Prediction of power and energy use in dwellings

Addressing apects of thermal mass and occupant behaviour

Fransson, Victor

2020

Document Version:
Publisher's PDF, also known as Version of record

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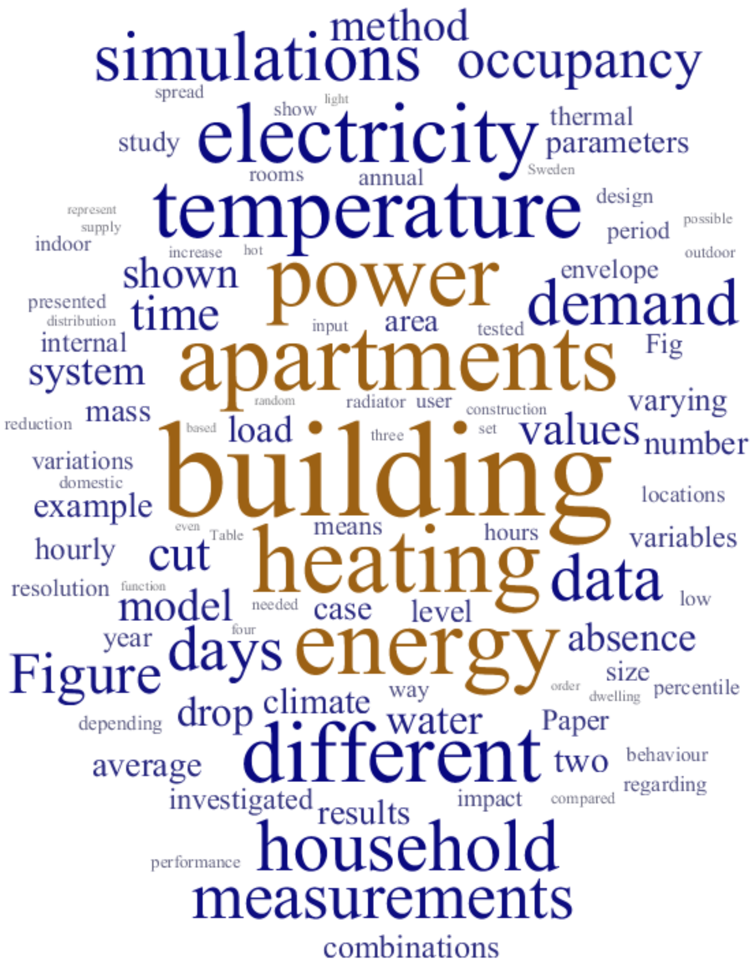

Lund University
Faculty of Engineering
Department of Building and Environmental Technology
Division of Building Services

ISBN 978-91-85415-11-3
ISSN 1652-6783
ISRN LUTVDG/TVIT-20/1002-SE(215)

LUND UNIVERSITY

Prediction of power and energy use in dwellings

Addressing aspects of thermal mass and occupant behaviour

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LUND UNIVERSITY

DOCTORAL DISSERTATION

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To be defended at John Ericssons väg 1, building "V-huset", lecture hall V:B.
Date 8th of June 2020, time 13:00.

Faculty opponent
Prof. Thomas Olofsson, Umeå Univeristy, Faculty of Science and Technology,
Department of Applied Physics and Electronics

Organization
LUND UNIVERSITY

Author: Victor Fransson

Document name Doctoral Thesis

Date of issue 2020-05-13

Title and subtitle Prediction of power and energy use in dwellings
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Abstract

Households are responsible for approximately 26 % of the annual energy use in the EU. Following the EU-directives regarding energy performance in buildings, international initiatives have been taken in Europe to help countries to define and include guidelines in their own building codes, for example, to establish the concept of zero energy buildings, ZEBs. This concept includes passive building energy-saving technologies, energy-efficient building services systems and renewable energy generation technologies. It is usually very difficult for a building to use zero energy and the concept has therefore been developed to include so-called net-zero energy buildings, or nearly zero energy buildings. These are usually defined as having a net-zero energy use on an annual basis and a nearly-zero energy use if they have a significantly lower use than stipulated in the respective national building codes. Technological advances have resulted in new buildings being very well insulated and, subsequently, using very little energy. However, the focus has now moved towards the use of renewable energy rather than only looking at the amount of energy used. Energy production can be achieved via numerous different arrangements and can be utilized in ways that are dependent on the time of day and the weather. Taking these different aspects into consideration, it can be assumed that the temporal variations regarding production can vary significantly. The heating demand of a building depends on the outdoor climate and the occupants' behaviour, which leads to an uncertain situation with regard to matching the renewable production and demand, and even more so when the occupants' behaviour is subject to temporal variations. In addition to the temporal variations, occupant actions or preferences are subject to large stochastic variations within a population. Thus, when designing to meet these challenges, the temporal resolution would have to be higher with regard not only to demand but also to the renewable energy production, in order to provide general benefits as well as covering a larger part of the possible future scenarios.

This thesis aims show how the use of household electricity and domestic hot water varies and how these variations impact the energy and power demand of buildings. Additionally, in order to achieve a higher possible level of load matching there is a need to time shift power loads. This is another building operation process that has been investigated.

The primary method in both cases has been to use building simulations with large amounts of measurement data for occupant behaviour as input to the simulation models. By randomly inserting different measurement data sets, and running simulations repeatedly, the outcomes were hundreds of annual energy and power demands that varied with the variation of the input.

Furthermore, load shifting was investigated by abruptly reducing the heating power supply to buildings. The heat stored in the building envelope and furniture was then used to reduce the effects on the indoor temperature. This thesis examines the temperature drops caused by such power reductions and the various factors that affect the size of the temperature drops, such as the thermal mass and the properties of the building envelope, as well as the stochastic behaviour of the occupants that creates the internal heat load

Key words Building simulation, thermal mass, thermal inertia, occupant behaviour, household electricity, domestic hot water

ISRN LUTVDG/TVIT—20/1002—SE(215)

Language English

ISSN 1652-6783 Prediction of power and energy use in dwellings

ISBN 978-91-85415-11-3

Recipient's notes

Number of pages 215

Security classification

Signature

Date 2020-05-06

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ISSN 1652-6783

Printed in Sweden, Lund 2020

L'épaisseur des murs était pour lui un véritable régal

Marcel Aymé – Le Passe-muraille, 1941

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 two divisions of Building Services and Building Physics at Lund University for your support.

The research was funded by Cementa Heidelberg Cement group, E.ON and the Swedish Energy Agency. 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 three sons, Jack, Allan and Ove for giving me the energy of love.

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

Sammanfattning

Hushållen står för cirka 26 % av den årliga energianvändningen i EU. Som följd av EU:s direktiv angående energiprestanda i byggnader har det genomförts olika internationella initiativ i Europa i syfte att hjälpa länder definiera och inkludera riktlinjer i sina egna byggregler som minskar energianvändningen, till exempel genom etablera konceptet nollenergibyggnader. Detta koncept inkluderar passiv teknik för energisnålt byggande, energieffektiva VVS-system och teknik för försörjning av förnybar energi. Det är vanligtvis mycket svårt att projektera en byggnad som inte kommer behöva någon uppvärmningsenergi och därför har en förändring av konceptet gjorts för att inkludera så kallade netto-nollenergibyggnader eller nära-nollenergibyggnader. De definieras vanligtvis som byggnader med energianvändning på årsbasis som är netto-noll eller väldigt låg i förhållande till vad byggreglerna kräver. Den tekniska utvecklingen har inneburit att nya byggnader idag är mycket välisolerade och använder väldigt lite energi. Därför har nu fokus flyttats mot användning av förnybar energi snarare än på mängden energi. Förnybara energikällor kan se väldigt olika ut och vara placerade på olika ställen, där utnyttjandemöjligheten ofta är beroende av vädret och tidpunkt på dygnet. Med hänsyn tagen till alla dessa olika aspekter är den sammanfattande slutsatsen att den tidsmässiga variationen i energitillförsel kan vara avsevärd. En byggnads värmebehov beror på utomhusklimatet och dessutom de boendes beteende vilket leder till en osäker situation när det gäller att matcha tillförsel av energi från förnyelsebara källor med efterfrågan på energi i byggnaderna. Ännu svårare blir det i ett projekteringsskede när de boendes beteenden ska förutses och modelleras, som idag görs genom att använda årsmedelvärden och statiska scheman. Till skillnad från dessa förenklingar finns det stora stokastiska variationer mellan olika hushåll med avseende mängden energi man använder i hushållet och när man använder den. För att ta hänsyn till sådana variationer vid utformning av byggnader måste tidsupplösningen vara högre, inte bara för den förnyelsebara energitillförseln utan även för efterfrågan i byggnaden. För att projekteringar ska ge ha en så god chans som möjligt att få ett bra utfall och fungera i praktiken är det också viktigt att olika typer av framtida brukare kan testas, som då representerar en så stor del som möjligt av byggnadens framtida användning.

Syftet med denna avhandling är att visa hur hushållens el- och varmvattenanvändning varierar och i sin tur hur denna variation påverkar byggnaders energi- och effektbehov. För att använda en större andel förnyelsebar energi till uppvärmning är lastförflyttningar ett tillvägagångsätt. Man använder då byggnadernas inneboende tröghet och den värme som finns lagrad i byggnaden för att flytta effektbehov. Påverkan på inomhustemperaturen av lastförflyttning undersöks också i avhandlingen.

Den primära metoden i avhandlingen har varit att använda byggnadssimuleringar med en stor mängd mätdata om de boendes beteenden som indata i modellerna. Genom att därefter slumpmässigt skapa olika boendekonstellationer, representerade av mätdataserier, kunde olika framtida scenarier undersökas genom simuleringar. Detta kunde göras upprepade gånger och resulterade i hundratals energi- och effektbehov för samma byggnad men som varierade beroende på variationen i indata.

Lastförflyttning undersöktes på samma sätt genom simulering under det att värmeffekttillförseln i en byggnad stängdes av. Påverkan på inomhustemperaturen kopplat till värmen som lagrats i klimatskalet och inredning har också undersökts med mätningar. Denna avhandling undersöker temperaturfallen efter sådana avstängningar och de olika aspekterna som påverkar temperaturfallen, såsom den termiska massa och byggnadsskalets egenskaper men även det stokastiska beteendet hos brukarna som bidrar till värmebalansen.

Abstract

Households are responsible for approximately 26 % of the annual energy use in the EU. Following the EU-directives regarding energy performance in buildings, international initiatives have been taken in Europe to help countries to define and include guidelines in their own building codes, for example, to establish the concept of zero energy buildings, ZEBs. This concept includes passive building energy-saving technologies, energy-efficient building services systems and renewable energy generation technologies. It is usually very difficult for a building to use zero energy and the concept has therefore been developed to include so-called net-zero energy buildings, or nearly zero energy buildings. These are usually defined as having a net-zero energy use on an annual basis and a nearly-zero energy use if they have a significantly lower use than stipulated in the respective national building codes. Technological advances have resulted in new buildings being very well insulated and, subsequently, using very little energy. However, the focus has now moved towards the use of renewable energy rather than only looking at the amount of energy used. Energy production can be achieved via numerous different arrangements and can be utilized in ways that are dependent on the time of day and the weather. Taking these different aspects into consideration, it can be assumed that the temporal variations regarding production can vary significantly. The heating demand of a building depends on the outdoor climate and the occupants' behaviour, which leads to an uncertain situation with regard to matching the renewable production and demand, and even more so when the occupants' behaviour is subject to temporal variations. In addition to the temporal variations, occupant actions or preferences are subject to large stochastic variations within a population. Thus, when designing to meet these challenges, the temporal resolution would have to be higher with regard not only to demand but also to the renewable energy production, in order to provide general benefits as well as covering a larger part of the possible future scenarios.

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The primary method in both cases has been to use building simulations with large amounts of measurement data for occupant behaviour as input to the simulation models. By randomly inserting different measurement data sets, and running simulations repeatedly, the outcomes were hundreds of annual energy and power demands that varied with the variation of the input.

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1 Introduction

The main purpose of buildings is to provide us with somewhere to reside and to shelter us from the outdoor environment, for example, from heat and the sun or from cold, wind and rain, while offering a comfortable indoor environment. One of the main goals for building designers has, until recently, been to design buildings that fulfil these purposes while maintaining the lowest possible levels of energy use. Today, however, this requirement should be changed to maintaining the lowest possible impact on the environment, taking into account the entire life cycles of the buildings. It is in the light of this new approach that this study was begun.

1.1 Background

Approximately 26 % of the annual energy use in the EU originates from households [1]. Following the EU-directives [2], [3] regarding energy performance in buildings, there have been a number of international initiatives in Europe, such as ZEBRA 2020 [4] and Horizon 2020 [5], to help countries formulate guidelines and include them in their own building codes, for example, to establish the concept of zero energy buildings (ZEB). This has also led to ratification of the EU-directives on national levels, exemplified in [6], [7]. The interpretation and definition of the ZEB concept can vary significantly depending on the system boundaries, both spatial and temporal, i.e. with regard to how and when energy is used [8], [9]. In a recent review article [10], the ZEB covers three main fields: *passive building energy saving technologies*, *energy efficient building services systems* and *renewable energy generation technologies*. It is usually very difficult for a building to use *zero* energy and a development of the concept has been made by adding the letter *n*, meaning either a net-zero energy building or nearly-zero energy building depending on your point of view [11]. Net-zero buildings are usually defined as those having a net-zero energy use on an annual basis and nearly-zero buildings as those having significantly lower energy use than stipulated in the respective national building codes. To summarize the outcome of the review article, nZEB buildings are characterized by having an exterior envelope with low thermal transmittance [12], [13] and efficient building services, for example, with heat recovery from the ventilation air flow [14], and the use of heat-pumps [15] coupled with renewable energy generation in some way. The generation of renewable energy can entail widely differing arrangements or utilization that are usually heavily weather dependent. For example, the energy generation can be on- or off-site, coming from different sources such as the wind and sun, or take place in a district heating system using renewable sources or waste heat from industries. Considering these different aspects, it can be deduced that the temporal variations of these forms of energy generation can vary significantly in comparison with the demands of a building, often leading to load mismatching. This undesirable situation might lead to the need of using fossil fuels to meet demands, or making the renewable energy generation redundant in a short-term perspective if storage is not possible [16], [17].

Economic factors are often the driving forces, or create significant constraints, in the implementation of new concepts such as nZEB and there have been many studies regarding how to cost-optimize building designs to attain nZEB [18], [19]. The costs, however, are associated with the energy and power use during the operation of a building, for the production of the building components, and at the end-of-life of these components. As new buildings are increasingly better insulated and use less energy, attention has been moving towards *Life Cycle Assessment* (LCA), a method to estimate the environmental impact during the entire life-span of a building [20], [21]. With regard to environmental impact over a building's life-cycle, the construction phase can have a predominant effect, especially for low energy buildings [22].

From an energy system point of view, making new buildings even better calls for a new perspective, one in which buildings are not viewed as single units demanding energy but rather as parts of a larger whole. Parts that are important and that can collaborate and be more dynamic in relation to and through interaction with the energy supplier and other parts (buildings) of the energy system. This involves changing from a somewhat forced coexistence, where every stakeholder looks for an own advantage, into an energy system in which all parts communicate and act to reach the overall goal of a lower environmental impact of the built environment. Such steps have been taken and technology exists to enable communication in the form of *Smart Grids*, [23], [24], [25] and *Demand Side Management*, [26], [27]. Rescheduling heating, cooling or electricity loads to more suitable points in time [28], [29], in order to ensure use of primary energy from renewable sources to the largest possible extent, is another way of accepting a loss in functionality, i.e. a temperature drop in order to benefit the larger system. Renewable energy generation technology is another important factor. Typical examples include local intermittent energy supplies from wind [30] and the sun [31], technologies to decrease load mismatching by smart charging electric vehicles [32] and hybrid renewable energy systems, [33]. These technologies are also connected to local energy distribution and storage in micro-grids [34], [35], [36]. Shared energy systems for district heating and cooling are another example [37]. With this in mind, the researchers in this field aim to model and predict city and district level energy use [38], [39].

With regard to the energy and power demand of a building, the occasions when it is most difficult to meet the primary energy demands using renewable sources will probably occur during power peaks and these will be met by using fossil fuels, as sufficient power is seldom available from sunlight, wind or biofuels. This problem could be avoided, for example, by buildings working together in a smart configuration to achieve a smaller environmental impact than the sum of the individual impacts. This would be possible to achieve if the buildings needed different types of energy (heating, cooling) at different times. Additionally, when designing a building, there is a need for reliable data regarding the end-users of the building. One factor, which is subject to large variations, is occupant behaviour in residential buildings. This is a concept that is very broad but necessary to investigate as the relative impact of occupants in an nZEB will increase [40]. Actions within a building, such as window-opening [41], [42], the use of household electricity (appliances) [43], [44], [45], [46] and domestic hot water use [47], [48], [49] are all subject to temporal stochasticity. In addition to the temporal variations, these actions or preferences are all subject to large stochastic variations within a population [50]. Thus, when taking such circumstances into account when designing buildings, the temporal resolution would have to be higher not only with regard to demand but also to renewable energy generation in order to benefit the most.

A crucial question, with the above in mind, is how to design buildings as integral parts of these new energy systems and what input data do we need in order to predict how the future building will operate.

Currently available building simulation software, with regard to energy calculations, is quite good at modelling the physical world [51] – as long as the input parameters represent actual conditions. With regard to some aspects, for example, occupant behaviour, more knowledge is still needed [52]. Furthermore, in building codes, in an international perspective, there is a general consensus about the need for incentives for code compliance [53]. However, with respect to energy use, a gap often appears between the designed and in-use values [54], [55]. It must be kept in mind that building simulation software is only as good as the designer who uses it and the input data that is available. In Sweden, deterministic limits for code compliance [56] coupled with normal climate and normal occupants, [57], set the framework for how and when a building can fulfil official requirements. In order to fully evaluate an in-use building, every aspect of the climate and occupant behaviour would have to be measured and compared to the design case, which, of course, is difficult. The same applies for the physical parts of the building. In this case, the properties of a built wall, for example, would only have to be measured once, not over the entire year. This means that the uncertainties regarding the physical aspects of a building concern the starting point, i.e. did the building correspond to what was designed? Once built, a wall will not change rapidly or in a stochastic way, as the everyday use of the building can, and probably will.

To summarize, when designing a building and predicting the future energy and power demands, the outcome is highly dependent on the naturally varying variables. In order to counterbalance the lack of analyses regarding these variations, in this thesis, large measured data sets were used. This material was used as input data in the simulations and can be assumed to represent those stochastic variations over time and within a large group of households. .

1.1.1 The heat balance and energy demand of a building

Heat transmission, air leakage and ventilation losses – these are all factors associated with the heat loss of a building, Equation 1.1. The losses are the parts of the heat balance, shown in Figure 1.1 that drive the demand, i.e. the heat needed to be supplied in order to maintain the indoor temperature that the building was designed for. The magnitude of the losses in Equation 1.1 can be reduced by having a well-insulated (reducing P_{tr}) and air tight (reducing P_{leak}) building envelope, Equation 1.2 and 1.4. The heating power needed to cover the ventilation losses can be reduced by having a ventilation system with high thermal efficiency (reducing P_v), Equation 1.3.

The heat balance is also dependent on another category of factors, the *unavoidable* factors, via which energy is added to a room or building in different ways. Examples include heat emanating from occupants, heat from electrical appliances and lighting (P_{int}) and, when the sun is up, heat from sunlight through the windows (P_{solar}). The reason for choosing the word *unavoidable* for these factors in the heat balance is because their effects could either be positive, in the winter heating season (reducing P_{syst} for heating) or negative, in the summer, when there is a need to remove excessive heat to maintain a comfortable indoor temperature (turning P_{syst} negative for cooling). The word *unavoidable* is also meant to highlight the fact that these factors are associated with activities in, or properties of, a building that have to be present in its in-use phase, i.e. people will be living there, emanating heat. The use of and, consequently, the heat from, appliances depends on the people living in a particular apartment. When looking at the use of appliances and the amount of electricity used to run them, one aspect is, of course, connected to the occupants and for how long they use them. Another aspect is how energy-efficient the appliances are. For example, a fridge, a freezer and a washing machine are appliances that are needed in every home and, together with lighting, are suitable targets for energy efficiency measures.

The amount of power supplied to (or removed from) a building at any given time, P_{syst}, is governed by the type of heating system, regulation scheme and desired indoor temperature. The part of the heat balance denoted P_{mass} represents the entire mass within the insulation layer that can absorb or discharge heat. Equation 1.1 describes an instantaneous heat balance in which the amount of stored heat affects the rate of change of the indoor air temperature, T_{air}, with heat capacity, C_{air}, in a transient and dynamic situation. The energy demand of a building can be calculated using Equation 1.5, in which the power supplied by the system, P_{syst}, is multiplied by a chosen time step and then summarized over the desired simulation period, usually a year (1.5).

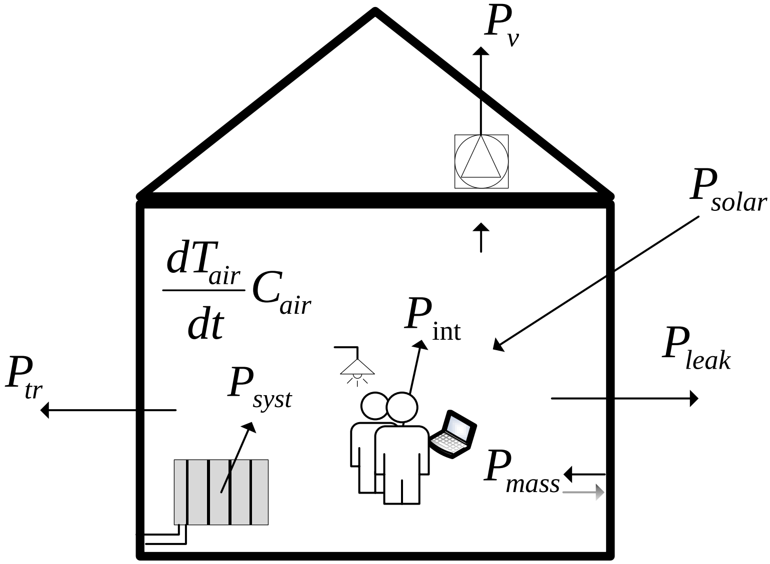

Figure 1.1 Schematic view of a building and its heat balance.
The parts of the heat balance in Equation 1.1 are visualized to show what they represent.

$$\frac{dT_{air}}{dt} C_{air} = P_{tr}(t) + P_{leak}(t) + P_v(t) - P_{int}(t) - P_{solar}(t) - P_{mass}(t)$$

$$-P_{syst}(t) \quad (W) \qquad 1.1$$

$$P_{tr}(t) = \left(\sum_{i=1}^{n} U_i \cdot A_i + \sum_{i=1}^{n} \Psi_i \cdot l_i + \sum_{i=1}^{n} X_i \cdot N_i \right) \cdot (T_{in} - T_{out}) \left(\frac{W}{K}\right) \qquad 1.2$$

$$P_{vent}(t) = (1 - \eta) \cdot \rho_{air} \cdot c_{air} \cdot q_{vent} \cdot (T_{in} - T_{out}) \quad (W/K) \qquad 1.3$$

$$P_{leak}(t) = \rho_{air} \cdot c_{air} \cdot q_{leak} \cdot (T_{in} - T_{out}) \quad (W/K) \qquad 1.4$$

$$E_{syst} = \sum_{i=1}^{N} P_{syst,i} \cdot dt_i \quad (kWh/a) \qquad 1.5$$

$$U_i = thermal\ transmittance\ for\ exterior\ area\ \left(\frac{W}{m^2K}\right)$$

$$A_i = area\ of\ surface\ (m^2)$$

$$\Psi_i = thermal\ transmittance\ of\ lengthwise\ thermal\ bridge\ \left(\frac{W}{mK}\right)$$

$$l_i = length\ of\ thermal\ bridge\ (m)$$

$$X_i = thermal\ transmittance\ of\ point\ thermal\ bridge\ \left(\frac{W}{K}\right)$$

$$N_i = number\ of\ point\ thermal\ bridge\ (-)$$

$$T_{in} = indoor\ temperature\ (^{\circ}C)$$

$$T_{out} = outdoor\ temperature\ (^{\circ}C)$$

$$\eta = heat\ recovery\ efficiency\ of\ the\ ventilation\ system\ (-)$$

$$\rho_{air} = density\ of\ air\ \left(\frac{kg}{m^3}\right)$$

$$c_{air} = specific\ heat\ capacity\ of\ air\ \left(\frac{J}{kgK}\right)$$

$$q_{vent} = supply\ and\ exhaust\ air\ flow\ of\ a\ balanced\ system\ \left(\frac{m^3}{s}\right)$$

$$q_{leak} = unwanted\ air\ flow\ through\ the\ building\ envelope\ \left(\frac{m^3}{s}\right)$$

1.1.2 Building simulation in the building design process

Designing a building involves many processes, among which the prediction of the future energy demand and indoor climate are extremely important. When predicting the future, two factors are focused on in this thesis: how the building will be used and what outdoor climate it will be exposed to. Figure 1.2 shows a simplified design process related to building simulation, a common tool for evaluating the performance of a building's design, with focus on indoor climate and energy use. With this in mind, the goal of a building is to achieve good functionality for the occupants (good indoor temperature, for example) and to create it in an efficient way by using as little energy as possible or using energy that comes from renewable sources. The building design process starts by defining these goals, for which limits are set by the building codes. To make an accurate prediction of a future building, a model of the physical building is required as well as a simulation of its operational phase. Next, the simulated performance is evaluated and, if necessary, changes are made to the design. The research questions are formulated based on how this building design process relates to variations in input data, with the ambition to shed new light and supply results that are applicable in this context.

