Thermal and uncertainty analysis of a lightweight floor with integrated TABS and ventilation system

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Abstract

The HiLo living lab combines numerous novel multifunctional building elements, including a floor system that integrates TABS and ventilation system into complex geometry and lightweight structural components. The purpose of this study is to investigate the operational performance of the floor system and to compare it with the performance predicted by a white-box model in TRNSYS. Although the model can accurately and reliably predict the actual performance of the floor system with a median CV-RMSE index of 3.35%, the limited variability in the data and the unique conditions of the living lab may limit the generalisability of the model.

Highlights

- The integration of a ventilation system with TABS improves temperature distribution homogeneity of the novel floor system.
- The white-box model can accurately predict the thermal performance of the novel floor system if there are low disturbances in the measured data.
- To improve model generalisability, future data collection should account for living lab disturbances.

Practical implications

Practitioners should perform uncertainty analyses to assess the robustness of their models of novel technical solutions, like TABS in complex geometry and lightweight structural components. They should consider the impact of disturbances in measured data and the unique conditions of a living lab that may limit generalisability.

Introduction

Buildings account for 36% of global energy consumption (United Nations Environment Programme, 2021). To significantly improve the energy efficiency of buildings, and thus contribute to a reduction in global energy consumption, many novel technical solutions have been developed. However, the actual efficiency of these solutions often falls short of expectations, partly due to a lack of actual operational data to demonstrate their effectiveness. To address these challenges, the HiLo living lab was recently built in NEST (Next Evolution in Sustainable Building Technologies), a modular research and innovation building in Dübendorf, Switzerland.

Designed around the guiding principle of "high performance, low emissions", HiLo combines numerous novel multifunctional building elements, including thermally activated building systems (TABS) integrated into complex geometry and lightweight structural components. Integrating a hydronic pipe network into the building structure, the TABS transform the internal ceilings of two offices into radiant surfaces for heating or cooling by utilising the physical properties of concrete for heat storage or thermal inertia. This leads to a time shift of the peak heat load and a time lag of the sensible heat from the concrete to the interior air. In addition, the use of TABS in lightweight structures decreases the connection between the radiant panel and the structural supports, resulting in faster attainment of steady-state operation and less thermal loss to the structural materials during heating.

During the design phase of HiLo, extensive experimental and numerical studies were carried out on the TABS to design, size and integrate them into the lightweight structural components. These studies included a low-resolution model based on a Lesosai whole-building simulation to estimate the thermal loads of the building and the interaction with the district-scale systems (Lydon et al., 2017). High-resolution models utilising ANSYS Fluent focused on resolving product development issues between the building services and structural domains (Lydon et al., 2019). As HiLo was the first implementation of the innovative TABS approach, it was essential to understand the system's operational characteristics before constructing the first demonstrator. A medium-resolution model was set up to gain insight into the operation of the TABS at HiLo and the interaction with the other heating, ventilation and air conditioning (HVAC) systems. This white-box model (Royer et al., 2014) was based on the Transient System Simulation Tool (TRNSYS) and provided an understanding of the thermal capacity of the TABS and possible control strategies.

During the construction phase, sensors were installed at various locations, e.g. in the concrete in the plane of the pipe network of the TABS, to measure critical parameters of the TABS during the operational phase of HiLo, which started in the spring of 2022. The purpose of the present study is to investigate the operational performance of the unique floor system with integrated TABS and, in one of the two offices, an integrated ventilation system and to compare it with the performance predicted in the design phase by the white-box model.

Methods

The methodological approach of this study was quantitative and drew on research data from sensor measurements taken in HiLo and simulations performed with TRNSYS. By employing quantitative modes of enquiry, this study attempted to holistically shed light on the novel floor system with integrated TABS and ventilation system. The study consisted of two steps. First, a thermal analysis was conducted to statistically investigate the operational performance of the floor system. The performance criteria of particular interest were the heating/cooling capacity of the integrated floors and the temperature distributions of the TABS across the ceilings. Second, an uncertainty analysis was used to compare the measured performance data of the floor system with the simulated performance data to determine the robustness of the TRNSYS model.

