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Impact of Building Design Parameters on Thermal Energy Flexibility in a Low-Energy Building

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Abstract

This work focuses on demand-side management potential for the heating grid in residential buildings. The possibility to increase the flexibility provided to the heat network through specific building design is investigated. The role of different parts of the building structure on thermal flexibility is assessed through a parameter variation on a building model. Different building designs are subjected to heat cut-offs, and flexibility is evaluated with respect to comfort preservation and heating power peak creation.

Under the conditions of this study, the thermal transmittance of the envelope appears to have the largest impact on thermal flexibility. The importance of window design, namely the size, U-value and orientation, is underlined due to its critical influence on solar gains and heat losses. It is eventually observed that thermal mass has a secondary influence on the evaluated indicators; its variation only affects thermal flexibility if the thermal resistance of the envelope is sufficient.

Introduction

The share of renewable energy sources should represent at least 55% of the European gross energy consumption in 2050 (European Commission, 2011). Their production being inflexible and highly dependent on weather conditions, a high penetration of renewable sources might create a risk for energy security of supply. One of the solutions to this challenge is demand-side management as defined by Gellings (1985), which aims at adapting energy consumption to a fluctuating production rather than the opposite. This idea is particularly studied in the building sector, where implementation of demand-side management would permit to reduce the energy footprint of buildings, while providing flexibility to the energy grid as a whole (Kolokotsa, 2015).

EnergyLab Nordhavn is a full-scale research project investigating the possibility of intelligent energy operation across the neighbourhood of Nordhavn, Copenhagen. As a part of that project, the present study aims at understanding how energy efficient buildings can adapt perturbations in a city's heat and power grids. Focus is set here on thermal energy flexibility, specifically defined in this work as the capacity of a building to provide a good indoor comfort in spite of changes in delivered heating power. The understanding of this potential can then be used by the grid operator to optimise heating schedules. Thermal demand-side management is moreover seen as a tool to ensure electrical grid stability, via a coupling of the heat and power grids (EnergyLab Nordhavn, 2015; Müller et al., 2015).

An interest presented by low-energy buildings in the flexibility issue is their ability to retain heat for a long period of time, therefore acting as a storage medium in the heating grid. However, even though buildings' thermal flexibility potential is being investigated, few of the studies specifically evaluate the influence of design features on a building's flexible behaviour. The impact of different wall properties on their ability to store energy is well documented in literature (Asan, 2006; Borresen, 1973; Ma & Wang, 2012; Moffiet et al., 2014; Orosa et al., 2012; Wang et al., 2014) and their importance for load shifting was also specifically studied by Reynders (2015). Yet, it is valuable to extend the impact assessment to other building components than its sole thermal mass: all parameters having an influence on indoor comfort variations with time (through heat gains, losses and storage) are of interest when assessing a building's resilience to heating perturbations. Therefore, window parameters must also be investigated. Some researchers pay attention to the role of windows and solar gains (Orosa et al., 2012; Reynders, 2015; Wang et al., 2014), however more with respect to thermal buffering than flexibility. Similarly, research has been carried out on the role of window orientation in energy savings, but literature about its contribution to flexibility potential is rare (Reynders, 2015; Zhu et al., 2009).

Moreover, the achieved flexibility is often quantified in terms of financial savings (Masy et al., 2015; Reynders, 2015), shifted heating energy (De Coninck & Helsen, 2016) or capacity (Oldewurtel, 2013). The implications of heating control strategies on the occupants' comfort are generally not quantified.

This study is the first step of a larger project aiming at assessing the ability of low-energy buildings to ensure an active role in a city's heat and power grids. The goal of this preliminary study is to determine how the design parameters of a given low-energy building can influence its capacity to adapt simple perturbations on the heating grid in which it is integrated. Focus was set on passive flexibility strategies, in particular heat storage in the building structure. A parameter variation was carried out on a simulation model of a dwelling, investigating the role of the different building components in the flexibility potential of the building regarding its heat load. This paper does not consider the role of building services systems, e.g. space heating and ventilation, on flexibility since this is the theme of a parallel work that will be published separately.

This work has two main outcomes. First, a set of two indicators was built, quantifying theoretical heat flexibility in a building in terms of indoor comfort and heating demand. Second, this work provides an understanding of the heat storage processes in a low-energy building, permitting to identify the issues related to heating power perturbations and the extent to which building design can respond to it.

Methodology

Investigated building

The impact of design features on thermal flexibility was evaluated on a model of an apartment created according to the geometry, materials and systems of an existing apartment in Copenhagen, Denmark. The modelled apartment is located in the northern district of Nordhavn, in a nearly-zero-energy building currently under construction. The chosen building is representative of the current and future constructions in Denmark, which are bound to low energy consumption due to the strict Danish Building Regulations. It was chosen to focus the study on a single apartment in order to be able to get a thorough understanding of the obtained results. This choice allows getting deeper into the heat transfer mechanisms occurring at a smaller scale and to give a straightforward explanation of the findings.

