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Thermal conditions in households and assessment of building's flexibility potential. Variations in time, space and between dwellings

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ABSTRACT

There is little specific knowledge of actual temperature conditions in buildings. This paper contributes with results from a detailed long-term monitoring campaign of temperature conditions in 17 households. Furthermore, these measurements are combined with qualitative interviews with 22 occupants in 16 households, on their heating practices. Implications for the assessment of the heat demand flexibility potential are discussed, and it is suggested that including occupants in future experiments can be a way to reach the full potential of buildings flexibility potential to a renewable energy sources dependent energy system. Quantitative data show that temperature conditions vary with time and space within each dwelling and between dwellings. In the same apartment, the temperature difference between spaces can be 7 K. The living rooms have the most homogeneous temperature distribution during 24 h period and the bedrooms most significant variations. Qualitative data indicate that aspects of: Activities performed by occupants; Caring for things, others and oneself; Comfort; Convenience; Natural and material surroundings affect occupants' heating practices.

1. Introduction

The energy systems worldwide are under paradigm shift towards green and smart energy infrastructure [1]. In Denmark, the decarbonisation process foresees stepwise increase of renewable energy sources (RES) with full elimination of fossil-fuels in 2050. The increased reliance on intermittent energy sources calls for stronger coupling of individual energy sectors, i.e. power and district heating, and for flexibility at the demand side. Since residential buildings accounts for 40% of the final energy demand worldwide [2], modulating their demand have a prominent role in smooth and bottlenecks-free operation of energy system, and thereby viable and successful transition towards low-carbon future [3]. In the cold and temperate climates the heating consumption is the dominant part of buildings' energy use, e.g. in a typical Danish house, 85% of energy is used for heating. Therefore, the scope of this paper is limited to the shift of space heating demand in residential buildings.

The flexible building concept is based on the idea of modulating buildings heat demand according to the availability of RES in the smart energy system. When there is an excess of RES production, the buildings should be able to use more and/or store energy, and with shortage of RES at production side, the buildings' energy demand should also decrease. The modulation of the energy demand is limited to a few hours and can be achieved by activation of thermal energy storage (TES) systems as water tanks [4–7] or HVAC components [8,9]. In this work, the focus is on heat demand modulation achieved by variations of temperature set-points and thereby activation of the structural thermal mass of a building as TES [10]. This means that there are periods when building is in preheating mode, i.e. temperature set-point increases above the typical settings and the heat demand is higher than the heat demand required to meet the thermal comfort requirements and the surplus heat is stored in the structural thermal mass of the building, namely internal and external walls, floor slabs. In the opposite situation, the building is in discharging mode, i.e. no or very little heat is purchased from energy infrastructure and the heat demand needed to maintain the thermal comfort is met by utilising the heat stored in the structural thermal mass.

A cornerstone in the concept of loading and discharging the thermal mass is the temperature set-point variations and changing thermal conditions inside living spaces. In the studies describing the modelling

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work the methods used to determine and deviate the thermal conditions are diverse. In the investigations of a single building, the thermal conditions vary between spaces and in time, though in a simplified manner. Reynders et al. [11] divided the detached building model into 3 zones, i.e. kitchen and living room, bathroom and bedroom, and used recommendations from ISO 7730 [12] to define constant temperature set-points of 22.5°C, 24°C and 18°C, respectively, for the reference, non-flexible case. In the flexible control strategies, a temperature bandwidth of 2 K in each zone was allowed. In the follow-up study [13] on quantification of flexibility potential of different typologies of the Belgian residential building stock, the spaces in single-family buildings were grouped into day and night zones with two temperature set-points of 21°C/16°C, and 18°C/16°C, for occupied and unoccupied periods in all models, respectively. Also here, the temperature increase of 2 K for thermal mass activation was allowed. Le Dreau and Heiselberg [14] modelled the passive house and the house from 1980s′ according to the original building layout, yet with constant temperature set-point of 22°C for all zones and the temperature span of ±2 K. In order to activate the upward or downward heat modulation strategy the area weighted temperature was calculated. Foteinaki et al. [15] modelled two building typologies, namely a detached single-family house and a multi-family apartment block. In both models, the same approach of one zone per household unit with constant temperature set-point of 22°C for the heating season was adopted. Similar to Refs. [11,14], the loading and discharging of the thermal mass and thereby heat demand modulation, was allowed for the temperature span of ±2 K [15]. The same modelling approach and building model was used by Foteinaki et al. [16] in the study where control strategies were developed with the aim to flatten the load curve in district heating grids and to move the heat consumption away from morning and afternoon peaks. Pedersen et al. [17] adopted the grey-box modelling approach in their investigations of space heating modulation potential of a renovated apartment block with ten units. Each apartment unit was modelled as single zone with constant temperature set-point; however, Pedersen et al. differentiated the set-points between the units. Half of the units had settings of 20°C and the reaming half 22°C. All apartments units had the allowed temperature increase of +4 K. The temperature variations between units allowed investigating the interaction between the units, namely the heat flux between units with different temperature set-points. Vellei et al. [18] introduced a novel framework for energy flexibility modelling that combines occupant model, building model, thermal comfort model and thermostat adjustment model and tested it for two single family houses (i.e. old-existing and newly-built). Both households were modelled as single zone and had the same temperature set-points of 21°C for day and of 18°C for night. The flexibility was activated by 2 h or 4 h downward heat modulation with minimum temperature setback of 15°C. There was no differentiation of thermal conditions between the rooms. Yet, the novel components in the modelling framework that accounted for occupants' thermal comfort sensation and interaction with thermostats during flexibility event allowed for investigation of acceptance/rejection of thermal conditions changes.

When the modelling work is conducted at the district level with the aim to assess the impact of the heat modulation on the performance of the district heating network, the buildings' models and the temperature conditions are further simplified. Cai et al. [19] and Dominkovic et al. [20] use the same constant standard values for temperature set-points given in EN 15251 [21] for all household units, and allow for deviation of ±2 K in order to load or discharge the thermal mass.

Finally, the real-file tests of heat storage potential of buildings connected to district heating (DH) network are close to the practices applied to the district modelling, with no variations in space and in time. In the real-life investigation of heat demand flexibility potential of multi-family apartment blocks located in Sweden described by Kensby et al. [22] only one temperature reading per apartment is used to control the temperature deviations from the set-point, and thereby adjust/modulate the heat delivered to the apartment unit. Moreover, no indication of the location of sensors is given, and the temperature conditions and their variations for set-points are presented as the average values over a period of 4–6 weeks, which fully shade the real life conditions. In the field study that deployed demand-shifting technology on a sample of 28 homes connected to a DH network in England described by Sweetnam et al. [23] also only one temperature sensor located in the living spaced was used for control.

