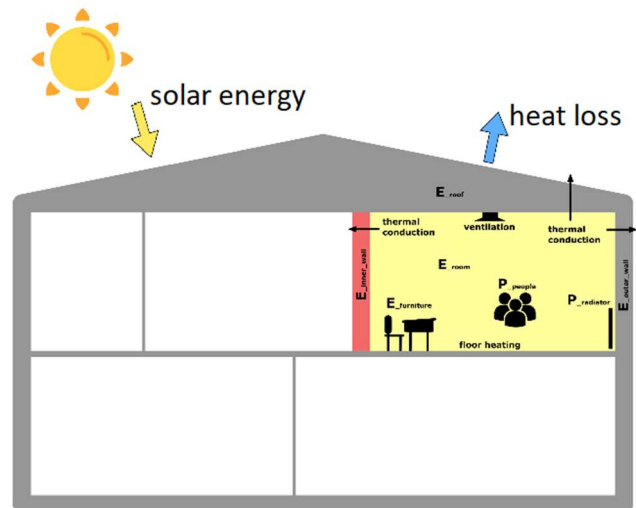


Figure 1. Thermal loss model of building

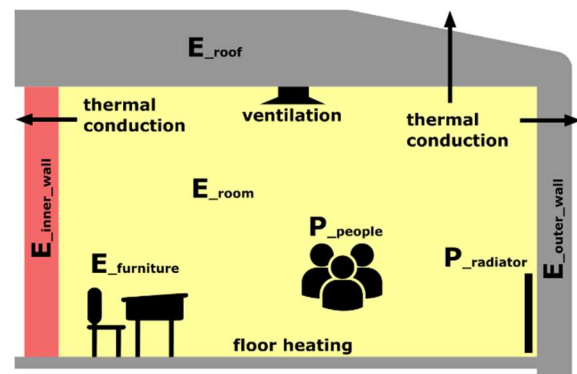


Figure 2. Energy sources and thermal losses in the room

The outer wall of the room is 22m² of which 55% is window surface. The floor and roof surface is 63 m². We assume zero heat transfer across the inner walls of the building. There are no doors exposed to ambient air.

In our work, we use the following building design parameters:

Heat transfer coefficient (U-factor)

- Outer wall: 0.17 W/m²K
- Roof: 0.13 W/m²K
- Windows: 0.85 W/m²K

Heat capacity (h):

- Outer wall: 12 Wh/m²K
- Roof: 10 Wh/m²K
- Window: 3 Wh/m²K

3.2 Furniture

Changes in the air temperature will change the furniture temperature. Depending on the furniture mass, this can cause a shift in the modeled air temperature compared with measurement.

For design basis, we assume 30kg of furniture per student (900 kg total for the room in this work). We assume a specific heat capacity of 1000J/kgK for the furniture.

3.3 Ventilation

The ventilation provides a flow of fresh air to the room. The airflow rate (mass based) at inlet to the room is the same as the airflow rate leaving the room (per mass). The control system measures the volumetric airflow rate. This is a rudimentary measurement based on the valve position. During normal use, the valve position is adjusted automatically based on the actual demand regulated by the temperature setting of the room and the air quality (local measurements of carbon dioxide).

The flow rate to the room is zero when the ventilation system is shut down and 1300 m³/hr at full flow. During normal operation, the control system schedule sets ventilation flow rate.

We assume air as an ideal gas with constant specific heat capacity (isochoric) of 717.3 J/kgK and a density of 1.2 kg/m³ for the air.

3.4 Floor-heating

The building floor-heating is installed in the basement, shared rooms, library and the main hall. Water circulates in piping embedded in the floor. A geothermal heat pump heats the water. Electric heaters allow for higher temperatures during the cold season. The water flow rate is per design and not adjusted after commissioning

There is no floor-heating in the room used in our model and the flow rate is therefore set to zero in this work.

3.5 Radiator

Most rooms have one radiator. Water circulates through the radiator and the heat is released through natural convection to the air. Each radiator can provide up to 1400W heat to the room. The actual heat release depends on the valve setting in the water loop. The water flow rate is not measured.

