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– Methods for Improved Prediction and Verification of Energy Use and Indoor Climate

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– Methods for Improved Prediction and Verification of Energy Use and Indoor Climate

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Doctoral Thesis

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Abstract

Reducing CO_2 emissions is one of the most important goals in Europe as well as the rest of the world. To reach that goal, the use of energy must be reduced. Thus, the building industry is facing a great challenge. Not only energy efficiency but also sustainability is desirable in the building stock. This thesis presents and suggests methods that can be used to improve prediction and verification of building performance regarding energy use and indoor climate.

Predictions of energy use and indoor climate generally do not agree with results from measurements in buildings during operation. These discrepancies are counter-productive to the implementation of energy-efficiency and sustainability measures. This thesis addresses these issues and suggests viable partial-solutions to the problems encountered. This research project has measured several energy use and indoor climate related parameters in multi-family buildings in Sweden. The monitoring was frequent, at least once per hour, and the measurements lasted at least one year, which makes it possible to present reference data for the measured parameters and their variations on different time scales and during different conditions. Based on the analysis of the measurements, several methods offering partial-solutions on different levels to the addressed problems have been developed. Examples of these methods are:

- A method to assess useful solar heat gains in actual buildings during operation.
- A method to assess window airing and air leakage in actual buildings during operation.
- A method to assess occupancy level in actual buildings during operation.
- Methods to generate hourly input data on hygrothermal conditions that take into account both outdoor conditions and user behaviour.
- A method to make meteorological corrections to energy use that takes into account several outdoor climate parameters and the characteristics of the building concerned.

The methods aim to describe reality more accurately and can be applied to predictions and verifications. The methods are fully developed and ready to use in practice. These methods together with the discussion and argumentation in this thesis provide the building sector with useful and positivistic recommendations. If these are used, it is believed that it will be possible to increase the quality of predictions and verifications, and agreement between them, as well as to provide buildings displaying increased sustainability, with low energy use and good indoor climate.

Contents

1 Introduction

The average temperature of the earth has increased by 0.74 °C during the 20th century and the increase per decade was twice as high during the last 50 years compared with the last 100 years. The temperature increase during the 21st century is estimated to between 1.1 and 6.4 °C according to IPCC (2007). The temperature increase is believed to be mostly due to global warming caused by increased greenhouse gas concentrations in the atmosphere. Emissions of greenhouse gases are to a large extent a result of human activities, mostly from CO_2 emissions in connection with the burning of fossil fuels and land use change. Between 1970 and 2004 the CO_2 emissions increased by 80 %. In 2004, the CO_2 emissions represented 77 % of the total green-house gas emissions (IPCC, 2007). It is of global interest to decrease the greenhouse gas emissions to enable a future for the earth as we know it today.

Within the European Union, 32 % of the CO_2 emissions are from energy use in residential and commercial buildings, which use around 40 % of the total final energy use (European Union, 2009). The EU Heads of State and Government set a series of demanding climate and energy targets to be met by 2020 (European Commission, 2010) as follows:

- A reduction in EU greenhouse gas emissions of at least 20 % below 1990 levels;
- 20 % of EU energy consumption to come from renewable resources;
- a 20 % reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.

Sweden will have to reduce its 2005 greenhouse gas emissions by 17 %, excluding sectors included in the carbon emission trading system, before 2020 in order to meet the goal of reducing EU's greenhouse gas emissions by 20 % before 2020 (Commission of the European communities, 2008).

Sweden will have to reduce its 2005 greenhouse gas emissions by 17 %, excluding sectors included in the carbon emission trading system, before 2020 in order to meet the goal of reducing EU's greenhouse gas emissions by 20 % before 2020 (Commission of the European communities, 2008).

Energy use in the dwellings and services sector, which consists of residential buildings, commercial buildings excluding industrial buildings, services buildings, agriculture, street lighting, sewage and power stations, accounts for 36 % of the total energy use in Sweden. Within this sector, 87 % is used in residential and commercial buildings for space heating, domestic hot water heating and operation of installations (Swedish Energy Agency, 2006). According to Klimatberedningen (2008) there is a need for more powerful means of stipulating regulations in the Swedish building regulations, which should also include renovation, if the EU climate goals are to be met.

As a step towards decreasing energy use, and thus carbon dioxide emissions within the European Union, focus has increased on both low-energy buildings and the ability to simulate the energy use of buildings properly, in order to produce buildings that fulfil the requirements for low energy use. According to the recast of the Energy Performance of Buildings Directive, from 2021 all new buildings within the European Union will have to be nearly zero-energy buildings and energy will, to a large extent, have to come from renewable sources. From 2019, this will apply to buildings owned or occupied by public authorities. To produce a nearly zero-energy building, it will probably have to be designed as a zero-energy building, defined as a building in which, 'as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site' (European parliament press service, 2009). The recast also addresses energy efficiency measures in the existing stock when buildings are renovated.

This means that the building industry is facing a great challenge. Energy efficiency has to be significantly improved in new as well as existing buildings. This calls for action from all involved in the building process, from architects and designers to construction workers and operation managers. During the design phase, calculations and simulations of building performance are prerequisites for the analysis of the effects of different designs and systems on the performance of the building and the prediction of the degree of fulfilment of the stipulated requirements. If these predictions of performance are used as a basis for decisions, it is of the greatest importance that they represent the actual building's performance during operation. Otherwise, decisions that affect the building's performance, as well as its economical viability and the environment, might be made based on insufficient information.

Research on the agreement between predicted and actual energy use in residential buildings in Sweden shows that measured use of energy for space heating during operation almost always exceeds predicted use, even in low energy buildings. Elmroth (2002) refers to a number of residential buildings in Stockholm, Sweden, built during the 1990s that have measured energy uses exceeding those predicted by 50 to 100 %. Lindén (2006) studied the energy use at a housing area built in 2001 in Stockholm. The buildings were designed to use no more than 60 kWh/m² annually, including all electricity. During operation, none of the buildings fulfilled that goal. Lindén concluded that the energy restriction set to 60 kWh/m² was impulsive and not based on what could be achieved in reality. Nilsson (2003) studied the energy use in the multi-family dwellings built for the Bo01housing exhibition in Malmö, Sweden, after their first year of operation. The buildings were designed to fulfill a highest total annual energy use requirement, including space heating, domestic hot water, household electricity and common electricity, of 105 kWh/m^2. The actual use was about 50 % higher than predicted. This was partly because an energy simulation tool that was not appropriate for the actual buildings was used during the design phase (Bagge et al, 2006). Karlsson et al (2007) studied energy use in passive houses built in Lindås, Sweden. The measured energy use during operation was 50 % higher than the use predicted during the design phase. According to Karlsson et al. this was partly due to higher indoor temperatures and less efficient heat exchangers than predicted. (Malmö stad, 2010) studied energy use in multi-family buildings at eleven properties in Malmö. The buildings were erected during 2007 and 2008 and were designed to fulfil a highest total annual energy use requirement, including space heating, domestic hot water, household electricity and common electricity, of 120 kWh/m^2. The results showed that none of the properties used less than what was required. On average, the use of heating was 40 % higher than predicted and the use of electricity was on average 18 % higher than predicted.

Computer simulation tools that assess hygrothermal conditions in constructions are becoming available for both research and the building industry. The following references indicate that these assessments might have the same problems, with poor agreement between predictions and actual measurements as discussed regarding energy use. Kalamees and Kurnitsky (2010) studied the dampening effect of hygroscopic materials and concluded that there were considerable differences between simulated values and measured values. According to Rode and Grau (2008), whole-building hygrothermal simulations show that the amplitudes of indoor humidity can be significantly different depending on whether the moisture buffering effect of building materials is included or not.

Karlsson et al. (2007) stressed the importance of accurate input data for the energy simulations of buildings. The behaviour of the user of a building is very important in low-energy buildings and is the hardest to model according to Karlsson et al. (2007). Corrado and Mechri (2009) carried out sensitivity analyses for building energy ratings and found that the five most important factors regarding uncertainties in energy ratings are indoor temperature, air change rate, number of occupants, metabolism rate and equipment heat gains. Burke (2009) highlights that almost all moisture simulation tools make assumptions which may affect their accuracy and the importance of the user of the tool being aware of the tool's limitations. Page et al. (2008) argued that although simulation models are developed to represent the physics of the buildings more and more accurately, the model of the behaviour of the occupiers is too simplified, which leads to errors in predictions. Simulations are often executed using conditions that are not typical for real buildings and, for example, variations in the quality of workmanship are hard to take into account in simulations according to Kalamees et al. (2009). Levin et al. (2011) studied 18 different simulations of the same residential buildings and compared the simulation results to measured energy use in the actual building. The different simulations were carried out by different Swedish consultants who had the same information regarding the building characteristics, for example, drawings and technical systems. Different tools were used by the different consultants. It was found that there was a large spread in the simulation results from the different consultants and an even bigger spread in the input data used, although all had been given the same information about the building. It was concluded that the user of a tool had at least as much impact on the spread of the results as the tool itself and several of the consultants did not even seem able to interpret the results obtained. Another conclusion was that the actual energy performance in the studied buildings was not at all as good as should have been expected, based on drawings and technical systems used.

Almost all factors that affect a building's energy use, affect not only energy use but also the indoor environment and moisture resistance. An example of such a factor is thermal bridges. Thermal bridges typically occurs where different parts of the construction meet, for example, the connection between a wall and the foundations. Thermal bridges increases the conductive heat loss, which results in a higher energy use. At the same time, the internal surface around the thermal bridge will have a lower surface temperature, which can affect the indoor environment by creating poor thermal comfort due to lower operative temperatures, thermal radiation asymmetry and draughts. There is a risk of moisture damage due to condensation on the cold surface around the thermal bridge, which can lead to degradation and mould growth, in turn creating indoor environmental problems and the risk of health problems for the occupant.

Not only energy efficiency but also sustainability is desirable in the building stock. An energy-efficient building that has mould problems after a few years of use is not sustainable. Renovation processes to fix the mould problems might use a lot of energy and occupants might suffer mould-related health problems, which can be costly both for the occupants and society. A systematic method that handles the interaction between energy use, moisture conditions and the indoor environment, through the whole building process, from setting requirements to follow-ups, building operation and management, will be crucial for the quality of the future building stock.

A conclusion drawn from the above is that there is a need for methods that support better prediction and verification of building performance as well as methods that support better agreement between the two. Based on published results, it seems that especially user-related parameters and indoor conditions are uncertain and are believed to explain why prediction and verification differs. If that is the case, better descriptions of these parameters and a better understanding on how they affect building performance should form part of the solution to the problem. There are several studies that have measured and analysed user-related parameters, of which some are presented in the following.

Tso and Yau (2003) studied the daily usage patterns of household electricity in about 1500 households in Hong Kong. Usage was about the same during a 24 hour period, except for a large peak in the evening. No noticeable differences were found between the patterns for weekdays and weekends. Usage was higher during summer than the winter due to the use of air-conditioning to cool the apartments. Riddell and Manson (1995) studied power usage patterns of domestic consumers in New Zealand. It was found that mid-morning and early evening peaks displayed the same trends. Capasso et al (1995) monitored the electricity use in 95 households in Milan. The daily average load profile showed a small peak at eight o'clock in the morning and a bigger peak at eight o'clock in the evening. Usage was least around five o'clock in the morning. After the morning peak, usage stayed at a higher level than at night. Paatero and Lund (2005) monitored use of household electricity in 702 households in Finland. The variations during the day had a large peak around eight o'clock in the evening during both weekdays and weekends. The use increased during the morning but there was no peak. Between mornings and evenings, the use was higher during weekends than weekdays. Common to these different projects was that there were generally two peaks during the day, one during the morning or at noon and one during the evening.

Papakostas et al (1995) monitored domestic hot water heating in four apartment buildings in a Solar Village in Greece. Average domestic hot water use patterns were analysed for each day of the week. During weekdays, the patterns showed equal characteristics. There was one peak during the evening and one at noon. During weekends, the peaks appeared earlier and usage was more uniform. Vine et al (1987) monitored domestic hot water use in four apartment buildings in San Francisco. During a typical day, there was a peak during the morning and another peak in the evening. Different usage patterns were observed for weekdays and weekends. Lech et al. (1996) measured the amount of time spent indoors and Papakostas and Sotiropoulos (1997) studied occupational and energy patterns for 158 families living in the outskirts of Athens, using questionnaires. Occupancy rate patterns during the day were described for different family members and typical families, and activity patterns for different electrical appliances were presented. Kalamees et al. (2006) presented a thorough literature review regarding moisture supply. Common for the previous studies was that the indoor climate had only been studied for shorter periods. Kalamees et al (2006) measured indoor humidity loads in 100 bedrooms and 79 living room in 101 single-family detached houses in Finland during 2002 and 2004. During periods with outdoor temperatures at or below 5˚C, the average moisture supply was 1.8 g/m^3, and during periods with outdoor temperature over 5 ˚C, the average moisture supply was 0.5 g/m^3. The difference between bedrooms and living rooms was small.

Holgersson and Norlén (1984) presented measured indoor temperatures in multi-family dwellings. The indoor temperatures were measured in the living rooms between March and May and the average indoor temperature was 21.8 ˚C. Indoor temperature and relative humidity were measured in 1800 single-family houses and apartments in multi-family buildings in Sweden (Boverket, 2009). Measurements were carried out during two weeks in each house or apartment with measurements every 15 minutes. The two week measurement period started between October 2007 and May 2008 depending on location, which meant that the measured data originates from different measurement periods as well as different geographic locations. The average indoor temperature, relative humidity and moisture supply in the multi-family dwellings were 22.3˚C, 30 % and 1.22 g/m^3 respectively. Distributions between buildings were presented but not distributions during the measurement periods or the relationships to the outdoor temperature. Unfortunately, measurements were only made during the heating season and it is not clear whether their measurement period starting times were evenly distributed between October and May.

Although studies of user-related energy use and indoor climate parameters exist, they might not be applicable to Swedish conditions. Studies made in Sweden are generally based on measurements taken during short measurement periods, which make it impossible to study the measured parameters during different conditions, or from longer measurement periods with low time-resolved measurements, which makes it impossible to study variations during, for example, a single day. As building techniques are continually being developed and user behaviour is continually changing, energy use and indoor conditions probably change over time, which can make results from older studies outdated.

Based on the identified shortcomings presented above, this project has studied, for a whole year, time-resolved measurements of several parameters relating to energy use and indoor climate in multi-family buildings in Sweden. Based on the results of the analyses, several methods offering solutions to the identified problems are described. If these methods are used, it is believed that it will be possible to greatly increase the quality of predictions and verifications, and agreement between them, as well as to provide buildings displaying increased sustainability, with low energy use and good indoor climates.

Examples of the methods presented are:

- A method to assess useful solar heat gains in actual buildings during operation.

- A method to assess window airing and air leakage in actual buildings during operation.

- A method to assess occupancy level in actual buildings during operation.

- Methods to generate hourly input data on hygrothermal conditions that take into account both outdoor conditions and user behaviour.

- A method to make meteorological corrections to energy use that takes into account several outdoor climate parameters and the actual buildings characteristics.

2 Research question

The main problem discussed in this thesis concerns the disagreements between building performance predictions, with respect to energy use and indoor climate, and the verification measurements made during actual use. These issues hinder effective implementation of energy-efficient and sustainable buildings. To correctly analyse the reasons for the deviations between predictions and verifications it is important to understand the processes that precede them and that take place between them.

Figure 2.1 gives an overview of the actions that take place between prediction and verification of building performance. The intention of Figure 2.1 is not to describe the entire picture or to describe every individual action but to put the research question into context and visualize a system.

During the design phase, *predictions* of the building performance are most often carried out with the support of different *tools*, often computer simulations. One reason for predicting building performance is to ensure that it will fulfil requirements. Requirements can be set by legislation, for example, the building requirements, or by the local municipality, the developer or the client. Other reasons for making predictions are to ensure the optimisation of building techniques and building services, and to investigate life cycle cost assessments and optimisations. Based on these *tools* and *predictions*, different structural components, such as walls, and systems, such as for heating and ventilation, are designed. The *tools* and *predictions* require *input data* that is either known or assumed based on *reference data*. The *prediction* of building performance should reflect the *reality* that is subsequently assessed by *measurements* on which *verifications* are then based. There is always a time-span between prediction and verification of performance and during this time the building will have been constructed, inaugurated, operated and managed.

