For the evaluation of the predicted room acoustic properties, measurements were performed after completion, respectively during construction in a pre-finished sample open space office area. The measurements of room acoustic parameters of open plan offices are described in ISO 3382-3 (2012-05). Furthermore, to verify the acoustic field of the open space working area, acoustic measurements were performed.

Table 1 lists the results for different receiver positions for certain standard room acoustic parameters (Early Decay Time (*EDT*), Reverberation Time T_{20}, Definition and Clarity). If these measurements were compared with the results of the acoustical simulation (results are for a frequency of f = 1.000 Hz), it can be seen that the simulation and measurement results are compatible.

Table 1. *Evaluation of the acoustic simulation with measurements of different acoustic parameters in a finished sample open space area*

Receiver Position (Acoustic Camera)	*Early Decay Time* *EDT* [s]		*Reverbera-tion Time* *T* [s]		Definition D_{50} [%]		Clarity C_{80} [dB]	
	Mea.	*Sim.*	*Mea.*	*Sim.*	*Mea.*	*Sim.*	*Mea.*	*Sim.*
R1 (with acoustic insulation)	0,72	0,70	0,86	0,70	59,9	58,0	5,2	4,9
R2 (with acoustic insulation)	0,70	0,70	0,71	0,70	62,4	58,4	6,0	5,1
R3 (without acoustic insulation)	0,74	0,60	0,69	0,60	60,7	61,4	5,6	5,9
R4 (with acoustic insulation)	1,11	1,00	1,20	0,70	45,4	40,2	2,2	2,1

Thermal simulation and evaluation

The thermal simulation of a room with a thermally activated concrete slab was divided into two parts. First, the simulation results of the thermal behavior of rooms with TABS and acoustic ceiling clouds were compared with published results of measurements. Secondly, the validated thermal model of the covered concrete ceiling was used for the thermal simulation of the open space area of the office building.

For evaluation the heat loads during the cooling period in summer (solar and internal gains) are compared with the heat losses (Figure 5, left). To maintain the energy balance the room is cooled by means of the cooling ceiling. Further thermal losses were considered due to ventilation, infiltration, and heat conduction in the construction elements of the building envelope. Values for heat loads and losses are published in the German standard DIN 4108 (2013-02). As shown in Figure 5 (right), excess temperatures increase with higher percentages of ceiling clouds beneath the cooling ceiling. Even though, heat loads and losses are balanced regardless of the percentage of the covered ceiling, the latter has influence on the room temperature. Therefore, the room temperature will increase the more the cooling ceiling is covered.

Regarding the excess temperature of 25 °C the increase is linear for a cover ratio of up to 50%. For a covered ceiling area of more than 50% the increase is exponential (Fig. 5, right, blue data). With a slightly higher excess temperature of 27 °C, an increase of hours will only occur if more than 80% of the cooling ceiling is covered (Fig. 5, right, red data). Without acoustic ceiling clouds (cover ratio = 0%) the cooling of the room is supplied almost solely of the cooling ceiling (Fig. 5, left, light-blue column). Due to the increase of the cover ratio of the cooling ceiling by 10% increments radiation is shielded and convection takes a higher percentage. Up to a cover ratio of 50% the decrease of the direct radiant cooling load is constant. Thereby, the increase of ceiling clouds is taken into account by the heat loss via the building envelope (dark-blue column).

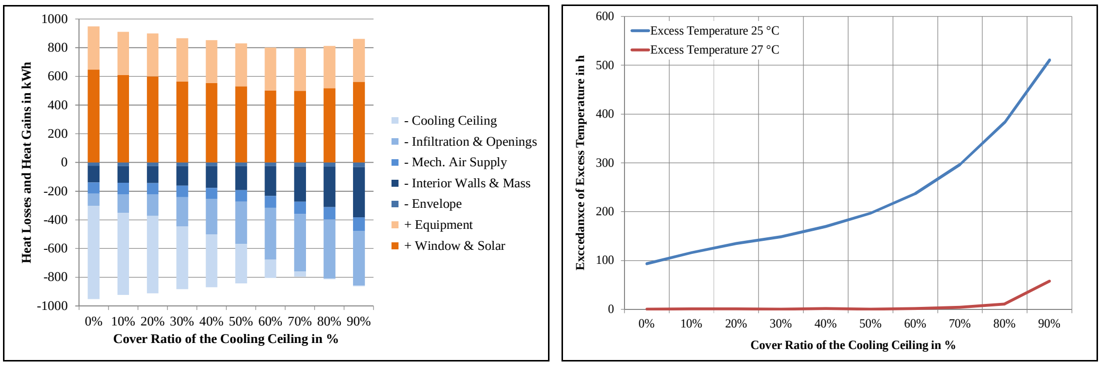

Figure 5. *Comparison of heat loads and losses as a function of the cover ratio of the cooling ceiling (left). Even though, heat loads and losses are balanced (due to active cooling) the exceeding of the excess temperature of 25 °C increases with the cover ratio of the cooling ceiling (right).*

In Peperkamp und Vercammen 2009 a cover ratio of 50% resulted in a measured reduction of the cooling load of 20% to 25%, while a cover ratio of 85% decreased the cooling load of approx. 40%. Similar values were measured by Weitzmann et. al. 2008 with a decrease of the cooling load of approx. 30% and a cover ratio of 80%. However, there was no measureable change in the cooling load up to a cover ratio of 67%. In Muet et. al. 2013 the increase of the room temperature was measured as a function of the cover ratio of the cooling ceiling. An increase of approx. 0.3 K was measured for a cover ratio of 50% and an increase of ca. 1 K with a cover ratio of 70%.