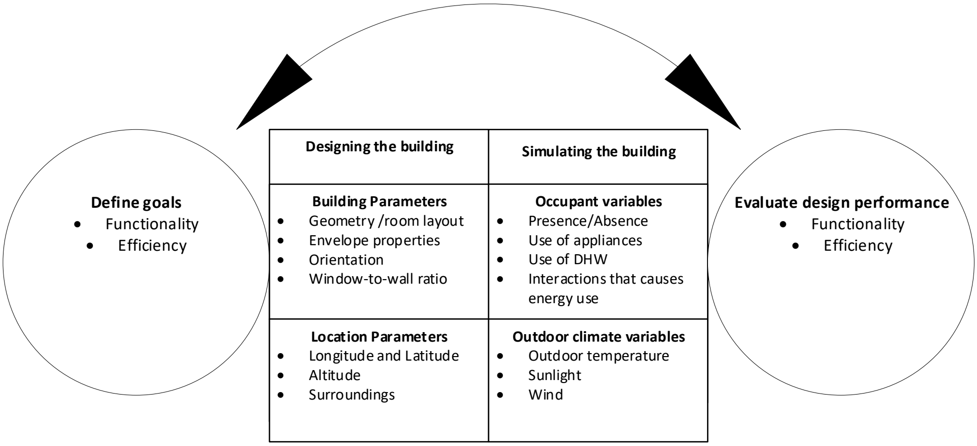

Figure 1.2 The building design process for indoor climate and energy demand using simulations. The goal of a building can be examplified by its functionality in terms of comfortable indoor temperature and energy efficiency, and the costs involved in acheiving that functionality in the designed building and its simulated use (operation).

Defining the goals

Swedish building regulations set the framework for acceptable functionality in the built environment as well as limits regarding the energy use needed in order to achieve this, i.e. a building's efficiency. Following directives from the EU, the Swedish building code has also changed with regard to the use of primary energy sources. These are now classified differently, depending on the type of energy used, i.e. electrical, district heating, fossil fuel and biofuel. Other organizations, both national, such as Miljöbyggnad [58] or FEBY [59], and international, such as LEED [60] or BREEAM [61] have different levels or criteria regarding energy use and environmental impact. The criteria regarding environmental impact are still in their initial stages. However, when it comes to building codes, a Swedish standardisation organisation, Miljöbyggnad [58] has, in its latest version, added a mandatory LCA. However, the LCA only has to take into account the production of the building materials and their transportation to the site. The criteria state that a certain percentage of the building materials must have gained the internationally accepted Environmental Product Declaration (EPD) certificate.

All of these regulations and standards usually have deterministic single point limits. Another point of view is the way that the predicted energy or power demand of a building, addressed using randomization with a Monte-Carlo approach, is regarded. This method can be used to see the risk or probability of something fulfilling the defined goals, i.e. how often certain energy levels would be reached or a design power demand surpassed and whether the building should only meet the criteria during a *normal year* with the right set of *normal occupants.*

In order to reduce environmental impact, reducing heating power in the building and supplying it at another point in time is a proven method that has been investigated in several studies. This means making the building more efficient at the cost of its functionality, for instance by having a lower indoor temperature. The perspective when viewing this functionality becomes more difficult and would require more detail to take full advantage of such a scheme. For example, in the building code, regulations usually state a minimum allowable temperature in steady-state conditions but say little about transient conditions. The acceptable level of discomfort can be viewed in many different ways and a well-established method of using *Predicted Mean Vote* (*PMV*) and *Predicted Percentage Dissatisfied* (*PPD*), originally published by Fanger [62], still forms the basis for many international standards on indoor comfort, such as ISO 7730 [63]. The indoor temperature for evaluation could be the yearly minimum temperature or the lowest daily mean temperature; the list is a long one. However, in the ISO standard, several ways of evaluating the outcome from Fanger's methods are presented. One of these methods takes into account how many hours during a year that the temperature was below a certain limit. What is not taken into account is the spatial perspective, i.e. when moving from one temperature in a single apartment to a number of temperatures corresponding to a number of apartments. With regard to functionality, in how many of the apartments of a building, and for how long and at what levels could the design temperature be ignored while still being accepted by the occupants?

Designing the building

A building simulation model could be simplified to the heat balance in Equation 1.1. In such a model, parameters chosen by the designer are governed by Equations 1.2 to 1.4 and relate to properties of the exterior envelope as well as the ventilation and heating system. Other parameters, not governed by the designer, are connected to the location. Examples of these parameters are shown in Figure 1.2.

With regard to building design, parameters in this thesis will be related to fixed aspects of the building, such as its geometry and location. However, there are also variations and unwanted uncertainties regarding these parameters. These uncertainties could include differing heat conductivities, loss-coefficient of windows [64], [65], varying airtightness [66], or be due to deviations during construction. These aspects could be viewed as uncertainties and possible differences between a model and the real building. However, there is a degree of control regarding the uncertainties as they could be minimized by carefully controlling the manufacture of building materials, by using certificates etc, or by on-site testing, such as pressurization tests for airtightness and checking the commissioning of the ventilation system. To summarize, the parts in Equations 1.2 to 1.4 connected to the physical parameters could be subject to variations that would lead to a higher or lower heating demand.

Simulating the building

After deciding the goals and building design, the performance of the building needs to be tested by simulations in its future environment, i.e. its location and the outdoor climate, as well as with the presumed composition of the future occupants' and their ways of using the building. Again, the model could be reduced to the heat balance, using Equation 1.1, which can be solved deterministically. The output would be the amount of energy, Equation 1.5, needed to maintain the design temperature by adding or subtracting using the term P_{syst}. The energy over the period in question is gathered by stepwise moving forward in time, solving the heat balance for each time step followed by multiplying the power by the length of the time step and then summarizing the energy from all time steps.

When proceeding from the design to the simulation of the building, the main focus is on the choice of environment, i.e. the outdoor climate and the use of the building. The aspects associated with this will, from now on, be called variables and some examples are shown in Figure 1.2. The main difference between parameters and variables is that variables vary over time to a much greater extent than parameters. For example, comparing the parameter thermal transmittance to the variable outdoor temperature, associated with the outdoor climate, it is obvious that the outdoor temperature will vary in time, both on an hourly basis and a yearly basis whereas the thermal transmittance over a short time-span is practically constant but may degrade over the years. Even on a longer time scale the difference is both moderate and expected, as the deterioration of building materials might cause small changes in the thermal transmittance from one year to the next. However, the climate can be anything, from very cold to very warm.

The outdoor climate, consisting of many variables, varies naturally from year to year, also within the same year, and governs the magnitude of the heat losses from transmission, air leakage and ventilation. The amount of available heat from the sun is also determined by the outdoor climate. When designing a building in a particular location a typical outdoor climate for the location is often used, for example by using a simulated yearly outdoor climate file patched together from many years of local measurements, and thus can be said to represent a normal outdoor climate for that location. These outdoor climate files, in a building simulation environment, usually have hourly resolution available as input. By creating an outdoor climate input file from measurements of real outdoor climate with hourly resolution, the temporally stochastic nature of the outdoor climate is usually accounted for. However, using a typical outdoor climate excludes the impact of extreme outdoor climates that could lead to overheating during unusually hot summers, if no cooling exists, and to a very high power demand, or unacceptably low indoor temperatures, in buildings during particularly cold winters. Another deviation could occur when changing from a macro to a micro outdoor climate, which is often a problem when using an outdoor climate file derived from measurements at an airport for the location of the building.

The complexity of variables can be divided into temporal resolution and stochastic variation, visualized in Figure 1.3. This complexity is represented by two pyramids, where the bases symbolize the highest level of detail and all possible stochastic variations respectively, and the tops a more simplified approach. Three levels have been visualized using horizontal lines in each pyramid to exemplify the different levels of detail. Starting in the right-hand pyramid, household electricity use is chosen as an example of an occupant behaviour related variable. The upper line represents the approach for modelling household electricity loads in Sweden. To carry out a simulation with an occupant(s), supposedly representing a normal occupant, i.e. one which would correspond to a certain annual use of household electricity derived from empiric studies. Reverting to the heat balance, and how the residual heat from this electricity use is added to the room, it becomes obvious that for an arbitrary point in time during the heating season the impact of the magnitude of the internal heat gain will affect the power demand of the system. How this is then represented in the model is important. The household electricity, shown as the upper line in the left-hand pyramid, could be described as a continuously constant supply of power over the year shown at the least detailed level. The level of temporal resolution could be increased to monthly data – and would then show a normal occupant's use of appliances during each month and down to weekly, daily and hourly use. The middle level describes daily average schedules, which is one way of increasing the temporal detail even further by introducing a daily pattern even though the annual use remains the same. The bottom level shown in the left-hand triangle corresponds to hourly data, which means that the occupants are modelled with the same temporal resolution that the outdoor climate is usually modelled. The graphs at the bottom of Figure 1.3 show how the impact on the energy demand could look schematically when based on the choice of temporal resolution and stochastic variation of the investigated variable. When modelling at a single occupant level, as described above, the energy demand is shown by the black lines and these will have different values depending on the chosen temporal resolution.

The next step is to move back to the right-hand pyramid and move down a level. Instead of one single occupant, the stochastic variation of the population is represented by groups with different probabilities of occurring. For example, three groups with low, medium and high level users of electricity. The frequency of occurrence and spread of possible energy demands are shown by the red bars in

Figure 1.3. The last level of detail, exemplified in the right-hand pyramid, is when there is a large set of data from different occupants from which to choose. Carrying out many simulations with randomly chosen occupancies could create the blue graph and the largest corresponding spread in energy demand. In both of these cases, depending on the temporal resolution, the centre of gravity of the corresponding graphs varies along the x-axis, thus indicating different energy demands.

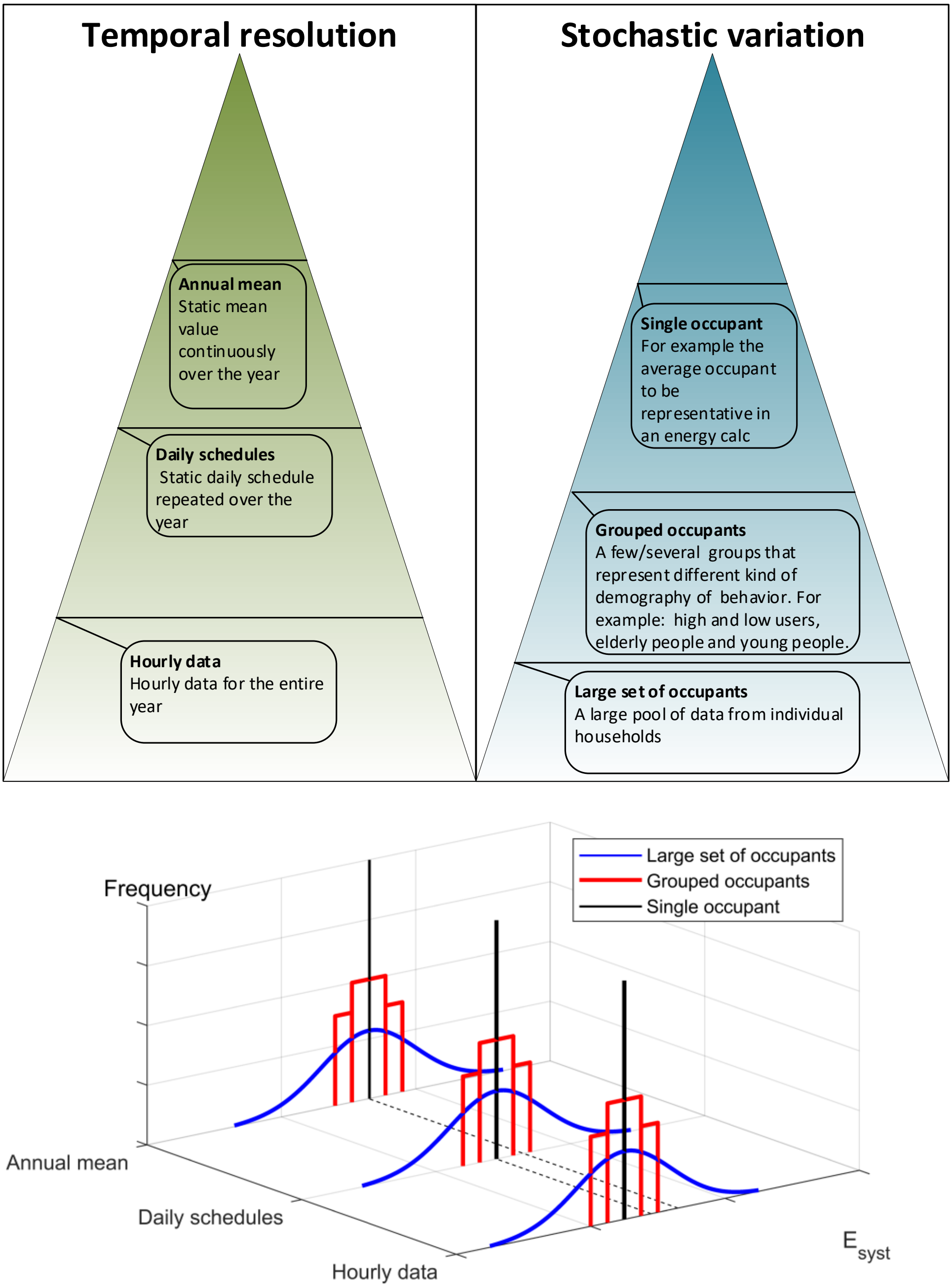

Figure 1.3 Impact of different levels of temporal resolution and stochastic variations on the energy demand. Two aspects, temporal resolution and stochastic variation, can be used when simulating variables. Examples of different levels of detail are presented in the pyramids and the corresponding energy demands are shown in the graphs. The colours and shapes of the graphs represent the impacts of the stochastic variatons and the postions of the graphs represent the impacts of the temporal resolutions. The y-axis shows the frequency or probability of different outcomes using the different levels of detail.

Evaluating design performance

The present method for evaluating and deciding the design of a building is usually based on commercial building simulation software. IDA ICE [67] is an example of such software, well-established in the research community both in Sweden and internationally.

Choosing to use simulations as an evaluation method means that the researcher, when investigating a particular aspect, has complete control of all the other variables and parameters, making it possible to isolate the aspect in question. Another advantage of using simulations to analyse the design performance is that new equipment and operating schemes, that could otherwise cause tremendous discomfort to the occupants if tested in a real case, can be tested.

1.2 Aim & objectives

With the overall goal of reaching a sustainable society, both today and probably even more in the future, when and how power is used becomes just as important as how much energy is used. The aim of this thesis is to increase knowledge and understanding about the energy and power demands for heating in residential buildings with focus on variations in occupant behaviour and ways a building can be operated. A particular objective was to study how heating power could be reduced by utilizing the thermal mass of buildings by taking different occupant behaviour into account. The results of this thesis provide information on how stochastic variables influence energy and power demand. This information can be used when designing future buildings and energy systems.

1.3 Limitations

The energy and power performance of buildings can be a very complex matter when all the different kinds of buildings are taken into account. There are many types of buildings, for example, residential, commercial and educational buildings. This thesis, therefore, limits its analysis to residential buildings, which form both a large part of the total building stock and are stringently defined types of buildings, in terms of how the buildings are used. Commercial buildings can be used for very different types of activities and their geometries are usually more spectacular. This thesis does not focus on introducing new building materials or new HVAC equipment that reduce the heat losses but more on the way the buildings are used and operated.

1.4 Research questions

Based on the aims, objectives and limitations, the main research questions are:

- How does heating power and energy demand vary due to different occupant behaviour?
- How are indoor temperatures affected by heating power reductions in varying conditions?
- How can occupancy be described using existing measurements of energy and water use?

1.5 Summary of appended scientific publications

This thesis is based on six appended scientific papers that are briefly described in this section. The Roman numerals assigned to each paper will be used for referencing throughout the thesis. Details on place of publication and authors of each paper is presented. Together with a summary followed by a short paragraph that describe the contribution of the authors. In this short paragraph the authors are represented by their surnames. For all papers, all co-authors have contributed by reading and giving feedback. First name was the corresponding author in all cases

Paper I

Fransson V., Johansson D., Bagge H. 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. *Thermal Performance of Exterior Envelopes of Whole Buildings XIII – International Conference.* Clearwater Beach, FL.

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 technologies create 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 behaviour 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 analysed. The influence of different building envelope parameters, including thermal capacity, insulation levels and airtightness, were also analysed. The purpose of this study was to investigate how combinations of these variables and parameters affected the indoor temperature drops during the different power reduction schemes.

Fransson did the simulations, data analysis and wrote the draft. Johansson and Bagge provided with input data and developed the research project and idea for the paper.

Paper II

Fransson, V., Bagge H., and Johansson D., *Investigating parameters affecting the indoor temperature drop after a power cut – In-situ measurements and simulations.* Building and Environment, 2017. 125**:**p. 401-413.

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 times could be one way of dealing with this issue. This paper investigates the temperature drops after a power cut both using 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.

Fransson did the measurements, modelling, simulations, data analysis and wrote the draft. Johansson and Bagge provided with input data. The authors developed the idea for the paper together.

Paper III

Fransson, V., Bagge H., and Johansson D., *Impact of variations in residential use of household electricity on the energy and power demand for space heating – Variations from measurements in 1000 apartments.* Applied Energy, 2019. 254: Article: 113599

Low-energy buildings are usually characterized by a very well insulated building envelope and an efficient ventilation system that makes use of the heat in the exhaust air. Internal heat gains from residents and their use of appliances can cover the heating demand to a certain extent. The magnitude of internal heat gains that cover demand are often modelled in a simplified way and thus can be associated with a large uncertainty. Hourly measurements of household electricity use in over 1000 apartments over a year, serves as a basis for this study. These measurements show a large variation between households with regard to the annual electricity use. Furthermore, each measurement series representing the unique behaviour in an apartment, shows a variation in household electricity use over time. Carrying out Monte Carlo simulations that use the measurements as stochastic input, this study shows that heating energy demand can vary by up to 50 % due to the different habits of the residents in a building. This study also shows that the detail at which internal heat gains are modelled is not negligible regarding the relative impact on energy and power demands for low-energy buildings. Reducing the resolution of the measurements from hourly means to monthly means neglects important variations in the data, which, in turn, underestimates the heating power-demand.

Fransson did the modelling, simulations, data analysis and wrote the draft. Johansson and Bagge provided with input data. Bagge and Johansson developed the research project. The idea for the paper was developed by all the authors.

Paper IV

Fransson V., Johansson D., Bagge H. *Analysing the effects of heating power cuts in a generic apartment using measured input data with a Monte Carlo approach.* Submitted to Journal of Building Performance Simulation April 2020

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 economic 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 total 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 drops can be described in terms of probabilities. For example, the temperature drop, described as the 10-percentile, could vary between 0.5 °C and 3 °C in a passive house envelope, 0.7 °C and 4 °C in a standard building code compliant envelope and between 1 °C and 9 °C in a 1960's building envelope, depending on the respective envelope properties, heating systems and durations of the power cuts.

Fransson did the modelling, simulations, data analysis and wrote the draft. Johansson and Bagge provided with input data. Johansson and Bagge developed the research project and idea for the paper.

Paper V

Fransson, V., Bagge H., and Johansson D., *A method for estimating occupant absence in apartments based on water use.* Under revision for Building and Environment

Today, every new building is constructed with the ambition of attaining a very low energy demand, or even a neutral demand, when taking into account both production and operating demands over a year. In such modern low energy or nearly zero-energy residential buildings the occupants' behaviour becomes an increasingly influential factor in terms of the energy performance of the building. Occupants using appliances reduce the amount of heat needed to be supplied by the heating system and in a low energy building this reduction becomes a larger part of the heat balance. Knowledge about occupant behaviour is, therefore, necessary. That occupant behaviour affects the energy demand is a well-established fact and many studies have focused on how to model behavioural patterns. As presence, absence and behaviour are hard to measure without being intrusive, occupancy is often derived from statistics gathered from questionnaire surveys or from measurements of other variables connected to occupancy, such as the household electricity use. This study uses such measurement data regarding household electricity, domestic hot water and cold water, gathered hourly over a whole year in over 1000 apartments. A method was proposed that classifies an apartment as empty if no water (hot or cold) was used during an entire day. Using this method, it was found that a period of 10 days was found to be the median number of absence days among the apartments with an interquartile range of 1–31 days. The outcome of estimating absence using only one of the measured variables was also evaluated and showed cold water usage to be a good alternative method

Fransson did the data analysis and wrote the draft. Johansson and Bagge provided with input data. The idea for the paper was developed by all authors.

Paper VI

Bagge H., Fransson, V., and Johansson D., *Variations in energy use in buildings due the naturally varying use of domestic hot water – hourly measurements in approximately 1000 apartments over six years.* Submitted to Energy and Buildings May 2020

This paper presents results from the measured use of domestic hot water in more than 1000 apartments in Sweden. Statistics regarding the measurements are presented and the measurements are used to analyse the impacts that different combinations of users have on annual domestic hot water volumes and maximum hourly flows in apartment buildings of different sizes. In low-energy buildings, energy use for domestic hot water heating is of the same order of magnitude as the energy use for space heating. The domestic hot water power demand is also an important parameter to keep at a low level in view of the current transitions to renewable energy supplies. In this paper, the results regarding when power peaks for domestic hot water occur and the effects of its simultaneous use in many different households are presented. Both of these are important aspects when optimizing systems in connection with locally produced renewable energy. The extensive six-year data sets from the same apartments also enabled an analysis of demands and usage changes over time. Both technology and behaviour are aspects focused on in this paper and these need to be taken into account to enable reductions in energy use and power requirements for domestic hot water.

Fransson did the data analysis and made the graphics. Bagge wrote the draft. Johansson and Bagge provided with data. The idea for the paper was developed by all authors.

1.6 Outline of the thesis

The initial part of this thesis describes the circumstances and settings from which the results presented should be viewed. This is followed by a method section that discusses the reasons for adopting the chosen methods and the benefits and drawbacks that were encountered. Additionally, a broad perspective of the methods, approaches and data that have been used both in the papers are presented as well as additional methods that complimented the papers. The results section presents and discusses the results related to the main research question with regard to the objectives. The most important findings conclude the thesis.

2 Method

From an epistemological perspective, the research conducted in this thesis has mainly had a positivistic approach. Positivism as a research philosophy is difficult to explain in a simple way but can be summarized as knowledge obtained through experience [68]. Physical observations and measurements are inherent to the positivistic way of acquiring knowledge. In this thesis, measurement data representing human behaviour is a fundamental piece of information used. Based on this measured behaviour, hypotheses can be formed and predications can be made. From the positivistic point of view, these measurements can represent the world without an understanding of the underlying motives for the behaviour, as opposed to the interpretivist point of view in which they would not be interesting without understanding the social context. Using measurements to form hypotheses to predict future events are often called hypo-deductive methods [69]. Another aspect associated with hypo-deductive methods is that they are built on quantitative (numbers and statistics) research rather than qualitative – which again would involve the human aspect, i.e. become more subjective. Empirical evidence is often described as what we can see or touch. Today, however, we tend to trust information or measurements obtained through equipment that translates the physical world into numbers and statistics and to use tools made by others to make the predictions. Such a tool is building simulation software – a tool that, today, is used to model the physical world in order to predict the future indoor climate and energy use of a building, [67].

A problem associated with modern advanced simulation software is the availability and reliability of the input data used in the model [70]. As the models tend to be more detailed, a higher level of detail is required of the input data in order to utilize their potential, and this can be hard to find. By combining measurements of human behaviour, to be used as input data in simulations, a lot of quantitative results can be produced that would otherwise be hard to obtain. For example, using real empiric measurement data of a building's energy use would only show the results from that one particular building and only during a specific period in time for a particular climate. Furthermore, the empiric data would only show the response to the particular composition of the occupants, and their behaviour, living in the building at the time of the measurements. It would be very difficult, and require lots of resources, to measure the impact of different occupants on a building's energy demand. Instead, measurements of isolated variables, associated with behaviour, were used as input for simulations in this thesis. By using this method the input data could be combined and varied in an unlimited number of ways to investigate the impact of different occupant behaviour on the heating demand, something that is not possible when carrying out measurements.

The use of building simulations was the primary tool to answer the research questions and this was supported by measurements in buildings in use for input data for the simulations and, in some cases, for validations of the models. Figure 2.1 shows a schematic overview of how the publications are connected to the research questions and to the methods and data that were used. In the following section these methods and measured inputs to the building simulations are explained. Data verification that was not part of the appended papers is also presented together with a more general view of the simulation procedure.