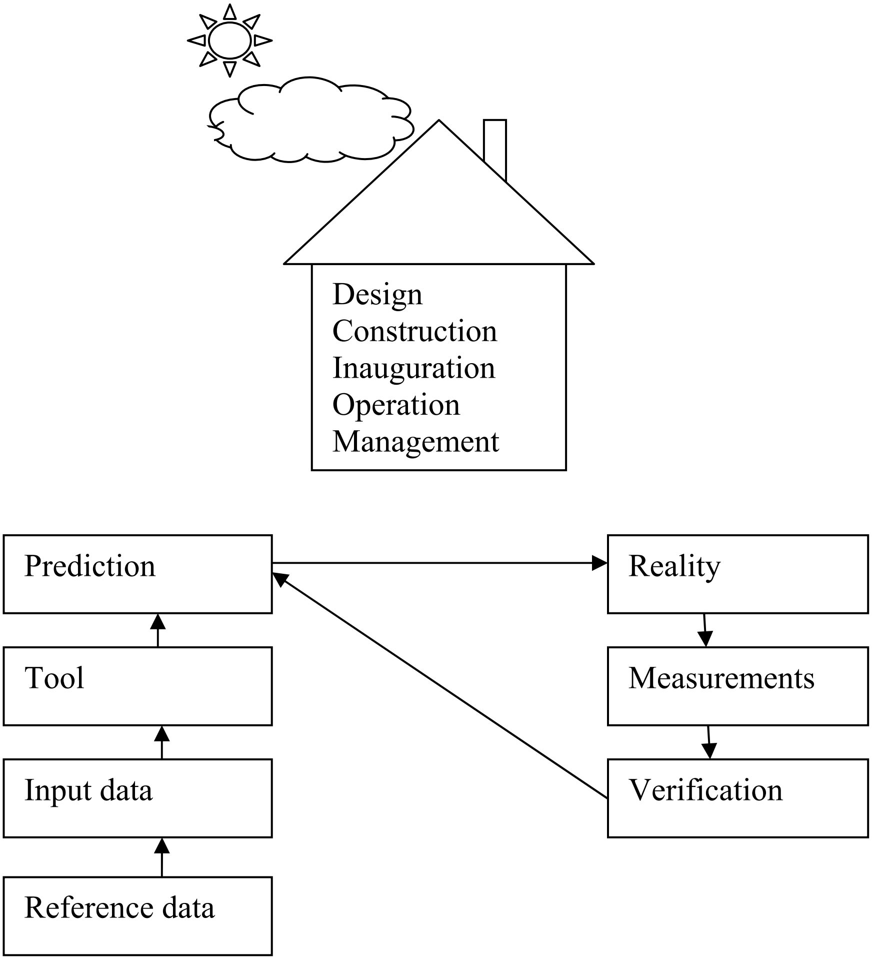


Figure 2.1 Schematic of the operational processes from prediction to verification of building performance.

During each of the described actions and between the actions, sources of possible errors can be identified that might have an impact on whether the *verification* will agree with the *prediction*. Questions to be asked here include:

- Are the requirement outcomes predictable?
- Do tools aid predictions sufficiently well?
- What input-data can the tools handle?
- Is reference data available?
- Is available reference data good enough?
- How is reality measured?
- How can valid verifications be made?
- What happens during the time between prediction and verification?
- How can measurements and verifications be used as feedback?

If these questions can be answered, partially or fully, it is believed that better agreement between prediction and verification can be supported, thereby improving the energy-efficiency and sustainability of buildings. Better agreement is of interest to everyone. From a global perspective, greenhouse gas emissions would decrease. From a societal perspective, the energy systems could be designed more accurately, which would enable better implementation of renewable energy sources and more efficient use of state money. Avoidance of moisture damage would reduce the cost of health-related problems among the occupants and renovation costs. From a business perspective, a product that is predictable would be a safer choice for both the seller and the client. It would also be advantageous if the client could verify that requirements had been fulfilled. The client would probably make better economic decisions regarding investments, if operational costs, for example energy use and maintenance, could be accurately predicted. This would most probably increase investments in energy-efficient and sustainable techniques. From the users' perspectives, a healthy indoor climate would almost certainly improve their quality of life.

2.1 Aims and objectives

The research presented in this thesis aims to provide better insights into several of the identified problems presented in Section 2. This is done by using the results from analyses of time-resolved measurements of a relevant number of energy use and indoor climate related parameters. These parameters were chosen because it is physically possible to measure them in buildings while in operation during long measurement intervals, several years, and with a high time resolution, at least hourly. Another aspect when choosing the parameters was that it would be possible to apply the results from this thesis to measurements in actual buildings and thereby provide the building sector with hands-on and useful recommendations.

The studied parameters were:

- Indoor temperature
- Occupancy level
- Household electricity
- Air leakage heat losses
- Useful solar heat gains
- Indoor relative humidity
- Moisture supply
- Space heating
- Domestic hot water heating

2.2 Dissertation structure

This thesis has nine appended papers. Each paper's relation to the research question and the studied parameters is presented in Section 2.3. Section 3 presents the research method and the measurement cases. In addition to the analyses in the appended papers, Section 4 presents analyses that are based on the results and analyses in the appended papers. Section 5 discusses the overall results in relation to the research question. Finally, Section 6 presents conclusions.

2.3 The appended papers in relation to the research question and the objective

To tackle the research question, see Section 2, a number of studies were carried out and these are presented in the appended papers. Each of the appended papers deals with topics related to one or more actions shown in Figure 2.1. Table 2.1 puts the studies in the appended papers in context in relation to the actions in Figure 2.1. Each paper deals with one or more of the studied parameters and these are shown in Table 2.2.

Table 2.1 The primary references to the actions in Figure 2.1 in the appended papers, AP 1 to AP 8.

	AP 1	AP 2	AP 3	AP 4	AP 5	AP 6	AP 7	AP 8
Prediction	x		x	x		x	x	x
Tool	x	x	x					
Reality								
Measurements		x	x		x	x	x	x
Verification		x	x	x	x	x	x	x
Reference data		x			x	x	x	x
Input-data	x	x			x	x		x

Table 2.2. The primary references to the studied parameters in the appended papers, AP 1 to AP 8.

	AP 1	AP 2	AP 3	AP 4	AP 5	AP 6	AP 7	AP 8
Indoor temperature						x		x
Occupancy level		x						
Household electricity	x			x	x		x	
Domestic hot water				x			x	
Moisture supply						x		x
Relative humidity						x		x
Air leakage heat losses			x					
Useful solar heat gains			x					
Space heating	x		x	x				

2.4 Limitations

The research was based on a number of studied cases. Some of the cases were selected before the project started while others were chosen based on availability and measurement possibilities. The cases chosen based on availability and measurement possibilities should be representative but randomness cannot be guaranteed. There is a huge number of influencing factors that affect parameters related to energy use and indoor climate in buildings. All studied cases were multi-family buildings located in Sweden. No analysis of the statistical strength of the generalizability of measurements was made. The number of cases studied was limited and therefore the descriptive results cannot be considered to be generally valid.

3 Methods

The methodological emphasis of this research has been on measurements of physical parameters in empirical cases. Statistical tools and simulation tools have been used to analyse the measurements. Specific methods used in the appended papers are presented in the respective papers.

When energy use is analysed, the only method that provides reasonable accuracy involves measurements of the physical parameters in a positivistic research approach. Analysis of indoor climate could have been accomplished by questionnaires or interviews. However, a positivistic approach, with measurements of physical parameters, was chosen, as it offers advantages over a hermeneutic approach when it comes to the time resolution and the length of the measurement period, which would limit the use of questionnaires and interviews.

A combination of both hermeneutical and positivistic aspects would have been interesting to use, especially since several of the studied parameters, regarding both energy use and indoor climate, are related to the occupants' behaviour. In this research project, however, focus has been limited to measurements. The positivistic research in this thesis is both descriptive and predictable. This research project has had a broad focus on energy use and indoor climate based on the research question. This differs from some traditional research projects, where a narrow field is analysed in great detail.

3.1 Measurements of energy use

Energy use was measured in buildings built for the international housing exhibition Bo01 in 2001. The exhibition was held in Västra hamnen, in Malmö, in the south of Sweden. This housing exhibition had an ecological and sustainability focus and the area was supposed to be self-supporting regarding energy with 100 percent locally produced renewable energy and there was supposed to be an annual balance of energy supply and energy use in the area (Lövehed, 2005). Several well-known Swedish architects were involved in designing the multi-family dwellings, hence they reflect modern architecture.

Regarding the energy supply systems, heat is mainly generated by a heat pump, which takes heat from an aquifer and from the sea. Solar collectors placed on several of the buildings provide some additional heat. Electricity is primarily generated by a wind turbine, with additional electricity provided by solar electric photovoltaic panels. The heat and electricity production systems in the area are connected to the public grids, through which the buildings get their heat and electricity. By connecting the heating and electricity production systems to the public supply systems, it is possible to use heating and electricity from these systems during days when the energy use of the area is larger than production. Alternatively, during days when production is higher than use, it is possible to deliver heat and electricity to the public supply systems.

To achieve a balance between energy used and produced in the area, all buildings were designed to use a maximum of 105 kWh/m² energy annually including space heating, domestic hot water, common electricity, and household electricity (Quality Programme Bo01, 1999). The developers used different techniques to achieve the restrictions regarding energy use. Before being granted a building permit, the developers had to present calculations that proved that their building's energy use fulfilled the demand of 105 kWh/m². The quality program demanded that the energy used at the properties was measured for two years after inauguration.

Before this research project was formed, the energy use measurements were outlined. The energy use data was collected hourly by E.ON., the energy provider. The resolution level was 1 kWh. Outdoor climate data was available from Heleneholm's weather station in Malmö and bought from SMHI. Measurements presented in this thesis are from 2005.

The building techniques and the characteristics of the buildings in the examined properties have been described by Nilsson (2003) and Nilsson (2006). In seven of the properties, there were both high-rise buildings and terraced houses. In two of the properties there were only high-rise buildings. Table 3.1 presents key data of the buildings in the examined properties regarding number of apartments and floor area, Table 3.2 presents key data regarding heating, ventilation and heat recovery systems. The energy use in the properties during the first years of operation is presented in Nilsson (2003) and Bagge (2007).

Table 3.1 The number of apartments and relevant floor areas in each investigated property.

	Apartments in the high-rise building	Apartments in the terraced house	Total area /m²	Heated floor area excluding garage /m²	Apartment area /m²
Property 1	37	4	7550	5463	4001
Property 2	9	2	1570	1445	1242
Property 3	16	7	4749	3546	2002
Property 4	15	5	4075	2623	1657
Property 5	23	-	6251	3115	2656
Property 6	8	3	1750	1739	1309
Property 7	27	-	4322	3467	2667
Property 8	21	1	3772	2437	2686
Property 9	13	5	3366	2390	1621

Properties 1, 5 and 8 had commercial space. In Property 1 there were two clothes shops, in Property 5 a coffee house and in Property 8 two restaurants and a clothes shop. In Properties 2 and 6, each apartment has its own air handling unit consisting of supply and exhaust air fans and a heat pump. The heat pump primarily heated the domestic hot water and secondarily heated the supply air. In Properties 4 and 9, the supply air to the garage is the extract air from the apartments.

Table 3.2 Characteristics regarding heat distribution system, ventilation system and ventilation heat recovery shown for each property respectively. Electrical heaters in bathrooms could be towel driers and/or underfloor heating.

	Heat distribution system			Ventilation system		Ventilation heat recovery	
	Hydronic radiators	Hydronic underfloor heating	Electrical heaters in bathrooms	Mechanical exhaust air	Mechanical supply and exhaust air	Exhaust air heat pump, space heating	Exhaust air heat pump, domestic hot water
Property 1	x		x	x		x	
Property 2	x		x		x	x	x
Property 3	x		x	x		x	
Property 4	x		x	x			
Property 5		x	x	x		x	
Property 6	x		x		x	x	x
Property 7	x	x		x			
Property 8		x		x			
Property 9	x		x	x			

3.2 Measurements of indoor climate

Indoor climate parameters were measured in 19 cases comprising 351 apartments at four different locations in Sweden, from latitude 56° to latitude 67°. The parameters were measured as building averages. Measuring at a building level meant that many apartments could be studied at a reasonable cost but forced a number of assumptions into the study, increasing the risk of errors and making some analyses impossible. For example, it was not possible to study the effects of window airing and leakage, both of which affect moisture conditions, or occupancy distribution between apartments in a particular building or between individual rooms in a specific apartment.

The parameters measured were carbon dioxide levels in the central exhaust unit and outdoors, ventilation airflow, temperatures in the central exhaust unit and outdoors, and relative humidity in the central exhaust unit and outdoors. Using these parameters, occupancy levels, moisture supply, moisture production and indoor temperatures can be obtained or calculated.

Measurements were taken every 30 minutes to make it possible to obtain daily and weekly time variations. Measurements were carried out during one year to obtain annual time distribution data and to be able to evaluate the method during different outdoor conditions.

The measurements do not give detailed information about levels in each room of each apartment but instead give airflow-weighted averages of the apartment levels for a large number of apartments, which was the aim of the study. This means that it is difficult to know whether a measured value is the airflow-weighted point value at the exhaust devices or if it is the airflow-weighted average value of all the apartments. In fact, it will be a combination of both. By taking the measurements in the main exhaust air duct of residential buildings, a large number of apartments could be included in the study at a reasonable cost and effort, compared with measuring in every individual apartment.

The measurement sensors, for measuring the indoor temperature and relative humidity, were placed before the exhaust fan in the main duct of the exhaust ventilation system. Outdoors, the sensors were positioned so that they were shielded from too much wind and from rain. Temperature, humidity and carbon dioxide concentrations were measured and temperature, wind, solar radiation and relative humidity data was bought from SMHI (2005).

The studied cases are presented in Table 3.3. All the buildings used mechanical exhaust air ventilation. Exhaust air from kitchen stoves was led through the same ducts as the rest of the exhaust air. Exhaust air was, in general, taken from bathrooms and kitchens, and outdoor air inlets were located in bedrooms and living rooms. The measurement period lasted for one year, starting during the summer and autumn in 2008 and continuing until the summer and autumn in 2009.

Table 3.3. Characteristics of the studied cases.

Location	Case	Erected, year	Number of apartments	Number of storeys
Karlstad	1	2005	26	4
	2	2005	23	4
	3	2005	22	4
	4	1964	34	9
	5	1964	36	9
	6	1940	24	2
Kiruna	1	1963	9	3
	2	1963	9	3
	3	1963	12	3
	4	1963	10	3
	5	1963	11	3
Malmö	1	1971	24	8
	2	1971	16	8
	3	1971	16	8
	4	1971	16	8
Sundsvall	1	1969	12	3
	2	1969	18	3
	3	1969	18	3
	4	1969	15	3

4 Additional analysis

To support the solving of the problems identified in the research question, this section presents analysis of the measurements based on combinations of results from the appended papers or as extensions of the results presented in the appended papers.

4.1 Internal heat gains

The characteristics of household electricity were studied in AP 5 and AP 1 and the characteristics of occupancy levels were studied in AP 2. Based on the results from these papers, the total internal heat gains can be described for different times of the year and the day. In multi-family dwellings, it is reasonable to assume that almost all household electricity is converted into heat gains indoors. If outdoor lightning or outdoor infrared heaters are used, heat gains from these will obviously not occur inside the building envelope. If dishwashers and washing machines are used in the apartments and the water is heated by electricity, some of the heat will be evacuated through the sewage pipes. Battery-operated appliances (or even toys) might be charged indoors and then used outdoors. Additional heat gains might have arisen from domestic hot water systems, candles and battery-operated equipment, though these were not studied.

The total internal heat gain pattern during weekdays was calculated for the different seasons of the year. The occupancy level during the different seasons of the year is shown in Figure 1 in AP 2. Heat gain from occupants is assumed to be 100 W per person. The average household electricity heat gain during different seasons is according to Figure 2 in AP 1. The yearly average use of household electricity was set to 5.3 W/m^2 apartment area which is the average in buildings without electric comfort heaters in bathrooms according to AP 5. It is assumed that all household electricity results in heat gain. Table 4.1 presents the seasonal and yearly averages. On average, the heat gain from occupants is a quarter of the total heat gain.

The variation in total heat gains during the day was obtained by superpositioning the heat gains from occupants and household electricity for each season of the year. The seasonal daily pattern for heat gains from occupants was obtained by applying the seasonal pattern according to Figure 4.1, scaled by the corresponding season's average daily span of occupancy according to Table 4.2 and assumed heat gain of 100 W/person. The seasonal daily pattern for household electricity was obtained by applying the daily pattern according to Figure 3 in AP 1 to the seasonal averages according to Table 4.1.