In total, the published results and tendencies match the simulated changes of the cooling capacity respectively the predicted increase of the room temperature.

Therefore, the developed ceiling model for the thermal simulation was found to be applicable for the simulation of the open space office area. As can be seen in Figure 6, similar results were predicted where a comparison of the minimal increase of the room temperature with and without ceiling clouds is shown (left). Furthermore, the cumulative room temperatures are compared with the excess temperatures of 25 °C respectively 27 °C. As can be seen, there are only minor differences in the room temperature and a cover ratio of more than 60% is necessary to exceed 25 °C significantly (Figure 6, right, blue line).

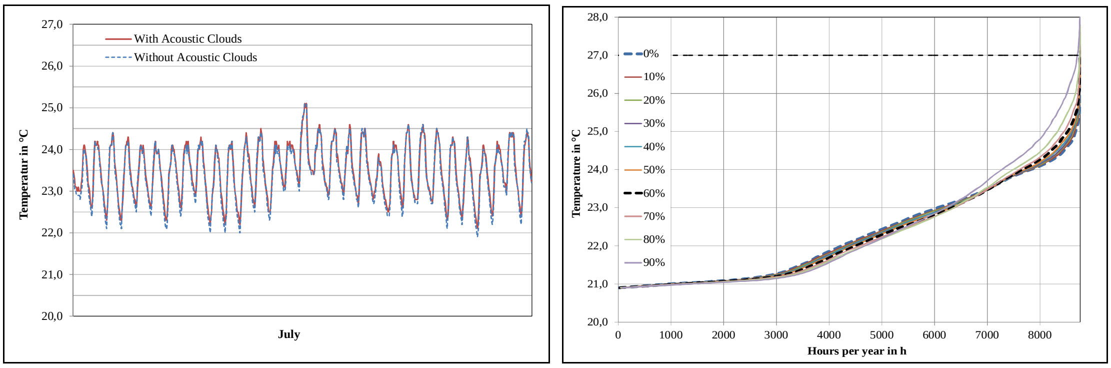

Figure 6. *Comparison of the room temperature in the open space office with and without ceiling clouds (left) and the cumulative room temperatures for the simulated year (right). While there is only a minimal difference in the room temperature (left), a cover ratio of the cooling ceiling of more than 60% is necessary to have a significant influence of the excess temperature of 25 °C (right).*

DISCUSSION

The described simulations confirm the findings of Weitzmann et. al. 2008, Pepercamp and Vercammen 2009, and others, since partly covered thermally activated concrete ceilings with acoustic ceiling clouds do not have a significant negative effect for the room temperature. Contemporaneous the acoustic properties of open space office areas improve significantly. Thereby, counterproductive effects can be revealed in acoustic simulations (such as lowering the reverberation time will increase the speech transmission among working spaces). As proved, the used model in the thermal simulation with IDA ICE to emulate the ceiling clouds was suitable for predicting the room temperature. Nevertheless, the physical effect of thermal exchanges by radiation and convection between occupant and thermally activated ceiling (respectively the partly covered ceiling) were not modeled. Therefore, the evaluation of thermal comfort parameters might be difficult. Also, the ceiling clouds have an effect of the air movement, and thus it might be necessary to model the air movement with an air flow simulation (CFD). Due to the computational effort of a CFD simulation it is necessary to validate the effects of thermal exchange by radiation and convection with in-situ measurements. With this, the application of a simplified calculation with a thermal simulation shall be proved. Further research should also include natural and artificial lightning to investigate the consequences of acoustic measures for the reflection of light (e.g. the reflection of light from a ceiling cloud is different than the reflection of light from a concrete ceiling with baffles).

CONCLUSION AND IMPLICATIONS

Commercial buildings with large transparent areas of facades can use Thermally Activated Building Systems (TABS) to provide stable and adequate thermal conditions during summer. Thereby, TABS are an energy efficient solution by using the thermal capacity of the building structure and with these large areas, the energy demand for cooling is low and renewable energy sources can be used to provide the cooling medium (e.g. ground water). Next to the thermal comfort the acoustical properties in open space offices have to be considered. Thereby, it is necessary to provide an adequate acoustical surrounding. The thermal and acoustical effects of different free hanging units were investigated with simulations. With these results it can be stated, that

- the thermal behavior of partly covered thermally activated ceilings can be emulated with a suspended ceiling while the other areas remain as concrete surface. Therefore, the room has to be divided in two zones (one with concrete ceiling and the other areas with suspended ceiling),
- the two zone model for the ceiling can predict the room temperatures but cannot simulate physical effects of radiation and convection,
- the room temperature did not change significantly when TABS are covered up to 50% of the total ceiling area,
- adequate room acoustics can be achieved with less than 50% ceiling clouds, when additional acoustical measures are used (such as acoustical partition walls),
- acoustical properties might be counterproductive since a shorter reverberation time might increase the speech transmission index.

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