Description of HiLo and unique floor system

HiLo is located on the top platform of NEST, which consists of a central backbone and three open platforms. On these platforms, individual units are installed for a limited time according to a plug-and-play principle, i.e. once the research and development work is completed, they can be removed again to make room for new units (Richner et al., 2017).

HiLo is a two-storey unit designed with an open-plan approach. As shown in Figure 1, the ground floor is composed of two enclosed rooms, named office 1 oriented towards the west and office 2 oriented towards the south, while the rest of the space is open-plan. These two offices are equipped with the novel floor system with integrated TABS. Office 2 also has a ventilation system integrated into the floor system, as well as an adaptive solar façade (ASF), which is a fixed building element that generates electricity and controls solar gains while optimising daylight conditions and outside views.

The floor system in the HiLo unit consists of:

Symbol	Parameter	Unit	Sensor type
🔵	Concrete temperature T_c	°C	Belimo 01CT-1BH
🔴	Water supply temperature T_{ws}	°C	Belimo 01CT-1BH
🟠	Water return temperature T_{wr}	°C	Belimo 01CT-1BH
🟢	Water flow rate V_w	m³/h	Belimo 22PEM-1UC
●	Indoor air temperature T_{ia}	°C	S+S Regeltechnik AERASGARD RFTM-LQ-CO2

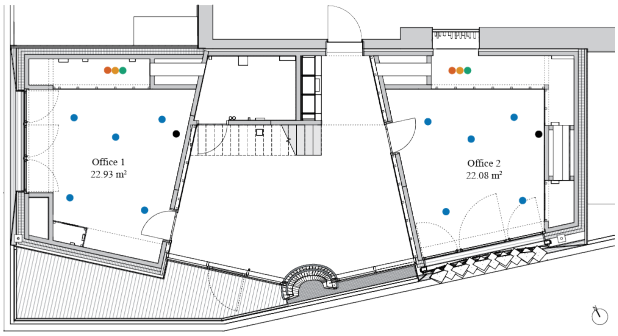


Figure 1: Floor plan of HiLo with the location of sensors indicated by dots.

- a funicular floor with a concrete thickness of only 20 mm for both the vaults and stiffening fins, significantly reducing embodied carbon emissions compared to common reinforced concrete slabs (Ranaudo et al., 2021);
- a hydronic pipe network for the TABS, consisting of three loops of 16 mm diameter pipes within the vault sections;
- expanded polystyrene (EPS) insulation blocks as permanent formwork in locations that improve the structural and thermal performance of the floor system.

Four air ducts for ventilation are also integrated into the floor system in office 2, as shown in Figure 2.

Figure 2: View of the lightweight floor with integrated TABS and ventilation system in office 2, the four air outlets are at the bottom. Photo: Roman Keller.

The floor system was cast in two-sided formwork. The upper formwork consisted of the EPS insulation blocks, which were used to create the rib structure of the floor as well as to control the placement of the TABS during fabrication. This ensured good surface contact between the concrete and the pipe network. The lower formwork was used to create the double-curved surface of the ceiling, which increased the spacing of the hydronic pipes at the central section of the floor.

Measuring equipment

HiLo is connected via the NEST backbone to a vertical energy district through several bidirectional thermal and electrical grids (Lydon et al., 2017). In addition, HiLo has its own building automation system (BAS) that communicates with the backbone via Ethernet. All automation functions from HiLo's BAS were programmed with a centralised programmable logic controller (PLC) based on a Beckhoff control system. The PLC integrates HiLo's building systems, sensors and actuators, as well as the weather station on the roof of NEST, whose data are communicated to the HiLo unit via the NEST control system, directly on one platform.

HiLo is equipped with more than 1,500 sensors, including sensors that measure relevant quantities of the HVAC systems, such as water flow rate and temperature at various depths of the TABS. In this study, several sensors at TABS, ventilation system and room level were deemed relevant. Figure 1 includes a list of these sensors along with the specific types of sensors that are installed in HiLo.

