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Investigation of the Flexibility Potential by Decoupling Building Mass and Room Temperature

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Abstract. Using the thermal building mass as a thermal storage received increasing attention in research during recent years. Due to the large mass of concrete, it offers a large storage capacity and thus a high potential for flexibility. However, passive heat losses during cool down of a thermally activated building influence room temperature and thus limit its flexibility potential. In this contribution a multi-layer activation concept was investigated which thermally decouples the building mass and room air. The study aims to analyse the cool down of a thermally activated building in terms of different charging parameters while considering other heat sources such as solar gains. A dynamic building simulation of a demonstration building was set-up and compared to simulative studies from literature to proof the validity of its dynamic behaviour. In the simulation model the room temperature could be kept above 19 °C between 100 - 190 h. However, when charging the building structure quickly, room temperatures above 24 °C are reached easily. Considering other heat sources such as solar gains, advanced control algorithms are required for efficient operation of the heating system.

Keywords: Thermally Activated Building Systems, Dynamic Building Simulation, Flexibility of Buildings, Room Temperature Decoupling

1. Introduction

The integration of renewable energies into the domestic heating sector plays a crucial role in reaching the European climate goals defined in the Green Deal [1]. Flexible operation of a building is required to integrate the renewable but non-controllable energy sources such as solar and wind power. In the IEA EBC Annex 67 the flexibility options of a building were investigated in detail [2]. According to the report, a building can provide flexibility based on a water storage, an electro-chemical storage (e.g. battery), and the building mass itself.

In recent years the usage of the building mass as a thermal storage capacity has been a focus in research. This is based on the large theoretical flexibility potential due to the large storage capacity of the building's concrete which many buildings have. In the literature, this technology is referred to as thermally activated building systems (TABS).

The authors Thür et al. has investigated the flexibility potential of TABS to shift the operation of a ground-source (GSHP) and an air-source heat pump (ASHP) to match the electricity generation of an onsite PV-system [3, 4]. Based on both studies the authors conclude that the self-consumption rate can be increased by 35% for a GSHP and by 50% for an ASHP if the building mass is used as thermal storage capacity. In the studies, the overheating of the room temperature was also investigated. While in the study considering the ASHP the room temperature increased to 22°C at maximum, in the study considering the GSHP the room temperature was reaching values of up to 26°C. The latter case will lead to unacceptance of the occupants and thus would not be applied. Thus, one main limitation of using the building mass as a thermal storage is the existing thermal coupling between building mass and the indoor room temperature.

Olsthoorn et al. [5] give an overview about the possibilities and limitations of TABS in different scenarios. They categorize the reviewed studies regarding their concrete activation technique. Each technique has a different impact on the response of the indoor room temperature to a temperature change of the concrete. Due to its thermal inertia, the indoor air will react earlier, if the concrete is activated close to the surface compared to when it's activated in the centre of the concrete. The review studies were compared in terms of their relative operational cost reduction. For an activation close to the surface the operational costs could be reduced by up to 21%. This can be increased by up to 68% for an activation of the concrete core. The reviewed studies give insight into the potential of using TABS as the flexibility source. However, the identified potential depends on the considered scenario (e.g. climate, control algorithm, building structure, usage of the building, …) and the reference case to which it is compared to. The authors also conclude that the main limitation of using TABS as a flexibility option is the thermal comfort of the occupants which limits the temperature of the concrete.

In the research project *optLWP* a single-family house is monitored in real operation which includes a so-called multi-layer TABS concept. In the concept an insulation layer between the activation layer and the surface to the room is added. In Fig. 1 a typical TABS and the multi-layer TABS concepts are shown schematically for the example of a ceiling heating system.