The energy balance calculated at the start condition of the simulation determines the heat input to the room. We use a constant radiator heat input of 290 W in this work, which is the initial state equilibrium of the room for the measurements used in here.

3.6 People

People using the room will release heat to the surroundings. The energy performance standard recommends a heat release of 12 W/m² per person for design of school buildings. The effect of people is not included in this paper because we collected the building data for a time where there were no people in the building.

4 Thermal Model

We use MALAB Simulink, v.10.0 (R2019b) for the simulations. Our system is an open system with conservation of mass (air). From the first law of thermodynamics, assuming zero work, we find that the change in internal energy from the initial state 0 to the final state is equal to the change in heat (Q) in the system:

$$E_{air} - E_{air0} = \int Q dt \quad (1)$$

where E_{air} is the energy of the air in the room and 0 indicates the initial state.

The net heat transfer to the room is the sum of heat flowing into or out of the system.

The air temperature at the initial state is calculated from the internal energy:

$$T_{room} = \frac{E_{air}}{cv_{air} \cdot \rho_{air} \cdot V_{room}} \quad (2)$$

Where cv_{air} is the isochoric specific heat capacity of the air; ρ_{air} is the density of air, assumed constant; V_{room} is volume of the room), Figure 3.

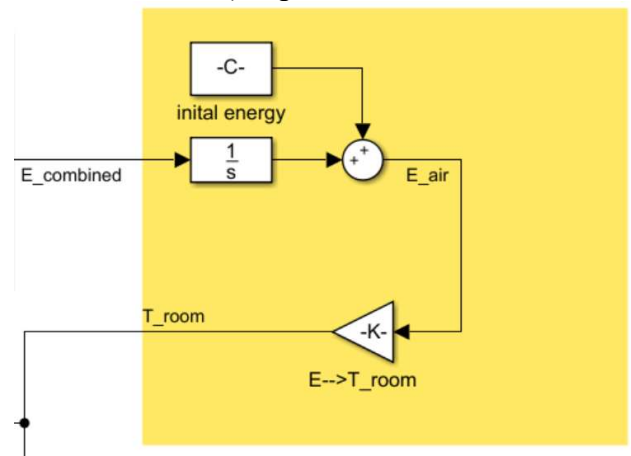


Figure 3. Room temperature calculation in MATLAB

4.1 Wall, Window and Roof

The wall is modelled by the thermal resistance, eq.3, Figure 4:

$$E_{wall} = \int Q_{wall} dt + E_{w0} \quad (3)$$

We base the wall model on Fourier's law of heat conduction where the heat transfer through a material is proportional to the (negative) gradient in the temperature and to the area perpendicular to that gradient. The U-factor determines the heat transfer.

$$q_{conduction} = (T_{wall} - T_{outside}) * U_{wall} * A_{wall} \quad (4)$$

This heat flow does not directly interact with the room but reduces the temperature of the wall that again increases the heat flow through the convection model.

We include the heat (storage) capacity of the material in our model to allow for a delay in the development of the air temperature inside the room:

$$q_{wall} = (T_{room} - T_{wall}) * h_{wall} * A_{wall} \quad (5)$$

where, A_{wall} is the surface area of the outer wall.

This is as well the interface for this sub model to the central room model, as it transfers heat between the air in the room and the thermal mass of the wall.

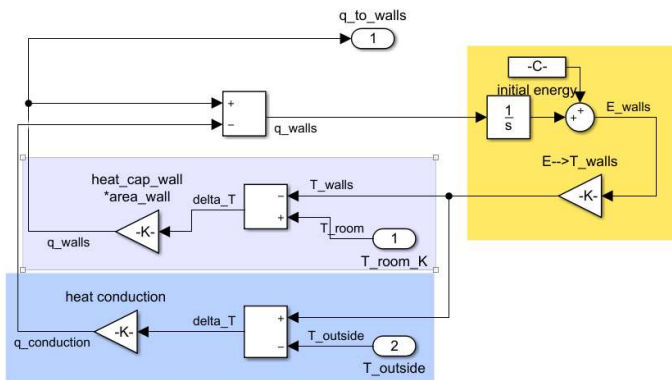


Figure 4. Wall model in MATLAB

The windows and roof models are analogous to the wall model with different properties as listed in Section 3.1.