In the vast majority of the studies investigating the flexibility potential of thermal mass, the thermal conditions inside the living spaces are modelled or monitored in a simplified manner. This approach might be satisfying, when modelling the whole building stock with the aim to estimate the aggregated thermal flexibility potential. The predominant literature body on modelling work on thermal flexibility of single building uses the conventional methods of thermal comfort developed by Fanger [24] and adopted in the international standards ISO 7730 [12] or EN 15251 [21]. However, as highlighted by Peeters et al. [25] the conventional models are set up for steady state, office-like environments. The thermal condition in the residential buildings are much more complex and dependent not only on physical parameters, such as clothing level (clo), activity level (met) or outdoor temperature (°C). They are also dependent on different activities in different rooms, and different ideas of what home and comfort are related to both rooms and activities and variations during days and seasons [26,27]. The temperature preferences and corresponding space heating demand relates also to building typology and to socioeconomic characteristics of the occupants. Occupants living in newer, more energy efficient housing, tend to prefer and hold higher temperatures compared to people living in older houses [28]. Furthermore, a study of conventions and expectations of comfort have shown how different aspects such as temperature, daylight, noise, and fresh air, are related to each other and that women and elderly tend to value comfort higher compared to men and to younger generations [29]. Finally, a recent quantitative study of occupants' interaction with ecobee thermostats during a demand response (DR) event, which a precondition for the energy flexibility activation, in over 6000 dwellings in North America has presented that average tolerated indoor temperature variation during DR event was +1.07 K with few events with temperature increase beyond 2.7 K [30]. Moreover, the authors have concluded that thermal conditions defined for the DR event were overridden by occupants due to their habitual set-point change frequency, outdoor temperature, event duration, and previous experience with DR.

The paper contributes to the research on thermal conditions in the residential buildings by firstly providing a quantitative evidence that preferences for thermal conditions varies across three dimensions and secondly affording insights into the social dynamics of these variations. It describes the results from two empirical studies: a) long-term temperature measurements in 17 households and b) interviews with 22 occupants in 16 households, on how and why they heat their homes in a spatiotemporal manner. This paper with quantitative and qualitative data documents and explains that the temperature conditions vary in three dimensions, namely in space, in time and between households and that standards for thermal comfort developed to meet requirements of an average occupant at the workplace and satisfy thermal needs of majority are not necessary accurate for residential buildings.

2. Methods

This paper is based on a mixed empirical methods approach, i.e. it combines quantitative detailed indoor environment measurements and qualitative in-depth interviews and home tours with occupants. Measurements and interviews are from two different field studies, and do not represent the same buildings nor occupants, yet both empirical datasets include detailed knowledge on how temperature conditions may vary in time, space and between households. The combination of these two methods allow for detailed analysis of actual variation in thermal conditions and comprehensive understandings of the social dynamics behind these temperature preferences of occupants. The quantitative dataset was collected during the measuring campaign in the H2020 project Mobistyle [31] and qualitative data from interviews was collected in InterHUB project [32]. The following sections describe the two datasets in details.

2.1. Description of case study and the quantitative data

The quantitative dataset was collected in a residential multi-family social housing complex located in Aalborg, Denmark. The complex was in 2015 renovated to NZEB standard. The renovation process included exchange of the building envelope, i.e. new concrete sandwich elements in the facade and new insulation in the roof construction, as well as installation of the new kitchen, bath and all building installations. Heating is supplied by a district heating network. Heat in the apartments is distributed through underfloor heating in hallways and bathrooms and radiators in the remaining rooms. The heat emitters are equipped with thermostats that allow users to adjust the temperature set points according to their comfort level. Only the manual control of the thermostats is possible and no central control panel is available. Mechanical exhaust with constant airflow is located in kitchens and bathrooms. Occupants can only adjust the airflow in the kitchen exhaust hood. Fresh air is supplied through window vents. Cooling and extra ventilation needs are meet by manual window opening. The apartments are not equipped with any external solar shading. The socio-economics of residents in this area can be characterized as belonging to middle to lower middle class. In the monitoring campaign took part 17 residential units of different area (67–130 m^2) and household size (1–4 persons), see details in Table 1.

Each apartment, depending on its size and layout, from four to five rooms, including kitchen, living room and bedrooms, were equipped with LAN-WMBUS sensors [33] monitoring indoor environment quality (IEQ) (i.e. operative temperature, relative humidity, CO_2 level) and window open/close status. The location of the sensors was selected to eliminate the local temperature increase due to direct solar gains, see Fig. 1. The IEQ data were logged with a time step of 15 min and accuracy of ±0.3 °C, ±3% RH and ±(50 ppm + 3%). The monitoring period included 16 months, i.e. November 2018–March 2020. The concept of loading and discharging the thermal mass affects primarily the thermal comfort, therefore, only the operative temperature readings are analysed in this paper. In this study only data collected on thermal conditions from the first heating season, i.e. November–April are used. Occupants usually have better options to control the temperature conditions during heating season than in summer time.

Fig. 2 presents the temperature sensors' location in four units selected for the detailed analysis described in chapter 3. Since the temperature sensors were located in multiple spaces of the 17 apartments, in order to be able to present the variations of temperature conditions between the households an area weighted average operative temperature was calculated for each apartment as

$$\overline{T_i} = \sum_{j}^{n} T_{ij} a_j \bigg/ \sum_{j}^{n} a_j$$

where the area weighted average operative temperature for the apartment $\overline{T_i}$ in a time step i is a ration between the sum of operative temperature reading T_{ij} in specific i and space j multiplied by area of that space a_j and sum of area of all spaces. $\overline{T_i}$ was calculated for the time step if maximum one T_{ij} was missing.

Table 1
Overview of the units' size and number of occupants.

Apartment no.	Area (m^2)	Occupants	No. of rooms
1	111	2 adults	4
2	110	2 adults	4
3	91	2 adults	3
4	72	1 adult	3
5	91	2 adults	4
6	110	1 adult +2 kids	5
7	112	2 adults	5
8	130	2 adults +2 kids	5
9	111	2 adults	5
10	111	2 adults +2 kids	4
11	130	2 adults +2 kids	5
12	111	2 adults	4
13	67	1 adult	2
14	111	2 adults	4
15	111	2 adults	4
16	111	2 adults +2 kids	4
17	111	2 adults +2 kids	5

2.2. Description of case study and the qualitative data

The qualitative in-depth interviews and home tours were conducted with 22 occupants living in 16 different households, all located in the Greater Copenhagen area, Denmark. Interviews with occupants were equally distributed between four different case buildings [34] each representing a multi-family complex with varying unit area (35–210 m^2) and households size between 1 and 6 occupants. Table 2 displays characteristics on building and technology and on basic socio-demographic variables among the four different case studies. Heating were in all study cases supplied by a district heating network, but distribution of heating within the apartments differed between underfloor heating and radiators. Three case buildings were recently built (2016–17), and one was constructed in 2004. All residential units were equipped with connected technologies for heat management, allowing for automatic and remote control of heating. The specific details for each residential unit are presented in Table 2. The interviewed occupants are considered 'frontrunners' in relation to the possibility of smart heat management, as this is not prevalent in DK housing. However, the penetration rate of smart home technologies in households are expected increase and to be part of demand response initiatives, utilising buildings heat demand flexibility potential.