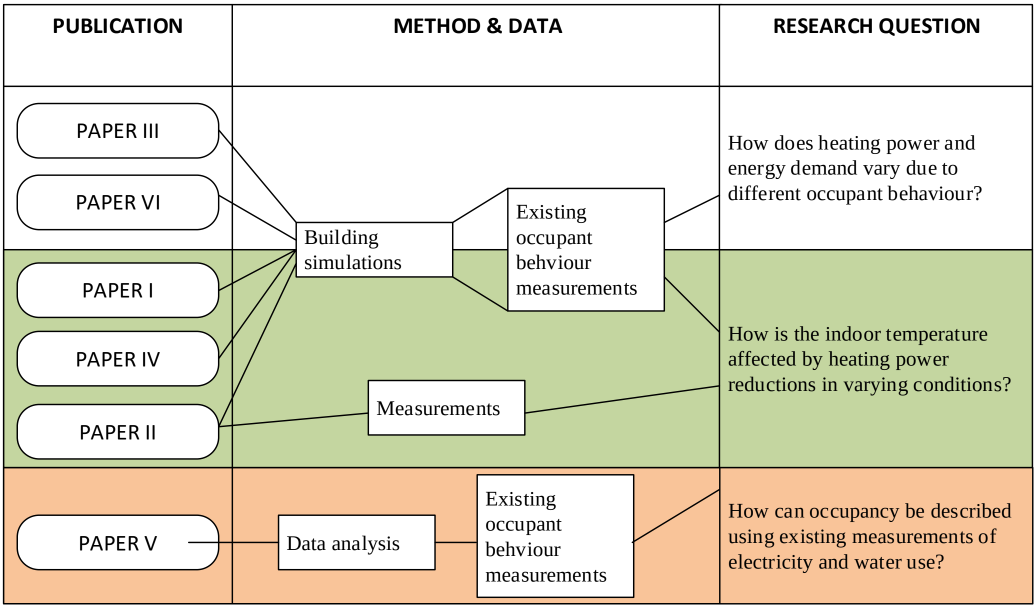

Figure 2.1 Connections between publications, method and research questions.

2.1 Input data – buildings in use and building design

Occupant behaviour is a very broad concept which will not be covered in its entirety in this thesis. However, one of the aspects in focus will be household electricity use and the corresponding residual heat. This residual heat, that helps to heat the building, will vary with the magnitude of the household electricity use, which, in turn, depends on the occupants. Furthermore, the impact of domestic hot water use and the number of occupants will also be investigated. Detailed measurement data of all these three variables was used. How they were analysed as input is described in detail in this section. In Table 2.1, an overview is presented of how each appended paper focuses on, and investigates, the variations and the stochasticity associated with each of these variables: household electricity, domestic hot water and occupancy.

Table 2.1. Overview of stochastic variables in the Papers.
How the three different variables – household electricity, domestic hot water and occupancy – were modelled and investigated in the different papers.

Paper	Household electricity	DHW	Occupancy
I	Daily profiles – 5, 25, 50,75, 95 percentiles	-	Daily profiles – 5, 25, 50,75, 95 percentiles
II	-	-	Measured, actual
III	Randomized actual series: hourly, daily, weekly, monthly and yearly mean values. 1000 series		Simplified average value
IV	Randomized hourly data sets from whole year measurements. 1000 data sets.	-	Randomized hourly data sets from two week measurements. 100 data sets
V	Base load	Daily mean	-
VI	-	Hourly values	-

2.1.1 Occupancy

One of the variables, labelled internal heat load in the heat balance and presented in Equation 1.1, is heat from occupants, i.e. a product of the time present and number of occupants using the building. In energy simulations this variable is usually modelled or defined as a static mean value throughout the year or follows a repeated schedule. In Sweden, the recommended occupancy for energy calculations is a presence of 14 hours each day of the year with a certain number of residents, as shown in Table 2.2, each emitting an average of 80 W of heat [57].

Table 2.2. Number of residents living in apartments of different sizes [57].

Apartment size	1 room	2 rooms	3 rooms	4 rooms	5 rooms	6+ rooms
Number of residents	1.42	1.63	2.18	2.79	3.51	3.51

This recommended occupancy is assumed to represent typical Swedish households. However, the total occupancy (presence) during a year can vary significantly between households, even for apartments with the same number of rooms. The temporal resolution, how occupancy is spread out over the year, in the Swedish building code assumes the same behaviour each day of the year although this is, intuitively, not the case.

From the heat balance, it can be seen that this temporal resolution can have a large impact, as the internal heat can only be utilized when there is a need for heating, during autumn and winter. There is also another aspect of the temporal resolution of this variable, the diurnal one. The heat from the occupants generated during the day does not necessarily match (or counterbalance) the daily sinusoidal outdoor temperature change, with a cold night and slightly warmer day.

In Figure 2.2, the occupancy profile corresponding to a Swedish two-room apartment is shown with the occupancy profiles derived by Bagge and Johansson [71]. In their article, the profiles were normalized with regard to apartment area, but in Figure 2.2 have been converted to represent the occupancy of a 60-m²-apartment, a common size of a two-room apartment. These profiles were used in Paper I.

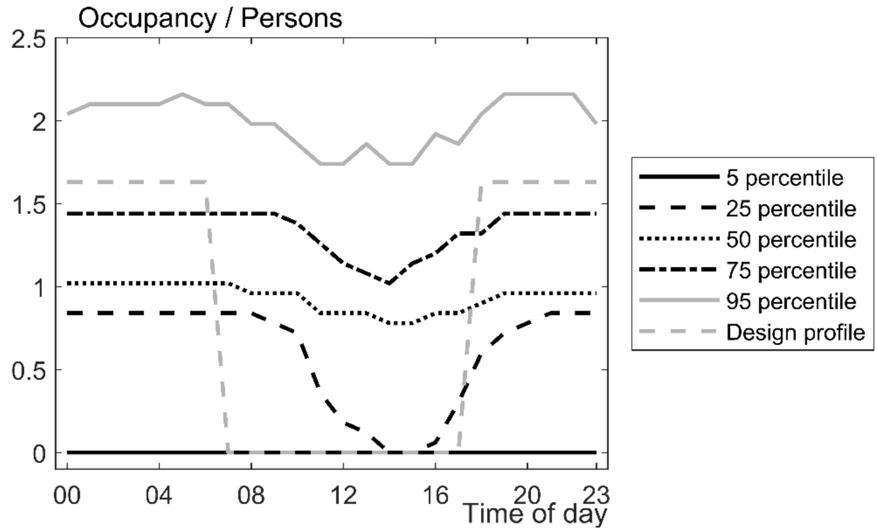

Figure 2.2. Occupancy profiles.
Number of persons present each hour of the day, typical for a two-room, 60-m²-apartment, presented as percentiles representing different magnitudes of occupancy derived from measurements, together with the Swedish design profile.

If the design profile is supposed to represent the average behaviour, Figure 2.2 shows a rather poor correlation between the median profile derived from the measurement data and that of the design profile. The profiles derived from measurements do not show the long duration of vacancy during the day up to the 25 percentile and, regarding the number of people present during night time, the design value corresponded to the 75 percentile of the measurements. However, this comparison should be viewed knowing that the measurements of the occupancy were not as extensive as those available regarding household electricity, both concerning the measurement duration of 11 to 17 days compared to a whole year, and the number of households participating in the measurement studies, 90 compared to over one thousand.

To use the raw measurement data as input would be closest to reality and Figure 2.3 shows an example of the entire measurement period regarding occupancy in four different apartments. The measurements took place in the autumn of 2013 and lasted eleven days. Specifically, each hourly value was the average occupancy during that particular hour, exemplified by the possibility of seeing measurement data for 0.5 persons present during an hour. In reality, there would have been one person present for half of that hour (or two persons for a quarter of the hour). The raw measurement data regarding occupancy was used in Paper IV.

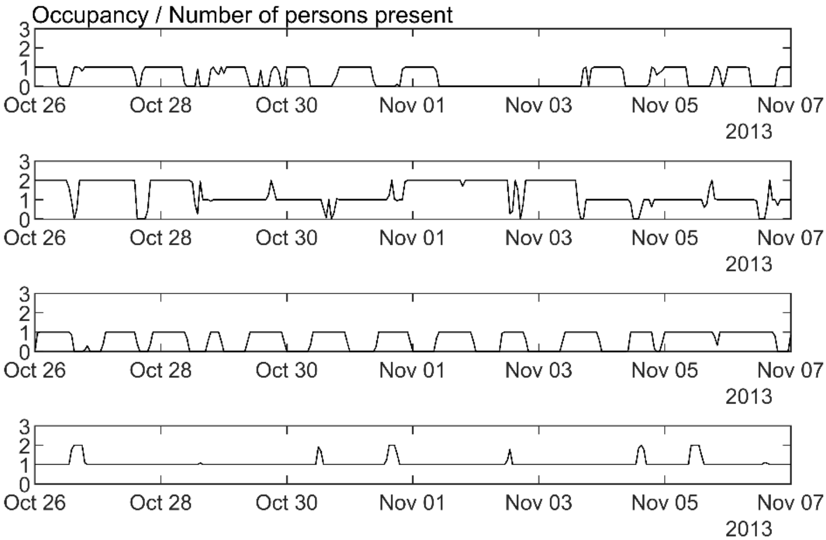

Figure 2.3. Exemples of hourly occupancy.
Examples of hourly occupancy in four different apartments gathered by Johansson and Bagge [71] by using electronic diaries.

2.1.2 Household electricity use

In Figure 2.4 the household electricity profiles developed by Bagge, Lindstrii and Johansson [72] are shown together with the design value for household electricity, represented by a constant power level that is equivalent to an annual use of 30 $kWh \cdot m^{-2}$, which is the standard design value in Sweden. These profiles were used in Paper I. In this case, the design value correlates quite well with the median profile derived from the measurement data. This is to be expected as the design level was chosen to represent a Swedish household’s use of electricity, and the measurements were based on over 1000 households. However, there is a diurnal change with a dip at 05.00 in the morning and a peak at around 20.00 in the evening and the design levels do not exhibit these changes. Furthermore, the aggregated profiles can represent residents or apartments with either higher or lower levels of use, i.e. a greater stochastic variation is taken into account in this way.

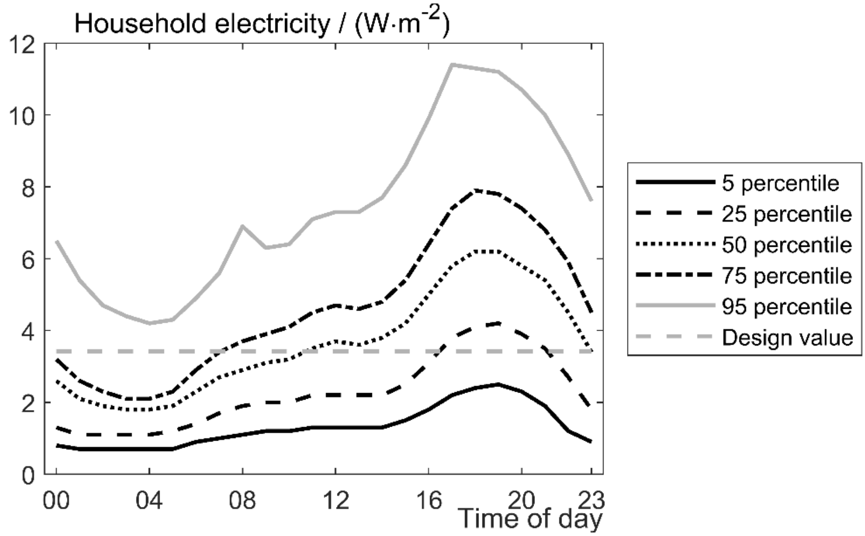

Figure 2.4. Household electricity profiles.
Household electricity profiles, in W· m-² apartment area, representing percentiles of different usages derived from measured data gathered by Bagge, Lindstrii and Johansson [72].

A more elaborate way of handling the household electricity, regarding both temporal resolution and stochastic variation, was first tested in Paper IV. However, the hourly measurement data previously presented by Bagge, Johansson and Lindstrii [50], [72] was used as input data without any modification as it was not the main focus of this article. The aim here was to investigate the impact of the thermal mass of the building.

Figure 2.5 shows the household electricity use in four apartments for an equivalent duration of time as for the occupancy measurements, although the measurements were taken over an entire year. The reason for showing these figures is to highlight the stochastic pattern of the two variables, which is not possible to capture with an average profile. This is further shown in Figure 2.6 in which the hourly household electricity use is compared to the derived user profiles. Four days of hourly data is compared to the same profiles applied each day and it is quite clear that the hourly use in one apartment can alternate between the usages shown by all the profiles and, at certain times, even higher use is shown. Furthermore, in this example, the peak hour of the daily use of household electricity does not coincide with that of the average resident and the magnitude and duration of the peak varies significantly from day to day. The impact of the temporal resolution and stochastic variations regarding household electricity was analysed in Paper III by using the raw measurement data from 1000 apartments with an hourly resolution.

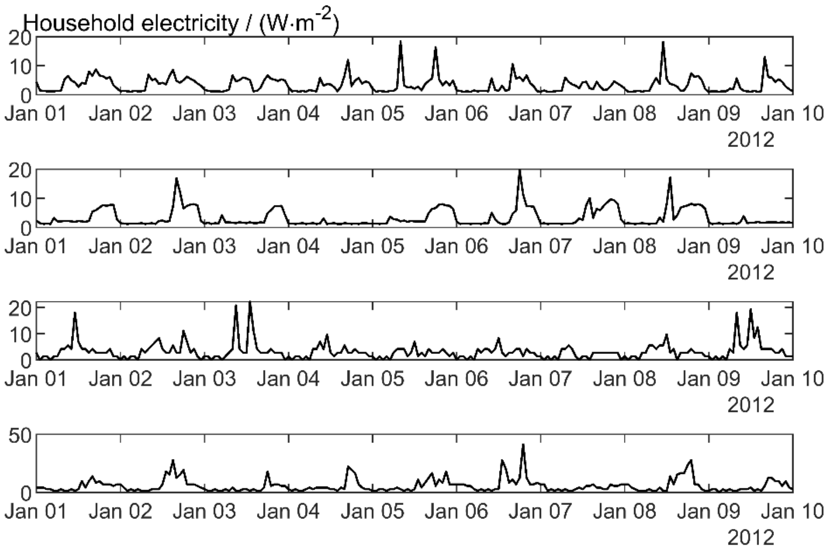

Figure 2.5. Examples of hourly household electricity use.
Examples of hourly household electricity use in four apartments over nine days. The hourly power use in W·m-2 corresponds to an hourly mean use of electricity normalized with regard to apartment area.

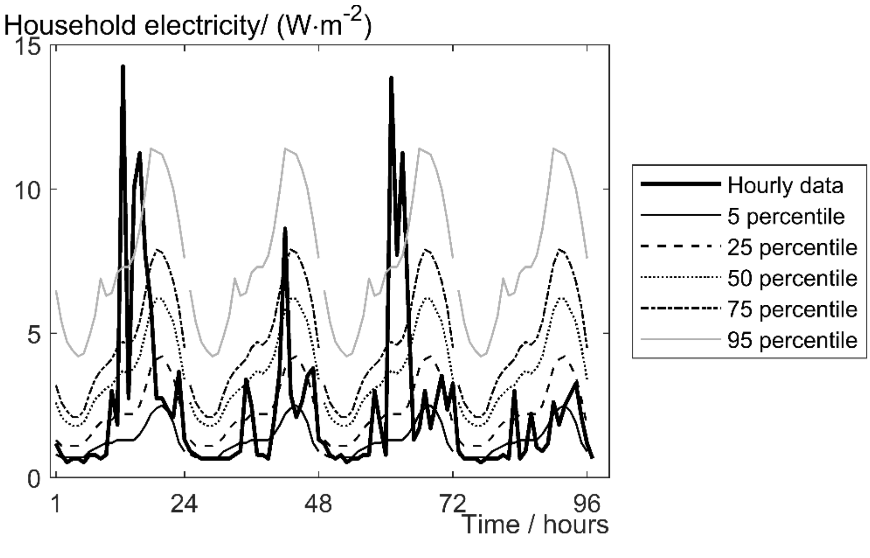

Figure 2.6. Hourly household electricity use compared to average use.
Hourly use of household electricity in an apartment over a period of four days compared to the percentile profiles corresponding different levels usage.

Looking back at the different parts of the heat balance in Equation 1.1, it is obvious that the power needed to be supplied by the heating system in order to maintain a desired indoor temperature is subject to a much higher variation when modelling all parts of the heat balance with more accuracy and better time resolution. In Paper III, the main focus was explicitly the variations regarding household electricity use and the corresponding varying demands of the building's heating system. In this paper, the stochastic variation (varying annual use) and the temporal resolution (and variation) over the year were thoroughly investigated. The heating demand, both in terms of energy and power, was analysed. To be more precise, the aim was to exemplify and quantify the introduced discrepancy when decreasing the resolution of the household electricity load. This procedure is shown in Figure 2.7 in which the hourly resolution is reduced, step by step, to a yearly average. The heating demand supplied by the heating system over a year was simulated five times using the same apartment configurations but with a decreasing time resolution regarding the household electricity.

Besides temporal variations over the year, the annual use of energy varied significantly in the 1000-plus apartments. These variations are shown in Figure 2.8 as annual energy use and also as average annual power use, in both cases normalized to apartment area. The household electricity use is also shown depending on the number of rooms but, as the figure shows, no clear correlation associated with the number of rooms can be identified.

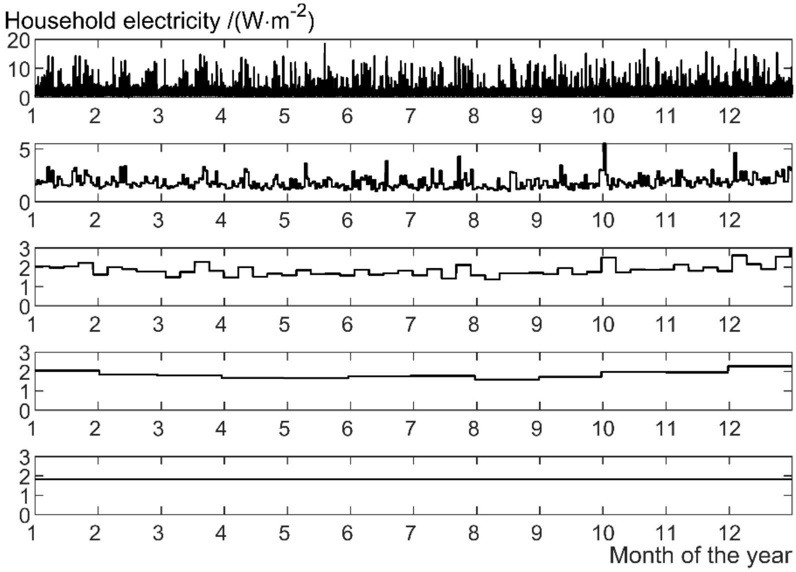

Figure 2.7. Example of household electricity use in a single apartment during one year with different degrees of time resolution.
The electricity load for a single apartment was modelled in five different ways and is shown, from the top down, in houry, daily, weekly, monthly and yearly resolutions.

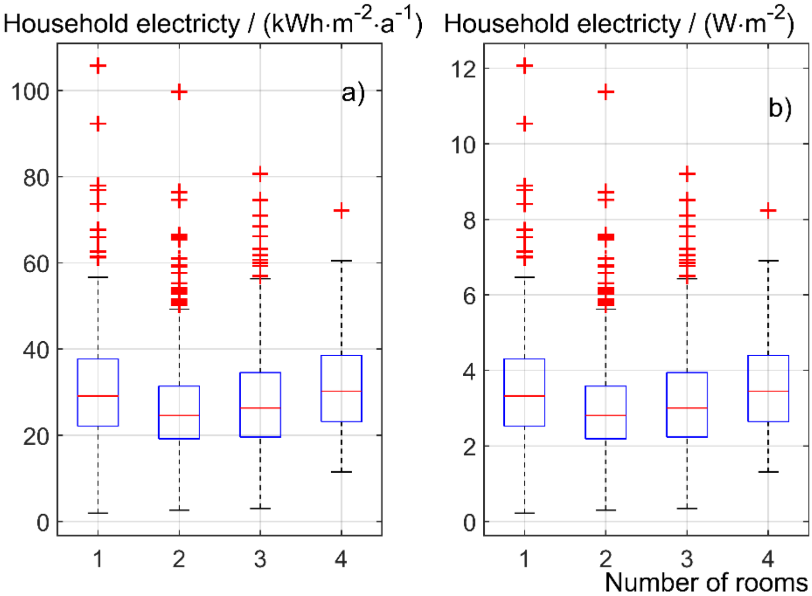

Figure 2.8. Annual household electricity use in 1067 apartments as a function of the number of rooms. Shown in a) as the average annual energy normalized to apartment area and in b) the average annual power normalized by apartment area.

2.1.3 Domestic hot water use

The domestic hot water use was analysed without incorporating the use as an input in a simulation model in Paper VI. The data came from the same study by Bagge, Johansson and Lindstrii [50]. Instead of using simulations, statistical analyses could be carried out using the measurement data directly. Six years of measurement data at an hourly level was available and the number of valid measurement series each year varied between 800 and 1300, Figure 2.9. Continuous measurement data existed for all the six years in 268 apartments. One of the objectives was to show how much the DHW use could vary compared to the design value, depending on building size, i.e. the number of apartments in the building.

By using the comprehensive, six-year-long measurement data sets, it was possible to investigate how DHW use changed over time. It was also possible to study how the use of DHW in these apartments changed over time. Randomly selecting different households, represented by data sets, to construct different configurations of occupants for the same building, enabled the investigation of simultaneous use of hot water at an hourly level. Additionally, it was possible to investigate how the maximum hourly water use varied in buildings of the same size, between the different building sizes, and how the maximum hourly flows correlated with the annual volume of DHW.

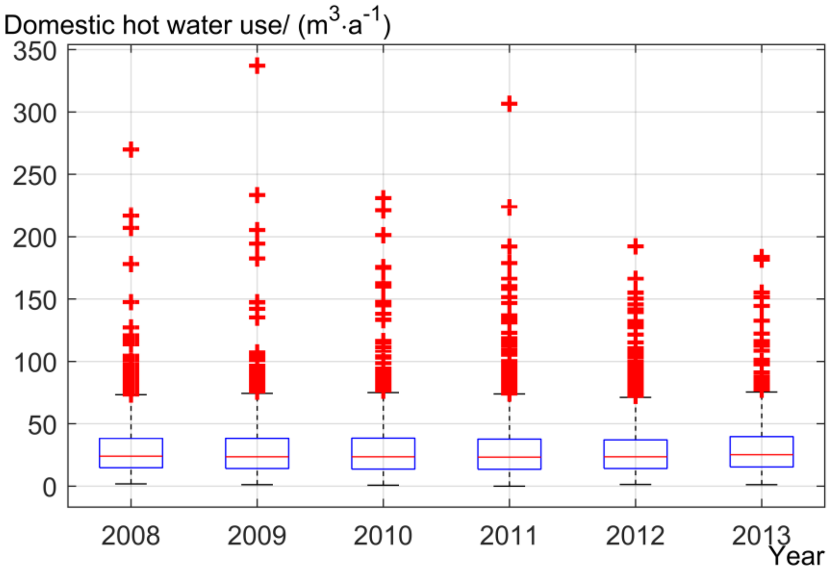

Figure 2.9 Measured domestic hot water use in Swedish apartments.
The number of apartments with valid measurements each year varied between 800 and 1300 apartments. Continuous measurements over all six years in the same apartments were available from 268 apartments.

2.1.4 Outdoor climate, location and building design

Even in a low energy building the outdoor climate is still an important driving force for energy and power use in buildings. Different outdoor climates and locations have, therefore, been tested in the appended papers. The characteristic most associated with energy, the outdoor temperature, together with the properties of the building envelope and the ventilation system determine the energy performance of a building. Three different locations in Sweden were primarily used: Malmö in the far south with a mild climate, the capital city of Stockholm with a moderate climate, and Kiruna in the far north above the Arctic Circle with a very cold climate. In Paper IV, international weather files for energy calculations were used (IWEC2,[73]) for the three locations. In order to show variations between climates in the same location, weather data for 10 years was gathered from the Swedish Meteorological Institute [74, 75] for the three locations.

However, when adding the resident interaction with the building, influenced by the outdoor climate, further complicates the matter of the outdoor climate impact. In addition to the inherent variations, both stochastic and temporal, the impact of the outdoor climate in combination with occupant behaviour and the building can be divided into direct and indirect impacts. Heat from the sun in combination with occupants is an example of a direct impact. Solar shadings, for example, manually operated by the occupants (blinds, awnings etc.) are subject to the stochastic behavioural variations of the occupants. Even more complexity can be added and this is connected to designer choices, such as size and orientation of the windows, and form and shape of the solar shading. These aspects, together with the opening and closing of the windows, are two energy and power related occupant behavioural aspects not investigated in this thesis.

An indirect impact is the effect of different outdoor climates at the same location, i.e. the outdoor temperature that drives the heating demand and the free energy from the sun that differs between years. If the energy supplied by the building heating system is to be reduced, energy needs to be supplied by other means, either by heat from the sun, heat from occupants or from residual heat from electrical appliances.

For example, if it is assumed that the desired indoor temperature and all the variables that govern the free energy are the same throughout the year, then the relative amount of positive gain from that free energy would be entirely dependent on the outdoor temperature at the location. More precisely, it means that the duration and the magnitude of the low temperatures during the heating season (if there is no active cooling) would determine how much of the free energy that could be used. In Malmö, with a rather mild climate and a short heating season, the possible gain from these free sources would be small and unnecessary during a particularly mild winter. If there is no need for heating, the free energy cannot replace heat otherwise supplied by the heating system of the building and, consequently, would become excessive or even disadvantageous due to possible overheating. This indirect aspect connected to the climate is something that will be looked at in both Paper I and Paper III.

When assessing climate variations in connection with occupants in the context of a building's energy performance another important aspect needs to be considered. It might be obvious but the exterior envelope area of the building that is in contact with the outdoor climate can be just as important as the climate itself or at least be a large factor. For example, among buildings with similar constructions but with different ratios between their exterior envelopes and residential floor areas, the impact on energy use is never negligible.