Figures 4.2 to 4.5 show the daily heat gain patterns for occupants, household electricity and the total for the different seasons of the year. Figure 4.5 show the yearly average daily heat gain patterns. During winter, when, typically, there is a space heating demand, the daily average internal heat gains were higher than during other times of the year.

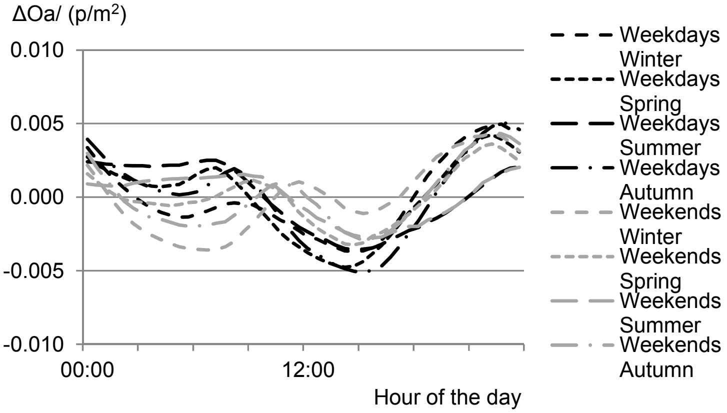


Figure 4.1 Variations in occupancy level, persons per m^2 during the day for different seasons, presented for weekdays and weekends respectively. The presented values are average values of all locations according to AP 2.

Table 4.1 Seasonal and yearly averages of heat gains from occupants and household electricity.

	Occupancy /(W/m^2)	Household electricity /(W/m^2)	Total /(W/m^2)
Year	1.7	5.3	7.1
Winter	2.1	6.6	8.7
Spring	1.8	5.2	7.0
Summer	1.2	4.1	5.3
Autumn	1.9	5.5	7.4

Table 4.2 Daily spans of occupancy and their standard deviations during different seasons, based on the data in Figure 8 in AP 2.

	Occupancy /(persons/m^2)	Standard deviation /(persons/m^2)
Year	0.013	0.007
Winter	0.014	0.007
Spring	0.013	0.007
Summer	0.011	0.005
Autumn	0.014	0.008

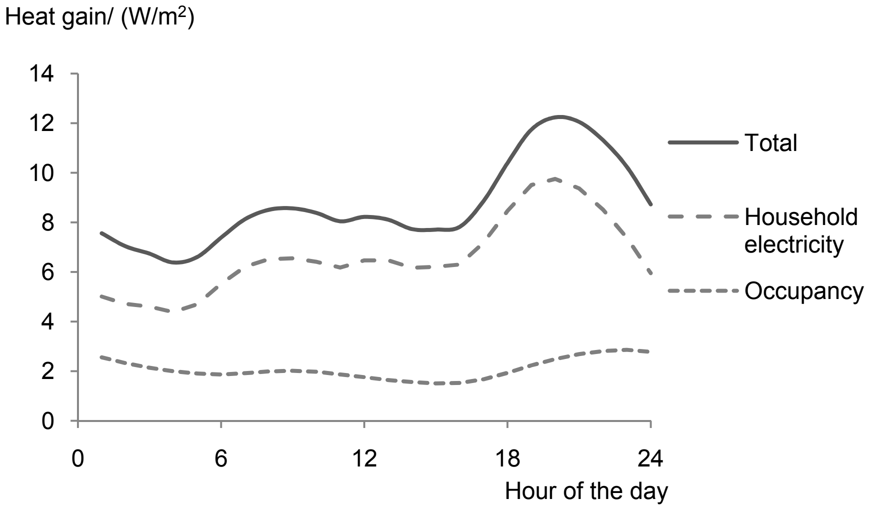


Figure 4.2 Internal heat gain patterns for weekdays during winter. Heat gains from occupants, household electricity and total gains.

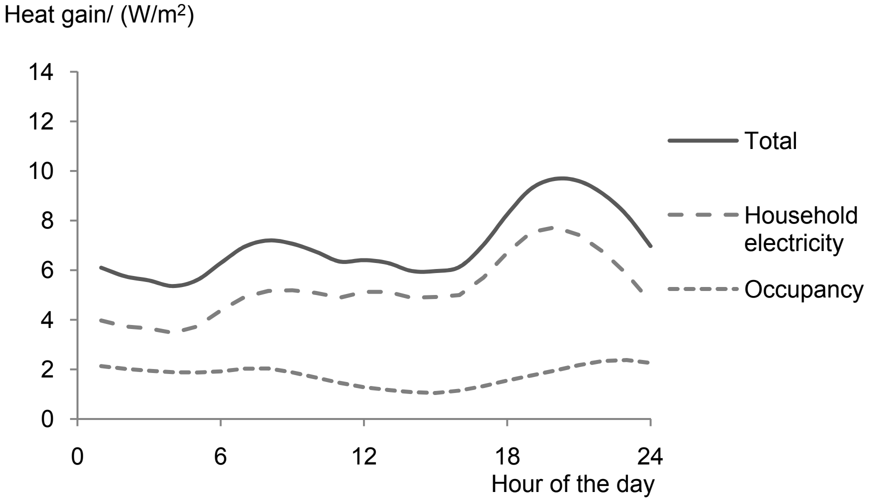


Figure 4.3 Internal heat gain patterns for weekdays during spring. Heat gains from occupants, household electricity and total gains.

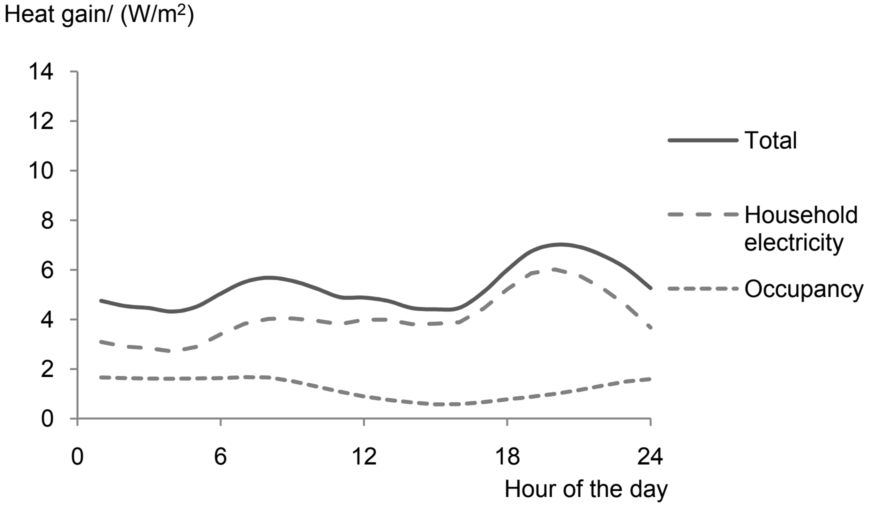


Figure 4.4 Internal heat gain patterns for weekdays during summer. Heat gains from occupants, household electricity and total gains.

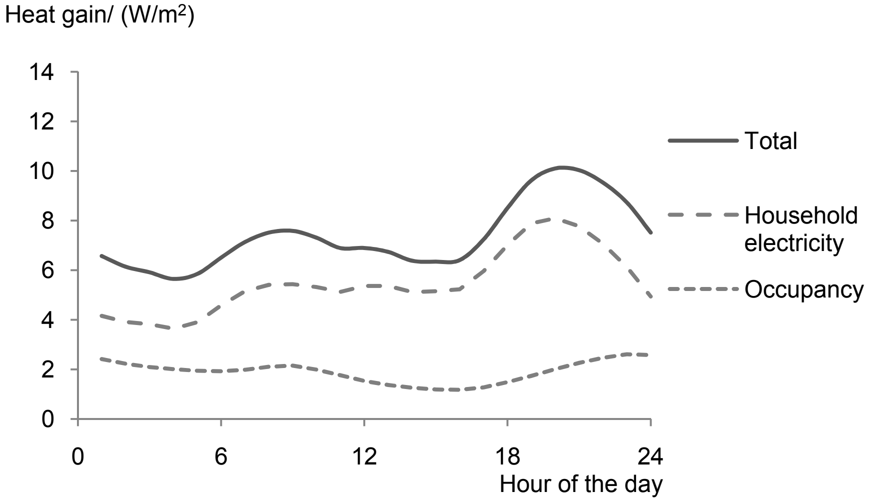


Figure 4.5 Internal heat gain patterns for weekdays during autumn. Heat gains from occupants, household electricity and total gains.

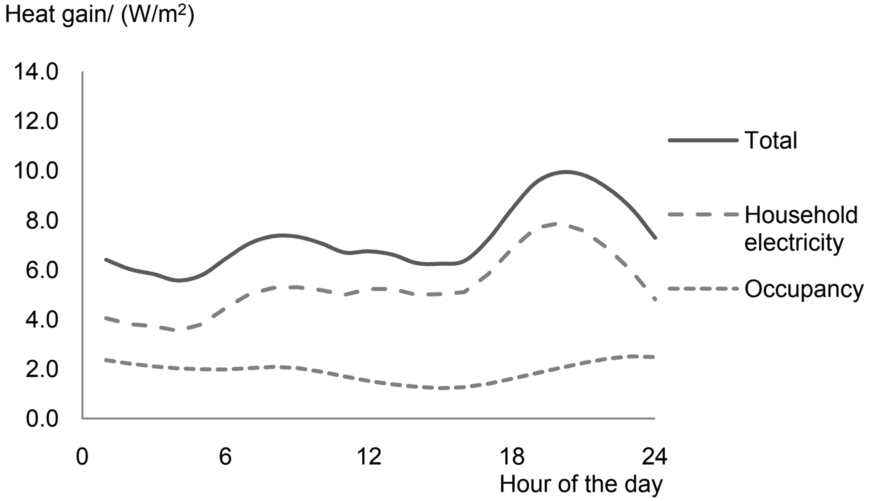


Figure 4.6 Yearly average internal heat gain patterns for weekdays. Heat gains from occupants, household electricity and total gains.

The super-positioning of the heat gains shows that the peaks related to the individual heat gains sometimes amplify and sometimes reduce the peaks of the total heat gain. The daily average span of the total heat gain will not be the sum of the two daily average spans. Table 4.3 shows the daily average spans for the heat gains during different seasons and the yearly average. During all seasons except winter, the daily span of the total heat gain is equal or less than the daily span of the household electricity. The time of peaks for the total heat gain differs slightly from the corresponding times for household electricity. Generally, the peaks occur one or two hours later.

The four total internal heat gain conditions during different seasons of the year presented here can be used to study the average conditions during different seasons. However, according to Figure 1 in AP 2 and Figure 2 in AP 1, the variations during the year are not step functions of different seasons but change continuously.

Table 4.3 Daily spans of internal heat gains.

	Occupancy /(W/m^2)	Household electricity /(W/m^2)	Total /(W/m^2)
Year	1.3	4.3	4.4
Winter	1.4	5.4	5.9
Spring	1.3	4.3	4.3
Summer	1.1	3.3	2.7
Autumn	1.4	4.5	4.5

The method described above for obtaining the total internal heat gain can be used to obtain, based on the presented characterization of measured data, each individual hour’s total internal heat gain, which can be used as input data for energy simulation tools.

An algorithm that gives the hourly values of household electricity use can be described by the following 3 steps:

1. Annual average household electricity power is chosen based on available reference data.
2. Based on the day of the year, the daily average is multiplied by the corresponding percentage in Figure 2 in AP 1 to obtain the daily average.
3. The daily average is distributed during the day according to the daily pattern for a weekday or a weekend according to Figure 3 in AP 5.

An algorithm that gives the hourly values of occupancy level can be described by the following 5 steps:

1. Based on the time of the year, the daily average occupancy level is determined from Figure 1 in AP 2.
2. The daily average occupancy level is corrected based on the characteristics of occupancy level during the week according to Figure 3 in AP 2 and scaled by the weekly span shown in Figure 5 in AP 2.
3. The characteristic of how the occupancy level varies during the day is determined from the patterns in Figure 4.1.
4. Daily patterns in Figure 4.1 are chosen depending on whether it is a weekday or a weekend and which season it is.
5. The daily pattern is scaled so that the differences between the highest and lowest values during the day align with the values shown in Table 4.2 , depending on the season.
6. Each hour of the day's occupancy level is obtained by adding the occupancy level determined by steps 3 to 5 to the daily average occupancy level obtained by steps 1 and 2.

The hourly values generated by these algorithms could be used as input data for energy simulations. If these characteristics are representative on a national level, the above described method and algorithms could be included in energy simulation tools for Swedish conditions. This means that the user would only have to determine the annual use of household electricity and average occupancy level, and the tool would calculate the respective value for each hour.

Figure 4.7 shows the temperature differences that the daily spans during winter correspond to for different building heat loss factors. These temperature differences can be compared with the average differences between the highest and lowest values of the outdoor temperature, 4°C in an outdoor environment in southern Sweden, as discussed in AP 7. The temperature difference of 4°C and the daily span of the total heat gain correspond to a heat loss factor of 1.5 W/(m^2·K). Studied properties that just meet energy requirements in the current building regulations have, in most cases, total heat loss factors of less than 1.5 W/(m^2·K) (Malmö stad, 2010; Bagge, 2007).

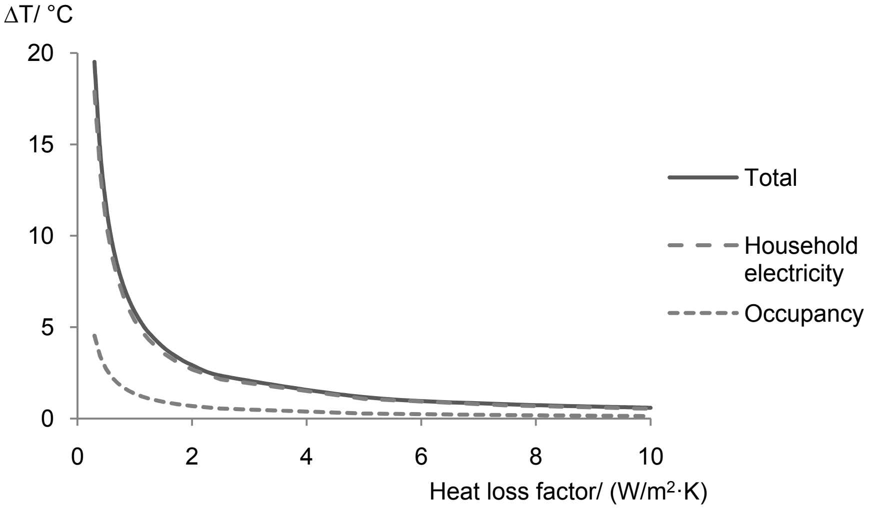


Figure 4.7 Temperature differences for different heat loss factors and daily spans of internal heat gains.

The presented heat gain from household electricity use in this section is from buildings without electric comfort heaters in bathrooms, under-floor heating or towel dryers. If these electric heating sources are used, the use of household electricity increases by about 2000 kWh per apartment per year according to AP 5 and Persson (2005). This corresponds to a yearly average increase of 2 W/m^2 in a 100 m^2 apartment. The increase of 2 W/m^2 is based on the assumption that the comfort heaters are used all year round. If under-floor heating in bathrooms is not used outside the heating season, the increase in household electric power will be higher than 2W/m^2. The increase would be 3 W/m^2 if the heating season is eight months. According to the daily use patterns shown in Figure 3 in AP 5, the relative difference between daily highest and lowest values are the same for buildings with and without electronic comfort heating. This mean that the daily use pattern will have a greater difference between daily top and bottom values and hence would represent higher corresponding temperature differences for different heat loss factors compared with the values presented in Figure 4.7.

4.2 Hygrothermal characteristics of the indoor air

The hygrothermal condition of the indoor air was studied in AP 6 and AP 8. AP 6 presents typical variations of the indoor temperature, moisture supply and relative humidity during the year week and day. AP 8 describes the mentioned parameters as functions of the outdoor temperature and suggests hygrothermal classes based on the measured data as a complement to the corresponding classes in the standards EN 13788 and EN 15026.

It is known that the indoor hygrothermal parameters depend on the outdoor temperature. Besides the outdoor temperature, user behaviour will have an effect on the conditions. The variation during the day, shown in Figures 9 to 14 in AP 6, is believed to depend more on user behaviour than the outdoor temperature. User behaviour might, on the other hand, depend on the outdoor temperature and other outdoor climate parameters. For example, window airing, which increases the air exchange rate, is believed to increase with increasing outdoor temperature and increasing solar heat gains. Also, users might use window airing in the morning, if the bedroom ventilation is not sufficient at night.