The interviews were conducted as semi-structured and had a duration of 1 ½ to 2 h. All interviews were conducted with adult householders (18+), but in some cases, children were present and naturally took part (specifically in the home tours). The interviews followed a predrafted interview-guide, covering themes of comfort, everyday routines, smart home technology and interactions between occupants, home and technology. Given the semi-structure of the interview-guide, occupants could pursue their own reflections and follow-up questions were frequently asked. A detailed overview of the interviews (interview-guide and qualitative coding) can be found in Ref. [35]. The purpose of the interviews was to understand perceptions heating and how it related to notions of home, comfort and experiences with smart home technology. Furthermore, ethnographic methods were used in order to capture occupants routinized way of doing heating. Occupants were asked to conduct a home tour, showing and explaining their routines and activities and how they unfolded spatially. This methodological approach provided insights into occupant's ways of doing heating, which is often considered inconspicuous or invisible by occupants. The home tours served as a way of stimulating reflections on how and why heating was conducted, and furthermore occupants were asked to simulate routines, showing their engagement and understanding of heating installations.

Occupants were recruited through, respectively flyers and direct contact e.g. e-mail and telephone. The sample of occupants was aimed at gaining a broad representation of different households in relation to household size, age, gender and educational background. While the sample included variation in age, household size and gender, a bias was present in relation to educational background and occupational profession. The majority of occupants was employed in medium to high-level jobs. The interviews were audio recorded, transcribed and an

Fig. 1. Layout and location of the four to six temperature sensors in four apartments.

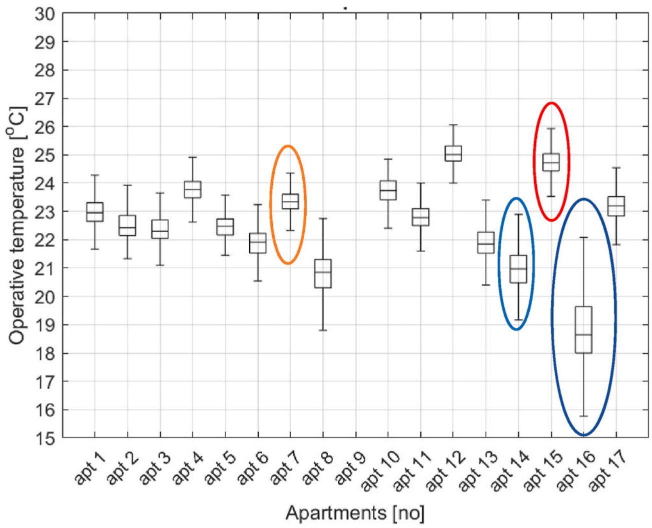

Fig. 2. Box plot of the area weighted operative temperature during the heating season for 16 apartments.

Table 2
Characteristics on case buildings.

Study case no. and location	Building and Technology characteristics	Interview details	Smart home setup
Study case 1 Trekroner Roskilde	35–39 m^2 Constructed in 2004 Radiators in rooms, underfloor heating in the bathroom	4 interviews conducted 1 male and 3 females. Household composition: 1-2 Age: 21-25 Occupation: students	Zonal control from central unit (either app or in-home display). Possibility to schedule space heating. Smart thermostats on all emitters
Study case 2 Nordhavn, Copenhagen	100–200 m^2 Constructed in 2016 underfloor heating in all rooms.	4 interviews conducted: 4 males and 3 females. Household composition: 2-5 Age: 35-58 Occupation: Senior-level jobs	Automated fuel-shift solution (smart unit reacting to utility signals). Wall-mounted digital thermostats allowing for zonal control. Visualization and feedback on consumption in app a browser interface.
Study case 3 Nordhavn Copenhagen	45–210 m^2 Built in 2017 underfloor heating in all rooms.	4 interviews conducted: 3 males and 3 females. Occupants composition: 2-4 Age: 21- 58 Occupation: Senior-level jobs and 2 students.	Integrated system connected operation of ventilation and space heating. Thermostatic controller in each room allowing for zonal control and (local) feedback on temperature, relative humidity and CO2). Control possible from app,
Study case 4 Nordhavn Copenhagen	55–146 m^2 Built in 2016 underfloor heating in all rooms.	4 interviews conducted: 3 males and 2 females. Occupant composition: 1-4 Age: 35-56 Occupation: Senior-level jobs.	Zonal control from central unit (either app or in-home display). Possibility to schedule space heating. Smart thermostats on all emitters

abductive coding was subsequently conducted.

3. Results - Quantitative measurements of temperature conditions

3.1. Variation between households

As it is illustrated on Fig. 2 Figure and Fig. 3the temperature conditions in the monitored apartments are diverse and not in line with thermal comfort conditions of 22^{O}C recommended by the standards [12, 21]. For 12 households the mean operative temperature is above 22^{O}C. Apartment 12 and 15 represent the households were occupants keep temperature close to 25^{O}C. On the other hand, are the apartments 14 and 16, where the mean operative temperatures is 21 and 18.5^{O}C. Moreover, for most of the apartments, in 15 households, for 95% of the heating season the area weighted operative temperature varies less than with 1 K. Of course, there are single hours with either high or low peak, but they constitute less than 5% of the heating season. Fig. 3depicts that even with the same outdoor temperature conditions the occupants can have very different temperature preferences, the difference between the apartments can be up to ±7 K. Fig. 3 shows also the seasonality of the preferences and their bigger differentiations for low outdoor temperatures. With outdoor temperature increase, mid-April, the difference in operative temperature reduces and the temperature conditions are more uniform in all apartments.

