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Impacts of occupancy on energy demand and thermal comfort for a large-sized administration building

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ABSTRACT

In the framework of various research projects at Hamburg University of Technology, a large-sized, non-residential building was investigated in a post-occupancy evaluation for several years. The building is designed as a lightweight construction with thermally activated ceilings, geothermal assisted heating and cooling, and partly manual ventilation. Thus, the users become part of the energy concept in terms of ventilation during summertime. The building's final energy demand is primarily covered by thermal energy from the ground for heating and cooling purposes. During winter, ground-coupled heat pumps characterize the overall electricity demand with seasonal fluctuations, whereas user-related electricity demands were comparatively constant throughout the year. User-related energy demands must be considered, since they were found to be a significant part of the electricity demand, especially for highly efficient office buildings, as this demand category accounted for around 50% of the total primary energy demand of the building considered, under standard conditions. As a counterpart of keeping thermal energy demands as low as possible, thermal comfort was maintained at a high level throughout the year, except for small limitations in winter due to the absence of humidity control, causing increased thermal discomfort at outside air humidity ratios beyond the desired indoor comfort zone. Furthermore, influences of manual user interventions on thermal comfort are considered. This study aims to contribute to a better understanding of the effects of user-related energy demands on the total energy performance of a building, and the interaction of fully-automated and manual building systems, with regard to thermal comfort.

1. Introduction

Against the background of the environmental impact of energy use, depletion of primary energy resources and economic consequences, significant efforts are being made to construct more environmentally-friendly buildings, and thereby reduce the carbon dioxide emissions caused by the building sector. According to the European Commission, the final energy demand of the building sector was around 40% of the total EU final energy demand in 2016 [1]. The current development of designing more energy-friendly buildings is related to several challenges. On the one hand, legal minimum requirements for efficiency and sustainable energy supply have gradually increased in recent years. On the other hand, today's buildings are increasingly complex systems. This holds especially true for non-residential buildings, which are often designed individually and manufactured as prototypes, supporting individual usage profiles at high user comfort levels. Commissioning of such buildings requires a period of intensive adjustment and improvement, regarding individual system components as well as the overall system. But even during operation, skills and tools are required to consequently ensure user comfort, as well as to efficiently maintain low energy demand and operating costs. Additionally, the energy demand related to indoor thermal comfort should be as low as possible. Within this context, a common challenge regarding the overall building efficiency, especially for non-residential buildings, is user influence, as well as the performance gap between predicted and measured energy performance [2]. Numerous studies have analyzed the reasons for performance gaps between predicted and measured energy demands [3–5]. From these studies, it is evident that there is little coherence between predicted energy demands from the design stage and actual energy demands during building operation, which tend to be twice as high. Thewes et al. [3] addressed the need for systematic analysis of building energy demands, in order to improve the reliability of actual energy demands of the current building stock. The authors analyzed a variety of educational buildings in terms of electrical and thermal energy demands. They found increasing primary energy demands for newer buildings due to increased user-related energy demands. On the other

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hand, thermal energy demands should be viewed less critically, due to the usually highly-insulated building envelope of modern buildings. An energy audit of a university dining hall was investigated in Bangerth et al. [4]. A significant additional energy demand in building operation compared with the predicted energy performance and LEED Silver certification was found. The authors set up a simulation model in order to identify the main energy-saving opportunities. These opportunities were related to poor control strategies as well as poor system performance, or even component failures. To decrease the performance gap, Dronkelaar et al. [5] analyzed differences between predicted and measured energy demands for several non-residential buildings. The authors found an additional average measured energy demand of 34% compared with the predicted values. Some of the main reasons for these deviations were uncertainties in building modeling and occupants' behavior. The authors recommend the use of operational performance data to improve the results of design simulations regarding building energy demands. Menezes et al. [6] also discussed reasons for discrepancies between energy modeling prediction and actual performance of non-residential buildings. From their post-occupancy evaluation, the authors highlight the need for better understanding of user behavior in office buildings. Realistic energy demand prediction needs to take different user-related patterns into account. Against the background of the goal of ensuring that the energy demands of a building are as low as possible, while at the same time placing high demands on thermal comfort, many studies have investigated the challenges regarding energy demand and indoor comfort requirements, especially for non-residential buildings [7–15]. Within this context, recent studies focus on academic buildings regarding energy demands and indoor air quality, as well as thermal comfort. Nevertheless, a few studies evaluate both building energy demands and indoor air comfort, as well as their interconnections. Merabtine et al. [7] investigated energy demands as well as thermal comfort for a school building experimentally and numerically, for three years of operation. An experimental investigation of different energy demands showed higher operational demands compared with design estimations according to the French standard, resulting in higher operating costs. Within an experimental and numerical investigation of thermal comfort, the authors found shortcomings caused by indoor air temperature below the required set point, whereas they found satisfying results regarding CO_2 concentration levels.

Karyono [8] investigated thermal comfort and building energy demands for several office buildings in Jakarta, Indonesia. As part of the study, it was determined that the air-conditioned buildings investigated were often too low in temperature, which was associated with restrictions in thermal comfort and increased energy demands. For new buildings, a favorable orientation of the building, a well-insulated building envelope and shading devices are recommended, in order to increase thermal comfort with low energy demands. Corgnati et al. [9] numerically studied the relationship between thermal comfort requirements and building energy demand. The energy demand related to different indoor thermal comfort levels was calculated for a typical office space of 19.8 m^2, expressed in terms of the predicted mean vote (PMV), according to Fanger's approach [16]. They found significant reductions in energy demand for a not fully mechanically controlled building with a dynamic adaptive comfort approach, compared with a fully mechanically controlled building, and performed comfort evaluation relying on Fanger's approach for the same number of dissatisfied occupants. The effects of low humidity levels on human comfort were investigated experimentally in Tsutsumi et al. [10]. Based on the investigations, the authors found the effects of relative humidity on indoor thermal comfort can be mitigated with the approach of effective temperature. Chowdhury et al. [11] numerically investigated the performance of different low energy cooling technologies and their influence on thermal comfort for an office building. With the help of a system comparison, their study shows that systems relying on chilled ceilings satisfy the highest thermal comfort requirements throughout the year in subtropical regions. Saelens et al. [12] numerically addressed the influence of occupants' behavior on the energy performance and thermal comfort of an office building with thermally activated building systems, for moderate Belgian climate conditions. They analyzed the differences between standardized and probabilistic occupant behavior. The authors found a non-negligible impact of user behavior on cooling demand and thermal comfort. Cooling demand was lower for the standardized user behavior. The importance of a well-coordinated shading device is emphasized. Wan et al. [13] presented a method to achieve minimum energy demand for the desired level of indoor air conditions relying on a central air conditioning system. They used the approach of effective temperature as an assessment criterion for thermal comfort. With the help of a parameter variation study, they found that occupants are more sensitive to variations in temperature compared with variations in relative humidity during summer. Allab et al. [14] considered options for reducing the energy demand of educational buildings in France, paying special attention to maintaining or even improving a high level of thermal comfort. With regard to thermal comfort in the original state, the authors often noticed overheating of classrooms in the buildings examined. They found demand-oriented air conditioning to be suitable, in terms of improving both thermal comfort and energy efficiency. The benefits of combining the evaluation of thermal comfort, indoor air quality and building energy demands were highlighted in terms of developing appropriate recommendations for future building retrofitting. In terms of further evaluation of user behavior, the effect of manual night ventilation on thermal comfort was investigated in this study. The effects of night ventilation on thermal comfort were examined in the study of Landsman et al. [15] for three different buildings at different locations. The results showed that the indoor operating temperature was kept below the upper 80% acceptance comfort limit using night ventilation. In some cases, overcooling occurred at mild climate conditions. For a heavyweight building, the effect of night ventilation was very limited compared with a lightweight building construction.

Even though thermal and electrical energy demands as well as thermal comfort have been investigated in different studies, the scientific literature has shortcomings in terms of the impact of user-related demands on building energy demands, especially exergy demands and the effects of a lean building construction as well as occupants' interventions on thermal comfort, in particular for large-sized office buildings. To the authors' knowledge, no study has yet provided experimental results of detailed energy demands, indoor air quality for different office spaces, as well as detailed user-related demands for a lean non-residential building, relying on thermally activated ceilings with partly fully automated building systems, covering a period of several years.

Within this study, energy demands and thermal comfort, both with special regard to user-related demands and behavior, were investigated within a post-occupancy evaluation of an administration building for the period from 2014 to 2016. Based on a complex energy concept, thermal and electrical energy demands were analyzed. A detailed investigation of user-related energy demands was completed. Furthermore, thermal comfort and user influence were investigated for several specially-equipped office spaces, in order to show the benefits and limitations of thermal comfort for an almost fully automated office building.

2. Office building

The office building, located in the city of Hamburg in Northern Germany, its interior design and some technical installations are shown in Fig. 1. It was built as the headquarters of the Hamburg Ministry of Urban Development and Housing. In total, the building consists of seven lower building sections (referred to as buildings A-D & F–H) and one high-rise building section (referred to as building E) which are interconnected in two building wings. Each of the lower building sections has five floors; the high-rise building consists of 13 floors, excluding basement areas and underground parking. The building envelope consists of several mounted façade elements, or it is partially realized as mullion

Fig. 1. Exterior (left) and interior (middle) view of the office building, characteristic air handling unit (right).

and transom façade, with an overall ratio of transparent façade of around 32%. Furthermore, the external appearance of the building is characterized by the curved façade construction and colored horizontal ceramic panels, as shown in Fig. 1. The building was built within the framework of the "Energy-Optimized Building Construction" (EnOB) research initiative, funded by the German government. Providing a net floor space of 46,500 m^2, the building contains space for around 1500 workplaces within 1250 offices. The building was awarded the highest rating of "Platinum", formerly "Gold", according to the German Sustainable Building Council (DGNB) criteria. Characterized as an energy-efficient and sustainable building, it was planned to achieve a primary energy demand of lower than $Q_{\mathrm{PE,target}} = 70\ \mathrm{kWh_{PE}}\ (\mathrm{m^2a})^{-1}$ and a very low heating demand of $Q_{\mathrm{h,target}} \approx 15\ \mathrm{kWh_{th}}\ (\mathrm{m^2a})^{-1}$. The building is part of a district heating (DH) grid.