The results in AP 6 show that the typical variation during the day varies with the different seasons of the year. It also varies between weekdays and weekends, which is believed to be due to user behaviour and not outdoor climate, since the outdoor climate should not be related to which day of the week it is. According to Figures 3 and 4 in AP 2, the occupancy level is higher during weekends than weekdays. Higher occupancy level should result in higher moisture supply and higher indoor relative humidity. However, according to Figures 6 and 7 in AP 6, neither moisture supply nor relative humidity is higher during weekends than weekdays. One hypothesis is that, for example, the number of showers per person per day does not depend on the time spent at home during the day.

In residential buildings, the indoor hygrothermal conditions during the different hours of the year will depend on both the outdoor conditions and the behaviour of the occupants. Describing the indoor hygrothermal conditions based on a combination of the outdoor temperature and typical variations during the day should give a better description of the conditions compared with describing the conditions based on outdoor temperature only or as typical conditions during different times of the year only. The combination of the two takes into account the parameters dependence on both the outdoor climate and user behaviour.

Based on the proposed hygrothermal classes presented in AP 8 and the typical variations during a weekday during different seasons, presented in AP 6, the typical seasonal weekday patterns are presented as examples of how the conditions vary at different times. The method for obtaining these patterns can be used to obtain the conditions during each hour of the year taking into account the outdoor temperature and the variations during the day, weekday and weekend respectively, for different seasons. In the following, algorithms for obtaining each parameter's hourly value, based on the results given in AP6 and 8, are determined.

The hourly values generated by these algorithms could be used as input data for computer simulations of heat, air and moisture. If it is assumed that these characteristics are representative on a national level, the algorithms could be included in heat, air and moisture simulation tools for Swedish conditions.

4.2.1 Indoor temperature

Figure 4.8 shows the average temperature class T_0 according to Figure 5 in AP 8 and weekday daily patterns for different seasons according to Figure 10 and Table 6 in AP 6.

An algorithm that gives the hourly values of indoor temperature can be described by the following 5 steps:

1. Based on the daily average outdoor temperature, the daily average indoor temperature is determined from Figure 5 in AP 8.
2. The characteristic of how the indoor temperature varies during the day is determined from the patterns in Figure 10 in AP 6.
3. Daily patterns in Figure 10 in AP 6 are chosen depending on whether it is a weekday or a weekend and which season it is.
4. The daily pattern is scaled so that the differences between the highest and lowest values during the day align with the values shown in Table 6 in AP 6, depending on season.
5. The indoor temperature for each hour of the day is obtained by adding the temperature determined by steps 2 to 4 to the daily average indoor temperature obtained in step 1.

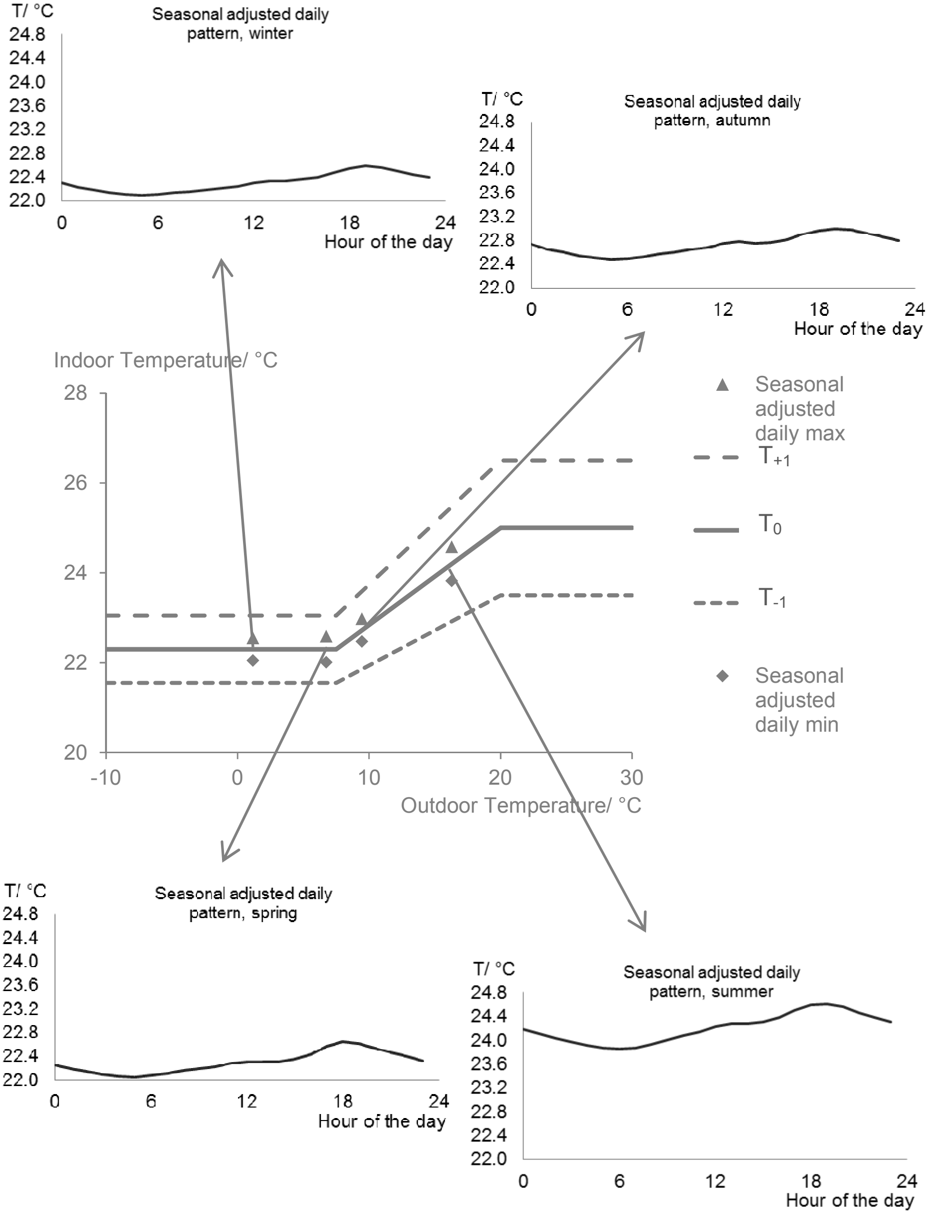


Figure 4.8 Seasonal adjusted daily patterns of indoor temperature for different seasons.

4.2.2 Moisture supply

Figure 4.9 shows the average moisture supply class $v_{sup, 0}$ according to Figure 6 in AP 8 and weekday daily patterns for different seasons according to Figure 14 and Table 6 in AP 6.

An algorithm that gives the hourly values of moisture supply can be described by the following 5 steps:

1. Based on the daily average outdoor temperature, the daily average moisture supply is determined from Figure 5 in AP 8.
2. The characteristic of how the moisture supply varies during the day is determined from the patterns in Figure 14 in AP 6.
3. Daily patterns in Figure 14 in AP 6 are chosen depending on whether it is a weekday or a weekend and which season it is.
4. The daily pattern is scaled so that the differences between highest and lowest values during the day align with the values shown in Table 6 in AP 6, depending on season.
5. The moisture supply for each hour of the day is obtained by adding the temperature determined by steps 2 to 4 to the daily average moisture supply obtained in step 1.

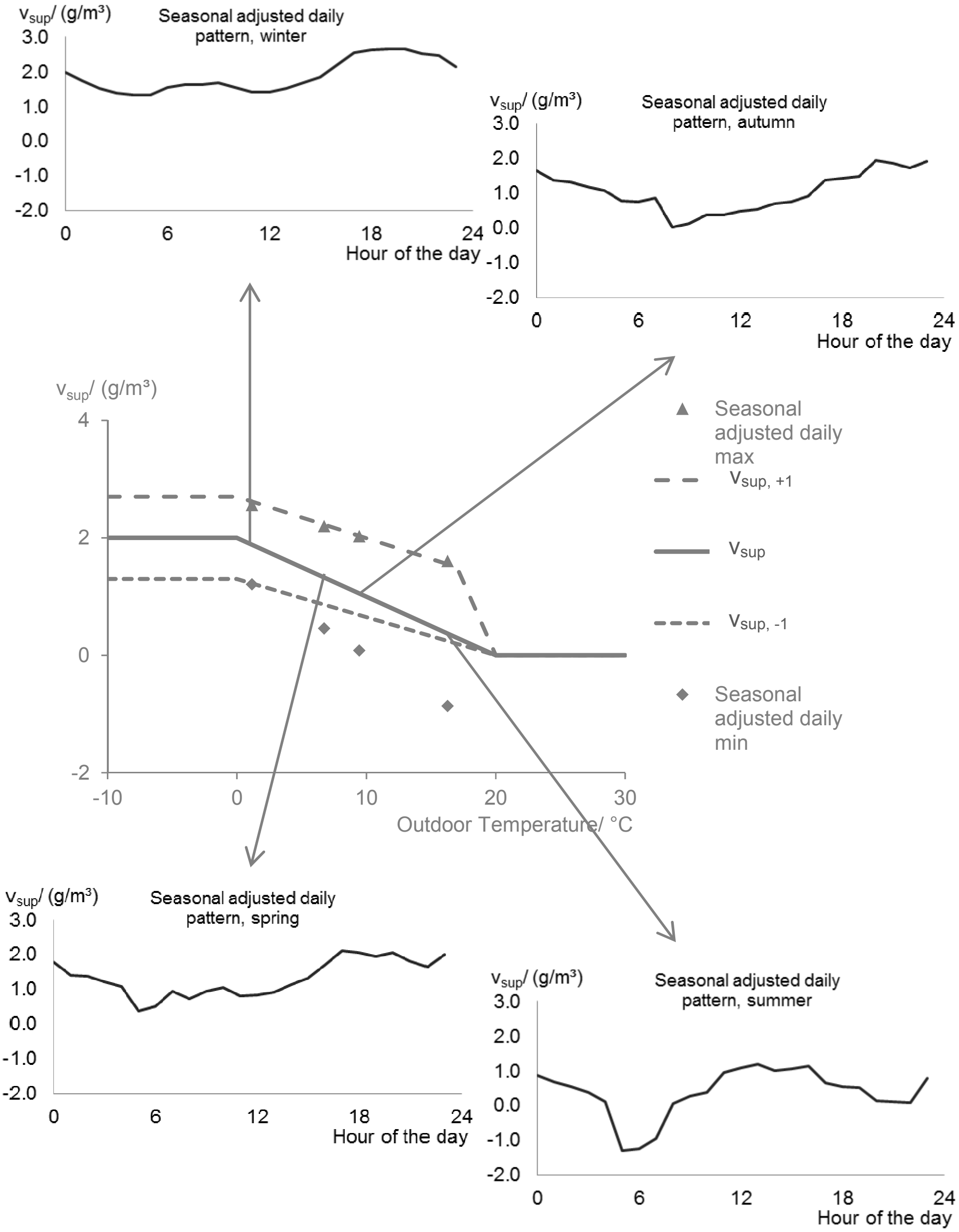


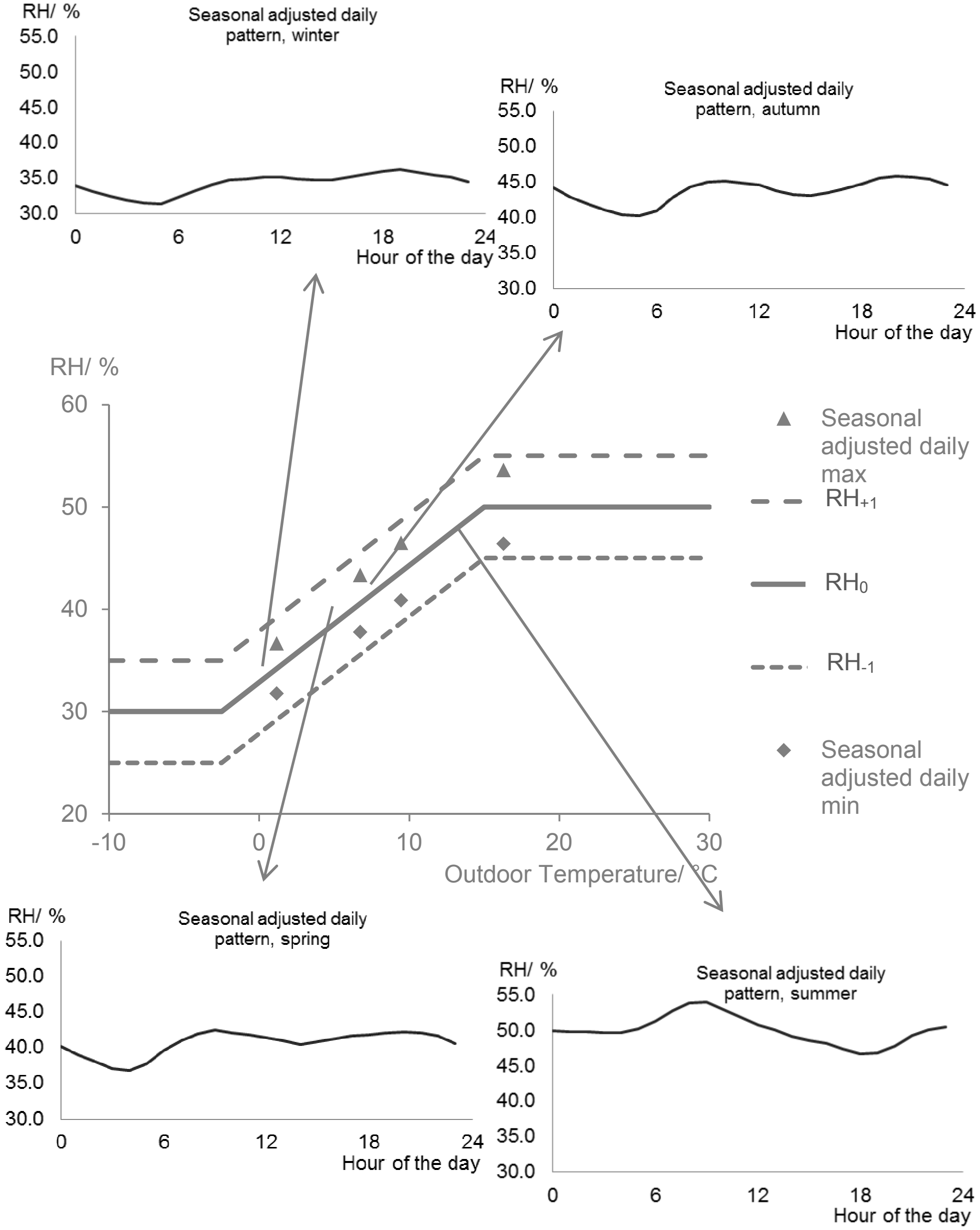
Figure 4.9 Seasonal adjusted daily patterns of moisture supply for different seasons.

4.2.3 Relative humidity

Figure 4.10 shows the average relative humidity class RH_0 according to Figure 7 in AP 8 and weekday daily patterns for different seasons according to Figure 12 and Table 6 in AP 6.

An algorithm that gives the hourly values of relative humidity can be described by the following 5 steps:

1. Based on the daily average outdoor temperature, the daily average relative humidity is determined from Figure 7 in AP 8.
2. The characteristic of how the relative humidity varies during the day is determined from the patterns in Figure 12 in AP 6.
3. Daily patterns in Figure 12 in AP 6 are chosen depending on whether it is a weekday or a weekend and which season it is.
4. The daily pattern is scaled so that the differences between highest and lowest values during the day align with the values shown in Table 6 in AP 6, depending on season.
5. The relative humidity for each hour of the day is obtained by adding the temperature determined by steps 2 through 4 to the daily average moisture supply obtained in step 1.


