Investigating Dwellings' Response to Heating Power Cuts

Simulations and Field Tests

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– Simulations and Field Tests

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Preface

I would like to thank my supervisors Dennis Johansson and Hans Bagge for your support in my development as a doctoral student and for many interesting discussions and guidance. I would also like to thank all my colleagues at the division of Building Services and Building Physics at Lund University for your support. In addition, I would like to thank Ronny Andersson and Anders Rönneblad, Cementa, together with Helen Carlström, E.ON, for initiating the project. Furthermore, thanks to Ronny, Anders and Jonas Lindhe and his colleagues at E.ON for your inputs and valuable discussions. Finally, to my family, my wife Rebecca and my two sons, Jack and Allan for giving me the energy of love.

This licentiate thesis is part of my graduate studies at Lund University, Faculty of Engineering, Department of Building and Environmental Technology, Division of Building Services. The work was done in cooperation with, and support from, the Division of Building Physics

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Victor Fransson, Lund 2017-03-17

Abstract

Reducing energy use, increasing the use of renewable energy sources, and adapting to stricter building regulations and certification systems – these are all examples of the challenges facing the building industry and society. Looking at the energy supply at a larger scale than a single building, like a neighborhood or a city, the stack effect of peak power demands can cause problems on the production side, either economical or concerning the environment and greenhouse gases when fossil fuel is used to cover these peaks. This is connected to the overall issue and one way of dealing with this issue is to let the demand side reduce their heating demand in times of difficulties in the production. The heat stored in the building envelope and furnishings would then be used to reduce the impact on the drop in indoor temperature. This thesis delves into this impact and the various aspects that affects the magnitude of the temperature drop such as the thermal mass, envelope properties and the stochasticity of the internal heat loads. The method used in this thesis is one that employs extensive simulations with randomized input variables, derived from measurements, in order to statistically show the risk or probability of a certain temperature drop following a power cut.

Sammanfattning

Att minska energianvändningen, öka användningen av förnybara energikällor, och anpassa sig till strängare byggregler och certifieringssystem - dessa är alla exempel på de utmaningar som byggbranschen och samhället står inför. Om man tittar på energiförsörjningen i en större skala, som en stadsdel eller en hel stad, kan den sammanlagda effekten av toppeffektkrav bli ett problem för produktionssidan, antingen ekonomiskt eller miljömässigt då växthusgaser släpps ut när fossila bränslen används för att täcka dessa toppar. Detta är således kopplat till den övergripande frågan om att öka användningen av förnybar energi och ett sätt att hantera detta problem är att låta hushållen sänka sitt värmebehov i tider av svårigheter för produktionen. Då värmebehovet sänks kan värmen som lagrats i klimatskalet och inredning sedan användas för att minska påverkan på inomhustemperaturen. Denna avhandling undersöker temperaturfallet efter sådana sänkningar och de olika aspekterna som påverkar storleken på temperaturfallet, såsom den termiska massan, byggnadsskalets egenskaper och det stokastiska beteendet hos brukarna som ger upphov till de inre värmelasterna. Den metod som används i denna avhandling är en som använder omfattande simuleringar med slumpade internlaster, som härrör från mätningar, för att statistiskt visa risken eller sannolikheten för ett visst temperaturfall efter att värmen stängts av.

Contents

1. Introduction

Reducing energy use, increasing the use of renewable energy sources, and adapting to stricter building regulations and certification systems – these are all examples of the challenges facing the building industry and society[1, 2]. However, a recently recognized issue that also concerns these challenges is heating power demand. Today, the supply of this type of power is driven by demand and, in turn, this demand is driven by the heat loss in a building and the behaviour of its residents. This arrangement would work perfectly, if the cost of supplying one additional unit of power (Watt) were constant, both in terms of price and environmental impact. Obviously, this is not the case, as the heating power supplier needs to start additional generators, perhaps with lower efficiency, and to use different fuels, usually fossil fuels, to cover peak demands. Consequently, the cost and environmental impact of production vary. From a supply side point of view, acquiring control over these variations could provide both economic and environmental advantages. The latest smart grid technology creates new opportunities for communication between a heating power supply company and a building management system (BMS) [3, 4]. This provides an opportunity for the heating power supplier to send a price signal or a request that the demand side BMS can respond to. A request, for example, could be that the demand side reduce their heating when the production side is uneconomical or particularly fossil fuel intense [5, 6]. The heat stored in the building envelope and furnishings would then be used to reduce the impact on the drop in indoor temperature.

In short, the key to shifting heating power demand is to keep the duration and magnitude of the power reduction from causing unacceptable indoor temperatures while still providing economical advantages. A viable path of communication between the production and demand sides is also necessary. There are many possible ways of thermal energy storage in buildings and they are well described by Heier [7] and Arteconi, Hewitt [8].

The primary concern when reducing heating power supplies during the heating season is the impact on the indoor temperature. One of the important factors connected the effect on the indoor temperature is the amount of heat stored in the internal mass. This was studied both by simulations and measurements already in the 1980s in America by Burch, Krintz [9] and Burch and Arumi-Noe [10]. In these studies it was shown that having a high thermal mass was advantageous when temperatures were allowed to deviate from the thermostat set points, a consequence of the building structure being charged by internal heat loads. There was also extensive studies of the thermal mass and thermal inertia of buildings in Sweden where Jóhannesson [11] studied the active heat capacity through thermal network calculations. Stenlund [12] did extensive calculations derived from measurements regarding the temperature drop when using night setback.

More recently field studies have been performed in which the power has been reduced and the temperatures measured, and these have shown only small impacts in the indoor temperatures [13-16]. Kensby et al. show that describing the decreasing indoor temperature, when the heating output has been reduced, using the fixed building time constant is not a valid option for short periods of power reduction, this is in congruence what Isfält and Bröms [17] showed. Instead, the use of a building’s thermal mass during the heating season can be considered, offering a new way of measuring the stored heat in terms of degree-hours instead of the building time constant [16]. In their paper, Kensby, Trüschel [16] show, in addition to this new proposed approach, a weighted impact on indoor temperature correlated to the decrease of power. This was based on a weekly average over the measuring period and used for determining the impact of the power reductions. Using the building frame to delay the heating power load demand has also been investigated using simulations for a single-family house [18]. Heat was supplied using a heat pump when electricity prices were most favourable while allowing the indoor temperature to vary within different intervals. Up to 60 % peak power reductions were obtained if a 4 °C drift was allowed from the design temperature. Another case in which electricity peak demands can be easily avoided is when a building has underfloor heating. However, if radiator heating is the case, caution should be taken not to create a too low indoor temperature [19]. Experimental studies were performed by Henze, Kalz [20] together with simulations. There has also been many studies on how to use the building thermal mass in order to reduce the peak power load of the cooling system during the day [21].

In previous research, there has not been much focus on the variables impacting the indoor temperature, such as loads from appliances, occupancy and sunlight. Kensby et al. [16] measured this impact but used an average temperature to show the impact of the heating reduction and disregarded the specific impacts of each variable. Kensby et al. also only looked at two apartments for each investigated building. Fixed occupancy schedules were used in the paper by Reynders et al. [18]. In this case, however, a more sophisticated approach regarding the appliance load is applied.

Many field studies have shown that it is possible to reduce the power output in residences without causing problems with the indoor temperature. Due to the limited nature of field studies, both in time and number of test subjects, not all of the natural variations occurring in a building are accounted for. For instance, the internal heat gains often associated with buildings, such as the occupants themselves and the electricity they use (electricity that becomes heat), vary a great deal and this is confirmed in a study by [22-24]. Furthermore, different types of building envelopes and heating systems are the parameters that most likely affect the outcome of a power reduction. This study aims to provide a way of investigating them using large-scale simulations, the key to covering the large spread of the variables affecting the indoor heat balance. Instead of looking at a particular case, a new more appropriate way of looking at heating power reductions in terms of risk or probability can be established. By randomizing the input variables from a database of measured values, the probability of achieving a too low indoor temperature, following a power reduction, can be identified.

Regardless of how well we can mathematically describe and perform calculations of a certain physical phenomenon or perform measurements thereon, there is no way of knowing the exact boundary conditions, in a mathematical sense, of, for example, the weather or the residents in a particular apartment. And, due to the fact that residents affect the heat balance and individual households can have very different impacts, a way to handle this, by studying many different cases, had to be found. Furthermore, another set of parameters affecting the magnitude of the temperature drops are the envelope properties. Looking at the entire residential building stock, there are obviously widespread differences and these also need to be addressed.

1.1 Aim

The aim of this thesis is to investigate the indoor temperature drop in dwellings after a total power cut, taking into account the stochastic nature of internal heat loads as well as the large spread of occupancy factors between individual households. Thus, instead of showing the results as mere temperature drops in the traditional way, they will be shown in terms of risks or probabilities of the occurrence of specific temperature drops.

In addition, this thesis aims to investigate the usefulness in terms of power-saving potential coupled to the temperature drop. In order to cover the broad spectrum of the Swedish building stock, buildings with different envelope properties, representing different periods, are investigated.

Furthermore, the influence of another variable, the internal mass – such as furniture – is studied through simulations. The aim here is to show how this variable can be treated in simulations when designing for intermittent heating.

2. Methodology

Field-tests, lab-tests, analytical calculations and numerical calculations – these are all possible ways of addressing the issue of declining temperature after a power cut. All of them have their strengths and weaknesses. Field-tests that have been performed show promising results. However, they lack a more comprehensive perspective on input data variation. Analytical calculations could be an option but, as buildings become more complex, describing them would be difficult, or even impossible. Furthermore, as discussed earlier, the unpredictability of the residents occupying the buildings adds another degree of complexity. Thus, a numerical approach through simulations was chosen together with experimental tests in the field. The selection of the numerical calculations was extended by a stochastic approach not commonly used in building design. The basis for this was to have a large data base of measurements of internal heat gain factors, such as occupancy and household electricity, combined with a method of applying the data by randomization to the building simulation.

2.1 Thesis content

In order to answer the questions expressed in the aim, this thesis presents the results from three papers together with a chapter named additional analysis. These papers will be referred to as Papers I, II, III. The papers are appended to the thesis and a detailed explanation of the method used can be found in each paper. However, a short summary with key results can be found in the section Appended Papers.

The key to addressing the aim of resolving the varying input data of buildings was the new approach, i.e. the running of a large number of simulations with varying inputs and parameters. Even though a single simulation would only take a couple of minutes to perform, repeating this 500 times for each parameter change would take a very long time. Therefore, a simulation method was developed and this was used in all the papers and the additional analysis. This method makes it possible to run a great number of building simulations with varying inputs automatically, once the set-up has been made.

Papers I and II use this method to investigate the impact of the variables occupancy, household electricity and outdoor climate in combination with different building envelope properties and heating systems. The additional analysis widens the scope of Paper II. Paper III analyses temperature measurements after a power cut and compares them to simulations. A short summary of the papers follow and Table 1 gives an overview of the main focus of the Papers as well as the additional analysis. The key aspects, shown in Table 1, are critical for reaching the aim. The need for building simulation models and how to run hundreds of simulations efficiently are explained in section 2.2. The input data that forms the foundation for the randomization of data used in the building simulations, and the level of detail at which this has been carried out, is explained in the next section. The parameters of interest are shown in the section Parametric Analysis. And the last section describes the experimental field study and how the results from the measurements were compared to the results from the simulation model.

The thesis consists of:

- Paper I – Whole building simulations of a multi-family building during the entire heating season. A simplified, statistically determined resident model was used for randomization. Different building envelopes were tested.
- Paper II – Simulations of one generic apartment in a multi-family building represented the worst-case scenario, as it was located in an upper corner. Measured hourly occupancy and electricity data were used as inputs from 35 and 500 different households respectively. The month of January was used for the simulations.
- Paper III – Measurements and simulations of two cases, one single family and one multi-family building, were carried out. Measurements were analysed and a parametric analysis of the identified variable internal mass (amount of furniture) was performed for the single-family building.
- Additional analysis – Complementing Paper II, showing results from a generic apartment located in the middle of a building, thus not as affected by the outdoor conditions. Two other locations, corresponding to the far south and far north of Sweden, and consequently having very different climates, were investigated. Furthermore, one case without internal heat gains was investigated.

Table 1. Overview of Paper contents

	Paper I	Paper II	Paper III	Additional analysis
Simulations	X	X	X	X
Measurements	-	-	X	-
Simplified input data	X	-	-	-
Detailed input data	-	X	-	X
Parametric analysis	X	X	X	X

Furthermore, in the discussion section, the results from the papers and the additional analysis are discussed as a whole. And conclusions are made concerning how to use the results.

2.2 Simulations

The strength of simulations in comparison to field measurements is that they allow us to test limitations and cover a much broader spectrum of outcomes by combining different parameters and variables. A simulation method was therefore developed in order to perform large-scale simulations. IDA-ICE [25], a building simulation software that has been tested and verified in accordance with EU-standards for energy-calculation software [26,27], and a programming software, were used for pre-processing input data, randomization and changing of parameters, starting the simulations and saving the output. For example, before each simulation, the occupant was chosen randomly from the database of measurements and, in the same manner, the household electricity usage and weather conditions. The chosen variables were then transferred into the IDA-ICE software that solve the building physics model and returns the output to be saved, making it ready for the next simulation. This method was used in all three papers and the additional analysis described in depth in Paper II.

This method also made automation possible, enabling simulation batches to run for several hours or days. This was a key factor in addressing the issue at hand through a statistical approach entailing a large number of simulations with randomized input. If it was desirable to reduce the power output in a certain type of building at a certain time, this method could, to some extent, give a more nuanced answer to the problem. Instead of the answer being a specific temperature drop, it would be a multitude of temperatures with a certain distribution, or probability for occurring, correlated to the spread of the input data, in which the input data had been obtained from real measurements.

2.3 Input data

One of the key factors for the simulations to give a representative result is the input data in terms of internal heat loads and boundary conditions determined by the weather. The impact of varying internal heat gains of residential buildings, caused by many variables such as occupancy and household electricity use, can be shown by field studies. This is usually done by carrying out measurements in one or a couple of apartments or buildings over a limited amount of time. The need for these large-scale simulations was brought about by the variations between different households and different climatic years, as these can vary considerably for the same location and over time. Three main variables were chosen in this study – occupancy, household electricity use and weather. Among the properties of these variables at least two common and clearly distinguishing attributes can be identified that need to be handled in the simulations. Firstly, on a short time scale, for instance hourly, the variables can be described as almost stochastic (though maybe not the weather). Secondly, there is a difference in the cumulative measured data between individual apartments and climatic years, during, for example, a month or a year (total electricity use, total occupancy and mean temperature). The first attribute is taken into account by using measured hourly data as input and the second by using a Monte-Carlo approach, where the input data set for each simulation is randomized. This approach contrasts with the more common approaches in which static occupancy schedules and yearly averages for household electricity are used to model resident behaviour.

The domestic electricity data used in this study consists of hourly measurements from 542 two-room apartments in Sweden in 2012 [23]. The occupancy data is hourly data averaged from instantaneous measurements using electronic diaries (logs) in 37 two-room apartments over a 14-day period in 2013 [22]. These hourly values are used in Paper II and averaged daily profiles corresponding to different percentiles derived from this database are used in Paper I.

Looking at the heat balance of an apartment, the magnitudes of two important variables, occupancy and household electricity use, and when they are used play a key role and these are dealt with in this study. However, there are resident-induced schemes that can also affect the indoor temperature and that do occur in reality but these are not covered by this study. The two primary ones identified are window-opening behaviour and management of solar shading, such as blinds and awnings. It is an established fact that window-opening occurs quite extensively, even during the heating season [28, 29]. The major part of the simulation study was carried out using a January climate, to avoid the influence of the sun, and thus to minimize the need to deal with solar shading operation in detail.

The weather data was gathered as hourly values from the Swedish Meteorological and Hydrological Institute (SMHI) [30, 31]. Twelve consecutive climatic years are used in this study. Table 2 summarizes the contents of the papers regarding the inputs and the level of detail.

Table 2. Variable levels of detail in the papers.

	Paper I	**Paper II**	**Paper III**
Occupancy	Simplified	Detailed	Detailed
Household Electricity	Simplified	Detailed	Detailed
Window opening	-	-	-
Operation of solar shading	-	-	-
Heating set point	Constant	Constant	-
Climate	Detailed	Detailed	Detailed
Ventilation	CAV	CAV	Natural ventilation

2.4 Parametric analysis

The strength of simulation tools is, as mentioned previously, the possibility to cover a broad spectrum of outcome and extreme conditions, not easily obtained through field-studies. Apart from the impact of the variables mentioned previously, the building envelope properties impact the temperature drops after a power cut, as shown in Paper I and II. Both these papers address the problem of different building types, represented by buildings from different periods, specifically a 1960s building, a standard building code building and a building with Passive House standard. The building envelope properties used are summarized in Table 3 and are derived from the study by [23]. Furthermore, different levels of thermal mass are investigated and the behaviour of a building with hydronic radiators compared to hydronic underfloor heating systems is also investigated in Paper II. A third option, with air heating, often used in Passive Houses, has not been investigated.

Table 3. Building envelope properties of different periods.

Building comp	PH Values	Std Values	60s Values
$U_{Exterior\ wall}$	0.1 W/(m²K)	0.18 W/(m²K)	0.4 W/(m²K)
U_{Roof}	0.08 W/(m²K)	0.13 W/(m²K)	0.25 W/(m²K)
U_{Window}	0.8 W/(m²K)	1.3 W/(m²K)	2 W/(m²K)
U_{Ground}	0.1 W/(m²K)	0.18 W/(m²K)	0.4 W/(m²K)
Air leakage	0.3 l/(s m²) ext. area at 50 Pa	0.6 l/(s m²) ext. area at 50 Pa	1.2 l/(s m²) ext. area at 50 Pa
Thermal bridges	20 % of $U_{tot} \cdot A_{tot}$	20 % of $U_{tot} \cdot A_{tot}$	10 % of $U_{tot} \cdot A_{tot}$

2.5 Measurements versus simulations

Power reductions were also investigated through measurements in two types of buildings. A simplified step-response field test was performed in one single-family dwelling and one multi-family dwelling from the mid-1900s. This was combined with simulations of the two cases in order to assess the ability to simulate the thermal behaviour of a building subjected to a power cut.

Important aspects, such as the amount of internal mass or fictive furniture, were studied. In the simulations, internal mass was added, using different amounts of surface area and mass, and was compared to the measurements. Another variable that was identified was a differing temperature between the rooms and between the apartments. When designing a system for intermittent heating there is a need to handle these variations, for example regarding the amount of furniture, and this could be seen as a first step in creating a base for consultants to work from. This is covered in Paper II.

3. Appended Papers

This section provides short summaries of the papers on which this thesis is based. The main results and the relevance of the findings will be shown as well as one or two example figures from the papers to highlight the way in which the results are presented.

3.1 Paper I

The purpose of this paper was to investigate the temperature drop following a power cut in a multi-family building using an approach with large numbers of simulations of randomized input data for each apartment. The results were presented as temperatures with their probabilities of occurring. A first step towards handling the varying residents was to apply simplified daily profiles derived from the measurements by [23]. The daily profiles varied and are expressed in five steps, from low to high, regarding both household electricity usage and occupancy. From these five profiles one was randomly picked for each apartment and was applied for each day of the simulation.

The main conclusion from this study is that having an underfloor heating system while being subject to a power cut the probabilities are fairly low of creating a too low indoor temperature, even after a complete cut in power for 6 hours. This is also true for buildings with envelope properties corresponding to the 1960s standard but then the need for a heavy building frame becomes more prominent.

The simulated building was an existing building in Malmö in the south of Sweden, built in 2013. It has an apartment floor area of 1077 m^2, with 15 apartments in sizes varying from 60 to 90 m^2. There is an underfloor heating system embedded in the concrete floors in each apartment.Three main simulation tests were performed, based on:

1. Household electricity and randomized occupancy
2. In addition to 1, different climatic years
3. In addition to 1, different building envelope properties and amounts of internal mass

The power was cut off completely during a time span of either 2, 4 or 6 hours, starting at midnight or six in the morning. These power cuts were in turn tested each day during the entire heating season and in addition to this the resulting temperature drops differ due to the different areas of the apartments (geometry), the amount of internal heat gain and the duration of the power cut.

In Test 1, only the internal heat gains were randomized and the outside climate and envelope were kept the same. Test 2 repeated Test 1 for different climatic years for the same location. In Test 3, envelope properties of three different eras were investigated, combined with different amounts of internal mass. The results from Test 1 are shown in Figure 1 and a detailed description of how to read the diagram is given in the caption. Each of the six curves in the figure represents a specific power cut duration and consists of minimum temperatures following this cut. The curves, individually, consists of the minimum temperatures from all the 15 apartments for each day during all the heating seasons for the specific power cut duration, sorted in ascending order. In this case, 60 heating seasons were simulated with randomized internal heat loads.

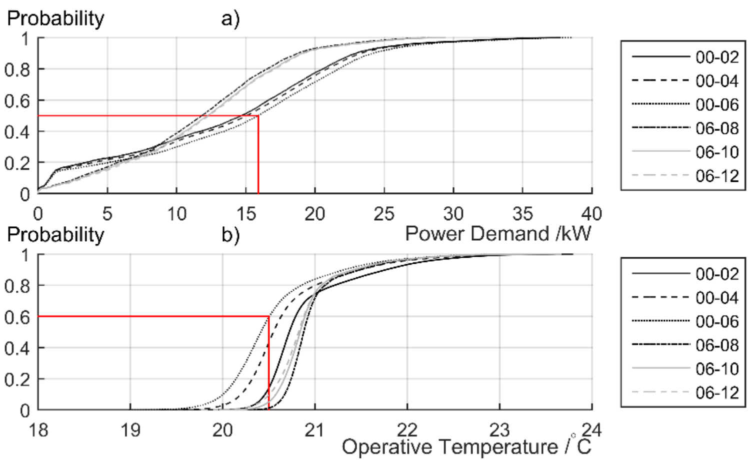

Figure 1(a) Distribution of power demand shown for each of the six different durations without power. 1 kW = 3412 btu/h. (b) Distribution of minimum operative temperature for each of the six different durations without power. 20 °C = 68 ºF. In a) each curve represents the power demand for each day of the heating season for the whole building. The red line shows median power demand for the cut-off period between 00-06 (15.9 kW). In b) each curve shows the temperature after the cut-off each day of the heating season for the 15 apartments. The red line in illustrates the probability of having a lower temperature than 20.5 °C for the same cut-off period (00-06).

3.2 Paper II

The purpose of this paper was to more thoroughly investigate the impact of different residents by using hourly data from measurements as input and the entire database of residents' household electricity usage and occupancy that the daily profiles in Paper I were based on. Another important aspect is the two different heating systems that were investigated, hydronic radiators and underfloor heating. A generic apartment, situated in the upper corner of a four-storey building, with four of its six 'sides' in contact with the outdoor environment, i.e. the apartment most subjected to the climate conditions was used for the simulations. The envelope properties of the three building eras in Paper I were also tested in this paper. For each of the three envelope properties, the impact of two cases of thermal mass, heavy and light, were investigated. A way to correlate the temperature drop to the duration of the power reduction and the outdoor temperature is presented as well as an option directly linking the power output in the apartment, just before the power reduction, to the temperature drop.

Although this is considered to be a worst-case scenario with a very exposed apartment and no internal mass, neither from furniture nor internal walls separating rooms, the results are still promising, primarily for buildings with a heavy envelope. Underfloor heating again performs best thanks to the closeness of the heating supply and the mass in the concrete floor, thus raising the entire mass of concrete to a higher temperature than in the radiator case, where the concrete floor is closer to the air temperature.