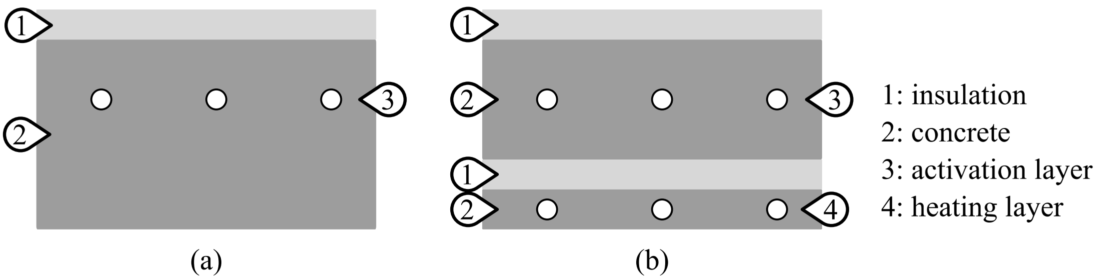

Figure 1. *Cross-section schematic concepts of (a) a typical thermally activated building and (b) a multi-layer thermally activated building system with an additional insulation and heating layer*

In Fig.1 (a) a typical TABS concept is shown. It consists of an insulation layer (1) at the top of the concrete layer (2) to prevent heat losses to either the room above or to the ambient. The concrete is activated by pumping warm water through the pipes located at the activation layer (3).

In Fig. 1 (b) the alternative TABS concept is shown which includes the additional insulation layer below the activated concrete. This concept will be referred to as "multi-layer TABS". The additional insulation layer reduces the heat flux to the room below. On the one side, this offers the possibility to heat up the concrete layer without overheating the room temperature. On the other side, it also reduces the heating power to the room below which might be needed during cold winter periods to ensure a minimal indoor temperature. An additional heating layer (4) is needed close to the surface to provide the minimum heating power required by the building. Thus, two independent hydraulic cycles are used: one for activating the concrete layer and one activating the heating layer. This offers the possibility to actively discharge the concrete layer by connecting the activation and the heating layer and thus, use the building's structure as an active managed storage capacity. Still, heat losses through the insulation layers affect the room temperature which can jeopardize the thermal comfort of the occupants.

In the framework of the research project *Windheizung 2.0* different set-ups of the multi-layer TABS concept were investigated [6]. Simulative studies have been performed to quantify the heat losses of each concept. The most promising results have been validated using measurements. In addition to the multi-layer TABS a high temperature stone storage was used to extend the available thermal storage capacity. In the used test-cases it was demonstrated that enough thermal energy could be stored to bridge the building's heat demand over 7-10 days.

In this contribution, the dynamic behaviour of the multi-layer TABS concept is modelled for the example of the demonstration building which is monitored in the research project *opt-LWP*. The results are compared to the results of the research project *Windheizung 2.0*. Due to the different set-up of the TABS this study adds further insight into the potential of such an activation concept. The presented study shows the importance of comprehensive control strategies predicting the building behaviour based on weather and load forecasts to fully utilize the flexibility potential of the building structure without jeopardizing the thermal comfort of the occupants.

1.1 Description of the demonstration building

The demonstration building is located in North Bavaria, Germany and was newly built in the year 2019. During the construction the energy efficiency was considered thoroughly. The building has two heated floors above ground and an unheated basement. According to DIN V 18599 the final energy consumption of the building was calculated to be 5.1 kWh/(m²a). In Figure 2 the CAD-model of the building is shown in the south-west view.

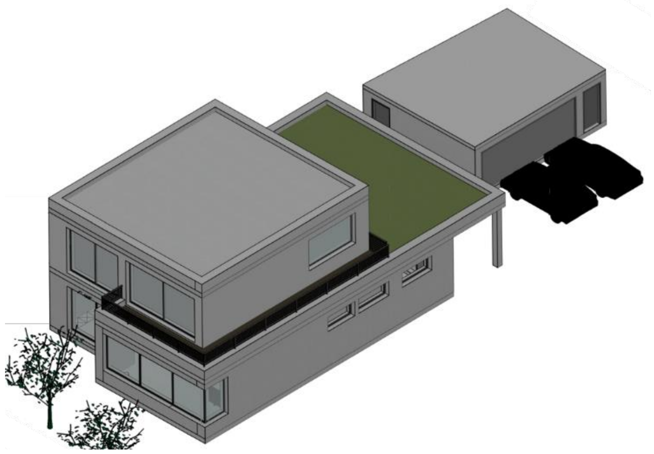

Figure 2. *CAD-model of the demonstration building in south-west view*

The ground floor and the first floor do not equal in living area. While the ground floor is around 157 m² the first floor is around 77 m². The details of the used materials and U-Values are shown in Table 1.

