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Implementation of a User Feedback System and its Impact on User Satisfaction and Energy Demand

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ABSTRACT

This paper focuses on a thermal simulation model of office rooms and experiments necessary to adequately estimate the required model parameters. For this, we investigated step responses for different parameters, e.g. the set point temperatures of the façade ventilation units and the concrete core activation, in the E.ON ERC Main building, to enable predictive modelling of the temperature in the office rooms. This enables us to build a user-interface, which in addition to providing the user with feedback regarding the historical data, can also estimate the impacts of user interactions on the future room temperature. The simulation is accurate enough as to provide the occupant with an estimate on when or whether their desired temperature can be reached on that day.

INTRODUCTION

People spend 87 % of their time indoors, partly in office environments (Klepeis et al., 2001). We want to ensure that the people in our office building can know at all times, what the current temperature of their office is, and to enable them to set their desired temperature range, to make themselves more comfortable. We built a system that allows occupants to select a room, see its historical, current and predicted temperature graph and vote for a desired temperature range. This allows us to regard individual preferences when setting the office temperature in the building automation system. In this paper, we elaborate on the existing building automation system and a simulation model for predicting the room temperature over the course of the day. We also conducted experiments to determine the necessary model parameters and developed a user interface. The goal of this experiment is to enable future research at our institute in which we educate occupants on their impact on building energy usage. We plan on achieving this, by giving them a clear and understandable estimate of the energy usage of different behaviours or set point adjustments.

EXISTING BUILDING ENERGY SYSTEM

The surveyed office building is located in Aachen, Germany and equipped i.a. with a concrete core activation (CCA), a façade ventilation unit (FVU) system and windows, which can be opened manually. All of these should ensure the thermal comfort of the offices occupants. A PID Controller regulates the inlet temperature of the CCA heating and cooling loop. The set-point of the inlet temperature of the CCA bases on a linear relationship of the current outdoor temperature. In future research, we want to investigate the speed at which the system achieves this set-temperature, to enable us to develop a control algorithm, which uses the weather forecast to regulate the temperature based on future

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demands and not the current outdoor temperature. The FVU provide a maximum of 300 W of cooling power for each 3-person office. Because the solar load and other internal gains in the offices, for example the heat given off by the occupants, exceed the cooling power of the façade ventilation units, the concrete core activation has to provide the remaining load. Fütterer and Constantin provide an overview of the design of the building automation system in the E.ON ERC main building (Fütterer and Constantin 2012).

ROOM TEMPERATURE SIMULATION MODEL

We built and calibrated a room temperature simulation model, to show a prediction of a room's temperature in a web interface. We conducted step response experiments and used the python package GEKKO (Beal et al. 2018) for a least square optimization in order to determine individual parameters of the simulation model. Building the simulation model in the GEKKO optimization suite also allowed us to implement the simulation directly in the web-interface's Django backend. This is possible because both are python based and the simulation is executed fast enough to run every time the website requests the newest data-set. The subsequent subchapters explain the simulation, the experiments and the calibration methodology.

Simulation methodology

In order to predict the future room temperature, we use a simulation model based on a simplified resistance-capacitance (RC) approach. The aim is to create a gray-box model with less parameters, which can be easily estimated in a calibration process. The model includes one capacity for the room temperature, one capacity for the inner wall temperature and three resistances for the heat flow from the room to the ambient air ($R_{OuterWall}$), to neighboring rooms ($R_{InnerWall}$) and to the concrete core activation (R_{CCA}), which is installed in the ceiling, see equation (1) and equation (2). Further, the model considers the enthalpy flow caused by the façade ventilation unit, the internal gains (e.g. occupants and electrical appliances) and the solar radiation. The solar radiation that goes into the room depends on the shading of the window. Since the current position of the window shading is unknown, we scale the radiation with the parameter $\mathrm{f_{win}} \in [0,1]$, which we estimate in the calibration process and assume as constant for the prediction horizon. Here, a value of $\mathrm{f_{win}} = 1$ means that shading is fully opened, while a value of $\mathrm{f_{win}} = 0$ means that no sun light enters the room. The solar radiation I_{solar} is given by weather data or weather prediction. For this we use the solar global radiation as measured by the German weather service (see DWD 2020) and calculate the total in-plane irradiance total in-plane irradiance irradiance with the "get_total_irradiance function" of the python library pvlib (see Holmgren et. al. 2018). For the simulations we set the temperature of the adjacent rooms $T_{neighboringRoom}$ as a constant value, equaling the daily mean temperature of the surveyed office.