As mentioned before, the generic apartment was tested for three envelope types representing building properties of different eras. For each of these cases, two different heating systems, hydronic radiators and underfloor heating, were tested as well as two cases of thermal mass, heavy and light. These properties are denoted, Rad L or H and Floor L or H in the two figures below showing the results from the apartment with a Passive House envelope. Figure 2 correlates the temperature drop with the amount of power output just before the power was cut off. It is analysed using two percentiles, the 5- and 50-percentile, for each parameter combination, for example Rad L. Together with the denoted parameter combination, the duration and time for the power cut corresponding to each temperature drop can be seen on the x-axis.

Figure 3 correlates a single parameter, Kh or degree hours, to the temperature drop. This parameter is defined as the difference between the design temperature of 21 °C and the mean outdoor temperature during the power cut multiplied by its duration. This is a way of combining two aspects of the power cut affecting the indoor temperature drop, i.e. its duration and outdoor temperature. This difference, correlated to the loss coefficient of the apartment, gives the power output needed to make up for the temperature difference. The fact that this parameter behaves similarly, regardless of time of day or duration of the power cut, makes it a valuable indicator when predicting the outcome of a power cut at a certain outdoor temperature for a certain duration.

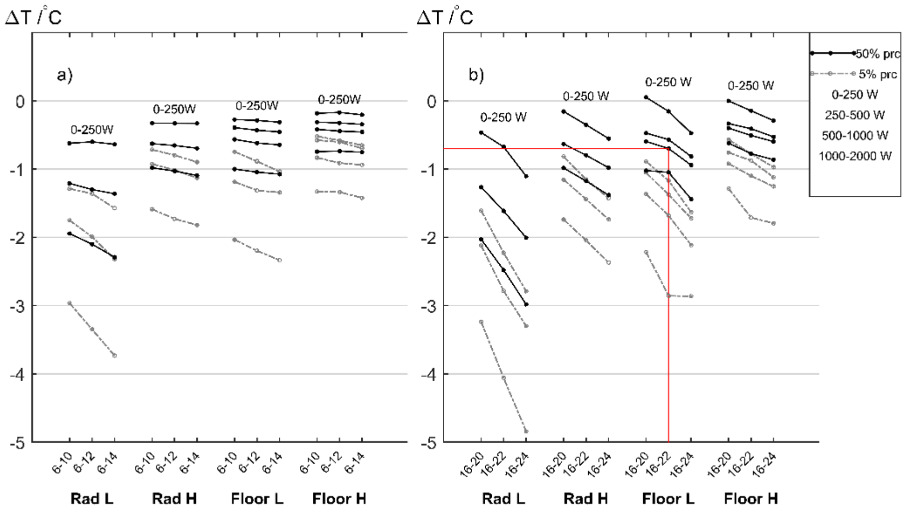

Figure 2. The impacts of the power cuts on the indoor temperature for the Passive House envelope in a) the morning cases and b) the evening cases. For each heating parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence. The red lines show an example. They show that the 50-percentile corresponds to a 0.8 °C drop in the case with a light envelope and underfloor heating during a power cut between 16-22. In this case, the power cut lies within the interval of 500-1000 W.

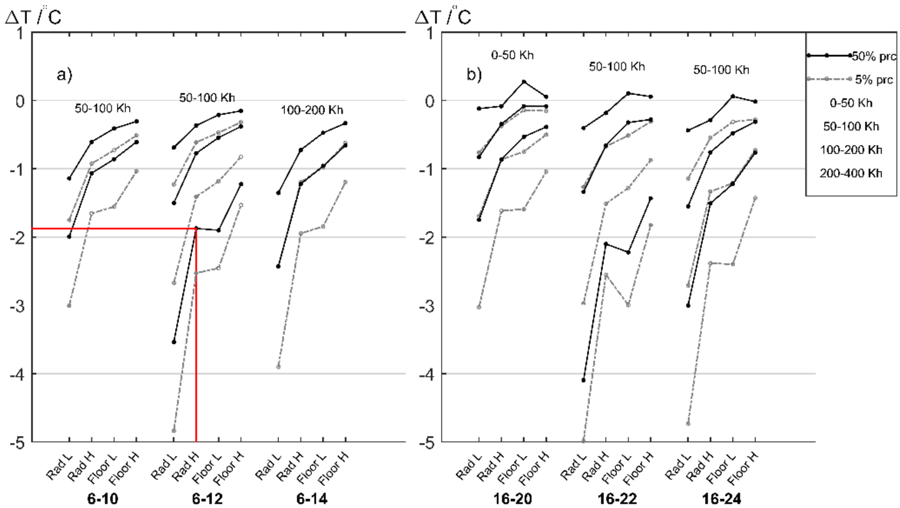

Figure 3. Degree hours (Kh) linked to the indoor temperature drop for the Passive House envelope for a) the morning cases and b) the evening cases. The four parameter combinations are grouped together for the three power cuts for the morning and evening. The temperature drops are grouped into intervals depending on the number of degree hours on each occasion and are represented by two percentiles for each interval, the 50-percentile (black) and 5-percentile (grey). These are plotted as dots, aligned over the respective parameters and the dots are then connected for all the parameters in the same percentile within the power cut period.

3.3 Paper III

The main purpose of this paper was, firstly, to show how the parameters furniture, ventilation and heat transmittance influence the possibility of cutting off power. This was done through field-studies of a single-family dwelling with temperature measurements in every room and a multi-family dwelling with one measurement in each apartment. The single-family dwelling was subject to a power cut of eight hours in contrast to the multi-family dwelling that was subject to a very long power cut (days). Secondly these measurements were compared to simulations and parametric analyses regarding the variable amounts of furniture to see whether correlations could be found. The main focus of the parametric study was furniture, or amount of internal mass, and the surface area of this mass in contact with the indoor air.

Two buildings were investigated. One was a single-family house built in 1956, located in the south of Sweden [long, lat]. This was a building in use with furniture and people present during the tests. The second building was a multi-family building built in 1966 located in the north of Sweden [long, lat]. This was an unoccupied building that was about to be demolished. The reason for this was not that it had reached the end of its service life but because of the need to expand an existing iron ore mine.

The two different building types investigated were therefore tested differently. The single-family house had the heating turned off during one night, approximately 8 hours. The temperature in the multi-family dwelling was measured at the time when the heating supply to the building was permanently cut off and during a subsequent cooling period of about two weeks. Due to the different sizes of the buildings, the number of sensors used also varied, with one being used in in every room in the single-family house and one in each apartment in the multi-family building.

In Figure 4 the measured temperature drop in the main rooms of the single-family house is shown. It is notable that the initial temperatures differ but the slope, or the declination rate, is quite similar in all the rooms.

Figure 5 shows the results from the parametric study of internal mass, or fictive furniture mass and ventilation rate. The case was simulated 96 times using different parameters and the results were investigated during periods of 2, 4, 6 and 8 hours looking at the differences between measured and simulated temperatures. These differences were plotted as distribution functions with negative values representing temperatures lower than measured and positive values temperatures higher than measured. Values close to 0 are the parameter set-ups where actual temperature drop curves are similar to those measured.

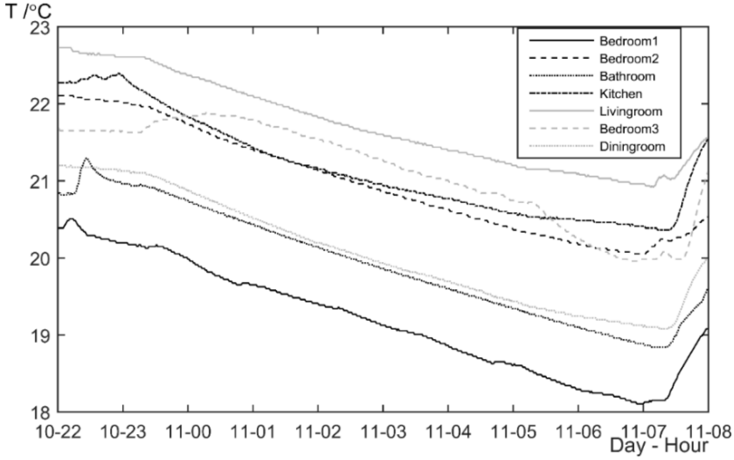

Figure 4. Measured temperature during an 8-hour power cut during the night, 23:00- 07:00, on 10-11 March. Displayed are the temperatures for the main rooms of a single-family building. The mean outdoor temperature during this power cut was 0 °C

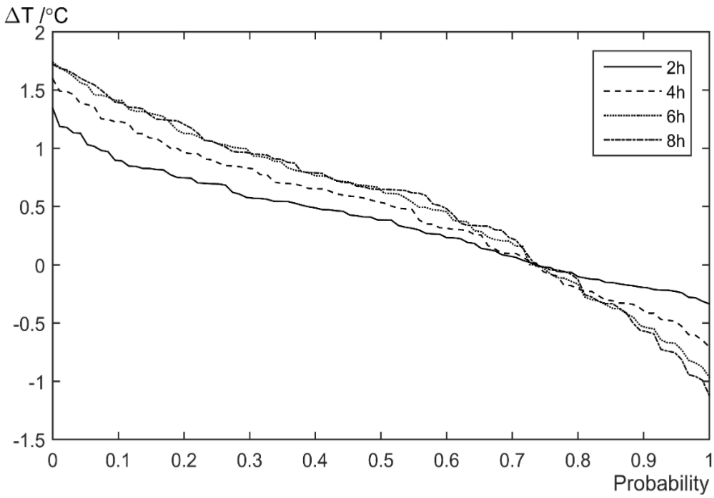

Figure 5. The differences between measured and simulation temperatures after 2 h, 4h, 6h and 8 h for 96 parameters shown as four distribution functions. Values close to 0 mean that the simulated parameter set-up had a temperature curve very close to the measured one. Positive values indicate a low simulated temperature and negative values a too high temperature.

4 Additional analysis

This analysis covers parts that are not shown in the papers and thus contributes to the aim by adding more information on the subject, for example regarding different geographic locations, mid-building generic apartments and a case in which the only exterior variable, the weather, was applied in the simulations. The method used in this additional analysis is the same as in Paper II and is explained extensively there.

4.1 Mid-building apartment

Paper II presents a wide range of results from a generic apartment situated in the upper corner of a multi-family building. This is a good representative of the worst-case scenario in terms of location with the highest possible number of exterior surfaces. A mid-building apartment would therefore not suffer the same temperature drop, with the same resident as the top corner apartment, and in this section an example is shown for Stockholm. The apartments here, however, with 1960s envelope properties, do not have exactly the same sets of variable inputs due to the randomization but they are all derived from the same database. On the other hand, as shown in Paper II, the dependency of the outcomes on the variables can be overcome by carrying out enough simulations to adequately cover the spread of the input, which means that the input differences should not matter.

Using the same simulation method as in Paper II, this part broadens the spectrum further by allowing us a view of the differences if we had chosen a mid-building apartment as a focal point for this thesis. The differences were significant but we have chosen to present only one example in order to demonstrate that looking at a corner apartment provides the maximum boundary conditions and all other apartments in a building are subject to lower probabilities for similar temperature drops.

Figure 6 shows the upper corner apartment and Figure 7 the mid-building apartment, for a building with envelope properties of the 1960s. The upper corner apartment has a much higher probability of dropping to a very low temperature following a power cut of the same duration as the mid-building apartment. It is clear that the location of the apartment matters significantly, especially for light envelope apartments and apartments with radiators.

However, it is worth noting that the power demand varies in magnitude between these apartments. This means that the comparisons need to be made between the probabilities related to the same power intervals.

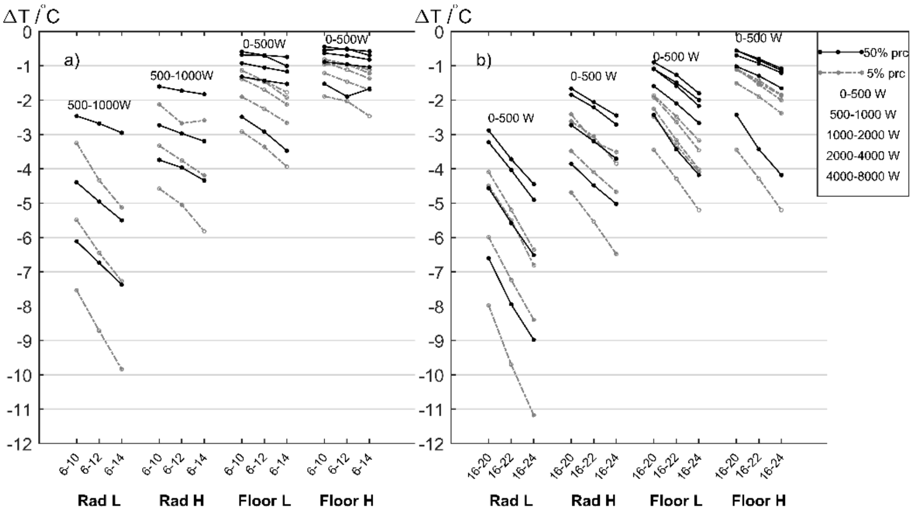

Figure 6. The impact of the power cut on the indoor temperature drop for an upper corner apartment with a 60s house envelope for a) the morning cases and b) the evening cases. For each heating parameter and power cut period the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence.

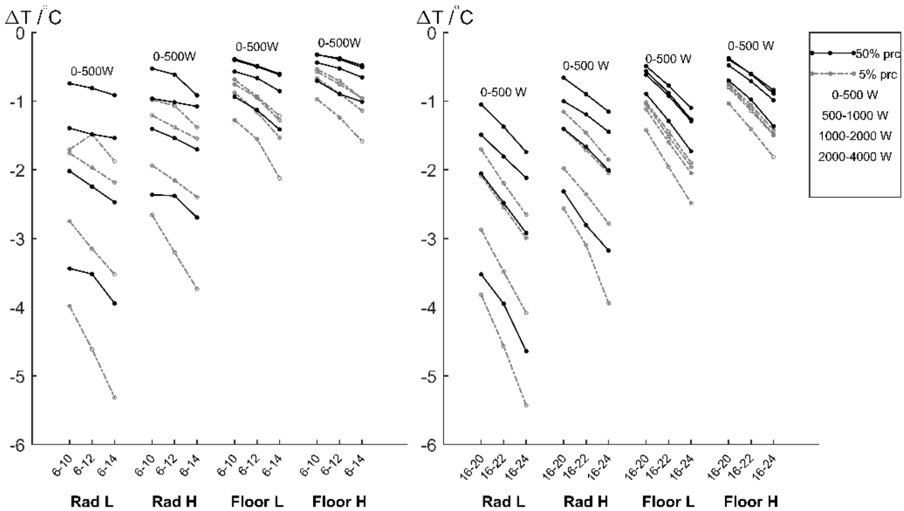

Figure 7. The impact of the power cut on the indoor temperature drop for a mid-building apartment with a 60s house envelope for a) the morning cases and b) the evening cases. For each heating parameter and power cut period the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence

4.2 Different geographic locations

Although it is safe to say that the outdoor conditions affect the indoor heat balance, and to the greatest extent in older buildings with envelopes of another standard than modern buildings, there are also variations between the climates of different years, making this impact greater or smaller. In Paper II, the geographic location of Stockholm [Latitude 59, Longitude 18] was studied and 10 different climatic years formed the basis for the randomization. Furthermore, the variations between different climatic years is one thing but even greater variation could be find should another location be studied. Stockholm can be considered to have a moderate Swedish climate and in this section two new locations in Sweden were studied, one in a northern colder climate (Kiruna [Latitude 68, Longitude 20]) and one in a southern warmer climate (Malmö [Latitude 56, Longitude 13]).

Figures 8-10 show the results from all three locations for standard building envelopes and upper-right corner apartments in the following order:

Stockholm, Malmö and Kiruna. Weather data for the same 10 years as used in Paper II were also applied in the studies of the other two locations.

Looking at these results, it is obvious that the outdoor climate is an important factor when considering the temperature drops. However, it is clear that the effects differ greatly between the parameter set-ups for the three different geographic locations. This means that a light and radiator heated building in a very cold climate is unsuitable for implementing power cuts while a heavy and underfloor heated one might be acceptable. This distinction is not that clear for a building located in a milder climate.

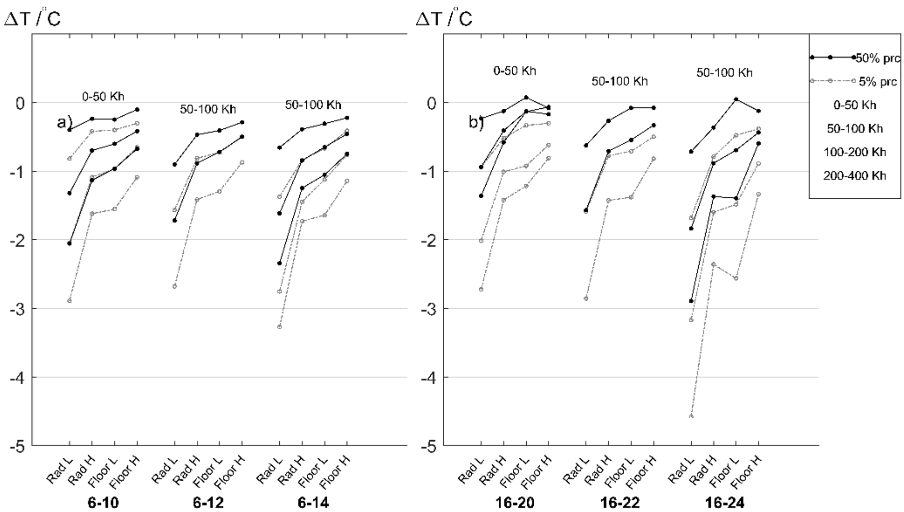

Figure 8. The impacts of the power cuts on the indoor temperature for an apartment with a standard house envelope located in Malmö for a) the morning cases and b) the evening cases. For each heating parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence.

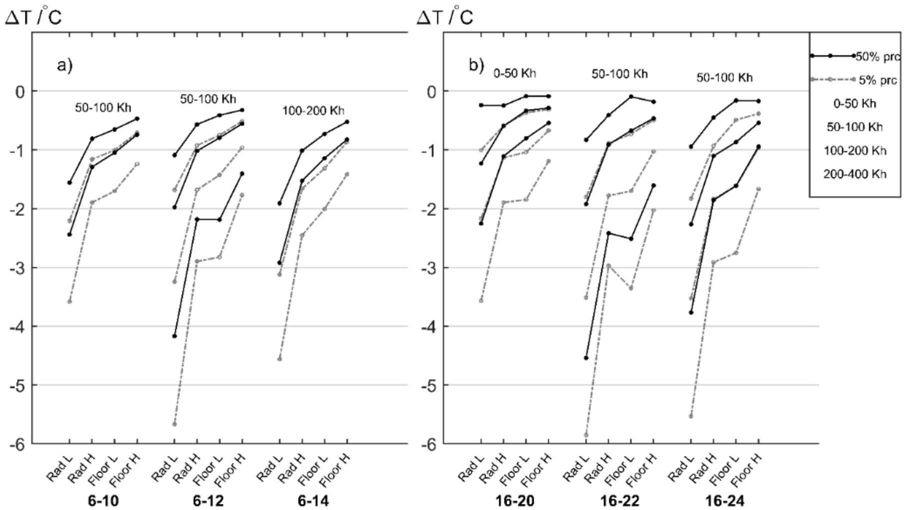

Figure 9. The impacts of the power cuts on the indoor temperature for an apartment with a standard house envelope located in Stockholm for a) the morning cases and b) the evening cases. For each heating parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence.

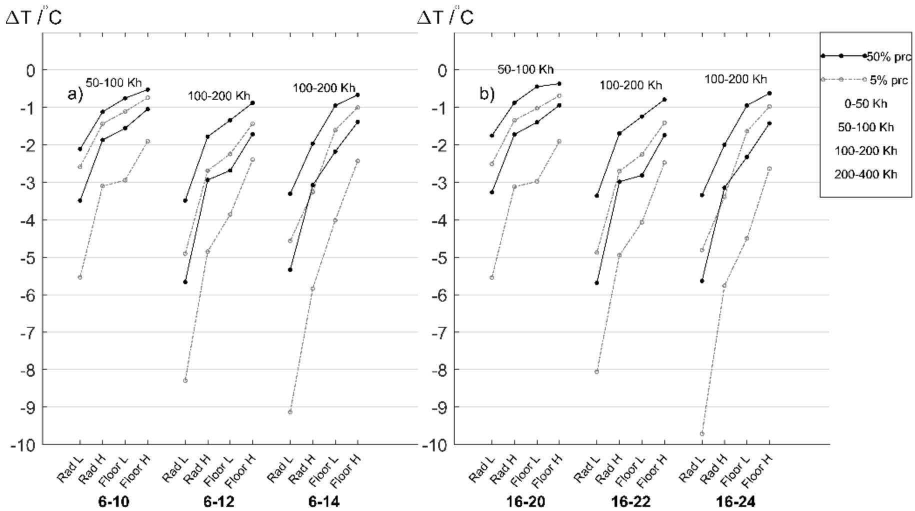

Figure 10. The impacts of the power cuts on the indoor temperature for an apartment with a standard house envelope located in Kiruna for a) the morning cases and b) the evening cases. For each heating parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence..

4.3 With and without internal heat loads

The last additional analysis investigates the difference between a case without internal heat gains and a case with randomized gains as presented in Paper II. The results are shown for a standard building envelope and Stockholm climate. The basic case is shown in the first figure, Figure 11 and the case with no internal heat gains is shown in Figure 11.

The difference between the two cases is not very large but it is nonetheless discernible. For the same probabilities about 1 degree less is lost in the case with internal heat gains. The heavy cases with underfloor heating are not affected this much. Also worth noting is that the required heat output from the heating system differs between the two cases, which also illustrates that the internal heat gains contribute positively to the heat balance.

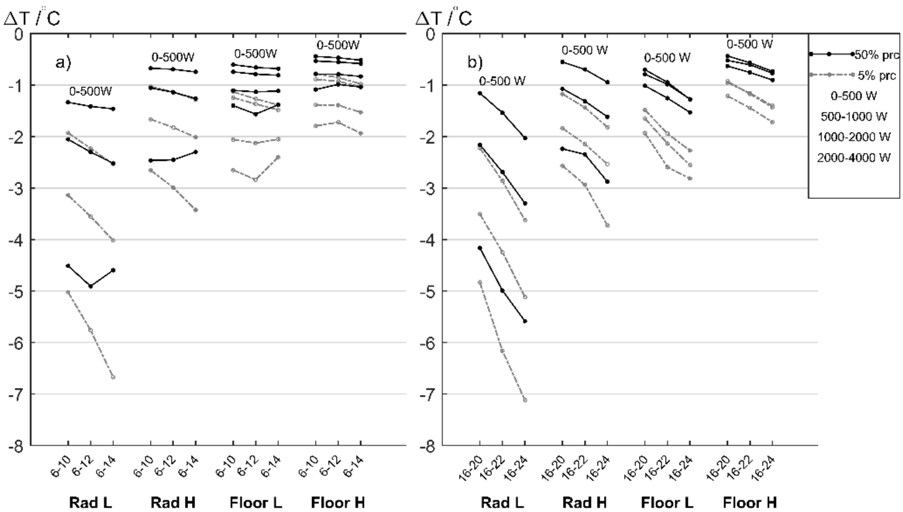

Figure 11. The impact of power cuts on the indoor temperature drop for a top corner apartment with standard house envelope for a) the morning cases and b) the evening cases. All simulations contained internal heat loads randomized from the input database. For each heating parameter and power cut period the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence

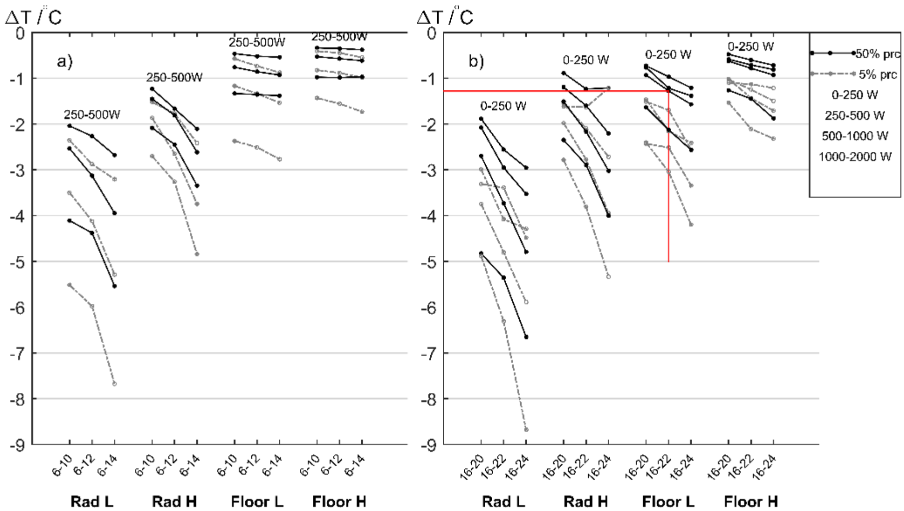

Figure 12. The impact of power cuts on the indoor temperature drop for a top corner apartment with standard house envelope for a) the morning cases and b) the evening cases. No internal heat gains were present in the simulations from which the results in this figure are derived. For each heating parameter and power cut period the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected to the same percentile for the same interval for the next power cut occurrence

5. Discussion and conclusions

The main conclusion from this study is that power cuts, the most severe form of power reduction, are possible to implement with low probabilities of achieving a too low indoor temperature. This is true mostly for heavy buildings with underfloor heating systems. However, this result was derived from a generic apartment without considering any internal masses such as furniture and internal walls. Measurements from a building in use correlated to simulations showed that the temperature drop after a power cut was lower in reality than in the simulations, if the furniture and internal masses were not taken into account.