2.1. System layout

Fig. 2 shows the schematic layout of the thermal energy supply.

Energy in the form of heat is primarily supplied by two ground-coupled heat pumps (nominal thermal power output each: $\dot{Q}_{\mathrm{GCHP,nom}} = 264\ \mathrm{kW_{th}}$ at B0/W35) in parallel operation. A district heating connection (nominal thermal power output: $\dot{Q}_{\mathrm{DH,nom}} = 750\ \mathrm{kW_{th}}$) is installed to supply domestic hot water (DHW) as well as to cover thermal peak loads of space heating. The electrically-driven ground-coupled heat pumps (GCHP) are connected to approximately 950 energy piles within an energy pile plant below the building. Both systems feed a central thermal storage system for hot water with a capacity of 5 m^3. During winter mode, the building is primarily heated using thermally activated building systems in the form of thermo-active ceilings (TAC), with a maximum temperature level for the heat transfer fluid of 32 °C. This applies to most of the office spaces. Each building section is divided into two TAC circuits, with an individual control strategy according to the orientation of the building section. Room-by-room temperature control is not implemented. Other functional areas, e.g. corridors and basement areas, are heated using underfloor heating ($\vartheta_{\mathrm{nom}} = 35$ °C) or static heating ($\vartheta_{\mathrm{nom}} = 50$ °C). Additionally, dynamic heating is used to reheat process air to the desired supply air temperature within the air handling units. If the building's heating demand cannot be covered by the GCHP systems, district heating is integrated into the hot water circuit as shown in Fig. 2. During summer mode, cooling of the building is achieved through free geothermal cooling. Another thermal storage system for cold water of 5 m^3 is integrated into the cold water circuit, to enlarge the energy storage capacity of the system. Generally, cooling of buildings using TAC enables the use of heat sinks operating at a higher temperature level compared with conventional cooling circuits. Cooling using TAC requires a temperature level of cold water above 16 °C. Thus, the geothermal system is used efficiently throughout the year as a heat sink and heat source. Except for TAC and domestic hot water supply, no other heating circuits are used during summer mode. To control the overall system fully automatedly in winter and summer operation mode, dynamic averaging of outside air temperature for the past 36 h is used: the latest averaged outside air temperature is compared with the set points for winter and summer mode. Two dry re-cooling units can also

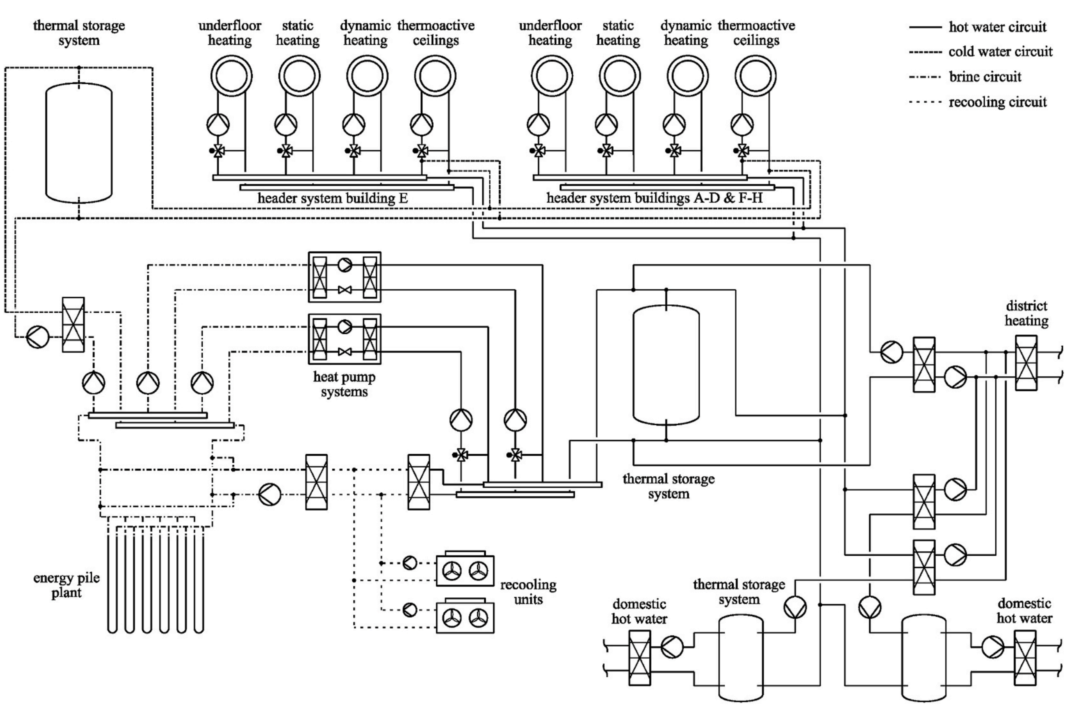


Fig. 2. Schematic system layout of thermal energy supply.

be used for cooling applications at appropriate outside air conditions. Functional areas that are not associated with office space, e.g. utility, server and elevator machinery rooms, are conditioned throughout the year using conventional compression chiller units.

The domestic hot water supply is ensured throughout the year. Central domestic hot water as shown in Fig. 2 is provided for the canteen and changing rooms within the building, using separate hot water stations. Domestic hot water within other functional areas, e.g. pantry areas, is provided using decentral electrical instantaneous water heaters. Central domestic hot water also relies on the principle of instantaneous water heating. Thus, domestic hot water is not provided within a thermal storage system. In winter mode, hot water for the DHW supply is preheated by the hot water circuit of the building. It is reheated to the required hot water temperature within water-to-water heat exchangers supplied by district heating. During summer when the GCHP systems are not operated, the DHW supply is provided by thermal energy from the DH system only. To enlarge the thermal storage capacity of the system, two additional thermal storage systems of 1.5 m^3 each are integrated into the hot water circuit. Domestic hot water is provided by downstream water-to-water heat exchangers.

2.2. Ventilation concept

Every building section is equipped with an air handling unit (AHU) for mechanical ventilation of the related office space and other functional areas. These are equipped with separate air handling units to cover individual ventilation requirements of special functional areas like the canteen or the conference area. The ventilation concept is designed in accordance with winter and summer mode of the entire energy concept of the building. Fig. 3 shows the layout of a characteristic AHU. During winter mode, outside air (ODA) is preheated within a cross-flow heat exchanger (1→2a). Part of the process air flow can be bypassed if the outside air temperature is high enough (1→2b). If necessary, process air is heated to the desired supply air (SUP) temperature in a sensible water-to-air heat exchanger (2 → 3). Extract air (ETA) from the conditioned space consists of two extract air streams: extract air from the office area (4a) and extract air from the sanitary areas (4b). Thus, the fan to ensure ventilation of the sanitary areas can be operated independently from the main AHU. Extract air is used for sensible heat recovery (4 → 5) before it is emitted to the environment in the form of exhaust air (EHA). Volume flows of supply air are controlled to be constant at 3200 – 32000 $m^3\,h^{-1}$, depending on the floor space of the corresponding building section. SUP volume flows are equalized for each swirl outlet. Room-to-room ventilation control is not implemented.

During summer mode, the main AHU is not operated in general, whereas mechanical ventilation of sanitary areas is also ensured during summer (4b→6). Mechanical ventilation of office areas is then replaced by manual ventilation using weather-proofed ventilation flaps integrated into the façade elements.

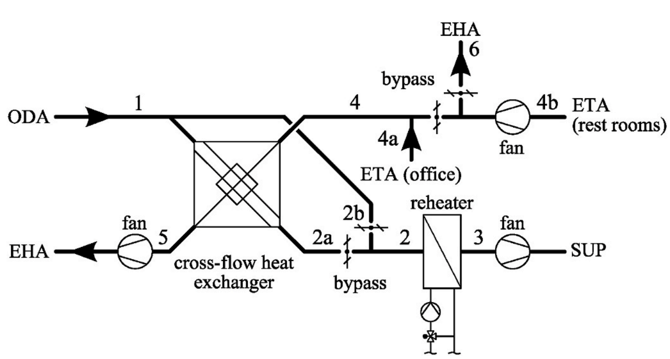


Fig. 3. Characteristic air handling unit of a building section.

2.3. Geothermal system

Due to the sandy underground conditions present, the building is founded on 1600 foundation piles. Around 950 of these foundation piles are thermally activated and designed as double U-tube borehole heat exchangers. As shown in Fig. 4, the final drilling depth of each pile is approximately 13 m. The horizontal distance between foundation piles is at least 3 m. The geothermal system consists of 3 main paths connected in parallel. These are merged at a central point in the basement of the building, where the geothermal system is connected to the heating and cooling circuits of the building (also see Fig. 2). Along these 3 main paths, 11 header systems are integrated, which are connected in parallel on each main path. Each header system consists of 6–10 geothermal circuits, where energy piles (EP) are assembled in groups of 10 using the Tichelmann principle. Generally, the geometric arrangement of foundation piles corresponds directly with the static aspects of the building, due to the sandy building site. The geothermal system is used for heating during winter, feeding 2 ground-coupled heat pumps. During summertime, the geothermal system is used for cooling according to the principle of free cooling. The soil primarily consists of medium and coarse sand up to a depth of 2 m below the ground surface. Below this is a layer of peat silt. For the remaining depth below 3 m, the EP are surrounded by fine, medium and coarse sand. The final drilling depth of the EP is approximately 13 m; significant groundwater flows generally do not occur at the drilling location. A grouting material with a thermal conductivity of $\lambda = 2.3$ W $(m\ K)^{-1}$ is used for thermal connection between EP ducting and the surrounding soil.