Parameter variation

As the output of a literature study, six design parameters were chosen to be investigated further. Several values were chosen for each of them, covering a realistic range of possibilities as found in the literature (Gianniou et al., 2016; Reynders, 2015) and which reflects the construction characteristics of Danish building stock. Even though the ranges of values investigated for the different parameters are heterogeneous, they can all be interpreted as the complete range from the worst to the best-performing building components currently available – or in the case of the glazing-to-wall ratio and building orientation, as the whole set of values observed in Danish buildings. The corresponding difference in flexibility potential between extreme design cases thus represents the overall potential improvement that can be triggered by a realistic change of the considered parameter.

Table 1 presents the chosen parameters, the value of these parameters in the investigated apartment, and the variation range for each of them.

Different versions of the original apartment model were created, each giving a different value to a single one of the investigated parameters. The goal here was to perform a local sensitivity analysis in order to isolate the impact of each of the parameters on thermal flexibility.

Table 1: Investigated parameters, value in the base apartment model and variation range

Parameter	Original value	Studied range
External wall concrete thickness (cm)	15	[2 ; 30]
External wall insulation thickness (cm)	27.5	[0 ; 32]
Floor concrete slab thickness (cm)	6	[3 ; 25]
Glazing-to-external-wall ratio[1] (-)	0.42	[0.1 ; 0.55]
Window U-value (W/m²K)	0.81	[0.75 ; 2.5]
Orientation of the main facade[2]	S	N; E; S; W

Flexibility assessment and indicators

The flexibility assessment performed on the different models included two elements: a protocol, and a set of indicators quantifying the apartment´s flexibility potential. The overall protocol was the following: a cut-off in the heating schedule was performed, and the consequences of this perturbation were measured with focus on two aspects: the occupants' comfort and the heating power profile. This led to the two flexibility indicators developed.

The first test, focusing on occupants' comfort, consisted of cutting heat off in the apartment at 7 AM on Monday, January 19th and observing the decrease in operative temperature in the living room. The climate files and schedules used in the simulation are detailed in the "Model description" section. The living room was chosen as the target of the study since it is assumed to be the space where occupants are the most present during daytime and therefore where thermal comfort is valued the most. Moreover, its large glazed surface makes it likely to suffer from large temperature swings. This heating control strategy corresponds to a peak shaving operation under its most extreme form: heat is completely cut off in the residential buildings to shave the morning heating peak. This scenario was chosen for its

[1] The glazing-to-external-wall ratio was modified by changing the size of the windows in the different rooms simultaneously and by the same factor.

[2] The orientation was changed by rotating the entire building model.

simplicity: indeed, implementing a preheating period of a specific duration or reducing heat supply by a certain percentage would create a bias on the results, while this bias is reduced when using a fundamental signal such as a total cut-off. The corresponding indicator was the time (measured from the cut-off) after which the operative temperature dropped below the lower bound of the occupants' acceptability range. In this work, this minimum acceptable temperature was set to 20°C, corresponding to Category II of EN/DS 15251. Figure 1 gives a simplified graphical representation of the indicator calculation.

In practice, given the large fluctuation of indoor temperature, temperature can drop for some minutes below 20°C and rise again, which is not a real threat to indoor comfort. Therefore, a tolerance factor was introduced, which made the indicator practically calculated as the duration of the time interval, starting from the cut-off, during which operative temperature in the living room has been above 20°C for 90% of the time since the cut-off.

This indicator was introduced to reflect in simple terms the degradation of indoor comfort in the living space. It is a tangible measure of occupants' perception. Following the variation of this indicator when modifying the apartment's design parameters permits to understand the theoretical ability of these investigated parameters to preserve indoor comfort, in case of a change in heating schedule ordered by the thermal grid operator. The simplicity of the protocol permits to obtain a fundamental comparison of the parameters' role – more complex control strategies will be implemented in a further study.

The second test consisted of cutting heat off in the apartment between 7 AM and 4 PM on Monday, January 19th, which corresponds to a heat prioritization strategy: dwellings are heated up in the evening and during the night, and offices during working hours. It was chosen to measure the maximum heating power level reached in the following two days (between the 19th and the 21st of January) in the simulation with heating cut-off and to compare it with the maximum power level in case of

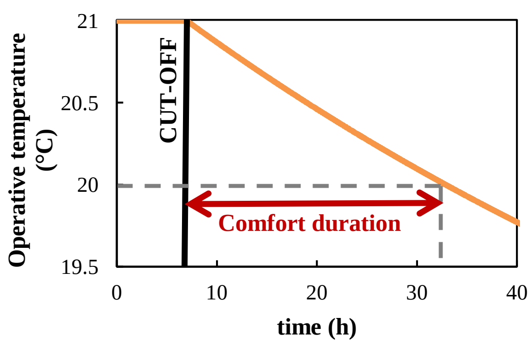

Figure 1: Duration of the comfort period

normal operation (with a setpoint at 21°C) during the same period. The heating power is defined as the heat input in the floor heating system for the whole apartment. This output constitutes the second flexibility indicator (1). Q_{max} and $Q_{max,ref}$ are represented in Figure 2.