The rooftop elements in ground and first floor are insulated using Polyurethan-foam (PUR) of 16 cm thickness. Additionally, tapered EPS elements are used due to drainage. The inclination is 1.5% and is assumed to be equally for the rooftop elements on both floors. Further layers (e.g. Bitumen) are used to prevent water penetration.

Ground and first floor are thermally decoupled using an oak layer (2 cm), screed layer (5 cm), PUR-elements (3 cm) and foamed mortar of (10 cm). The staircase is thermally insulated by a glass wall to prevent air exchange between both floors.

Table 1. *U-Values according to the planning documents of the demonstration building*

Element	Total Thickness m	U-Value W/(m²K)
Outer walls	0.535	0.132
TABS (rooftop)	0.55	0.087
TABS (storey ceiling)	0.50	Not documented
Windows	-	0.880
Basement Ceiling	0.50	0.151
Inner wall	0.11 0.24	2.476 1.200

For the outer walls, vertically perforated bricks including perlite filler of 49 cm thickness are used along with a small layer of plaster on the in- and outside of 4.5 cm in total. The perlite filler increases the thermal resistance compared to typical perforated bricks with air gaps. The windows are triple glazed and mainly south oriented to optimize the solar gains of the building during winter period. The inner walls of the building are built using two different vertically perforated bricks without filler of 11 and 24 cm thickness respectively. The ground floor is thermally insulated towards the unheated basement using the same oak, screed, PUR elements and foamed mortar layers as between first and ground floor. Below these layers, a concrete layer of 20 cm and an additional insulation of PUR elements of 10 cm thickness is used. Since the basement is unheated and the ceiling between ground floor and basement is insulated, the thermal inertia of walls and foundation plate of the basement are expected to have low impact on the dynamics of the whole building behaviour. Thus, the basement is not considered for the studies in this contribution.

1.2 Realized Multi-Layer TABS concept

The multi-layer TABS concept was implemented in the demonstration building using a ceiling heating system as the heat distribution in the building. First, premanufactured concrete plates including pipes were placed on top of the inner walls. These plates represent the heating layer in Figure 1 (b). Insulation plates made from PUR were placed on top of the heating layer leaving space for static relevant elements (e.g. reinforcement steel). According to the planning documents, the gaps between two insulation plates are 20 to 24 cm. Unfortunately, no further information about the geometry of the insulation plates is given. Presumably this is because the plates are adjusted individually on-site to take different restrictions in geometry into account. In Figure 3 the gaps between the insulation plates (light blue elements) can be seen in a picture which was taken during the construction process.

Figure 3. *Picture of the multi-layer TABS during the construction process, the insulation layer shows gaps due to required reinforcement steel elements for stability of the ceiling*

The pipes for the concrete activation are placed on top of the insulation plates using spacers. In this case spacers of 6 cm were used. As last step, concrete is added on-site to fill up the gaps between the insulation plates and the concrete layer to be activated. In Figure 4 the cross-section of a final exemplary multi-layer TABS element is displayed.

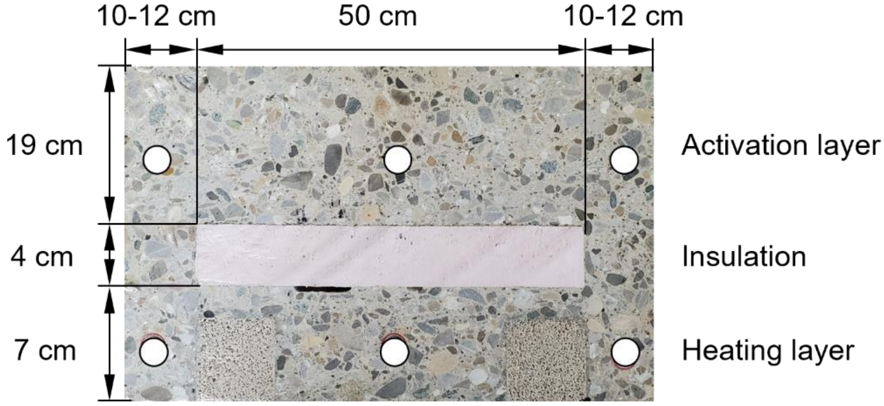

Figure 4. *Cross-section of the investigated multi-layer TABS element*

2. Set-up of the dynamic building model

A building model was set up to calculate the dynamic behaviour including the thermal inertia of the different building elements. The model was set up in MATLAB Simulink using the CARNOT Toolbox [7]. The Toolbox offers validated models for the calculation of conventional and regenerative HVAC systems. In Figure 5 the modelled elements and their thermal interconnections are shown schematically.