We use room air temperature to connect the sub-models as seen in Figure 5. The air temperature calculation converges to steady state at each time step.

4.2 Furniture

The furniture model uses the thermal mass model since there is no sufficient data for a convection-based model and no heat conduction is taking place. See Figure 5.

4.3 Ventilation

The ventilation model uses volumetric flowrate \dot{V}_{vent} and initial air temperature T_{vent} to determine the heat flow of the incoming air to the room:

$$q_{vent_in} = T_{vent} * c_{air} * \rho_{air} * \dot{V}_{vent} \quad (6)$$

Figure 6 shows the model of the ventilation at the inlet to the room, the heating and the heat input from people.

Because air pressure inside the room is constant, the air mass flow from the room is the same as at the inlet. The heat flow of the outgoing air from the room becomes (air density assumed constant):

$$q_{vent_out} = T_{room} * c_{air} * \rho_{air} * \dot{V}_{vent} \quad (7)$$

where the temperature of the outgoing air is the temperature of the bulk air temperature in the room. The model is shown in Figure 5 (purple box).

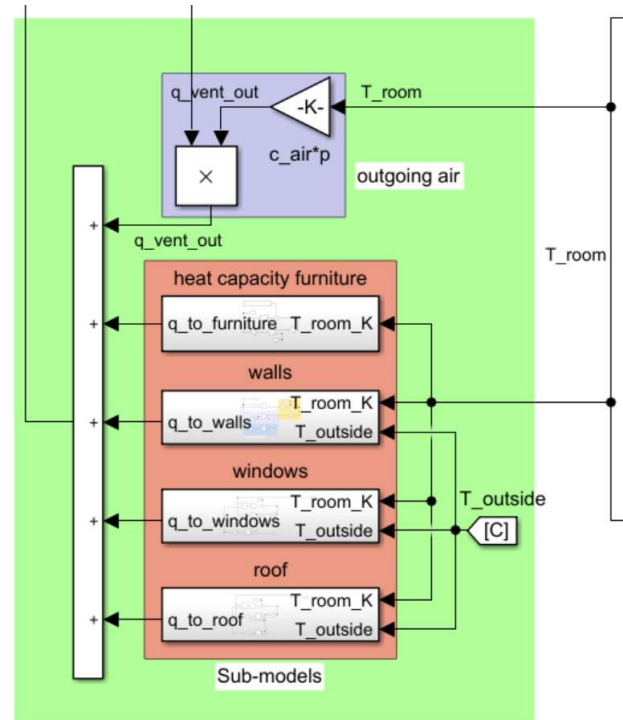


Figure 5. Thermal models connected by air temperature

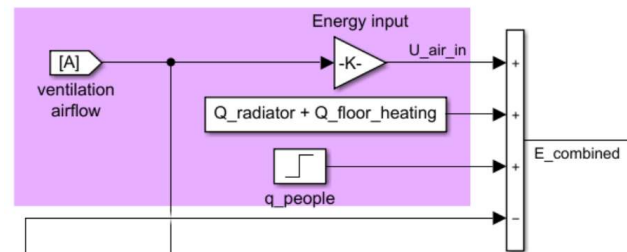


Figure 6. Ventilation flow model in MATLAB

4.4 Floor-heating

The floor-heating model is based on the difference in water temperature as measured at the inlet and outlet of each building zone. The water flow rate is constant.

$$q_{floor} = c_{water} * \rho_{water} * \dot{V}_{water} * (T_{in} - T_{out}) \quad (8)$$

Floor-heating is set to zero in this paper.

4.5 Radiator

We use a constant heat input of 290W from the radiator to the air; see Figure 6 and Section 3.5.