2.4. Measurement devices and data acquisition

Relevant parameters characterizing the status of working fluids within the different subsystems are measured and recorded. Air temperature is measured at the inlet and outlet of each component, whereas relative humidity is measured at other relevant positions within the air handling units. The labeling of each air state is shown in Fig. 3. Volume flows of supply and extract air are measured within selected air handling units. Each hydraulic circuit is evaluated by measurement of volume flow at the inlet or outlet, and fluid temperature at the inlet and outlet. Electrical energy demands of relevant components (e.g. heat pumps, fans, circulation pumps) are also measured. Referring to Fig. 4, an optical fiber cable is integrated in selected energy piles for site-resolved temperature measurements within the soil, according to the principle of distributed temperature sensing. In total, 15 energy piles are equipped with temperature sensing. Additionally, monitored boreholes within and outside the energy pile plant are used as reference boreholes to analyze the impact of geothermal energy provision on the surrounding soil. A specific evaluation unit is installed to provide measured temperatures with a special resolution of approximately 1 m and a time interval of 1 h. All other relevant measurement signals are recorded every minute, with the help of a LabVIEW program which is used as an OPC client. Relevant information about the measurement devices and the related measurement uncertainties are listed in Table 1. A Honeywell controlling system is used to control and regulate the overall system.

Measurement uncertainties presented in the following figures were determined according to Gaussian error propagation law. Regarding the uncertainties of electrical and thermal energy demands, the separately measured and cumulative energy demands were weighted with the associated uncertainties on a monthly basis.

3. Monitoring results

The results presented in this study essentially rely on data measured during building operation from January 2014 to December 2016. The following evaluation is subdivided into three parts. First, relevant thermal and electrical energy demands during winter and summer

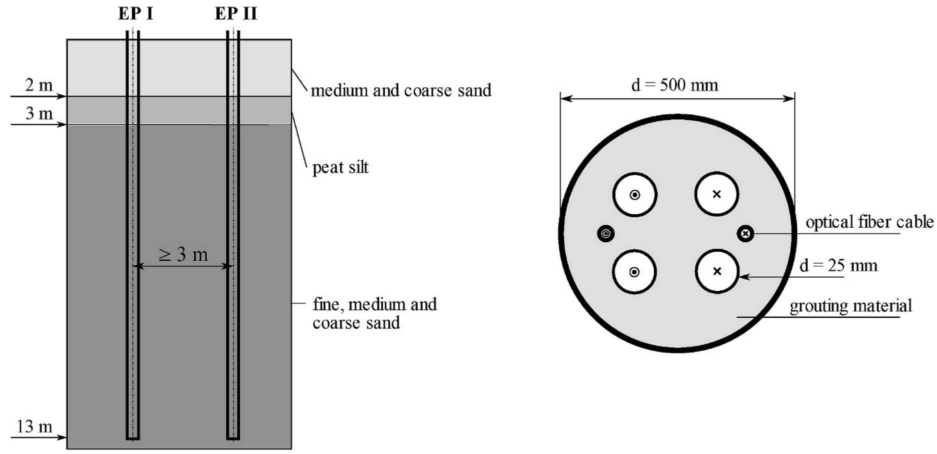


Fig. 4. Structure of the soil and energy piles.

Table 1
Measurement devices and related measurement uncertainties.

Measured value		Sensor type/ measuring principle	Measurement uncertainty
Temperature (air)	ϑ	NTC 10k thermistor	± 1.28 K for -30 to $+110$ °C or $\pm$ 1 % of full scale (0 – 50 °C)
Temperature (water)	ϑ	Pt500 resistance thermometer	$\pm(0.5 + 3 \cdot (\Delta\vartheta_{min} / \Delta\vartheta))$ % with 3 K $< \Delta\vartheta <$ 150 K
Temperature (soil)	ϑ	Optical transmission system	± 0.2 K
Relative humidity	ϕ	Capacitive humidity sensor	± 3 % RH for 40 – 60 % RH, else ± 5 % RH
Pressure difference (air)	Δp	Piezo resistive pressure transducer	± 1.5 % of full scale (0 –2500 Pa) or ± 6 Pa for $\Delta p <$ 250 Pa
Volume flow (air)	$\dot{V}$	Differential pressure	$\pm$(5 Pa + 1.5 % of reading)
Volume flow (water)	$\dot{V}$	Impeller flow meter	$\pm(2 + 0.02 \cdot (\dot{V}_{max} / \dot{V}))$ % of reading, but $\leq$ 5 % of reading
Thermal energy	Q	Heat meter	± 6 % of reading
Electric energy	W	AC energy meter	± 1 % of reading for $I >$ 100 mA, else ± 2 % of reading

operation are presented and analyzed. Thereafter, the performance of the system investigated is evaluated regarding target figures. Finally, thermal comfort is evaluated using different concepts. In order to characterize the weather impact on the building's energy demands, two key weather factors in the form of heating degree days (HDD) and monthly average outside air temperature (MAT) are determined for the three years of operation. Both data are provided free of charge by the German Weather Service for the corresponding location [17]. With respect to Fig. 5, all three years under consideration show similar annual profiles for averaged ODA temperature in the form of MAT.

Nevertheless, ODA temperature was higher in 2014 during spring and fall compared with 2015 and 2016. Additionally, summer was more inhomogeneous, with ODA temperature peaking in July and lower temperature levels for the rest of the summer season. The temperature profile for 2015 shows nearly constant monthly average temperatures from October till December at a higher level compared with the previous and the following years. HDD are defined according to the German standard VDI 3807 [18]. There are no obvious anomalies for the periods considered. The months of July to September show the lowest HDD in general, except for September 2015 due to low average ODA temperature in this comparison. The resulting annual HDD are close together at 3183 Kd (2014), 3484 Kd (2015) and 3478 Kd (2016); the relative deviation is below 10%. Additionally, considering the number of frost and ice days according to the German Meteorological Service [19,20], the winter seasons investigated can be characterized in the range of moderate to average. Table 2 shows the number of frost and ice days for the years 2014–2016 and the long-term average values for the years 1981–2010.

3.1. Thermal and electrical energy demands of the building

As shown in Fig. 6, the maximum heating load is larger than the

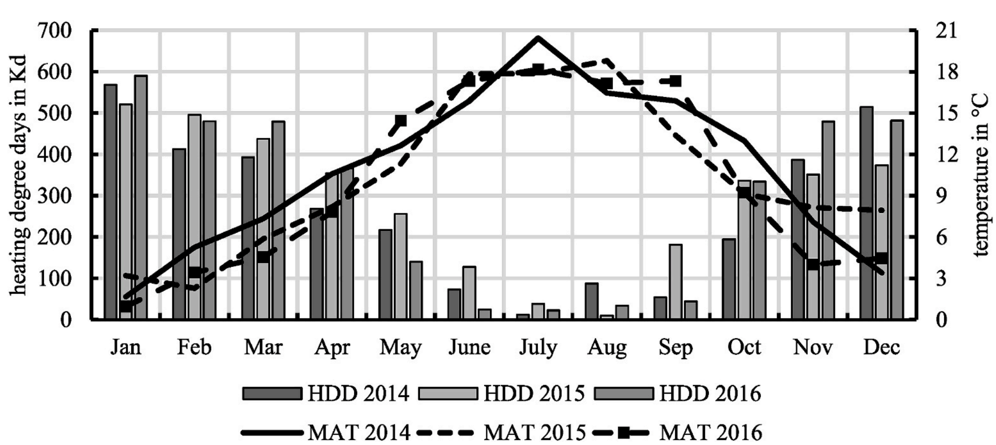


Fig. 5. Heating degree days and average outside air temperature for the years of operation considered.

Table 2
Climate data for the winter seasons investigated.

Climate data	Winter 2014	Winter 2015	Winter 2016	Ø 1981–2010
Frost days ($\vartheta_{d,ODA,min} < 0\,°C$)	41	43	69	70
Ice days ($\vartheta_{d,ODA,max} < 0\,°C$)	15	1	11	16

corresponding cooling load. The maximum total heating load was 1080 MWh_{th}, whereas the maximum cooling load amounted to 479 MWh_{th}, both in 2016. The ratio of thermal energy for heating applications supplied by the backup system (DH) was reduced from 29.2% (2014) to 21.3% (2016) as a result of improving the interaction between space heating and DHW, see Fig. 6(a). Annual electricity demand of the GCHP systems varied according to the heating demand, but the increased seasonal performance of these systems caused a reduced use of electricity. This especially holds true for the 2016 heating mode. The electricity demand of auxiliary energies (e.g. circulation pumps for energy distribution) was nearly constant at 11% of the total electricity demand during heating mode.

Considerable effects of improving building operation were achieved for the cooling mode, as shown in Fig. 6 (b). The amount of thermal energy for cooling was increased significantly by a factor of 2.9 in 2016 compared with the previous years, by extending the operating conditions for cooling mode in general - to improve thermal comfort during summer, as well as to improve the annual energy balance of the EP plant. At the same time, the electricity demand for the cooling of functional areas was slightly reduced during the periods considered. Due to user interventions on the control units, the IDA temperature within these areas could not be kept just high enough to achieve the required cooling. Nevertheless, further electricity savings for the compression chiller units are estimated to be low. As shown in Fig. 7(a), the thermal energy balance of the soil was not equalized throughout the periods considered, but extending the cooling mode nearly doubled the ratio of geothermal assisted cooling in 2016. This positively influenced the energy balance of the EP plant in conjunction with natural regeneration of the soil. However, ongoing long-term monitoring is recommended for this kind of large-scale geothermal system with several energy piles or borehole heat exchangers influencing each other.