3.2. Variation in time and space

It can be suggested that area weighted operative temperature is not the representative parameter to evaluate the actual temperature conditions inside the apartments. Therefore, the following sections describes the actual temperature readings from all monitored spaces in four selected apartments. The key selection criteria was percentage of collected data during the heating season. In the selected apartments, more than 75% of data must be available for all monitored rooms. Furthermore, the group of in-depth investigated households should include the units with big and small temperature variations and high and low temperature preferences. Following these criteria, four apartments have been chosen for the detailed analysis. Apartment 16 and 14 represent low temperature preferences with high and low variations, respectively. Apartment 15 and 7 represent high temperature preferences with high and low variations, respectively. Yet, in these two units the variations of operative temperature is not so significant like for apartments 16 & 14. This result could indicate that occupants with high temperature preferences are stricter with controlling the conditions inside their spaces.

Fig. 4 presents a week of temperature conditions in January for four apartments. In all units, the temperature conditions varies between the spaces, with living rooms having the highest and bedrooms the lowest temperatures. The diurnal temperature variations are minor or even not present in the living rooms in apartments 7, 14 and 16. Yet, they are present in the bedrooms in apartments 7, 15 and 16, with clear temperature increase in the night-time due to occupants sleeping in the room and generating heat gains, on average 100W/person. In the bedroom in apartment 7 clear temperature drops are registered. It is most likely the consequence of the morning airing of the bedroom. During the weekend the temperature drop of 3 K is registered, which clearly correlated with the low outdoor temperature of around -6^{O}C. The temperature profile in the kitchen also follows typical occupants' daily routines, with afternoon cooking peak (i.e. generation of heat gains) on 21st - 23rd January in apartment 16. Room 2 and room 1 had different functions in the four apartments. They could be used as kids room or an office. Unfortunately, the real use of the rooms was not registered. The low temperature in the staircase in apartment 16 is the result of window opening. This is also the case for room 2, where 28% of the time during the heating season the window was open, primarily during the daytime,

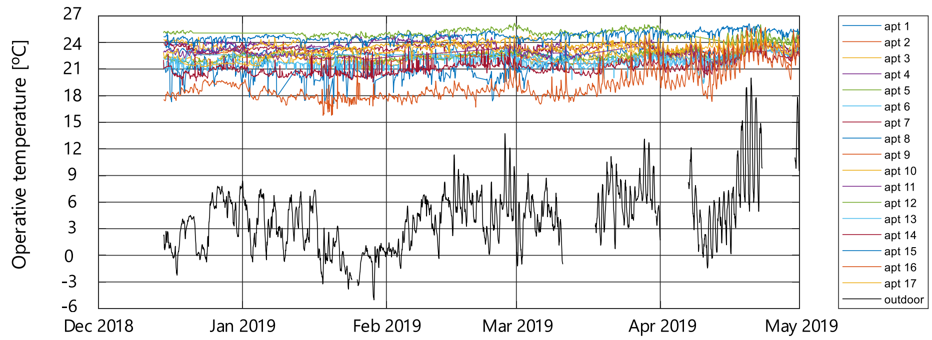

Fig. 3. Hourly profile of the area weighted operative temperature in 17 apartments during the heating season.

which is also visible in the temperature profile.

The solar radian and passive solar gains do not affect the thermal conditions inside the spaces, since as presented in Fig. 5 during the analysed week in January the time with solar ration was limited or even zero for three days.

The profiles of the area weighted average temperature represent the mean thermal conditions in the apartments, yet, they do not represent the actual situation in the house. For the apartments with big temperature variations between spaces, such like apt. 16, the mean temperature profile does not capture the afternoon peaks in the kitchen and the night peaks in the bedrooms either.

Fig. 6 shows the cumulative distribution of the operative temperature for all spaces in four apartments during the heating season. It can be noticed that the median values for single rooms can vary up to ±4 K (apartment 14 and 15). The living room is the space with most stable operative temperature with variations around ±2 K in all apartments. On the other end is the bedroom, where due to temperature increase during night-time (heat gains form people and sleeping with closed window), and temperature drop in the morning (airing after sleep), the variations are the biggest.

Finally, apartment 16, which is the household with biggest variation of temperature conditions both between space and in time, is occupied by a family of 2 adults and 2 kids. The other apartments are occupied by 2 adults. The different number of occupants, with various temperature preferences, could also be the reason why the temperature conditions varies more for a bigger household.

The described results present that in some households the temperature conditions are more constant between spaces and do not change in time, which is a case of apartment 15. In the other three apartments, the occupants differentiate the temperature between the rooms as well as in time. These results indicate that the thermal conditions inside homes are not only the output of outdoor temperature but also depend closely on the occupants' space heating practices.

4. Results - Qualitative interviews

As shown in the previous section, temperature conditions varies in both time and space and between household units. Drawing on qualitative in-depth interviews with occupants this section presents insights on why and how occupants heat their homes in a spatiotemporal manner. Based on the analysis of the interviews five themes emerged, displaying different ways in which temperature settings unfolded in a spatiotemporal manner. The analysis also revealed how two dimensions of temperature variations (time and space) are interdependent. All five themes seemed further to be closely interconnected and thus not mutually exclusive. The themes are: i) Activities performed by occupants ii) Caring for things, others and oneself iii) Comfort iv) Convenience v) Natural and material surroundings. The following will present how spatiotemporal variation in temperature conditions can be understood within each of these themes.

4.1. Activities performed by occupants

Activities performed by occupants within and outside of the home result in spatiotemporal variations of temperature conditions. Some occupants thus explained that when leaving their home, they would adjust the temperature accordingly. The duration (and thus variation in temperature setting in time) was depending on for how long they occupants were away from their home. For activities such as grocery shopping, or meeting with friends, heating would only be turned down for a short period. For short-duration activities outside of the home, adjustments of heating were managed on an ad-hoc basis, as occupant Peter explains:

> Peter: Yes, I use the pause function when I have to go shopping, because I live a 15 minute walk away. So when it's the small trips, I use the pause function and when it's for a longer time, I put it on holiday-mode.