Using a large of amount of data as a basis for input for simulations and then applying it by randomization in a great number of simulations, in order to create results in terms of probabilities, is an interesting new way of evaluating the impact of power cuts instead of looking at one particular building or apartment. It does, however, build on the belief that the data used adequately represents reality and that is something that needs further research.

The major contribution of this thesis is the new way of approaching the issue of intermittent heating and how it affects the indoor temperature drop. This was accomplished by running a large number of simulations. This approach handles the stochasticity of the internal heat loads, which determines the impact of the power reduction, by using real measured data as input applied by randomization. Running the simulations over different days, with different residents while reducing the power similarly a distribution of temperature drops is obtained correlated to the variety of the input. This answers the question of impact on the indoor temperature after a power cut not only for a particular apartment with a specific resident at a certain outdoor temperature but rather probable outcome of a certain power cut covering a wide range of residents and outdoor climate conditions.

A well-known fact is that the heavier the building the better it can withstand a power loss or reduction. This resistance is often based on the time constant, which is used for determining the design power of the heating system. The time constant works on a different time scale than the one interesting here. For example, the time constant can be 50 or 100 hours while we are interested in what happens during the first 8 hours at the most. When looking at this time frame the time constant is no longer a valid option for evaluating the capacity of the building, hence this new approach. However, the results do show that in heavier buildings, in fact, there is a much lower probability of the temperature dropping too low when compared to a light-framed envelope with the same transmission loss coefficient. An even more important factor is the choice of heating system, with underfloor heating embedded in a concrete floor being superior to the more common system in Sweden using hydronic radiators. The choice of heating system depends on many factors and, looking at the results, this could be another reason for making a different choice.

Comparing measurements and simulations of a power cut showed the importance of another possible variable connected to the resident, namely the amount of furniture or internal mass. Relatively simple measurements were performed and an attempt to find a level of furniture fitting the temperature drop curve of the real case with that of the simulations were made and promising, though slightly unrealistic results, were found.

This thesis does not fully answer all the issues at hand but raises a new interesting question and provides an opening for another discussion when presenting the results as distributions of possibilities or probable outcomes. What should the limits be? Fanger [32] showed that we tend to tolerate a minor drop from the optimal temperature, of 1.5–2 °C. Furthermore, Fanger's results shows that, in the end, there are always some people who are dissatisfied. Taking this further, should residents be compensated, for instance financially, if they were to allow a certain temperature drop and would that make them more inclined to agree to one? The business model for implementation of this kind of intermittent heating is not within the scope of this thesis but does raise the question whether comfort could be translated into actual money. How much do the residents value a certain temperature? These are interesting issues and could be the subject of further studies.

In order to perform the huge amount of simulations required, a similarly huge database of input was required, input that represented all possible types of residents living in average homes. The database for this study was extensive and the issues relating to this data are discussed further in a sub-section below.

5.1 Method

The method used in this thesis is one that employs extensive simulations with randomized input variables in order to statistically show the risk or probability of a certain temperature drop following a power cut. The power was cut each day during the simulations and the resulting temperature drops were evaluated. This meant one temperature drop in each apartment for each day of the simulated period. All these temperature drops can then be seen as a distribution dependent on the input in that particular simulation. The "answer" is thus an interval with a minimum and a maximum temperature and all the other temperatures fall within this range. Probabilities of certain temperature drops occurring can then be established, for instance 1 °C.

Some measurements were also made, temperatures were measured in each room of a single-family building during a field test with a power cut. Another field test was performed showing the impact of a power cut over a much longer period of time for a multi-family building.

It has already been stated that the generic apartment investigated is the worst-case scenario due to its many sides exposed to the outdoor climate. A simplification making it even more vulnerable is the apartment being modelled as one coherent zone or room. This means that no internal mass in terms of walls etc. were accounted for. Also, IDA-ICE models each zone as one air node connected to the walls, which means that all the air is directly connected to the exterior walls in the simulations, which, of course, is not the case in reality. When comparing measurements with simulations this issue might become crucial. The temperature was measured in one location in the apartments of the multi-family building, and later modelled as one zone, and in one location in each main room of the single-family building, this was made in Paper III. The spatial temperature difference that does not exist in the simulation software (due to all the air being one accumulated mass) is another issue that could be a reason for not obtaining correlations.

In the evaluation, the temperature or temperature drops shown are derived from the minimum operative temperatures after the power cuts. The minimum temperature obviously shows the most severe impact in the indoor temperature but occurs almost momentarily just before the power is turned on again. As the minimum temperature says one thing an alternative way of describing the temperature drop could be the mean temperatures during the entire period without heat or the lowest hourly average during the same period instead of the entire period. There are many alternatives and it all comes down to the one which will translate these results into something applicable. Whatever the case, it is necessary to know what kind of temperature drop can we allow and what residents will accept. Therefore, it might have been more interesting to look at averages over longer periods of time instead of momentary values.

In the opening text of this chapter, the outcome of each simulation batch was a range of temperature drops creating a distribution with minimum and a maximum temperature. The width and look of the distribution depends on the input variables, duration of the power cut but also on how many simulations the batch contains. This distribution, together with the width of the interval, changes with the number of simulations, thereby representing more of the input variable combinations as the number of simulations increase. To cover all combinations for each parameter set-up was not possible as the simulations would have been too time-consuming, and a sufficient number of simulations had to be estimated. To make this even more difficult, the weather alone comprised 5 different variables, all of them time-dependent. This means that one cannot look at a solitary hourly extreme value (however unlikely) as it might be worse to have 20 consecutive moderately severe values. Due to these complexities, a large batch of simulations with randomized input were performed and the results from these were used as the “true” distribution. This data was then used to determine how many simulations it would take before certain percentiles converged. If the very extreme combinations in each batch were to be covered, an extreme number of simulations would be needed.

5.2 Internal heat loads

The internal heat loads can be expressed as two different variables: occupancy and heat transformed from electrically powered household devices. A third possible source is heat emitted into a room due to domestic hot water usage, and the opposite negative value due to the use of cold water, both of these cases were not investigated. These are all “primary” sources of internal heat gains. There are also heat gains, or losses, caused by the residents’ interactions with the building. In these cases, the heat balance is usually affected by the outdoor climate in some way, either by a resident operating solar shadings or by opening a window. These resident induced actions are not included into this study.

Simplifications were already made during the gathering of the data input material as it was collected as hourly averages. What would have happened if we had had an even higher resolution in our measurements and simulations is something for further investigation. The choice was made to consider the whole measured amount of electricity being converted into heat in the apartment. This could be regarded as an exaggeration and that is probably true. On the other hand, to have been completely correct, measurements would have to have been made for each individual socket load and that would have been impossible. This factor could be added as another variable with a certain probability, for example the amount included for the apartment could vary between 0-100 %, where the extremes obviously would have low probabilities. It is also more likely that household electricity is used inside the apartment than outside. However, data to form this probability function does not exist and therefore the measured values were chosen. Looking at the occupancy, the data input material was less extensive than for the household electricity and for obvious reasons. The measurement of electricity does not need to involve the residents, unlike the electronic diaries used for registering the occupancy. However, there is a very great lack of data with high resolution in time for occupancy in dwellings and the data that was obtained, even though it was from a small database, showed great variations, both over time in the same household and between households.

Furthermore, the actual heat emitted from each person varies with their current activity, which is also an unknown factor. 1 MET was the value used throughout this study and it corresponds to someone sitting down at rest. This value might be the best one to represent the residents but there are occasions when we for example cook, clean or play with children that would increase it.

In an ideal world, there would be a data bank of extensive measurements of every variable in order to determine the distributions of the sort shown in this thesis. This would allow the performance of a building to be simulated, producing a range of outcomes, with different probabilities, covering nearly everything possible in the "real world". The first step would be to actually measure these variables and that is a great project in itself. However, the number of simulations needed in this thesis would be impossible for consultants to engage in timewise. Nor would they have the computer capacity, when designing a normal project, even if the data existed. There is a need for more research to create knowledge of these variables and create suitable guidelines and benchmarks that can be easily applied in simulation models for consultants when designing new buildings.

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Appendix

Using the Thermal Mass of a Building to Reduce the Magnitude of the Peak Power Demand of the Primary Heating System- A Whole-Building Simulation with Parametric Analysis **PAPER I**

Victor Fransson, Dennis Johansson, Hans Bagge (2016)

Thermal Performance of the Exterior Envelope of Whole Buildings XIII – International Conference 2016

Using the Thermal Mass of a Building to Reduce the Magnitude of the Peak Power Demand of the Primary Heating System—A Whole-Building Simulation with Parametric Analysis

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ABSTRACT

The idea of using the thermal mass of a building to maintain a more constant indoor climate is not new. This particular property of a building, including its exterior envelope, plays an important part in the reduction of peak power demands, which is becoming an increasingly urgent issue for the heating energy suppliers. The latest smart-grid technology creates new opportunities where communication between customers and heating energy suppliers, and the resulting invoicing on a shorter time-basis, is concerned. Smart-grid technology can be used to lower the primary energy use as the magnitude of the power peaks and, consequently, their impacts can now be reduced. Reducing peak power demand will, however, impact the indoor temperature. At present, there is a lack of knowledge regarding how different factors determine the magnitude and rate of temperature drop when power levels are reduced. These factors include a combination of the heat transmittance, airtightness, and thermal mass of the exterior envelope, as well as the internal thermal mass of the building, the building services, and occupant behavior over time. In this study, the IDA-ICE *building simulation software has been used to perform whole-year simulations of an existing apartment block with 15 apartments. Different power reduction schemes were tested and the impact of variables, such as household electricity usage, occupancy levels, and outdoor climate, were analyzed. The influence of different building envelope parameters, including thermal capacity, insulation levels, and airtightness, were also analyzed. The purpose of this study was to investigate how combinations of these variables and parameters affected the indoor temperature drop during the different power reduction schemes.*

INTRODUCTION

Reducing energy usage is one of the many challenges the building industry has to face. However, a more recently recognized problem is not the energy use itself but how much power is required and the point in time when it is needed. If the simultaneous production and demand levels for power are examined, there are always occasions when these levels will be mismatched. However, this mismatch is not caused by an actual shortage of power (i.e., when the maximum capacity on the supply side is reached) but by the way in which the power is produced or distributed. Mismatches occur during the heating season when demand is high: when cheap fuel is limited there are economic issues, and when fossil fuels are needed to meet demand there are environmental issues. In the case of district heating, which is a major source of heating for multi-dwelling buildings in Sweden, there are other factors to consider, such as the efficiencies of boilers, the starting up and shutting down of boilers, and the capacity of the pipes supplying different parts of the city. There is also the question of significant investments being required to lay new pipes in order to add new customers. To summarize, this paper is based on the fact that utility companies want to reschedule when their power production takes place, as it is sometimes either unnecessarily expensive or "dirty" in terms of CO_2 emissions.

One way to address this issue it to use demand-side management, which has been made possible thanks to the new smart-grid technology, whereby the demand side modifies its heating requirements in order to lessen the demand on the heating supplier. Extensive studies where carried out in the 1980s concerning the benefits of thermal mass during the heat-

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ing season. Burch et al. (1984) carried out measurements that were verified by simulations. They showed that having a high thermal mass was advantageous when temperatures were allowed to deviate from the thermostat set points, a consequence of the building structure being charged by internal heat loads. A test to use the thermal mass of buildings in a smart-grid system, by offsetting the supply temperature to the hydronic heating system (Kärkkäinen et al., 2003), was performed and resulted in a reduction of the heating load by up to 25%, with an indoor temperature drop of only 2°C. Werner and Olsson Ingvarsson (2008) carried out measurements in apartments while offsetting the outdoor sensor by up to 10°C, causing the control system to turn the heat off. This, in turn, caused the indoor temperature to decline by up to 2°C. Johansson et al. (2012) had another approach when investigating a system in which an oil-fired heating system handled the peak loads: a scheme to avoid using the heating system as much as possible, by using the properties of the heavy structure of the building, was devised and good opportunities for reducing CO_2 emissions were observed without compromising the indoor climate. Kensby et al. (2015) had a similar approach to that of Werner et al, and offset the outdoor temperature sensor in order to discharge and charge the building in their pilot test. The test was performed in five multi-dwelling buildings, constructed between 1920 and 1940, and the temperature was measured in two apartments in each building. The impact on the indoor temperature was, in the worst case, 0.5°C as a weekly average. Reynders et al. (2013) showed, using simulations of a single-family building, the gains achieved when using its thermal mass and varying the heating loads over time by using a heat pump for which the price of electricity varied. An underfloor heating and radiator system was investigated, and it was found that the peak power demand reductions were between 75% and 95% if a 4°C drop in the design indoor temperature was accepted.

Aim

As stated above, many field tests have been carried out to study this issue, and these have shown promising results. Field tests are usually subject to limited time, money, or access, and although they are authentic, they are usually performed over a rather short period and in a limited number of cases. This study aims to show the impact of reducing the power load during each day of whole heating seasons, of different heating seasons, for different building envelope properties, and for randomized internal loads in 15 apartments. The simulation variables chosen to focus on in this paper are weather, occupancy, and household electricity loads combined with the building envelope properties' U-factor, thermal mass, and air leakage. A whole-building simulation covers differences between apartments due to geometry. For example, corner apartments can have a much larger surface area exposed to the outdoor conditions, and facades with different orientations can be subject to different wind effects. A complete shutdown of the heating system is used to get a clear picture of its impact on the result and to avoid having to deal with the problem of turning off the system in practice. One proposed way of achieving this could be that suggested by Kensby et al. (2015) in which the supply temperature of the water that feeds the hydronic heating system is reduced. However, here it is of greater importance to see how the building reacts with regard to internal loads and the outdoor climate. The reason for not using a more sophisticated model for determining the point in time to reschedule the loads is because, as mentioned in the introduction, it varies depending on the specific location and grid layout, fuel prices, boiler types, etc. This paper thus focuses on what happens in the different apartments in terms of temperature and, at a whole-building level, in terms of the power demand that could be reduced.

METHODS

The simulated building is an existing building in Malmö, in the south of Sweden, built in 2013. It has an apartment floor area of 1077 m^2 divided into 15 apartments, with sizes varying from 60 to 90 m^2. There is an underfloor heating system in each apartment embedded in the concrete floors. For the first and second simulation tests the parameters of the actual constructed building were used, and these can be found in Table 1. The ventilation rate for every simulation was 0.35 $L(s{\cdot}m^2)$, the rate required to fulfill the regulations stated by the Swedish Building Agency, with a heat exchanger with a temperature transfer efficiency of 78%. The design temperature in all the apartments was 21°C.

Table 1. Building Envelope Areas and Thermal Properties

Building Envelope	Area, m^2	U/W, m^2K	U·A, W/K	% of Total
Walls	630	0.16	100.5	16.2
Roof	330	0.17	56.2	9.1
Windows	199	1.36	270.5	43.6
Ground	330	0.07	25.0	4.0
Thermal bridges	—	—	168	27.1

The *IDA-ICE* 4.6.2 (EQUA 2014) building simulation software was used for this study. The model was created in *IDA-ICE* and run through its batch mode using MATLAB (The MathWorks 2015) for automation and changing variables and parameters.

Simulation Setups

Three different simulation setups were used. For each of them, the household electricity load and occupancy load were the profiles shown in Figure 1. The household electricity load was derived from hourly measurements in over 1000 apartments in Sweden during a two-year period (Bagge et al. 2012). The occupancy profiles were derived from measurements using electronic diaries in 86 apartments over a period of 12 to 13 days (Bagge and Johansson 2015). In order to randomly select these variables, the percentiles were assigned different probabilities covering the intervals around the existing five percentiles. For example, the probability of choosing the 50% percentile is, in this case, 25%, corresponding to covering the interval between 37.5% and 62.5% percentiles. The same probability was assigned for the 25% and 75% percentiles, whereas the 5% and 95% percentiles cover only half that interval and are thus assigned only 12.5% probability. This random assignment of internal loads was made prior to each simulation for each of the 15 apartments. The chosen household electricity profile was applied for all the days of the year, and the occupancy profile was randomized every two weeks, corresponding to the measured period from which the data was derived.

Due to the reasons discussed earlier, it is not known when it is most favorable for the heating supply company to desire a lower heating demand. Therefore, three different durations without supplying heat were investigated: two, four, and six hours. These three durations were then investigated using two different starting times, midnight (00:00) and six o'clock in the morning (06:00), resulting in six different ways in which the heating system could be turned off. These cutoff parameters were applied to each day of the simulation.

First Setup. The building envelope was as shown in Table 1. This setup was run through 60 heating seasons with randomized internal loads for each of the six different periods without heat.

Second Setup. The building envelope was as shown in Table 1. Twelve different climate years for the same location were investigated. The weather data was collected from the Swedish Meteorological and Hydrological Institute database (SMHI 2015a, 2015b). The internal load variables were randomized in the same manner as in the first study. Five heating seasons for each year were investigated for each of the six cutoff periods without heat.

Third Setup. In this study, the impact of the building envelope was investigated. The climate year was kept the same and the variables were changed in the same way as before. Building envelopes from three different periods were investigated: building properties were obtained from Bagge et al. (2012) and are presented in Table 2. The three building envelope types are passive house (PH), a standard Building Code building (Std), and a typical building from the 1960s. Changes to the exterior envelope where made, while keeping the heat transfer coefficient

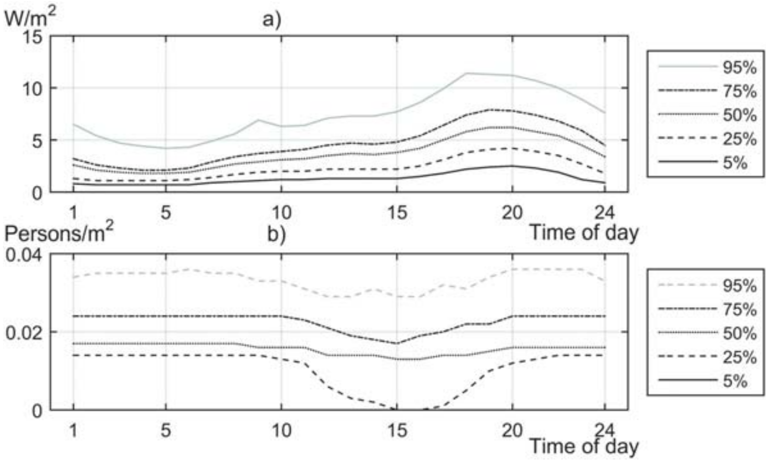

Figure 1 *(a) Household electricity load in W/m² apartment area for each hour of the day, shown in percentiles from measured data. 1 W/m² = 0.32 Btu/h ft². (b) Number of persons per square meter of apartment area present during each hour of the day, shown in percentiles from measured data. 1 m² = 10.76 ft².*

constant. Two cases of thermal mass were investigated for each of the building types, heavy and light. In the heavy case, concrete was added on to the interior sides, 10 cm to exterior walls and 20 cm to the roof. In the light case, there were curtain walls (non-load-bearing facades) with insulation, wooden studs, and a 13 mm gypsum board on the interior side. Three different areas of internal walls were also added (in addition to the walls separating the apartments): 20, 40, and 60 m^2 respectively. The interior walls were simulated as 10 cm concrete walls or as curtain walls in the same way as the exterior walls but with double gypsum boards on both sides. Each of the 18 cases were investigated during five heating seasons for each of the six periods without heat.

RESULTS

The results are presented as distribution functions for the first two setups and summarized in tables; the results from the third study are shown only in table form. Each data point regarding temperature corresponds to the minimum operative temperature in one apartment during the period without power. The power demand is for the whole building and each data point corresponds to the heating demand for all 15 apartments just before the heating system is turned off each day. The percentage results of each setup should not be compared to one another, as they are derived from different numbers of simulations.

First Setup

The results from the first setup are shown in Figure 2 and Table 3. Notable, but reasonable, is that most power can be saved during the night. As discussed previously, the power demands on the heating supply companies can be due to a number of different factors. Not only the outdoor temperature but also behavioral aspects (such as high use of domestic hot water, which is prominent during the morning hours) affect the demands. Turning off the heating during the morning hours almost never causes the temperature to drop more than 0.5°C from the design value, thus "saving" up to 30 kW in power demand.

Second Setup

Three years that differed visibly were chosen and are shown in Figure 3. Here, all the six cutoff periods are combined into a single graph for each year. The results from all twelve heating seasons are summarized in Table 4. For most of the years, the results are similar. However, they can differ. Looking at the two extremes, in the 0.5°C temperature drop there is a twofold spread, which increases to a fivefold spread in the 1°C temperature drop.