The two offices have individual room control that is achieved through a continuous flow control of the TABS. In addition, each office is equipped with a multi-split system to support the heating and cooling provided by the TABS. The occupants can adjust the room setpoint temperature for each office individually by using a control panel.

The data in HiLo are acquired with a frequency of one minute (changeable if necessary) and stored in the NEST database. Both live and historical data are stored and can be accessed via a REST API, an application programming interface (API) that conforms to the design principles of representational state transfer (REST), using Python or other clients.

In the present study, historical data stored in the NEST database with a one-minute frequency from 1 April 2022 to 31 March 2023 were used. The data were accessed via Python, where they were analysed and visualised directly using the Python packages Pandas and Matplotlib, among others.

Thermal analysis

The thermal analysis of the novel floor system with integrated TABS and ventilation system consisted of two stages: (1) quantifying the floor system's thermal performance during operation using a statistical analysis and (2) analysing the ventilation system's effect on surface temperatures using infrared images.

First, a statistical analysis was carried out to develop an understanding of the parameters that affect the floor system's operational performance. The parameters of interest were the heating/cooling capacity (Q) of the integrated floors and the temperature distributions of the TABS (T_{c}) across the ceilings.

The heating/cooling capacity was defined as the heat extracted by the water circulation according to Shinoda et al. (2022) and was equal to:

$$Q = \frac{\dot{m} \cdot c_{\mathrm{p}} \cdot \Delta T}{A} \tag{1}$$

$$\Delta T = T_{\mathrm{wr}} - T_{\mathrm{ws}} \tag{2}$$

where $\dot{m}$ is the water flow rate in kg/s, c_{p} is the specific heat capacity of water (4182 J/kgK), T_{wr} and T_{ws} are the return and supply water temperatures in °C and A is the ceiling area in m^2.

The performance of the integrated floors was quantified for a typical winter and summer week. Typical periods were determined as December to February for winter and June to August for summer. The dataset was then filtered to include the typical periods only, and the average values were calculated for each week in the defined periods to identify the typical weeks.

Second, the effect of the ventilation system integrated into the floor system in office 2 on surface temperatures and the TABS performance was analysed using infrared images, which are an effective instrument for studying the temporal variations in the homogeneity of surface temperature distributions (Yang et al., 2022). Two tests were conducted: one with both TABS and ventilation system activated on 26 January 2023 and one with only TABS activated on 27 January 2023. To allow the TABS to cool down naturally and be free from any thermal effects, the TABS and ventilation system were turned off for sixteen hours from 18:00 to 10:00. After switching on the TABS (and ventilation system) with a setpoint temperature of 24 °C, infrared images were taken every 5 minutes for six hours with a FLIR E76 thermal camera. The ceiling lamps were turned off during the experiments to avoid altering the infrared image colours.

Model development

The white-box model was built in TRNSYS, a software tool for simulating transient system behaviour. The program is used for research and industry analysis, mainly in the building domain. TRNSYS consists of a simulation environment where system components may be connected, and interactions are described using input/output connections. Components can be selected from the TRNSYS library, or custom components can be created for specific applications.

TRNSYS provides a whole building model with a detailed TABS model. This TABS representation (Empa model) was developed by Koschenz and Lehmann (Gwerder et al., 2008) and is also implemented in several other building simulation tools (e.g. IDA ICE). The Empa model accounts for the combined behaviour of thermal inertia and the active system with a set of resistance/capacitor elements. The dynamic performance of a TABS in a floor, wall or ceiling, within specific boundary conditions, can be estimated. Full-scale experiments have been used to validate the Empa model (Nageler et al., 2018). In addition, for the HiLo project, TRNSYS was coupled with CONTAM to improve the modelling precision of the ventilation systems, and MATLAB was used to automate the model and results processing.