$$Ind_2 = \frac{Q_{max} - Q_{max,\ ref}}{Q_{max,\ ref}} \tag{1}$$

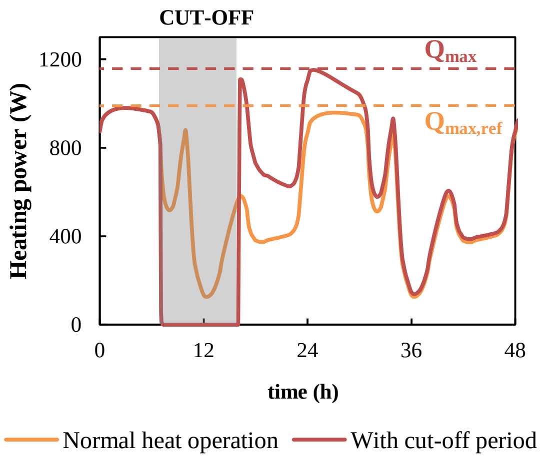

Figure 2: Peak power variation

The goal of this indicator is to assess the pressure set on the heating system when performing a heating control operation. Indeed, in order to satisfy indoor comfort requirements, there is a risk that the system reacts by a large increase in heating power when the cut-off period is over, which can in some cases go against the goals of performing a load-shifting strategy. Calculating this indicator under different design solutions permits to identify the magnitude of this potential problem; if the problem can be predicted; and if it is particularly affected by specific design parameters. In a future work, different controls strategies will be applied to mitigate this problem, in particular a ramp for the temperature setback rather than the simple on/off control tested here. In this indicator, the peak levels that are compared are not necessarily occurring at the same time: they are the overall maxima over the considered days. This approach gives information about the extra capacity that would be needed to accommodate the new peaks.

The two flexibility indicators were calculated for each of the models, and their variation was related to the change in the parameters' value by a graphical representation. The impact of the different parameters on the chosen indicators could then be appreciated.

Model description

This study was based on a set of numerical models created on the building performance simulation software IDA ICE 4.7.

Figure 3: Building overview (source: Alectia)

Geometry

The building that was investigated is a 5-floor low-energy residential building located on the waterfront, with the water-facing facade oriented 10° from South. One apartment of this building was modelled in this study. It is a 95m², 3-room apartment located on the 4th floor, with the main facade facing the waterfront.

The geometry of the IDA ICE model is shown in Figure 4. The rest of the building volume was included in the model, but only with regards to shading calculations: it was assumed that the adjacent apartments are similarly heated spaces, so there is no heat exchange with the rest of the building.

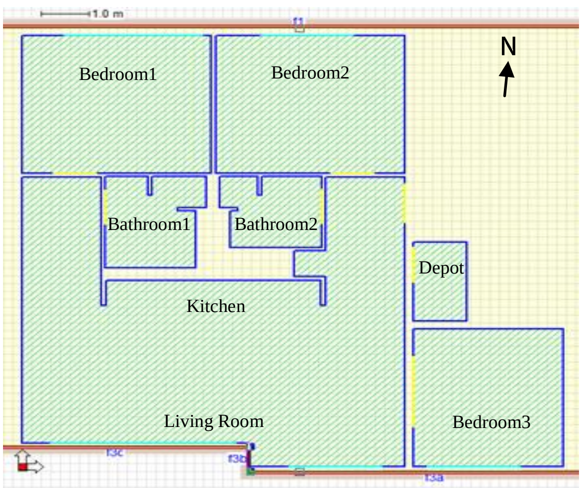

Figure 4: IDA ICE apartment model - floor plan

Building materials

The external walls of the building included a thick layer of concrete on the inside and a brick external façade, with mineral wool insulation in-between. Two sorts of internal walls were used: bearing walls made of a single concrete layer, and non-bearing walls made of aerated concrete, used to separate the bedrooms and in the kitchen corner. The floor of the bedrooms, living room and depot room was covered by oak planks lying on a concrete screed. The windows consisted of three glass panes filled with argon, with an aluminium and wood frame. The total U-value of the apartment is equal to 0.49W/m²K. Table 2 details the different construction layers.

Systems

All the apartments were equipped with a floor heating system connected to the district heating network, with supply and return temperatures of respectively 40 and 35°C. The heating setpoint was chosen to be 21°C and no cooling system was included. The domestic hot water circuit was not modelled in this study due to its little influence on heat flexibility in the absence of individual hot water storage system for each apartment. The mechanical ventilation system was balanced CAV (constant air volume) with 80% heat recovery. Fresh air was supplied in the bedrooms and the living room with a setpoint of 17°C and the return air was exhausted from the kitchen and the bathrooms.