Table 2. Building Envelope Properties for the Different Periods

Building Component	PH Values	Std Values	1960s Values
Exterior wall	0.1 $W/(m^2 \cdot K)$	0.18 $W/(m^2 \cdot K)$	0.4 $W/(m^2 \cdot K)$
Roof	0.08 $W/(m^2 \cdot K)$	0.13 $W/(m^2 \cdot K)$	0.25 $W/(m^2 \cdot K)$
Window	0.8 $W/(m^2 \cdot K)$	1.3 $W/(m^2 \cdot K)$	2 $W/(m^2 \cdot K)$
Ground	0.1 $W/(m^2 \cdot K)$	0.18 $W/(m^2 \cdot K)$	0.4 $W/(m^2 \cdot K)$
Air leakage	0.3 $l/(s\ m^2)$ ext. area at 50 Pa	0.6 $l/(s\ m^2)$ ext. area at 50 Pa	1.2 $l/(s\ m^2)$ ext. area at 50 Pa
Thermal bridges	20% (U·A)	20% of U·A	10% of U·A

Table 3. Summary of the Distribution Functions

Time	Lowest Temp.	Probability of <0.5°C	Probability of <1°C	Highest Demand, kW	50% Percentile, kW	90% Percentile, kW
00–02	19.9	14	0	37.6	14.7	23.0
00–04	19.3	43	3	37.7	15.0	23.3
00–06	19.0	60	10	38.6	15.9	24.2
06–08	20.3	1	0	29.4	11.8	18.8
06–10	20.0	5	0	29.3	12.3	19.1
06–12	19.8	10	0	29.4	12.3	19.2

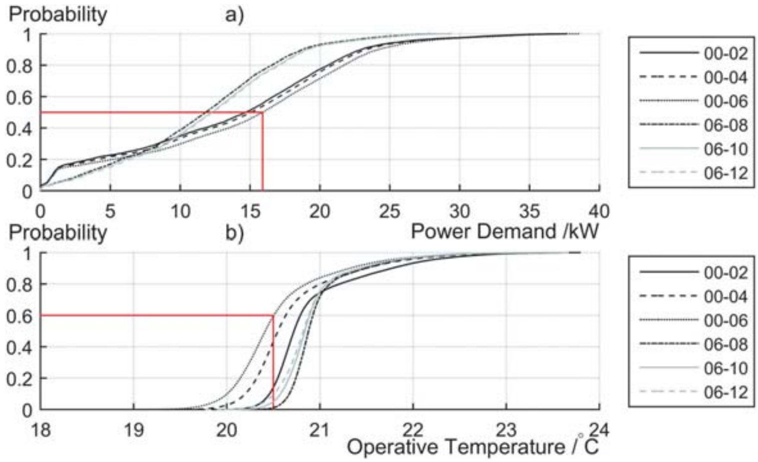

Figure 2 *(a) Distribution of power demand shown for each of the six different durations without power. 1 kW = 3412 Btu/h. (b) Distribution of minimum operative temperature for each of the six different durations without power. 20°C = 68°F. In (a) each curve contains the power demand of each day of the heating season for the whole building just before the power cutoff. The red line shows median power demand for the cutoff period between 00–06 (15.9 kW). In (b) each curve shows the temperature after the cutoff each day of the heating season for the 15 apartments. The red line illustrates the probability of having a lower temperature than 20.5°C for the same cutoff period (00–06).*

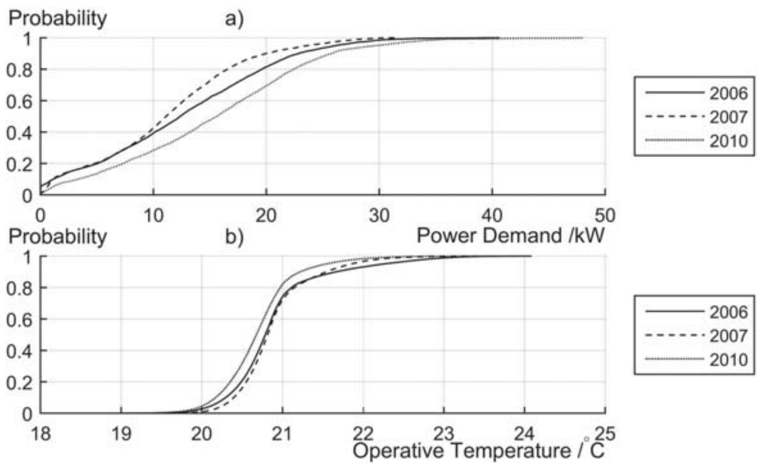

Figure 3 *(a) Distribution of power demand shown for three different heating seasons. The different durations without heat are combined into a single graph. 1 kW = 3412 Btu/h. (b) Distribution of minimum operative temperature. The different durations without heat are combined into a single graph. 20°C = 68°F.*

Table 4. Distributions during All the Investigated Years

Year	Lowest Temp.	Probability of <0.5°C	Probability of <1°C	Demand Highest, kW	50% Percentile, kW	90% Percentile kW
2002	19.2	21	2	43.5	13.2	21.6
2003	18.7	23	3	43.1	13.3	23.1
2004	19.0	21	2	34.9	13.1	21.9
2005	18.8	21	2	37.7	12.6	23.5
2006	18.8	21	3	40.6	12.4	22.8
2007	19.2	16	1	31.4	11.1	20.0
2008	19.2	18	1	33.8	11.6	20.5
2009	19.1	22	2	37.6	13.4	22.0
2010	18.6	32	5	48.0	15.6	25.8
2011	19.1	20	2	35.4	12.3	22.0
2012	18.9	21	2	39.7	12.3	23.9
2013	18.9	23	3	40.6	13.1	23.8

Third Setup

The results from the third setup are summarized in Table 5. Many combinations were investigated, and it is clear that the heavy, more massive buildings offer more advantages when rescheduling power loads; looking at the 1960s case there is twelve-fold difference for the 1°C drop. It can also be seen that the passive house construction has a very low power demand in absolute terms, rendering it a poor subject for heating suppliers and to warrant power load rescheduling. Adding more mass indoors also clearly lowers the risk of unwanted low temperatures when subjecting apartments to a heating power cutoff.

CONCLUSION AND DISCUSSION

Simulation software is a very powerful tool when there is a need to handle many variables and different parameters. It makes it possible to investigate factors that would be impossible to apply in real cases. However, as it only provides simulations, the results should be viewed as indicators. It is not the investigated temperatures themselves that are the major advantage of using a simulation software but being able to compare different simulation setups with one another.

Randomizing occupancy and household power demand is one way of imitating reality. The profiles used might sometimes seem imprecise, as the same profiles are applied for long periods of time. But, as two of the variables are randomized, namely household power demand and occupancy, with the latter over a shorter time period, two weeks, numerous different combinations of these will arise. Repeating them over many heating seasons allows these combinations to occur at different times of the year. This is one way of trying to handle such stochastic variables as occupancy and appliances. However, it should be noted that the values used are averaged percentiles and, for a more realistic simulation, real hourly data of these two variables on a yearly basis would be needed.

It is clear that the most critical case is the six-hour cutoff from midnight, as this would take place during the coldest hours of the day and also the hours with low internal loads. A complete cutoff of power would be quite drastic and would probably not be accepted in reality. However, reducing the power instead of cutting it off completely would result in less impact on the indoor temperature. This paper shows the worst case in terms of temperature drop and maximum reduction of power.

The majority of the buildings in Sweden that use a lot of energy (power) have similar properties to the one representing a typical 1960s building in this study. As they have poor building envelopes and consequently high power demands, they are also the buildings with the best prospects of reducing unfavorable power demands. The results show that the heavy 1960s buildings hardly ever experience a greater drop than 1°C, as shown in previous field tests. However, many of the buildings of this period do not have heat recovery in their ventilation systems, which is the case in this study. On the other hand, these buildings usually have natural ventilation, turning air leakage into ventilation losses instead of having both ventilation and leakage losses. Another factor is the use of underfloor heating, which can be presumed to be favorable in comparison to radiators or airborne heating systems, as the mass of the building structure is directly connected to the heating system.

Table 5. Distributions of All the Investigated Envelope Combinations

House Type	Mass	Added Interior Wall Area, m^2	Lowest Temp.	Probability of <0.5°C	Probability of <1°C	Max. Demand, kW	50% Percentile, kW	90% Percentile, kW
PH	Light	20	19.5	9	2	3.2	1.5	2.1
		40	19.7	6	1	3.2	1.4	2.1
		60	19.7	4	0	3.2	1.4	2.1
	Heavy	20	20.2	1	0	3.2	1.5	2.1
		40	20.3	1	0	3.2	1.5	2.1
		60	20.3	0	0	3.2	1.4	2.1
Std	Light	20	18.7	22	2	38.6	13.5	23.3
		40	18.9	17	1	39.0	13.4	23.3
		60	19.0	14	1	40.9	13.4	23.5
	Heavy	20	20.0	5	0	40.7	13.5	23.8
		40	20.1	3	0	40.7	13.8	24.0
		60	20.1	2	0	40.9	13.3	23.3
1960s	Light	20	17.5	38	12	56.6	23.0	35.3
		40	17.8	32	8	56.9	22.6	35.5
		60	18.0	27	6	59.3	22.5	36.3
	Heavy	20	19.3	18	1	56.4	21.6	34.6
		40	19.4	15	0	57.1	21.6	35.1
		60	19.4	13	0	57.0	21.5	35.1

Finally, we used the instantaneous power demand just before the cutoff, which, of course, is what the heating supply companies would save at that moment. However, what would happen in the hours to come is harder to say. The power demand is dependent on the outdoor conditions as well as the internal loads and, if these remain unchanged, it can be presumed that a constant and reduced level of power demand would be experienced throughout the cutoff period.

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Analysing the effects of heating power cuts in a generic apartment using measured input data with a Monte-Carlo approach **PAPER II**

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Analysing the effects of heating power cuts in a generic apartment using measured input data with a Monte-Carlo approach

Abstract

A currently emerging issue is that of heating power and the magnitude and point in time when it is actually in demand, rather than the amounts demanded over certain periods of time. Power production is, as a rule, directly linked to varying demands, and costs and environmental impacts are also tied to the way the power is produced. From a supply side point of view, acquiring control over these factors could provide both economical and environmental advantages. One way to achieve this would be to request the demand side to reduce its power demand when the production side is uneconomical and, instead, to use the heat stored in the building envelope and allow minor indoor temperature drops. This paper shows the impact on the indoor temperature in buildings with different insulation properties and heating systems during complete power cuts, using a statistical approach. Three important variables affecting the indoor heat balance are used: occupancy, household electricity use and climate data. The stochasticity of these variables is created using measured data on an hourly basis. The data concerning the cumulative differences, different occupancies and different climatic years are, in turn, investigated using multiple simulations in which the variables are randomized. Using this approach, the temperature declinations can be described in terms of probabilities. For example, the temperature drop, described as the 10-percentile, could vary between 0.5 and 3°C in a passive house envelope, 0.7 and 4°C in a standard building code envelope and between 1 and 9°C in a 1960s envelope, depending on the respective envelope properties, heating systems and durations of the power cuts.

1 Introduction

Reducing energy consumption, increasing the use of renewable energy sources, and adapting to stricter building regulations and certification systems – these are all examples of the challenges facing the building industry. However, a recently recognized issue that concerns these challenges is heating power demand. Today, the supply of this type of power is driven by demand and, in turn, this demand is driven by the heat loss in a building and the behaviour of its residents. This arrangement would work perfectly, if the cost of producing one additional unit of power (W) were constant, both in terms of price and environmental impact. Obviously, this is not the case, as the heating supplier needs to start additional boilers, perhaps with lower efficiency, and to use different fuels, usually fossil fuels, to cover peak demands. Consequently, the cost and environmental impact of production vary. From a supply side point of view, acquiring control over these variations could provide both economical and environmental advantages. The latest smart grid technology creates new opportunities for communication between a heating supply company and a building management system (BMS). This provides an opportunity for the heating supplier to send a price signal or a request that the demand side BMS can respond to. A request, for example, could be that the demand side reduce its heating demand when the production side is uneconomical. Thus, the heat stored in the building envelope, floors and internal walls can be used to make up for this reduction by allowing a modest indoor temperature decrease.

The primary concern when reducing heating power supplies during the heating season is the impact on the indoor temperature and many field studies have been performed in which the power has been reduced and the temperatures measured, and these have shown only small impacts in the indoor temperatures (Olsson Ingvarsson and Werner 2008; Wernstedt and Johansson 2008; Kärkkäinen et al. 2003; Kensby, Trüschel, and Dalenbäck 2015; Reynders, Nuytten, and Saelens 2013). Kensby et al. shows that describing the decreasing indoor temperature, when the heating output has been reduced, using the fixed building time constant is not a valid option for short periods of power reduction. Instead, the use of a building's thermal mass during the heating season can be considered, offering a new way of measuring the stored heat in terms of degree-hours instead of the building time constant (Kensby, Trüschel, and Dalenbäck 2015). A modification of this approach, using degree-hours, will be used in this paper. In addition to the new proposed approach, a weighted impact on indoor temperature correlated to the decrease of power can be shown. This was based on a weekly average over the measuring period and used for evaluation. Using the building frame to delay the heating power load demand has also been investigated using simulations for a single-family house (Reynders, Nuytten, and Saelens 2013). Heat was supplied using a heat pump when electricity prices were most favourable while allowing the indoor temperature to vary within different intervals. Up to 60 % peak power reductions were obtained if a 4 °C drift was allowed from the design temperature. Another case in which electricity peak demands can be easily avoided is when a building has underfloor heating. However, if radiator heating is the case, caution should be taken not to create a too low indoor temperature (Arteconi, Hewitt, and Polonara 2013).

Summing up, the key to shifting, or staggering, heating power demand is to keep the duration and magnitude of the power reduction from causing unacceptable indoor temperatures. A viable path of communication between the production and demand sides is also necessary.

In previous research, there has not been much focus on the variables impacting the indoor temperature, such as loads from appliances, occupancy and sunlight. Kensby et al. (Kensby, Trüschel, and Dalenbäck 2015) measures this impact but uses an average temperature to show the impact of the heating reduction and disregards the impact of these variables. They also only look at two apartments for each investigated building. Fixed occupancy schedules are used in the paper by

Reynders et al. (Reynders, Nuytten, and Saelens 2013), however, a more sophisticated approach regarding the appliance load is applied.

This paper focuses on examining how the indoor temperature is affected when the heating is reduced. The first important matter when investigating the impact on the temperature regards the different variables influencing the indoor heat balance. In this paper, three of these are chosen for further investigation: occupancy, household electricity use and climate data.

Bagge et al. measured the household electricity usage in over 500 two-room apartments in Sweden, over a whole year and on an hourly basis. The annual amount of energy use recorded varied between 2 and 118 kWh/m² with a mean value of 29 kWh/m² (Bagge, Lindstrii, and Johansson 2012). If 118 kWh/m² were to be transformed into an average power input over a year, close to 700 W would be supplied constantly throughout the year in a 50-m² apartment. Similarly, Bagge et al. registered occupancy, the number of persons present at any time, in 86 apartments in Sweden over a period of 14 days. This was carried out using electronic diaries for which the residents pressed a button on leaving or entering. In this paper, the measured hourly household electricity use and occupancy levels according to Bagge et al. (Bagge, Lindstrii, and Johansson 2012; Bagge and Johansson 2015) will be used as input data. Where the last variable is concerned, the climate in Stockholm (longitude 18°, latitude 59°), which corresponds to a moderate Swedish climate, was chosen. 10 different years of climate data were gathered from the Swedish Meteorological and Hydrological Institute (SMHI 2015a, 2015b).

When looking at these three variables one can identify at least two common and clearly distinguishing attributes that need to be handled in the simulations. Firstly, on a short time scale, for instance hourly, the variables can be described as almost stochastic (though maybe not the weather). Secondly, there is a difference in the cumulative measured data between individual apartments and climatic years, during, for example, a month or a year (total electricity use, total occupancy and mean temperature). The differences regarding annual household electricity usage are mentioned in the previous paragraph. The first attribute is taken into account by using measured hourly data as input and the second by using a Monte-Carlo approach, where the input data set for each simulation is randomized. This is a new approach and contrasts to the more common, static occupancy schedules and yearly averages for household electricity applied when people are present.

The second important matter causing the indoor temperature to drop in different ways are the more static parameters of the building envelope. As the building stock in Sweden obviously consists of buildings of different ages and different envelope properties, the scheme to reduce power then needs to be applicable to any type of building of any age. Therefore, this study also investigates the impact of building envelopes from different periods, different heating systems and available thermal mass in combination with the stochastic variables mentioned above.

2 Method

In order to use the Monte-Carlo approach, it was necessary to solve detailed energy and indoor climate simulations and analyse them using different parameters, and to run them many times in order to take into account the impact of the differing variables. This was done using two commercial software tools – the IDA Indoor Climate and Energy program (IDA-ICE) (EQUA 2014) for solving the building physics and energy calculations and the MATLAB program (The MathWorks 2015) for pre-processing the input data, starting the simulations and saving the output. This set-up made it possible to run different detailed energy simulation calculations automatically for days. Each simulation covered one month, January, which corresponds to a cold winter month in Sweden. This month was tested 500 times for each different building set-up and power reduction scheme. This section describes in detail the manner in which this was carried out.

2.1 Description of building parameters and heating power reduction schemes

This section summarizes the general building attributes, such as apartment size and window area, followed by a description of the parameters that were tested in the simulations.

2.1.1 General building attributes

A generic apartment, situated in the upper corner of a four-storey building, with four of its six 'sides' in contact with the outdoor environment, i.e. the apartment most subjected to the climate conditions, was used for the simulations. Its floor area was 60 m² (7.5 m X 8 m) which corresponds to a typical 2-room apartment in Sweden. The apartment however, was modelled as a single zone. This simplification was chosen in order to avoid the need to add another uncertainty regarding where in the apartment the internal heat loads were assumed to be added, as this level of detail is not available in the measured data used as input. This simplification also helps reduce simulation time, which is dependent on the number of zones. The apartment had six windows, equally divided between the north and south façades, with a total area of 9 m². This is equivalent to 15 % of the floor area and considered good in terms of daylight requirements in the Swedish building regulations. The generic apartment had two set-ups regarding its heating system, with radiators and underfloor heating respectively. In the first set-up, the radiators were placed under each of the windows and were of equal size. The underfloor heating covered the whole of the apartment floor space. The design indoor temperature was set to 21 °C. The ventilation rate was 0.35 l/(s m²), the airflow stipulated by the Swedish building regulations (Byggregler), in all the cases.

2.1.2 Building parameters

Building envelope properties representing three different periods were tested – Passive House standard, Swedish building regulations standard and 1960s standard. The U-values, air leakage and thermal bridges of these are listed in Table 1. In turn, these three building types were examined with two different levels of thermal storage capacity, of light and of heavy construction. The amount of available thermal mass at these two levels can be found in Table 2. The heat loss coefficient for each building part was the same for both cases. The heavy construction variant corresponded to 10 cm of concrete on the warm side of the exterior walls, 15 cm on the ceiling and 10 cm of solid concrete for the interior walls. The light construction variant consists of light insulation with a 13-mm gypsum board on the warm side. The internal floors comprised 15 cm of concrete with a thin floor coating in both the heavy and light variants. The Passive House and standard building each had a heat exchanger with an 80 % and 75 % temperature recovery rate respectively. The building with the 60s-standard had no heat recovery equipment.

The different building types, with different insulation properties, were simulated using different capacities with regard to their heating systems, in order to make up for these differences. For example, the average U-value differs by a factor of two between Passive House and 1960s envelopes.

The design power was also increased due to the need to raise the temperature back to the design value in time for the next power cut, as it was of interest to carry out tests every day of the month.

Table 1. Building envelope parameters

Building comp	PH Values	Std Values	60s Values
$U_{Exterior\ wall}$	0.1 W/(m²K)	0.18 W/(m²K)	0.4 W/(m²K)
U_{Roof}	0.08 W/(m²K)	0.13 W/(m²K)	0.25 W/(m²K)
U_{Window}	0.8 W/(m²K)	1.3 W/(m²K)	2 W/(m²K)
U_{Ground}	0.1 W/(m²K)	0.18 W/(m²K)	0.4 W/(m²K)
Air leakage	0.3 l/(s m²) ext. area at 50 Pa	0.6 l/(s m²) ext. area at 50 Pa	1.2 l/(s m²) ext. area at 50 Pa
Thermal bridges	20 % of $U_{tot} \cdot A_{tot}$	20 % of $U_{tot} \cdot A_{tot}$	10 % of $U_{tot} \cdot A_{tot}$

Table 2. Building envelope heat storage capacity

Building comp	Light Constr. [kJ/m²K]	Heavy Constr. [kJ/m²K]
Exterior wall	12.9	202
Interior walls	28.1	202
Roof	12.9	202

2.1.3 Cutting off the heating power

The power reduction was chosen to be in the form of a complete power cut and was assessed for three different time spans, 4, 6 and 8 hours, starting at 06.00 in the mornings and at 16.00 in the evenings. These power cuts were made each day of the month in order to investigate the combined effects of all the variables.

2.2 Randomized variables

When carrying out energy simulations for buildings with regard to their yearly performance, static schedules or even yearly averages for household electricity and occupancy are commonly used. As can be seen in Figure 1, there is a large spread within the groups of variables, representing different occupancy levels or climatic years, when looking at the monthly average.

The variation within a day and between days is even greater and needs to be addressed. In this paper we have taken these variations into account using real hourly measured values.

The domestic electricity data used in this study consists of hourly measurements from 542 two-room apartments in Sweden in 2012 (Bagge, Lindstrii, and Johansson 2012). The variation in the use of household electricity between different users can be seen in Figure 1. The occupancy data is hourly data averaged from instantaneous measurements using electronic diaries (logs) in 37 two-room apartments over a 14-day period in 2013 (Bagge and Johansson 2015). As there is no whole consecutive month of measurements of occupancy data, the existing data for each user was repeated to make up all the 31 days of January. Not all the occupancy measurements were done in January, however, but they were made during the heating season. In the simulations, the residents are modelled having an activity level of 1 met. Furthermore, the household electricity load and occupancy in this study are presumed to be independent variables, which, of course, is not true but no simultaneous measurements of appliance loads and occupancy were available. Bagge et al. (Bagge, Lindstrii, and Johansson 2012) showed that if the apartments were grouped based on their number of rooms, no correlation between the household electricity usage and the area of the apartment could be found. A small correlation was found, shown as an increase of household electricity use with an increase in number of rooms. . been investigated through the three papers is visualized in table give an indication of the variation of the variables, the mean values for each variable are shown in Figure 1. The averages were calculated from each of the 744 hours of January. For example, there are 37 apartments with measured occupancy and the mean occupancy varies by a factor of 5, from 0.35 up to 1.9 persons. This could have been investigated in much more detail as the three variables also varied differently during each day and between different days.

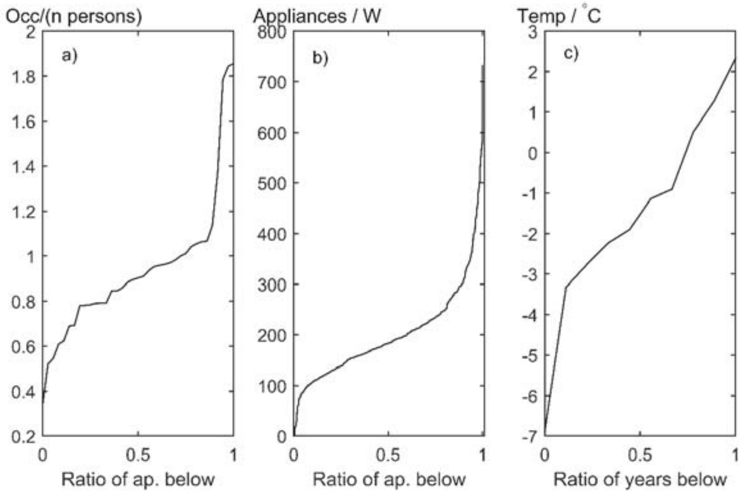

Figure 1. a) Cumulative distribution of occupancy shown as monthly mean values for the 37 data sets. b) Cumulative distribution of appliance load showing monthly mean values for the 542 apartments in January. c) Cumulative distribution of outdoor temperatures shown as mean temperatures in January during 10 different years.

2.3 Simulation procedure

This section describes how the two simulation software tools were used to run the simulations and how the different steps of the simulation process are linked together. In the last part of this section, an investigation into how many iterations for each parameter set-up are needed to cover an acceptable range in the variety of the variables.

2.3.1 IDA-ICE models

The basis for the simulations comprises six different building models created in IDA-ICE, two for each type of building frame, one with radiators and one with underfloor heating. The different variables are changed via MATLAB prior to each simulation. The building parameters can be changed using a script that MATLAB runs in IDA-ICE before the simulation. The reason for having six models is that they differ so much and having one "mother-model" would basically only contain the geometry and the scripts then needed to add the differences would be very large. The composition of the wall, changing the thermal mass, and power cut periods are more easily changed in a script through MATLAB and thus do not need separate models.