To control the room temperature, the supply air temperature of the façade ventilation unit T_{FVU} and the temperature of the concrete core activation T_{CCA} can be manipulated. The variable $T_{Room,set}$ describes the room set point temperature, which the occupant would be able to adjust. This is the variable we changed during the step-response experiments, on which we elaborate in the subsequent subchapter. To simulate the FVU's supply temperature, we added the additional set point temperature variable $T_{Set,FVU}$. The supply temperature T_{FVU} follows the set point temperature $T_{Set,FVU}$ with a first order behavior, see equation (3). An internal controller of the FVU determines the set point $T_{Set,FVU}$ based on the room set point temperature $T_{Room,set}$. For this simulation we simplified the original FVU's control strategy into a proportional controller, see equation (4). The parameter K_p is the gain of the controller and is set to 3 in this study. The parameter τ_{FVU} is the time constant of the first order element for the FVU. Since the supply temperature of the FVU is bounded by the buildings temperature supply system, we added a $tanh$-function to set upper and lower-bounds of 16 °C and 33 °C with a continuous differentiable function. We used the results of the step response tests to estimate the time constant. The concrete core activation temperature does not fluctuate largely, because its time constant is larger than the design of the experiment, which is why we set its temperature as a constant in these simulations.

$$c_{Room} \cdot \frac{dT_{Room}}{dt} = c_p \cdot \dot{m}_{AirExchange} \cdot (T_{FVU} - T_{Room}) + 1/\mathrm{R}_{CCA} \cdot (T_{CCA} - T_{Room}) + 1/\mathrm{R}_{InnerWall} \cdot (T_{InnerWall} - T_{Room}) + 1/\mathrm{R}_{OuterWall} \cdot (T_{Environment} - T_{Room}) + I_{solar} \cdot A_{Window} \cdot \mathrm{f}_{\mathrm{win}} + \dot{Q}_{Gains} \quad (1)$$

$$c_{InnerWall} \cdot \frac{dT_{InnerWall}}{dt} = 1/\mathrm{R}_{innerWall} \cdot \frac{1}{2} \cdot (T_{innerWall} - T_{Room}) + 1/\mathrm{R}_{InnerWall} \cdot \frac{1}{2} \cdot \left(T_{innerWall} - T_{neighboringRoom}\right) \quad (2)$$

$$T_{Set,FVU} = \tau_{FVU} \cdot \frac{dT_{FVU}}{dt} + T_{FVU} \quad (3)$$

$$T_{Set,FVU} = 16\,°C + \frac{\tanh\left(K_P \cdot (T_{Room,set} - T_{Room})\right) + 1}{2} \cdot (33\,°\mathrm{C} - 16\,°\mathrm{C}) \quad (4)$$

Table 1. Example of set-points during the experiments

Date and Time	$T_{Set,Room}$ in °C	Fan power in %
2020-1-31 19:00	22	50
2020-1-31 21:00	19	50
2020-2-01 01:00	25	50
2020-2-01 05:00	Regular controller	Regular controller
2020-2-01 19:00	22	50
2020-2-01 21:00	19	100
2020-2-02 01:00	25	100
2020-2-02 05:00	19	50
2020-2-02 09:00	25	50
2020-2-02 13:00	19	100
2020-2-02 17:00	25	100
2020-2-03 01:00	19	100
2020-2-03 05:00	Regular controller	Regular controller