The elements are categorized to active (dashed line) and passive (solid line) elements. An active element can be used to actively add thermal energy into the corresponding element while passive elements only react to its convective and radiative boundary conditions. Since the heat distribution in the building is done by a ceiling heating, the storey ceiling and the rooftop elements have been modelled as active elements. Due to heat losses, an activation of the storey ceiling leads to a temperature change on both floors. Thus, a two-zone approach was used to model the indoor air volume of the building.

The walls and ceilings of the building have been modelled using a one-dimensional heat transfer approach. This assumes only a temperature gradient perpendicular to the walls. Each wall has been modelled by considering the material properties including their thickness according to the planning documentation described in chapter 2.

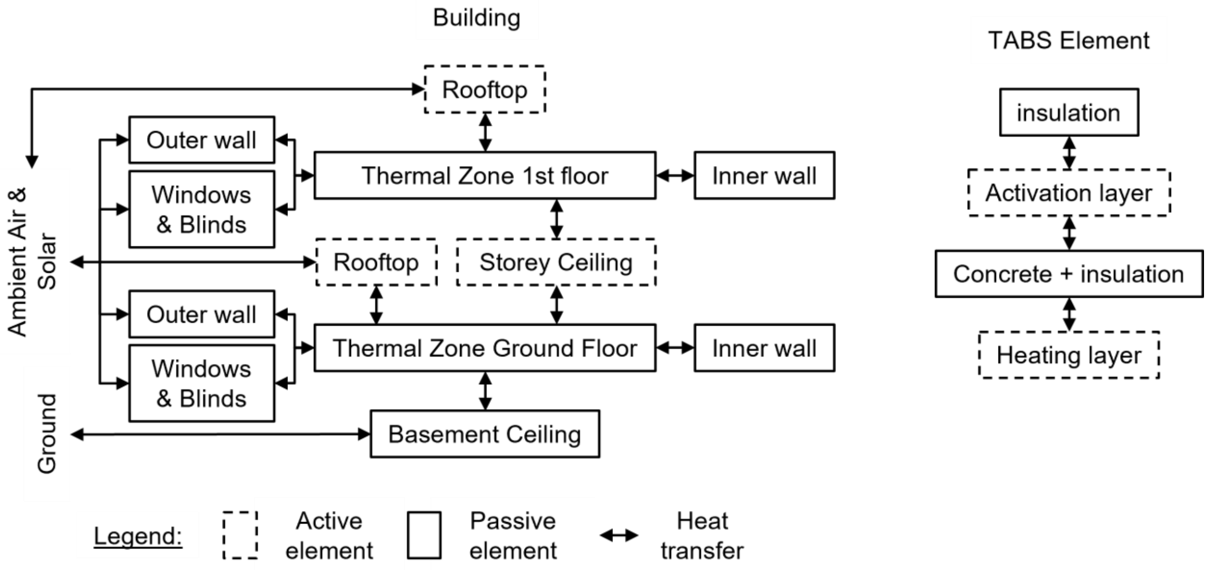

Figure 5. *Elements used in the building simulation model and the considered heat transfers*

Since the insulation layer of the TABS elements is a two-dimensional heat transfer problem (c.f. Figure 4), the heat transfer was reduced to a one-dimensional heat transfer problem. This was done based on the equations for a parallel heat transfer problem. The thermal resistance was reduced to an equivalent total resistance R_{tot}

$$R_{tot} = \frac{R_i \cdot R_c}{R_i + R_c} \tag{1}$$

where R_i and R_c refer to the thermal resistance of the insulation and concrete material. The thermal resistance of each homogeneous layer was calculated according to

$$R = \frac{d}{\lambda \cdot A} \tag{2}$$

where d is the thickness of the layer, λ is the thermal conductivity of the considered material and A is the surface through which the heat flux will occur. By combining equation (1) and (2), the total thermal conductivity of the insulation layer can be calculated according to