Outdoor conditions and internal gains

In order to isolate the results from the influence of fluctuating outdoor conditions, the base outdoor temperature was set constant to -5°C, representing a cold winter day, with 90% relative humidity. Due to the difficulty to predict the wind-driven infiltration in the context of a semi-exposed building, a constant value for infiltration of 0.1 L/s/m^2 floor area was used. Some solar gains were defined based on an average radiation in a short winter day. This pattern was repeated every day of the simulation period.

A standard pattern for the heat flux from occupants and electrical appliances was defined. The day was divided in four periods, and different uses were defined for weekdays and weekends in the different rooms. It was considered that four people live in the apartment, which is common for this specific building: Bedroom 1 was considered double. The four occupants were always present in the apartment from 5 PM to 9 AM, and all day during the weekends. None of them was present from 9 AM to 5 PM during workdays. Equipment units were positioned in every room apart from the depot room and the bathrooms.

A daylight-related control was designed for lighting

Table 2: Composition and U-value of building parts

Building part	**Layers (from outside/from bottom)**	**Total U-value (W/m²K)**
External wall	• Brick (10.8 cm) • Mineral wool (27.5 cm) • Concrete (15 cm)	0.13
Bearing internal wall	Concrete (20 cm)	3.43
Non-bearing internal wall	Aerated concrete (10 cm)	1.13
Floor	• Hollow concrete (22 cm) • Termotec insul. (14.6 cm) • Concrete screed (6 cm) • Oak planks (3 cm)	0.27
Window	Triple-pane Argon-filled	0.81

as advised in BR15 (The Danish Building Regulation, 2015). Shading devices were included and supposed to be manually activated by the occupants in case of excessive lighting conditions.

Simulation parameters

A dynamic simulation was chosen: the program made an initial guess and reached convergence while simulating from the 1st of January to the 18th of January, then started the simulation from the 19th of January, day of the cut-off. The maximum simulation time step was 12 minutes, but it was automatically reduced when more accuracy was needed.

Results

The graphical representation of the obtained flexibility results is shown in Figure 5. The two indicators (duration of the comfort period in the left graphs and peak power variation in the right graphs) are plotted against the different design parameters, which are gathered in three groups: material layers, window features and main facade orientation. In each of the graphs, the points representing the original building are darker and circled in black.

Material layers

As seen in Figure 5a and Figure 5b, the thickness of the concrete layer in the external walls shows impact on none of the two indicators under the considered conditions. Between a 2-cm and a 30-cm concrete layer, the duration of the comfort period in the living room varies between 72 and 74.5 hours, which is almost negligible in comparison to the impact observed for other parameters. Identically, the peak power in a period perturbed by a heat cut-off gets approximately 19% higher than under normal operation in the same period, independently of the concrete thickness in the external walls. This result questions the role of heat storage in the external walls in response to a heat cut-off: in this particular case, the increase in thermal storage capacity does not affect the apartment's energy flexibility potential.

On the contrary, the duration of the comfort period after cut-off in the living room shows a large dependence on the thickness of the insulation layer in the external walls. While a non-insulated external wall permits to retain heat in the living space for 21 hours before the comfort limit is reached, adding 10 centimeters of insulation brings this figure to 69 hours. Above 10 centimeters of insulation, the corresponding improvement in comfort conditions is relatively small, namely reaching 32 centimeters of insulation results in an increase in the comfort period duration from 69 to 81 hours. This result shows that a minimum thermal resistance is necessary to allow heat retention: if the insulation is too poor, energy is lost too rapidly towards the ambient to be stored in the building structure (external walls). The insulation thickness of the external walls also has a significant impact on the heat consumption peak: a heat cut-off in a non-insulated apartment leads to a rapid temperature decrease, and therefore to an important heating peak when heat is turned on again at 4 PM: the peak gets 60% higher than the maximum heating power in normal operation (with no cut-off). The peak power variation due to a cut-off gets less important when the insulation layer gets thicker: for an apartment with more than 18 centimeters insulation, the peak due to a cut-off is around 20% higher than the peak power in normal operation. Both tests show that even though a minimum level of insulation is required, the apartment's flexibility potential is not significantly improved for an insulation thickness higher than 20 centimeters, which is a valuable piece of information when drawing design guidelines.

Varying the thickness of the concrete slab that embeds the floor heating pipes from 3 to 12 centimeters leads to a change in the comfort period from 72 to 93 hours (Figure 5a), while increasing the slab thickness from 12 to 25 centimeters increases the comfort period duration by 3 hours only, from 93 to 96 hours. This result may be due to the fact that the pipes are located only one centimeter below the surface of the concrete slab in all of the cases, which limits the penetration of heat in the lower layers of the concrete. The study of the impact of the depth of the pipes into the concrete was not within the scope of this work. There is nevertheless room for improvement in the investigated building: increasing the concrete slab thickness from 6 cm to 12 cm could save up to 20 hours of heating in the living room. The analysis of the peak power variation due to a cut-off does not show a clear dependence on the slab thickness (Figure 5b). The results nevertheless show an optimal behaviour when the slab thickness approximates 12 centimeters.