To further evaluate the performance of geothermal assisted heating and cooling, key figures are defined, relating transferred thermal energy to the corresponding electrical energy demand. These performance indicators are

$$SPF_{GCHP} = \frac{\int_a \dot{Q}_h \, d\tau}{\int_a P_{GCHP+PU} \, d\tau}, \quad SPF_{EP} = \frac{\int_a \dot{Q}_{EP} \, d\tau}{\int_a P_{PU} \, d\tau} \tag{1}$$

The term $P_{GCHP+PU}$ includes the electricity demand of a single heat pump and the corresponding feed pump to tap the geothermal source. The same holds true for the term P_{PU} for free cooling. Due to the underlying operating strategy, seasonal performance factors (SPF) of both GCHP systems were approximately equal, as indicated in Fig. 7 (b). A slight increase in the average seasonal performance from $SPF_{GCHP} = 3.2 \pm 0.2$ in 2014/2015 to $SPF_{GCHP} = 3.6 \pm 0.2$ in 2016 is notable for the timeline considered. Without auxiliary energies (evaporator feed pump), these key figures would be increased by $SPF_{GCHP} = +0.1$. Increasing SPF_{GCHP} throughout the periods considered was primarily caused by improving even circulation within the EP plant piping, and limiting the influence of the required supply temperature for DHW. Thus, compared with the previous years, the required supply temperature for DHW was adjusted exclusively by district heating in 2016. According to the German Renewable Energies Heat Act (EEWärmeG) [21], the GCHP target value of annual performance is $SPF_{GCHP} = 3.8$ if DHW is at least partially provided by GCHP. Compared with the target value, the annual performance measured is generally lower. For the periods of 2014/2015, relative deviation was approximately $-13\,\%$, whereas for the year 2016 a considerable convergence towards the quantified target value was achieved; the remaining deviation is within SPF measurement uncertainty. This development indicates improved performance at an appropriate level. According to Eq. (1), seasonal performance is defined in a slightly different way for geothermal assisted cooling. Seasonal performance factors for cooling were in the range of 56.3 ± 3.6 (2014/2015) and 53.0 ± 3.4 (2016), indicating a steadily high efficiency of the geothermal heat sink.

Calculating the energy performance of a building under standardized conditions according to the German Energy Saving Ordinance (EnEV) does not consider any user-related demands (URD), including such aspects as data processing, IT offices, pantry areas and elevators. Nevertheless, analyzing URD is beneficial, as these are significant and primarily exergy demands, especially for large non-residential buildings, e.g. administration buildings. As shown in Fig. 8, the electrical final energy demands according to DIN V 18599-1 [22] are plotted for one year, including the corresponding total URD. The results shown in Fig. 8 rely on data measured and appropriate extrapolation for the entire building where required. For example, electricity demand for lighting is only measured for individual floors, and was extrapolated based on the number of illuminants for the entire building.

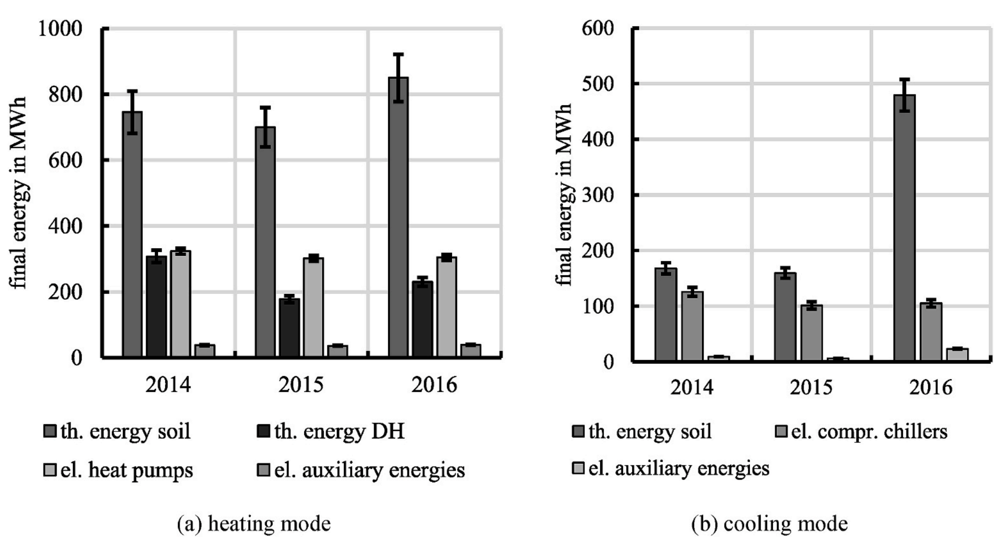
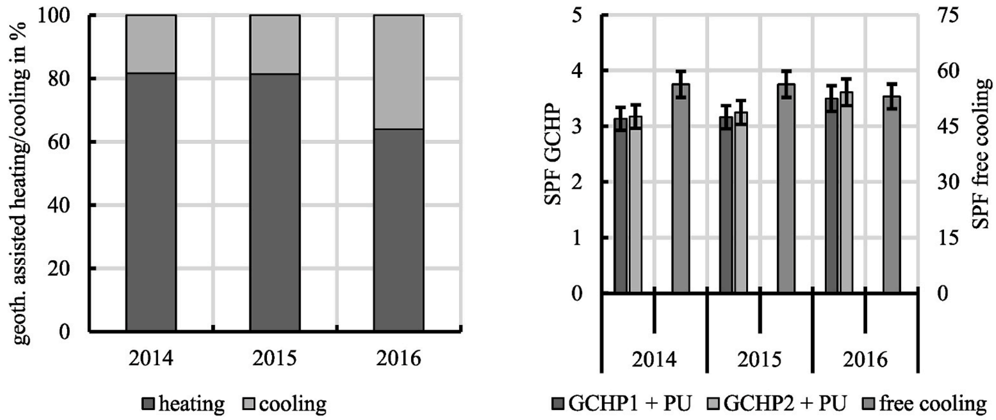


Fig. 6. Annual demand of final energy required for heating (a) and cooling (b) applications.



(a) (b)

Fig. 7. Annual utilization of the soil as a heat source and heat sink (a) and seasonal performance of geothermal assisted heating and cooling (b).

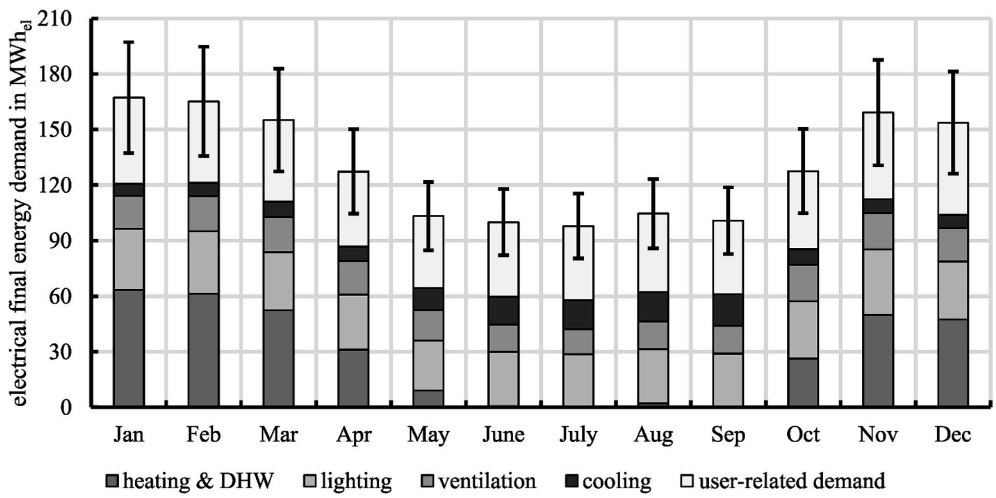


Fig. 8. Electrical final energy demands according to DIN V 18599-1 and additional user-related demands for 2016.

Considering the annual slope, the category of “heating & DHW” shows significant variability, primarily caused by the GCHP systems. Thus, the maximum total electricity demand was achieved during January ($W_{tot,max} = 167$ MWh$_{el}$) and in July total electricity demand was at a minimum ($W_{tot,min} = 98$ MWh$_{el}$). An opposite situation was detected for cooling applications as a result of seasonal ODA temperature. Except for these variable requirements, most electricity demands were comparatively constant throughout the year. This was also true for URD. Total URD was in the range of 39 – 50 MWh$_{el}$, accounting for an electricity ratio of 28% in January and a maximum ratio of 41% in July. Considering user-related energy demands, which are mostly characterized by electricity demands for office and

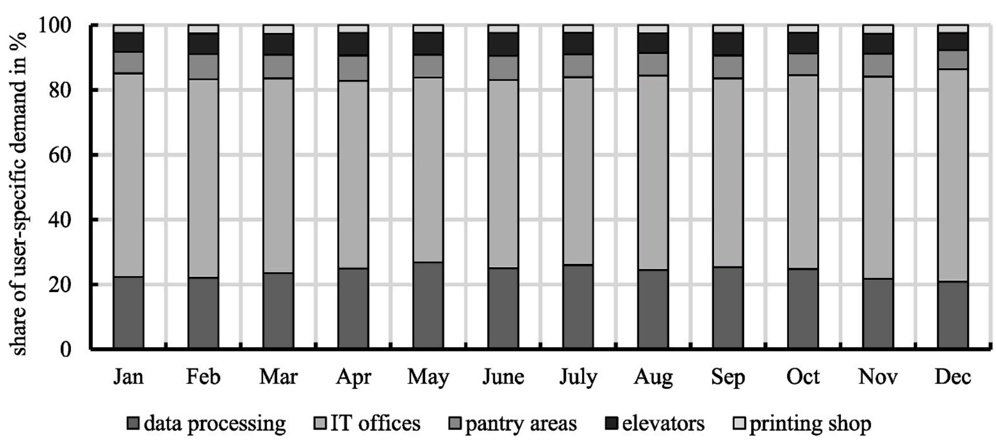


Fig. 9. Relative distribution of electrical user-related demands for one year.

administration buildings, these generally represent a significant part of the total electrical energy demand, and should therefore not be neglected in energy considerations. Thus, URD should be included in energy assessments for future new building projects, in addition to the existing energy assessment process.