Another type of activities outside the home, were those with a regular rhythm, the most dominant being if the occupants were at work/university or not, and most interviewees explained a clear difference between activities conducted on weekdays and on weekends. Some occupants explained that temperature settings could vary more in time during weekdays, compared to weekends. This could be reflected in a prescheduling of heating during weekdays. Occupant Anne explains:

> *Anne: It* [the heating installation] *has such a scheduling feature, where I can set it to when it should start and when it should end … I use a two-way split, so it is one temperature during the day … I think I have set it to heat from 08-12.30 a.m. … And then I have set it again from approximately. 4–10 p.m. that turns it on again. In the meantime, it's off.*

Variation in temperature settings during weekends were usually less planned, because amount and duration of activities outside the home varies. Occupant Anne gives an example:

> *Anne: For instance, I have to visit my parents this coming weekend, so I will not be here* [in the home] *from Saturday to Monday morning, so it* [the heating] *does not have to be on, and most often I would just set it at 12 degrees or something like that, so that it does not really heat up, but it really just keeps itself going.*

However, going away for longer trips did not result in turning down the heat for all of the occupants, as the occupant Benjamin explains:

> Benjamin: The first half year, I think it was interesting to tinker a little with the heating setup, because you can put it on that holiday mode for example. But then after half a year I forgot about it. It was a combination of that, and if we would have some friends coming by the apartment or my dad would come by and things like that. And then I thought that if you wanted to lend it [apartment] to some friends, it would be cold. Or I do not know. It is not something I have thought about consciously (…). I could easily do it again tomorrow if

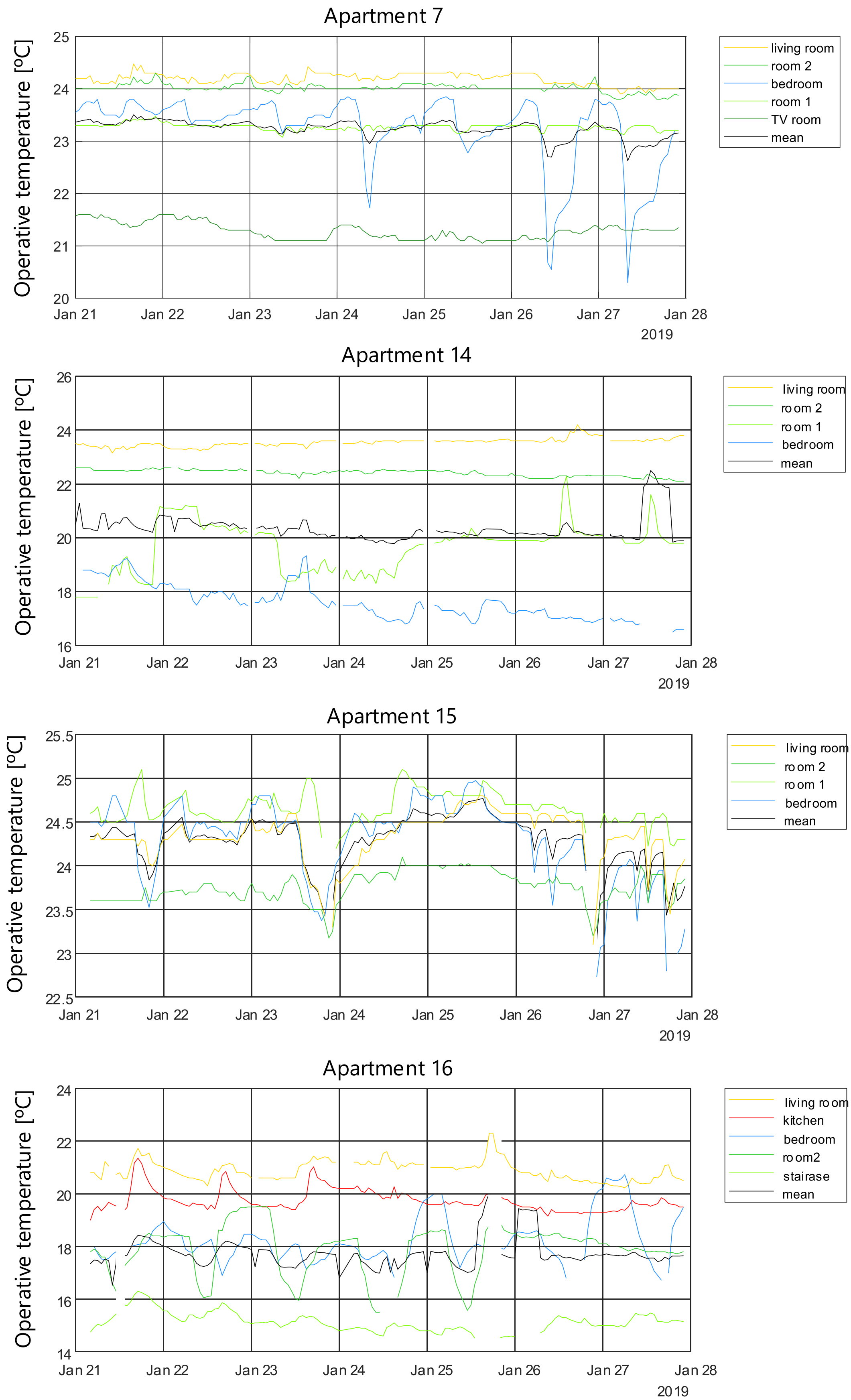

Fig. 4. Operative temperature profile for a week in January in all spaces of four selected apartments.

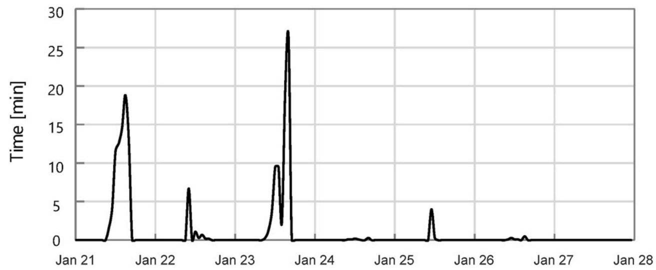

Fig. 5. Time with direct solar radiation on horizontal plane.

we were to leave for a week. I really think the primary reason is that you just forget about it.

Activities performed inside the home also resulted in variation in temperature conditions in both time and space. Most occupants explained that they preferred sleeping in a cold bedroom, resulting in lower temperature settings during night-time, though in most cases this was only done in one room, namely the bedroom. Sleeping was thus an activity which influenced variation in temperature conditions in time and in space with the bedroom being cold during night-time, but the rest of the house still maintaining the same temperature.

Activities that the occupants performed while being awake, could also explain spatial variation in temperature conditions. Activities, such as cooking, eating and bathing resulted in variation of temperature settings. For example, cooking may result in adjustments of temperature settings due to a sensory feeling of wanting to get the food smell out of the kitchen, therefore airing the kitchen while cooking. This action depending on the thermostat location can either lead to sudden temperature drop around the thermostat, if located close to the window opening and thus request for the additional heat resulting in temperature increase after the airing activity, or to temperature decrease if the thermostat is located far from window. Contrary, eating was related to more stable temperatures. Occupants who had less structured activities outside of the home during weekdays, e.g. university students, were more keen to make frequent adjustments of temperature settings resulting in a less rigid pattern. Other activities which resulted in variation of temperature settings in space were cleaning, relaxing, watching television, studying or doing fitness.