Window features

Both the window U-value and the glazing-to-external-wall ratio show a large impact on the calculated flexibility indicators. As seen on Figure 5c, when varying the window U-value from 0.75 to 2.5 W/m²K, the duration of the comfort period is approximately divided by 4 (from 75 to 19 hours). This result demonstrates that the heat loss from windows has a large responsibility in the heat retention performance of the considered building, in this particular case of a large window surface (glazing-to-floor ratio of 0.42) and relatively cold outdoor conditions. It is also found that the higher the U-value of the windows, the higher the peak in heating power observed after a cut-off period (Figure 5d). This is due to the larger heat loss during the cut-off period when window U-value is increased, leading to a need for higher heating power when heat supply is re-established. The window size has a very clear influence on the flexibility results. The larger the share of glazed surface in the external walls, the shorter time can heat be retained indoors, as seen in Figure 5c. It has to be noticed that the scale of Figure

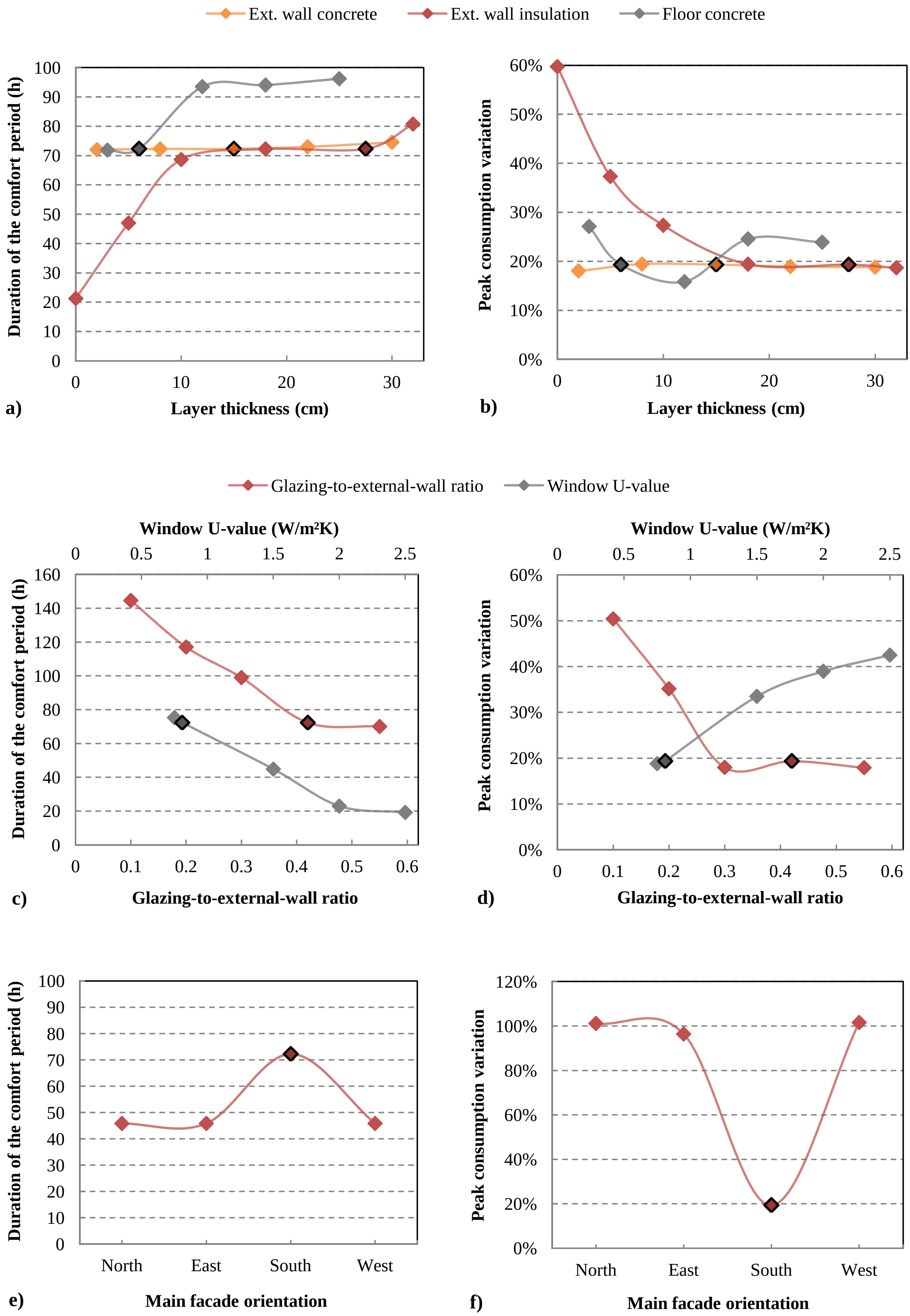

*Figure 5: Parameter variation results: duration of the comfort period (**a**,**c**,**e**) and peak consumption variation (**b**,**d**,**f**) in function of the thickness of different wall and floor layers (**a**,**b**), window properties (**c**,**d**) and orientation (**e**,**f**)*

5c has been extended, since for a glazing-to-wall ratio lower than 30%, good comfort conditions can be kept in the living room for more than 100 hours.