4.6 People

The heat released by the users is not included in this work; see Section 3.6.

5 Model Validation

We validate the model using actual data measurements from a room in the school building. We use two different data series:

1. Ventilation system fully closed (due to pandemic lockdown),
2. Ventilation system operated according to the standard building control scheme (with low flow during night).

The SCADA samples ambient temperature, room air temperature, and ventilation airflow rate at 1-minute intervals for both data series.

We use the measured ambient temperature and the ventilation airflow rate as input to the model and simulate the room air temperature. In the final digital twin, we will use a temperature forecast. The results presented in this paper are therefore assuming a perfect forecast.

Finally we compare the simulated air temperature to the measured air temperature, see Figure 7 for model.

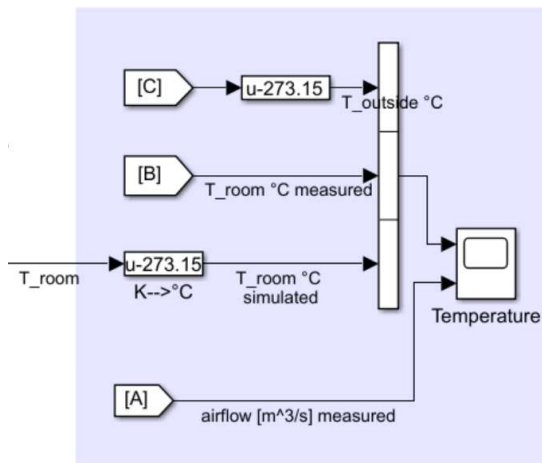


Figure 7. Room Temperature Validation

6 Results and Discussion

Figure 8 shows the simulated and measured room temperature for the case of the shutdown ventilation system. The ventilation airflow rate was zero during the time and the ambient temperature varies from -3°C to $+14^{\circ}\text{C}$ in diurnal cycles (14 days).

The thermal loss model predicts the response of room air temperature to the variation in ambient temperature. Figure 8 shows fair prediction accuracy with a maximum deviation of $\pm 1^{\circ}\text{C}$ between the simulated and the measured room temperature. After 7 days, the simulation starts to deviate from the measured data and the prediction is less reliable.

The prediction accuracy remains high despite the coarse resolution in the ambient air temperature measurement used as input to the model. The ambient temperature instrumentation installed in the building is accurate. The reduced resolution and observed data discretization is due to data truncation in the

measurement system. We recommend improving this for the future.

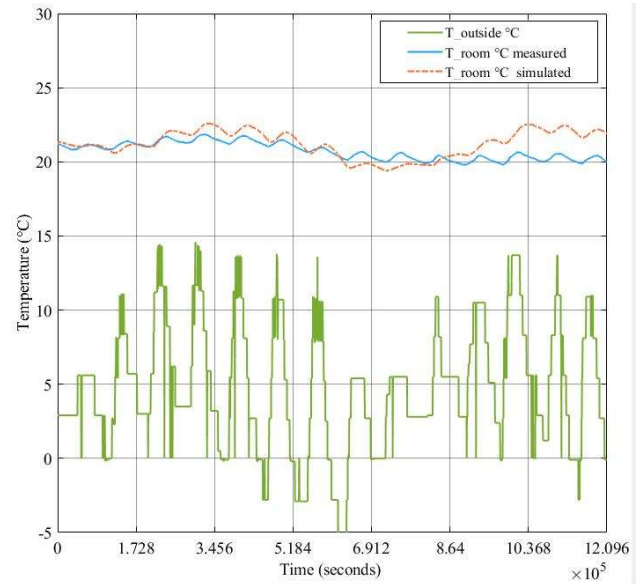


Figure 8. Room temp prediction with closed ventilation

Figure 9 shows the simulated and measured room temperature for the case with the ventilation system in normal operation. The ambient temperature varies from -3°C to $+28^{\circ}\text{C}$ in diurnal cycles (14 days). The ventilation airflow (Figure 10) is operating during daytime on the weekdays and fully closed during the weekend. The ventilation air temperature is constant for the full simulation.