4.2. Caring for things, others and oneself

In general, keeping a good indoor environment was perceived as important in relation to caring – both for things, for oneself and for other. Knowledge on how to keep a good indoor environment differed among occupants, where some reported following official guidelines (e.g. air the house 3 times a day) while others practiced sensory and ad-hoc approaches. Taking care of the buildings was by some occupants related to airing frequently and keeping a stable temperature settings when not being at home. Some occupants were drying clothes within their home. Doing so meant they would air more frequently, in order to maintain a good indoor environment, and taking care of things and people.

Caring for others and one self was also related to health considerations of e.g. keeping a high temperature complemented with frequent airing, for instance if an occupant felt sick. Occupant Anne explains:

> Interviewer: What could make you turn on the heating outside of the schedule?
>
> Anne: It would be in instances where I am ill, where I feel I need more warmth. I think that if I can keep it as warm as possible, I'll will recover faster. So I think most of the time is in situations where I'm sick. Or when someone else points out that they think it's too cold.

Temperature settings was adjusted (for shorter and longer periods), either because of well-established routines or because of ad-hoc

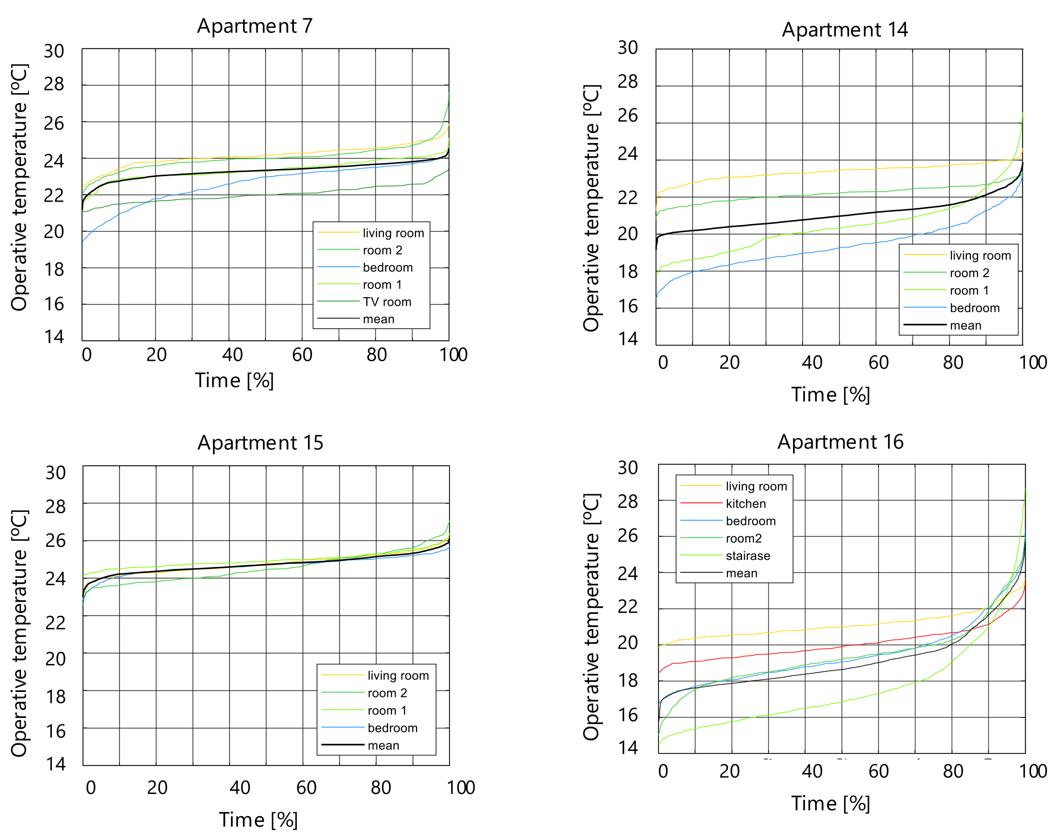

Fig. 6. Cumulative distribution of the operative temperature in all spaces of four selected apartments during the heating season.

concerns e.g. care for guests. The occupant Benjamin explained that he kept a stable temperature in their extra guestroom, in case that family and friends would come on an unexpected visit.

Another variation in temperature, was related to the caring for pets. One occupant explained that her way of adjusting temperature settings spatially were done in response to caring for her dog. According to the occupant Anne, she kept a higher temperature in her bathroom, because she noticed that her dog liked to sleep on the warm floor in the room. Furthermore, Anne's way of airing of her apartment had to take into consideration, that the dog did not 'escape' by running outside if a door or window were left open. Anne therefore performed a strategy of only airing one room at a time, thereby making sure that her dog could not run away.

Caring for other members of the household and their needs was also highlighted as important for keeping spatial variations in temperature settings. Some occupants explained how the doors within their apartment would remain open through the nights, despite keeping lover temperature during night in the bedroom. This was done in order for their children to feel safe and wonder into their room during the night.

4.3. Comfort

Notions of comfort seemed relevant for variations in temperature settings. To some occupants, coming home to a warm house were especially important, as Peter explains:

> Interview: And where and when would heating mean the most to you?
>
> Peter: At home in the middle of the day or coming home after doing an activity outside, such as scout or role-playing, where I have been out in the cold for a long time. Yes, so it depends on what I have done. So if I have been outside a whole day, then it's nice to come home to a warm room.

Another comfort aspect was related to sleeping in a cold bedroom, as already described. Many of the occupants consider thermal comfort as especially important when sleeping, and thus preferred to cool the bedroom before sleeping. Some occupants even opened the window during night time, in order to maintain a temperature of 17–18°. The occupant Jakob explained why he and his partner preferred a cool bedroom:

> Interview: You say that you always have the window open inside the bedroom … How can that be?
>
> Jakob: It is as psychological thing about the feeling of fresh air. We could in fact turn down the heating even further. I just do not think we have done it. I like the feeling that there is actually a little heat in the room, but at the same time a sense of fresh air.

Sleeping in cold spaces and having a warm bathroom are related to both comfort and heath and thus to caring for oneself and family members. The occupant Andreas explains:

> Andreas: The bathroom must be warm [laughs]. The bathroom should be warm and the bedroom should be cold. In the living rooms, it [the temperature] should be so that you can sit in a shirt or T-shirt. I might like to put on a blouse if it gets a little cold. I do the same at my job.

Variation in temperature conditions was also related to creating a cozy and comfortable atmosphere in their home. This feeling of comfort were more than merely thermal, and included feeling safe and cozy and typically aligned with activities, in which the interviewees relaxed. In these cases a higher temperature was preferred, and occupants described how they used other things, such as taking on more clothes or lighting candles, when wanting to feel comfortable. The occupants Maria and David had a liquid gas fireplace in their living room, and explained its use:

> Maria: It's very nice. But the problem is, It gives some heat, but there is heat already, so.
>
> Davis Yes, that's it. So if you sit where you sit, then it's very hot. It's nice for me, so it's a bit like that. We turn it on when there are guests, then we turn it off when it gets a little too hot. And turn it down a lot. So it's more of a cozy thing.