To validate the white-box model, measured data from office 1 on 5 January 2023 were compared to simulated results. The comparison day was carefully selected because HiLo is a living lab with significant occupant activity, and it is used to test various HVAC systems. Therefore, the selected day had a low number of occupants- and systems-related disturbance events. To prepare the white-box model, the state vectors for the TABS and the ventilation system were collected from the NEST database and transferred to MATLAB. The Meteonorm tool was used to convert the NEST weather data to a TMY2 format file, which is compatible with TRNSYS. The room temperature (T_{ia}) of office 1 was the comparison parameter.

Uncertainty analysis

Building performance simulations involve simplifications and abstractions of physical processes, which can affect the accuracy and reliability of the simulation results. To identify the sources and magnitudes of uncertainties and variability in input parameters and model predictions, an uncertainty analysis was conducted. The aim of this analysis was to gain insights into the robustness of the white-box model.

To reduce uncertainty, the predicted outputs of the model were compared to actual measured data for the same conditions (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2014). This comparison helped to reveal the underlying details of the thermal performance of the integrated floor system, thereby contributing to a better understanding of their in-use thermal performance.

The statistical indices used to measure the uncertainty of the model were the normalised mean bias error (NMBE) and the coefficient of variation of the root mean square error (CV-RMSE). The NMBE index gives the global difference between measured and simulated data points by normalising the average of the errors of a sample space and dividing it by the mean of the measured data points.

$$\mathrm{NMBE} = \frac{1}{\bar{m}} \cdot \frac{\sum\limits_{i=1}^{n} (m_{\mathrm{i}} - s_{\mathrm{i}})}{n-p} \cdot 100 \tag{3}$$

where $\bar{m}$ is the average of the measured data points, m_{i} is the measured data point for each model instance i, s_{i} is the simulated data point for each model instance i, n is the number of measured data points and p is the number of adjustable data points.

Although the NMBE index is a good measure of model accuracy, its main problem is the cancellation error, where the sum of positive and negative values reduces the value of the NMBE index (Ruiz and Bandera, 2017). Consequently, using this index alone is not recommended, and the CV-RMSE index was used as another uncertainty index, which measures the variability of the errors between measured and simulated data points, thereby indicating the model's ability to fit the data.

$$\text{CV-RMSE} = \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum\limits_{i=1}^{n} (m_{\mathrm{i}} - s_{\mathrm{i}})^2}{n-p}} \cdot 100 \tag{4}$$

The model's output variable of interest used to calculate the uncertainty indices was the indoor air temperature T_{ia}. The acceptable range of accuracy was based on American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14-2014 (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2017). According to this guideline, the hourly NMBE index is required to be less than 10% and the hourly CV-RMSE index is required to be less than 30% to consider a model as robust.

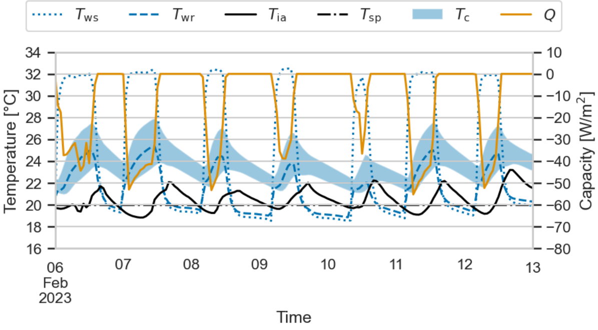
Results

This chapter provides an analysis of the thermal performance of HiLo's novel floor system during operation. It then goes on to compare the measured performance of the floor system with the performance predicted by TRNSYS. This comparison aims to evaluate the accuracy of the simulation model and to provide insights into the actual thermal performance of the floor system under real-world conditions.