Step response experiments

Over the course of four days in winter, we conducted step response experiments, by alternating the set point of the buildings concrete core activation and the room temperature set points of the façade ventilation units in 14 offices facing different cardinal directions. We adjusted both set points equally between the two extremes of 19 °C and 25 °C and the volume flow rate of the façade ventilation units between 50 % and 100 %. We tested every room twice or three times with every one of the four possible combinations. Table 1 shows the dates and combinations of the set points during the experiments in one room. The tests begin by setting an initial condition of the temperature set points for the façade ventilation unit and concrete core activation and the relative fan power of the façade ventilation unit. This enables a known and fixed starting point for the step response experiments. We ran the tests from Friday night until Saturday morning and from Saturday evening until Monday morning, to lower the chance of occupancy in the offices during the test period and eliminate occupant behaviour such as window or door opening.

Model calibration

We used the measured room and FVU temperatures of the experiments and the GEKKO optimization suite to determine the values of the resistances $R_{OuterWall}$, $R_{InnerWall}$ and R_{CCA}, the radiation factor $\mathrm{f_{win}}$ and the time constant τ_{FVU} in the simulation model. We optimized these values for each individual office. The resistances R and the parameter $\mathrm{f_{win}}$ are uncertain and vary for each room. In order to estimate R and $\mathrm{f_{win}}$, we performed a calibration using past measurements. The objective is to minimize the error between the simulated and measured room temperature:

$$\min J = \quad \left(T_{Room} - T_{Room,measured}\right)^2 \tag{5}$$

We achieved a root mean square error (RMSE) between the simulated and measured room temperatures of 0.39 K for the entire data set. Moreover, the simulated supply temperature of the façade ventilation units do resemble the measured temperatures less accurately. The RMSE of the supply air temperature of the façade ventilation units T_{FVU} for the entire data set is 3.44 K. This difference is so pronounced, because the supply temperature of the FVUs in four rooms did not exceed the value of 25 °C for the heating scenarios, contrary to most FVUs, which reached inlet temperatures of up to 34 °C. The control strategies of all FVUs are identical, which is why we have so far been unable to find an explanation for this behaviour. Disregarding these rooms, we reach RMSEs of 0.41 K for the room temperature T_{Room} and 2.27 K for the FVU inlet temperature T_{FVU}. Additional tests showed that changes in the concrete core activation set point temperature take longer than a single day to take effect, therefore we chose to assume the CCA temperature T_{CCA} as constant starting from midnight for single day simulations. The RMSE of the constant CCA temperature compared to the measured data was 0.18 K over the course of the FVU experiments. Since the aim of the simulation is to provide users with a single day´s temperature prediction, this simplification is sufficiently accurate but will prove insufficient for longer timeframes.

Figure 1 shows the measured and simulated results for one office on a single test day. The measured and simulated room temperatures are in good accordance at an RMSE of 0.28 K, while the façade ventilation temperatures show higher discrepancies with an RMSE of 1.16 K. The difference between the simulated and measured room temperature tends to accumulate over the course of the day. The spike in the measured FVU temperature at the end of the day is because of its valves opening and closing automatically at midnight. Since we intend to use the simulation in the web-based interface which we present in the next section, most simulations will occur during working hours and only for the remaining hours of the day. This limits the time horizon of the necessary simulation to less than 14 h.

WEB BASED INTERFACE

We designed and implemented an interface for the occupants to enable interactions with the building automation system. With this interface, users vote for their desired room temperature and get information on the chart of the day's previous and future room temperature in their current office or conference room. The system uses a Vue.JS based frontend, communicating with a Django backend. A separate python script gathers the buildings sensor data, saving them to an InfluxDB. We chose the Vue.JS frontend, because it enables us to integrate our desired functionalities and adding additional aesthetically pleasing elements, such as small animations upon interactions. The Django backend allows for wide range of functionalities when interacting with the database and other already existing scripts.