RH/ %
Seasonal adjusted daily pattern, winter
55.0
50.0
45.0
40.0
35.0
30.0
0
6
12
18
24
Hour of the day
RH/ %
Seasonal adjusted daily pattern, autumn
55.0
50.0
45.0
40.0
35.0
30.0
0
6
12
18
24
Hour of the day
RH/ %
60
50
40
30
20
-10
0
10
20
30
Outdoor Temperature/ °C
▲ Seasonal adjusted daily max
RH+1
RH0
RH-1
◆ Seasonal adjusted daily min
RH/ %
Seasonal adjusted daily pattern, spring
55.0
50.0
45.0
40.0
35.0
30.0
0
6
12
18
24
Hour of the day
RH/ %
Seasonal adjusted daily pattern, summer
55.0
50.0
45.0
40.0
35.0
30.0
0
6
12
18
24
Hour of the day

4.3 Leakage and window airing air exchange rate

Based on the multi-parameter regression analysis in AP 3, leakage and window airing air exchange rates are assessed in this section. AP 3 presents a method to quantify the effect wind speed has on the use of space heating in actual buildings. If the increase in energy use due to wind speed is assumed to be used for heating the air volume related to leakage and window airing, it is possible to calculate the air volume that the energy use corresponds to, if the temperature difference between indoors and outdoors is known. If annual values are used, as presented in AP 3, there is a problem in that the various differences between indoor and outdoor temperature, that the energy use due to air leakage and window airing refers to, are not known. A possible way to assess the air volume would be by calculating the energy use due to air leakage and window airing for small spans in outdoor temperature. This means that the temperature difference between the incoming air and the indoor temperature will be defined more accurately. Therefore, the air volume related to air leakage and window airing is calculated for daily average outdoor temperatures between 0 and 10 °C in steps of 1 °C. A limitation of this method is that the air exchange rate due to temperature differences between indoors and outdoors such as buoyance is neglected due to the independence of wind speed.

Figure 4.11 shows the average daily wind speed and the average daily accumulated global radiation during 2005 at different outdoor temperatures. The presented wind speeds and global radiation are the daily averages at outdoor temperatures between ± 0.5 °C of the presented outdoor temperatures. These outdoor climate parameters are used with the regression equations presented in Table 2 in AP 3 to calculate the air leakage heat losses, Q_{ALHL}, at the different outdoor temperatures according to Equation 1. This is the same method as used in AP 3 but applied to small temperature spans. The leakage and window airing air exchange rate is assessed for Properties 4, 7, 8 and 9, see Table 3.1. These properties were chosen because they used mechanical exhaust air ventilation without heat recovery.

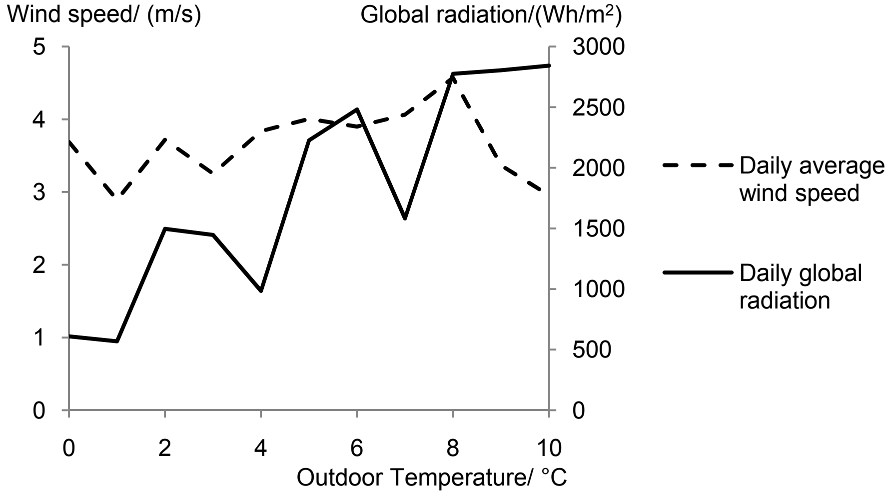


Figure 4.11 Wind speed and global radiation in Malmö during 2005 as functions of the outdoor temperature.

$$Q_{ALHL} = Q_{SH}^{*} - Q_{SH}^{**} \qquad [1]$$

Q_{ALHL}: Daily use of space heating, kWh/day, due to air leakage and window airing.

Q_{SH}*: Daily use of space heating, kWh/day, calculated according to Equation 1 in AP 3 with outdoor climate parameters according to Figure 4.11.

Q_{SH}**: Daily use of space heating, kWh/day, calculated according to Equation 1 in AP 3 with outdoor temperature and daily accumulated global radiation according to Figure 4.11, and daily average wind speed as zero.

The air volume, V_{Air}, that Q_{ALHL} corresponds to was calculated according to Equation 2 for the different outdoor temperatures. The air exchange rate and the actual air leakage including window airing that V_{Air} corresponds to were calculated according to Equation 3 and Equation 4 for the different outdoor temperatures.

$$V_{Air} = \frac{Q_{ALHL}}{(T_{Indoor} - T_{Outdoor}) \cdot \rho \cdot c_p} \quad [2]$$

$$L_{AER} = \frac{V_{Air}}{24 \cdot A_H \cdot h_R} \quad [3]$$

$$L_{Actual} = \frac{V_{Air}}{24 \cdot 3.6 \cdot A_E} \quad [4]$$

V_{Air}	Daily air volume	m^3
L_{AER}	Air leakage and window airing air exchange rate	h^{-1}
L_{Actual}	Actual air leakage and window airing airflow per envelope area	$l/(s \cdot m^2)$
$T_{Outdoor}$	Daily average outdoor temperature	°C
T_{Indoor}	Daily average indoor temperature	°C
A_H	Heated floor area	m^2
A_E	Building envelope area	m^2
h_R	Room height	m
c_p	Specific heat capacity	$kJ/(kg \cdot K)$
ρ	Density	kg/m^3

Heated floor areas in the different properties are given in Table 3.1. The daily average indoor temperatures at different outdoor temperatures were assumed to follow temperature class T_0 in Figure 5 in AP 6 which means that for outdoor temperatures higher than 7.5 °C, the indoor temperature increases with increasing outdoor temperature. The room height was assumed to be 2.6 metres and the ratio between building envelope area and heated floor area was assumed to be 1.4 for all studied buildings.

Figure 4.12 shows the leakage and window airing air exchange rates and the actual leakage in the different properties at different outdoor temperatures

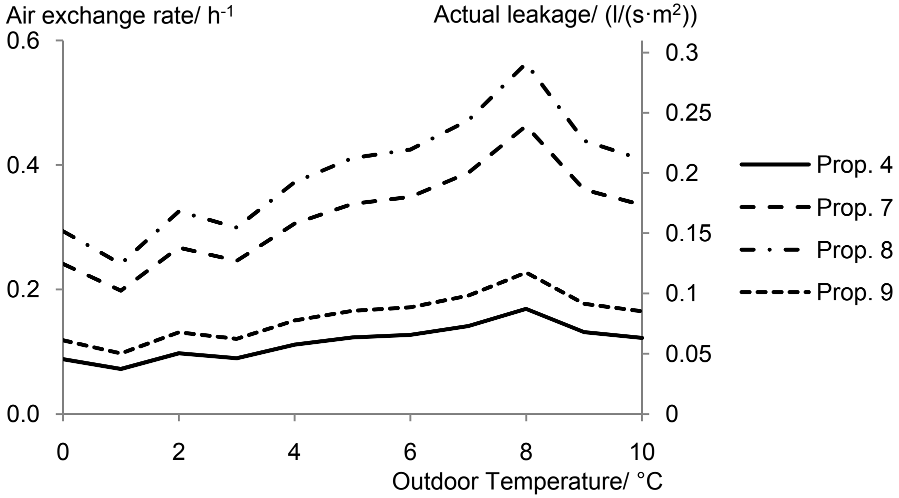


Figure 4.12 Leakage and window airing air exchange rates, and actual leakage at different outdoor temperatures.

The lowest air exchange rate, 0.07 h^{-1}, was in Property 4 at an outdoor temperature of 1 °C and the highest, 0.6 h^{-1}, was in Property 8 at an outdoor temperature of 8 °C. Generally, the air exchange rate increases with increased outdoor temperature and reaches a maximum at an outdoor temperature of 8 °C after which it decreases, which is also the case for daily average wind speed. The average air exchange rate in Properties 4 and 9 was 0.14 h^{-1} and the average actual leakage was 0.07 l/(s·m^2 building envelope). The average air exchange rate in Properties 7 and 8 was 0.35 h^{-1} and the average actual leakage was 0.18 l/(s·m^2 building envelope). In the Swedish building regulations, applicable until 2006 (Boverket 2011:2) which were in force when the studied building were erected, an airtightness of at least 0.8 l/(s·m^2 building envelope) at 50 Pa pressure difference between indoors and outdoors was required for residential buildings. The pressure difference between indoors and outdoors in the studied buildings during operation are not known but are believed to be less than 50 Pa.

The presented method can be used to verify leakage and window airing air exchange rate and actual leakage. A problem with the method is that the calculated air exchange rate can be due to air leakage both through the building envelope and by window airing. Window airing is believed to increase with increasing outdoor temperatures, which would result in increased air change rates with increasing outdoor temperature. If the increased air change rates at higher wind speeds result in decreased thermal comfort for the occupants, for example, because of draughts, the occupants might increase the indoor temperature to compensate. An improvement to the method would be to monitor the indoor temperature, which should increase the accuracy of the calculated leakage air exchange rate. The accuracy of the calculated air exchange rate and actual leakage would, of course, increase, if the specific room height and ratio between heated floor area and building envelope area in each building were also considered. However, the intention was to present a method and not to present reference values on air exchange rates and leakage.

It would be interesting to compare calculated air exchange rates and leakages to results from air tightness tests, for example blower door tests, and leakage detection. If this is done in a sufficient number of buildings, relationships between results from airtightness test and air leakage heat losses and actual leakage air exchange rates can be developed. If window airing is monitored or assessed by questionnaires on a sufficient timescale, this method could be used to assess the increase in energy use due to window airing, which is an uncertain parameter in energy simulations.

A building that was proven airtight by an air pressure test might still have a high actual air leakage, calculated according to the method presented in this section, which indicates that window airing must have been used. This exemplifies how the presented method can be used to investigate the reasons behind an actual energy use not aligning with the predicted use. In some cases, it might be the air exchange rate due to window airing that makes the energy use higher than required and the presented method introduces a way to quantify the effect from window airing and thereby a possibility to explain its effect on energy use in buildings during operation.

4.4 Meteorological corrections to use of space heating

This section analyses how differences in the outdoor temperature, wind speed and global radiation during different years affect annual and monthly use of space heating. The results in AP 3 show that a large portion of the use of space heating can be attributed to and described by outdoor temperature, wind speed and global radiation conditions. The R^2 value for the nine studied properties was on average 0.9 when these three outdoor climate parameters were included in the regression analysis. The R^2 value was 0.68 on average when global radiation and wind speed were excluded in the regression analysis. If it is known how the different outdoor climate parameters vary between different years, the multi-parameter regression equations in AP 3 can be used to study how much impact these variations would have on the use of space heating in the studied buildings, see Properties 1 to 9 in Table 3.1. To do this, outdoor climates from eleven years, 1991 to 2001, were used. The climates were from Lund and are believed to more or less represent the conditions in Malmö, which is located only 20 km away. Daily average conditions were used. Table 4.4 shows the annual averages of outdoor temperature, wind speed and daily accumulated global radiation for these years according to Johansson (2005). To study the impact from each parameter variation individually, two of the parameters were fixed while the third was varied according to the conditions during 1991 to 2001. The fixed parameters were according to the conditions in Malmö during 2005. In this way, eleven climates were obtained for each studied parameter. The 2005 daily average values were used as a baseline as the regression equations in AP 3 are based on the conditions during this year. The climates obtained are semi-synthetic climates based on measurements.

The regression equation, see Table 2 in AP 3, was used for each property, 1 to 9 in Table 3.1, to calculate the annual uses of space heating during different climate conditions, as well as monthly use of space heating during different months of the year. January, April and October were chosen to represent a winter, spring and autumn month respectively. A summer month was not included in this study because space heating is generally not used during the summer.

Table 4.4 Annual averages in Lund for the years 1991 to 2001and in Malmö during 2005.

	Outdoor temperature/ °C	Wind speed/ (m/s)	Daily accumulated global radiation/ (Wh/m^2)
2005	8.9	3.7	2810
1991	8.2	3.1	2521
1992	9.0	3.0	2874
1993	7.7	3.2	2616
1994	8.8	3.3	2774
1995	8.4	3.2	2845
1996	7.0	3.3	2661
1997	8.5	3.1	2821
1998	8.4	3.0	2479
1999	8.9	2.8	2787
2000	9.2	3.5	2705
2001	8.4	3.7	2767

Tables 4.5 to 4.8 show the statistical results regarding the use of space heating. The difference between the maximum and minimum use, $S.H_{max} – S.H_{min}$, in relation to the average use, $S.H_{Avg}$, calculated using the different outdoor climate parameter values, denotes the climate impact, $(S.H_{max} – S.H_{min})/ S.H_{Avg}$), on the use of space heating.

Table 4.5 shows the use of space heating calculated using the average values of all the parameters over all the years. The outdoor climates during the different years had an average impact of 26 % on the use of space heating, which varied between 18 % and 36 % in the different properties. During individual months, the impacts were greater and as much as 73 % on average during October.

Table 4.6 shows the use of space heating calculated using wind speeds and global radiation levels according to the conditions during 2005 and the outdoor temperatures according to the conditions during the period 1991 to 2001. The differences in outdoor temperature during the different years had an average impact of 27 %, which varied between 19 % and 37 % in the different properties, while the impact during October was on average 81 % and during January it was 26 %, slightly less than the annual average climate impact.

Table 4.7 shows the use of space heating calculated using outdoor temperatures and global radiation levels according to the conditions during

2005 and the wind speeds according to the conditions during the period 1991 to 2001. The differences in wind speeds during the different years had an average impact of 5.1 %, which varied between 2.5 % and 9.2 % in the different properties, while the impacts during individual months were greater. During October the average impact was 17 %.

Table 4.8 shows the use of space heating calculated using outdoor temperatures and wind speeds according to the conditions during 2005 and the daily accumulated global radiation level according to the conditions during the period 1991 to 2001. The average impact due to the differences in global radiation during the different years was 1.9 %, which varied between 1.2 % and 2.8 % in the different properties. During January, the average impact was less than the annual impact, while the average impact during October was 16 %.

In all properties, the differences in outdoor temperature during the different years had the strongest impact on the use of space heating, both on annual and monthly timescales. Annually, the impact due to wind speed was, on average, a fifth of the impact due to temperature and the impact due to global radiation was less than half of the impact due to wind. This indicates that, in these properties, on an annual timescale, the differences in wind speed and global radiation during different years have only a small impact on the annual use of space heating.

During October, the impact due to temperature was, on average, 81 % while the impact due to wind and global radiation was 17 % and 5.6 % respectively. During April the relationships were 39 %, 10 % and 16% respectively, which means that global radiation has higher impact than wind. If the use of space heating is assessed at timescales shorter than one year, wind speed and global radiation can have greater impacts than the corresponding annual impacts, which should be taken into account.

The results in Tables 4.5 to 4.8 show that the differences between the impacts in the different properties were of the same magnitude as the differences during different years for all studied parameters. This implies that it is not possible to make meteorological corrections to the use of space heating without taking the specific building’s characteristics, with regard to the dependency of the use of space heating on different outdoor climate parameters, into account. For example, Property 5 and Property 9 had about the same annual use of space heating according to Table 4.7 while the differences in wind speeds over the years had more than twice as much impact on Property 5 than Property 9.

Table 4.5 Statistical results regarding the use of space heating, S.H, calculated using the actual outdoor climate readings during the period 1991 to 2001. All units except for (Max-Min)/Avg are kWh/m^2.