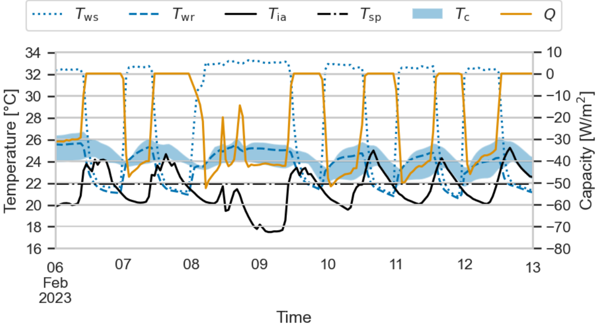
Thermal analysis

Figures 3 and 4 compare the operational performance of the novel floor system in offices 1 and 2, integrating TABS and ventilation, during a typical winter and summer week. T_{ws} and T_{wr} are the supply and return water temperatures of the TABS, T_{ia} is the indoor air temperature, T_{sp} is the setpoint temperature, T_{c} is the temperature of the concrete in the plane of the pipe network of the TABS and Q is the heating/cooling capacity.

During the winter week, the TABS in office 1 were switched off more frequently than in office 2, resulting in a lower heating capacity in office 1 (mean: -13.18 W/m^2, standard deviation (SD): 18.69 W/m^2) compared to office 2 (mean: -21.18 W/m^2, SD: 19.98 W/m^2). This was because the air temperature dropped below the temperature setpoint less often and to a lesser extent. Therefore, less reheating was necessary to create a more stable indoor environment in office 1, reducing the need for heating energy (office 1: 38.52 Wh/m^2, office 2: 56.63 Wh/m^2). One possible explanation for the less heating in office 1 may be higher solar gains due to the absence of fixed solar shading, such as the ASF in office 2. The ASF allowed a lower amount of solar energy to enter office 2 through the windows compared to office 1, thus increasing the heating demand in office 2.



(a) Office 1.

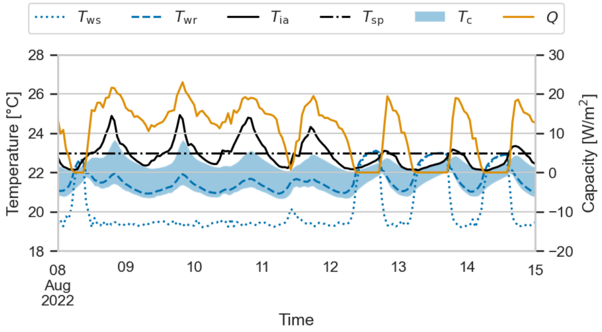


(b) Office 2.

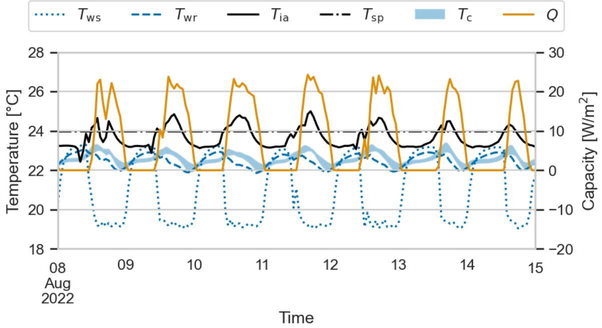
Figure 3: Operation during a typical winter week.

In contrast to the winter week, during the typical summer week, the cooling capacity in office 1 (mean: 10.75 W/m^2, SD: 7.03 W/m^2) was higher compared to that in office 2 (mean: 7.83 W/m^2, SD: 9.15 W/m^2). This was because the TABS were switched on continuously for several days to maintain the air temperature close to the temperature setpoint, requiring strong cooling. The reason for the prolonged use of the TABS in office 1 could be due to various factors, one of which might be again the absence of fixed solar shading. Compared to office 1, the ASF in office 2 prevented excessive heat from entering the interior, thus reducing the cooling demand in office 2 (office 1: 31.27 Wh/m^2, office 2: 21.89 Wh/m^2).

Apart from the solar gains, the heating/cooling capacity of the TABS was also affected by the temperature distribution of the TABS across the ceiling. In office 2, this distribution appeared to be strongly related to the integrated ventilation system. The maximum distribution of the TABS temperatures across the ceiling was higher in office 1 (winter: 6.98 °C; summer: 3.03 °C) compared to office 2 (winter: 5.11 °C; summer: 1.00 °C). This could be because office 1 does not have an integrated ventilation system, resulting in an uneven temperature distribution due to pipe placement. The ventilation system in office 2 helped to distribute heat/cold more evenly and reduce temperature differences.