$$\lambda_{tot} = \frac{A_i}{A_{tot}} \cdot \lambda_i + \frac{A_c}{A_{tot}} \cdot \lambda_c \tag{3}$$

where $\frac{A_i}{A_{tot}}$, and $\frac{A_c}{A_{tot}}$ refer to the share how much of the complete surface is covered by insulation and by concrete. Because in the planning documentation the shares are not given, an assumption was used. Assuming the same gap of 20 to 24 cm between the insulation plates on every side and a length of the plates of 2 m results in a share of 35% - 40% concrete surface for a 20 - 24 cm gap respectively. In this contribution, the worse case was considered, using a share of 40% concrete and 60% insulation. This yields in a total thermal conductivity of 1.02 W/(mK) of the insulation layer.

The radiative exchange on inner and outer surfaces and the convection on the outer surfaces of the building are calculated based on the wind speed dependent equation formulated in the standard EN 6946 [8]. The heat transfer due to convection on the inner surfaces is calculated based on a dynamic coefficient depending on the temperature difference between surface and room air [9].

The CARNOT Toolbox provides a sophisticated window model which was used in this building simulation. In the window model, the different heat transfer mechanisms are calculated based on the defined window geometry and material properties. In combination with the window size and orientation, the solar gains through the window surfaces are calculated. The geometry, orientation and U-Value of the windows have been adjusted according to the planning documents. The G-Value was assumed to be 0.5 which represent a typical value for triple-glazed windows. Due to not available data sheets of the windows, the thermal capacity of the window was not adjusted. The default values given in the toolbox were used which represent a double-glazed window. Since the thermal capacity of the windows are negligible in comparison to the thermal capacity of the building structure, the influence of this assumption is expected to be of minor influence on the dynamic behaviour of the building.

The indoor room temperature for each thermal zone was calculated based on the thermal exchange with its connecting elements (outer wall, ceiling / floor, inner wall, window), solar gains through the windows, internal gains, and passive and active ventilation losses. As the focus of this contribution is on model of the building dynamics, internal gains and active ventilation have been neglected in this study. Passive ventilation is assumed to be constant and without thermal recovery.

The dynamic behaviour of the basement is not considered in this study as was mentioned before. Thus, a constant basement temperature of 18 °C was assumed. This assumption is of less impact on the results if short time periods (e.g. few days or weeks) are investigated since the temperature of an unheated basement is expected to remain constant over short periods.

Heat bridges are yet not considered in the building model. The heat bridges between ceiling (rooftop or storey ceiling) and outer / inner walls as well as between the storey ceiling and the rooftop element are neglected. This can influence the heat losses of the multi-layer TABS and may change the results of this study afterwards. Since the impact of these heat bridges depend on the geometry of the building and its rooms the impact on the results is difficult to assess. Furthermore, heat losses through the building's envelope are expected to be higher for the real building. In a first assessment of the planning documents, the impact of the heat bridges in the building's envelope are expected to be of minor relevance on the overall dynamic behaviour of the building. However, Investigations will be done to quantify the heat transfer through the described heat bridges.

3. Simulation results and discussion

The results include three steps which are described in the following. The first step was the verification of the static heat losses of the building model by comparing the U-Values from the planning documents with the calculated U-Values in the building simulation. This step is required to ensure a realistic representation of the demonstration building. In a second step the dynamic behaviour of the building model was investigated. Due to the lack of monitoring data, the simulation results were compared to the results from the research project *Windheizung 2.0*. As third step, another simple charging process was used to show case the flexibility potential of the building's structure and the importance of predictive control algorithms when operation TABS.

3.1 Verification of the static heat losses

In the simulation a constant indoor and outdoor temperature and the wind speed was defined to match the values in the standard EN 6946. No solar radiation or ventilation losses are assumed. Extracting the heat fluxes through each element from the simulation model, the U-Value was calculated according to

$$U = \frac{\dot{Q}}{A \cdot \Delta T}. \tag{4}$$

In Table 2 the calculated U-Values are shown along with the relative deviation from the corresponding values given in Table 1. A negative value in the relative deviance refers to a smaller U-Value in the simulation. Thus, the building in the simulation model is slightly more efficient than as outlined the planning documentation. However, the differences between planning documentation and simulation model with a maximum relative value of 0.8% are assumed to be negligible. Thus, it can be stated that the model matches the static heat losses through the envelope of the demonstration building well.