In order to further analyze URD, Fig. 9 shows the relative distribution of URD for one year, separated by different applications. The legend item “data processing” includes electricity demands for network infrastructure and server operation. The electricity demand of workstations including screens, phones and height-adjustable desks is summarized in the category “IT offices”. There are also other user-related applications that are subject to individual use and cannot be further specified.

According to Fig. 9, URD were primarily caused by IT electricity demands. These accounted for a range of 57 – 66 %. This is followed by the share of data processing, which is subject to increased fluctuations throughout the year and averages around 25%. The remaining share is roughly equally distributed between pantry areas and elevators, with an average share of around 7% each. Bearing in mind this consideration, using energy-efficient workplace equipment is required to decrease URD. The slightly higher heating demand during winter, caused by lower internal heat loads, is negligible. But during summer, thermal comfort is increased for the same reason. Furthermore, the quality of energy has to be taken into account since this is primarily exergy regarding URD.

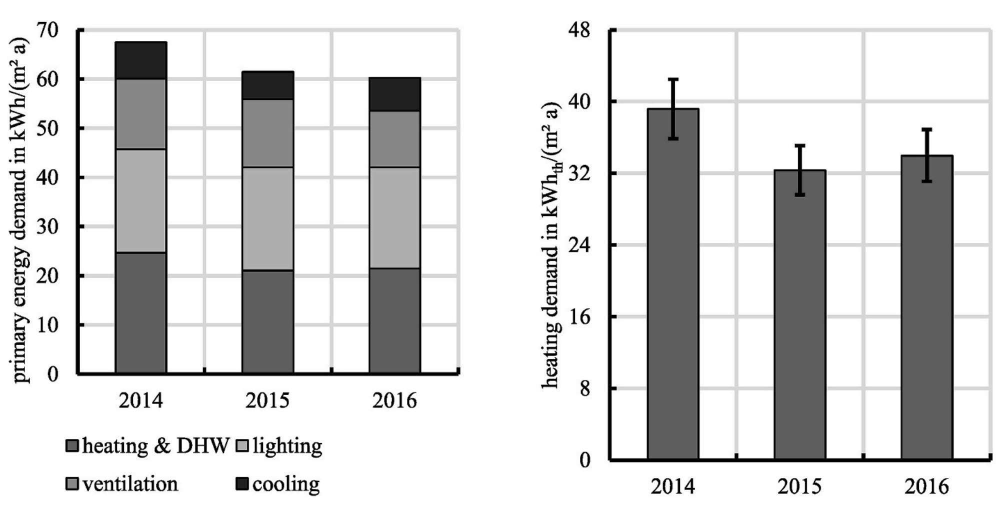
3.2. Overall energy performance evaluation

A common challenge regarding the analysis of buildings’ energy performance is the performance gap when directly comparing nominal values of energy demands from the design stage with energy demands measured during the operating stage. To show the actual energy performance, electrical and thermal energy demands measured were allocated according to the underlying standards used to estimate building energy performance. Thus, actual primary energy demand was calculated according to the approach in Refs. [22], and actual heating demand was determined according to DIN EN ISO 13790 [23], respectively. The primary energy factor for electricity was set equal to the primary energy factor used for building energy simulations ($f_{PE,el} = 2.6$, according to Ref. [22]). All energy demands were adjusted for location and weather variations according to Ref. [18]. Fig. 10 shows the results of the actual annual primary energy and heating demand.

A decreasing annual primary energy demand was detected for the periods considered. The initial value of $Q_{PE,2014} = 67.5\ \text{kWh}\ (\text{m}^2\text{a})^{-1}$ in 2014 decreased by 11% in 2016, as a result of continuously improving the operation of building systems. The most significant savings were made in terms of operating the air handling units which supply fresh and heated air to the office spaces. Improving operation times and airflow rates caused a decrease in primary energy use of 20% in this category. Furthermore, a 13% decrease in primary energy use was achieved for the operation of the GCHP systems due to several improvement approaches, e.g. increasing the output of the EP plant and improving the control software of the GCHP systems. Compared with the estimated primary energy demand of the building $Q_{PE,target} = 70\ \text{kWh}\ (\text{m}^2\text{a})^{-1}$, the actual value was lower for the period considered. Including user-related demands would account for an additional $30\ \text{kWh}\ (\text{m}^2\text{a})^{-1}$ on top of the actual annual primary energy demand.

Even though heating demand decreased throughout the periods considered, it was still above the estimated target value of $Q_{h,target} \approx 15\ \text{kWh}_{th}\ (\text{m}^2\text{a})^{-1}$. As shown in Fig. 10 (b), annual heating demand decreased by around 15% for the period considered. The remaining difference to the results of the thermal building simulation, implemented according to Ref. [23], is found in different boundary conditions. The thermal building simulation model was set up based on defined boundary conditions. Additionally, deviations of the building envelope insulation and air-tightness quality, as well as user influences, were not considered. Thus, the gap between actual and predicted heating demand corresponds with the expectations of required improvements as part of the monitoring process. Nevertheless, the present heating demand of the building is already at a very low level in general.

From the overall investigation of building energy demands, it can be concluded that operating a large-sized office building relying on geothermal assisted heating and cooling and partly manual ventilation requires well-considered and reliable interaction between the different building systems, to ensure high efficiency and low energy demands, while simultaneously providing a high level of thermal comfort. Thus, intensive monitoring activities are recommended for any large-sized non-residential building with a complex energy system, at least during the first years of operation. In addition to the installation of environmentally-friendly and energy-efficient technologies, their demand-oriented and energy-efficient operation is also crucial with regard to long-term economical building operation. In this context, building monitoring during building operation can make a significant contribution towards achieving the energy targets, and gaining experience of remaining deviations.



(a) (b)

Fig. 10. Annual primary energy demand according to DIN V 18599-1 (a) and annual heating demand according to DIN EN ISO 13790 (b).

3.3. Thermal comfort

All office spaces within the building considered are equipped with automated outer shading devices and manually controlled glare protection. As a large portion of sensible heating and cooling is exchanged in the form of radiation, TAC are considered comfortable because typical draft problems encountered with convective systems are reduced. To analyze and evaluate thermal comfort as well as user influence, the building is equipped with 32 reference office spaces. These are primarily office spaces of different orientation, floor plan and floor area, equipped with different measurement devices. Fig. 11 shows a simplified floor plan of the building investigated, presenting the distribution and orientation of reference office spaces. Reference office spaces characterized by "*" are extended reference office spaces as described hereafter. Reference office spaces are located on the third floor within low-rise building sections (rooms *i*) and on the fifth (rooms *i*) and tenth (rooms 1*i*) floor within the high-rise building. All reference office spaces are equipped with permanently installed measurement devices for air temperature and relative humidity. Furthermore, user influences are recorded in terms of presence time and opening state of ventilation flaps. For extended reference office spaces, sensors to evaluate radiation temperature and surface temperature of the ceiling as well as concentration of CO_2 are also installed. A combined measurement device for recording air temperature and humidity, or a sensor with additional radiation temperature and CO_2 concentration, is mounted on a wall at a height of 0.6 m above the floor. Presence time is recorded using an infrared sensor mounted above the office door, and the ceiling surface temperature is determined at one point on the surface of the concrete ceiling. Magnetic contacts are installed in the frame to determine the opening status of the window and ventilation flap. All measurements were carried out as one point measurements. A summary of measurement devices in use and related uncertainties is provided in Table 3. All measurement signals were continuously recorded at a frequency of 1 min. The following investigation of thermal comfort only includes these reference office spaces. Statements on thermal comfort within other functional areas of the building cannot be derived from this evaluation.

Table 3
Measurement devices and related measurement uncertainties for the evaluation of thermal comfort.

Measured value		Sensor type/measuring principle	Measurement uncertainty
Temperature	ϑ	NTC 10k thermistor	± 1 % of full scale (0 – 50 °C)
Radiation temperature	ϑ	Ni1000 resistance thermometer	± 0.4 K
Surface temp. TAC	ϑ	NTC 10k thermistor	± 1 % of full scale (0 – 50 °C)
Relative humidity	ϕ	Capacitive humidity sensor	± 3 % RH for 40 – 60 % RH

3.3.1. Investigation of indoor air conditions

Fig. 12 shows the outside and indoor air states for the entire years of 2015 and 2016 for the total number of reference office spaces.