2.3.2 MATLAB model and iteration process

A schematic of the simulation procedure can be seen in Figure 2. All the combinations of the three main parameters – Building characteristics, Heating system, Thermal mass – were systematically simulated for each of the six cases of power cuts. This was done 500 times for each of these combinations. The three variables were randomized from the previously described data sets and input files were created prior to each of the 500 simulations. For each of the three building types there were 24 possible combinations, each containing results from the 500 simulations. The simulations were not performed linearly from 1 to 500 but in batches of 12 running simultaneously using the full capacity of a computer with 12 cores. Running one batch of 12 models covering one month took approximately 30 seconds of which 5 to 6 seconds were spent pre-processing the variables and scripts needed to run the model. Additional time was needed after each sequence of 500 iterations when the variables were saved to release memory space, 0.6 – 0.85 GB/file. The time dependency of a single simulation depends on many factors, such as number of zones, complexity of the geometry, simulation period, number of output variables to store during the simulation and customized regulation of opening windows and doors etc.

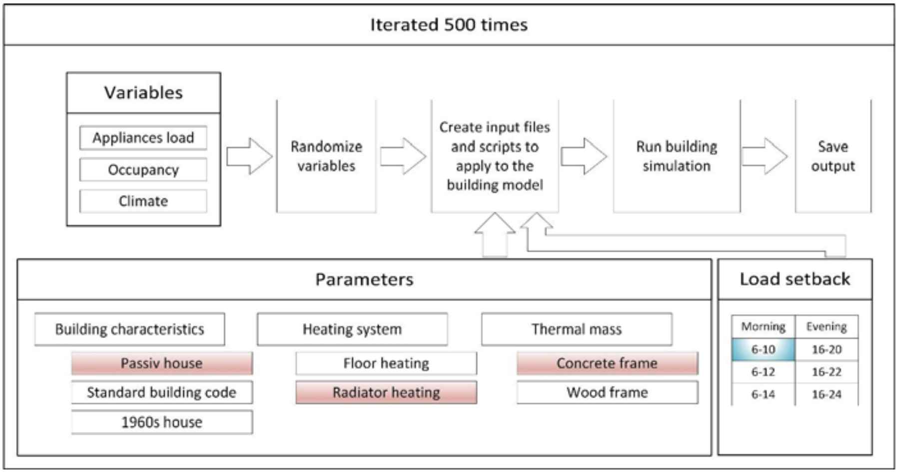

Figure 2. Schematic figure of the simulation procedure. The boxes in red indicate the parameter set-up currently under investigation and the blue box the power cut period. These are all examined over 500 simulations in which only the variables shown in the top left corner are randomized before each simulation. After these 500 simulations, the blue box changes to the next power cut period and the procedure is repeated until all these periods have been run through. They then start over again with the next parameter set-up.

2.3.3 Model development and testing (number of iterations needed)

The three main variables, if looking at them as single values, can generate just over 200,000 different combinations. For time reasons, running all combinations for each case would therefore not be an option. Furthermore, the randomized variables do not contain just one single value, but 744 hourly values, as a whole month is being simulated. Additionally, the climate is not described by only one variable but by six: temperature, relative humidity, wind speed, wind direction, and diffuse and direct solar radiation. As the combined effect of these three variables on the indoor temperature after a power cut is sought, there is also a time dependency in this combination. A very unfavourable combination, for example, would be a very cold and windy climate in combination with low internal heat gains for many hours.

In order to assess how many simulations to conduct for each set of parameters, a test set-up was used. Building parameters for the standard building with a light frame was used. The climate in Malmö (longitude 13°, latitude 56.6°)) was used (initially three different locations were tested) and the heating system with radiators was shut off between 06.00 and 10.00 each day. This set-up was run approximately 40,000 times with randomized variables. For each of the 40,000 simulated months we chose the lowest indoor temperature for the whole month as a representative figure to use for the statistical analysis. The results were grouped into intervals of 0.1 °C and the distribution is shown as a histogram in Figure 3. From this distribution, values were chosen and in Figure 4 the 5- and 50-percentiles, the minimum and maximum, values are shown as a function of the number of chosen values in steps of 10. The figure shows this procedure for two separate groups of 500 values. The 5- and 50-percentiles, together with the minimum values, seem to converge at around 200 iterations and the maximum values not at all. However, this result will differ every time these 500 values are chosen. One more step is therefore taken and the results can be seen in Figure 5. Here, every series of iterations, ranging in steps of 10 from 10 to 500, is randomized 500 times and the mean values of these are shown in the figure. It can be seen that the averages of the minimum and maximum values converge at around 500 iterations. To increase the chance of covering some more extreme values, 500 iterations were chosen rather than 200, which might have been enough to investigate the mean value.

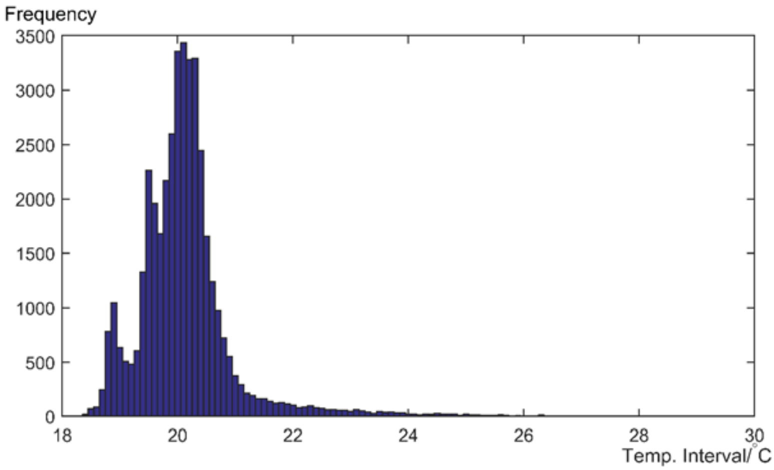

Figure 3. Distribution of minimum temperatures from 40,000 simulations of a January month with randomized variables. The bars represent an interval of 0.1 °C.

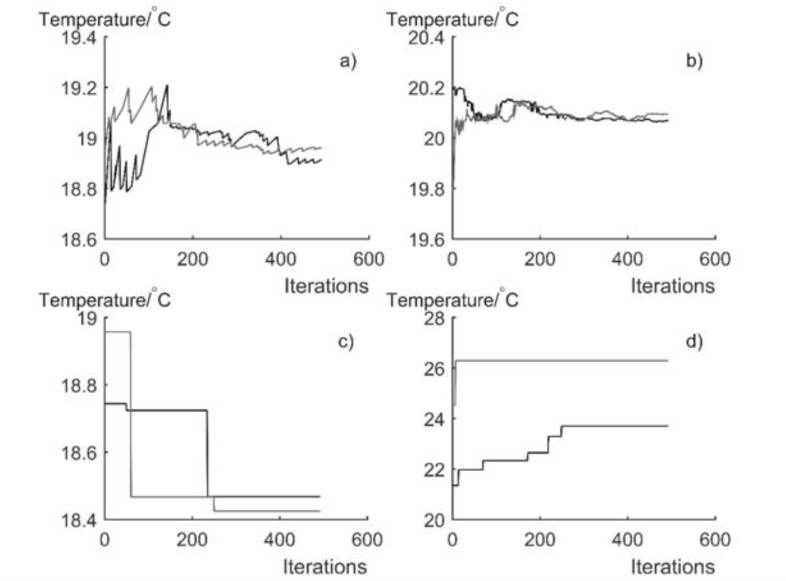

Figure 4. a) The 5-percentile temperature as a function of number of iterations from two pools of 500 randomly picked values from the distribution in Figure 3. b) The 50-percentile temperature as a function of iterations. c) Minimum value as a function of iterations. d) Maximum value as a function of iterations.

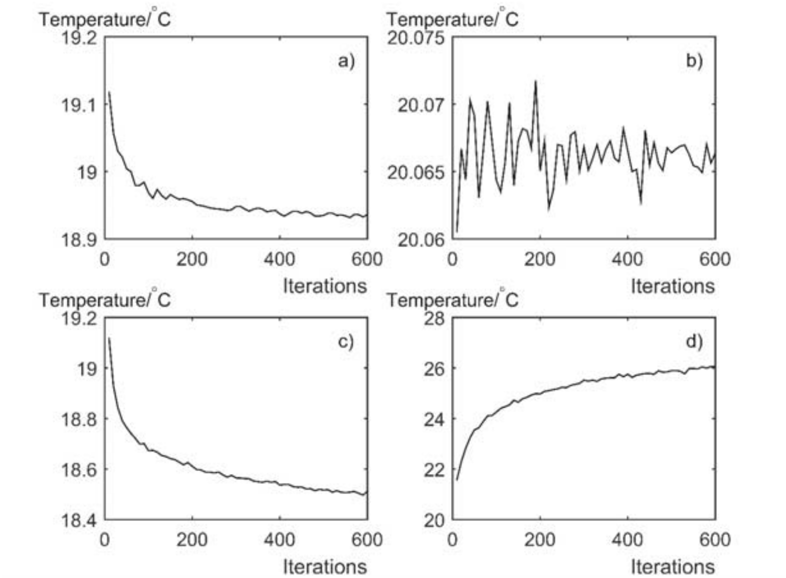

Figure 5. a) The average 5-percentile from 500 *runs of iterations are shown on the x-axis. b) The average 50-percentiles as a function of the iterations. c) The minimum values as a function of the iterations. d) The maximum values as a function of the iterations.*

3 Results and discussion

The results are presented in three main sections. The first one concerns the temperature drops alone for all the cases. The second concerns the relationship between the temperature drop and the power demand of the apartment just before the power cut. The third one relates the temperature drop to the duration of the power cut and the outdoor temperature. There are three figures in each section, each representing the three different types of building envelopes in the following order, Passive House, standard house, 60s house. Explanations of the results in the figures, important trends, patterns, deviations, similarities followed by a discussion are then given for each of the building types.

3.1 Temperature drop

This section shows the temperature drops for all the cases. Figures 6 – 8 are described in general here and then in more detail for each part. The minimum temperature after the period of no power was saved for each of the 31 days of January for each of the 500 simulations. Each parameter set-up is represented by a bar describing these minimum temperatures, corresponding to 15,500 temperature readings (31x500). On the x-axis, these parameters are grouped as four bars for each of the six different times during the day that the heating power is turned off. The four bars are specified as either radiators (rad on the x-axis) with light (L above the bar) or heavy (H) frames or underfloor heating (floor, L or H). The bar shows the spread of the 15,500 minimum temperatures seen in five percentiles, the 10-, 25-, 50-, 75- and 90-percentiles. The first figure also illustrates an example of how to read the results, described fully in the figure caption.

3.1.1 Passive House

The Passive House results are shown in Figure 7. The three morning groups show a clear resemblance. The largest spread, approximately 2°C, is found in the case with a light envelope and radiator heating, in which the highest risk for a low temperature is seen. In 90 % of the cases it is about 20.5 °C or colder and in 10 % between 18 and 19 °C or colder. The case with a heavy envelope and underfloor heating shows the smallest spread for the morning cases, 0.5°C, and it is notable that the risk of a temperature lower than 20.4 °C is only 10 %. The evening power cut are seen with a larger spread and are less uniform. The 90-percentiles are, in all but two cases, clearly above the design temperature set point of 21 °C, which means that the internal loads not only balance the absence of power but are also able to increase the temperature further. That this is the case for the evening (or afternoon) periods can be explained by the temperature outside being higher and combined with more internal loads. This assumption is strengthened by the fact that the risk of having a low temperature is smaller than in the morning periods for all but the last one. This period extends into the night when the temperature outside is presumed to drop again and the occupants have gone to bed (internal loads decline).

In all the heavy cases, the risk of having a temperature drop of 1°C or more is approximately 10 %. In the light envelope cases, there is a clear difference between those with underfloor heating and those with radiators. In the radiator cases, the risk of a 1°C temperature drop is 75 % and for the underfloor cases between 10 and 25 %.

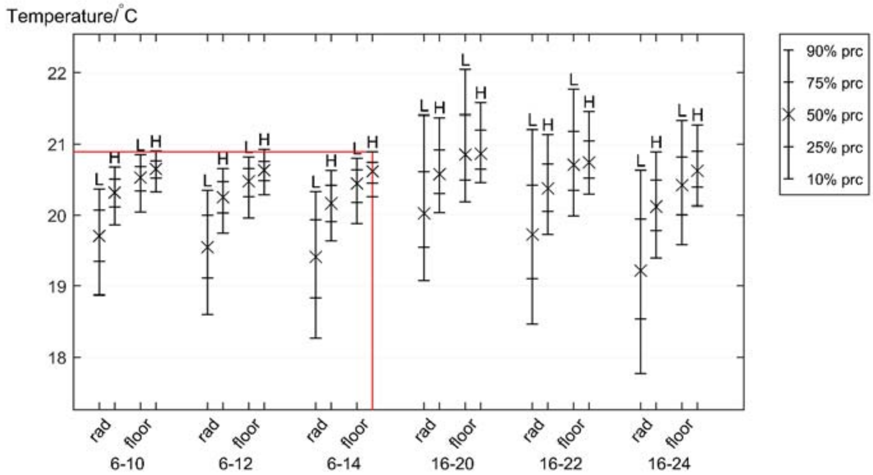

Figure 6. Percentiles of minimum temperature for an apartment with a Passive House envelope. The percentiles are displayed as bars and arranged together in groups of four for each of the six power cuts. The bars show five different percentiles for each tested parameter set-up. Parameter set-ups are as follows: Light (L) or Heavy (H) envelope together with radiator- (rad) or underfloor heating system (floor). The red lines illustrate an example. The 90-percentile of the minimum temperature for heavy (H) envelope with underfloor heating system after a power cut between 06.00 and 14.00 is 20.9 °C. In other words, in 10 % of the simulated days, the minimum temperature is higher and in 90 % lower than 20.9 °C.

3.1.2 Standard house

The results from the standard house (Figure 7) case are very similar to those in the Passive House in terms of uniformity between the morning groups and the change to a larger spread in the evening groups. However, there is now a distinction between the cases with heavy envelopes with radiators and those with underfloor heating. Whereas the first shows a risk of about 50 % for a temperature drop of 1 °C or more, the underfloor case, similarly to the Passive House case, still only risks this reduction in about 10 % of the cases. In the light cases, the risks have increased and are now almost 90 % for a 1°C drop in almost all cases with radiators. With underfloor heating, the results are better, with a 25 to 50 % risk of dropping 1°C.

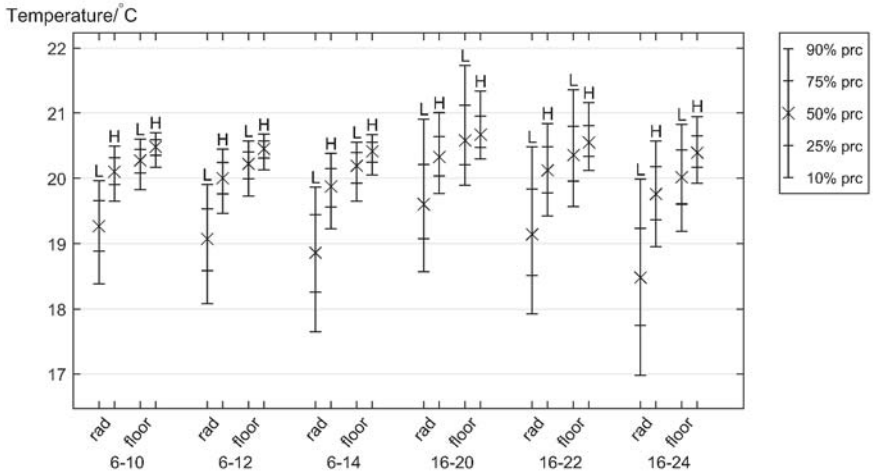

Figure 7. Percentiles of minimum temperature for an apartment with a standard house envelope. The percentiles are displayed as bars and arranged together in groups of four for each of the six power cuts. The bars show five different percentiles for each tested parameter set-up. Parameter set-ups are as follows: Light (L) or Heavy (H) envelope together with radiator (rad) or underfloor heating system (floor).

3.1.3 60s house

The results for the 60s house are shown in Figure 8. The 60s house has the most prominent difference compared to the other two cases as it has no heat recovery system. This appears to have a huge impact on the temperatures, in particular for the light envelope cases with radiator heating. In all these particular cases the entire spread is below 18°C. Where the heavy envelope cases with radiators are concerned, the 90-percentile lies around 19 °C and the 10-percentile between 16 and 17 °C.

The cases with underfloor heating show much better potential, with the heavy cases having a spread of 1 °C between 19 and 21 °C. When looking at the light envelope and underfloor heating variants the mornings have a similar spread to the heavy case. However, the long evening power cut increases the risk of dropping below 1 °C from 10 % in the previous case to as high as 50 % for the 8-h power cut.

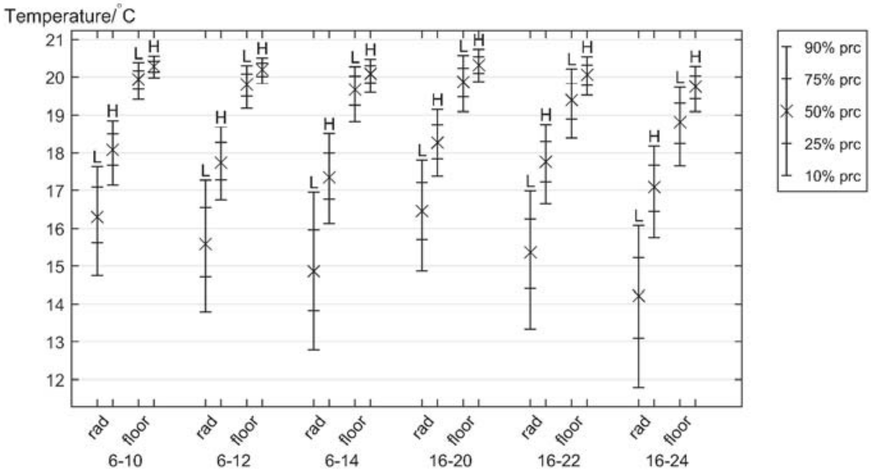

Figure 8. Percentiles of minimum temperature for an apartment with a 60s house envelope. The percentiles are displayed as bars and arranged together in groups of four for each of the six power cuts. The bars show five different percentiles for each tested parameter set-up. Parameter set-ups are as follows: Light (L) or Heavy (H) envelope together with radiator (rad) or underfloor heating system (floor).

3.1.4 Discussion

A heavy building envelope combined with underfloor heating is clearly favourable when wanting to turn off the heating power and the risk of dropping as much as 2 °C below the design temperature is only about 10 % for all these cases. This is also roughly the case with the same heating system and light envelope, for all but the 60s case, in which the risk dramatically increases to 25 % and to 50 % for the long power cuts at night.

The radiator cases do not show the same benefits, however, and combined with a heavy envelope, it shows about the same risk as with underfloor heating in houses with standard or Passive House insulation levels. For the 60s house, all the cases drop below 19 °C or worse in 90 % of the simulated days. This figure is even lower when looking at the case with a light envelope.

Many similarities can be found between the underfloor heating cases and these all have a rather narrow spread and a lower risk of dropping too far below the design temperature. That the difference is this small can be explained by the fact that in both cases the underfloor heating is embedded in the concrete floor. There is, however, a rather large difference between the heavy and light radiator cases, in which the 90-percentile for the latter corresponds to the 25-percentile on many occasions and almost the 10-percentile of the heavy envelope in the 60s house case.

3.2 Temperature drop related to power

This section describes the relationship between the power output, delivered by the heating system, immediately before the power cut and the resulting temperature drop. Figures 6 – 8 are described in general here and in more detail under each subsection. For each parameter, the 15,500 temperature readings described above are now placed into different groups depending on the heating power delivered to the apartment. These intervals of power have been chosen with either 0 to 250 W or 0 to 500 W as starting points. The next interval ends with a power rating corresponding to twice the previous one. The intervals are shown in a box in the top right corner of each figure. The data grouped into these intervals corresponds to a number of minimum temperatures. Two percentiles have been chosen to represent these temperature drops for each interval, the 5- and 50-percentiles.

The figures are divided into two parts: a) the morning power cut and b) the evening power cut. In these two parts, the parameters are divided into four groups, showing the heating system and type of envelope. These groups contain the three different power cuts for the morning and the evening cases. The dots correspond to the percentiles for each interval for one parameter and the lines connect the percentiles for the three cases in each group. The first figure also illustrates an example of how to read the results, described fully in the figure caption.

3.2.1 Passive House

The results for the Passive House are shown in Figure 9. The morning cases show significant uniformity within and between the parameter groups (Figure 9a). The case that differs is the one with a light envelope and radiator heating system, in which all the intervals carry a risk of a temperature drop of 4 °C, which is twice as much compared to the other three cases. The fact that there is almost no distinct difference between a 4-hour power cut and an 8-hour power might be due to an increase in outside temperature during the day or an increase of internal heat gain. One consequence of this is that the actual power demand also decreases as the day progresses, leading to a lower potential power cut need.

In Figure 9b there is a clear distinction concerning temperature drop in relation to the duration without heating power. This is to be expected, as the outside temperature drops and the internal heat gains are likely to diminish as occupants go to sleep. The best set-up is a heavy envelope with underfloor heating, with risk of dropping below 1 °C of about 5 % for the three shortest power cut periods. In the light envelope cases, the spread is much larger and the differences between the periods clearer. The cases with underfloor heating seem to use a bit more power (four intervals instead of three) than the radiator cases and this might be due to the time lag between when the heating power is demanded and it actually reaches the room. The underfloor heating system is embedded 2 cm deep in concrete.

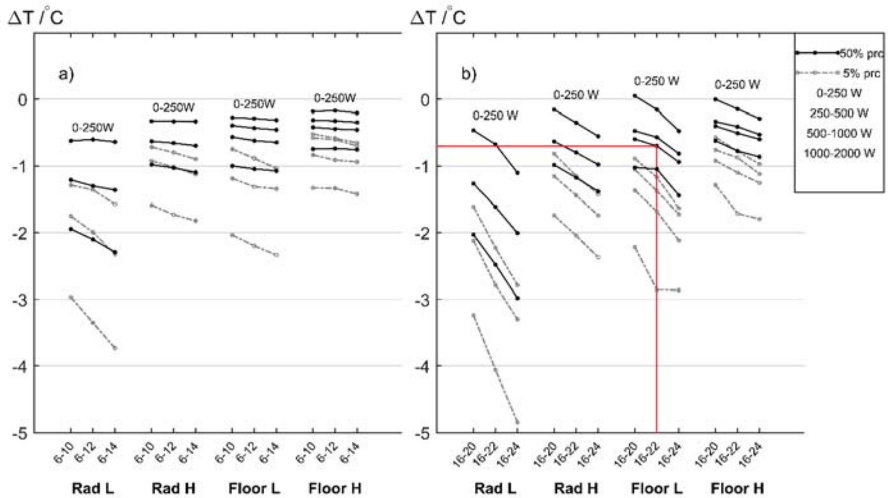

Figure 9. The impacts of the power cuts on the indoor temperature for the Passive House envelope in a) the morning cases and b) the evening cases. For each heating parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected with the same percentile for the same interval for the next power cut occurrence. The red lines show an example. They show that the 50- percentile equals a 0.8 °C drop for the case with light envelope and underfloor heating and a power cut between 16-22. In this case the power cut lies within the interval of 500-1000 W.

3.2.2 Standard house

In Figure 9a an interesting phenomenon can be seen. The temperature drop for the 50-percentile hardly decreases with increasing length of the power is cut. This might be due to a diurnal temperature swing, as it is still cold outside at 10.00 but slightly warmer by 14.00. It might also be due to natural randomness, where many favourable variable combinations happened to be picked for the 8-hour power cut cases but not the others. As in the Passive House cases, the lines are very even in the morning but have a clear declination in the evening. There is a bigger difference between the radiator cases and the underfloor heating cases when a higher power interval is examined. For the evening case b) the declinations are most pronounced in the radiator-light envelope case, with 1 to 2 ° differences between the 4-hour and 8-hour power cuts. This is hardly discernible in the case with underfloor heating and a heavy envelope.