(a) Office 1.

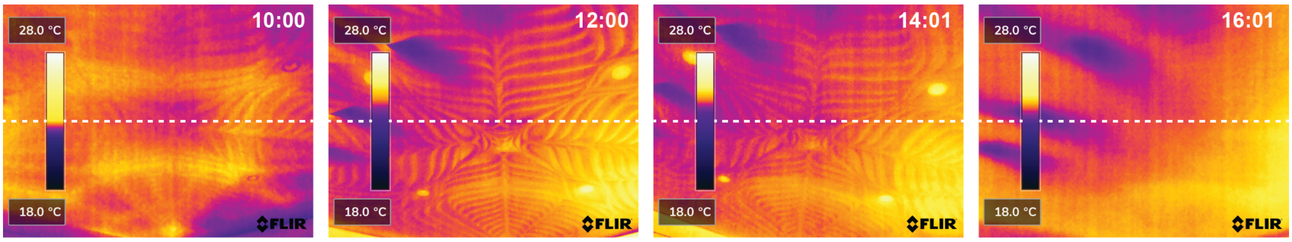


(b) Office 2.

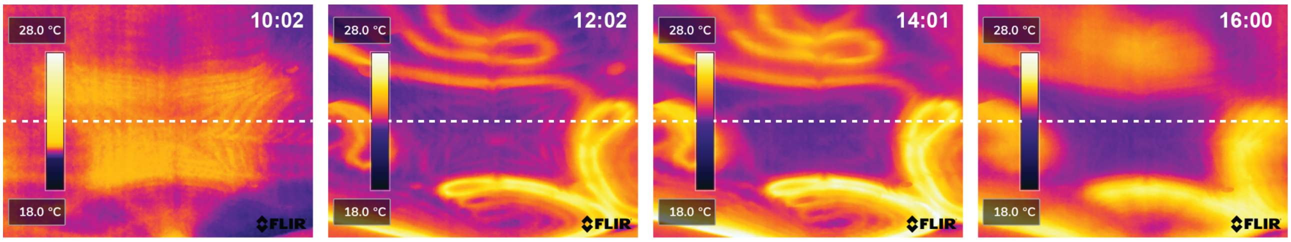
Figure 4: Operation during a typical summer week.

This finding that the integration of a ventilation system with TABS can improve the homogeneity of temperature distribution across the ceiling is supported by the infrared images presented in Figure 5. The images compare the temporal variations in surface temperature distributions on 26 January 2023 (Figure 5a) and 27 January 2023 (Figure 5b) and show significant differences in surface temperatures across the ceiling in office 2, depending on whether the ventilation system was activated or not. Specifically, the images indicate that the surface temperatures were more homogeneous when both the TABS and the integrated ventilation system were activated. However, if only the TABS were switched on while the integrated ventilation system was switched off, the surface temperatures became more uneven.

The presence of inhomogeneous surface temperature distributions is further supported by the temperature profiles obtained from the infrared images shown in



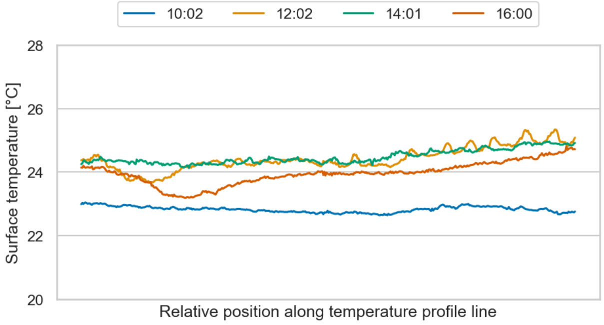
(a) TABS and ventilation system activated.