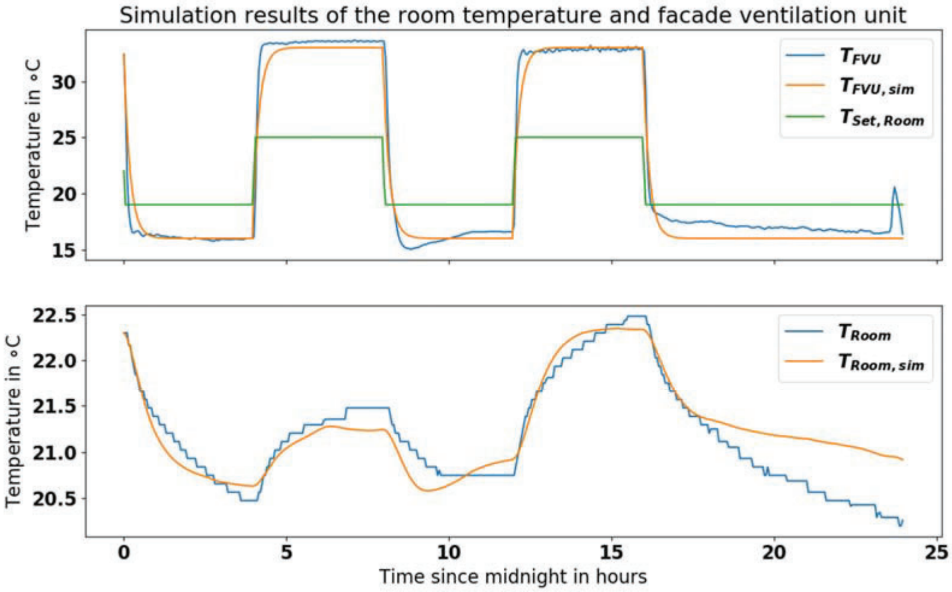
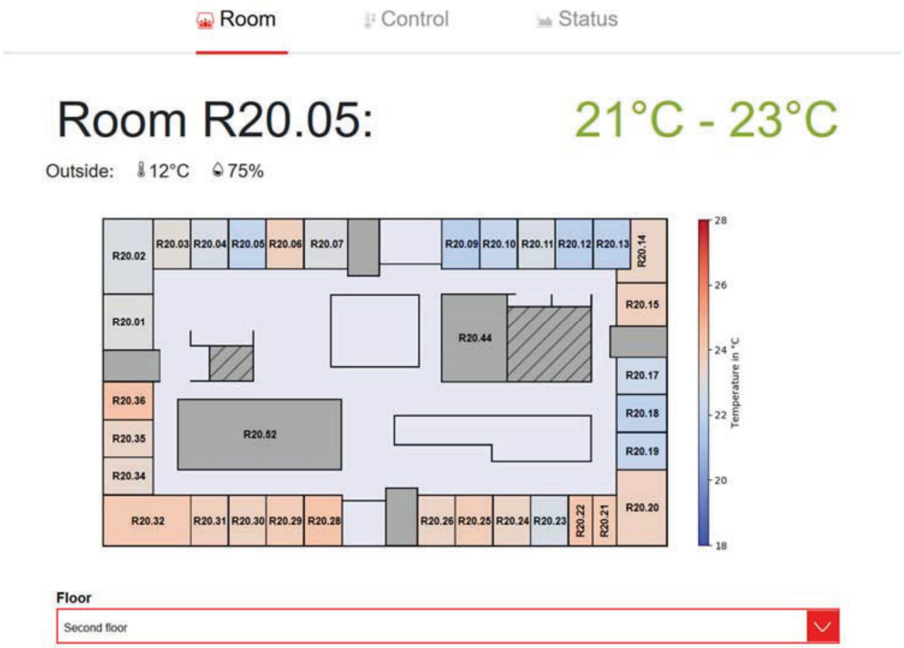


Figure 1. Simulated and measured temperatures of one day in one office.