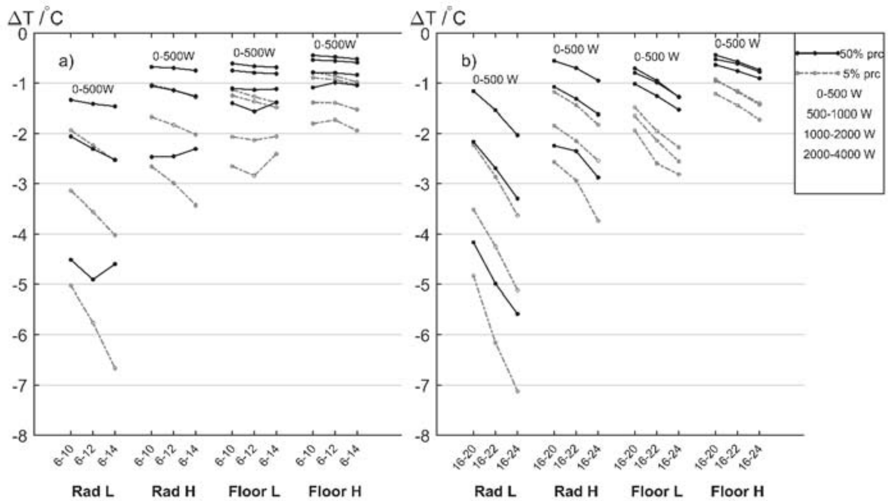

Figure 10. The impacts of the power cuts on the indoor temperature for the standard house envelope for a) the morning cases and b) the evening cases. For heating each parameter and power cut period, the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected with the same percentile for the same interval for the next power cut occurrence.

3.2.3 60s house

The results from 60s house are again the most distinct among the three building envelopes and are shown in Figure 11. The combination of the worst insulation levels and the lack of a heat exchanger makes it most susceptible to the power cuts. Despite these drawbacks, one case manages quite well. The heavy underfloor heated set-up only has a 5 % risk, during almost all intervals, to drop 2 °C or more (Figures 11a and 11b). The exception is the very worst case, with the longest power cut. It is five times worse than the light envelope case with radiators. Here, the 5 % risk is as low as a 10 °C drop, which, of course, would make the apartment uninhabitable. In the radiator cases, even at the low power intervals, the 5-percentile only points to a 3 to 5 °C drop.

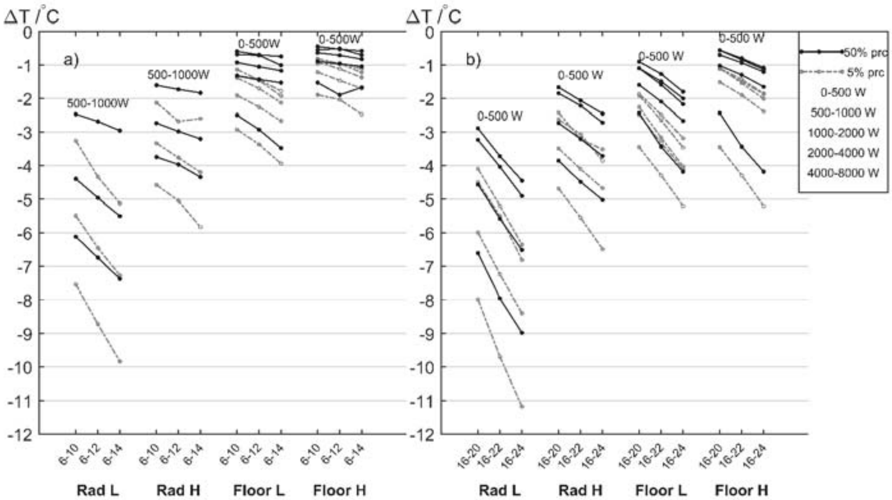

Figure 11. The impact of the power cut on the indoor temperature drop for the 60s house envelope for a) the morning cases and b) the evening cases. For each heating parameter and power cut period the observations were grouped into intervals depending on their magnitude (top right box). For each interval, the resulting temperature corresponding to the 50-percentile (black) and 5-percentile (grey) are plotted as dots, aligned over the respective heating parameters and power cut periods. These dots are then connected with the same percentile for the same interval for the next power cut occurrence.

3.2.4 Discussion

Summarizing the results from this section, it is clear that the heavy Passive House envelope set-ups, in most cases, have a moderately low probability of resulting in major temperature drops, even when high power outputs are cut. The light set-ups, however, can only handle shorter power cuts with lower magnitudes of power demand if they are to attain the same risk levels as the heavy set-ups.

The scenario is not as good for the standard house envelope case, in which only the heavy underfloor heated set-up manages the 2 °C drop with a 5 % risk. In all the other cases, shorter power cuts with lower power demands can attain the same risk level.

The 60s house set-up shows the same potential for the heavy underfloor heated case with some restrictions regarding the cuts at the highest power levels.

These results might completely rule out the use of these power cut schemes in older 60s buildings, buildings which comprise a large part of our building stock. However, these tests are worst case scenarios and the apartment investigated is the worst situated in a building, with 4 of its 6 sides in contact with the outdoor climate. It is safe to say that an apartment with only 2 of its 6 sides in contact with the outdoor climate would suffer less severely from a power cut. Therefore, it is essential when applying this kind of scheme on an actual building to make exceptions for these apartments and not turn off the heating supply completely.

3.3 Temperature drop linked to degree hours (Kh)

This last result section links the combined effect of the duration of the power cut and the outdoor temperature to the drop in indoor temperature. A new parameter, Kh, degree hours, is introduced and defined in Equation 1 where t_{pc} is the duration of the power cut in hours, T_{design} the indoor design temperature of 21°C and $T_{mean,out}$ the mean outdoor temperature during the power cut.

$$Kh = t_{pc} \cdot (T_{design} - T_{mean,out})$$

Equation 1.

This new parameter combines the two variables time and temperature. For example, if a 6-hour power cut takes place with a mean outdoor temperature of 0 °C, it would be equivalent to 126 Kh. Contrary to the previous section, in which the power that is cut off is related to the temperature drop, this new parameter provides a better description of the whole period without power.

As before, the 15,500 daily data readings for each parameter are grouped depending on the Kh value. The intervals chosen increase in doubled increments 0 to 50, 50 to 100 and so on. The Kh value is, of course, dependent on the duration of the power cut, which leads to a change in the figure set-up. Now, parameters are grouped into three categories for the morning a), and evening, b). In these groups, the four parameter set-ups are shown, labelled with the combinations of heating system and thermal mass. The data, divided into intervals, is then displayed as two percentiles for each interval, 50 % (black) and 5 % (grey) and plotted as dots above the respective heating parameters and power cut periods. These dots are then connected with all the parameter set-ups for the same percentile and interval. The top line in each group is indexed with its corresponding interval and the ones below follow in descending order as given in the top right corner box. The first figure also illustrates an example of how to read the results, described fully in the figure caption.

3.3.1 Passive House

The results for the Passive House envelope are displayed for the morning power cuts (Figure 12a) and evening power cuts (Figure 12 b). All of the set-ups manage power cuts corresponding to 50 to 100 Kh with the risk of 5 % to drop lower than 2 °C, in many cases as low as 0.5 to 1 °C. In the morning cases, power cuts between 06.00 and 14.00 do not have an interval at that low level but it can be presumed to drop within this boundary, as the next interval's 5-percentile only drops below this level for the light radiator set-up. Regarding the 100 to 200 Kh intervals, the same as above is true but for the light radiator cases in both Figures 12a and 12b. The toughest interval, 200 to 400 Kh is not seen for the shortest power cut periods as the mean outdoor temperature does not reach the low levels needed for that to happen. Only the heavy underfloor heated set-up manages to stay within a 2 °C drop at 5 % risk. In this interval and the previous interval, it is also clear that the light case risk of dropping to low temperatures increases significantly.

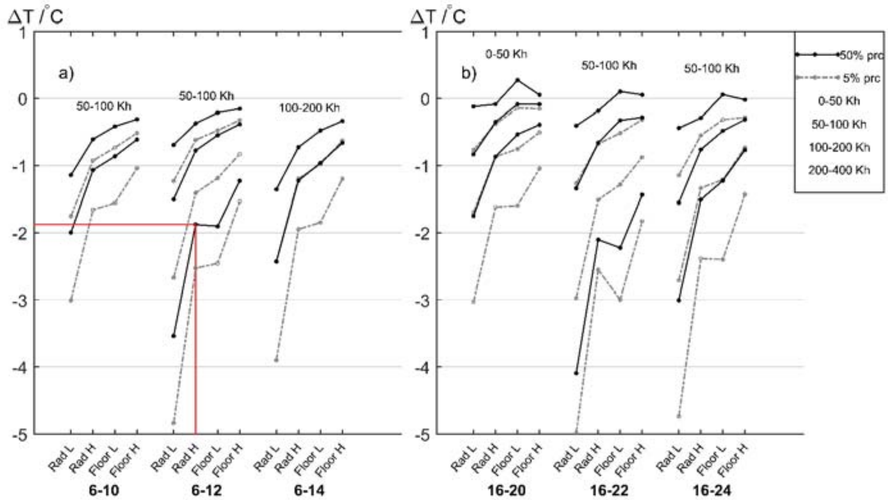

Figure 12. Degree hours (Kh) linked to the indoor temperature drop for the Passive House envelope for a) the morning cases and b) the evening cases. The four parameter combinations are grouped together for the three power cuts for the morning and evening. The temperature drops are grouped into intervals depending on the number of degree hours on that occasion and are represented by two percentiles for each interval, 50-percentile (black) and 5-percentile (grey). These are plotted as dots, aligned over the respective parameters and the dots are then connected for all the parameters in the same percentile within the power cut period. The red lines show an example. The vertical red line indicates the parameter set-up and the horizontal line shows the resulting temperature drop on the y-axis as about 1.9 °C. The third black dot from the top indicates the interval as 200-400 Kh. Black indicates that it is the 50- percentile of that interval.

3.3.2 Standard house

In Figure 13, the results from the standard envelope house are displayed for a) the morning cases and b) the evening cases. As in the Passive House case, there is a slightly higher risk of dropping below 2 °C for the 50-100 Kh power cuts. The heavy set-ups almost stay above a 1 °C drop at the 5 % risk level. With a similar risk and temperature drop, the underfloor heated heavy cases manage a 100-200 Kh power cut. The slopes of the connected lines get steeper as the interval increases, indicating that the differences between the set-ups will increase if the power cut periods are extended.

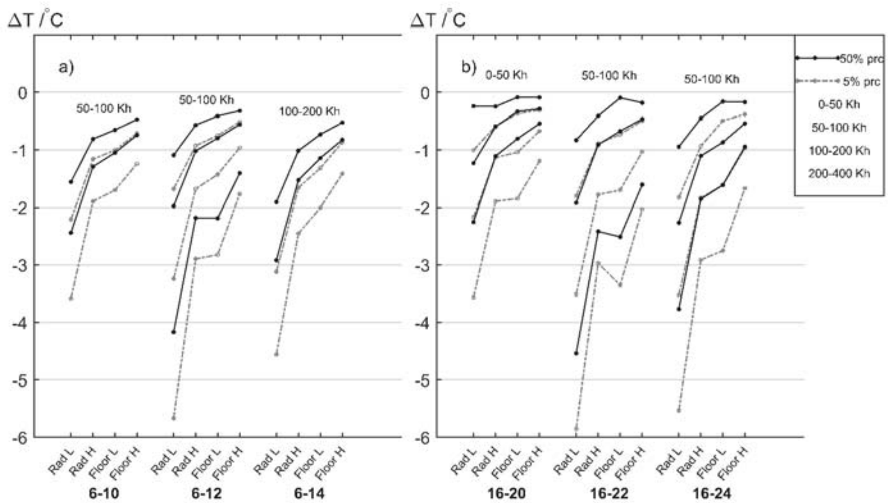

Figure 13. Degree hours (Kh) linked to the indoor temperature drop for the Standard House envelope for a) the morning cases and b) the evening cases. The four parameter combinations are grouped together for the three power cuts for the morning and evening. The temperature drops are grouped into intervals depending on the number of degree hours on that occasion and are represented by two percentiles for each interval, 50-percentile (black) and 5-percentile (grey). T These are plotted as dots, aligned over the respective parameters and the dots are then connected for all the parameters in the same percentile within the power cut period.

3.3.3 60s house

The results from the 60s house envelope are shown in Figure 14, for the morning cases a) and the evening cases b). It appears that the lines and the results lie much closer to one another than in the previous envelope set-ups. However, the scale of the axis has been changed to approximately twice that as before. This is due to the significant drops in temperature, with the worst cases dropping as much as 11 °C from the design temperature. Even for the lower intervals of Kh, the slope of the lines connecting the set-ups is steep. Contrary to the previous cases, the difference between the set-ups gets more distinct earlier. In this set-up, only the underfloor heated set-ups manage to stay above the 2 °C drops, with a low risk of 5 % during the 50-100 Kh power cut. The underfloor light case is close to the 2 °C line while the heavy case is closer to the 1 °C line. The radiator cases all suffer a higher than 50 % risk of dropping below 2 °C, during the 50-100 Kh power cut.

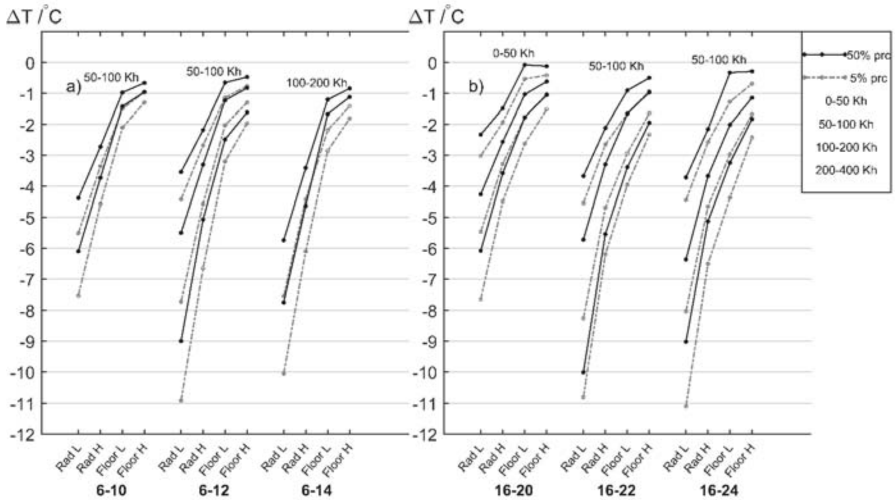

Figure 14. Degree hours (Kh) linked to the indoor temperature drop for the 60s house envelope for a) the morning cases and b) the evening cases. The four parameter combinations are grouped together for the three power cuts for the morning and evening. The temperature drops are grouped into intervals depending on the degree hours for that occasion and are represented by two percentiles for each interval, 50-percentile (black) and 5-percentile (grey). These are plotted as dots, aligned over the respective parameters and the dots are then connected for all the parameters in the same percentile within the power cut period.

3.3.4 Discussion

The Kh parameter that was introduced is a combination of the temperature and duration of the power cut. This means that the intervals, for example 50-100 Kh, correspond to different outdoor temperatures for the different lengths of time that the heating system has been turned off. Nonetheless, the results show, at least for the moderate intervals, a clear similarity between the power cut periods. For example, it would appear that turning off the heat for 8h with an outdoor temperature of 0 °C (168 Kh) would result in the same temperature drop as turning off the heating for 6 h with an outdoor temperature of −7 °C. This strengthens the choice of this parameter as being representative for a power cut period in comparison to the more straight forward approach of direct power cuts in W.

The temperature drops for the 5-and 50-percentiles differ in magnitude by about 0.5–1 °C within the Kh intervals, and the differences increase as the intervals become greater. One explanation for this could be that the larger intervals contain more extreme conditions, ones that occur less frequently, and thus imply a higher temperature drop for the lower fraction of the results.

Another interesting observation that can be made concerns the percentiles in relation to one another, i.e. the slopes of the lines connecting them. In the Passive House and standard house envelope cases, the low Kh intervals create results that follow a more horizontal line, with a slight declination in the light radiator case. The inclination indicates the apartment's capacity to withstand the power cut when compared to the other parameter set-ups. In the 60s house, the inclination of the slope is almost the same for all Kh intervals and the line is just moved down. One explanation for this could be the heat exchanger and the lack thereof in the 60s case. As the temperature drops, the indoor effectiveness of the heat recovery system declines and thus the slope increases. Without a heat exchanger, the drop commences immediately, primarily in the radiator cases.

4 Conclusions

From the first result section, general conclusions can easily be drawn and understood. If the power is cut for a certain duration of time, the risk of a corresponding temperature drop can be seen, depending on the type of the building. The second results section correlates the actual power output in the apartment prior to the power cut to the temperature drop after the period without a heating supply. This might be harder to use, as the heating demand of individual apartments is not always monitored, nor is the momentary power demand in the whole building. Should this be the case, the corresponding risk of temperature drop can be derived from the magnitude of the power that has been cut off.

When comparing the results of this study with previous research it must be noted that this study investigates cases in which there is a 100 % cut in the heating power supply, thus making this the limit for any possible reductions. This fact makes it slightly difficult to compare the results with those in previous research. Many of these earlier measurements, with reductions of 30 to 40 % of the normal heating input, were made without observing any significant impacts on the indoor temperature. Drops in the range of only 1 to 3 °C were found (Olsson Ingvarsson and Werner 2008; Kärkkäinen et al. 2003). When compared to the cases with Passive House and standard envelopes, the ones with heavy envelope set-ups only drop 1 °C or more from the design temperature in 10 % of the cases. In the research by Kensby et al. (Kensby, Trüschel, and Dalenbäck 2015) preheating occurs and the apartments only encounter a 0.5 °C drop on average over two weeks of measurements.

The third results section combines the outdoor temperature and the duration of the power cut into one parameter, Kh, defined in Equation 1. The results show that this quantity can be used to represent all the different cases, thus a short power cut at a low outdoor temperature would have roughly the same impact on the indoor temperature as a longer power cut at a higher outdoor temperature. This quantity is more useful when you look at the following function in Equation 2.

$$E = Q_{tot} \cdot G_t$$

Equation 2

$$E = Energy\ [Wh]$$

$$Q_{tot} = Heat\ loss\ coefficient\ of\ the\ building\ [W/K)]$$

$$G_t = Degreehours\ [Kh]$$

The Q_{tot} factor can usually be derived from a building's energy signature or power signature using the relationship in Equation 3.

$$P = Q_{tot} \cdot \Delta T$$

$$P = Power\ [W]$$

$$\Delta T = T_{indoor} - T_{outdoor}\ [K]$$

Equation 3

The same issues arise when data is only available at a building level. However, it should be possible to acquire energy data for each individual apartment. If this is the case, a reverse calculation can be carried out using a forecast of the outdoor temperature for the duration of the power cut and the Kh value calculated. This can then be compared to the graph corresponding to your house type to estimate the risk of a temperature drop.

It is important to take into account that this study concerns the worst situated apartment in terms of surface area in contact with the ambient climate, and thus the one most affected by a power cut. Apartments with neighbouring units on all sides would not be affected to such a great extent. In this study, to limit simulation time, no neighbours at all were modelled, thus making walls adjoining another apartment adiabatic. A simulation study at a building level, with 15 different apartments, has been performed (Fransson, Johansson, and Bagge 2016) showing promising results. However, the internal loads here were modelled with less accuracy. The apartments had an envelope corresponding to the standard envelope in this study and all were heated with underfloor heating systems. The study showed a very low risk of a temperature drop of more than 1 °C, roughly 10 % for the worst case. In this present study, the 10 % risk is at a 2-3 °C drop. From these results, it is clear that the most exposed apartments form the limits for carrying out a study like this at a building level and this needs to be taken into account. Three variables were chosen for this study although there are more uncertainties, primarily depending on occupancy, such as window-opening behaviour and management of solar shading. As this present study focuses on the month of January, the impact of the sun is small and will have a greater effect in months with more sunlight. Also, the design values for the indoor temperature differ in reality. Bagge et al. measured the indoor temperature in their comprehensive study and found that between the 10- and 90-percentiles for January there was about a 3 °C difference in apartment temperatures.

Regarding the internal loads, the full magnitude of the hourly measured values has been used as input into the apartment. However, these figures could be reduced to some extent. For example, the standard reduction used in the Swedish building industry is usually 70 % but this figure was derived from a 25-year-old report (Svensson, Kåberger, and Berg 1991) and includes the occupants use of washing and drying machines in their home. In multi-family housing in Sweden these appliances are usually shared. This value probably varies a great deal from apartment to apartment. The data need to be of that resolution as to know each individual appliance load in order to choose these reduction value. As this information for the particular measurements is not known, no attempt has been made in order to model it differently than the whole value as heating input.

It is also worth to discuss that the temperature chosen to describe the drop after the power cut is the minimum temperature, which occurs almost momentarily, before the heating is turned on again. If the mean temperature during the power cut were to be used instead, a higher temperature would then be achieved. The question then is what will people accept? Using the Fanger index, people with a clo value corresponding to winter conditions tend to accept a 1.5 to 2 °C temperature change. Nevertheless, using the mean temperature during the power cut or the worst temperature as reference is not an obvious choice, perhaps it would be better to use both.

Unfortunately, this article does not provide the full answer to these questions but raises the questions of risk or probability when assessing indoor climate. As the conditions in the apartments are subject to input that differs statistically, the results or investigated issues should also be determined in a similar manner.

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Investigating the parameters affecting the indoor temperature after a power cut – In-situ measurements and simulations

PAPER III

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Investigating parameters affecting the indoor temperature drop after a power cut -In-situ measurements and simulations

Abstract

When looking at energy supply on a larger scale than to a single building, such as to a neighbourhood or a city, the combined effects of peak power demands can be seen to cause problems on the production side. These can be both economic and environmental and lead to the emission of greenhouse gases when fossil fuels are used to meet these peaks. Encouraging the demand side to reduce their power demands at these time could be one way of dealing with this issue. This paper investigates the temperature drops after a power cut both through measurements in the field and comparisons of these results to simulations. A single-family dwelling in use and a multi-family dwelling about to be decommissioned were studied. The comparisons showed that the rates of the temperature drops in reality were slower than in the simulation models. A parametric study of the variables affecting the temperature drops, such as furniture, showed that they might explain these differences.

1. Introduction

When looking at energy supply on a larger scale than to a single building, such as to a neighbourhood or a city, the combined effects of peak power demands can be seen to cause problems on the production side. These can be both economic and environmental and lead to the emission of greenhouse gases when fossil fuels are used to meet these peaks. Scheduling intermittent power supplies might be one way for the demand side to contribute to the much larger energy system of a district or a city, in order to reduce the total demands. The actual timing would depend on when difficulties on the production side occur or on the fluctuation of energy costs. The main condition for allowing a power reduction on the demand side, with a resulting lower indoor temperature, is that the indoor climate remains at an acceptable level. Field studies (Kensby, Trüschel, and Dalenbäck 2015; Kärkkäinen et al. 2003; Olsson Ingvarsson and Werner 2008; Wernstedt and Johansson 2008) and simulations (Reynders, Nuytten, and Saelens 2013; Arteconi, Hewitt, and Polonara 2013; Henze et al. 2005) have shown promising results. However, in order to design or predict the result of demand side reductions, simulations are needed and, to make these simulations as reliable as possible, data from certain parameters connected to the indoor heat balance are needed as input. For older buildings, which the majority of the building stock obviously consists of, much of this data could be lacking or not as comprehensive as one could desire. Original building plans might be available but with the complication that changes might have been made, even during construction or over the years, without any record being made. Older buildings, especially single-family dwellings, are usually free-running (Norlén and Andersson 1993) which gives rise to uncertainties regarding the effects of their ventilation. The control of the heating system might be another uncertainty, compounded by poorly functioning thermostats, valves and sensors. There is also the issue of furniture and indoor materials, which might be seen as variables and would depend directly on the current residents in the building. Assuming that building energy and indoor climate simulation tools are able to accurately simulate physical phenomena and as long as all the inputs sufficiently reflect reality, the values of these inputs become important.