The sensory aspect of comfort may also relate to the type of heating installation and emitters, e.g. underfloor heating or radiator. The occupant Andreas elaborates:

> Interview: What do you think in general about having underfloor heating?
>
> *Andreas: I'm very excited about it. Like I said before, I think it provides a different indoor environment. I think the fact that the heat is evenly distributed and there is no direct heat source and radiant heat that you are affected by is quite nice. So the thing about that … I of course also like to sit next to a fireplace or a tiled stove or something, but I do not think it is very nice in the long run. It's too hot in some places and too cold in other places. The fact that it has a fairly uniform temperature, so does the underfloor heating … and I also like the fact that it is on my feet … I personally like that. The thing about wearing socks without freezing is nice* [contrary to wearing slippers]. *I'm always freezing on my toes and I just think that there is a heat source around the toes with underfloor heating, I think that's really nice. And much nicer than radiator heat. So I'm very happy about that.*

Comfort was also mentioned as a reason for keeping a spatial variation in temperature settings. Feelings of comfort were, by the occupants, related to specific rooms, with living rooms, bathroom and bedroom as examples of rooms with different temperature settings related to comfort.

Comfort seemed to be entangled in the many different practices that unfolded at home. Being comfortable were associated with doing specific activities, at specific times and in specific rooms. Comfort is thus also a spatial concept, in which each room represent different comfort standards, resulting in variation in temperature settings.

4.4. Convenience

In the interviews, some occupants expressed that their management of heating was often conducted in an unconscious manner and without much reflection. Their way of adjusting temperature conditions, was simply based on if it was the easy thing to do or not to. The occupant Simon, explained how he simply forgets to turn of the heating when leaving the house, because it is inconvenient and other everyday activities are more important.

> Simon: It is nice to have a button that you can press when you leaved the house and it [smart heating system] then turn off your heating - apart from the fact that you do not do that. Well, we have two children, and it's a struggle to get out the door with them, getting them in the right clothes and leaving at the right time, so you do not remember: I just have to press the "I have gone" button, and if you do, then you'll first turn it on again three days later.

Interestingly, whether something appeared convenient or was not both related to the design/setup of the heating installation, and if the occupants possessed a particular skillset or experience. The occupants, Johanne and Lars had underfloor heating in their new apartment, but perceived it as quite inconvenient to regulate, as Lars explains.

> Lars: No, you do not adjust, it is the effect of underfloor heating, the thing about going around and adjusting down when you are going on holiday and so on, you can not do that. Because you think all the

time, it takes a hell of a long time to get it warmed up again, so you do not

Contrary, other occupants perceived old analogue thermostats as more convenient in relation to adjustments of temperature settings as they were more visible to them, and included in a kind of 'check-list' of what to do, when leaving the house.

In all of the occupants' homes, heating was controlled by a smart home technology setup (for more information see Ref. [34]). While some occupants, found these new ways of control more convenient and explained that it helped them in regulating the temperature settings (e.g. adjusting when not at home), others explained how the new control system were perceived as disruptive and required an extra effort in order to control, resulting in less regulation of temperature settings (compared to earlier).

A similar picture was given, when occupants explained spatial variation in temperature settings. Some kept the same temperature all around their home, as it seemed as the most convenient, while others varied the temperature between spaces in their house, due to convenience. Again, what was perceived as convenient, was established in a mix between material things and occupants knowledge about how to use them. While some interviewees kept a low temperature in an unoccupied room (e.g. guestroom), others regulated the temperatures in the house more dynamically, due to new control opportunities or having skills for conducting it.

4.5. Surroundings (natural/material)

Material and natural surroundings form a backdrop, for spatiotemporal temperature variations. Building typologies, heating technology and the outdoor weather influence how activities are performed, what occupants perceive as comfortable, convenient and how care for others is performed. Spatiotemporal variations in temperature settings, also relates to occupants perceptions and engagement with the material and natural surroundings.

Most occupants adjusted their temperature settings following the seasonal shifts in weather and throughout the interviews, this was the most prevalent reason for adjusting temperature settings. During the summer season, heating was rarely used, and most occupants expressed that they would turn off heating during spring and turn it on again during the fall. When exactly temperature was adjusted was less clear and the occupants referred to either a sensorial feeling of when they felt cold outside or to more institutionalized knowledge of heating seasons determining when heating should be adjusted.

Natural and material surroundings were also an aspect which was considered in relation to heating on a spatial basis. Depending on how their apartment/dwelling were positioned and in which direction (and into which room) the sun was shining, occupants took use of the sun (or lack of such) when adjusting temperature settings in their home.

The immediate surroundings of the occupants' houses, also had an impact on how temperature settings were adjusted. Some of the occupants lived in a newly built area, with the results that the surrounding area were frequented by carpenters, builders, and heavy machinery, which generated both noise and dust. This resulted in less frequent airing and opening of windows, and in a strategy of heat management, which focused on balancing the need for airing with as little noise and dust disturbances as possible.

Within the occupants' homes, the material things and flows also had an impact on which rooms were heated and which were not. Overall, the spatial design of the house seemed to matter. The occupant Peter expressed that the kitchen was rarely heated as it was positioned just next to the main entrance. This resulted in heat flowing outside (main door being opened and closed), and thus Peter explained that due to the spatial design of his apartment, it did not make sense to heat the kitchen.

Other occupants expressed that it was difficult to keep difference in room temperature within the home, as the doors between the rooms were not 'fit' for closing off a room and preventing heat flows from one room to another. Two ways of how heat could flow from one room to another were present in the interviews. First, steam from bathing was a typical reason for airing the bathroom. If the bathroom had windows, these were opened after taking a bath (despite the apartment having mechanical ventilation). If the bathroom did not have windows, the door to the rest of the apartment, were opened in order to 'let out' the steam. The heat generating when cooking, was also used as a source for heating (especially the kitchen), and thus some occupants heated the kitchen when cooking. Others had a routine of opening the windows and airing when conducting this activity. Table 3 summarizes results on what aspects of residential life that temperature varies with in time and space.

5. Discussion

This paper has gone into details in showing temporal and spatial variations of temperature conditions in residential buildings by means of long-term monitoring and in-depth interviewing. Thus, the measurements have documented the variations in time and space and the qualitative interviews have provided ways of understanding these variations in temperature in relations to different aspects of everyday life.