	S.H/(kWh/m^2)	Prop. 1	Prop. 2	Prop. 3	Prop. 4	Prop. 5	Prop. 6	Prop. 7	Prop. 8	Prop. 9
Annual	Avg	56.4	73.8	56.9	76.8	103.5	64.4	174.0	239.8	100.6
	σ	5.1	4.7	3.7	4.6	8.2	4.9	9.3	12.0	5.8
	Min	47.1	66.5	49.5	68.4	89.2	55.3	158.5	222.8	89.8
	Median	55.6	74.2	56.5	77.4	102.1	64.8	175.5	241.3	101.2
	Max	67.4	84.0	64.9	87.0	120.8	75.1	194.5	266.3	113.3
	Max-Min	20.4	17.5	15.4	18.5	31.5	19.8	36.0	43.5	23.5
	(Max-Min)/Avg/%	36	24	27	24	30	31	21	18	23
Jan	Avg	10.2	12.7	9.7	12.0	18.8	11.5	26.2	35.3	16.3
	σ	1.4	1.0	1.0	1.0	2.1	1.1	2.0	2.5	1.3
	Min	8.7	11.4	8.6	10.9	16.3	10.3	23.9	32.5	14.9
	Median	9.6	12.3	9.2	11.6	18.0	11.0	25.4	34.3	15.7
	Max	13.2	15.0	11.9	14.2	23.6	13.9	30.7	41.0	19.2
	Max-Min	4.5	3.6	3.3	3.3	7.3	3.6	6.8	8.5	4.3
	(Max-Min)/Avg/%	44	29	34	28	39	31	26	24	26
April	Avg	3.9	5.7	3.7	6.4	7.4	5.1	14.6	20.7	7.7
	σ	0.7	1.0	0.5	0.8	1.4	0.9	1.7	2.1	1.1
	Min	2.7	4.4	2.9	5.2	5.3	3.8	12.2	17.8	6.2
	Median	4.0	6.0	3.8	6.4	7.6	5.2	14.7	20.7	8.0
	Max	4.9	7.0	4.4	7.5	9.4	6.3	17.1	23.9	9.2
	Max-Min	2.2	2.7	1.6	2.4	4.2	2.5	4.9	6.1	3.0
	(Max-Min)/Avg/%	57	47	41	37	56	49	33	29	39
Oct	Avg	2.7	5.8	3.4	5.7	5.8	4.6	13.5	19.4	7.8
	σ	1.1	1.2	1.0	1.1	2.0	1.2	2.3	2.8	1.5
	Min	1.6	3.9	2.3	4.0	3.3	2.8	9.9	14.9	5.6
	Median	2.6	5.9	3.4	5.9	6.0	4.8	13.8	19.8	8.0
	Max	4.5	7.6	5.1	7.6	9.0	6.6	17.2	24.1	10.2
	Max-Min	2.9	3.7	2.8	3.6	5.7	3.9	7.3	9.2	4.6
	(Max-Min)/Avg/%	108	63	82	63	99	84	54	47	59

Table 4.6 Statistical results regarding the use of space heating, S.H, calculated using fixed wind speeds and global radiation levels, and the actual outdoor temperatures during the period 1991 to 2001. All units except for (Max-Min)/Avg are kWh/m^2.

	S.H/(kWh/m^2)	Prop. 1	Prop. 2	Prop. 3	Prop. 4	Prop. 5	Prop. 6	Prop. 7	Prop. 8	Prop. 9
Annual	Avg	56.0	71.7	56.0	75.7	101.6	63.0	171.3	236.5	98.2
	σ	5.1	4.3	3.8	4.4	7.9	4.7	8.9	11.4	5.5
	Min	46.4	63.3	48.5	66.9	86.1	53.7	154.1	216.4	87.3
	Median	55.5	72.4	55.4	76.3	101.3	63.5	173.3	238.4	98.8
	Max	66.9	81.1	63.9	85.3	118.5	73.1	190.9	261.9	110.2
	Max-Min	20.5	17.8	15.4	18.5	32.4	19.4	36.8	45.5	22.8
	(Max-Min)/Avg/%	37	25	27	24	32	31	21	19	23
Jan	Avg	10.7	13.4	9.9	12.4	20.2	11.8	27.2	36.5	16.8
	σ	1.4	1.0	1.0	1.0	2.1	1.1	2.1	2.6	1.3
	Min	9.4	12.5	9.0	11.5	18.3	10.9	25.3	34.2	15.6
	Median	10.0	12.9	9.4	11.9	19.3	11.4	26.3	35.4	16.2
	Max	13.5	15.4	12.0	14.4	24.4	14.0	31.2	41.6	19.4
	Max-Min	4.1	2.9	3.0	3.0	6.1	3.2	5.9	7.4	3.8
	(Max-Min)/Avg/%	38	22	30	24	30	27	22	20	23
April	Avg	3.7	5.2	3.3	6.1	6.8	4.8	14.1	20.1	7.1
	σ	0.6	0.6	0.4	0.6	1.0	0.7	1.2	1.6	0.8
	Min	2.5	4.2	2.5	5.1	4.9	3.6	12.1	17.6	5.8
	Median	3.9	5.3	3.5	6.2	7.1	4.9	14.2	19.9	7.3
	Max	4.5	6.2	3.8	7.1	8.2	5.8	16.1	22.7	8.3
	Max-Min	2.0	2.0	1.3	2.0	3.3	2.2	4.0	5.0	2.5
	(Max-Min)/Avg/%	53	38	40	33	48	45	28	25	36
Oct	Avg	2.7	5.4	3.3	5.5	5.7	4.4	13.0	18.9	7.4
	σ	1.1	1.3	1.0	1.3	2.0	1.3	2.5	3.2	1.6
	Min	1.2	3.5	1.9	3.6	2.6	2.3	9.2	14.0	5.0
	Median	2.5	5.5	3.3	5.7	5.5	4.5	13.3	19.3	7.6
	Max	4.4	7.3	4.8	7.5	8.8	6.5	16.9	23.8	9.9
	Max-Min	3.2	3.9	3.0	3.9	6.1	4.1	7.7	9.8	5.0
	(Max-Min)/Avg/%	115	72	89	70	108	95	59	52	67

Table 4.7 Statistical results regarding the of use of space heating, S.H, calculated using fixed outdoor temperatures and global radiation levels, and the actual wind speeds during the period 1991 to 2001. All units except for (Max-Min)/Avg are kWh/m^2.

	S.H/(kWh/m^2)	Prop. 1	Prop. 2	Prop. 3	Prop. 4	Prop. 5	Prop. 6	Prop. 7	Prop. 8	Prop. 9
Annual	Avg	53.5	69.6	53.8	73.4	97.2	60.6	166.6	228.7	95.4
	σ	0.6	1.5	0.4	0.7	2.4	0.8	2.0	2.8	1.0
	Min	52.6	67.5	53.3	72.4	93.9	59.5	163.7	224.5	94.1
	Median	53.6	69.2	53.7	73.2	97.1	60.5	166.1	228.1	95.2
	Max	54.9	73.1	54.6	75.0	102.9	62.4	171.4	235.3	97.7
	Max-Min	2.3	5.7	1.3	2.7	9.0	2.9	7.7	10.8	3.6
	(Max-Min)/Avg/%	4.3	8.2	2.5	3.7	9.2	4.7	4.6	4.7	3.8
Jan	Avg	8.5	11.4	8.4	10.7	16.2	10.1	23.7	32.2	14.7
	σ	0.2	0.4	0.1	0.2	0.7	0.2	0.5	0.6	0.2
	Min	7.9	10.5	8.1	10.3	14.5	9.7	22.5	30.8	14.1
	Median	8.5	11.5	8.4	10.8	16.5	10.2	23.9	32.4	14.8
	Max	8.7	11.8	8.5	10.9	17.0	10.3	24.2	32.9	15.0
	Max-Min	0.8	1.3	0.4	0.6	2.5	0.7	1.7	2.1	0.9
	(Max-Min)/Avg/%	10	11	5.0	5.9	16	6.7	7.3	6.6	5.8
April	Avg	2.8	4.6	2.6	5.5	5.3	4.1	13.0	18.8	6.3
	σ	0.1	0.2	0.1	0.1	0.4	0.1	0.3	0.3	0.1
	Min	2.6	4.4	2.5	5.4	4.8	4.0	12.6	18.4	6.2
	Median	2.8	4.6	2.6	5.5	5.3	4.1	13.0	18.8	6.3
	Max	3.1	5.0	2.7	5.7	6.2	4.3	13.5	19.4	6.6
	Max-Min	0.4	0.6	0.2	0.3	1.3	0.3	0.8	1.0	0.4
	(Max-Min)/Avg/%	15	13	8.1	5.5	25	7.8	6.4	5.4	6.4
Oct	Avg	1.9	4.7	2.5	4.7	4.0	3.5	11.5	16.9	6.4
	σ	0.1	0.4	0.1	0.2	0.5	0.2	0.5	0.6	0.2
	Min	1.8	4.3	2.4	4.5	3.4	3.3	10.9	16.3	6.1
	Median	1.8	4.6	2.4	4.7	3.8	3.4	11.4	16.8	6.3
	Max	2.0	5.4	2.6	5.1	5.0	3.9	12.5	18.1	6.9
	Max-Min	0.2	1.1	0.2	0.6	1.6	0.6	1.5	1.9	0.8
	(Max-Min)/Avg/%	13	24	8.7	12	40	17	13	11	12

Table 4.8 Statistical results regarding the use of space heating, S.H, calculated using fixed outdoor temperatures and wind speeds, and the actual daily accumulated global radiation levels during the period 1991 to 2001. All units except for (Max-Min)/Avg are kWh/m^2.

	S.H/(kWh/m^2)	Prop. 1	Prop. 2	Prop. 3	Prop. 4	Prop. 5	Prop. 6	Prop. 7	Prop. 8	Prop. 9
Annual	Avg	53.9	69.7	54.6	73.4	98.0	60.8	166.5	228.9	95.8
	σ	0.2	0.6	0.3	0.3	0.5	0.4	0.7	1.1	0.6
	Min	53.5	68.8	54.1	72.9	97.0	60.1	165.3	227.4	94.7
	Median	53.8	69.8	54.6	73.5	98.1	60.9	166.7	228.9	96.0
	Max	54.2	70.7	55.2	73.9	98.9	61.4	167.7	231.5	96.9
	Max-Min	0.7	2.0	1.0	1.1	1.9	1.4	2.4	4.1	2.2
	(Max-Min)/Avg/%	1.2	2.8	1.9	1.4	1.9	2.3	1.4	1.8	2.3
Jan	Avg	8.9	12.1	8.6	11.1	17.6	10.5	24.6	33.4	15.2
	σ	0.0	0.1	0.1	0.0	0.1	0.0	0.1	0.1	0.1
	Min	8.9	12.0	8.5	11.1	17.5	10.4	24.5	33.2	15.1
	Median	8.9	12.1	8.6	11.1	17.6	10.5	24.6	33.3	15.1
	Max	9.0	12.2	8.7	11.2	17.7	10.6	24.8	33.5	15.3
	Max-Min	0.1	0.2	0.2	0.1	0.2	0.1	0.2	0.3	0.2
	(Max-Min)/Avg/%	1.0	1.6	1.9	0.9	1.4	1.3	0.9	0.8	1.5
April	Avg	3.0	5.2	3.0	5.8	6.0	4.5	13.6	19.5	7.0
	σ	0.1	0.4	0.2	0.2	0.4	0.2	0.4	0.5	0.4
	Min	2.8	4.6	2.6	5.5	5.4	4.1	12.9	18.7	6.3
	Median	3.0	5.2	3.0	5.8	6.1	4.5	13.7	19.6	7.0
	Max	3.1	5.7	3.3	6.1	6.7	4.9	14.2	20.3	7.6
	Max-Min	0.4	1.1	0.7	0.6	1.2	0.8	1.3	1.5	1.3
	(Max-Min)/Avg/%	12	22	23	10	20	17	9.3	7.9	19
Oct	Avg	1.8	4.8	2.6	4.8	3.9	3.6	11.6	17.0	6.6
	σ	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Min	1.7	4.7	2.5	4.7	3.7	3.5	11.4	16.9	6.5
	Median	1.8	4.7	2.6	4.7	3.9	3.6	11.5	16.9	6.6
	Max	1.8	5.0	2.7	4.9	4.0	3.7	11.8	17.3	6.9
	Max-Min	0.1	0.3	0.2	0.2	0.4	0.2	0.4	0.4	0.4
	(Max-Min)/Avg/%	5.7	6.6	7.8	3.4	9.3	6.1	3.0	2.5	5.7

SMHI (2011) describes a method that, in addition to outdoor temperature, takes sun and wind into account, but not how the actual building's energy use depends on these parameters. If the dependency of the building's energy use on the climate parameters is not included in the analysis, the differences between the energy uses at Property 5 and Property 9, during different outdoor climate conditions, would not be correctly assessed and both properties would be assumed to behave in the same manner when subject to the same outdoor climate conditions. In buildings where space heating use increases with increasing wind speed, or where space heating use decreases with increasing global radiation, in addition to increasing with decreasing outdoor temperatures, the outdoor climate parameters – wind speed and global radiation – should be included in the corrections for differences in outdoor climate. These must also take into account how the use of space heating in individual buildings depends on the different outdoor climate parameters.

The use of space heating in energy-efficient and airtight buildings should not be affected by wind speed during the heating season, if the building methods employed and the building services installed can supply the desired indoor climate, which makes window airing unnecessary. If window airing is used, even a very airtight building will have space heating that depends on the wind speed. It can be discussed whether window airing is occupant behaviour or a result of the chosen building method and building services. If it is possible to open the windows and the occupants need to use window airing to obtain the desired indoor climate, window airing should be considered as a part of the operation of the building. For example, a building with large window areas facing east, west or south can have uncomfortably high indoor temperatures even at low outdoor temperatures on sunny days. If the building does not use solar shading or if the solar shading is insufficient, the only means of controlling the indoor temperature is by window airing. Radiators are commonly placed under windows and, if these are open, cold air could flow past the radiator thermostat and register the temperature of the outdoor air instead of the indoor air. In energy-efficient and airtight buildings, it should be possible to make efficient use of solar heat gains. However, solar heat gains cannot be effectively utilized if they result in uncomfortably high indoor temperatures and the need for window airing during the heating season.

With better insulated building envelopes, air tightness and ventilation heat recovery, the increase in use of space heating with increasing temperature difference between indoors and outdoors decreases, which means that internal heat gains can make up for the heat losses during longer periods and thus shorten the heating season. The internal heat gains in residential buildings are typically from occupants and household electricity. If it is assumed that the occupancy level and the use of household electricity varies between years and that these variations affect the use of space heating, the use of space heating during different years should be corrected for differences in internal heat gains in addition to outdoor climate. It is an area of future research to study and analyse typical differences in internal heat gains during different years and their effect on use of space heating.

5 Results and Discussion

The research question, Section 2, deals with the overall problem of predicted building performance, with respect to energy use and indoor climate, not aligning with verifications during operation. Figure 2.1 presented a system of actions that are related to prediction and verification, and the overall problem was broken down to identified problems related to the different actions in Figure 2.1.

Figure 5.1 is the same as Figure 2.1 but with arrows added between actions that take place before and after the construction of the building. The added arrows illustrate that there are interactions between the actions and pinpoint between what actions the results in this thesis are thought to improve with respect to the problems identified in the research question. The results in the appended papers and in Section 4 are discussed based on their connection to the different actions and interactions of actions. Each arrow is discussed in the following subsections.

The aim of the subsections is to exemplify, discuss and put forward ideas about how the results in this thesis can be used at different phases of the building process. Concrete examples of how the results can be used are suggested and the need of future studies and development of methods are discussed. The overall objective is to enable better predictions, verifications and better alignment between the two, which should result in buildings with low use of energy and good indoor climate.

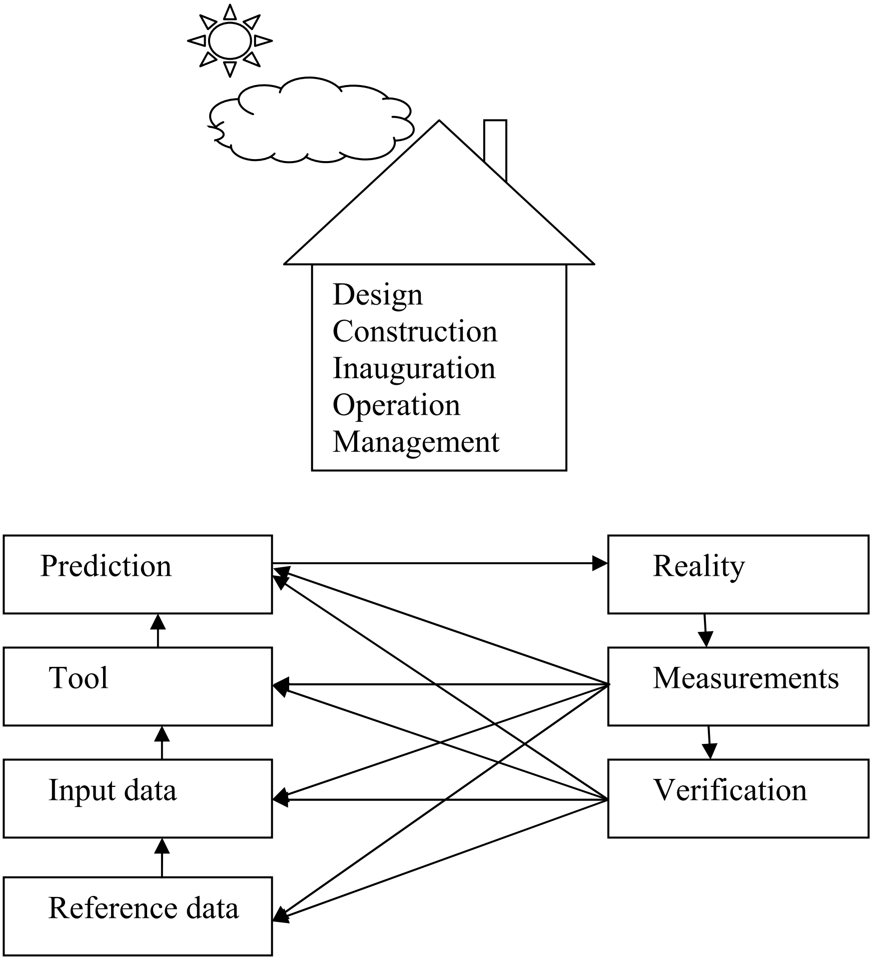


Figure 5.1 Schematic of the process of operations from prediction to verification of building performance and the interactions between actions.