This result also confirms the predominance of thermal resistance in the flexibility issue: indeed, windows are both a source of heat loss and of solar gains, but the losses seem to have a much larger impact on flexibility in this apartment since reducing the window size has such a positive effect on heat retention. However, a further analysis has to be carried out investigating whether this effect is due to the greater wall volume when window size is reduced, increasing the apartment's thermal mass. The analysis of the heating peak gives different results (Figure 5d). For glazing-to-wall ratios below 30%, the solar intake is low and does not contribute much to heating up the space. Consequently, the impact of cutting heat off is larger and the change more brutal, leading to a relatively high peak when heat is turned on at 4 PM (up to 50% higher than normal). For glazing-to-wall ratios higher than 30%, the height of the peak stabilizes between 18 and 19% above its level in absence of a cut-off. Solar gains constitute an immediate source of heat able to balance heat losses, hence their impact on the heating power required after a heating control operation. For large window sizes, the positive impact of solar gains is balanced by the increased heat loss from the extra surface, keeping the peak power surplus constant for glazing-to-wall ratios of 30 to 50%. The Danish BR15 building regulation sets a minimum of 15% for the glazing-to-floor ratio, which corresponds in the present apartment to a glazing-to-wall ratio of 24%. Going above this value shows to be beneficial from the point of view of peak power minimization, but leads to a shorter comfort period in case of a cut-off. However, daylight being an important component of indoor comfort, it is not advisable to introduce a lower threshold for window size in a new version of the building regulation.

Main facade orientation

As seen on Figure 5e and Figure 5f, all orientations but the South give similar flexibility results in the studied apartment for both indicators: the comfort period lasts around 45 hours, and a several-hour long heat cut-off triggers a heating power peak twice the height of the maximum power in normal operation. Orienting the facade 10° to the South, as done in the existing building, permits to extend the comfort period up to 72 hours, which is a favourable scenario when considering energy flexibility. This result permits to qualify the interpretation of the findings from the window size investigation. Indeed, even though solar gains show to have, in the present case, a smaller impact than heat losses through windows on thermal comfort preservation after a heating control operation, their absence significantly degrades the performance described by the indicator.

A South orientation permits to greatly limit the heating peak, making it only 20% higher than the maximum power in normal operation. This result confirms the finding from the glazing-to-wall ratio investigation: solar gains have a prevailing moderating impact on the heating power increase following a cut-off.

Holistic analysis

In order to get a better understanding of the findings, all the investigated cases were gathered. The two flexibility indicators were plotted over both the UA-value of the apartment and its total effective internal heat capacity, giving a point for each of the different design cases. The latter was calculated including the thermal mass of external and internal walls, floors and ceilings, calculated accordingly to DS/EN ISO 13790 (2008). The results can be seen in Figure 6.

The thermal resistance of the envelope appears as the primary factor able to guarantee a satisfactory response to a control operation in terms of indoor comfort. As shown in Figure 6a, the duration of the comfort period shows a clear dependency on the apartment's total UA-value, with little dispersion. As highlighted in the study, the insulation level of the external walls and the U-value of the windows are critical parameters in the preservation of thermal comfort during a heating control operation such as, in the most extreme case, a complete heat cut-off. Reducing the window size also permits to preserve comfort for a longer time, even though this results in a lower solar energy intake. These three parameters impact the heat loss rate through the envelope, thus influencing the duration of the comfort period.

The conducted parameter analysis shows that the envelope's thermal performance has a decisive impact on the possible extreme heat power peaks following a heat cut-off. Indeed, a poor thermal performance leads to high heat losses during the cut-off period, thus the need to quickly increase heating power to satisfy indoor comfort requirements. However, Figure 6b makes it clear that even though an increase in UA-value globally leads to an increase in peak surplus, another factor has a much higher influence on this parameter: the facade orientation, responsible for a doubling of the peak height when changed from the South to any other direction. Solar gains show to strongly attenuate the risk of creating heat consumption peaks after a cut-off period.