Figures 2 shows the design of the room selection page. This page enables the users to select an office or conference room which they want to steer or whose temperature graph they want to see. This page contains individual floor plans, where the color of the rooms shows their current temperature. By clicking the different rooms, the occupants are able to choose the room they are currently in or otherwise want information on. Additionally, we show the outside weather conditions, to give the user an indication, on whether they might be able to open their window to reach their desired temperature.

Once they have chosen their office, the user can proceed to the control page shown in figure 3. On this page we enable them to vote for a temperature range for the given office or meeting room. Additionally, we show the current temperature range in the chosen room and display a reminder, that the building energy system and especially the façade ventilation units only operate properly while the windows are closed. An automated script gathers the votes every quarter hour and calculates the mean temperature vote, regarding every individual user's last vote in the respective room during the last two hours. Therefore, it decreases the chance of considering votes from people, who might not be in the room anymore and also does not overemphasise a specific temperature range, if one person voted multiple times.

Figure 4 shows the temperature graph for the given room and the aggregated temperature votes. It shows the occupants the measured temperature graph of the current day for the chosen room in a dark green color temperature. The Django backend calculates the future temperature data every time a user opens this page, based on the current weather and indoor climate conditions, the current setpoint and the previously calibrated model. This enables the users to see the room temperature over the course of the rest of the day, which is displayed in the graph in a lighter green color. It also allows them to get a good estimate on how fast the temperature they chose might be reached, or if it is even possible under the given conditions. Additionally, we can show the aggregated temperature votes for the chosen room, placed at the times they occurred and at the corresponding temperature interval height. We show the measured and predicted temperature graph without their corresponding values on the y-axis, to prevent complaints from occupants using their own uncalibrated thermometers to find out, whether we achieved their desired temperature or not.



Room R20.05: 21°C - 23°C

Outside: 12°C 75%

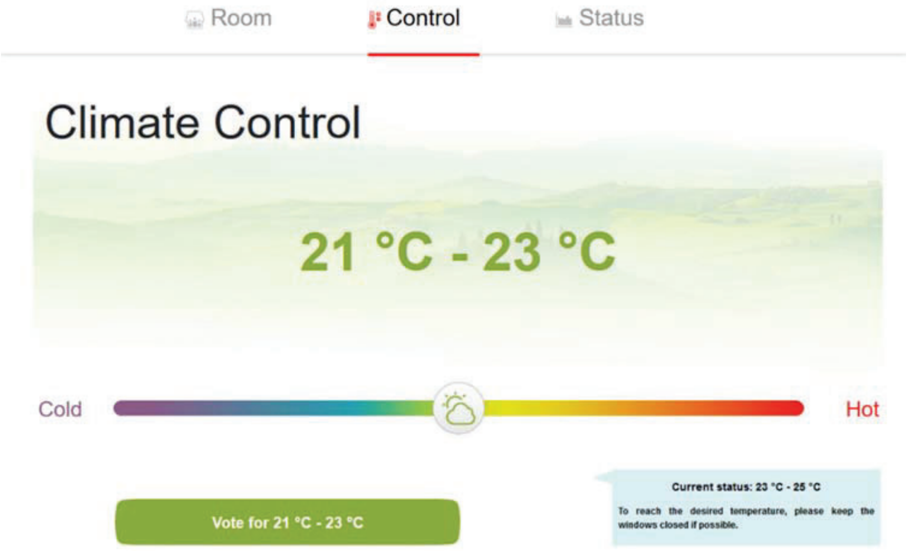
Floor: Second floor

Figure 2. The room selection page for second floor.

CONCLUSION

In this paper we showed a simple thermal simulation model for individual office rooms and performed experiments in which we determined the necessary model parameters. The experiments results show that the devised simulation can give a rough estimate of the future room temperatures. The prediction is accurate enough as to give the occupant an estimate on when or whether the system can achieve their desired temperature, but inaccurate in simulating the individual façade ventilation supply temperatures. The experiments were insufficient in their length to establish the time constant of the concrete core activation correctly.