The building is designed to comply with comfort requirements according to category II as defined in DIN EN 15251 [24]. This includes less than 10% of occupants being dissatisfied with the present indoor air conditions. All air states shown are within the main occupancy time of the building between 7 a.m. and 6 p.m. For 2015, cat. II was maintained for 88.5% of occupancy time and cat. III was matched for an additional 9.8% of occupancy time. The average IDA temperature was $\overline{\vartheta}_{\text{IDA},2015} = (22.5 \pm 0.3)\,^{\circ}\text{C}$ with an average IDA water content of $\overline{x}_{\text{IDA},2015} = (6.5 \pm 0.2)\ \text{g}_{\text{w}}\text{kg}_{\text{air}}^{-1}$. These numbers are similar for 2016. Maintenance of cat. II is slightly lower with 86.1% of occupancy time, and cat. III was maintained for an additional 12.2% of occupancy time. Regarding the IDA parameters, an average IDA temperature of $\overline{\vartheta}_{\text{IDA},2016} = (22.2 \pm 0.3)\,^{\circ}\text{C}$ and an average IDA water content of $\overline{x}_{\text{IDA},2016} = (7.0 \pm 0.2)\ \text{g}_{\text{w}}\text{kg}_{\text{air}}^{-1}$ was achieved. For both periods, more than 95% of IDA states were within a temperature range of 20.4 – 24.9 °C.

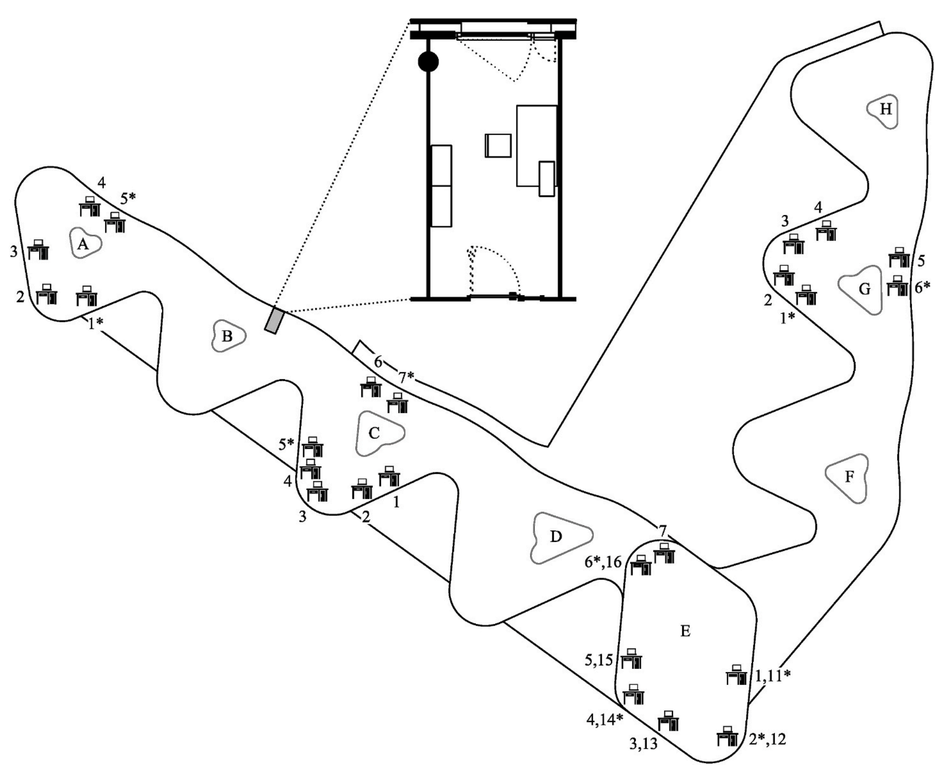
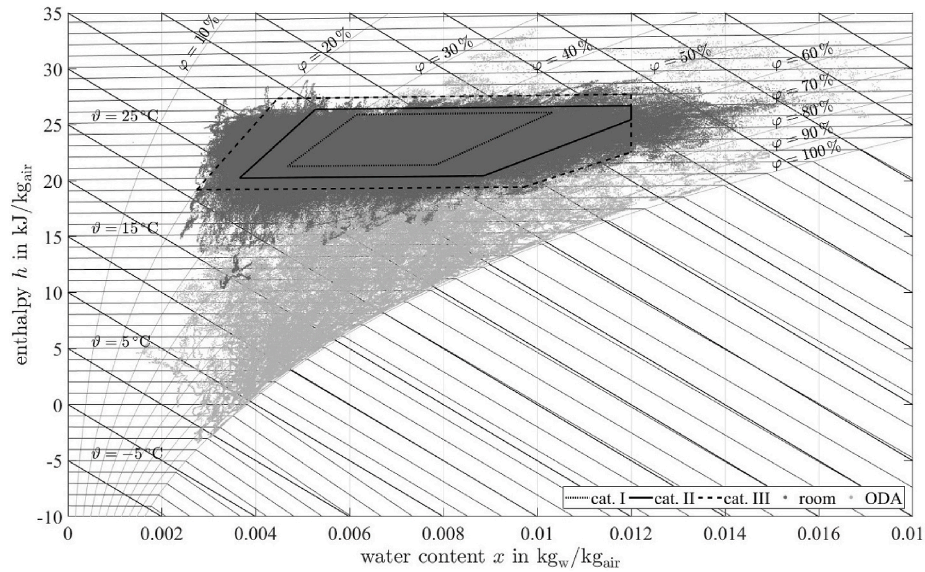
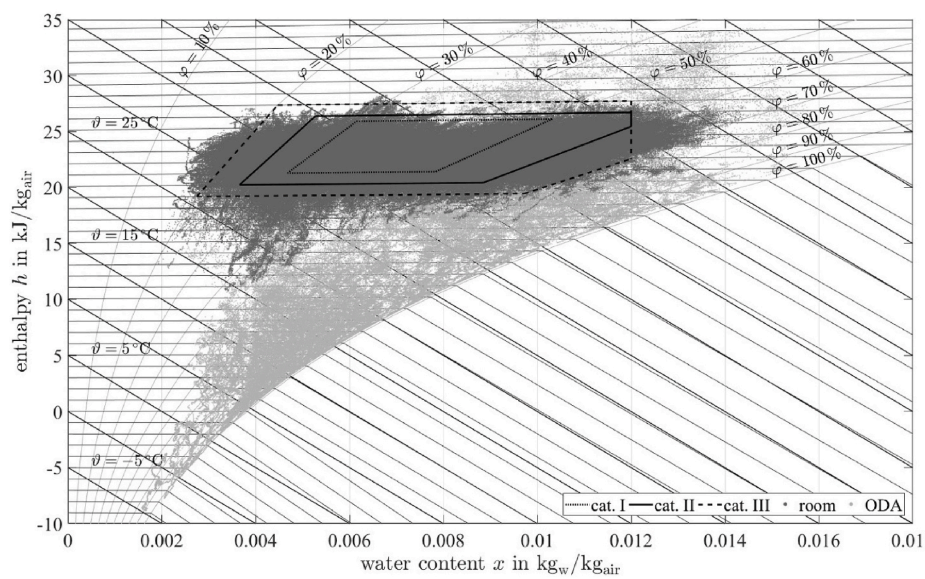


Fig. 11. Simplified distribution and orientation of reference office spaces within the building investigated and zoomed simplified floor plan of a standard office space.



(a) 2015



(b) 2016

Fig. 12. Outside and indoor air conditions during occupancy time for the total number of reference office spaces investigated.

Since IDA humidity ratio is not controlled by the AHU, its range of values ($x_{IDA} = 3.2 \ldots 10.7\ g_w kg_{air}^{-1}$) directly depends on the ODA humidity ratio, at comparatively constant indoor latent loads. Additionally, indoor latent loads were found to be at approximately $2\ g_w kg_{air}^{-1}$, causing IDA water content below the minimum set point according to Ref. [24] for cat. II at ODA humidity ratios below $2 - \ 2.5\ g_w kg_{air}^{-1}$. Thus, air humidity ratio is more crucial than IDA temperature level in terms of thermal comfort for the building considered. In particular, low humidity ratios during winter operation can increase the prevalence of occupants' discomfort or even illness. The average values for IDA temperature and water content are quite similar for the different building sections; differences are below $\pm 0.5\ °C$ and $\pm 0.5\ g_w kg_{air}^{-1}$, representing a homogeneous distribution of sensible and latent heat flows within the entire building. Nevertheless, a trend was identified of lower IDA water content in the high-rise building section compared with the lower building sections investigated. Besides other effects, this is a result of reduced air exchange rate for the lower building sections, which increases IDA humidity levels within the building. Reducing the air exchange rate was not possible for the high-rise building section, due to its construction.

During summer operation when the air handling units are not operated for mechanical ventilation, individual use of the ventilation flaps is required to induce the air exchange rate for office spaces. Due to the lack of dehumidification, IDA conditions beyond the desired comfort zone occurred as shown in Fig. 13 for July 25th to 29th, 2016 with better visibility. The desired comfort category II was maintained in the range of $29.8 - 65.5\ \%$ of occupancy time for the building sections investigated; cat. III was maintained for the additional remaining $31.2 - 64.0\ \%$. The violations present were almost exclusively justified by IDA humidity ratios above the upper limit of cat. II. The corresponding profiles of IDA temperature and water content for the summer week considered, as mentioned above, are shown in Fig. 14.