Many field tests have shown good results, with short-term cuts in heating power having only limited and acceptable effects on indoor temperatures. However, when considering applying this new approach, i.e. the use of intermittent power supplies to a building, it would be of great interest to be able to simulate these effects. This paper aims to identify, with relatively simple measurements and simulations, key parameters affecting temperature drops after a power cut.

2. Method

Two buildings were investigated. One was a single-family dwelling built in 1956, located in the south of Sweden [Latitude 56, Longitude 13]. This was a building in use, with furniture and people present during the tests. The second building was a multi-family dwelling built in 1966, located in the north of Sweden [Latitude 68, Longitude 20]. This was a decommissioned building that was about to be demolished. The reason for deconstruction was not that it had come to the end of its service life but due to the expansion of a nearby iron ore mine.

The two different building types investigated were therefore tested differently. In the single-family dwelling the heating was turned off during one night, for approximately 8 hours. The temperatures in the multi-family dwelling were measured from when the heating supplies to the buildings were permanently cut off and for a cooling period of about two weeks. Due to the different building sizes and the number of sensors used, one in in every room compared to one in each apartment, two different levels of accuracy were achieved.

The commercial building energy simulation software IDA Climate and Energy (IDA ICE) was used for the simulation (EQUA 2014). The software had gone through comparative testing in which it was compared to other similar software with respect to EN and ASHRAE standards (Kropf and Zweifel ; EQUA 2010). Also in an Annex (Loutzenhiser, Manz, and Maxwell 2007), simulations were performed using a test house as a basis for comparing measured values with simulated results. In order to run the systematic parametric analysis efficiently, a second commercial programming software, MATLAB, was used to handle the parameter inputs, to start the energy simulations and to gather the output results. This is exemplified in Fransson, Bagge, and Johansson (2016).

2.1 Case 1 Single-family dwelling

2.1.1 Building properties

A single-family dwelling located in the south of Sweden in the town of Ängelholm [Latitude 56, Longitude 13] was investigated. The house was constructed in 1956 and had an area of 106 m² divided between two floors. The upper floor had a sloping ceiling and there was a basement beneath the whole ground floor. The layout of the house and the connected unheated buildings, a garage and a conservatory, can be seen in Figure 1. The house had not been subject to any major refurbishments to increase the thermal insulation level of the exterior envelope. The load-bearing frame of the building was made of bricks (interior walls), concrete (floors) and lightweight concrete (exterior and interior walls), the latter also serving as the insulation of the exterior walls. The properties of the building envelope are summarized in Table 1. The material properties were those included in the simulation software and the properties of the layers of the different envelope parts were gathered from the existing building plans. Thus, the values in Table 1 might not fully represent reality due to differences in material properties, the degradation of insulation materials or other imperfections. Translating reality into a simulation model also introduces inconsistencies, as simplifications always have to be made.

Table 1. Building envelope properties

Building comp	Properties
$U_{Exterior\ wall}$	0.64 W/(m²K)
U_{Roof}	0.77 W/(m²K)
$U_{Attic\ floor}$	0.82 W/(m²K)
U_{Window}	2.9 W/(m²K)
U_{Ground}	3 W/(m²K)
Air leakage	1.6 l/(s m²) ext. area at 50 Pa
Thermal bridges	5 % of $U_{tot}{\cdot}A_{tot}$

Hydronic radiators supplied the heat to the rooms and this secondary system was the one originally installed. However, the primary heating source had changed from an oil-fired boiler to district heating. The radiators had no thermostatic valves, only manually operated valves. The temperature of the water leaving the primary system depended on the outdoor temperature and, presumably, on the difference between the indoor temperature measured at one location in the middle of the house and the desired temperature. The device measuring the indoor temperature was also the device by which the design, or preferred, indoor temperature was selected. In this test, it was used to turn off the heat by reducing the setpoint from 21 to 10 °C. The building was free-running, or naturally ventilated, and therefore the input data from the ventilation was unknown. In the simulations, a ventilation rate of 0.23 l/s·m² was chosen. This is the mean ventilation rate of Swedish single-family dwellings from this period, determined through a nationwide investigation of the Swedish building stock (Norlén and Andersson 1993).

2.1.2 Measurement set-up

The test was performed in March, during the night, with an average outdoor temperature of about 0 °C. Temperature loggers were placed in each main room (not every small closet) and set to log the temperature every minute. To record the local outdoor temperature, one logger was placed on the north façade of the house. Climate variables needed for the simulations and not measured at the location of the house, such as wind speed, wind direction, and diffuse and direct solar radiation, were obtained from measurements taken at the Swedish Meteorological and Hydrological Institute (SMHI) climate station located 19 km away (SMHI 2016b, 2016a). There were four residents living in the house during the test, two adults and two children (6 months and 5 years old). The only active electrical goods during the test were the fridge and freezer.

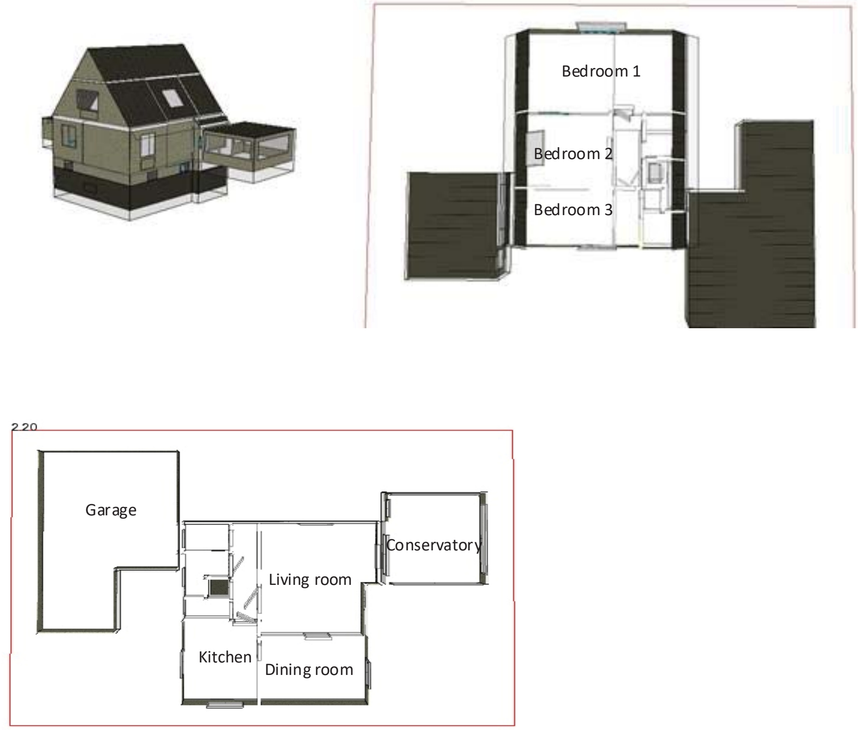

Figure 1. Layout of the single family dwelling as modelled in IDA-ICE.

2.1.3 Measurements and base-case simulation

The first step was to analyse the measured temperatures in the building, in order to see what the resulting temperatures actually were prior to the power cut. As there were no heating controls for individual rooms, these measured temperatures were needed in order to simulate the rooms. This, again, reflects the difficulty in carrying out simulations when the design temperature during specific conditions is not known and could vary between rooms.

The base-case simulations, with the resulting measured temperatures as design values, were performed with a ventilation rate of 0.23 l/(s·m²), the mean ventilation rate in buildings from the 1950s gathered from the nationwide investigation ELIB (Norlén and Andersson 1993). The radiator model in IDA-ICE, used in the base-case simulation, does not take into account the mass of the radiator nor the volume of water inside. This means that once the power is cut no remaining heat is assumed to be emitted from the radiator. This led to a very severe initial temperature drop though this was not observed in reality. A new radiator model was implemented to make up for this difference. In this new model, the radiators were assigned a mass with the thermal capacity of water, as the metal in the radiators had to be incorporated into that mass, because of the way it was simulated. In order to find a value for this mass, data for radiators produced today was used. The amount of energy in the radiator before the power cut depended on its mass and the temperature of the radiator. This energy was then emitted into the room, using the same radiator coefficients, but with declining surface temperatures as the energy level declined.

2.1.4 Parametric analysis

This section is in three parts, the first of which is the most extensive with a systematic analysis of ventilation rates, and using fictive furniture mass and surface area in contact with the indoor air. The second part begins with a chosen parameter set-up and an investigation of the impact of the thermal insulation levels. The second and third parts only show results from the simulations and the last part visualizes the correlation between the temperature drops and the mass and surface area of the fictive furniture.

2.1.4.1 Ventilation and furniture

The parametric analysis focuses on the parameters furniture (internal mass) and ventilation rate. In the simulation software, the rooms are modelled as zones where each zone is represented as a single node or point with a mass (the air) and a temperature in contact with the surrounding surfaces. Heat and mass transfer takes place between these modelled zones and the exterior climate. The furniture can be modelled as internal masses transferring heat to the air node with a fixed convective heat transfer coefficient. Contact between this mass and the air node also depends on its surface area, while the amount of heat stored depends on the volume and the thermal capacity of the mass. In the simulation software, the internal mass is defined as a flat body with an area and a thickness. Both sides of this flat body are in contact with the air node. The heat transfer from the other interior surfaces to the air is also governed by a convective heat transfer coefficient and this is calculated continuously during the simulation, depending on temperature differences and ventilation rate.

The material chosen to represent the furniture corresponds to chipboard with a density of 1000 kg/m³, a specific heat capacity of 1,300 J/(Kg·K) and a heat conductivity 0.13 W/(m·K). Four different areas, 10–80 m², and five different thicknesses, 0.01–0.1 m, were combined, representing masses varying between 100–8,000 kg. The latter was obviously unrealistic but used in order to cover a large span of masses and show their effects.

Four different ventilation rates were tested, the first rate being zero. The second and third were statistically determined values from the ELIB investigation (Norlén and Andersson 1993), the second being the 25-percentile and the third the mean value (also used for the base-case). The fourth was the minimum ventilation rate required to fulfil current Swedish building regulations.

The values of these parameters can be seen in Table 2, all the 96 combinations were simulated and presented.

Table 2. Parameter used in the analyzis

Thickness /m	Area / m²	Ventilation rate / (l/(sm²))
0.01	10	0
0.02	20	0.1
0.04	60	0.23
0.08	80	0.35
0.1	-	-

The simulated temperature drops were investigated at four different points in time – 2, 4, 6 and 8 hours after the power cut – and were compared to the measured values after the same times. Parameter set-ups both with good and poor agreement with reality are shown in the results section.

2.1.4.2 U-value reduction

As discussed previously in the Building Properties sub-section, the assumptions in the simulation model, regarding the envelope materials as well as the layers within their construction, might have differed from reality. The purpose of this section was to test how the temperature drops were affected when the U-values were different to those of the initial model.

Two cases were studied, with a moderate ventilation rate of 0.23 l/(s·m²), and identical internal masses of 600 kg, but with different surface areas, 20 and 60 m² respectively. Both these cases had the base-case U-values shown in Table 1, when averaged denoted as $U_{base,tot}$. Each of these cases was tested for 12 reductions of the base-case U-value. Test values varied from $0.9 \cdot U_{base,tot}$ to $0.35 \cdot U_{base,tot}$ in steps of 0.05. Again, the temperature was investigated after four periods – 2, 4, 6 and 8 hours after the power had been cut off. The differences between the temperatures after these periods were compared to the temperature differences obtained when using the base-case U-value. The differences were calculated using the initial U-value in the parametric study above.

2.1.4.3 Correlation between temperature drop, area and mass of the fictive furniture

As previously mentioned, contact between the air and the fictive furniture depends on the surface area of the internal mass, as all cases are modelled with a constant heat transfer coefficient. The aim here was to investigate whether the mass or the area was the limiting factor when releasing the energy stored in the fictive furniture.

2.2 Case 2 Multi-family dwelling

2.2.1 Building Properties

This part deals with the measurements and simulations of a multi-family dwelling built in 1966 in Kiruna [Latitude 68, Longitude 20] in the far north of Sweden. The building consists of twelve apartments located on three floors. There are two staircases, denoted C and D, centrally located in the building, serving six apartments each. The apartments vary in size from 60 to 105 m². The design of the building and the floor plan of the second floor are shown in Figure 2. As no original design drawings were available, the material composition of the envelope was gathered empirically thanks to destructive sampling, carried out to investigate moisture damage in the envelope after the measurements had been made. The load-bearing walls were made of concrete, as were the internal walls separating the apartments and rooms, and the floors. The flat roof comprised a load-bearing concrete slab with loose mineral wool in the small attic space. Non load-bearing walls were made of lightweight concrete and next to the balconies the walls were made of mineral wool, wooden studs and beams. Load-bearing external walls at the gables were made of concrete and mineral wool. The windows had been upgraded at some point during the 1990s. The air leakage was measured using a blower door test (Jönsson, Johansson, and Bagge 2014) and the mean value was used as input in the simulation model. A summary of the exterior envelope U-values can be found in Table 3. During the tests, the apartments were empty. There were no residents or pieces of furniture.

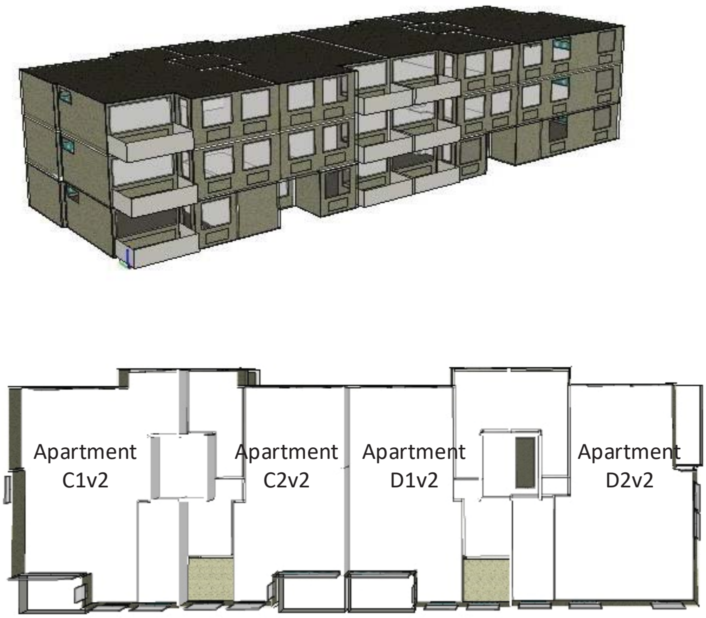

Figure 2. Layout of the multi-family dwelling as modelled in IDA-ICE. The apartment code comprises the staircase designation (C or D), the apartment number (1 or 2), and the floor level (v1, v2 or v3).

Heat had been supplied to the building via a district heating system and distributed to the apartments using hydronic radiators. These were controlled by thermostatic valves. However, as the heat was cut off completely on the primary side, any malfunctioning or poorly maintained thermostats could not affect the test.

Table 3

Building comp	Properties
$U_{Curtain\ wall}$	0.69 W/(m²K)
$U_{Gable\ wall}$	0.30 W/(m²K)
$U_{Parapet\ wall}$	0.45 W/(m²K)
U_{Roof}	0.17 W/(m²K)
U_{Window}	1.9 W/(m²K)
U_{Ground}	0.44 W/(m²K)
Air leakage	1.6 l/(s m²) ext. area at 50 Pa
Thermal bridges	5 % of $U_{tot} \cdot A_{tot}$

2.2.2 Measurement set-up

The power was cut off on 19th March at approximately 8.15 in the morning. One temperature logger had been placed in each apartment prior to this. The loggers were placed in the hallway close to the entrance to the apartment. The temperature was monitored every five minutes for two weeks. However, in this study, we had limited ourselves to looking at the temperature drops during the first eight days after the power had been cut off. The outdoor temperature was not measured locally in the same manner as in Case 1, with a logger on the north side of the building, during this measurement period. Instead, all outdoor climate parameter values were obtained from the SMHI weather station in Kiruna. Previous outdoor temperature measurements of the microclimate at the location showed that that the correlation with the temperature from the weather station was very good. The mean outdoor temperature during the eight investigated days was –7 °C.

2.2.1 Measurements and simulations

The main focus in this second case study was not to perform a parametric analysis but rather investigate the differences between the apartments regarding the measurements and simulations. However, some comparisons were made.

The apartments were modelled as one coherent zone with no internal walls or masses. This simplification was made due to the fact that the temperature was only measured at one location and to test a different level of detail compared to the single-family house case. The dynamic radiator model, identified as necessary in the previous case, was, however, implemented. The fact that the building was not in use made it possible to look at temperatures after a much longer period of time without power, i.e. at temperatures that could never be allowed in occupied houses, as well as on the same time scale as the single-family house.

3 Results

The results section is in two main parts covering the tests and simulations of the two different buildings. Both parts begin by displaying the temperature measurements followed by combined or separate analyses of measurements and simulations.

3.1 Case 1: Single-family dwelling

3.1.1 Room temperature measurements

The power was cut off at 23.00 and Figure 3 shows the indoor temperature in the main rooms until the power was turned back on at 07.00, adding up to an 8-hour period without heating power. There was a spread of approximately 2 °C between the room temperatures prior to the power cut. This difference remained after the power cut period. This means that the temperature drops appear to be quite similar between the rooms. However, two rooms do differ, the kitchen and bedroom no. 3. The fact that there is a difference in temperatures between the rooms is interesting in itself and can be explained by the lack of thermostats to control each room individually. In this case, due to all radiator valves being fully open, the resulting temperatures depended on the supplied water temperature, which was the same for all rooms, as well as the sizes of the radiators and each room's heat loss coefficient. The internal heat load was that of the residents sleeping in their bedrooms, although bedroom no. 1 still had the lowest temperature. While we have established that there was a difference between the rooms, one room, the living room, was chosen for the analyses and comparisons in the following sub-sections. Investigating one room only means less crowded figures and, as the temperature seems to have dropped similarly in all the rooms, it was a viable choice.

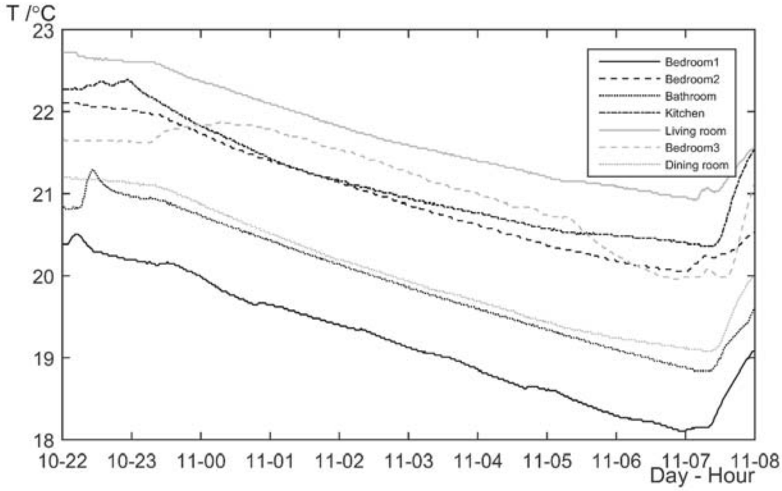

Figure 3. Measured temperatures during an 8-hour power cut during the night, 23:00–07:00, on 10–11 March. The temperatures of the main rooms of a single-family dwelling are shown. The mean outdoor temperature during this power cut was 0 °C.

3.1.1 Measurements versus base-case simulations

The initial simulation was carried out using the envelope properties in Table 1. The simple radiator model without a designated mass was used for the base-case. As can be seen in Figure 4, the temperature curve for this case drops immediately after the power is cut. Also shown in the same figure are measured temperatures and the temperatures from the simulation with a dynamic radiator model. The dynamic radiator model avoids the initial steep temperature drops, as it allows the radiator to emit the heat stored in its mass after the system had been turned off. Also worth noting, when comparing the measurements to the simulations, is the dead time. The dead time, commonly used in control theory, is the time it takes after a change made in a system is noticed. In the measurements, the temperatures do not start to drop immediately at 23:00 although that is when the design temperature is changed to 10°C. This is clearly visible both when power is cut and when it is turned on again. The temperature in the simulations is affected immediately in contrast to the measured temperatures that start to change after about 20-30 minutes following a change.

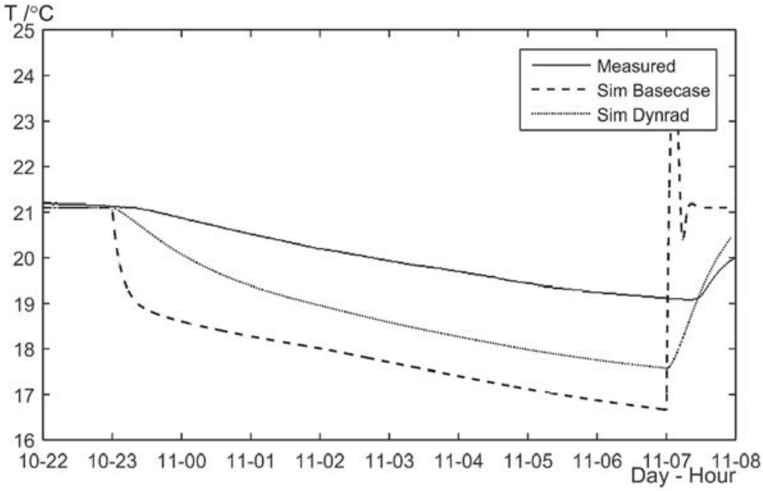

Figure 4. The temperature in the living room during the power cut, measured and in two simulated cases. The base case simulation shows the model without a radiator taking into account the remaining warm mass of the radiator and the Dynrad shows the temperature when the new radiator model was applied.

3.1.2 Parametric analysis

The simulated resulting temperatures, for the 96 combinations, following the power cut are presented in Figure 5. The 96 combinations consist of three parameters of which the first two are the surface area (10-80 m²) and thickness (0.01-0.1 m) of the internal mass and the third the ventilation rate (0-0.35 l/s·m²).

In this figure, each parameter set-up is represented by four temperature differences: measured temperature – simulated temperature 2, 4, 6 and 8 hours after the power cut. The 96 temperature differences in each graph were then plotted as distribution functions. The fact that the different temperatures can be both positive and negative means that there are combinations giving both too high and too low temperatures compared to the measured temperatures. This output was also used to quantitatively identify parameter combinations that gave a close match to the measured data, using a restriction of ± 0.15 °C. Having identical values after the four different periods would have yielded the closest matches. However, the restriction used was not that severe. If the parameter set-up, containing a value for each of the four investigated periods, showed ΔT temperatures of ± 0.15 °C, they were chosen as a good match and were plotted as shown in Figure 6.

Five combinations with good matches were found although no correlation, regarding the actual parameters, between these matches could be seen. What can be established is that the smallest area, 10 m², did not meet the criteria for a good match. The results from four parameter combinations with poor matches are shown in Figure 7. These were chosen from the two different ends of the distribution in Figure 5, which meant that there were temperatures both exceeding and inferior to those measured. From Figures 6 and 7 it is obvious that the extremes regarding the parameters gives poor results. Where the good matches are concerned, the internal mass changes with the change in surface area, leading to the mass varying between 1,600-3,200 kg. Areas between 20-80 m² were among the good matches. However, consistency was not achieved in the cases of the same mass giving the same results. For example, the set-up with an area of 20 m² and 0.08 m thickness would give the same mass as 80 m² with 0.02 m thickness but, nonetheless, does not show as a good match.