With respect to the actual geometry, when modelling a building, which means translating and simplifying the actual construction and geometry into a simulation environment, there are details that might get lost. Some simplifications arise from limitations associated with the chosen simulation software and to the designer of the building. Additionally, when modelling, there is an incentive to strive towards reducing the complexity of the model in order to speed up the simulation. Such measures might include the reduction of the spatial resolution, for example, by only taking different apartments into account, not individual rooms, or even by disregarding apartments and only taking into account different floors. Simplifications of this kind will impact the energy and power demand. In this thesis, apartments were, in most cases, reduced to one single zone.

2.2 Data verification

Erroneous data and missing data – these are both important issues when measurement data is used and analysed. In the context of this paper, the variables were mainly water use and household electricity use in apartments, both measured on an hourly basis. The data came from equipment that was installed for billing purposes and therefore the accuracy was believed to be acceptable. However, this was never established as a fact. Assuming the uncertainties caused by the equipment were within an acceptable range, the question was how to verify the usefulness of the data in terms of other anomalies in the data series. One way would have been to devise an algorithm that discarded all inadequate measurement series. However, that procedure would need universal knowledge about all possible errors that could occur in order to create an algorithm that removed them. This was not possible, as no such universal knowledge existed. However, some knowledge did exist. In the text files containing the raw data, all the missing values had been replaced by the mean values of the existing measurement points. One way to discard data would be by removing all the series with missing data. This would, unfortunately, leave no data at all to work with due to the fact that the year 2012, from which the data was gathered, was a leap year and this caused a number of issues concerning the measurements as the last days in all the files were missing, see the red crosses in Figure 2.10.

Initially, the measurement data from 1509 apartments was available, see Table 2.3. The first step to discard inadequate series was to remove those with more than 3 % of missing data out the 8784 hourly measurements [72]. However, when working with the remaining data, different kind of anomalies were found, such as very high averages and inexplicable spikes. This prompted a more thorough way of making sure the data was valid for further analysis and could be used as input for simulation models. Without knowledge about the kind of deviations that could occur, i.e. it was not possible to write an algorithm and solve the problem, the way forward was visual inspection. When the measurement series with more than 3 % missing data had been removed, 1447 series remained. For each dataset, an A4 page, see Figure 2.10, was created making it possible to visually identify deviating patterns in the data. The page shown in Figure 2.10 was used for fast visual assessment and does not show units on the axes. The first four graphs were, hourly and daily mean values for household electricity followed by the hourly and daily mean use of DHW. The text boxes contain key figures such as area, hourly maximums and minimums, and annual usages. Furthermore, an average daily profile of the actual measurement series was compared to the average profile of the entire data set.

A particular error, found rather quickly, was *unrealistic values*. As a consequence, limits for acceptable hourly values were chosen. For electricity it was 11 kW during an entire hour, which is the highest electricity output possible with a 16 ampere three-phase circuit-breaker, a limit commonly used in Swedish apartments. Where

DHW use was concerned, the limit was harder to decide but was ultimately set to one litre per second for a whole hour, or 3.6 m^3 an hour. Furthermore, one criterion was to have continuous data for DHW and household electricity together and this prompted an error that can be seen in Figure 2.11. Besides the red crosses that show missing data there is clearly, or at least very likely, missing DHW data at the start of the year. This assumption is based on the varying household electricity load but absolutely no DHW use for over 3000 hours.

Finally, a checklist was made for the visual inspection, see Table 2.4, coupled to an index file that connected the specific errors to the correct measurement data file. About 25 different recurring deviations were found and the frequencies at which they were found are show in Figure 2.12. The sum of the errors in Figure 2.12 exceeded the number of removed apartments during the visual inspection, in total 380, as several errors could occur in the same dataset. The row marked in red was an identified deviating behaviour but was not deemed an error. This behaviour was thought to be due to the change of occupants in the apartments.

Table 2.3. Number of measurement data series remaining after rejection process.
The 1509 initial data sets were from 2012 and consisted of hourly data for three variables: household electricity, DHW and domestic cold water (DCW). Consistant and valid data was found for 1005 data sets or 67 % of the total number.

Initial number of measurement series	Passed the 3 % missing data limit	Passed visual inspection, Electricity and DHW	Passed visual inspection Electricity, DHW and DCW
1509	1447	1067	1005
100 %	95.9 %	70.7 %	66.6 %

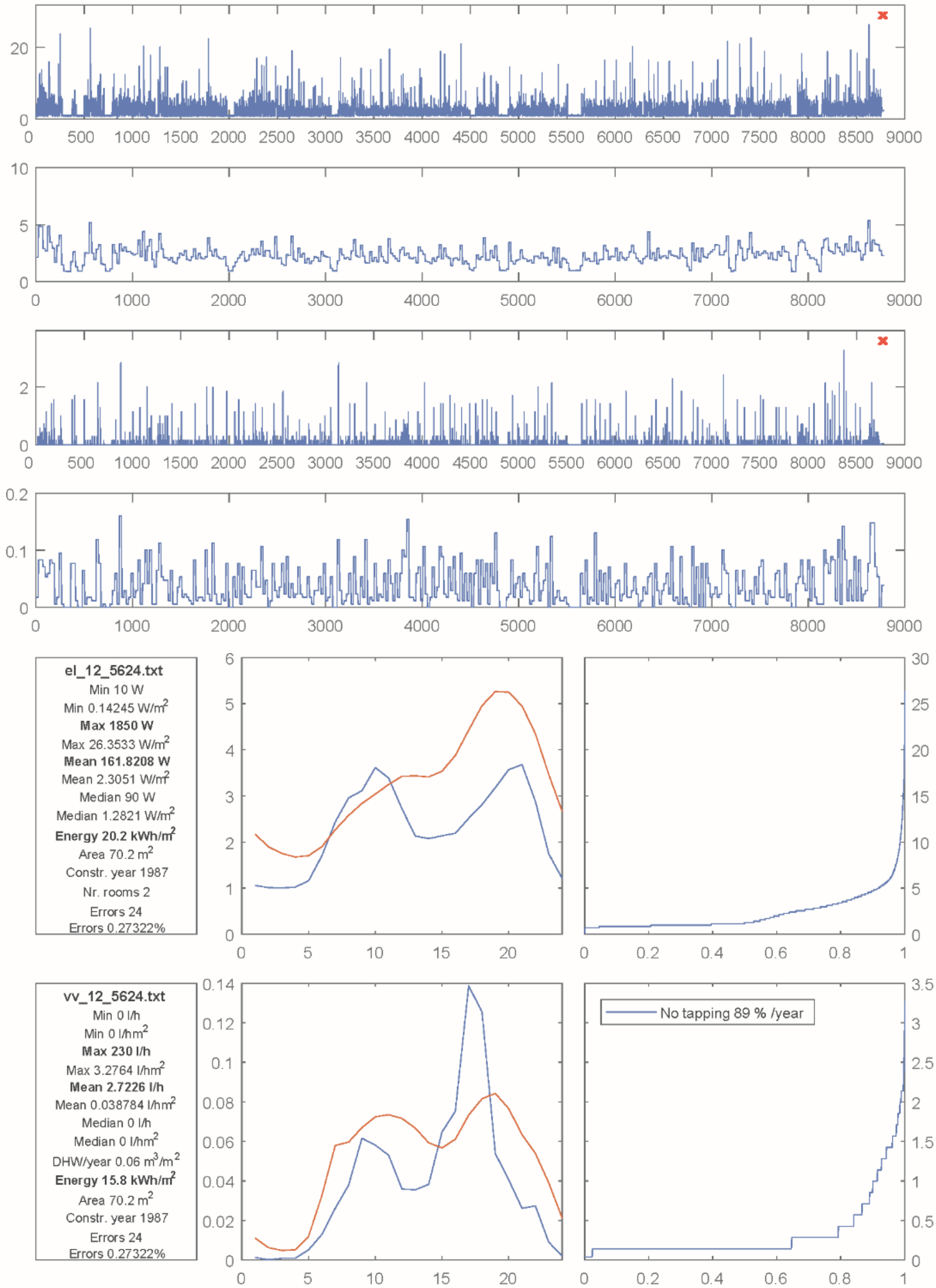

Figure 2.10. Example of data from an apartment that passed the visual inspection.
The top two graphs show electricity use in W· m-² and the following two DHW use in l·h-1·m-².The red crosses in the blue graphs show missing data.

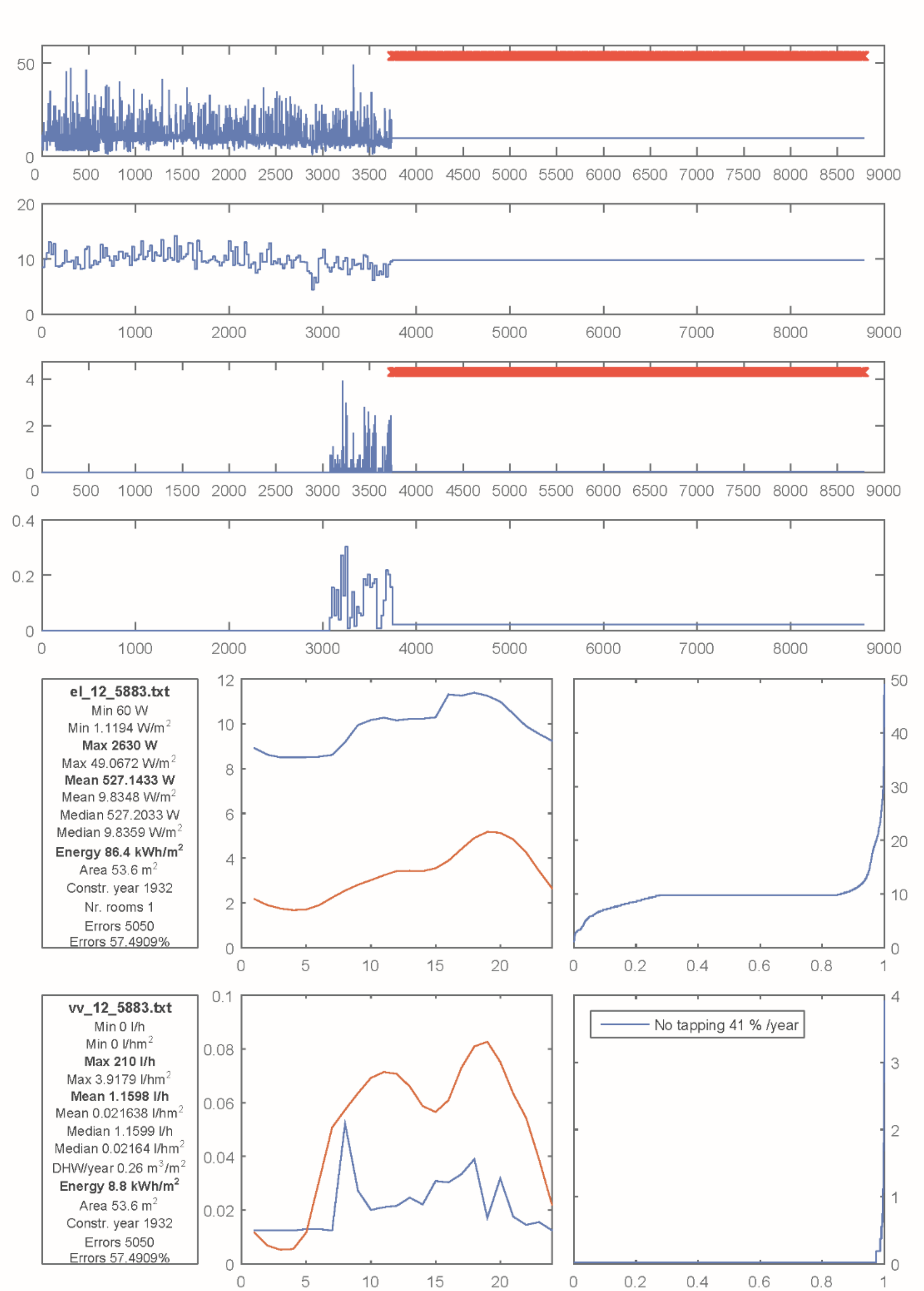

Figure 2.11. Example of data from an apartment that did not pass the visual inspection.
The top two graphs show electricity use and the following two DHW use. The red crosses show missing data.

Table 2.4 List of identified errors and deviation patterns in the measurement data.
The visual inspection of the data rendered 25 different types of errors or deviation patterns using the template in Figure 3.8. The meauserment series 'Very differing user pattern' in the row marked in red was not discarded.

	Type of error/ strange patterrn
1	Missing consecutive data
2	Very differing user pattern
3	Possible error, from base load to 0, stepwise changing baseload, electricity
4	Deviating behaviour electricity (oscillation) , simultaneous reduction of DHW
5	Single spike affecting average daily use significantly (electricity)
6	Single spike affecting average daily use significantly (DHW)
7	Distinguishing increasing/decrease, offset, over a period of time (electricity)
8	Distinguishing increase/decrease over a period of time (DHW)
9	Extremely low usage (sporadic), electricity
10	Extremely low usage (sporadic), DHW
11	Multiple spikes affecting average daily use significantly (electricity)
12	Multiple spikes affecting average daily use significantly (DHW)
13	Missmatch electricity/DHW, electricity 0 while other in use
14	Missmatch electricity/DHW, DHW 0 while other in use
15	Replaced unrealistic value (electricity)
16	Replaced unrealistic value (DHW)
17	Long duration of no use (both electricity and DHW) more than 4 months
18	Repeating the same pattern (1000 h) for the entire year
19	Three different user patterns
20	Almost constant value (electricity)
21	Almost constant value (DHW)
22	Not eligible (mismatches, missing data etc)
23	Replaced unrealistic value (electricity – reoccurring pattern in many series)
24	Replaced unrealistic value (DHW – reoccurring pattern in many series)
25	Not in use for almost the whole year

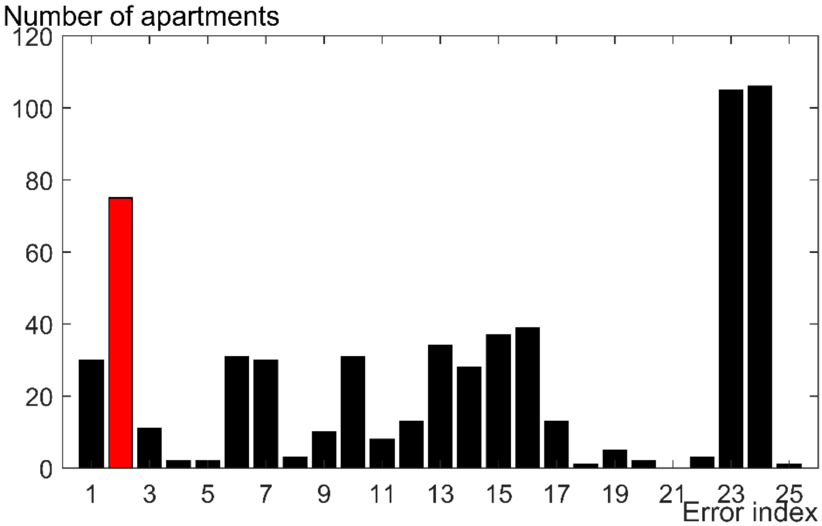

Figure 2.12. Frequency of occurrence of the identified errors in the measurement series.
Several errors could be found in each measurement series. All series with errors 1 to 25, except number 2 shown in red, were discarded and deemed inadequate for further use.

2.3 Estimating absence using existing measurement data

Occupancy, or the presence and absence of occupants in an apartment, is difficult to measure in a non-intrusive way. The measurement data for occupancy that was used in this study was detailed but was only gathered from a limited number of households over a limited period of time. Gathering this type of data is often associated with intrusive methods for recording presence and absence and requires the involvement of the occupants, which often limits the length of time that they are willing to participate. Therefore, a non-intrusive method to estimate absence was proposed, in which measurement data for other variables associated with occupants being present was used.

This non-intrusive method, the baseline method, was based on the assumption that if no water had been used during an entire day, from midnight to midnight, the apartment could be classified as being empty during that day and, consequently, the occupants had been absent. No quantitative or qualitative data on the actual presence or absence in the apartments existed. Thus, two validation methods, based on two hypotheses, were created to test the validity of the baseline method quantitatively using the measurement data. The first was based on the assumption that a higher number of absence days would be found during the Swedish national holidays, the main summer vacation period, and at weekends. The second validation method was based on the hypothesis that if the apartment was occupied, more household electricity would be used and subsequently, during days of absence, a lower use of household electricity would be found.

In Sweden, it is becoming more common to invoice individual apartments for their use of domestic hot water instead of including this cost in the rent and, consequently, spreading total costs evenly among all the tenants. In the light of this, and the presumed increased availability of individual DHW data, one aim in this section was to show whether measurements of domestic hot water alone could serve as a method for estimating absence days with a similar accuracy as using total water use. The applied method was adopted from medical diagnostics but could be used in many fields, [76]. The method was used in different ways when trying to determine occupancy from household electricity smart meter data in [77-80].

To describe this method in an easy way, the first step is to reduce the problem to a binary, yes or no question. For example, in this study: was the apartment occupied or were the residents absent? The criterion for an empty apartment was having no water use during an entire day, the baseline method, against which other methods estimating absence days were tested and compared. A total of five methods, of which the DHW method was one, were tested and these are shown in Table 2.5. The methods proposed different ways of classifying an apartment as empty for estimating the number of days of absence and the outcomes were compared to the outcomes from the baseline method. The DHW and DCW methods were very similar to the baseline method but used hot and cold water respectively instead of total water use to estimate the number of days of absence. The use of different daily mean values of household electricity as indicators of absence was another way of trying to classify the apartments that were tested.

Table 2.5 The five different methods to determine absence that were tested against the baseline method.

Method	Description
1	Apartment classified as empty if mean household electricity load <25th percentile during an entire day
2	Apartment classified as empty if mean household electricity load <50th percentile during an entire day
3	Apartment classified as empty if mean household electricity load <75th percentile during an entire day
4	Apartment classified as empty if no DHW is used during an entire day
5	Apartment classified as empty if no DCW is used during an entire day

2.4 Simulating variations

Previous sections have described the variables associated with stochastic behaviour, such as outdoor climate and residents. This section describes the procedure for investigating these variations through a simulated environment that handles varying data. As mentioned in the introduction, there are different ways to approach the modelling of stochastic occupant behaviour. One procedure used multi-agent modelling [81], [82] in which each occupant's actions and interactions with the building were assigned a certain probability of taking place or, for example, if someone was at home and the temperature was 21 °C, the probability of that person opening the window would be very low. If the temperature were to rise to 25 °C, the probability would increase. Interdependency of events, i.e. the increase in probability of an event occurring due to different circumstances, is another factor. These types of multi-agents can be derived from measurement data. However, when there is a lack of data, they can be derived from behavioural data based on experience or hypotheses. The second procedure to model stochastic occupant behaviour was to use specific sets of inputs or scenarios. These could be thousands of data series from which data is randomly picked and inserted into the model, which, in turn, simulates the designated period. The key to both of these methods is to have not only good quality input data but also the possibility to run many simulations in order to allow the variations to be found. Finally, the predominating method in the building industry, i.e. the use of single-value estimates for the outcomes, was abandoned and the results are now studied using probabilities and risks.

2.4.1 General simulation setup

Whole-building simulation software for indoor climate and energy, with good transparency in terms of the equations regarding the heat balance of the building, was needed, with publications of verification as opposed to a non-transparent software or the need to construct an entire own software.

Besides being able to control the parameters in the simulation software, it was possible to investigate the impact of user behaviour in many different types of building envelopes, at different locations and during different climatic years. To use this method, only input data for user behaviour was necessary. This data was available regarding the use of household electricity and domestic hot water and the number of occupants present.

Furthermore, variations of the kind associated with occupant use of household electricity, as in the previous example, is difficult to describe analytically, as there are variations both in the magnitude of the annual use and how the energy use is distributed over the year. These difficulties could be handled by simulation software as it was possible to use measured data as input, even though the data was irregular, stochastic and without a continuous pattern. However, the need for two software tools arose, one to handle the building physics and one to handle the randomization.

The software used to perform these large numbers of building energy simulations were MATLAB, [83] and IDA ICE, [67]. The simulation procedure is schematically visualised in Figure 2.13. Schematic overview of the simulation environment chosen to investigate the impact of the stochastic variables MATLAB, programming software was used to handle the automatization, i.e. to start new simulations, scripting to carry out changes prior to starting these simulations and randomizing the variables to be inserted into the models. IDA ICE was the software in which the models were built and where buildings in use were simulated.

Automation was necessary to execute thousands of simulations without manual involvement. Scripting enabled MATLAB to change IDA ICE in different ways prior to the simulations and thus, together with the automatization, made it possible to set up a batch of simulations with random input and systematically test different locations and different sizes of buildings with different properties. The randomization procedure used the random number generator (RNG) in MATLAB to randomly select data sets from the pool of the 1067 datasets remaining after the data verification, by using the *drawing with replacement* procedure. The simulation setup also took advantage of the 12 cores of the computer by the running of 12 simulations simultaneously. The number of models and the amount of output data required a systematic and structured way to save and index the results of all the simulations. This was also done in MATLAB. After the finalization of these simulations, MATLAB extracted the data from the output text files and stored it in the computer RAM (in MATLAB) until it was stored in bigger batches on the computer solid-state drive (SSD) disk in a structured way using a MATLAB format. When running thousands of simulations of operations during a whole year the time taken to save the output data was a significant portion of the entire simulation.

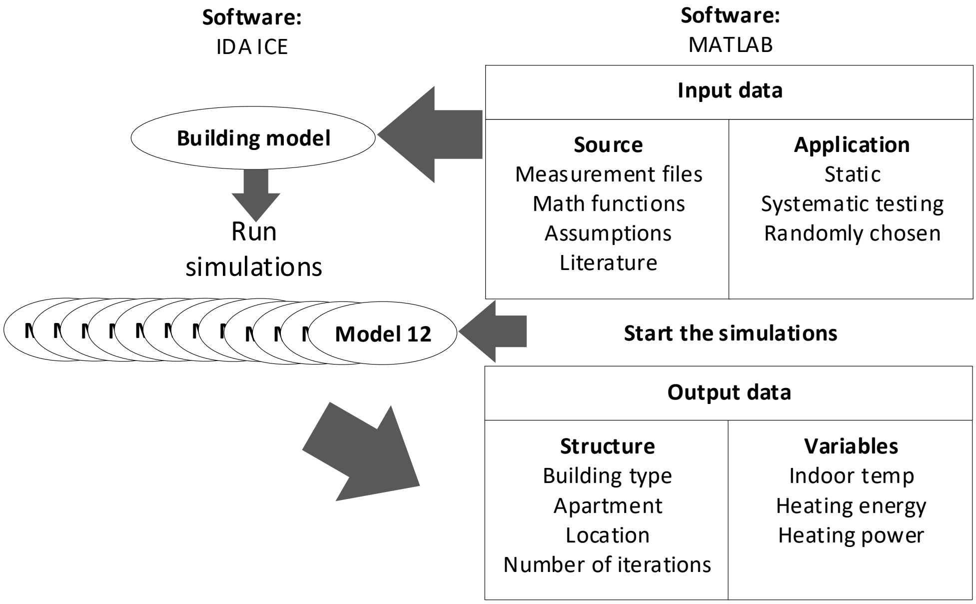

Figure 2.13. Schematic overview of the simulation environment chosen to investigate the impact of the stochastic variables.

2.4.2 Example of a simulation setup

An example is given below to illustrate a typical simulation setup. The case concerns the investigation of an apartment building with four apartments. The building is a low energy building and the model geometry, envelope configuration, and heating and ventilation system were created manually beforehand in IDA ICE. The impact of varying household electricity use on energy and power for heating supplied by the system is the main focus. The input data is the daily average household electricity use derived from the hourly measurement data in the 1067 datasets. Figure 2.14 shows a visual representation of this scheme. In the first iteration, four separate datasets were randomly picked and inserted for each apartment according to Figure 2.14. This was repeated for four iterations, shown in Figure 2.14, and it is clear that four quite different sets were picked each time. However, theoretically, the same dataset could have been picked four times in the same iteration as the same datasets were available for each random selection when using the *drawing with replacement* procedure. The four iterations can be seen as the start of 300 iterations for this four-apartment building in one specific location. Once the chosen number of simulations had been performed, a new model was opened in which a similar building was simulated in a new outdoor climate or with different building properties.