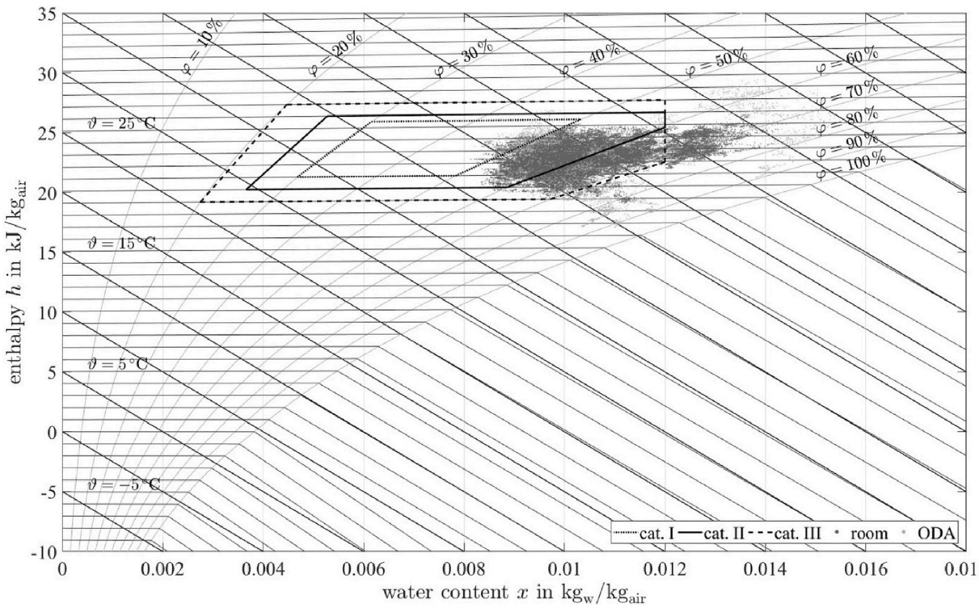


Fig. 13. Outside and indoor air conditions during occupancy time for July 25th to 29th, 2016.

Sensible cooling loads were effectively covered using TAC; IDA temperature was kept in the range of $21 - 24\ ^\circ C$. Manual use of the ventilation flaps by the users during the night for additional heat removal from the office spaces is not visible from the temperature slopes as shown in Fig. 14 and will be discussed in the following section in more detail. The average IDA humidity ratios are mostly above $10\ g_w kg_{air}^{-1}$, causing discomfort within the office spaces.

To summarize, the investigation of thermal comfort during summer and winter shows the IDA humidity ratio to be the crucial comfort parameter. In contrast, a highly comfortable IDA temperature level was achieved using TAC for heating and cooling purposes. Ashrae standard 90.1 [25] defines the term of *unmet load hours* to quantify the number of annual operation hours of a building at unmet cooling and heating loads. It is recommended not to exceed 300 h throughout the year (8760 h). This equates to a coverage ratio of 96.6%. Considering the total number of reference office spaces throughout the year, a coverage ratio of 97.7% was achieved for both of the years 2015 and 2016, indicating a high level of thermal comfort. Nevertheless, this evaluation does not take into account the total number of functional areas. This applies in particular to the office spaces on the lower floors, where IDA temperature level was generally lower, causing an increase in thermal discomfort during winter seasons. Generally, thermal comfort could be increased by implementing individual TAC control. As long as different office spaces are aggregated to a single TAC zone, room-to-room heat gain variations cannot be handled. Another challenge is determining the optimal operation strategy, due to the long response times of concrete core activation. This occurs particularly in transitional periods with changing requirement profiles. Addressing this aspect, cooling mode was activated to improve thermal comfort as soon as the 36 h average temperature was above 16 °C, since the building generally warms up quickly from solar radiation due to the small thermal storage mass.

3.3.2. Extended investigation of thermal comfort

In the following section, extended reference office spaces are inves-

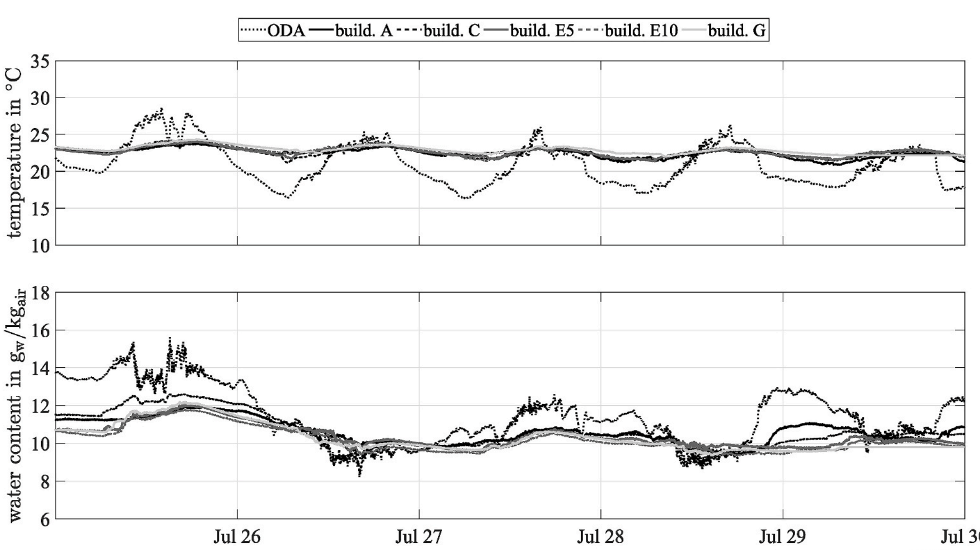


Fig. 14. Average profiles of ODA and IDA temperature and water content for the reference office spaces investigated during summer operation for July 25th to 29th, 2016.

tigated in terms of comfort parameters according to DIN EN ISO 7730 [26]. The influence of office space orientation was investigated in terms of solar radiation. Assuming properly functional solar-tracking outside blinds and similar use of ventilation flaps, only a slight influence of solar radiation on IDA temperature and PMV values was detected. Fig. 15 shows the slope of solar altitude as well as PMV and PPD values for the reference rooms considered; the location of the rooms is according to Fig. 11. Regardless of the individual initial situation for each room, solar radiation influences IDA conditions in terms of increasing PMV values. The corresponding PPD values simultaneously decrease, due to getting closer to an optimal PMV value of PMV = 0. Assuming summerlike clothing insulation of $I_{cl} = 0.6$ clo (including insulation of the office chair), PMV and PPD mostly met the requirements according to cat. B, which is equivalent to cat. II according to Ref. [24]. Although IDA temperatures were equal for both office spaces, PMV values indicate higher thermal comfort for E6 compared with E14, due to the location of the sensor. This could be caused by objects blocking the sensor in E14. This example shows the difficulties and uncertainties that remain when evaluating measurement data, if not all of the boundary conditions are known, or if the user behavior cannot be influenced without restrictions.

To further evaluate user influence on thermal comfort, the manual use of ventilation flaps was investigated. The building is equipped with ventilation flaps for cooling purposes and air exchange during summer. Making use of the temperature difference between IDA and ODA, these ventilation flaps can be used to support removing heat loads from office spaces overnight. As cooling efficiency strongly depends on ODA temperature, a suitable operation strategy is required for the use of ventilation flaps. To evaluate user influence on thermal comfort using ventilation flaps, two contrary user profiles are considered as shown in Fig. 16. Room numbering is according to Fig. 11. Both rooms were occupied during working hours for the period considered, see Fig. 16 (c). Generally, manual ventilation during the night supports keeping IDA temperature at a lower level compared with an office space with a closed ventilation flap during the night, if ODA temperature is lower than IDA temperature overnight. As shown in Fig. 16 (d), the ventilation flap in room A5 was primarily used for cooling during the night, and temporary air exchange during presence time. In contrast, the ventilation flap in room G1 was generally closed during the night, and opened for mostly

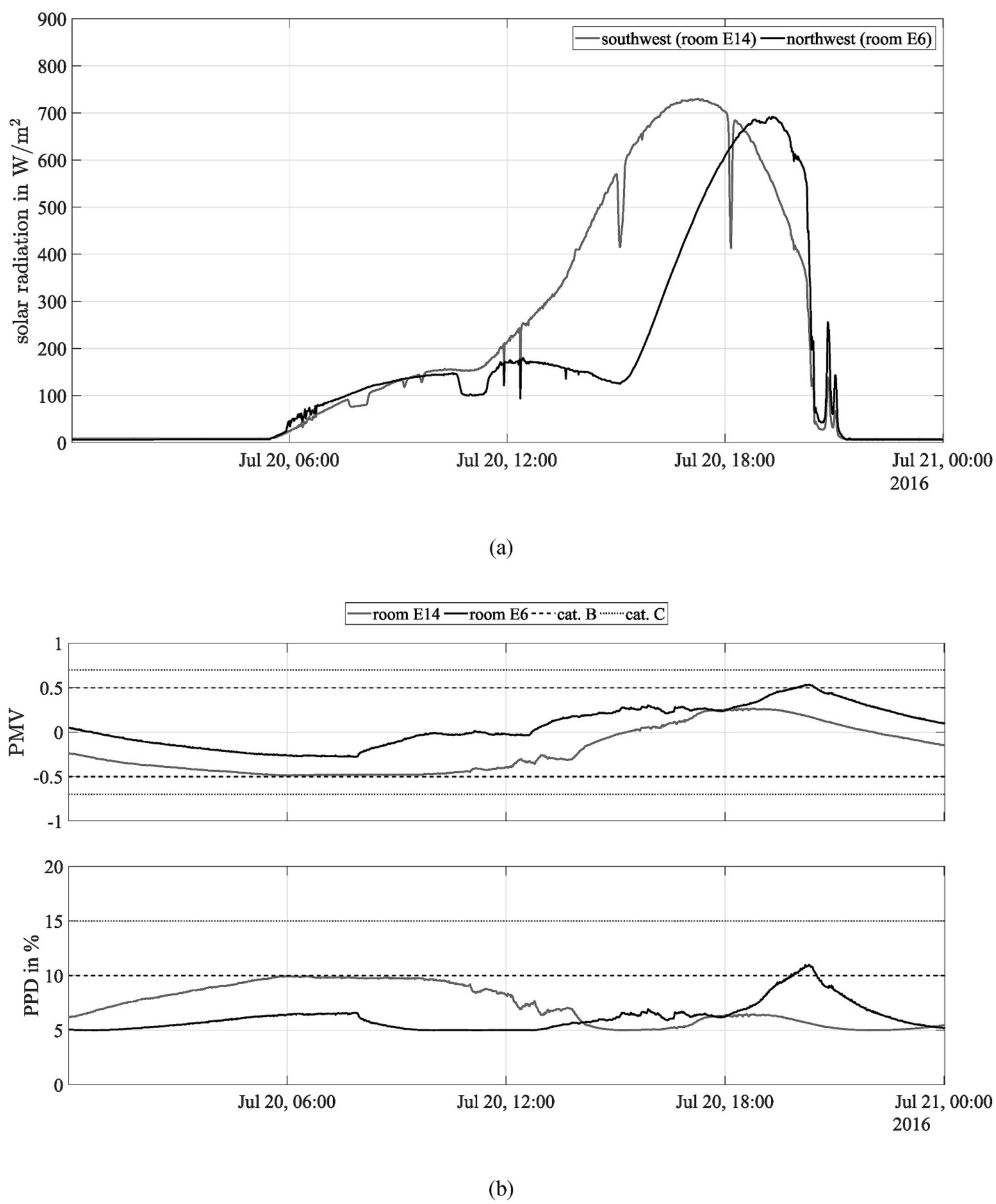


Fig. 15. Influence of solar radiation on thermal comfort for chosen extended reference office spaces; (a) direction dependent solar radiation, (b) PMV and PPD values.