Table 2. *Calculated U-Values in the buidling simulation model and their relative deviation in comparison to the planning documentation*

Element	**U-Value (simulation) W/(m²K)**	**Rel. deviation**
Outer walls	0.1318	-0.2 %
Rooftop	0.0864	-0.7 %
Windows	0.873	-0.8 %
Basement Ceiling	0.153	0.0 %

3.2 Verification of the dynamic building behaviour

The verification of the dynamic behaviour was done in accordance with the methodology used in the project *Windheizung* 2.0. The activation layer was used to heat up the indoor room temperature to 22 °C. After the room temperature reached this point, the heat input was stopped, and the cool down phase of the room temperature was analysed. To quantify the cool down phase, the duration when the room temperature drops below defined limits are identified.

As weather data, a cold and cloudy week from the test reference year provided by the German Weather Service for the location of Ingolstadt, Germany was used [10]. The weather data used during the cool down simulation is shown in Figure 6.

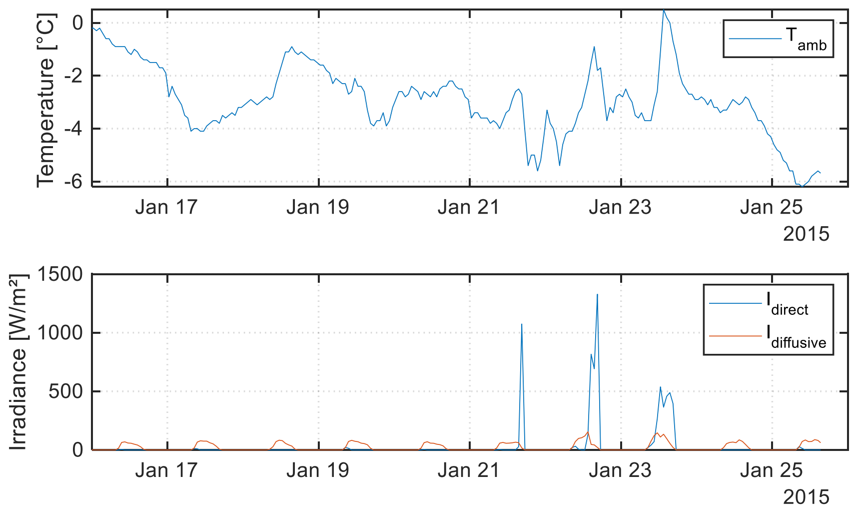

Figure 6. *Weather data of the test reference year used to calculate the passive heat losses of the multi-layer TABS*

During the simulation, infiltration losses using a constant air exchange rate of 0.4 1/h and no sunshade were considered. To activate the building structure a mass-flow of 3 l/min per heating cycle with a supply temperature to 54 C was used. In Table 3, the evaluation results of the cooldown phase for the ground and first floor are shown.

Table 3. *Results of the simulated building cool down phase with full sunshade in comparison to the results of the project Windheizung 2.0*

Temperature limit	Demo building Ground floor	Demo building First Floor	Windheizung 2.0 Living room
Charging time	12 h	10 h	7 h
21 °C	103 h	103 h	117 h
20 °C	129 h	117 h	158 h
19 °C	187 h	137 h	202 h
18 °C	213 h	191 h	-

The calculated charging time to reach a room temperature of 22 °C in case of the modelled demonstration building described in chapter 2 ranges from 10 to 12 h in both floors. For the used weather data, the room temperature remains above 19 °C for a duration of 137 h on the first floor and for 187 h on the ground floor. This difference can be explained by the different living areas. A larger living area surface also represents a larger ceiling surface and thus more activated concrete volume, the ground floor has with 157 m² a larger thermal inertia compared to the first floor with only 77 m². However, the activated ceiling of the ground floor heats up the first floor additionally which influences the cool down behaviour of the first floor.