Through the analysis of different orientations and windows sizes, it is made clear that solar gains participate in preserving indoor comfort after a heating perturbation, but that in the current case, the amount of heat lost through windows is higher than the amount gained from solar radiation, which limits the relevance of increasing the window size. In the studied apartment, heat accumulation in the thermal mass (specifically external walls and floor) plays a limited role, as highlighted by the study and confirmed by Figure 6c. Increasing the heat storage capacity in the external walls triggers no change in

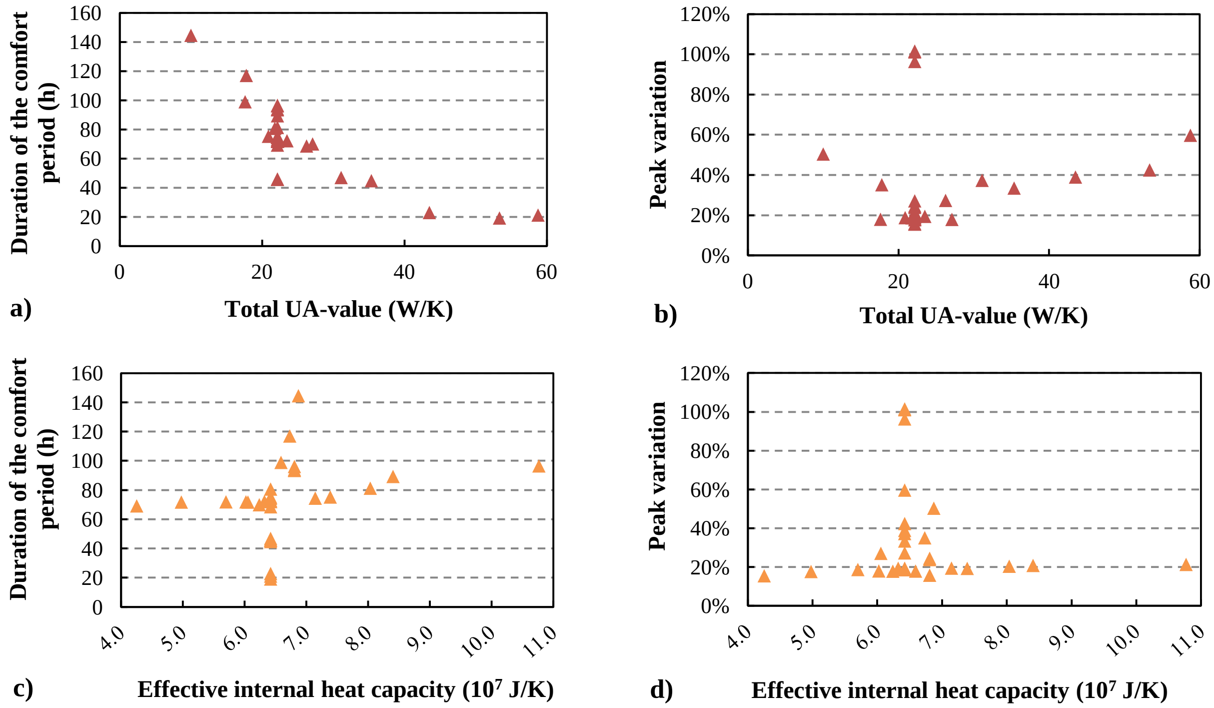

*Figure 6: Flexibility indicators as function of total UA-value (**a**,**b**) and effective internal heat capacity (**c**,**d**)*

the duration of the comfort period, while increasing the available storage volume in the floor slab that contains the floor heating pipes helps counteract heat losses in the space up to a certain volume (Figure 5a). Figure 6c shows a globally flat profile with a high dispersion, demonstrating that internal heat capacity is not a decisive parameter in this case. This result could find an explanation in the large window surface resulting in a limited external wall volume. In order to confirm this hypothesis, the impact on the indicators of a simultaneous change in the window area and in the heat storage capacity should be investigated. Identically, the building's thermal mass shows no direct impact on heat power peaks following a cut-off (Figure 6d). As an example, the different design cases that keep an internal heat capacity of around 6.5×10^7 show a large variability in peak power variation, which indicates no correlation between the indicator and the internal heat capacity. The value of the indicator is rather sensitive to other parameters such as the window orientation or the insulation thickness, which variations have no influence on the internal thermal capacity.

Discussion

This study is based on simulations that aim at understanding and comparing the influence of different design parameters on heat flexibility. Assumptions and simplifications were used in order to be able to isolate the influence of the investigated parameters from other factors. Thus, the results cannot be used as such to establish a heating control strategy for example, since they have been obtained in a context that could deviate from other cases. The purpose of the obtained flexibility results is rather to show the evolution of the flexibility potential when varying a parameter and to observe the different impact that they would have. The results have to be read in relative terms, the trend being more interesting and reliable than the level itself. Among the main simplifications are the constant outdoor temperature and infiltration, the periodic heat gains and the scheduled occupants' behaviour. An analysis of the sensitivity of the present flexibility results to these assumptions is available in a complementary publication by Zilio et al. (2017).

Moreover, this paper describes a local sensitivity analysis, which has the advantage of isolating every parameter's impact while requiring a limited number of simulation runs. The influence of one of the parameters on the results given by the other, through a multi-parameter analysis, is under investigation for some particular parameter combinations and the results are to be published in a coming article. This complementary analysis is expected to permit to make the whole analysis applicable to a wider range of buildings.