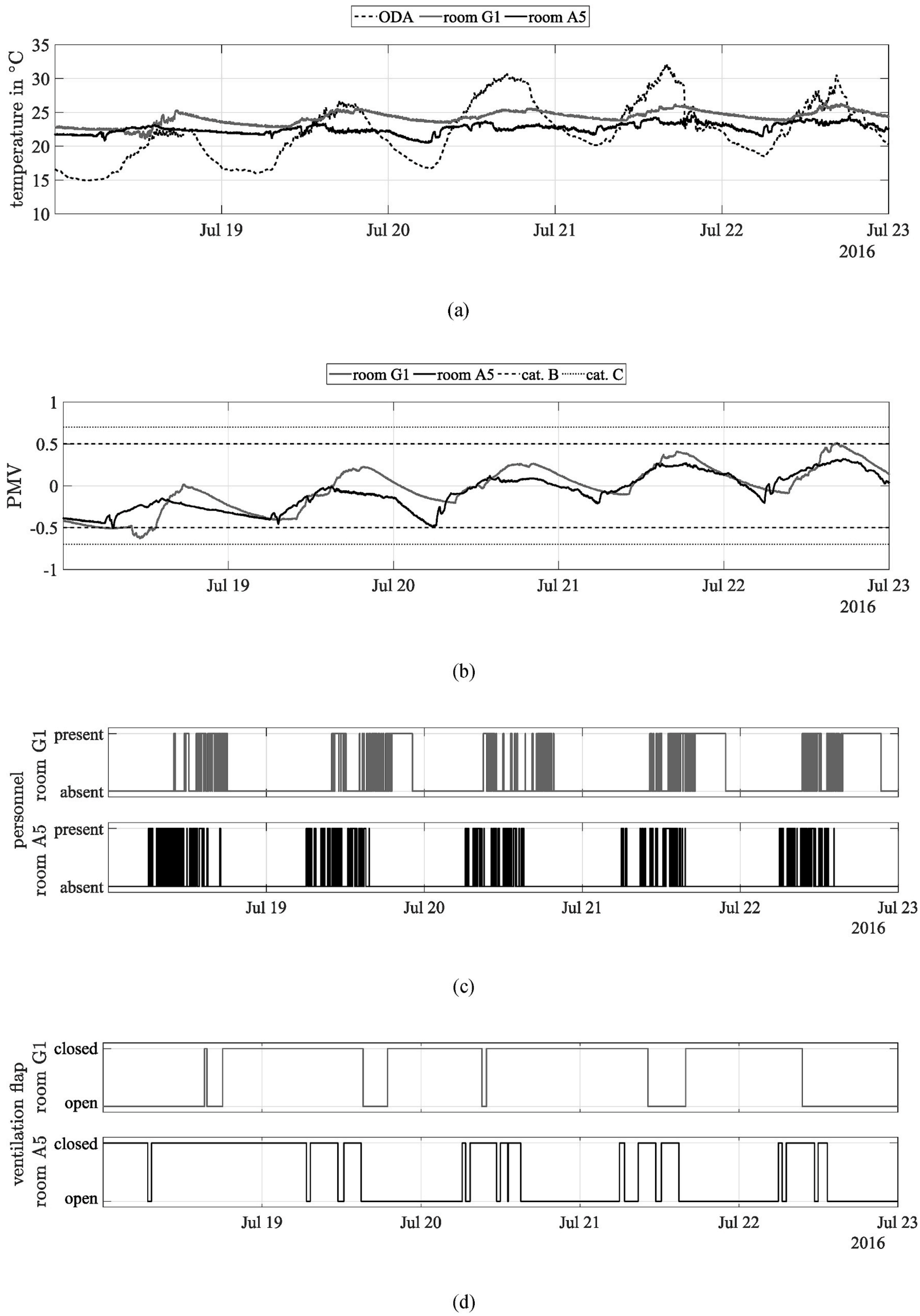


Fig. 16. User influence on thermal comfort using manual ventilation flaps during summer; ODA and IDA temperatures (a), PMV values (b), users' presence (c) and user profiles for ventilation flaps (d).

longer periods during presence time compared with the previous office space. These ventilation strategies result in mostly lower or equal PMV values for room A5, see Fig. 16 (b). An increasing ODA temperature level limits the cooling efficiency of the ventilation flaps during the night. Thus, initial temperatures in the morning were equalized for both rooms under consideration for July 21st and 22nd. Nevertheless, the maximum IDA temperature was still lower for room A5, with suitable use of manual ventilation during presence time.

These results show that user interventions in a building's energy concept can have an impact on thermal comfort. This is more evident for the building investigated compared with conventional office buildings that rely on fully automated building equipment, since the user in this building is an active part of the energy concept. Targeted user instruction is therefore of importance, in order to improve the interaction between automated and manual systems for technical building equipment. Studies on user behavior have shown that appropriate use of the ventilation flaps for overnight cooling in summer has a beneficial effect with regard to the IDA temperature level that arises. A comparison of the resulting IDA temperatures with the ventilation flap open or not open during the night was used to derive a high efficiency of free cooling, if there is a sufficient temperature difference to the outside air.

4. Conclusions

Post-occupancy investigations of energy demands and thermal comfort for a large-sized non-residential building were conducted for this study. Enhanced detailed knowledge was gained about how energy demands are connected to user-related applications and their magnitude, as well as about thermal comfort and user influence on thermal comfort. Additionally, the effects and impacts of system monitoring during the first three years of building operation on energy demands and system performance were presented in detail. The main findings can be summarized as follows:

- User-related energy demands can have a significant influence on the overall exergy demand of a large-sized non-residential building, as URD is mostly related to electricity demands. URD represented up to 41% of the total final energy demand of the building, according to the standard energy demand categories in DIN V 18599-1.
- The primary energy demand of the building investigated was similar to the corresponding estimated target value. Additionally, the decrease in primary energy demand achieved during the first three years of operation shows the significant impact of detailed building monitoring in general.
- Estimating heating demand is not highly accurate for large-sized office buildings, due to the simplified assumptions required for the building simulations during the design stage. Thus, methods of estimating energy demands of a building during the design stage must be assessed critically in terms of the underlying system boundaries in general, to avoid misleading analysis of performance gaps during building operation.
- A high level of thermal comfort was achieved using TAC. The desired comfort criteria were maintained for more than 97% of occupancy time throughout the year for the reference office spaces investigated. Nevertheless, the lack of air conditioning in terms of air dehumidification and humidification caused discomfort at very low or high ODA humidity ratios.
- Operating a building that relies on fully automated building systems in combination with manual systems controlled by the individual user can cause reduced thermal comfort due to unexpected user behavior. Thus, users must be instructed carefully and should become involved in the overall process. Remaining uncertainties due to a lack of restrictions on user influence and limited metrological detection of user behavior must be taken into account, and lower the resilience of measurement results.
- Long-term building monitoring is recommended for any large-sized non-residential building that relies on a complex energy concept, in order to improve the interaction of building systems, and to operate the building at reasonable energy demands with correspondingly low CO_2 emissions, and a high level of user comfort.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

Symbols

I_{cl}: clothing insulation clo $= 0.155\ m^2K\ W^{-1}$
Q: thermal energy kWh_{th}
p: pressure Pa
PPD: predicted percentage of dissatisfied –
PMV: predicted mean vote –
SPF: seasonal performance factor –
$\dot{V}$: volume flow $m^3\ h^{-1}$
W: electrical energy kWh_{el}
x: water content $kg_w\ \ kg_{air}^{-1}$
ϑ: temperature °C
ϕ: relative humidity % RH
Δ: difference –
$[\overline{...}]$: averaged quantity –

Subscripts and Abbreviations

a: annual
AHU: air handling unit
d: day
DGNB: German Sustainable Building Council
DH: district heating
DHW: domestic hot water
EHA: exhaust air
el: electrical
EnOB: Energy-Optimized Building Construction
EP: energy pile
ETA: extract air
GCHP: ground-coupled heat pump
h: heating
HDD: heating degree days
IDA: indoor air
MAT: monthly average outside air temperature
max: maximum value
min: minimum value
nom: nominal
ODA: outside air
PE: primary energy
PU: circulation pump
SUP: supply air
TAC: thermally activated ceilings
target: target value
th: thermal
URD: user-related demands