In Table 3, also the results from the simulative study performed in the research project *Windheizung 2.0* are shown. The comparison between both simulations can be done only qualitatively, due to following reasons. Instead of a whole building, only the living room was evaluated. This fact changes the thermal losses of the considered envelope significantly as rooftop and floor as well as two walls are connected to thermal zones of the same room temperature. Different weather data was considered having a 4 °C colder mean ambient air temperature of approximately -7 °C. The average specific solar gains during the cooldown phase of approximately 15 W/m² are higher in comparison to 7 W/m² in case of the demonstration building. The ventilation losses are the same in both cases. Heat bridges between ceiling and walls are considered for the living room. According to the report this heat bridge can increase the thermal losses of the TABS from 6 to 42 % depending on the room geometry and implemented insulation measures. The room temperature in the living room remains for about 202 h above 19 °C. This duration is 10 – 45 % longer compared to the calculated duration of the ground and first floor of the demonstration building. However, having the differences between both studies in mind, the deviation is assumed to be plausible and the dynamic behaviour of the modelled multi-layer TABS realistic. But further model development is needed to take necessary heat brides into account.

3.3 Evaluation of the activation process

In the previous section, the process for a simple activation of the building structure was described. In as mentioned before, a mass-flow rate of 3 l/min per heating cycle and a supply flow temperature of 54 °C was used during the activation. Compared to the design value of 2 l/min per heating cycle the used values are rather high. Further benefits regarding the efficiency of a heat pump a lower supply temperature can be beneficial. Thus, another activation and cool down process using the design volume-flow rate and a supply temperature of 40 °C was simulated and compared to the previous results. To take the effect of solar gains into account the activation using the design volume-flow rate and lower supply temperature was simulated again with full sunshade. Based on both scenarios a best- and worst-case analysis in term of solar gains prolonging the cool down phase has been done. The set-up and corresponding results of the different scenarios are listed in Table 4 and Figure 7 respectively.

Table 4. *Set-up of three different activation scenarios*

Abbreviation	Volume-Flow Rate per heating-cycle	Supply Temperature	Sunshade
V1	3 l/min	54 °C	0 %
V2	2 l/min	40 °C	0 %
V3	2 l/min	40 °C	100 %

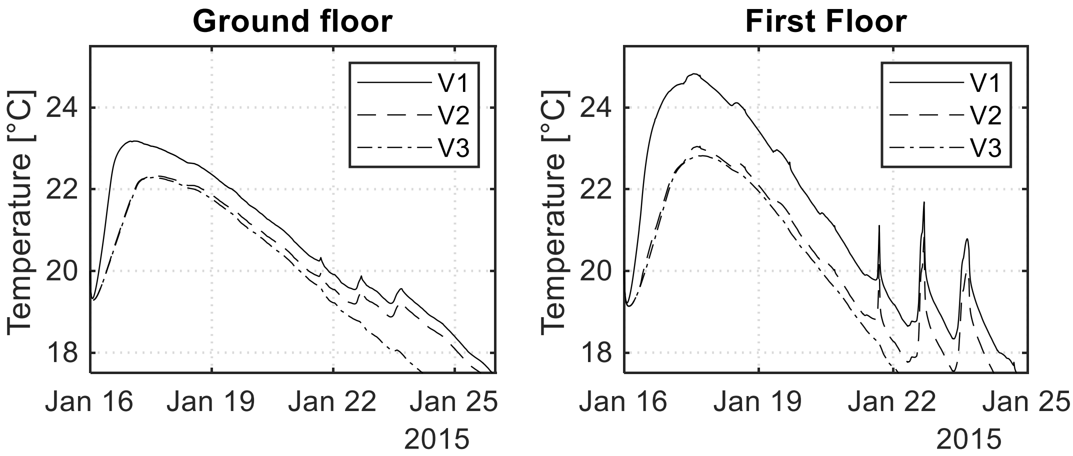

Figure 7. *Calculated room temperatures in ground and first floor of the demonstration building during three different activation and cool down scenarios*

The room temperatures start to increase after a short drop which is related to the thermal inertia of the multi-layer TABS and an initial temperature of 20 °C. After the activation is stopped (room temperature reaches 22 °C) the room temperature in all scenarios still increases. This is again based on the thermal inertia of the TABS and still heat up the room even after the concrete core is not heated any longer. The after-heating effect is obviously more prominent using the faster activation (V1) compared to a slower activation (V2 and V3). Due to the smaller living area and the double heating effect of the multi-layer TABS of the ceiling and the storey ceiling between both floors, the maximal room temperature on the first floor is in all three scenarios higher compared to the maximal room temperature on the ground floor. With 24.8 °C the maximal room temperature on the first floor is in the scenario V1 the highest of all simulated scenarios and about 1.6 °C higher compared to the ground floor of the same scenario. Using a slower activation process, a maximal room temperature of 23 °C on the first floor and 22.3 °C on the ground floor is reached while nearly no variation between the scenarios with (V3) and without (V2) can be observed. Since the solar irradiation during the first five days is close to zero, the missing variants can be expected.