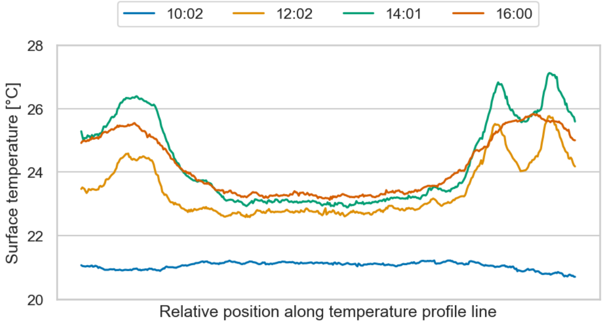
(b) Only TABS activated.

Figure 5: Temporal variations of surface temperature distributions across the ceiling in office 2 under two different settings; the dashed horizontal lines show the temperature profiles as plotted in Figure 6.

Figure 6. The profiles suggest that the surface temperatures of the ceiling reached the setpoint of 24 °C homogeneously within two hours of activating both the TABS and ventilation system at 12:00. In contrast, when only the TABS were switched on, the ceiling did not reach the setpoint of 24 °C uniformly even after six hours at 16:00. The outer areas of the ceiling surpassed the temperature setpoint, whereas the inner areas remained below it.



(a) TABS and ventilation system activated.



(b) Only TABS activated.

Figure 6: Comparison of temperature profiles obtained from infrared images, as shown in Figure 5.

Uncertainty analysis

The predicted data of the TRNSYS model were compared with the actual measured data from 5 January 2023, and a good agreement was found, as shown in Figure 7. This figure compares the measured and predicted outdoor air temperature (T_{oa}) and indoor air temperature (T_{ia}). It also shows the measured water flow rate ($\dot{m}$) and the predicted state of the TABS (0=off, 1=on). Additionally, it includes the measured occupancy in office 1 using a PD-C 180/i 16 Touch KNX sensor (0=no occupancy, 1=occupancy, values between 0 and 1 due to hourly averaging of the data). There was a disturbance in the measured data at 10:00, which changed the state of the TABS earlier than predicted by the TRNSYS model. This event was likely caused by a short period of occupancy in office 1, during which the open door caused a mixing of air between office 1 and the main space.

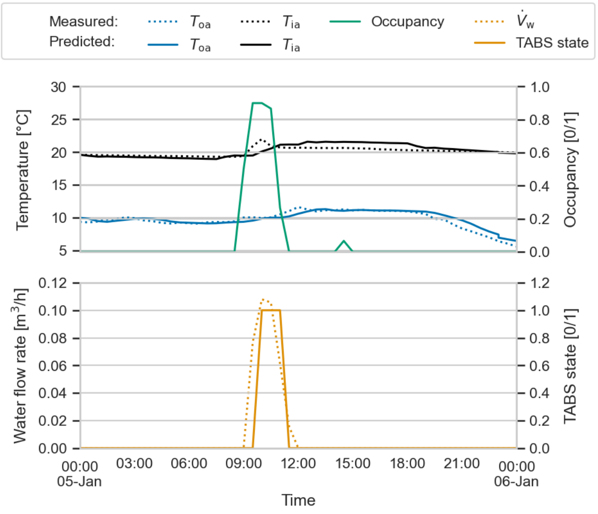


Figure 7: Comparison of measured and predicted data from 5 January 2023.

Descriptive statistics were then used to analyse the measured and predicted data, and the summary statistics for the uncertainty indices NMBE and CV-RMSE are compared in Table 1. The data in the table show that the minimum and maximum values for the NMBE index were well below the ASHRAE requirement of 10% for hourly empirical data. With a median value of -0.17% for the NMBE index, the TRNSYS model tended to slightly over-predict the measured data. However, since NMBE indices close to zero indicate a small difference between the predicted and measured indoor air temperature, it suggested that the model had a sound goodness of fit.

Table 1: Summary statistics of uncertainty indices.

Index	Median	Minimum	Maximum
NMBE [%]	-0.17	-1.99	2.11
CV-RMSE [%]	3.35	0.35	10.56

Similarly, the minimum and maximum values for the CV-RMSE index were well below the ASHRAE requirement of 30%, also indicating a good model fit.