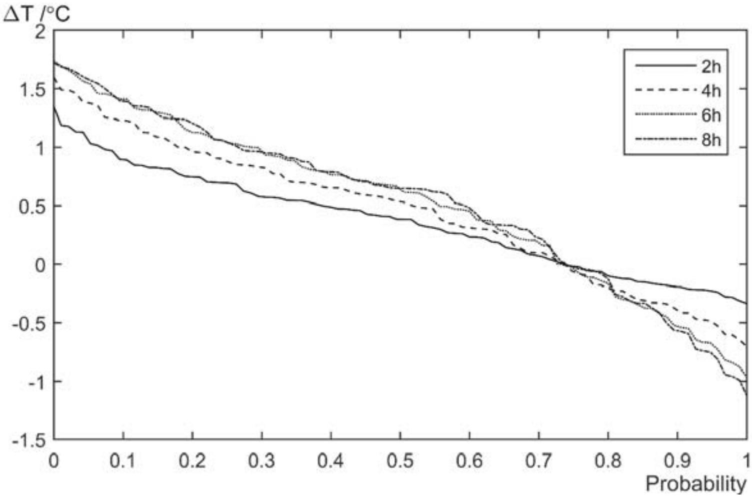

Figure 5. The differences between measured and simulated temperatures after 2, 4, 6 and 8 hours for 96 parameters shown as four distribution functions. Values close to 0 mean that the simulated parameter set-up had a temperature curve very close to the measured one. Positive values indicate low simulated temperatures and negative values temperatures that are too high.

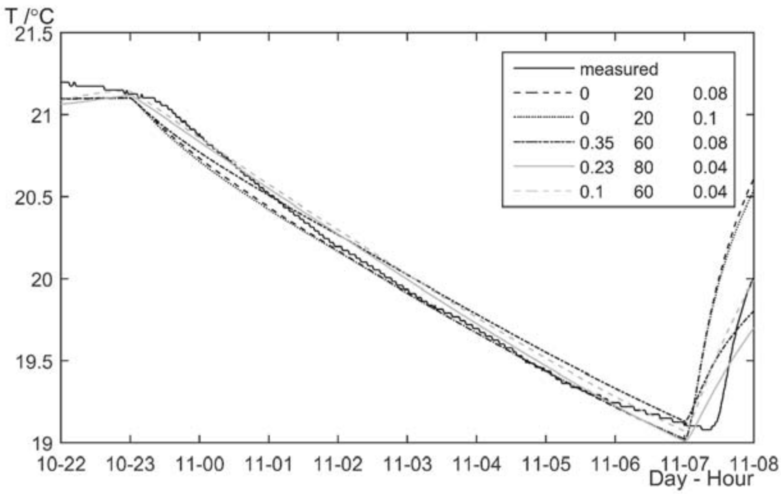

Figure 6. The temperatures during the power cut for five parameter set-ups with good correlations to the measured temperatures. The measured temperatures are also shown and the most prominent differences are still the dead time, at the beginning and end of the power cut. When a change was made in the simulations, the temperature reacted instantly whereas in reality it took 20-30 minutes.

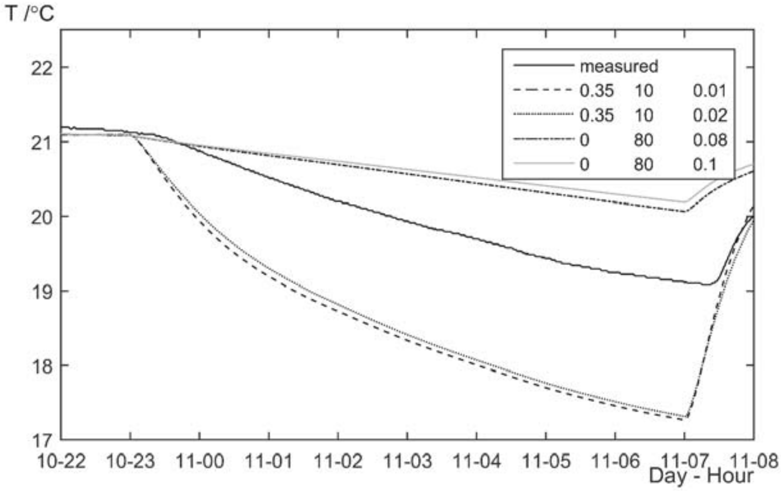

Figure 7. The temperatures during the power cut for four parameters set-ups with poor correlations to the measured temperatures. Two parameters which gave results with inferior temperatures and two which gave temperatures exceeding the measured ones are shown. The most prominent differences between the two cases concern the internal mass. Between the highest and lowest mass there is a factor of 80.

3.1.2.1 Evaluating the impact of different U-values

This section investigates the impact of the U-values chosen in the simulations. Reduced U-values were applied to two different parameter combinations and the temperatures were investigated over four periods of time in each case. The results are shown in Figure 8 as differences between the measured temperatures and the temperatures achieved with a reduced U-value. The two parameter combinations had the same ventilation rate, 0.23 l/sm², the same internal mass, 600 kg, but different surface areas, 20 and 60 m². The initial simulations placed these two combinations well below the measured temperatures. The starting points in the figures are when there were no reductions in U-values. Obviously, the differences between measured and simulated values decrease as the thermal insulation level becomes higher (reducing the U-value) and behaviour is similar in both cases. It is also obvious that the U-value itself cannot compensate for the entire difference, as there is also a ventilation loss. The 10-20 % reduction might be within the range of errors with respect to how construction simplifications and material properties match reality. Looking at the temperature differences connected to these reductions, they can be seen to range between 0.1-0.3 °C for the 4-, 6- and 8-hour power cuts and about 0.1 °C after the 2-hour power cut.

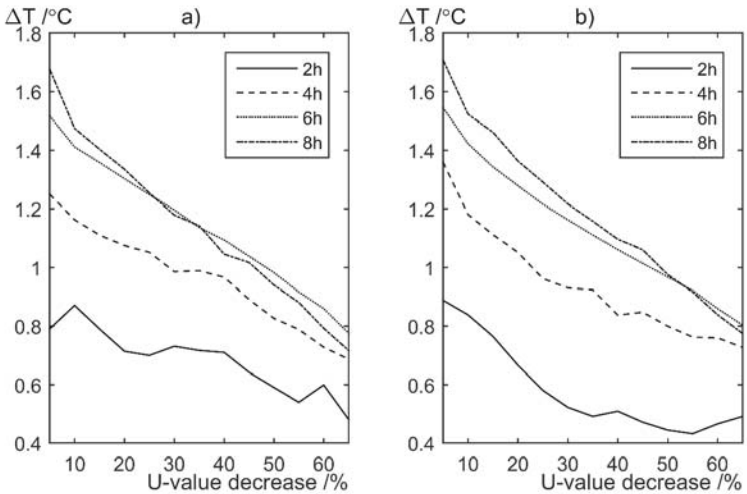

Figure 8. Differences between measured and simulated temperatures, 2, 4 ,6 and 8 hours after the power cut, correlated to the U-value. The U-values, on the x-axis, start from the base-case down to a 65 % reduction. In both figures the same internal mass was investigated (600 kg) but with different surface areas, a) 20 m² and b) 60 m².

3.1.2.2 Correlation between temperature and the mass and surface area of the fictive furniture

Another aspect was investigated using the results from some of the 96 parameter combinations. For one ventilation rate, 0.35 l/sm², 24 combinations of surface areas and thicknesses were investigated with a focus on internal masses in relation to the surface areas. Figure 9 shows distribution curves for the temperature differences between measured and simulated values after four different periods of time after the power cut. In each figure, these temperature differences, y-axis, are divided into four groups depending on their surface areas and correlated to the internal masses on the x-axis. It is evident that the amount of mass sets the limit for the temperature differences, as these are greater at low amounts. The closer to the measured value we get, the more mass is needed. The b), c) and d) plots indicate, for the spread covered, that surface areas do not affect the temperature differences. There are slight differences in the 2-hour case, where a greater surface area seems to be favourable.

In Figure 10, a similar approach was investigated but with a constant internal mass of 2,000 kg and varying surface areas. The surface areas now covered a wider spread 1-60 m², where the smaller surface areas corresponded to an almost cube-like form. Figure 10 a) shows a case with no ventilation and b) a case with a 0.35 l/sm² rate. The temperature differences were investigated in the same manner as in the previous sub-sections, with one graph for each of the four investigated points in time after the power cut. Now it is clearly discernible that the surface area of the internal mass (fictive furniture) does matter. The temperature differences change significantly at the lower end of the range of surface areas, 1-10 m². When the graphs level out, one could say there is no more dependency on the surface area. In Figure 10 b) with a ventilation rate of 0.35 l/sm², the surface dependency seems to be different when looking at the four periods after the power cut. After 8 hours, the graphs level out at 10 m² but after only 2 hours this occurs for surface areas of 30-40 m².

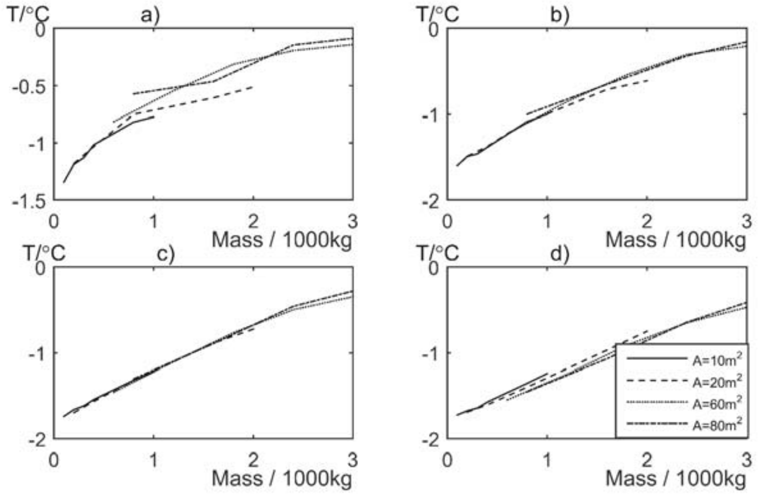

Figure 9. Temperature differences between simulations and measurements after four different periods, a) 2 hours, b) 4 hours, c) 6 hours and d) 8 hours, correlated to the simulated internal masses and surface areas. From these figures, the change in internal mass seems to be affecting the temperature differences while surface areas ranging between 10-80 m² do not. The ventilation rate in these investigated cases was 0.35 l/(s·m ²).

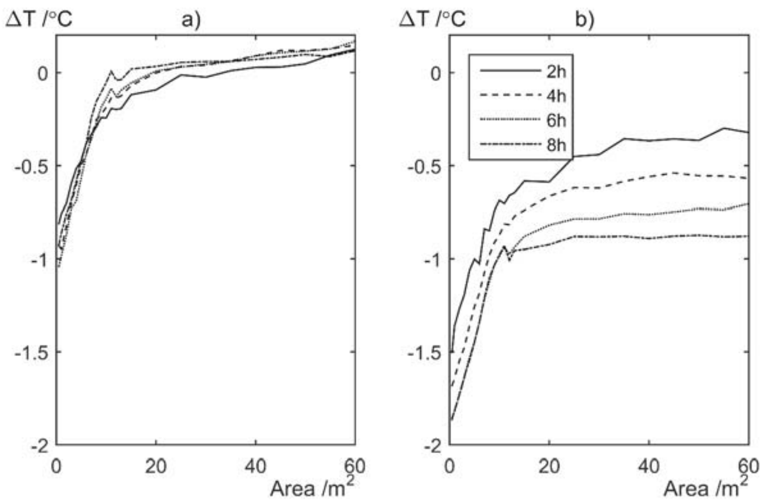

Figure 10. Temperature differences between simulations and measurements after four different periods, 2, 4, 6 and 8 hours, with identical simulated internal masses of 2,000 kg, correlated to different surface areas. Surface areas varying from 1-60 m² and two cases of ventilation rates were investigated, a) 0 /(s·m ²) and b) 0.35 l/(s·m ²).

3.2 Case 2: Multi-family dwelling

3.2.1 Apartment temperature measurements

The power supply to the building was cut permanently on 19th March at 8.15 in the morning. The resulting temperatures in the twelve apartments are shown in Figures 11 and 12, the six apartments served by each staircase are shown separately. Figure 11 shows the first 8 hours and Figure 12 the first 8 days following the power cut.

Looking at Figure 11, it can be seen that the starting point or initial temperature varied between the apartments, from slightly above 20 °C to slightly below 25 °C. The difference between the apartments served by the same staircase were somewhat smaller, 2-3 °C. Apart from different starting temperatures, the rate of the temperature drop varied significantly. The most obvious case is b), with the two apartments on the first floor dropping 2-3.5 °C during the first 8 hours while in the top floor apartments the temperatures barely change. During the first 8 hours, the mean outdoor temperature was –6.3 °C and only varied by a few degrees.

In Figure 12, the temperature drops after eight days are shown. Since the period now stretches over days, the outdoor temperature, while still averaging –7 °C, varied much more than in the shorter tests. It varied during individual days and between days, falling to a minimum of –18 °C and rising to a maximum of + 2 °C. These diurnal variations can be seen in the more wave-like plots. The small peaks could indicate that the sun also affected the indoor temperatures for short periods of time in some of the apartments. However, it is possible to see that that the two ground floor apartments show the fastest drop rates, or the steepest slopes, in the same manner as during the first 8 hours.

Figure 13 shows the magnitude and the spread of the temperature drops of all the 12 apartments at 8 different points in time after the power cut. The differences between the apartments, discussed earlier, is more clearly visible here.

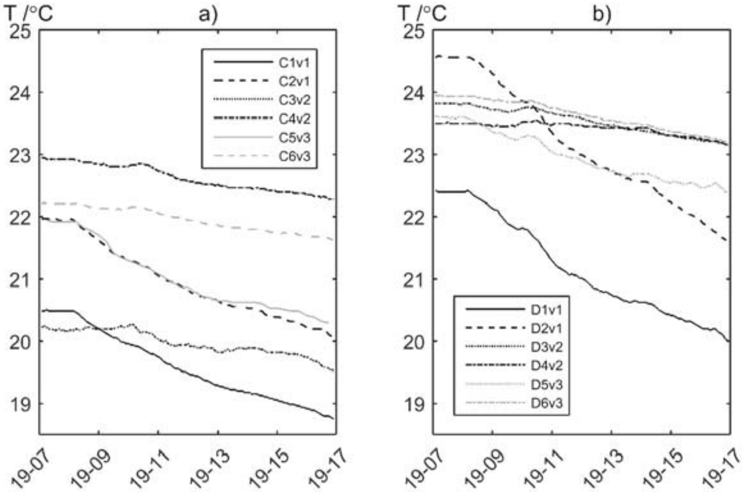

Figure 11. Measured temperatures during the first 8 hours after the power cut in a multi-family dwelling with 12 apartments served by two separate staircases a) and b). There were two apartments on each floor, denoted by the floor number as the last digit in the legend. The mean outdoor temperature during the first 8 hours after the power cut was –6.3 °C.

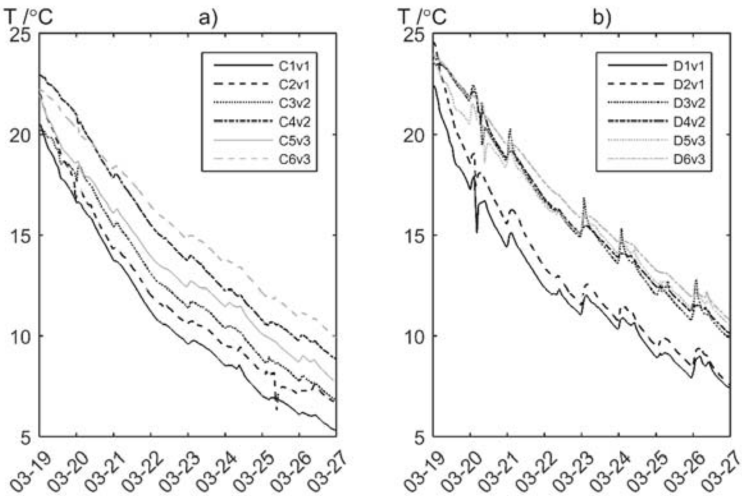

Figure 12. Measured temperatures during the first 8 days after the power cut in a multi-family dwelling with 12 apartments served by two separate staircases a) and b). There were two apartments on each floor, denoted with the floor number as the last digit in the legend. The mean outdoor temperature during the first 8 hours after the power cut was –7 °C. However, the outdoor temperature varied between –17.9 and –1.7 °C during this period, causing the diurnal peaks.

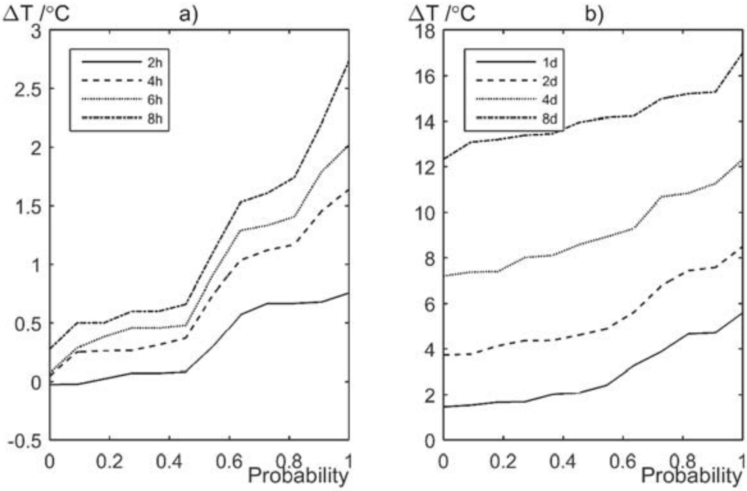

Figure 13. a The differences between initial and measured temperatures 2, 4, 6 and 8 hours after the power cut, plotted as distribution functions. b) The differences 1,2,4 and 8 days after the power cut, plotted as distribution functions.

3.2.2 Measurements versus simulations

Simulations of the multi-family dwelling were carried out for the same measured power cut and the results are presented in Figure 14. The results are shown as differences between measured and simulated temperatures at eight points in time after the power cut and are plotted as distributions. The simplification of modelling an entire apartment as one zone could explain the differences between simulations and measurements and, furthermore, the differences compared to the single-family dwelling.

The fact that no internal structures or furniture were simulated can therefore explain the rather large differences, even after the first 8 hours. The consequence of having studied more rooms in the apartments would have been having to take into account more internal walls. The fact that the internal walls were made of concrete means that the additional mass from the structure lacking in these simulations would have been quite large. Furthermore, another phenomenon that the simulations did not seem to take into account were the different behaviours of the individual apartments, as seen in the measurements. For example, there were initial slow rates of temperature drop in some of the apartments as well as very fast ones. If the distributions were constant around a certain temperature this would mean that all the apartments in the simulations had had the same differences at a certain point in time. Instead, there are spreads, between 2-6 °C as shown in Figure 14 a), and between 2-10 °C in the most prominent distribution as shown in Figure 14 b). This means that the simulated temperature drops in some apartments are only slightly different to the measured ones and some are much larger after similar times after the power cut. This implies that, in the simulations, the drops are quite similar whereas, in reality, they differ significantly between the apartments.

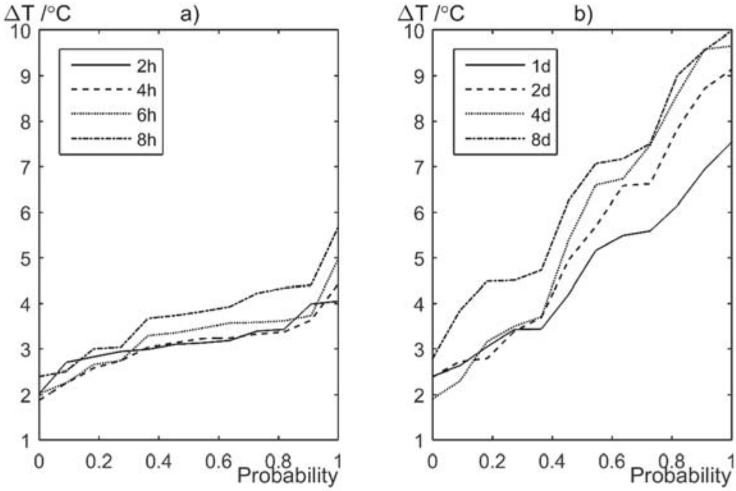

Figure 14. aThe differences between measured and simulated temperatures 2, 4, 6 and 8 hours after the power cut, plotted as distribution functions. b) The differences 1,2,4 and 8 days after the power cut, plotted as distribution functions.

4. Discussion and Conclusion

Comparing a simulation model to real measurements can be difficult – reality is complex. Creating a simulation model of a building requires information that must be translated into input data for the model. This includes, for example, parameters such as the structure of the walls, material properties, ventilation rates and furniture, to name a few. Furthermore, variables such as climate, internal loads and stochastic resident behaviour need to be modelled. These are only a few examples and input uncertainties, big and small, will always exist. This means that simplifications must be made on different levels and at different impact levels. The number of uncertainties when modelling an older building without having access to the original plans or building services documentation are likely to increase.

In this study, power cuts were investigated using measurements in a single-family dwelling and a multi-family dwelling and simulations were made to cover the same events. The measured temperature drops were small in both the single-family dwelling and the multi-family dwelling, when studying durations without heat of up to 8 hours. Even though all the power was cut, the results were in accordance with previous studies.

Single-family dwelling – parametric analysis

The initial simulations differed significantly from the measured values, which could have been expected as no radiator masses or internal masses were initially modelled. The first modification was to allow for radiators having a residual mass with a temperature corresponding to that prior to the power cut. This modification rectified the issue of the instant temperature drop of about 1 °C directly following the power cut in the simulation model. After this modification, a parameter investigation was performed in order to see whether fictive furniture could make up for the difference.

Matches were found for internal masses between 1,600-4,800 kg, at different ventilation rates. The surface areas that were investigated were shown to have no impact in the ranges of the parameter set-up between 10-80 m². Dependency on surface areas was shown to have its highest impact shortly after the power cut. This was to be expected as it was directly linked to the rate at which heat could be transferred from the mass to the room. Whether the areas and masses truly represent reality is hard to say for certain, as some people have a lot of furniture and some have very little. Having almost 5,000 kg in a single room is not likely to be the case but having 1,600 kg might not be impossible. In reality, the furniture and materials inside the insulated envelope have very different thermal properties, masses and surface areas. However, combining all of these different properties together in the simulation model did give promising results.

Multi-family dwelling – measurements

The focus of the investigation of the multi-family dwelling was the measurements and, with respect to temperatures, the twelve different apartments differed significantly, even before the power was cut. This could have been caused for several reasons – unbalanced heating systems, dysfunctional thermostats and apartments with heat loss coefficients above the design values, caused by degradation of the envelope.

Another matter that was identified was the rapid temperature drops shown by the two ground floor apartments served by each staircase. The cause of this could be connected to the heat loss coefficient, meaning that the ground floor, in reality, was much more poorly insulated than simulated. Another reason could have been the convective heat transfer upwards, between the apartments in the building. There is, nonetheless, a distinct difference regarding the temperature drops between the ground floor and top floor. The number and size of the radiators in the different apartments were the same, so what strengthens the assumption regarding convective heat transport upwards can be found in the simulations. In these, all apartments reacted similarly to the power cut, thus responding to the outdoor climate. However, no other connections, except transmission, were simulated between the apartments.

The positioning of the temperature sensors in the apartments, in a spatial sense, could have been significant when comparing measurements to simulations. The sensors were all placed in the entrance to each apartment, and these were situated in the middle of the building, where there were no external walls. In the single-family house, we could see that the differences between the rooms in the same household were 2-3 °C. However, all these rooms had walls that were connected to the outdoor climate. The same, and even more prominent differences, were seen between the apartments, although sensors had been placed in similar locations. Furthermore, a difference was to be expected between the rooms of the apartment. In the simulations, every apartment was modelled as one zone, which meant that the air node of this fictitious room was in direct contact with all the exterior walls of the apartment.

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