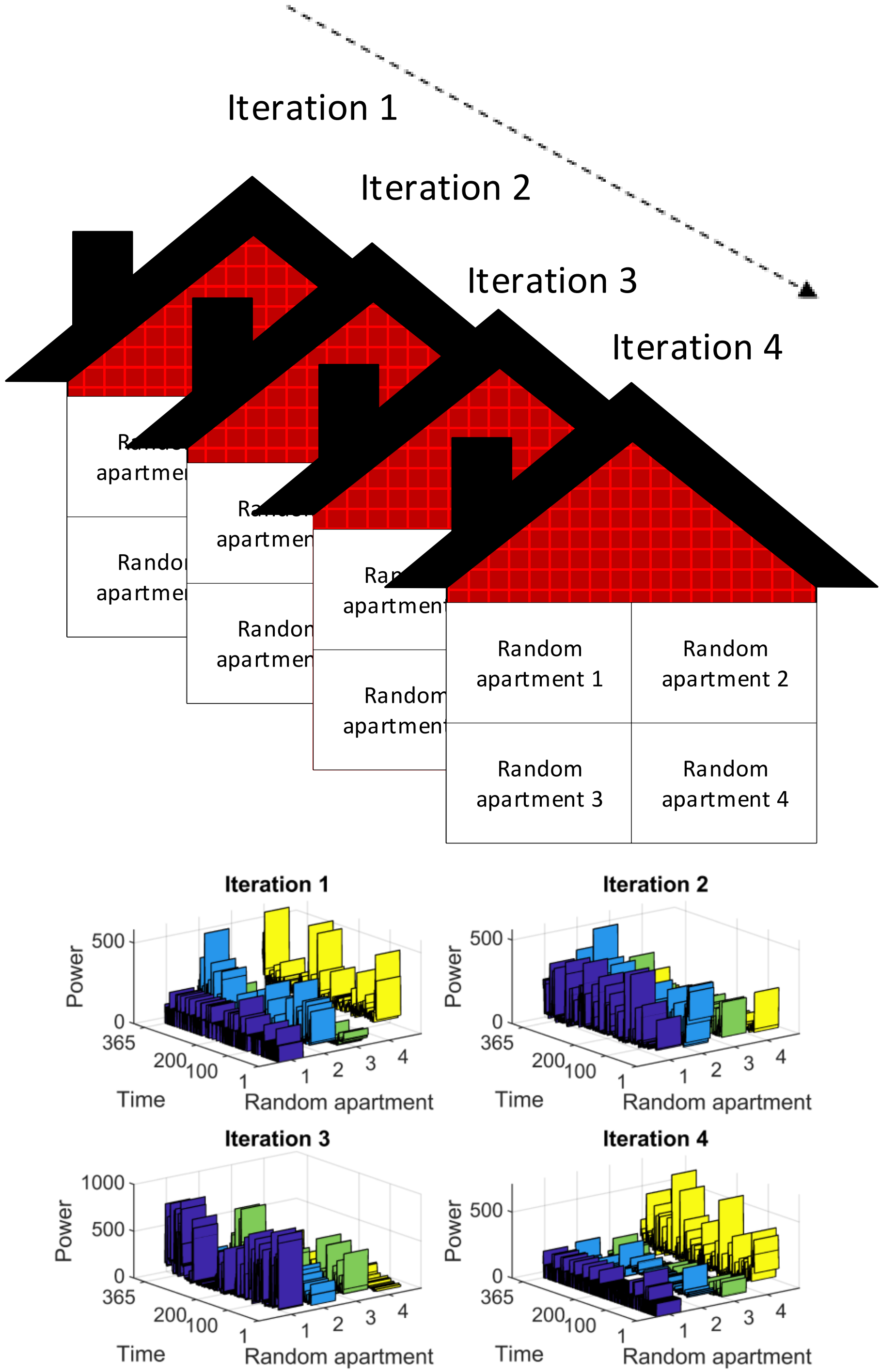

Figure 2.14. Examples of randomly picked household electricity data series in four apartment buildings.

2.5 Power reductions in varying conditions

Thermal energy storage can be used for both cooling and heating. The focus in this thesis was on heating. This meant investigating the reduction of the rate of heat transfer to the living areas of the building in relation to the actual demand. This measure could cause a drop in the indoor temperature that could cause discomfort issues.

The rate of air temperature drop is governed by the heat balance in Equation 1.1. Assuming a steady desired indoor temperature, T_{room}, the demand on the heating system is governed by the varying outdoor temperature in Equation 2.1 and the loss factor k [84] described in more detail in Equations 1.2 to 1.4, as well as varying internal heat gains from occupants and sunlight.

$$P_{loss} = \mathrm{k} \cdot (T_{room} - T_{outdoor}) \ \ (W) \quad 2.1$$

If the heat, P_{syst}, supplied by the system is removed, the temperature in the room will start to drop and the heat stored in the mass of the building will start to be emitted into the room to counterbalance the temperature drop. This heat is stored in the building frame and envelope as well as in every piece of furniture in the building. The magnitude and rate at which the thermal mass discharges heat into or takes up heat from the room is shown in Equation 2.2.

$$\frac{dT_{mass}}{dt} C_{mass,i} = h_{coeff,i} \cdot A_{surf,i} \cdot \left(T_{surf,i} - T_{room}\right) \ \ (W) \quad 2.2$$

This equation can be applied to all the masses within the building. The heat capacity, $C_{mass,i}$, describes how much energy per °C that the material can retain. The heat transfer coefficient, $h_{coeff,i}$, determines the rate of discharge from the surfaces of the interior masses to the air and cooler surfaces in the room. The surface areas of the materials in the room was denoted $A_{surf,i}$.

The need or desire to reduce a building's power demand at a certain point in time can be due to various reasons, such as a high strain on the distribution system or expensive supplies or impacts due to the outdoor climate. However, the points in time when this can happen can vary. These variations can be due to being in different locations, the time of the year, buildings with different properties, and different occupants living in them. A reduction of power can be described well using the equations above. The magnitude of the impact is the crucial and difficult aspect to predict, when occupant-related variables as well as the time of day and the day of the year are taken into account.

Consequently, this leads to a problem being formulated that cannot be solved analytically or deterministically. Instead, a large setup for testing different power reduction schemes, using a probabilistic approach, were created, see Figure 2.15 in which each combination of parameters was simulated at different locations and for multiple iterations with random occupants.

In the sections that follow, the methods used in this thesis regarding power reduction schemes are presented. In the last part of this section, a method is shown in which measurements were compared to simulations with focus on varying parameters, such as the heat capacity C_{mass}, surface area of the furniture A_{surf} and the transfer coefficient h_{coeff} .

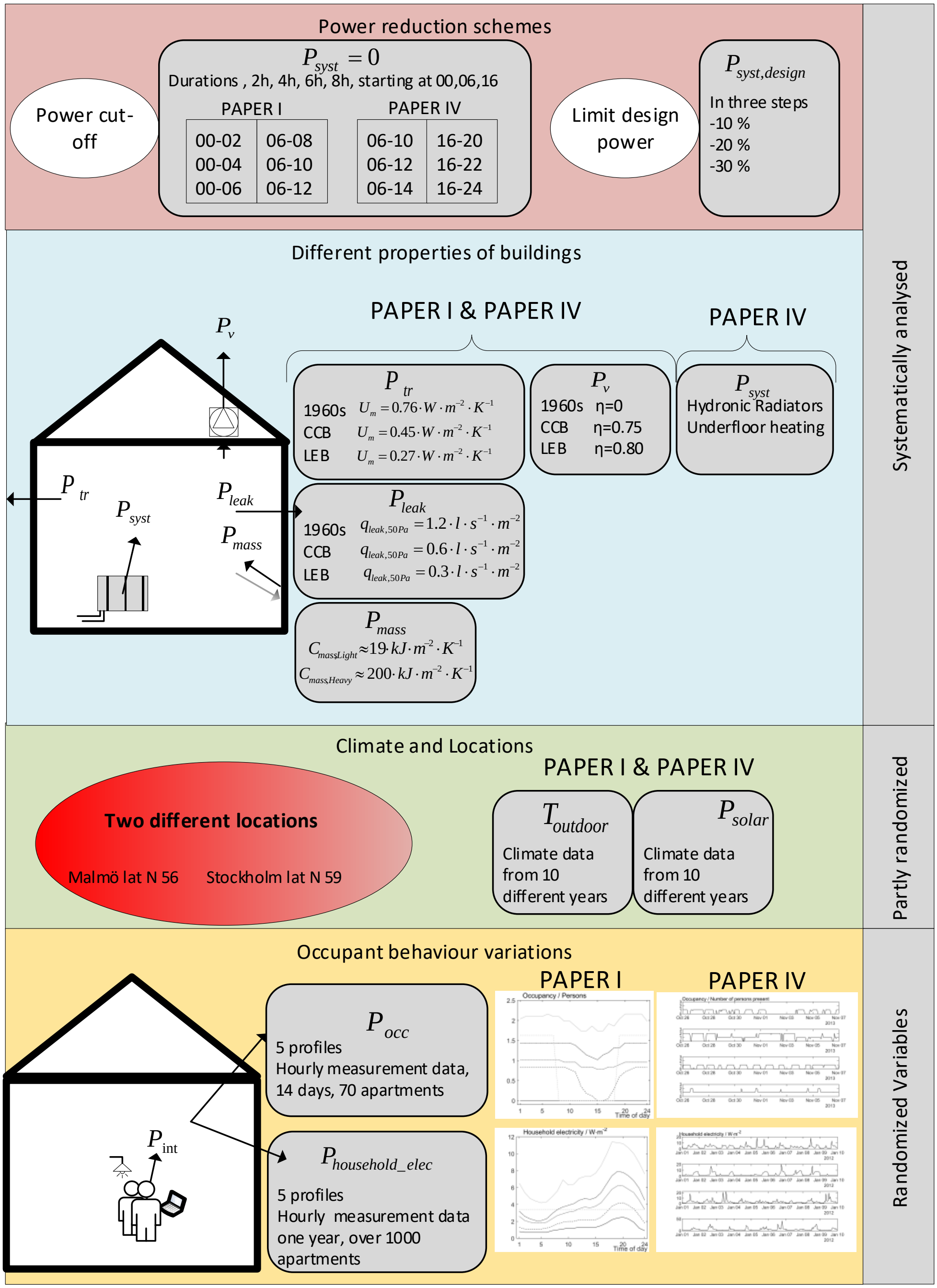

Figure 2.15. Schematic overview of the power reduction analysis procedure.
Power reductions and building properties were systematically simulated in different locations with varying outdoor climates and different occupants living the buildings.

2.5.1 Power reduction schemes

In the context of this research, it is very important to discuss how power reduction in a building could be carried out in practice and what other researchers have investigated, in order to put the method chosen in this thesis into perspective. In Sweden, the heating systems in residential buildings are usually hydronic systems, comprising either radiators, convectors or underfloor heating [85]. In older multi-family dwellings the primary system for heating is usually district heating [85]. A scheme to regulate the availability of power supplied to a multi-family dwelling heated by district heating was presented by Kensby, Trüschel and Dalenbäck [29]. They had an applied practical approach to regulating power and this entailed making the heating system deliver high or low supply temperatures depending on whether the building frame was required to give up or accumulate heat. This was a very applied and practical way of approaching the problem of power reductions in older buildings with hydronic systems. However, as the performance of such a scheme builds on the fact that the thermostats in the building have a large dead-band, they will not react to a short temperature drop by increasing the water flow through the radiators. Furthermore, in their study, they based the indoor climate effects on measurements in a few apartments over a limited duration of time and they analysed the outcome using average temperatures.

In order to analyse power reduction schemes in a more general way, for example in a modern building with more sensitive equipment, the scheme needs to be part of the heating system's operating schedules. This means that complete control of the design temperature in the different parts of the building would be needed. Even with this level of control it would be very hard to reduce the design temperature in the living areas and achieve a corresponding power saving. Additionally, this power saving would vary from time to time depending on the outdoor climate and occupant behaviour.

In summary, partly reducing the power in a hydronic system is difficult to regulate and, therefore, in this thesis, another approach was taken, with total power cuts. This is a worst-case scenario, not only in terms of reduction but also in terms of apartment position in the building, as a top corner apartment was chosen. Furthermore, instead of creating an average temperature, each minimum temperature, following this complete reduction of power, was given an individual meaning as the results would be presented as distributions.

The main power reduction scheme involved the complete removal of heating power to a building or an apartment and this method was presented in Paper I and Paper IV. The second reduction scheme involved limiting the design power capacity. This scheme has not previously been published in a paper and is, therefore, more thoroughly explained here both regarding method and results.

The procedure was, as shown in both Papers, to systematically apply the power reduction schemes to buildings during each of the three time periods and each of the two levels of thermal mass. In Paper IV, the type of heating system was added to the systematically varied parameters. Additionally, each of these cases was simulated a large number of times with randomly picked occupants and outdoor climates.

Space heating power cuts

In this scheme, the heating power was cut off entirely for different durations of time, starting at different times during the day. These times can be seen in the red area in Figure 2.15. In Paper I, an entire building with 15 apartments at the southernmost location (Malmö) was investigated. Paper IV analysed a worst-case scenario with a top-corner apartment located in Stockholm. The duration of the power cut periods varied from 2 to 8 hours in increments of two hours and the resulting temperature drops were analysed. Each cut-off period was applied to each day of the simulated period for each combination and iteration of random input. An example of this is shown in Figure 2.16, in which there was a four-hour cut-off period from 06:00 each day for four days. The key figure chosen to represent the impact on the indoor temperature was the minimum temperature following the power cut. Other important information regarding each power cut cycle included the outdoor temperature during and the heat power demand prior to the power cut. The choice of durations and starting times for these schemes could also have been subject to a randomization procedure. However, the points in time when there is a shortage of power on the supply side are usually during peak hours in the morning, when it is still cold outside and the demands of the occupants increase.

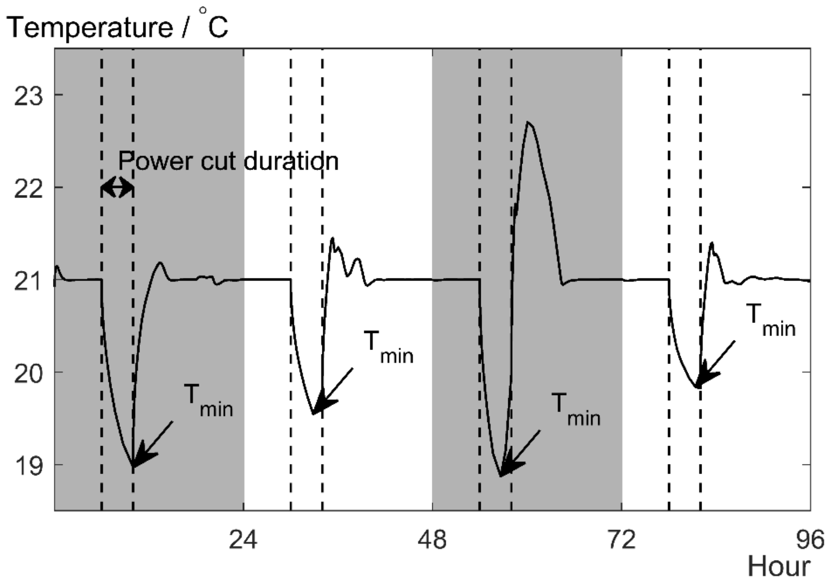

Figure 2.16. Examples of temperature drops during a four-day period due to heating power cuts.
Temperature drops due to four-hour heating power cuts, marked by the dotted lines, and the minimum temperatures.

Limit design power

The building setup was that of the apartment investigated in Paper IV. An additional apartment in the middle of the building was also investigated. The limitation of design power was investigated through using IDA ICE and MATLAB simulations in a similar manner as described Section 2.4.1. The building properties are summarized in Table 2.6 and the building layout is shown in Figure 2.17. The apartment floor areas were 60 m² (7.5 m x 8 m), which corresponds to a typical 2-room apartment in Sweden [86]. Six windows with a total area of 9 m², equally divided between the north and south façades, were added to each apartment. The window area was equivalent to 15 % of the floor area and considered acceptable in terms of the daylight requirements specified in the Swedish building regulations.

The apartments were assigned a maximum available power, in order to demonstrate the capacity of an actual heating system. This design power was sufficient to maintain the design indoor temperature in both apartments during the heating season. The heating system was modelled with fictive heaters, functioning like standard electronic heaters without mass or dead-bands, responding to deviations in indoor temperature by increased or decreased output. This differed from Paper IV, in which the heating system was modelled as a physical hydronic system. Additionally, the extent of the investigated combinations of parameters in this study was reduced. The scheme was only tested with two variations of parameters, i.e. different amounts of thermal mass denoting light and heavy construction, see Table 2.6. The location that was chosen was Kiruna (latitude N 68°) and an outdoor climate file (IWEC2) for energy calculations and simulations for the month of January were used, i.e. not for the entire heating season but in the same manner as in Paper IV.

The scheme was to reduce the amount of available power and then run the simulation multiple times with random occupancy. The occupants were, in this case, only represented by their household electricity load. In Sweden, the design power load is allowed to be reduced depending on the building time constant that is correlated to the thermal mass and heat loss of the building. The reductions related to this usually have a magnitude of 10 to 15 % [87]. In this study, the reductions of 20 %, 30 % and 40 % were chosen for the analysis. Hourly household electricity loads, representing the occupants, were drawn from the pool of data described in Section 2.2 for two-room apartments. The simulation procedure is shown schematically in Figure 2.18. Marked in dark blue is an example of combinations. Each setup in Tier 1 was simulated 50 times (50 January months) for each of the two cases of thermal mass (Tier 2). One important aspect in this analysis was to keep the same occupants when simulating buildings with different thermal masses. This means that for each of the reductions in Tier 1, 50 pairs of occupants were randomly picked from the household electricity data material and applied to the two cases of different thermal mass in Tier 2.

Each simulation rendered a number of temperature outputs that were analysed to see the impact of limiting available power. The temperature data was first averaged into hourly mean values and then rated by different limits. The design temperature was 22 °C and the thresholds chosen were 21.5 °C, 21 °C, 20.5 °C and 20 °C. The relative number of hours below these thresholds were calculated for each of the 50 simulations connected to every combination of parameters given in Figure 2.18. For example, if 74 hours were below 20 °C in one simulation, the number saved for this simulation would be about 10 % as there are approximately 740 hours in January.

Table 2.6. Heat transmission, airtightness and thermal mass.
Building envelope properties used in this analysis were the same as those used in Paper IV.

Building Property	Standard building values	Building part	Light Construction	Heavy Construction
$U_{Exterior\ wall}$	0.18 W/(m²K)	Exterior walls	14 kJ/(m²K)	202 kJ/(m²K)
U_{Roof}	0.13 W/(m²K)	Interior walls	28 kJ/(m²K)	202 kJ/(m²K)
U_{Window}	1.3 W/(m²K)	Roof	14 kJ/(m²K)	202 kJ/(m²K)
Air leakage	0.6 l/(s.m²) ext. area at 50 Pa			
Thermal bridges	20 % of $U_{tot} \cdot A_{tot}$			

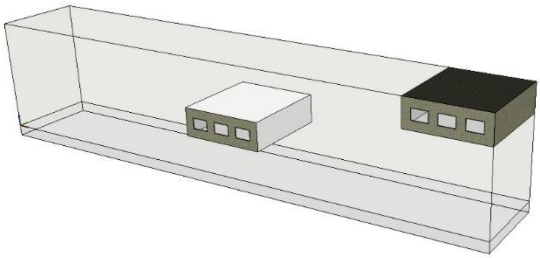

Figure 2.17. Spatial location of the two investigated apartments.
The two investigated apartments, with different ratios of envelope area subject to the outdoor climate but otherwise similar.

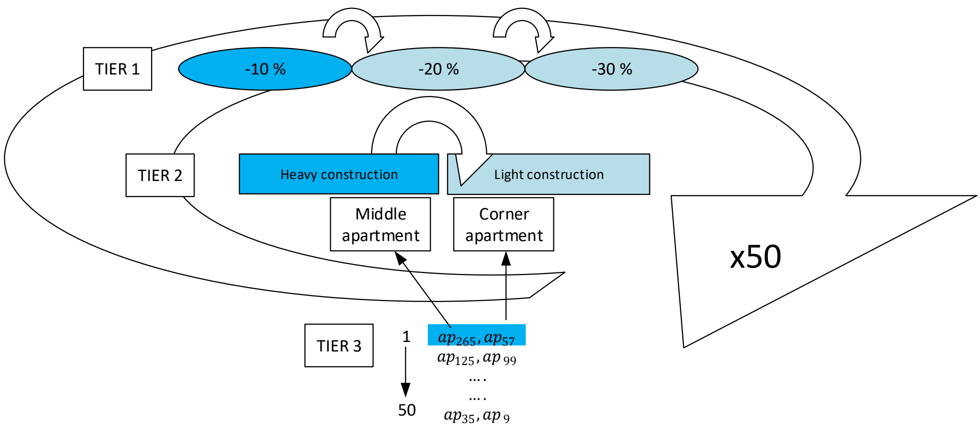

Figure 2.18. Schematic simulation procedure for the design power limitation scheme.
Areas in dark blue show an example of a simulation setup. The occupant's household electricity loads, in Tier 3, will then be varied 50 times while Tier 1 values are kept the same.

2.5.2 Measurements vs simulations

Power reduction or intermittent heating schemes are ways of operating a building that connect strongly to the indoor temperature. More detailed information about the actual rooms of a building are therefore required when performing such a building simulation. Reverting to the heat balance and the mass in the room in Equation 2.2, additional parameters, subject to variations and uncertainties, can be identified. The mass and surface areas of the furniture, the connection between the envelope (structure) and the room air, i.e. the area of exposure, can, to some degree, all be classified as stochastic. The heat transfer coefficient depends on the specific physical properties of each particular surface in terms of radiation and air movements. How the simulation software captured this behaviour when subject to a power cut was investigated by comparing measurements in two different buildings using the corresponding simulation models presented in Paper II. One occupied single-family dwelling and one multi-family dwelling that was to be decommissioned were analysed in Paper II. In the first case, the power was turned off during the night and in the second case the power was cut off permanently due to the building being decommissioned and the temperature was allowed to decline for over a week.

The single-family house was measured and modelled at room level, the multi-family building at apartment level. Some geometrical simplifications were made in the model when simulating the real world building. However, the biggest discrepancies were due to the fact that the two existing buildings were old and that the statuses of the building envelopes were hard to estimate. The buildings also had natural ventilation, which was another source of uncertainty.

In the IDA ICE 4.6 simulation software, furniture or internal mass was modelled as a flat body with two sides in contact with the room air. The body had a variable thickness and variable material properties. A static heat transfer coefficient was also used for this mass. Variable heat transfer coefficients were used for the internal and external wall contacts with the room air.

3 Results and discussion

The performance of a building can be characterized in two ways. Most importantly, as described in the introduction, is its performance with regard to achieving a comfortable and safe indoor environment. Secondly, is its performance with regard to having a low energy use from renewable sources. To design buildings, with the ambition to lower the energy use and still maintain a good indoor environment has been the challenge for many years. Recently, in the context of achieving a lower environmental impact, reducing the building energy demand has not been the only focus, but has also been to make sure that the energy comes from renewable sources. The environmental impact has its roots in the primary energy source, which, in turn, usually depends on the interplay between supply and demand in the larger energy system that the building is a part of. Thus, the power demand then becomes an import variable when designing a building. The impacts of different choices that can be made to reduce the power demand, when designing buildings today, could have the same or an even smaller impact than, for example, the naturally varying occupant behaviour.

3.1 Power reductions and the indoor temperature drop

The shortage of power in society leads to the need to be able to reschedule power demand by cutting it off when it would otherwise have been supplied. Having a high level of power available is expensive for the suppliers to maintain. They must build and own the plants, operate them and develop and connect new districts and customers and this affects both investment costs and operating costs. An economic benefit could be achieved by reducing these costs, for example, by connecting more customers to the existing grid.

The use of the thermal storage capacity of buildings can provide an opportunity for rescheduling power supplies and thus changing the magnitude of the design demand and operational demand in a building. Potentially, this could lead to a lower life-cycle cost as well as a lower environmental impact. With the presumed inclusion of electric vehicles in future energy systems and the following need for charging stations, the electric power demand in society will increase dramatically. This might provide an opportunity for the untapped potential of the thermal capacity of buildings to be utilized. By reducing the power on the demand side, the end-users, in this case the occupants, will have to accept a minor temperature drop to facilitate a more environmentally friendly process of supply and distribution of power in the energy system. Consequently, society or the power supplier are the ones who benefit. This temperature drop with regard to power reductions on the demand side was illustrated in Paper I and Paper IV. In Paper I, an entire building with 15 apartments was investigated and an example of the results is shown in Figure 3.1. They show that a complete power cut for up to 6 hours presented a very low risk of an indoor temperature drop of more than 1 °C in a building with good insulation properties and an underfloor heating system. The outcome of this paper led to the development of Paper IV in which a worst-case scenario was tested, i.e. a top-storey corner apartment. Combinations of different building envelope properties, heating systems and two levels of thermal mass were tested and summarized results are shown in Table 3.1. In this table, the 15 500 minimum temperatures from each parameter combination and power cut were compared with the fictive experience of a pre-defined occupant using Fanger’s definitions [62], also adopted in ISO 7730 [63]. For such pre-defined occupants with an activity of 1.2 met and clothing corresponding to 1.0 clo, 21 °C would be an optimal indoor temperature. If the temperature were to vary within ±1 °C from this temperature, 6 % of the occupants would be predicted to be dissatisfied. A temperature variation of ±2.5 °C or ±3 °C would mean 10 % and 15 % dissatisfied occupants respectively. The results are shown as a percentage of the 15 500 temperatures for each combination that failed to meet the three criteria. These are very conservative results but, even so, the only parameter combinations that showed a substantial risk of dissatisfaction were in a building with 1960s’ standard and a radiator heating system. One aspect that made the analysis conservative in Paper IV was that the apartment was modelled as a single zone without including the additional mass of the internal walls, furniture or mass of the heating system, which was later shown in Paper II to have a potentially significant impact, shown in Section 3.1.1. Furthermore, when analysing risk or probabilities of some occurrence, the problem that follows lies in the evaluation and decision-making based on the outcome. What level of risk is acceptable? The probabilities presented relate to the minimum temperatures that would only be experienced momentarily, usually at the end of the power cut period. The choice of indictor is also something that could be discussed. Nonetheless, it may need to be more specific and be related to the magnitude and duration of temperature drop and also be able to translate into comfort. Other examples could be lowest hourly mean, 15-minute mean or perhaps the rate of temperature drop. Additionally, the apartment investigated was the one worst positioned in the building in terms of exposure to the outdoor temperature. Should the risk be based on this apartment? If all apartments in a multi-family building were included, the probability of failing to fulfil the goal would be lower, which is shown in Paper I, with example results shown in Figure 3.1.