5.1 Tool → Prediction

Predictions of energy use and indoor climate are often based on results from computer simulation tools. The simulation tools should describe the conditions that the building will experience in reality. However, reality is often too complex to describe in a simulation tool, which introduces limitations that might affect the results to different extents. Other limitations of the tool might include the accuracy of the applied physics and numerical solutions. Predictions of building performance based on results from tools need to be judged qualitatively, which might result in that the predicted performance differing from the result from the tool.

According to the Swedish building regulations, it is recommended to use safety factors to assure that the energy use during operation does not exceed the predicted use (Boverket, 2011:1). However, no guidelines regarding the safety factors are given in the building regulations. The results presented in the introduction, Section 1, indicate that, in general, actual energy uses in buildings well exceed predicted levels.

Large differences between the results from a simulation tool and actual performance should put the usefulness of the tool to question, especially if using the tool is time consuming and costly. It is of the greatest importance that simulations are carried out carefully using suitable input data and that there is a critical examination of the results to get realistic predictions. The choice of tool should be based on what is to be assessed. It is important to be aware of the limitations of the tool. This is probably not always the case when tools are used (Nilsson, 2003; Bagge, 2007; Burke 2009; Levin 2011). User-friendly interfaces might make it too easy to achieve colourful presentations of results without knowing the limitations of the tool.

It is important to execute a critically examination of the simulation results and not only look at the final figures at the end of the presentation of results. Most simulation tools present detailed results in addition to the highlighted last figure in the result. A more detailed result can be used to assess the usefulness and accuracy of the result. For example, most energy simulation tools show solar heat gains, which can be compared with the useful solar heat gains in AP 3, as a reference to how buildings during operation assimilate solar heat gains.

5.2 Prediction → Reality

Between prediction and reality there is a timespan that might be several years. During this time span the building is designed, erected, inaugurated, operated and managed. Between prediction and reality, there might have been changes to the design that have affected the building performance and which were not assessed when the building performance was predicted. When changes to the design are decided, these should of course be communicated to the person responsible for predicting the building performance but there is a risk that changes might be have been done without the predictions of energy use and indoor climate being revised. These changes might also have occurred during the construction phase or during operation. If a window breaks during operation, will it be replaced by a window of the same performance or by a cheaper alternative? Several of these changes might have been due to savings in initial costs but could have been due to lack of knowledge of the effects that different types of changes have on building performance. Many of these changes can be observed and documented in the building. Examples of changes that that might be harder to observe after the building has been erected include type of insulation used and the occurrence of thermal bridges.

The results presented in (Malmö stad, 2010) show that, between prediction and reality, almost all the studied properties had been subjected to changes which could affect energy use and indoor climate. Some of these changes ought to have resulted in higher energy uses than those predicted while some ought to have resulted in lower energy uses. In some cases, windows with better thermal performance had been chosen. In reality, the buildings used more energy than predicted.

In reality, a building is operated and managed. Ventilation air exchange rates during operation might differ from predictions due to the management wanting a different air exchange rate or the occupants adjusting the air devices. In several cases, the heating control system has not been set up correctly (Malmö stad, 2010; Bagge et al, 2004). Maintenance of the building services and technical systems might not have been as frequent as desired. Another, commonly discussed, problem concerns indoor temperatures being higher than predicted. This ‘problem’ could instead be expressed as: There is a problem when those responsible for energy simulations make erroneous assumptions regarding indoor temperatures. These assumptions would probably be better if sufficient reference data regarding indoor temperatures was available and used.

The changes that occur between prediction and reality could be summarized in a safety factor corresponding to the effect that the changes have on predictions of performance. However, a safety factor including everything that might occur would probably be unrealistically high. A building process with good communication between the professionals at the design phase combined with a construction process that interacts with the designers, to ensure that what is built is in accordance with what has been designed, can probably decrease the uncertainty of what might happen between prediction and reality. If, during the construction phase, for example, another window type is suggested, the designers should be consulted and the suggested window's effect on the building performance investigated before a decision is made. The construction work needs to be carefully done, so that the different elements of the building and the technical systems match the design data, and the operation of the buildings technical systems needs to be carefully managed to make reality align with prediction.

5.3 Input data → Tool

Choosing appropriate input-data is as important as choosing the appropriate tool. Different tools require different input data but, generally, when energy use and indoor climate is assessed, the input data can be divided into the following groups:

- Building envelope and building technology
- Heating- and ventilation systems
- Outdoor conditions
- Indoor conditions

As buildings are getting more and more energy-efficient, it is becoming more and more important to assess the indoor conditions in order to correctly simulate the space heating demand. This is evident in so-called 'passive houses', which are designed to use internal heat gains as the primary heating system.

5.3.1 Different conditions at different times

How the performance of the building envelope, building technology and heating and ventilation systems change with time has not been studied in this research. However, it is assumed that these changes are slower than and not as cyclic as the changes in indoor and outdoor conditions that change with time, although on different time scales. The outdoor conditions vary during the year and during the day and the indoor conditions vary with outdoor conditions and the time of the year, week and day. The indoor conditions are also believed to depend to a certain extent on the behaviour of the building users.

Different commonly available energy simulation tools allow the use of different levels of detail in input data. In some simple tools, it is not possible to use more detailed input data regarding indoor conditions than annual averages (Isover, 2011, Equa, 2011), while some other tools are more or less restricted when it comes to describing a limited number of different conditions (Strusoft, 2011). If these tools are used, it is important to know the effects due to these limitations when the results are interpreted.

AP 1 analyses how different levels of details regarding the use of household electricity, a major source of internal heat gain, affects calculated use of space heating. Due to the variations during the year and the day, the internal heat gains from household electricity use will vary with the time of day and the time of year. It was found that, depending on how detailed the input data regarding use of household electricity was described, that this affected the calculated use of space heating. The most detailed description used took into account both the variations during the day and the year while less detailed descriptions only took into account the variations during the day only or the year only. The simplest description used was as a constant use all year round. If the use of household electricity was assumed to vary during the year, the calculated use of space heating was less than when constant use was assumed. The opposite applies if it was assumed to vary during the day. If it was assumed to vary during both the year and the day, the calculated use of space heating was higher than calculated when using an assumed yearly variation but less than calculated when using an assumed constant use.

When deciding how detailed the description of the input data should be for a specific simulation situation, it is important to have knowledge of how different levels of detail affect the results. For example, a consultant might think that the accuracy of a simulation is improved by describing the use of household electricity as varying during the year, rather than constant, without being aware that the use of space heating is often underestimated, if the variations during the day are neglected. The same applies if the use is assumed to vary during the day, which nearly always results in overestimation of use of space heating.

The above discussion deals with simulations of energy use but it is probably also applicable to simulations of hygrothermal conditions. The effects due to different levels of detail in the description of the indoor conditions on the results from hygrothermal simulations could be investigated with a similar method as used in AP 1.

It is an area of future research to study how the variations in indoor conditions affect energy use and hygrothermal conditions in real buildings of different types during operation. This should provide knowledge regarding when different levels of detailed input-data are appropriate for different cases. It should be possible to develop a qualitative method to choose the level of detail based on what is being assessed. Section 4.1 compares the differences in temperature during the day with how the differences in heat gains from household electricity during the day correspond to different heat loss factors, see Figure 4.6. It was found that the difference in heat gain from household electricity during the day for a heat loss factor of 1.5 W $(m^2 \cdot K)$ corresponds to the average difference in outdoor temperature during the day in a winter climate in southern Sweden. This can be interpreted as that it is at least as important to take daily variations in household electricity use into account as daily variations in outdoor temperature when simulating the use of space heating in buildings with a loss factor less than 1.5 W $(m^2 \cdot K)$.

5.3.2 Different conditions at different places

It is most likely that the indoor temperatures in different apartments in a multi-family building will not be exactly the same and it is most likely that the average indoor temperatures in different residential buildings will not be exactly the same. If the indoor conditions in a real case are exactly the same as in the predicted case it is probably because of luck. If assumed values in predictions are average values based on measurements from many buildings or apartments, the average value is accompanied by a statistical spread around that average. If the building performance is influenced by the indoor conditions, it might be appropriate to assess the performance with input data that is above and below, for example plus one and minus one standard deviation, the average would then show the impact from known variations in different parameters. To find worst cases, different combinations of variations in parameters should be assessed. For example, low use of household electricity and high indoor temperature. Based on known descriptive statistics of the parameters, the simulation tool could vary the indoor conditions to obtain predictions for different conditions. This could be included as a standard procedure in simulation tools to enable a more comprehendible result. The results in AP 1 show that if the use of household electricity is decreased then the use of space heating is increased by 60 % of the decrease in household electricity use. This is a typical example of the result of a sensitivity analysis that could be carried out for each parameter's effect on the different parts of the system and on the system as whole. The same applies to outdoor climates, which should be varied according to statistics to show how different outdoor conditions affect the performance. Section 4.4 shows that the performance can vary with outdoor climate. Knowing between which values the performance will vary due to typically differences in outdoor- and indoor-conditions might provide a more comprehensive result than the performance during a typical year. This would illustrate how the building would operate during dynamic conditions and would probably also support interpretation of verification measurements. AP 2 presents descriptive statistics on occupancy levels and AP 6 and AP 8 present descriptive statistics regarding indoor temperature, moisture supply and relative humidity.

This section, Section 5.3, can be summarized by the maxim “garbage in, garbage out”. If tools are supplied with input data that does not represent the conditions during which the results are supposed to be valid for, the results will not be valid.

5.4 Reference data →Input data

To enable the user of simulation tools to choose appropriate input-data, there must be sufficient reference data material as a base for the input data. One of the aims of the research presented in this thesis was to exemplify how appropriate input data can be obtained from time-resolved reference data and descriptive statistics regarding the reference data. It was found that appropriate reference data regarding indoor conditions did not exist. Existing reference data was either from shorter measurement periods, which means that the indoor conditions during different outdoor conditions could not be analysed, or was measured with a too low time resolution to allow analysis of variations during shorter periods.

Most reference data will need to be processed to different extents to form suitable input data for different tools. Different parameters vary on different timescales. The indoor temperature is believed to vary on a longer timescale than the use of household electricity, which changes rapidly from second to second according to the result in AP 7. If use of household electricity is to be described in an energy simulation tool, its variation on a timescale of seconds is believed to be too detailed, while its hourly variation has been proved to affect the result of simulated space heating, according to AP 1, compared with when it is described as a daily average.

It might still be of interest to have reference data described at a finer time-resolved level than normally used for input data, since the characteristic can be better described with better time resolution according to Section 5.6, which could improve the verification of the input data used. Section 4.1 exemplifies a method in which hourly input data for internal heat gains can be obtained based on the results presented in APs 1, 2 and 5. Section 4.2 presents a method to obtain hourly values of indoor temperature, moisture supply and indoor relative humidity based on results in AP 6 and 8.

Based on the available quantitative reference data, the users of simulation tools choose quantitative input data to use in the simulations. The input data is chosen qualitatively by the user of the tool. When this is done, it should be based on knowledge of the effect that the choice has on the results as discussed in Section 5.3.

User-related reference data will probably change over time since behaviour changes over time, for example, bathing and cooking habits. Implementation of low energy products will affect the use of electricity and tap water. This calls for reference data that is up to date and frequently updated, so that future buildings are not designed for conditions that are no longer relevant.

5.5 Reality → Measurements

Whether it is possible to measure ‘reality’ is a question of what is physically possible and also a philosophical question regarding what to measure to describe reality. What is more real, the measured indoor temperature or the experienced thermal comfort? Although the experienced reality might be more interesting than the physically measured, the physically measured reality is more suitable to assess, if quantitative data is to be obtained.

When it comes to measurement of energy use, it is of interest to measure as many parts as possible of a building's energy balance. If all parts of the energy balance cannot be measured, uncertainties are introduced which reduce the accuracy of assessments. However, some parts of the energy balance are hard to measure, for example, window airing. The occupancy level is often an uncertain parameter when energy use during operation is assessed. AP 2 presents a method to measure the occupancy level based on measurements of CO_2 concentrations in the extract air of apartments. This method could possibly be used to determine the occupancy level and introduces the possibility of comparing energy use, especially user-behaviour related parts of the energy use, to occupancy levels as well as comparing indoor moisture conditions to occupancy levels. Several of the user-related parameters are believed to relate better to occupancy level than heated floor area or apartment area, but are generally compared with some kind of floor area due to a lack of methods for measuring occupancy level. The method presented in AP 2 should be easy to use in both existing and new buildings.

Predictions of building performance should reflect real performance. Since reality can be hard to measure physically and simulation tools are calibrated to the part of reality that is physically measurable, it is questionable whether the results from tools and predictions provide predictions of the measurable or of the actual reality. A tool that presents results that are impossible to measure in reality should be of limited use, since they are impossible to verify. For example, actual assimilation of solar heat gains has been impossible to verify quantitatively in buildings during operation. AP 3 presents a method to assess useful solar heat gains during operation. This method is believed to be possible, after further development, to use to verify both building performance and simulation tools and predictions.

It has to be accepted that it is not possible to measure everything and with a high time resolution. This calls for further development of models that can assess parameters that are hard to measure based on measurable parameters. The method presented in AP 3 is an example of that as is the method presented in Section 5.6.3.

A limitation of the indoor climate parameters measured as building averages, which was the aim of this research, is that it is not possible to study the conditions in individual apartments. It might be questioned who's reality is measured, in this case maybe that of the building owner. The results in AP 3 show that the air leakage heat losses can be considerable and there is a large variation between buildings. These variations are believed to be partly due to differences in airtightness of the building envelopes. Stein (2008) showed that there was a ratio of 3 between highest and lowest air-tightness of apartments in an apartment building with 15 apartments. Although the average airtightness of a buildings envelope is sufficient, individual apartments might have a less airtight envelope, which will cause higher use of space heating in these apartments than in more airtight apartments. This is a problem for the tenants or the apartment owners, if use of space heating is paid for individually. It is questionable whether the general tenant or apartment owner are even aware of these problems. This underscores that it is important to be aware of whose reality is being predicted or measured, in order to make correct assessments.

5.6 Measurements → Verification

Everything that is predicted should also be possible to verify. Much of what is predicted regarding energy use and indoor climate can be verified based on measurements of physical parameters. In most cases, measurements have to be processed to different extents in order to obtain results that are possible to use to verify predictions. Perhaps the most obvious case is meteorological corrections to the use of space heating. Another common process is averaging during measurement periods and scaling based on heated floor area, apartment area or number of apartments.

5.6.1 Where does the usage take place?

When interpreting processed data, the effect of the used process or processes has to be taken into consideration. When comparing the energy use in two different buildings, one building can have the lowest energy use if energy use per heated floor area is compared, while the other building can have the lowest energy use if use per apartment is compared. This is exemplified in Figure 1 in AP 5 which shows that the process used can affect how results are interpreted. Based on the result in Figure 1 in AP 5, it would be correct to present either Property 5 or Property 6 as the property with the lowest use of household electricity and either Property 1 or Property 4 as the property with the highest use. The question is, which of these processes, dividing the use per heated floor area or per apartment, is the most correct. Considering that the use of household electricity probably depends on parameters such as apartment area, number of rooms and occupancy level, a correct verification of use of household electricity should include all parameters that affect the use.

5.6.2 Meteorological corrections

The appropriate method for meteorological corrections should be chosen based on the actual building performance in relation to different outdoor climate parameters. If, for example, a building has a space heating demand that is affected by wind speed, then wind speed should be included in the meteorological corrections, which must be based on the actual buildings use of space heating, which in turn is dependent on wind speed. The airtightness in two technically identical buildings might be different: the construction workers could have taken part in an airtightness workshop after working on the first building, resulting in the second building having a much air-tighter envelope. If the indoor conditions in these building are the same and the use of space heating is compared for years with different average wind speeds during the heating season but the same outdoor temperatures, the first building will have a higher use of space heating during the windy year compared with the second building. Obviously, when comparing the use of space heating in the two buildings and not taking their respective dependence on wind speed into consideration this might lead to erroneous conclusions. Low-energy buildings, well-insulated and airtight buildings, are believed to be less dependent on outdoor temperatures and wind speeds, and more dependent on solar heat gains than the buildings in this study.