Another assumption having an impact on the results is the choice of the cut-off time. In particular, the choice of the cut-off period in the heat power investigation is likely to give a bias to the role of solar gains in the peak power height, since the cut-off period includes the whole solar radiation period. The heating control strategies themselves include a bias in the obtained results: as an example, Wolisz at al. (2013) show that in the case where a pre-heating period is performed before the heat cut-off, the building's thermal mass plays a more important role.

However, even though the investigation mode itself induces some bias in the result, the difference in result presented by the two studies gives some valuable information. While the first indicator is an index of building performance from the occupants' point of view, the second indicator can rather be used when focusing on grid stability. Moreover, both measurements give information about the ability of the apartment to retain heat indoors, but under different angles. Measuring the duration of the comfort period after a cut-off answers the following question: how long can the building provide an acceptable temperature indoors without heating? Focusing on the heating peak after a temporary cut-off rather answers this question: after 9 hours without heating, how far is the temperature in the living room from acceptable conditions (namely the heating setpoint)? This difference in time span explains in particular why increasing the window size has such a positive impact on reducing the heating peak while its effect on the comfort period is overall negative: solar gains help increasing indoor temperature on the short term but thermal losses are predominant on a longer term.

Eventually, it would have been of great interest to be able to couple this study, which is based on a simulation model of the apartment, to actual measurements in the investigated building. The edifice still being under construction, it was impossible. However, measurements are scheduled in the context of the EnergyLab Nordhavn project and this aspect will be the topic of a further study. The influence of the occupants and of the outdoor conditions will in particular be made more clear and the evaluation of indoor comfort more detailed by distributing questionnaires to the occupants.

Conclusion

The present study deals with design of buildings as a tool to improve their ability to retain heat and thus adapt changes in heating schedule, the end goal being to provide energy flexibility to the heating network. In order to understand which of the building design parameters influence its flexibility potential and in which way each of them contributes to it, two investigations were performed on a number of design solutions for the building model. In the first investigation, a complete heat cut-off was performed at 7AM, and the time during which the operative temperature in the living room remained above 20°C was measured, constituting the first flexibility indicator. In the second investigation, heating was cut off between 7AM and 4PM and the heating power peak around that period was measured. Its relative difference with the peak level under normal heating operation constituted the second flexibility indicator. By comparing the results under different design versions, the influence of design parameters on heat flexibility in the present building was assessed.

It was found that the design parameters with the most influence on the temperature drop in the inhabited space after a heat cut-off are those impacting the heat losses through the building envelope. The insulation of the external walls is the parameter showing the largest impact on flexibility. Improving the U-value of the windows can multiply the duration of the comfort period by up to a factor of 4. Heat retention time strongly decreases when the glazing-to-external-wall ratio increases, showing that the losses due to a larger glazed surface impact more the indoor temperature than the increased solar gains when the window gets larger. The orientation of the apartment shows a moderated but clear impact on heat retention: any other orientation than South significantly reduces the time in the comfort range after a cut-off.

As to the thickness of the concrete layers of the different building components, its impact is less important than expected. The layer which thickness has the most significant influence on flexibility is the floor slab, since it embeds the heating pipes, but this is only true up to a certain thickness. The thickness of the concrete layer of the external walls shows a negligible influence under the conditions of this study.

A temporary heat cut-off performed during the day is followed by a heat power consumption peak that is influenced by the building design. The relative height of this peak with respect to the peak power in normal conditions is not affected at all by thermal storage in the building structure, but is greatly influenced by the thermal resistance of the envelope, namely by the insulation thickness and U-value. However, according to the present calculation methods, the main influence on the peak power seems to come from the presence of solar gains: orienting the main facade in any other direction than South greatly increases the heating power peak. Similarly, while smaller windows guarantee a better heat retention, they also lead to an important increase of the peak power.

This work has permitted to understand the mechanisms that lead to transmission and retention of heat indoors, which give the district heating operator the possibility to apply restrictions on heat supply when best for the system as a whole. The importance of an optimal building design is now obvious, and the role of the main building components has been clarified.

The present work is a preliminary theoretical comparison of the role of different building components in heat perturbations adaptation. This work also aims at giving an estimate of the energy flexibility potential that these newly-constructed apartment blocks can offer to the grid and which can be further utilized by the future heat supply of the area. Some multi-parameter investigations as well as analyses with different building shapes and indoor space organisation will complete this work, and help forming a set of guidelines for an optimal building design with focus on heat flexibility. An impact assessment of outdoor conditions and internal gains on the present flexibility results is developed by Zilio et al. (2017). The following steps of this work include yearly simulations using realistic weather data permitting to assess the building's response to both summer and winter conditions. Moreover, field measurements are being collected on the studied building and will be used to support the present simulation work. Finally, a study of different heating schedules is planned, including price-dependent scenarios.

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