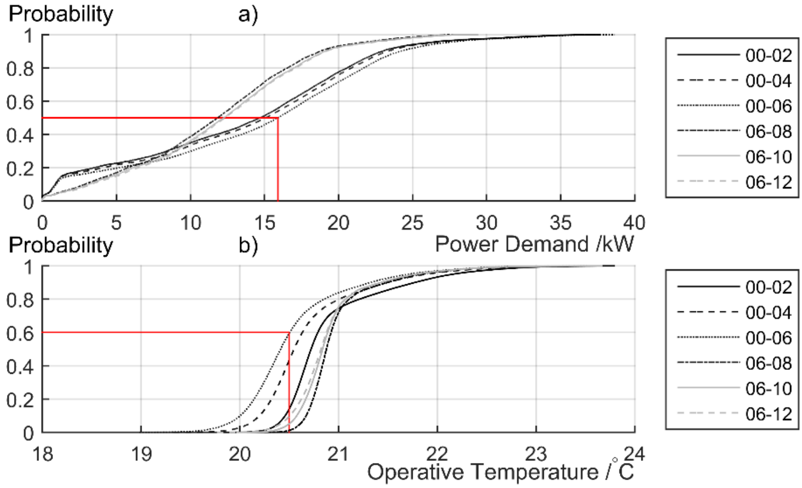

Figure 3.1 Distribution of power demand and temperature drop for the six different durations without power. In a) each curve shows the power demand for each day of the heating season for the whole building. The red line shows the median power demand for the cut-off period between 00-06 (15.9 kW). In b) each curve shows the temperature after the cut-off for each day of the heating season for the 15 apartments. The red line in shows the probability of having a lower temperature than 20.5 °C for the same cut-off period (00-06).

The probabilities of fulfilling the comfort criteria after a power cut are shown in Table 3.1 and are based on the results from Paper IV. The comfort criteria relate to a person carrying out the same activity and wearing the same clothing. However, studies have shown that people tend to adapt to their environment in the most efficient way available to them. In the case of a decreasing indoor temperature, increasing the amount of clothing would be an easy counteractive measure to maintain comfort. If this measure could be taken for a fact, the probabilities in Table 3.1 would be even lower. However, in order for this scheme to work, this measure, adding clothing, cannot be something forced upon the occupants as a consequence of the system failing to deliver what they are expecting. It needs to be a conscious action, one that the occupant is aware of and accepts in order to gain another advantage, or to help society.

In society today, sustainability and climate anxiety are high on the agenda. However, for a power cut scheme like this to result in the reduction of the power demand, the benefit is too abstract for the occupants who are subject to the effects on the indoor temperature. The benefit is gained by the supplier, or society, at the cost of sacrificed comfort for the occupants. The question then becomes: to what extent can the comfort level be lowered and is it possible to find other ways to make the occupants accept the situation? How much is it worth to have the indoor temperature drop a couple of degrees for a few hours? The temperature cannot be compensated for afterwards, 18 °C cannot be compensated by 26 °C later on. Other means of compensation or incentives are needed. Furthermore, the age distribution in society, with an increasingly larger proportion of elderly people living alone at home, often people who cannot adapt or need a higher indoor temperature, must be considered

Knowing how much one can reduce the simulated maximum power as a function of a building's thermal mass and to what minimum acceptable temperature would be an important outcome. However, it was not possible to find a general function or formula connecting these parameters in a reasonable way, as there are stochastic variables that can affect the outcome as well as the setup of the building parameters for a given case. As an extension to the analysis in Paper IV, temperature drop connected to power output prior to the power cut and connected to the outdoor temperature and duration of the power cut are presented in Section 3.1.2 The results from limiting the design power are presented in Section 3.1.3. The outcomes would be a lower design power demand of a system of buildings or the possibility of supplying more buildings in an existing network. More explicitly, additional apartments/buildings could be added to the grid if power reduction in the existing ones was allowed. However, these outcomes are limited by more than just the thermal mass. The level of acceptance, for example, the number of hours, or degree hours below a certain level, decide how many more apartments can be connected to the same network.

Table 3.1 Predicted percentages of dissatisfied occupants.
Three levels of dissatisfaction, 6 %, 10 % and 15 % PPD, correspondning to different temperature drops, were analysed for all the parameter combinations and lengths of power cuts. A colour scheme to distinguish the outcomes was used, in which green indicates acceptable outcomes, followed by yellow, orange and eventually red, indicating the largest percentage of failure to fulfill the PPD-index.

Low energy building													
		Radiators light construction						Radiators / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	70 %	77 %	79 %	46 %	62 %	75 %	17 %	24 %	32 %	9 %	21 %	40 %
10 %	21±2.5	4 %	10 %	13 %	4 %	10 %	23 %	0 %	0 %	0 %	0 %	0 %	1 %
15 %	21±3	1 %	4 %	6 %	1 %	5 %	13 %	0 %	0 %	0 %	0 %	0 %	0 %
		Underfloor heating / light construction						Underfloor heating / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	16 %	21 %	24 %	7 %	15 %	34 %	2 %	5 %	7 %	1 %	5 %	11 %
10 %	21±2.5	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %
15 %	21±3	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %
Building code standard													
		Radiators light construction						Radiators / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	90 %	92 %	94 %	69 %	81 %	91 %	39 %	51 %	62 %	22 %	42 %	65 %
10 %	21±2.5	12 %	22 %	35 %	8 %	26 %	51 %	0 %	0 %	1 %	0 %	0 %	3 %
15 %	21±3	4 %	9 %	18 %	4 %	12%	33 %	0%	0 %	0 %	0 %	0 %	1 %
		Underfloor heating / light construction						Underfloor heating / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	20 %	28 %	30 %	13 %	28 %	50 %	4 %	4 %	7 %	3 %	5 %	13 %
10 %	21±2.5	0 %	0 %	0 %	0 %	1 %	2 %	0 %	0 %	0 %	0 %	0%	0 %
15 %	21±3	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %
1960s standard													
		Radiators light construction						Radiators / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %	100 %
10 %	21±2.5	99 %	100 %	100 %	98 %	99 %	100 %	74 %	83 %	88 %	63 %	83 %	96 %
15 %	21±3	97 %	98 %	99 %	93 %	98 %	100 %	43 %	63 %	74 %	32 %	62 %	86 %
		Underfloor heating / light construction						Underfloor heating / heavy construction					
PPD	Temp	6-10	6-12	6-14	16-20	16-22	16-24	6-10	6-12	6-14	16-20	16-22	16-24
6 %	21±1	58 %	69 %	73 %	60 %	83 %	96 %	14 %	24 %	40 %	17 %	42 %	74 %
10 %	21±2.5	0 %	1 %	5 %	2 %	13%	36%	0 %	0 %	0 %	0 %	0 %	1 %
15 %	21±3	0%	0 %	1 %	0 %	5 %	18 %	0 %	0 %	0 %	0 %	0 %	0 %

3.1.1 Comparisons between measurements and simulations

The results from Paper II, when comparing measurements of power cuts to simulations of the same procedure, show that rather large discrepancies were found initially, Figure 3.2. Figure 3.2 shows the response of a room in a single-family building that was modelled with a rather high level of detail, with every room of the building regarded as an individual thermal unit. The first issue was the very rapid temperature drop in the simulation immediately after the power cut that was not seen in the measurements. Part of the answer to this question was the hydronic radiator model that was used at first, in which the radiators were modelled without having thermal mass, neither the radiators themselves nor the heated water in the radiator system. This meant that when the system was turned off this mass had a built-in amount of energy that could have been released and that the ordinary model did not take into account.

The difference between measurements and simulations was not fully answered with the improved radiator model that included the thermal mass of the entire system. Measurements of the real temperature drops showed an even slower rate of temperature drop. A parameter that was not modelled, and that was unknown, was the amount of furniture in the building. Nor was the ventilation rate known as the building was from the 1950s and had natural ventilation, i.e. had devices allowing the outdoor air to flow straight into the indoor environment, with the volumes depending on temperature differences, wind and airtightness.

In the simulation model, a parametric run was carried out in order to see whether the measured temperatures could be matched using a simulated model with a modified input. The parameters that were varied were the ventilation rate, the furniture (mass) and the area of the furniture exposed to the room air. The parameter combinations that gave good matches are shown in the legend box in Figure 3.3. The internal mass was modelled as a flat body in IDA ICE with a given thickness and surface area. The first column in the legend box shows the airflow ($l \cdot s^{-1} m^{-2}$), the second the area (m^2) and the third the thickness of the flat body (m). Thus, the mass would change with changing surface area, leading to the mass varying between 1600 kg and 3200 kg for the combinations that gave good conformity. Surface areas in the range 20 m^2 to 80 m^2 were among the good matches. However, consistency was not achieved in the cases with the same mass as they did not render the same matching temperatures. For example, the combination with an area of 20 m^2 and thickness of 0.08 m gave the same mass as an area of 80 m^2 with a thickness of 0.02 m but these proportions did not result in good matches.

The results show that it is not easy to model and simulate to match reality in an existing building due to uncertainties. Furthermore, the parameter combinations that gave good matches with the measured temperature drops in Paper II were rather unrealistic in terms of the amount of furniture (mass) added to achieve conformity with the measurements. This could partly be explained by the heat transfer coefficient, the aspect in addition to the surface area that determines the rate of heat transfer, that was modelled with a constant value for internal masses, such as furniture, in IDA ICE. This coefficient, in reality, varies due to physical phenomena, and a larger value than modelled in IDA ICE could be translated to a larger surface and a larger mass in the simulations.

One could argue the validity of the large-scale simulations when the comparisons between measurements showed few matches. IDA ICE is a well-known software, used by researchers as well as practitioners, and the results can be seen as being on the safe side without the furniture. Measurements were available for older buildings when the power was cut and when they were in operation though with a large amount of uncertainty. Ideally, measurements taken in modern buildings could have been compared to the simulations to reduce these uncertainties. Having more measurements would have been beneficial, but adding another variable, such as the amount of furniture, would have required even more data, for example, to match the amount of available occupant data for household electricity.

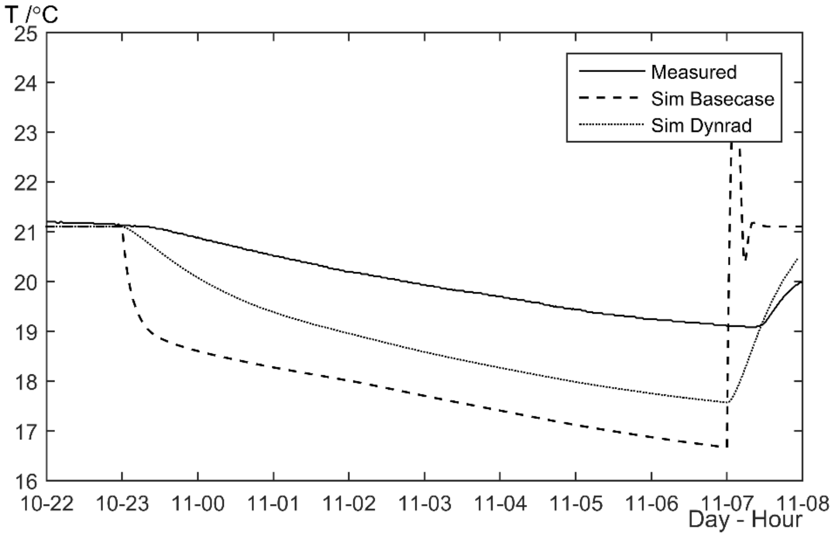

Figure 3.2 The temperature in a single room in a single-family building during a power cut.
Measured temperature response as well as two simulated cases. The base case simulation shows the model without a radiator but taking into account the remaining warm mass of the radiator, and the Dynrad shows the temperature when a new radiator model was used.

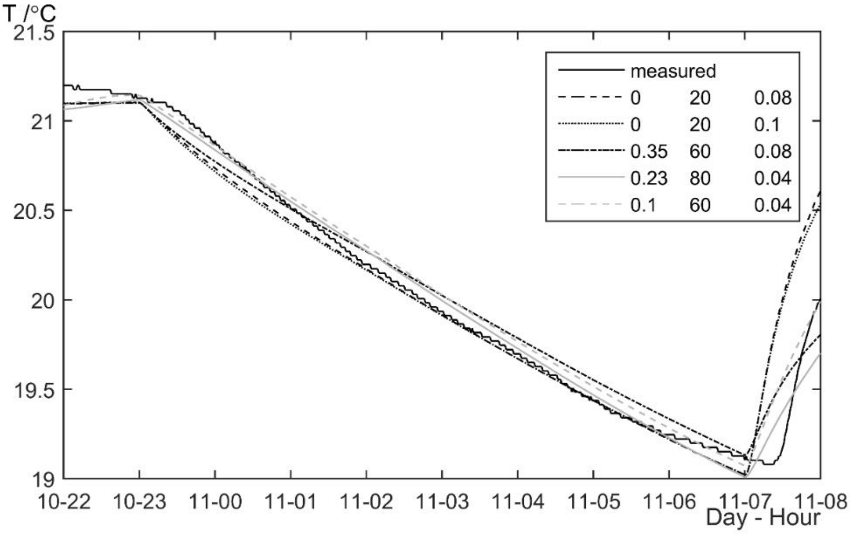

Figure 3.3 Indoor temperatures for five parameter set-ups with good correlations to the measured temperatures.
The measured indoor temperatures are also shown and the most prominent differences are the dead time, at the beginning and the end of the power cut. When a change was made in the simulations, the temperature reacted instantly whereas in reality it took 20-30 minutes. The first column in the legend box shows the airflow ($l \cdot s^{-1} m^{-2}$), the second the area (m^2) and the third the thickness of the flat body (m) representing the furniture.

3.1.2 Extended analyses of results not presented in Paper IV

Temperature drop linked to power demand

This section describes the relationship between the power output, delivered by the heating system, immediately before the power cut and the resulting temperature drop. Figure 3.4 are described in general here and in more detail under each subsection. For each parameter, the 15 500 minimum temperatures were placed into different groups depending on the heating power supplied to the apartment. The intervals of power were chosen with either 0 W to 250 W or 0 W 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. In the following figures, the resulting temperatures, from the different intervals and corresponding to the 50 percentile, are shown in black and the 5 percentile in grey, aligned over each respective parameter and power cut period.

The figures are divided into two parts: a) the morning power cuts and b) the evening power cuts. 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 cut periods 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 shows an example of how to read the results, described fully in the figure caption.

Low energy building (LEB)

The results for the low energy building (LEB) setup are shown in Figure 3.4. The morning power cuts show significant uniformity within and between the parameter groups, Figure 3.4a. 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 as the other three cases. The fact that there is almost no distinct difference between a 4-hour power cut and an 8-hour power cut might be due to an increase in the outdoor 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 3.4b there is a clear distinction concerning temperature drop in relation to the duration without heating power. This is to be expected, as the outdoor temperature drops and the internal heat gains are likely to diminish as occupants go to sleep. The most favourable parameter combination is a heavy envelope with underfloor heating, with a low risk of dropping below 1 °C, only about 5 % for the three shortest power cut periods. For the parameter combinations with a light construction, the spread is much larger and the differences between the intervals clearer. Buildings with underfloor heating seem to use slightly more power (four intervals instead of three) than buildings with radiators and this might be due to the time lag between when the heating power was demanded and when it actually reaches the room. The underfloor heating system was modelled as embedded 2 cm deep in concrete.

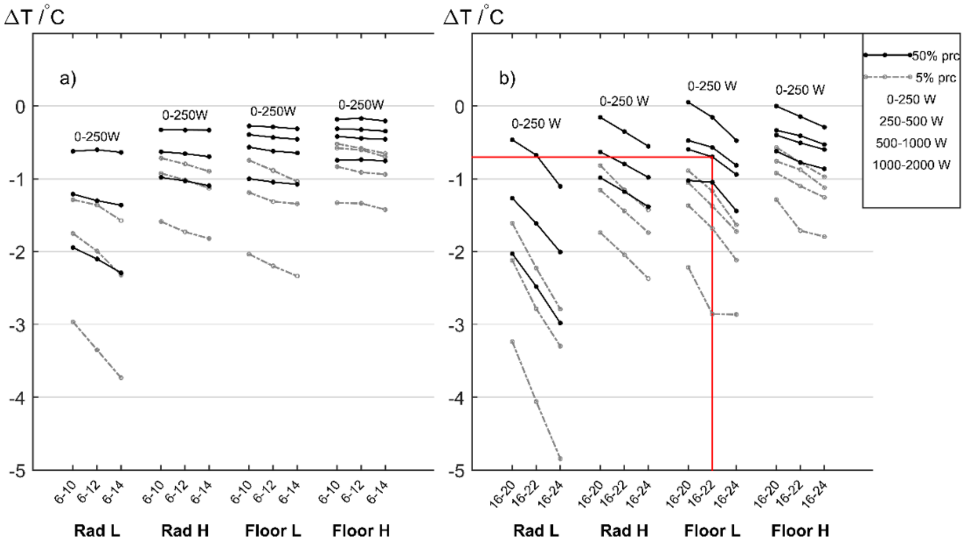

Figure 3.4 The magnitudes of the power prior to the cuts and corresponding indoor temperature drops in the low energy building (LEB).
The correlation between the magnitude of the power cuts and the indoor temperature drops for a) the morning power cuts and b) the evening power cuts. The red lines show an example of when power cuts within the interval 500-1000 W were carried out. The corresponding probable temperature change was -0.8 °C (in median) for this particular combination of parameters, i.e. a light construction with underfloor heating and a power cut between 16-22.

Code-compliant building (CCB)

In Figure 3.5a an interesting phenomenon can be seen. The temperature drops for the 50-percentile hardly decrease with increasing length of the power 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, whereby many favourable combinations happened to be picked for the 8-hour power cut cases but not the others. Similarly, as for the LEB combinations of parameters, 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 cases b) the declinations are most pronounced in the combination with a radiator and a light construction, with 1 °C to 2 °C differences between the 4-hour and 8-hour power cuts. This is hardly discernible in the cases with underfloor heating and a heavy construction.

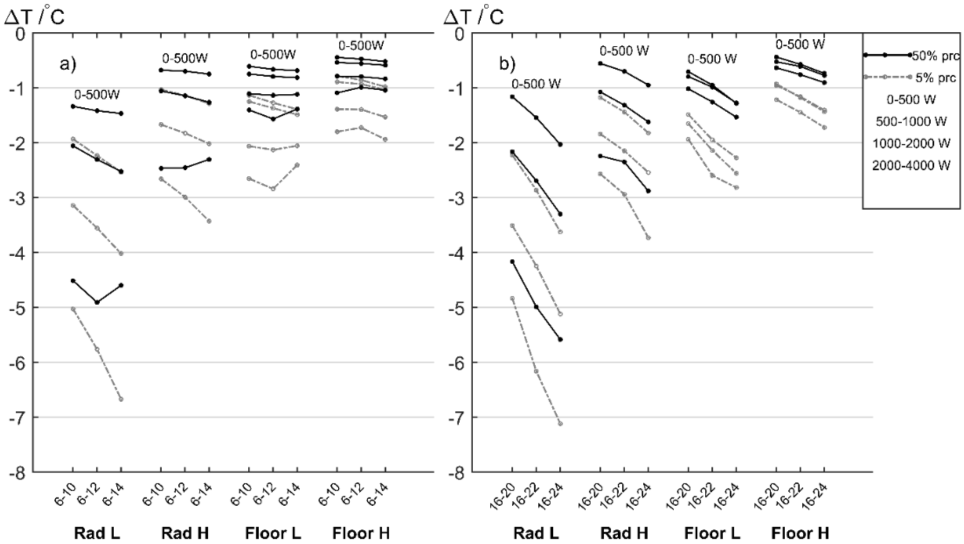

Figure 3.5 The impacts of the power cuts on the indoor temperature drops for the code compliant building (CCB).
The correlation between the magnitude of the power cuts and the indoor temperature drops for a) the morning power cuts and b) the evening power cuts.

1960s' building

The results regarding the building with 1960s' standard show the most distinct temperature decline among the three building types and these are shown in Figure 3.6. The combination with the worst insulation levels and lack of a heat exchanger makes this building standard most susceptible to the power cuts. Despite these drawbacks, one combination of parameters manages quite well. The heavy underfloor heated set-up has only a 5 % risk, during almost all intervals, of dropping 2 °C or more, Figure 3.6a and Figure 3.6b. The exception is the very worst case, with the longest power cut. For the combination of parameters light construction and radiators, the temperature drop is five times larger. Here, the 5 % risk is as low as a 10 °C drop, which, of course, would make the apartment uninhabitable.

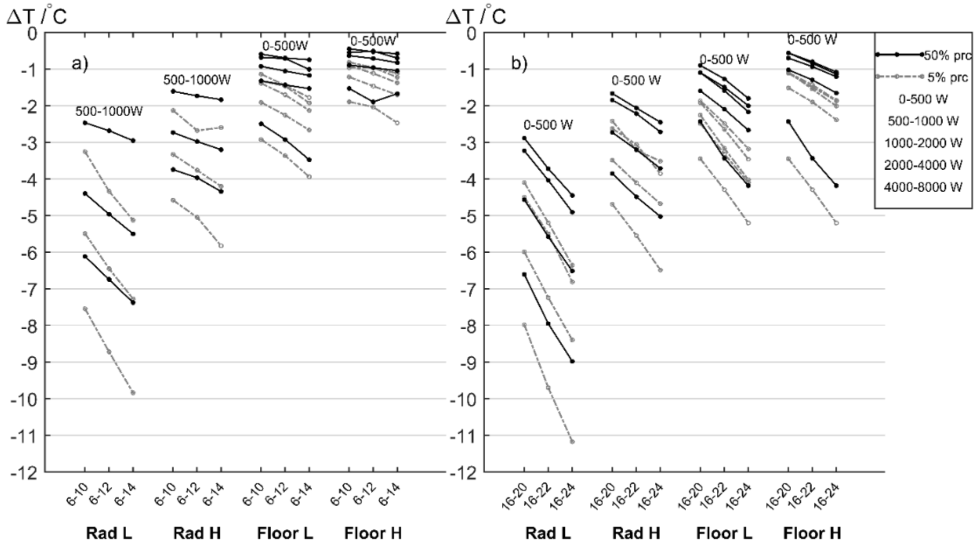

Figure 3.6. The impacts of the power cuts on the indoor temperature drop for the 1960s' standard building. The correlation between the magnitude of the power cuts and the indoor temperature drops for a) the morning power cuts and b) the evening power cuts.

Summary

Summarizing the results from this section, it is clear that the LEB with the combination of parameters involving a heavy construction, in most cases, has a moderately low probability of resulting in major temperature drops, even when high power outputs are cut. The combinations with a light construction, however, can only handle shorter power cuts with lower magnitudes of power demand, if they are to keep within the same temperature drops at the same risk levels as in buildings with heavy construction.

The outcome is not as good as for the CCB, in which only the combination of a heavy construction with underfloor heating manages the 2 °C drop with a 5 % risk. In all the other cases, shorter power cuts with lower power demands can cause the same temperature drops at the same risk level.

The 1960s' standard building shows a similar potential as the LEB and CCB regarding the parameter combination of heavy construction and underfloor heating, with some restrictions regarding the power cuts at the highest power levels.

These results might completely rule out the use of these power cut schemes in older 1960s' 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 the 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 implementing this kind of scheme on an actual building to make exceptions for these apartments and not to turn off the heating supply completely.

Temperature drops linked to degree hours

This section shows the correlated effects of the duration of the power cuts and the outdoor temperature on the indoor temperature drops. A new parameter, dh, degree hours, is introduced and defined in Equation 3.1 in which 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.

$$dh = t_{pc} \cdot \left(T_{design} - T_{mean,out}\right) \qquad (°Ch) \qquad 3.1$$

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 dh. Contrary to the previous section, in which the power that was cut off was 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 number of degree hours (dh) during the power cuts. The intervals chosen increase in doubled increments 0 to 50, 50 to 100 and so on. The dh value is dependent on the duration of the power cut, which leads to a change in how the results are shown in the following figures compared to the previous section. Now, parameters are grouped into three categories for the morning a), and evening, b) power cuts. In these groups, the four parameter combinations are shown, labelled with the heating system denoted *Rad* for radiators and *Floor* for underfloor heating system and the thermal mass is denoted *L* and *H* for light and heavy construction respectively. 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 shows an example of how to read the results, described fully in the figure caption.

Low energy building (LEB)

The results for the LEB are shown for the morning power cuts, Figure 3.7a, and evening power cuts, Figure 3.7b. All of the parameter combinations manage power cuts corresponding to 50 to 100 dh with a 5 % risk of dropping lower than 2 °C, in many cases only 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 dh intervals, the same as above is true except for the light radiator cases in Figure 3.7a-b). The toughest interval, 200 to 400 dh, 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 and the previous interval, it is also clear that the risk of the light case dropping to low temperatures increases significantly.