After reaching the maximal room temperature, the building cools down due to the heat losses through the building's envelope and ventilation. The cool down phases of the scenarios V2 and V3 are evaluated according to the process of the previous subsection. The results are given in

Table 5 and Table 6 respectively.

The charging times in both scenarios and both floors until the room temperatures reached 22 °C for the first time are between 23 and 27 h. Again, as the solar irradiation during the first five days is nearly zero and the parameters for volume-flow and supply temperature are the same, the charging times are expected to be close to each other.

***Table 5.** Results of the simulated building cool down phase with no sunshade (V2)*

Temperature limit	Simulation EG	Simulation OG
Charging time	26 h	23 h
21 °C	74 h	70 h
20 °C	103 h	90 h
19 °C	147 h	104 h
18 °C	192 h	125 h

***Table 6.** Results of the simulated building cool down phase with full sunshade (V3)*

Temperature limit	Simulation EG	Simulation OG
Charging time	27 h	24 h
21 °C	68 h	64 h
20 °C	97 h	81 h
19 °C	123 h	98 h
18 °C	157 h	114 h

Comparing the results for ground and first floor, the room temperature on the ground floor falls more slowly and longer durations until the temperature drops below the defined limits are reached. This can be explained by the larger thermal capacity of the TABS in the first floor due to the larger living area. Additionally, the ground floor level is attached to the unheated basement which was in the considered scenario to be constant 18 °C which influences the heat losses through its envelope. Thus, the specific heat losses to the ambient are expected to be smaller compared to the first floor.

By comparing both scenarios with and without sunshade, the total duration until the room temperature drops below 18 °C was increased by 21.2 % for the ground floor and 9.1 % for the first floor. This shows the impact of solar gains on the room temperature for the given building. However, as stated before during the first five days no solar gains are taking place when the maximal room temperatures are reached. Therefore, an unfavourable start of the activation process can quickly lead to overheating of the indoor temperature if the solar gains are not considered. This can also lead to higher ventilation losses and consequently higher thermal losses of the TABS which leads to lower system efficiencies.

5. Conclusion and Outlook

In this contribution a building simulation was set-up based on the planning documentation of a demonstration building. A special activation concept was introduced which uses multiple layers to thermally decouple temperature of the building structure and the room temperature. The static heat losses of the building model are well matching with the values in the planning documentation. In comparison to other studies from literature, it was shown that the dynamic behaviour of the building model is plausible. For further validation, the simulation results will be compared to monitoring data from the field-test of the demonstration building.

The flexibility potential was analysed using three different scenarios varying the duration of the activation process and the solar gains during cool down phase. Depending on the scenario, the room temperature remained above 19 °C for 100 to 190 h after a charging process. However, room temperatures above 24 °C occurred in the scenario of a fast activation process due to after-heating effects based on the large thermal inertia of the TABS. These situations would jeopardize the thermal comfort of the occupants and thus the acceptance of such a technology or at least increase the ventilation losses due to active ventilation to cool down the room temperature again. Thus, the dynamic behaviour must be considered for efficient operation and fully utilize the flexibility potential of the building structure. This can be achieved using advanced control approaches (e.g. model predictive control) which are investigated in future. The described building simulation can serve as development and optimization environment of these advanced control algorithms.

Author contributions

D. Schmitt – Methodology, Investigation, Software, Visualization and Writing – original draft

T. Reum – Formal Analysis, Writing - Review and Editing

T. Summ – Writing - Review and Editing

C. Trinkl – Writing - Review and Editing, Project Administration, Funding Acquisition

T. Schrag – Conceptualization, Supervision, Writing - Review and Editing, Funding Acquisition

Competing interests

The authors declare that they have no competing interests.

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