The proof of concept build of a user interface for future research was successful. This consists of a room selection option, a page on which users can vote for their desired temperature range, and a chart that displays a temperature graph for the current room. The temperature graph includes a simulated predicted temperature for the rest of the day.



Climate Control

21 °C - 23 °C

Current status: 23 °C - 25 °C

To reach the desired temperature, please keep the windows closed if possible.

Figure 3. The climate control page.

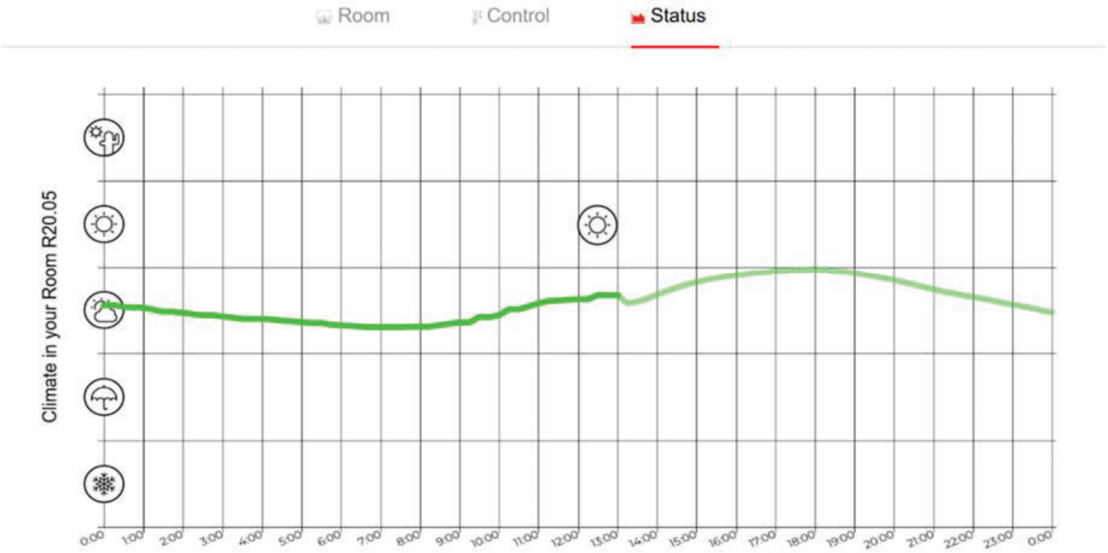


Figure 4. The status page.

OUTLOOK

In the future, we will conduct further investigations for parameter determination of the concrete core activation, since the conducted experiments were insufficient in their time intervals between the set temperature steps to ensure a noticeable response in the concrete core activations outlet temperature. Additionally, we will examine the supply volume flow rates of the FVU more closely, as well as implementing additional control strategies, to reflect the behaviour of the real FVU more closely in the simulation. Additionally, we plan on using the predicted temperatures of the adjacent rooms in future implementations of the simulation. We plan on gathering additional data in the future, and dividing it into training and test datasets, as to validate the accuracy of the simulation using data that have not been part of the dataset used for calibration.

Once we accurately determined the parameters of the concrete core activation, we will generate control algorithms that will control the concrete core activation based on the weather forecast, instead of the current outdoor temperature. This will eliminate unnecessary heating or cooling of the system and promises energy savings.

In future tests we will use this model to conduct occupant studies in our office building, investigating the interactions and satisfaction of the occupants with the system and the prevalence of different desired temperatures. Furthermore, we will examine the effectiveness of the system in providing these temperatures and different ways of aggregating temperature preferences of multiple occupants for one thermal zone into a single set point. We initially planned on conducting this field study in 2020. Unfortunately due the COVID-19 global pandemic, our offices were insufficiently occupied during most of 2020 as to enable us to conduct adequate research in our building. We plan on rectifying this in 2021, using an updated interface and a more sophisticated building temperature modelling approach.

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