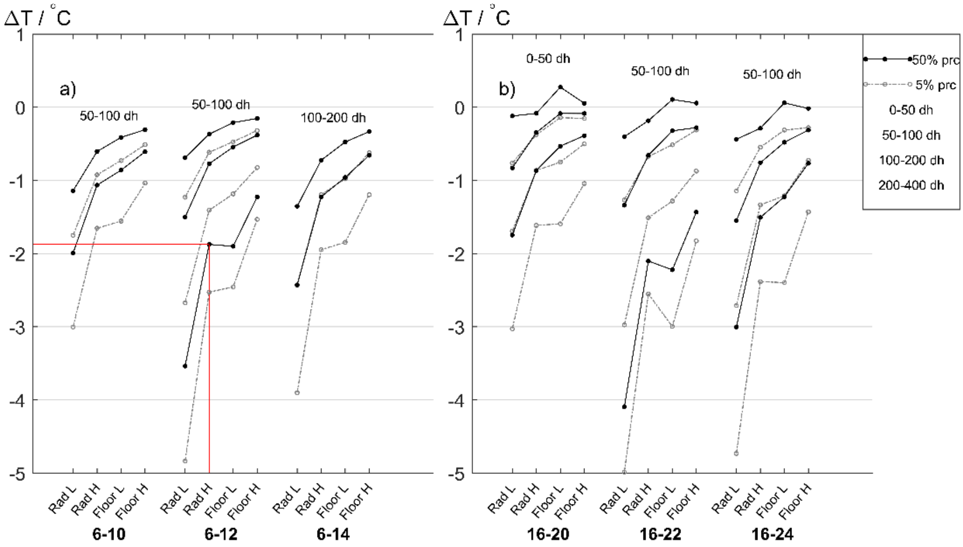

Figure 3.7. Degree hours (dh) linked to the indoor temperature drops for the Passive House envelope. Shown in a) the morning power cuts and b) the evening power cuts. The temperature drops are grouped into intervals depending on the number of degree hours on that occasion and are represented by two percentiles for each interval, the 50-percentile (black) and the 5-percentile (grey). 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 to be about 1.9 °C. The third black dot from the top indicates the interval of 200-400 dh and the 50 percentile.

Code compliant building (CCB)

In Figure 3.8, the results from the CCB are shown in a) the morning power cuts and b) the evening power cuts. As in the LEB, there is a slightly higher risk of dropping below 2 °C during the 50-100 dh power cuts. The parameter configurations involving the heavy parameters stay above a 1 °C drop at the 5 % risk level. With a similar risk and temperature drop, the underfloor heated building with the same parameter setup manages a 100-200 dh 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 periods without power are extended.

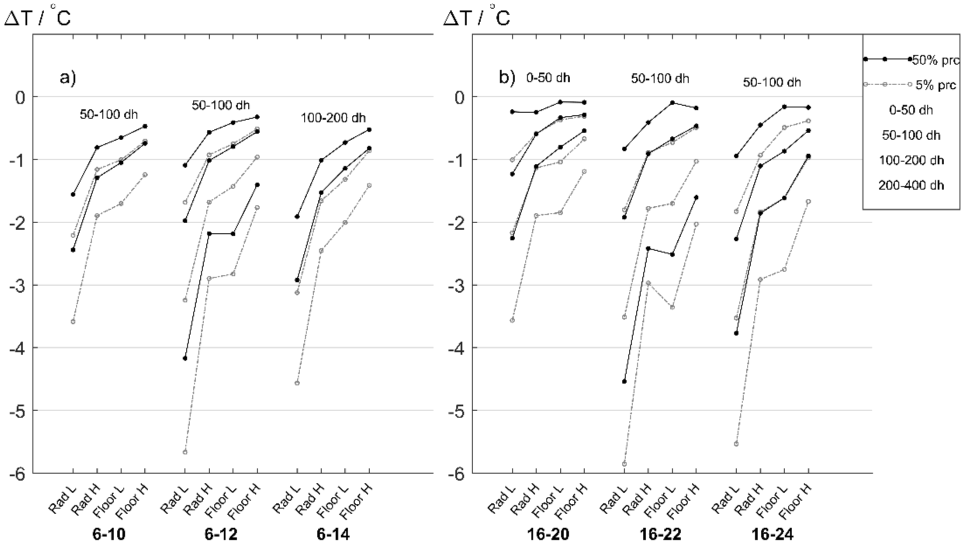

Figure 3.8. Degree hours (dh) linked to the indoor temperature drop for the Standard House envelope. Shown in a) the morning power cut-offs and b) the evening power cut-offs. The temperature drops are grouped into intervals depending on the number of degree hours on that occasion and are represented by two percentiles for each interval, 50-percentile (black) and 5-percentile (grey).

1960s' building

The results from the 1960s' building are shown in Figure 3.9, for the morning power cuts in a) and the evening power cuts in b). It appears that the lines and the results lie much closer to one another than in the previous parameter set-ups. However, the scale of the y-axis has been changed to approximately twice that as before. This is due to the significant drops in temperature, with the worst configurations dropping as much as 11 °C from the design temperature. Even for the lower intervals of dh, the slope of the lines connecting the set-ups is steep. Contrary to the two previous building types, the difference between the configurations becomes more distinct earlier. For this building, only the underfloor heated configurations manage to stay above the 2 °C drops, with a low risk of 5 % during the 50-100 dh power cut. The configuration with underfloor heating and light envelope is close to the 2 °C line, while the heavy envelope is closer to the 1 °C line. The configurations involving radiators all suffer a higher than 50 % risk of dropping below 2 °C, during the 50-100 dh power cut.

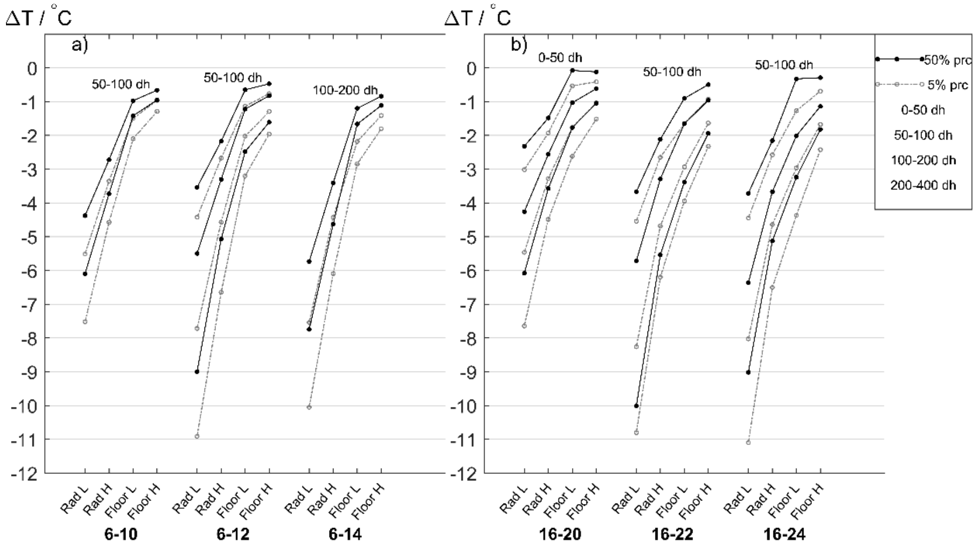

Figure 3.9. Degree hours (dh) linked to the indoor temperature drops for the 1960s' building envelope. Shown in a) the morning power cuts and b) the evening power cuts. The temperature drops are grouped into intervals depending on the number of degree hours on that occasion and are represented by two percentiles for each interval, the 50-percentile (black) and the 5-percentile (grey).

Summary

The dh 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 dh, 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 dh) 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 the dh parameter being representative for a power cut period in comparison to the more straightforward approach of describing the reduction in heating power in Watts.

The temperature drops for the 5 and 50 percentiles differ in magnitude by about 0.5 °C to 1 °C within the dh 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 ranges 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. For the Low Energy Building and the Code Compliant Building, the low dh intervals create results that follow a more horizontal line, with a slight declination for the configurations with the light envelope and radiator heating system. The inclination indicates the apartment's capacity to withstand the power cut when compared to the other parameter set-ups. In the 1960s' building, the inclination of the slope is almost the same for all dh intervals and the line is only displaced to a lower level. One explanation for this could be that a heat exchanger had been installed in the LEB and CCB but not in the 1960s' building. As the temperature drops, the temperature transfer rate of the heat recovery system declines, thus increasing the slope. Without a heat exchanger, the drop commences immediately, primarily in the building configurations involving radiators.

3.1.3 Results from limiting the design power

The results from a single simulation are shown in Figure 3.10, to illustrate how the results from all the simulations in the method used were obtained. In Figure 3.10, the temperatures in the two apartments are shown, the gable apartment at the top of the figure, the middle apartment in the middle and at the bottom the corresponding outdoor temperatures, which were the same for all the simulations. These two indoor temperature sets are outputs from one of the 50 simulations with a light construction and a 30 % reduction of the available design power. The gable apartment had a faster temperature drop, due to the lack of power, compared to middle apartment. This was expected as the ratio between heat capacity and loss undoubtedly was higher in the apartment situated in the middle of the building. However, even if the apartments would eventually reach the same indoor temperature drop, the additional internal heat loads from appliances in to the apartments could significantly affect the resulting temperature. In Figure 3.11, the same temperature data, but as hourly averages, is shown, and the days are now shown on the x-axis and the corresponding 24 hours of each day on the y-axis and each hour was assigned a box with a colour-coded temperature.

The next step, shown in Figure 3.12, was to apply the limits to the data and count the number of hours during the month below the different limits. The previously multi-coloured boxes have now been replaced by black and white boxes. The white boxes denote hours during which the chosen limit was not met and the relative number of those boxes was the primary output of each simulation. In the example in Figure 3.12 the gable apartment experienced 185 hours (25 %) below 21.5 °C and 113 hours (15 %) below 21 °C, where the latter is a subset of the former. The hours below the limits associated with the apartment located in the middle of the building were 37 (5 %) below 21.5 °C and 12 (1.5 %) below 21 °C. In Figure 3.13 (light construction) and Figure 3.14 (heavy construction) the results from all the simulations are shown. The y-axis shows the relative amount of time in January that the indoor temperature was below one of the four limits shown on the x-axis. Each of the 50 simulations gave an output represented by a relative amount of time below the different limits. The amount of time below the limits was represented by a percentage of the 774 hours of January. This percentage was affected by the random occupants, and the outcomes are therefore shown as boxplots, and for each parameter combination the minimum temperature is also shown. In Table 3.2, the median values from these boxplots have been extracted and shown. The first general comment to the result is that the apartments with a light construction had a higher probability of having periods below the limits. For example, the median numbers in Table 3.2 for the two different constructions can be compared. Looking first at the gable apartment, a 30 % reduction of available power affected the indoor temperature in a way that 10 % of January would have been below 21 °C for the light construction but only 4 % of the month for the heavy construction. One percent of January is equivalent to about 7.5 hours. With the same reduction in available power, the middle building apartment hardly experience any period below 21 °C. Furthermore, regarding the 40 % reduction, the indoor temperature was at least 0.5 °C below the design temperature for almost half of January in the gable apartments. The corresponding numbers for the middle building apartment were 19 % of the time for the apartment with light construction and 13 % for the apartment with heavy construction.

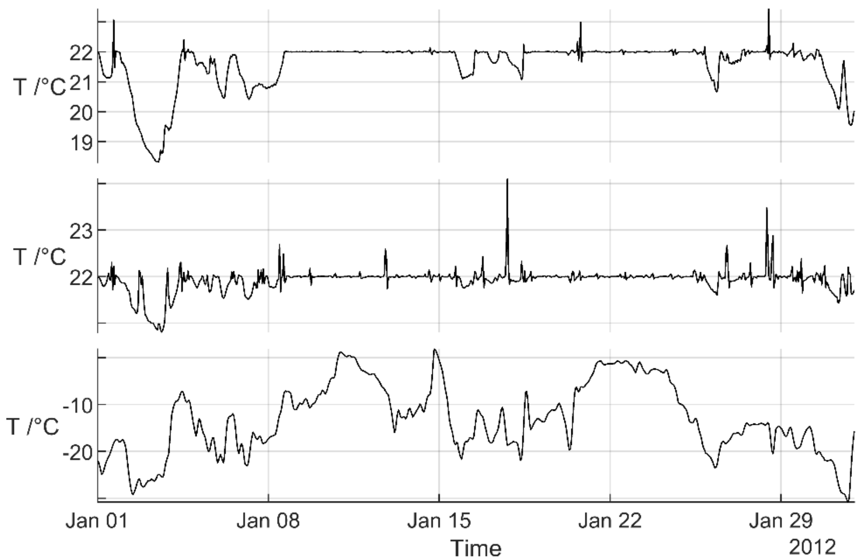

Figure 3.10 Indoor temperatures in the two apartments and the corresponding outdoor temperatures. At the top, the gable apartment with the higher ratio of envelope area to floor area. In the middle, the apartment located in the middle of the building and, at the bottom, the outdoor temperature.

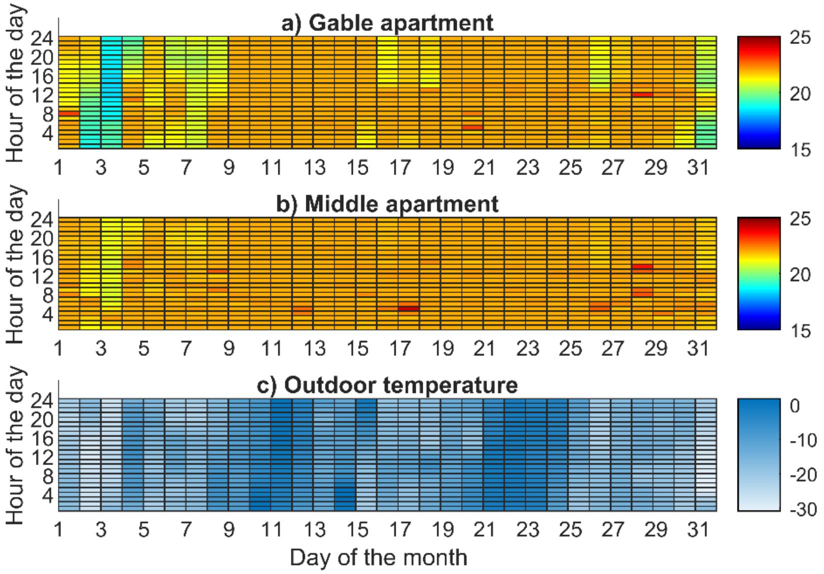

Figure 3.11 Indoor and outdoor temperatures as hourly averages.
The same temperature data as shown in Figure 3.7 but now shown as hourly values and the variations shown with colour.

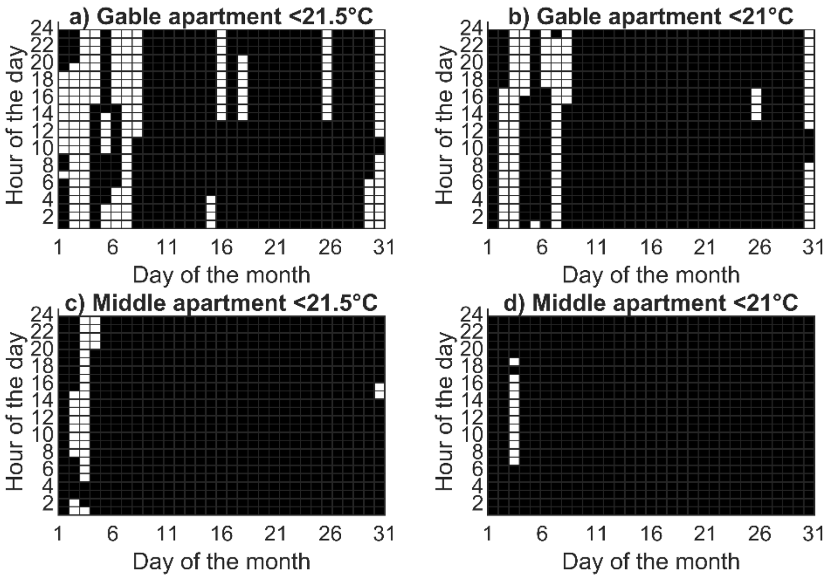

Figure 3.12 Hours in January below a certain temparature limit marked in white.
The hours below the limit of 21.5 °C in a) and c) and below 21 °C in b) and d), marked as white squares. This is an illustrationof the procedure for evaluating the impact of the temperature limitations in which the number of white squares indicated the outcome of a certain simulation.

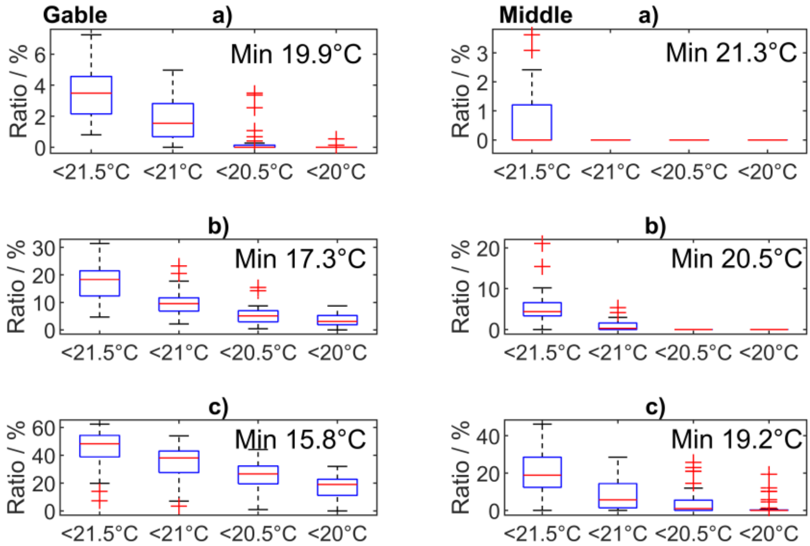

Figure 3.13 Outcome of the power reductions for apartments in buildings with light construction.
The temperature impact shown as the percentage of hours below four different limits for the two apartments. The gable apartment is shown on the left and the middle apartment on the right, with power limitations of a) 20 %, b) 30 % and c) 40 %.

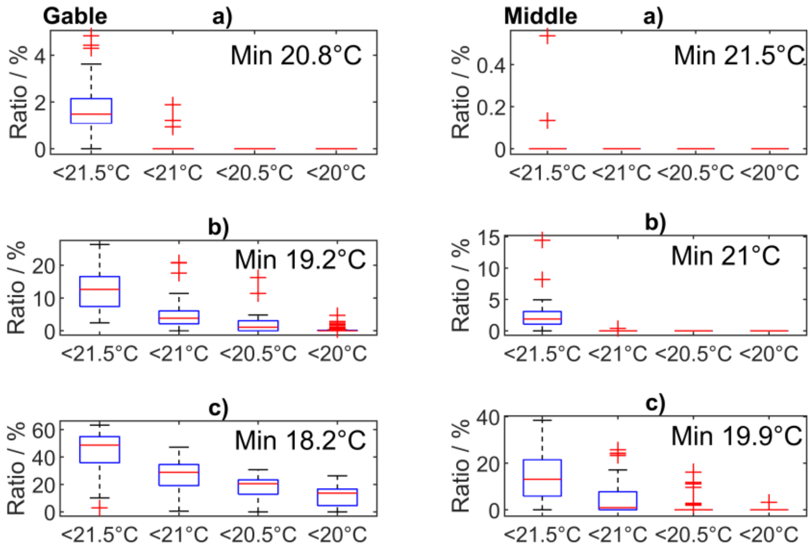

Figure 3.14 Outcome of the power reductions for apartments in buildings with heavy construction
The temperature impact shown as the percentage of hours below four different limits for the two apartments. The gable apartment is shown on the left and the middle apartment on the right, with power limitations of a) 20 %, b) 30 % and c) 40 %.

Table 3.2 Percentages of the periods in January below investigated temperature limits.
Median values from the boxplots in Figure 3.13 and Figure 3.14 in relation to the design power reduction and temperature limits. The percentages in the table are the median percentage of time below the limit for a particular combination of parameters.

	Gable apartment				Middle apartment			
	Light Construction							
Design power reduction	<21.5 °C	<21 °C	<20.5 °C	<20 °C	<21.5 °C	<21 °C	<20.5 °C	<20 °C
-20 %	3 %	2 %	0 %	0 %	0 %	0 %	0 %	0 %
-30 %	18 %	10 %	5 %	3 %	4 %	0 %	0 %	0 %
-40 %	48 %	38 %	27 %	19 %	19 %	6 %	1 %	0 %
	Heavy Construction							
-20 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
-30 %	13 %	4 %	1 %	0 %	2 %	0 %	0 %	0 %
-40 %	49 %	29 %	21 %	14 %	13 %	1 %	0 %	0 %

3.2 Impact on energy and power demand in apartments due to varying occupant behaviour

The impacts of varying occupant behaviours related to energy and power demand were investigated. The impacts of the two variables that were studied individually were those regarding household electricity and domestic hot water. The impact of occupancy was a part of the study when analysing the power reduction schemes. This section is divided into four parts and presents the impacts of the two studied variables on energy and power demand.

3.2.1 Heating energy demand with varying household electricity use

When designing a building for present day use the occupants' use of household electricity is usually modelled based on average users with constant behaviour over the year [57]. The problem in this case is that the possible future occupants might be far from average, i.e. a large part of the stochastic variation is unaccounted for. In this study, the household electricity use by over a thousand households represents these variations and, furthermore, the temporal resolution, represented by constant behaviour in traditional design, is investigated by using hourly data of real use. This is described fully in Paper III. No matter what you wish to investigate regarding the heat balance in a modern low energy building, the variations of this variable will have a more significant impact than in older, less energy-efficient buildings.

Buildings of different sizes and numbers of apartments were modelled and simulated with randomly chosen occupants (household electricity use). For each building and location, 300 simulations were made with randomly chosen occupants, rendering 300 different compositions of occupants with different annual use of household electricity and, subsequently, different needs for space heating. This is shown in Figure 3.15 for a 64-apartment building located in Kiruna. The stochastic variation of the 300 occupant compositions is shown on the x-axis, i.e. how much the annual use could vary. The corresponding heating energy is shown on the y-axis as a function of the building's total annual use of household electricity on the x-axis. As expected, a higher annual average use of household electricity is related to a lower annual calculated heating energy use, which was true for all building sizes and for all tested locations. The heating energy for the building in the example varies from just around 27 $kWh \cdot m^{-2} \cdot a^{-1}$ to just over 34 $kWh \cdot m^{-2} \cdot a^{-1}$, or ± 8 % from the median value.

The temporal resolution was analysed by running the 300 simulations of the example, with five different resolutions. Hourly data compared to monthly and yearly means is shown in Figure 3.15 by using the differently coloured markers. It is obvious that the temporal resolution affects the energy demand as it is based on exactly the same resident compositions, only modelled with different resolution. This is illustrated further in Figure 3.16, in which the differences along the y-axis between the different time resolutions is summarized. The differences caused by the temporal resolutions are smaller than the variations caused by the possibility of having different occupants.

Another important aspect is the impact of the location and building geometry on the degree of utilization of the household electricity, which is shown in Figure 3.17. The relationship between household electricity and heating demand could be expressed as regression lines with different slopes. The magnitudes of declination of these slopes are shown in Figure 3.17. The degree of utilization is the highest for a small building in Kiruna and the lowest for a 16-apartment building in Malmö, by almost a factor of two. The impact of having the right amount of household electricity will, therefore, be higher the colder the outdoor climate is.

In the Swedish building code the energy from domestic appliances (household electricity use) is not part of the energy limited by the regulations. However, it is taken into account when designing the building, in the rather simplified manner described previously. The first question one could ask is whether the heat from appliances can be considered as green energy, as it is basically waste heat from electricity and has therefore already served its purpose and is therefore basically a free gain. In this case, is residual heat from electric appliances better than heat from the building heating system? One could argue that it is so. However, in an apartment it would be hard to cover all heating demands using only internal heat gains. Furthermore, this way of thinking would also reward wasteful behaviour.

On the other hand, for example, we need lighting when it is dark. It is therefore unavoidable that electricity is used and there is no incentive to improve the quality of the appliances if the residual heat provides an acceptable solution. From that point of view, the emergence of LED lighting in our homes is only disadvantageous, according to the present building regulations. It could also be problematic to try and design and optimize for an average household, as an energy conscious family would in fact require more from the heating system.

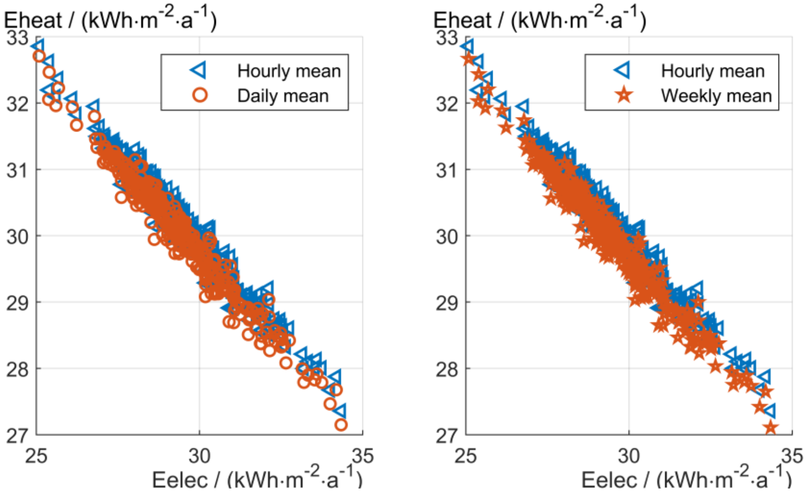

Figure 3.15 Heating energy as a function of household electricity use.
For a building with 64 apartments located in Kiruna, based on the same annual household electricity use. Comparisons between hourly and monthly time resolution, and hourly and yearly time resolution.