The results indicate that the applied control strategies of preheating the whole building area during the night-time with the same temperature increase in order to modulate heat demand during day time is not realistic. Occupants have different temperature preferences for different spaces and change them on diurnal and seasonal basis. Therefore, the modelling approach of constant thermal conditions either for the whole building [14,15,17,18] or for specific zones (i.e. bedrooms, living room and bathroom) [13] as baseline for evaluation of energy demand flexibility of a building might be too big a simplification. The measurements and interviews question the uniform control strategy for all rooms in the apartment. The upward heat modulation is not advised in bedrooms during night-time, since many occupants prefer to sleep in lower temperatures and might air the room before/after the sleep. Airing of spaces is also used in the kitchens during afternoon cooking routines and potentially downward regulation can be applied during these periods, as the upward modulation would not give the expected heat to be stored in the building construction. Duration of the heat modulation events is another aspect and similar like type and timing of the flexibility control strategy should be designed individually for each space depending on the performed activities (e.g. in the bedrooms the flexible window can be longer than in the kitchens or living rooms).

In relations to documenting variation of temperatures conditions in the built environment, the extensive review conducted by Rupp et al.

Table 3
Aspects driving the thermal condiction variations.

Type of variation	Variation of temperature in the home over time	Variation of temperature in the home in different rooms
Activity based	Different activities performed inside or outside of the home, following **temporal** rhythms	Different activities performed in different **rooms** inside of the home
Caring for things, others and oneself	Caring depending on **when** someone or something is in the house	Caring depending on who is **where** in the house
For comfort	The feeling of comfort varies with activities and their **temporal** rhythms	The feeling of comfort varies with activities and which **rooms** they are performed in
For convenience/ in-convenience	What is considered convenient is subjective and relates to **temporal** adjustments of heating	What is considered convenient is subjective and relates to **spatial** adjustments of heating
For surroundings (natural/ material)	Natural and material surroundings, both inside and outside of the home prefigure **temporal** variance in temperature settings	Natural and material surroundings, both inside and outside of the home prefigure **spatial** variance in temperature settings

[36] has indicated that the long-term field measurements of thermal conditions in residential buildings are a time consuming and costly activity that often interferes with occupants' private sphere. Therefore, very few studies document both variation in time, space and between the households. The work described by Brunsgaard et al. [37] on indoor environment in three Danish passive houses is found to be the closest to the presented measurements. The study has also documented variations in thermal conditions during the heating period between living rooms, kitchens and bedrooms, and that these conditions are different between households and vary in time. The measurements presented in this paper adds to this work by conducting the monitoring campaign in a different building typology, namely apartment units in multi-family blocks, which are characterized by the similar area, layout, room size and more homogeneous socio-economics of the occupants.

In relation to understandings of why people keep varying temperatures, other studies have similarly found that activities performed in the home are of importance for understanding variation in temperature preferences [38]. Studies have also documented that understandings of comfort varies with socio-economics [28] with materiality of the houses [27] and with ideas of what a home is [39] and that all of this relates to the sensorial aspects of how humans senses different aspects of comfort as temperature, air quality and daylight and noise [26,40]. The present study adds to this body of knowledge by suggesting the five aspects, which together constitute the background for understanding why temperatures setting varies within homes in time and space, thus the new contribution relates to combining these aspects. As the present study is based on small numbers of households, there is not a bases for larger statistical analysis on how these aspects varies with different types of people according to socio-economics, though this is relevant for future studies to continue studying this.

The merge of data from quantitative measurements and qualitative interviews drew one of a kind insight into dynamics of thermal conditions in residential buildings and social dynamics behind.

Moreover, the presented results are applicable and viable for other aspects e.g. related to building simulations, and billing methods of space heating. Modelling of buildings heat demand is used in various aspects of dealing with lowering energy consumption for space heating including determining policy related to energy retrofitting of buildings. In such modelling work, standard assumptions of temperature settings are used, and better knowledge of how temperatures actually varies may help close gaps between predicted and realized results. In relation to billing methods, discussions on fairness in distribution of heating consumption between apartments in building blocks typically rely on assumptions of similar temperature preferences within and between apartments. Knowledge on how temperatures varies in time and space can inform future discussion on such issues.

The authors should also name the limitations of the presented work. The first to name is the fact that the described quantitative and qualitative field studies do not deal with the same households. Yet, some common characteristics can be found: a) the building typology – apartments in multi-family blocks, b) standard of the building – new-built low-energy or renovated to NZEB. The second limitation is that the temperature sensors were not located in bathrooms, which often have unique thermal condition patterns compared with other spaces in the households. The reason behind is that the primary objective of the measurements was to investigate the indoor environment in the spaces where occupants spend most of their time. Moreover, the authors are aware of the potential impact of passive solar heat gains on indoor temperature variations. Yet, the apartments are located in the same complex, have similar East-West exposition have no external shading and as presented in the results chapter the time with direct solar radiation was very limited during the analysed week in January.

6. Conclusions

The aim of the study was to present the variations of temperature conditions in the households using quantitative and qualitative methods, and thereby question if the current approach to model the thermal conditions in homes when evaluating and quantifying the flexibility potential of residential building stock is realistic enough.

The presented results indicate that temperature conditions vary in time, space and between households. The in-depth interviews show that these temperature preferences are shaped by difficult to model aspects, namely the activities performed; the caring for things, others and oneself; the natural and material surroundings and general feeling of comfort in particular space.

Moreover, the results show that it is difficult to identify a representative room for each household. Even the area weighted temperature is not representing the actual conditions in any space, since the variations between spaces are too significant.

The way we see/model the temperature conditions is too simple, the results presented in this paper show that reality is much more complex. The modelling work to estimate the aggregated potential of the building stock might not necessary include the multi-dimensional aspects of thermal comfort variations, since they would even out between the residences. Yet, if we would avoid the gap between the modelling work of a single building and the reality more work/actions must be undertaken to understand occupants heating practices. The standard values are based on approaches to comfort grounded in laboratory settings, implying that the values may be too optimistic, as the reality is much more complex and building occupants are not driven only by the physical parameters. There are many more dimensions that impact their space heating routines and temperature conditions/preferences.

One thing is modelling work to estimate potentials of flexibility, another important implication of the presented results relates to real life experiments with buildings as flexibility generators. This paper shows how temperature settings and preferences, as well as airing habits related to opening of doors and windows varies in ways that are not possible to predict or model. If using the full potential of buildings flexibility potential rather than approaching buildings in a uniform manner, a relevant approach could be to include occupants more in deciding and managing the settings for delivering energy flexibility. Including occupants in delivering flexibility is not easy, and will imply different types of smart control distributed between occupants and utilities. Experimenting with which types of control, including different types of business cases and payment solutions will work best, have to be tested.

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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