The prediction accuracy of Figure 9 is reduced significantly compared to Figure 8. The model is not able to predict the behavior for more than 2 to 3 days. The simulation assumes a constant ventilation air temperature. In reality, the air temperature changes within the limits set in the building control system. This effect is not included in the simulation.

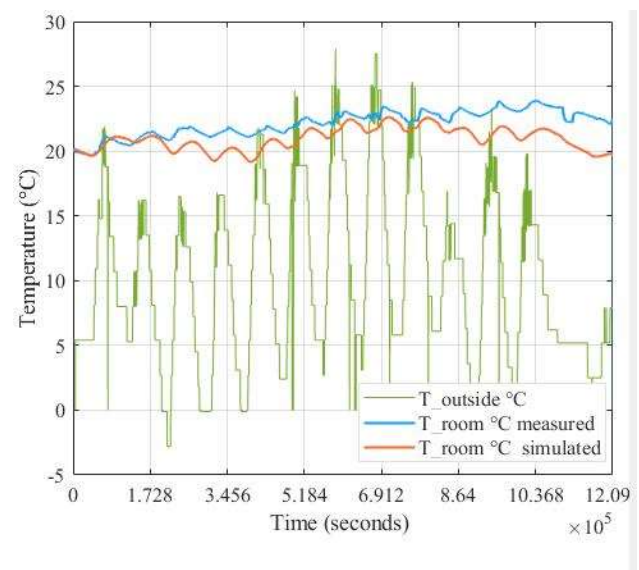


Figure 9. Room temp prediction, ventilation running in normal operation

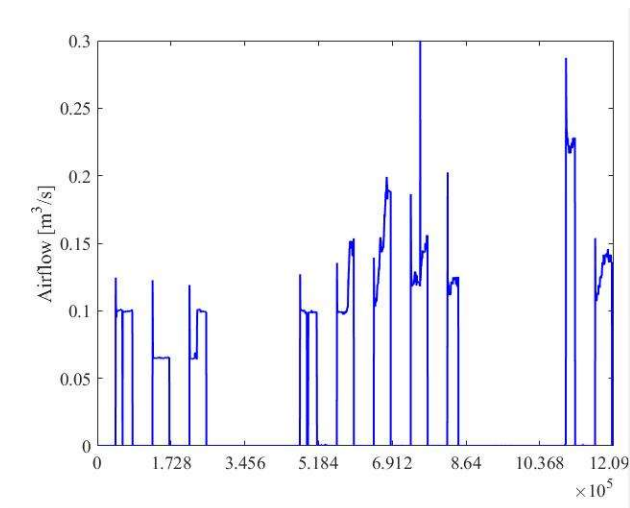


Figure 10. Ventilation air flow rate applicable to Fig 9

7 Conclusions and Further work

Low-energy buildings have significant heat loss to the surroundings. This causes diurnal temperature variation inside the building and drives the energy consumption. We search for a simple model to predict the thermal losses of a low-energy building. We will use the model to predict the energy consumption of the building for short time periods (up to 7 days).

Our model is based on a simple method of energy balance combined with heat conduction. The model data are based on the building design data. The model is validated using real data from the same building.

We tested the model based on real conditions over a 14-day period with and without ventilation air entering the building. The model is accurate within $\pm 1^\circ\text{C}$ for 7 days prediction for cases where the ventilation system is off.

For simulation with the ventilation system in normal operation, the model predicts the change in room temperature within an accuracy of $\pm 1^\circ\text{C}$ for 2 days. Additional accuracy for longer periods may require input of the ventilation air temperature. This should be checked in future work.

Future work should provide qualitative measures for the error between the measured and the predicted room temperature. This will help our understanding of the prediction accuracy.

We will extend the model to predict the effect of solar influx. Solar radiation is likely to affect the temperature of the walls and may result in a different thermal loss from the building.

Future models should verify the dynamic behavior of the building. The simplistic approach taken in this work is a possible oversimplification, and can lead to serious errors if not closely monitored.

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