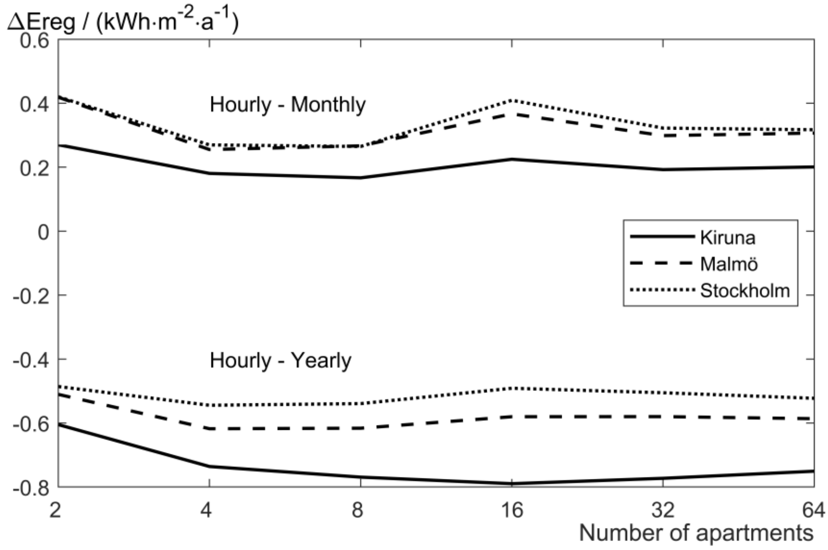

Figure 3.16 Differeces in energy demand between hourly and monthly, and hourly and yearly time resolution. The average differences between energy demand for hourly and monthly average values (the three upper lines), and between hourly and annual average values (the three lower lines) for all building sizes in three locations.

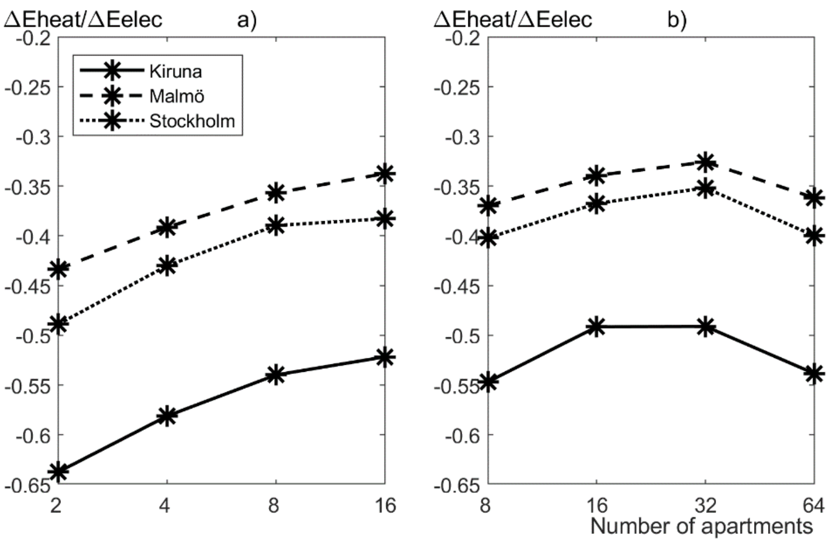

Figure 3.17 Utilization of household electricity for the different generic buildings in the three locations. (a) Distribution of apartments with 3 and 4 rooms and kitchen. (b) Distribution of apartments with 1, 2, and 3 rooms and kitchen.

3.2.2 Heating power demand with varying household electricity use

In this section the impact of varying household electricity use and the space heating power demand is discussed. The chosen aspect of the heating power demand was the annual maximum. In the same manner as for heating energy demand in the previous section, the power demand is now exemplified in Figure 3.18, correlated to the stochastic variation of the household electricity use. The example concerns a semi-detached house simulated in a Stockholm climate. The household electricity was used as input with the same temporal resolutions as described previously and the results from two extremes, the hourly and yearly mean values, are shown in Figure 3.18. It is important to keep in mind that the same 300 occupants are used, with their same annual uses, but modelled using different temporal resolutions. Instead of showing each result with a marker, the results were grouped depending on the annual use of household electricity. The intervals, increasing by increments of 0.5 $kWh \cdot m^{-2} \cdot a^{-1}$, are shown on the x-axis. The median value in each interval is marked with an x, and the vertical lines show the spread between the minimum and maximum values in the interval. The other temporal resolutions, monthly, weekly and daily, all indicated lower maximum heating demands when compared to using the annual mean. Using hourly values can be seen as being closest to reality, which means that reducing the temporal resolution leads to an underestimation of the heating power demand. A difference compared to the case when looking at the energy in connection with varying household electricity is that the temporal resolution can have a similar magnitude of impact as the entire spread in stochastic variation between different households (the x-axis). The black vertical lines show the spread due to temporal variations in each interval.

All the maximum heating powers that were acquired from hourly simulations, with randomized occupants, were gathered and sorted for all building sizes for the Stockholm location and are shown in Figure 3.19. The distribution function for each building size is shown together with the maximum power required to heat the building if no internal heat from household electricity was added. The spread in maximum power demand (height of the distribution functions) decreases with increased building size and the distance from the maximum value of the distribution function to the demand with no internal load increases. This means that there is a possible untapped potential for reducing the size of the heat exchanger for a district heating heated building or the heat pump for larger buildings in which there is a higher probability that occupants are present when it is very cold outside.

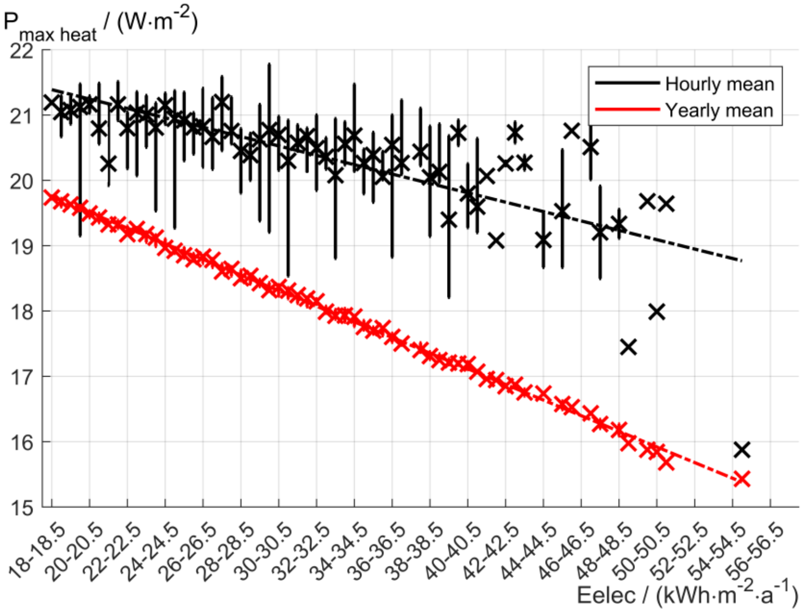

Figure 3.18 Maximum power demand for generic multi-family building (semi-detached house). Simulated using the Stockholm climate as a function of the annual household electricity use for 300 different occupant compositions and two different time resolutions, hourly and yearly. Household electricity use is divided into intervals of 0.5 $kWh \cdot m^{-2} \cdot a^{-1}$, where each cross shows the median within each interval and the bar shows the spread between maximum and minimum value in the interval.

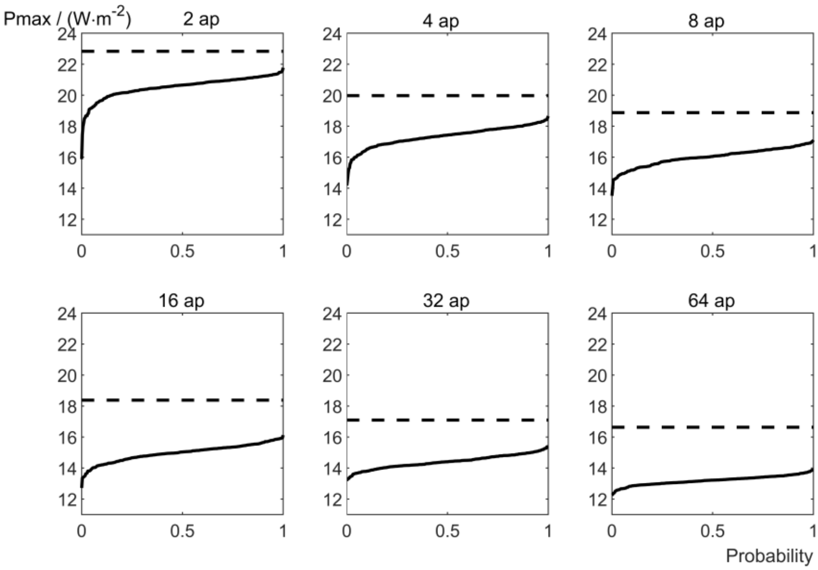

Figure 3.19 The maximum power demand for heating from 300 simulations with random occupants. The building was located in Stockholm and the plots show the order of magnitude of the power demand for each building size (solid lines). The maximum power demand without an internal load from household electricity is shown as dashed lines.

3.2.3 Energy and power demands due to varying domestic hot water use

Figure 3.20 shows the annual measured use of domestic hot water at apartment level during the six years of the study. The median annual use in the years 2008-2012 was 0.35-0.36 m^3_{DHW}/m^2_{UFA} while the median volume for 2013 was slightly higher at 0.39 m^3_{DHW}/m^2_{UFA}. The spread was greater between the median and the upper quartile of the measurement series than between the median and the 25 percentile. About 60 % of the interquartile distance is made up of data between the median and the 75 percentile. This is a reasonable observation as the use can never be lower than zero and the distributions, subsequently, tend to have slightly positive skews. Between 2008 and 2012, average use increased gradually from 0.42 m^3_{DHW}/m^2_{UFA} to 0.44 m^3_{DHW}/m^2_{UFA} and between 2012 and 2013 average use increased from 0.44 m^3_{DHW}/m^2_{UFA} to 0.47 m^3_{DHW}/m^2_{UFA}.

Figure 3.21 shows the domestic hot water use for 2012 for apartments of different sizes. The median annual use of domestic hot water per m^2 usable floor area is almost the same in the one- and four-bedroom apartments but slightly lower in the two- and three-bedroom apartments.

To investigate the maximum hot water flows in buildings with different numbers of households, 300 combinations of users were randomly chosen for each building size. For each of these 300 combinations, the hour, during the year, with the maximum use of hot water was identified and the results are shown in Figure 3.22 both as flows per m^2 usable floor area and flows at building level. The maximum flow at building level naturally increases with increasing number of apartments in the building and the spread of the flow also increases with the number of apartments. The reason is that there is less likelihood that fewer users will use excessive volumes of hot water at the same time. The opposite applies to the flow per m^2 usable floor area.

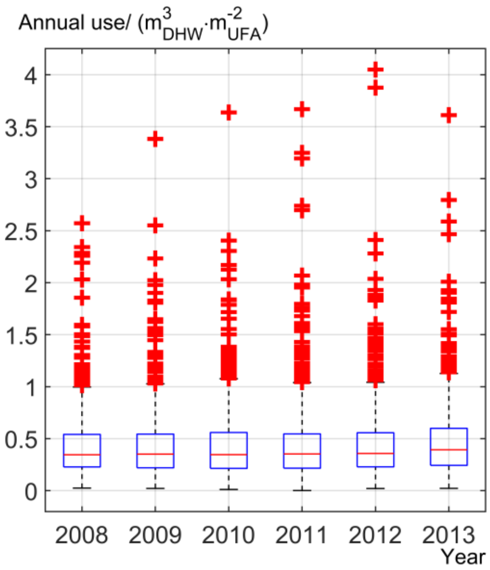

Figure 3.20 The measured use of domestic hot water at apartment level over the studied six-year period.
Subscripts: DHW=Domestic hot water, UFA=Usable floor area

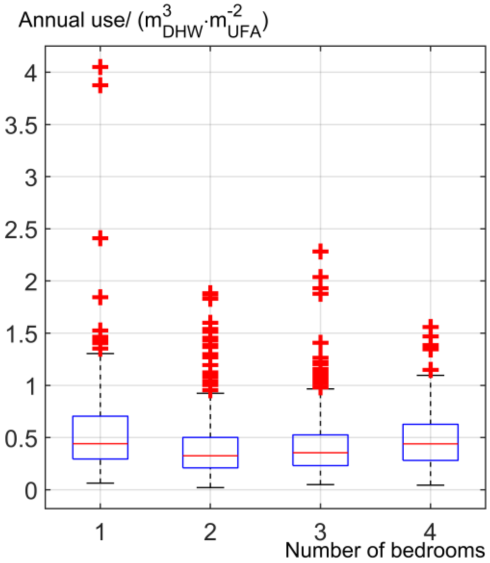

Figure 3.21 The use of domestic hot water in apartments of different sizes
Subscripts: DHW=Domestic hot water, UFA=Usable floor area

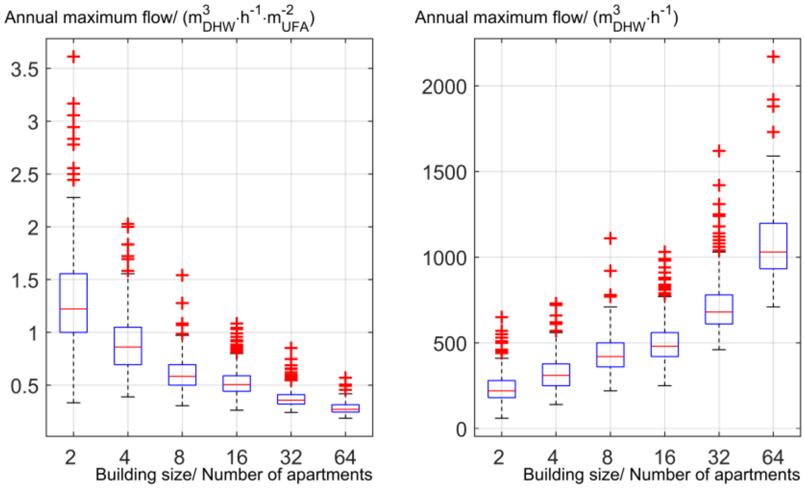

Figure 3.22 Annual maximum hourly flows for 300 different user combinations in generic buildings of different sizes.
Subscripts: DHW=Domestic hot water, UFA=Usable floor area

3.3 Estimating absence using existing measurement data

The estimated number of absence days derived using the baseline method proposed in Paper V are shown as distribution functions and as corresponding boxplots in Figure 3.23. The median period when residents were absent was 10 days and the interquartile range (between the 25 and 75 percentiles) was between 1 and 31 days. In 25 % of the apartments, at least 31 absence days were found while 20 % of the apartments were never found to be empty. Regarding consecutive days of absence, the median value was 4 days and the interquartile range from 1 to 8 days. One interesting finding was that in 20 % of the apartments water was used every day during the entire year and, consequently, no absence days were found. This number of apartments, without any absences, makes it difficult to discard the finding as being a random event or a flaw in the method. Furthermore, it would be quite unlikely to find timer-controlled appliances in apartments that used water.

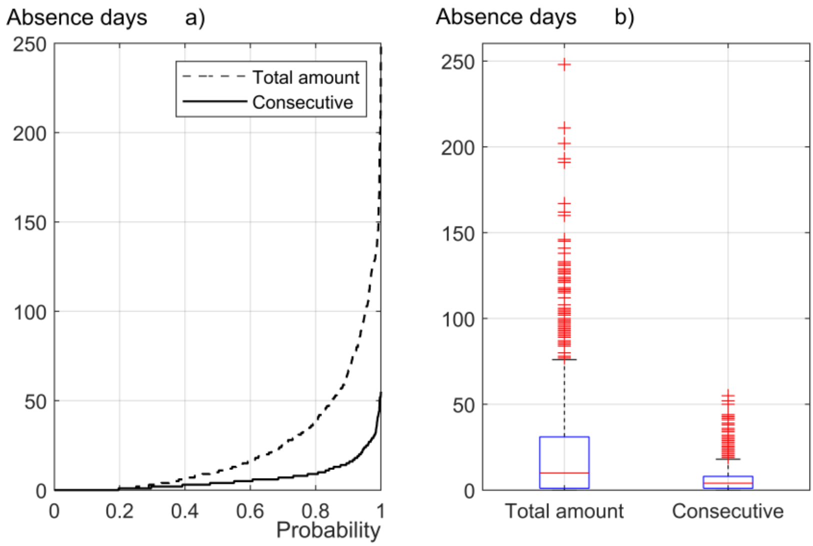

Figure 3.23 a) Distribution functions of the total number of absence days and consecutive absence days. b) the corresponding boxplots.

For verification, three specific dates in 2012 were investigated: Easter Sunday, Midsummer's Eve and Christmas Eve all had significant increases in absences on each of these days. These particular absences can be seen in Figure 3.24 that shows the number of apartments with absence days for each day throughout the year. During the three national holidays at *Easter*, *Midsummer* and *Christmas*, the number of apartments with absence days increased by about 100 apartments. Furthermore, a constant proportion of 4 to 8 % of all the 1005 apartments had absences each day, increasing during the summer months to a level of about 10 to 15 % each day. In Sweden, Saturdays and Sundays are the days when most people are free from work. The hypothesis stated that this could possibly increase the degree of absence, as people would have an opportunity to be away from home. An increase in number of apartments on Saturdays is actually the explanation for the fluctuating pattern visible throughout the year, as seen in Figure 3.24. The fluctuation in numbers comes from approximately 4 to 5 % of the apartments being empty from Sunday to Friday, which then increases by another 4 % on Saturdays.

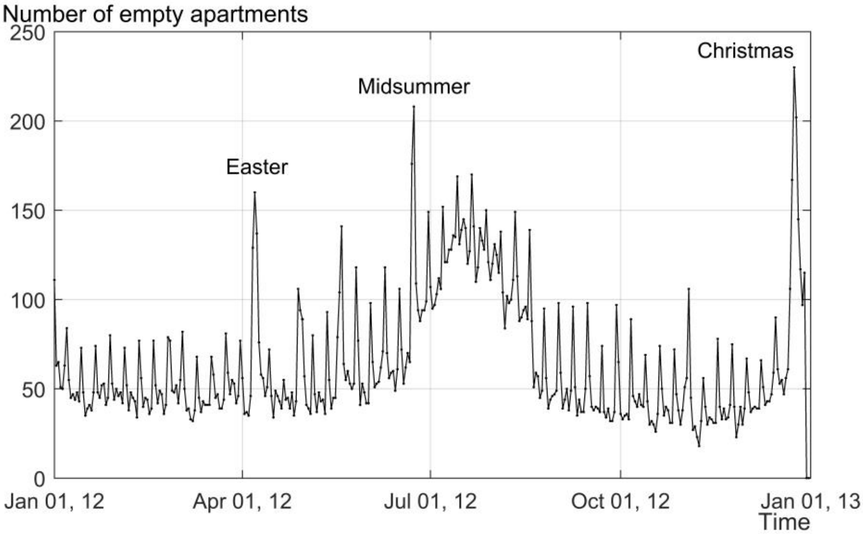

Figure 3.24 Number of apartments, of a total of 1005, with absence days each day over a whole year. The absences during three Swedish national holidays, Easter, Midsummer and Christmas, are easily distinguished.

4 Conclusions

Conclusions from each of the three research questions, stated in Chapter 1, are presented in the context of the overall aims and objectives of the thesis.

4.1 How do varying conditions affect indoor temperatures during heating power reductions?

This research question relates to the aims and objectives when trying to reduce the use of primary energy from non-renewable sources by time shifting power loads on the demand side. This was investigated by carrying out large scale simulations under varying conditions as discussed in Paper I and Paper IV. Additional results are also presented in this thesis with regard to the reduction of power demand. In Paper II, the measured impacts on indoor temperatures following space heating power cuts in two different buildings were analysed and compared to the simulated impacts on the buildings in which the measurements were made.

Analysis of the comparisons between measurements and simulations in Paper II identified a variable that was found to be important, a variable that is not usually modelled in energy simulations in practice although it does impact the rate of indoor temperature drop. The variable was the amount of furniture or other internal mass in addition to that of the structure of the building. The mass of the hydronic-system and the water in it was also an important variable. Despite including these masses, the differences between measurements and simulations could not be fully explained. The temperature drops were even slower in reality than in the models.

In the light of these results, the large-scale simulations were all on the safe side as no internal masses in the apartments were included. Furthermore, an apartment in an upper corner of a building, i.e. a worst-case scenario was investigated, and the results were still promising. In modern buildings there was a very low risk of indoor temperatures dropping by more than 1 °C, as shown in Paper I. In Paper IV the indoor comfort indicator, the PPD-index, was applied and for many combinations of physical building properties and combinations of types of households there was a low risk of reaching the limits of 10 to 15% dissatisfied occupants. All the temperatures that were used for analysis were instantaneous minimum temperatures, which was also a conservative approach. The conclusion from all of these different studies is that for most buildings there is an untapped potential in the building envelope that can be used for time shifting loads, even in the case of a complete power cut for up to eight hours, without a significant risk of causing discomfort for the occupants.

4.2 How does heating power and energy demand vary due to different occupant behaviour?

In buildings with small heating and power demands, the time resolution of the occupant behaviour input data for simulations can play an important role, particularly for the power demand. The investigation in Paper III provides examples of how variations in household electricity use, depending on time resolution and stochastic variation, can affect the energy and power demand for heating. It is not possible to know what type of occupants, with more or less unique usage patterns of household electricity, are likely to move into a building, and the results of this investigation show that heating energy demand can vary by ±40 to 60 % for occupants with uncommonly high or low use patterns and by ±5 to 20 % for the most common 50 % of occupant type combinations. With regard to the maximum power demand, the time resolution used in the model could have resulted in the same magnitude of impact as the stochastic variation in the energy use.

Paper VI shows the varying annual use of domestic hot water and that the use of the 50 % of the occupants closest to the median varied by a factor of two, from 0.25 m^3_{DHW}/m^2_{UFA} for the 25 percentile to over 0.5 m^3_{DHW}/m^2_{UFA} for the 75 percentile. This variation is of the same order of magnitude as twice the amount of energy a low energy building might need for space heating over a year.

4.3 How can occupancy be described using existing measurements of energy and water use?

A new method for estimating entire days of absence using existing measurement data for domestic hot water and cold water use were investigated in Paper V. The method classified an apartment as empty if no water had been used during an entire day.

The method was tested using data from over 1000 apartments in Sweden and the results showed that that median period of absence was 10 days with an interquartile range of 1 to 31 days. The longest continuous period of absence days in the apartments was also investigated and found to be 4 days, as a median, with an interquartile range of 1 to 8 days.

Different quantitative ways of testing the validity of the method were used, for example to see whether the method estimated an increase of absence during national holidays and weekends, with good results. The quantitative data showed an increase in absence during holidays and weekends.

Finally, different methods for estimating absence using measurement data were investigated and compared to the baseline method used in Paper V. This was done to show how well absence could be estimated when measurement data was only available for one of the variables DHW, DCW or household electricity. The use of cold water alone as an indicator of absence gave the best correlation with the baseline method, thus making it the best single variable for the purpose of estimating absence.

5 Future research

In this thesis, time shifting of heating power was investigated and the impacts of this on the indoor temperature have been shown. The impact on the indoor temperature was assessed by showing the probabilities or risks of it dropping a certain number of degrees below the design temperature. Whether these risks or probabilities would be acceptable, or finding economic models that could compensate for discomfort, was not investigated. A topic for future investigation could, therefore, have a more interdisciplinary approach, taking the three conflicting interests into account – functionality, environmental impact and economics. Furthermore, in this thesis, the desired indoor temperatures were assumed to have been constant and identical in all cases, as a result of the temperature drops also being related to the chosen design temperatures. The temperatures occupants actually want, and what they are willing to pay to have different temperatures, would be a very interesting topic for future research.

Advanced software is often used to simulate and optimize advanced building automation systems for in-use operation of a building, in which input data requirements do not necessarily have the same level of detail as the simulation software. Future research regarding the question of optimizing buildings with average use and normal climate, could be directed at analysing the assumed gains of the optimization if the in-use phase was shown to be completely different to that predicted. This thesis shows that the variations in occupant behaviour regarding household electricity are significant and the question could be for how many years in the future any optimization would work and for what type or combination of occupants would it actually be the optimum way of operating the building.

If the goal, when designing and predicting the future energy demand of a building, is to come closer to reflecting reality, this thesis clearly shows that naturally varying occupant behaviour needs to be taken into account. Today, buildings are designed using single value limits for climates that represent a *normal* year and residents who are *average* occupants. The probable outcomes from having many different types of occupants in many different outdoor climates would give a more representative picture of the actual outcomes when designing a building. A future area of research, therefore, could be to evaluate the possibility of refocusing building regulations so that a future building's energy use can be regarded as something that is allowed to have natural variations, and the different ways that these could be taken into account.

Finally, with the previous paragraph in mind, there is a need for more comprehensive reference data regarding occupant behaviour, preferably from a larger, more representative set of households with a higher level of detail. This could mean, for example, gathering data regarding individual plug loads with an even higher time resolution. Another important aspect for future research could be to investigate specific subsets within large datasets, for example, different demographic or socio-economic groups, or geographically related parameters. Yet another subject for future research could be to address the impact of technological advances, in the form of more sophisticated and intelligent appliances, on the demand for space heating

Att ta reda på fakta går sakta, men se saker i stort går fort

- Alf Henriksson

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