Discussion

This study set out to assess the operational performance of the novel floor system in the HiLo unit that integrates TABS and ventilation system into complex geometry and lightweight structural components. The results show that the operational performance was mainly related to two things. First, solar gains strongly influenced the floor system's operational performance. In winter, they provided additional heat, reducing the heating demand and capacity of the TABS. In summer, solar radiation increased the cooling demand and capacity of the TABS, requiring a longer operation. Adequate solar shading is hence needed to improve the lightweight floor system's performance and reduce the impact of solar gains. Second, the integration of the ventilation system into the ceiling of office 2 significantly improved the floor system's operational performance. It promoted even heat/cold distribution, resulting in more even TABS and surface temperatures across the ceiling. This integration may improve occupant comfort by preventing hot or cold spots, which can cause discomfort. Integrating ventilation into the floor system thus ensures an even temperature distribution, enhancing occupant comfort.

In addition to the performance assessment of the novel floor system in HiLo, this study sought to assess the robustness of the TRNSYS model. While the uncertainty analysis suggested that the simulation model can accurately and reliably predict the actual performance of the TABS integrated into complex geometry and lightweight structural components, the study also highlighted challenges in comparing predicted and actual performance data in a living lab context. The reason for this is that numerous disturbances in the measured data, including those caused by occupancy, can introduce variability into the data, making it difficult to distinguish between the effects of the disturbances and the effects of the model. It can also be challenging to account for these disturbances in the model, leading to inaccurate predictions of the system's behaviour on days with high levels of disturbances. In the study period from 1 April 2022 to 31 March 2023, only two days with a reasonable amount of disturbances were found. Therefore, the study suggests that comparing the model's predictions in a living lab context requires careful consideration of the disturbances present in the measured data. However, despite the challenges posed by disturbances, the uncertainty analysis indicates that the TRNSYS model is robust in predicting the performance of TABS integrated into complex geometry and lightweight structural components.

Conclusion

This study extends our knowledge of the unique floor system in HiLo that integrates TABS and ventilation system into complex geometry and lightweight structural components in two ways.

Firstly, the results demonstrate that integrating a ventilation system with TABS can improve the homogeneity of temperature distribution across the ceiling of the novel floor system. This study consequently provides evidence that TABS integrated into such components can enhance the operational performance of the floor system, particularly when combined with a ventilation system. This result supports the hypothesis that ventilation-assisted TABS can improve energy efficiency and comfort, as shown in a previous study by Henze et al. (2008) in cooling-dominated climates. However, the generalisability of this result may be limited by the data analysis, which focused only on a typical winter and summer week. Therefore, further studies should explore longer periods, mid-seasons and unusual weeks with extreme weather conditions to ensure the system's resilience in the face of rising temperatures due to climate change. Also, given that uneven temperature distributions across the ceiling can affect occupant comfort, future research should explore the full impact of the novel floor system on comfort in HiLo.

Secondly, the results indicate that the TRNSYS white-box model can accurately and reliably predict the thermal performance of the novel floor system, given there are low disturbances in the measured data. This finding suggests that the model has the potential for use in future studies. However, three important limitations need to be considered:

1. The findings may be limited by the lack of variability in the data as the uncertainty analysis was conducted on a single day only with relatively minor disturbances in the measurement data.
2. The white-box model was only tested for office 1

and cannot be directly extrapolated to the performance of the novel floor system in office 2 due to the integrated ventilation system in office 2.

3. The specific conditions of the HiLo living lab might not be representative of other buildings, which could limit the generalisability of the model.

To enhance the model's robustness, future work can collect more detailed data, such as occupant counts, to identify specific periods of time when disturbances occur in the living lab. Additionally, advanced analytical methods and simulations can be utilised to ensure that the model accurately reflects the real-world performance of the novel floor system. After all, TABS offer numerous advantages over air-based space-conditioning systems, such as large surfaces that allow a supply temperature close to the room temperature for heating or cooling. This decreases energy consumption, contributing to global climate change goals.

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