5.6.3 A method to verify user behaviour related parameters

To assess whether a measured user related parameter is normal, it is in most cases not enough to use averages during the measurement period. A measured annual use does not give information whether it is a very high use during summer months and no use during the rest of the year or a more uniform use the year around. If monthly measurements were assessed, this would have been noticed. This exemplifies that higher time resolution of measurements can improve the quality of verifications.

It is of interest to be able to verify whether the user behaviour related parameters are ‘normal’ and in accordance with the assumptions in the prediction, especially in buildings in which performance, to a large extent, depends on the user-related parameters. Often, the behaviour of the users is considered to affect the energy use to a large extent and considered difficult to predict and verify.

User-related parameters presented in this thesis are:

- Indoor temperature
- Moisture supply
- Relative humidity
- Occupancy level
- Use of household electricity
- Domestic hot water

Based on the results in the appended papers and in Section 4, a method for verifying these indoor climate, energy and user behaviour related parameters, based on time-resolved measurements, is suggested in the following.

Whether these parameters are ‘normal’ should be described not only by average values but also by different characteristics. These characteristics can include descriptions of daily, weekly and yearly patterns and statistical descriptive data, such as standard deviation, and maximum and minimum values for different time resolutions on scales from seconds to years.

This method was used to verify that the use of household electricity assessed in AP7 was ‘normal’. The hourly profile of the use during weekdays and weekends, Figure 2 and 3 in AP7, was compared with the corresponding profiles in Figure 3 in AP5 in addition to comparing average use during the measurement period to reference average values. Although the data in AP 7 is only from five days of measurements, the characteristics of the hourly profiles can be qualitatively compared. The following characteristics were found to similar:

- The use increased later during mornings at weekends than on weekdays.
- The use during evenings was much higher than during other times of day.
- The use during afternoons at weekends was higher than the use during weekday afternoons.

Based on these characteristics, using this method to decide whether the measured use during a short measurement period was ‘normal’ was, in this case, considered to provide a better verification than using average values only. Also, monitoring these parameters and comparing their characteristics to reference characteristics and history can give fast feedback on changes that affect the building performance. For example, a change in moisture supply characteristics might be due to a change in air exchange rate.

The method can be used to assess all the presented user-related parameters, given that the measurement time resolution is sufficient and that reference characteristics based on the corresponding time resolution exist for the parameters. AP 6, AP 7 and Section 4.2 present characteristics for indoor temperature, moisture supply and relative humidity. AP 5, AP 7, AP 8 and Section 4.1 present characteristics on household electricity. AP 2 and Section 4.1 present characteristics for occupancy levels and AP 8 presents characteristics for use of domestic hot water. Characteristics based on a much larger data base than presented in this thesis would be needed, if this method were to be applicable on a larger scale.

If combinations of these parameters have characteristics that are in accordance with what is considered ‘normal’, this might indicate that the behaviour of the building users is ‘normal’. A combination of several of the characteristics of the parameters could probably be used to define user behaviour, which would mean that normal user behaviour could be defined by physically measurable parameters and that the use of questionnaires and interviews, demanding an effort from the users, could be avoided in order to verify user behaviour. Knowledge about the correlation of these parameters to each other on different time scales and during different conditions should make even better verification possible and this is an area of future research.

Verification of building performance is not only applicable to new buildings. Before upgrading the building performance of existing buildings, the baseline performance and the performance after improvements should be verified, to enable verification of the performance improvement. If, for example, water taps are to be replaced by energy-saving taps, in order to reduce the use of domestic hot water, the use of domestic hot water should be verified before and after replacement. However, it might not be sufficient to monitor the use of hot water only. Since the use of domestic hot water depends on the occupancy level, a subsequent reduced use of hot water might, in fact, be due to a lower occupancy level. To correctly verify a parameter, other parameters that affect the parameter should also be taken into account in the verification.

5.6.4 More parameters from one parameter

AP 3 presents a method to obtain useful solar heat gains and air leakage heat losses based on time-resolved measurements of use of space heating and outdoor climate. This method can be used to verify parameters that are hard to directly measure physically and, if they can be verified, they can be compared with predicted values. This should improve the quality of verification of space heating since solar heat gains and leakage heat losses can be quantitatively assessed instead of qualitatively, in other words, the number of guesses is decreased.

This method can be used to verify whether a building behaves as expected during different conditions and should indicate whether the heating control systems work as expected. The method can be combined with measurements of the user-related physical parameters described in Section 5.6.3 to verify the indoor conditions and the behaviour of the building users. If the indoor temperature is measured, possible higher indoor temperatures during sunny days can be compared with the decrease in use of space heating. An increase in indoor temperature and no decrease in space heating during sunny days might indicate a malfunctioning control system. This exemplifies how time-resolved measurements of energy and indoor climate not only facilitate verifications of predictions but can also act as a real time feedback system regarding building performance.

5.7 Measurements and Verification → Reference data and Input-data

The primary reasons for measurements and verification are, in most cases, to verify predictions and fulfilment of requirements. However, results from measurements and verifications can be used as reference data and, in turn, input-data. One of the aims of this research was to exemplify how measurements can be used not only to verify predictions but also to make up reference data and input-data. As discussed in Section 5.4, especially reference data for parameters that are affected by user behaviour needs to be up to date and continuously updated. Since the building requirements require verification of energy use during operation, many measurements of energy use are, probably, made nowadays. Hopefully, these measurements of energy use will be combined with measurements of indoor climate to ensure that energy requirements are not met by sacrificing the indoor climate. However, it is not known whether these measurements will be publicly available, or even published in a form that makes them suitable for reference data, or whether the time resolution of the measurements will be good enough, in order to study characteristics and relationships as described in Section 5.6.3 and AP 3.

If the measurements that are carried out to verify fulfilment of the requirements in the building regulations were to be executed using time-resolved measurements together with measurements of energy use and indoor conditions, not only would better verification and feedback be supported but they would also provide high quality reference data, given that the results were publicly available or published. Perhaps a national database containing these measurements, providing up to date reference data, might be an option.

Reference data might also be compiled at a building level with regard to how buildings are affected by outdoor climate parameters, such as sun and wind. If the method presented in AP 3 is applied to many buildings with different characteristics, reference values regarding air leakage, heat losses and solar heat gains would be available. These are interesting reference values when comparing the performance of different buildings in order to find those in which energy efficiency measures and improvements have had the most impact on energy use and indoor climate.

As previously discussed, measurements suitable to be used as reference data need not only to be sufficiently time resolved but also to be measured over a period of at least one year in order to provide characteristics for seasonal variations. The resolution of the measurements has to be considered in respect to the time resolution used. It was found in AP 7 that the resolution of the meters that were used was not good enough for a time resolution of six seconds. The time resolutions of the respective parameters should be chosen based on what information can be gained by the time resolution compared with a lower time resolution. Higher time resolution means that more data has to be stored and analysed, and probably more expensive meters and equipment would have to be used. Reference data should have a better time resolution than the input data for which it is forming a base in order to enable verification of the characteristics as discussed in Section 5.6.3. For example, if reference data is used to obtain hourly profiles during the day, it should be of interest to know what a 30-minute profile would have looked like to ensure that the hourly profile is representative. A constant value at one-hour resolution might, in fact, alternate between very high and very low values at 30-minute resolution, which might mean that the constant used at one-hour resolution would not provide a good representation of the reference data.

Variation between years is a topic that has not been included in this research except regarding the outdoor climate. However, indoor conditions probably vary not only during the year, week and day but also during different years. This is probably most evident in single-family houses where a change in occupancy can probably result in very different indoor conditions, for example, due to window airing habits and occupancy levels. In multi-family buildings, it is unlikely that all occupants in all apartments change at the same time, which means that a change in a few apartments will not affect the average conditions as much as in a single-family house. It is an area of future research to study how the parameters related to indoor conditions vary during different years.

5.8 Measurements and Verification → Tool and Prediction

A primary reason for measurements and verification is to verify whether requirements are met, for example, that the energy use is not higher than stipulated in the building regulations. Although the main purpose of the verification might be to verify the fulfilment of the requirements, the measurements and the verifications can be used as feedback regarding the accuracy and quality of the results from tools and predictions. Comparison of the difference between results from tools and results from verifications should provide information about appropriate safety factors when using different tools.

There might be several years between predictions and verification. That means that it might take several years until feedback is available. Feedback is probably more effective the faster it is given. However, the quality of the feedback has to be considered in relation to how fast it can be delivered. If the time before feedback can be given is too long, there is a risk that faults might be repeated in other projects in the meantime.

The method presented in Section 5.6.3 can be used, based on time-resolved measurements from short measurement periods, to verify user-related parameters that affect energy use and indoor climate. Since user behaviour is believed to affect the energy use to a great degree, fast feedback about the user behaviour enables fast comparison between the measured values and the assumed values in the energy simulation tool. If the measured user behaviour differs from what is assumed, the prediction can be updated based on the measurements and give an indication as to how the building performance might change compared with the previously predicted performance.

The multi-parameter linear regression method presented in AP 3 can also be used to give fast feedback. Use of space heating during a short measurement period with varying weather conditions can be used to calculate how the building is affected by temperature, solar heat gains and wind speed. If the effect of wind speed is higher than expected, the airtightness of the building envelope might be less than predicted or the occupants might feel the need to use window airing to obtain the desired air quality. Less useful solar heat gains than expected might indicate a problem with the heating control system or that the indoor temperature during sunny days is too high, which forces the occupants to use window airing to control the indoor temperature.

Measured indoor conditions and actual outdoor conditions during the measurement period can be used as input-data for indoor and outdoor conditions in the energy simulation tool to calculate usage during the corresponding period. This will give a calculated value that can be compared with the measured value with the same indoor and outdoor conditions, which means that the result from the tool can be assessed without uncertainties regarding how differences in these conditions affect the result, given that the conditions are within the limitations of the tool. Not only the average values during the period can be compared but also the daily values originating from days with different outdoor and indoor conditions. Days with high global radiation can be compared with days with less global radiation to study whether the useful solar heat gains differ between the measurements and the predictions. The same applies for days with different wind speeds. If the calculated values differ from the measured values, then the building technology, the technical systems or the building users' interactions with the building have not behaved as expected. If the measured use is higher than predicted, this fast feedback will provide an opportunity to make quick improvements, which might result in the building fulfilling its requirements and a reduction in operation costs.

6 Conclusions

This thesis presents reference data and suggests methods that can be used to improve prediction and verification of building performance regarding energy use and indoor climate. Different areas of interest were addressed and analysed based on appropriately time-resolved measurements of several energy use and indoor climate related parameters in buildings during operation. The reference data is presented in forms that aim to make it suitable to use as input data for tools and as reference data for interpretation of measurement results. The methods aim to describe reality more accurately and are applied to predictions and verifications. The methods and reference data deal with the following areas:

- Useful solar heat gains – quantification of how much solar heat gains decrease use of space heating based on measurements of heating in actual buildings.
- Air leakage and window airing – quantification of how much air leakage and window airing heat losses increase use of space heating based on measurements of heating in actual buildings.
- User related energy uses – reference data on levels and typical variations during different times of the year and the day and the effect of heat gains on space heating demand.
- Occupancy level – continuously measured in residential buildings. Descriptive statistics and typical variations on different timescales. Enables user related energy uses to be related to the actual number of users.
- Indoor hygrothermal conditions – descriptive statistics for normal conditions. Methods to describe the conditions taking into account both outdoor climate and user behavior.
- Meteorological corrections that take into account not only several outdoor climate parameters but also actual building performance.

The methods enable more comprehensive predictions and verifications and thereby increased quality. The methods are fully developed and ready to use in practice, which means that the results presented in this thesis provide the building sector with positivistic and useful recommendations. Both new and existing residential buildings can benefit from the results. Use of these methods should result in buildings with energy uses and indoor climates that align with predicted values. They should also support better feedback in the building process and more energy-efficient and sustainable buildings.

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Simulating space heating demand with respect to non-constant heat gains from household electricity

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It is crucial to perform energy simulations during the building process to design a building that meets requirements regarding low energy use. In a low energy building, internal heat gains such as excess heat from household electricity are a large part of the heat balance of the building. The internal heat gains depend on the occupants and are not constant, although they are often assumed constant in simulations of space heating demand. This article analyses how different usage patterns of household electricity affects simulated space heating demand. Parametric studies of energy use-related parameters were done to study the influence from different designs. The results show that the different energy use patterns affect the space heating demand, especially in low energy buildings and during the colder parts of the year. To make accurate energy simulations of low energy buildings, household electricity use patterns should be taken into account.

Keywords: energy use; energy simulation; low energy building; internal heat gain; household electricity

1. Introduction

As a part of decreasing the energy use, and thus carbon dioxide emissions within the European Union, focus has increased on both low energy buildings and the ability to simulate the energy use of buildings properly to achieve buildings that fulfils requirements. According to the recast of the Energy Performance of Buildings Directive, from 2021 (DIRECTIVE, 2010), all new buildings within the European Union have to be nearly zero energy buildings and that energy should, to a large extent, come from renewable sources. This applies to buildings owned or occupied by public authorities from 2019. To achieve nearly zero energy buildings, buildings will probably have to be designed as zero energy buildings that are defined as buildings 'where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site' (European parliament press service 2009).

To design a building that fulfils requirements regarding low energy use, it is crucial to perform energy simulations of the building in question during the design process and the simulations must be representative of the building during operation (Bagge 2007; Feby 2009). Research on the agreement between predicted and actual use of space heating in residential buildings in Sweden show that measured use of energy for space heating during operation exceeds the predicted energy use between 50% and 100%, even in low energy buildings (Elmroth 2002, Nilsson 2003, Lindén 2006, Bagge and Johansson 2009). Karlsson *et al.* (2007) stressed the importance of accurate input data for the energy simulations of buildings. The building users' behaviour is very important in low energy buildings and is the hardest to model according to Karlsson *et al.* (2007). The use of household electricity is influenced strongly by the building users' behaviour and is a major internal heat gain. Household electricity is paid for by the occupants and includes electricity for refrigeration units, cooking, lighting, and electronic equipment such as televisions and computers. When optimizing the design of a low energy building, it is of great importance to know what amount of household electricity that is likely to be used and the characteristics such as how it varies over the year and during the day to understand the internal heat gain pattern.

Studies about household electricity use in newly built residential buildings in Sweden showed that the average electricity use varies between 27 and 35 kWh/m^2 (Elmroth *et al.* 2005, Lindén 2006, Wall 2006, Bagge 2008). The use of household electricity is not constant during the year or during the day. It varies due to, for example, the occupants' behaviour, and daylight conditions that affect the need for artificial

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lighting. Capasso *et al.* (1994), Riddell and Manson (1995), Norén (1998), Tso and Yau (2003), Paatero and Lund (2005), Sandberg (2006) and Bagge (2008) studied household electricity use patterns. Generally, there were peaks in the use during mornings and evenings with the evening peak being bigger. In warmer climates, the electricity use during summer was higher due to the use of air conditioning to cool apartments. In colder climates, the use was higher during winter, which was believed to be due to few hours of daylight which might increase the use of artificial lighting, and more time spent indoors.

Bagge *et al.* (2006) interviewed consultants who practised energy simulations of buildings. According to the interviews, the consultants seldom included household electricity use patterns in the simulations. Although the consultants believed that the use of household electricity varied during the day and the year, they assumed a constant load in the simulations. According to the consultants, this was because no data regarding the variations were available and that energy simulation programs for buildings, used by the companies where they were employed, were not adapted for input data that varied during the day and the year.

It is most likely that buildings with very low space heating demands are going to be the norm in a near future. Buildings with small heat losses imply that internal heat gains can make up for the heat losses during a large part of the year and thereby reduce the demand for space heating. Measurements on occupancy levels in Swedish residential buildings are lacking but Johansson (2007) estimated a level of 60%. With an assumption of 60 m^2/person and 100 W/person, there will be an annual load of 8.8 kWh/m^2 to be compared with the given household electricity gains of 27 35 kWh/m^2. That means that in Swedish residential buildings, household electricity is the largest internal heat gain. It seems to be common practice that consultants do not take the use patterns of household electricity into consideration in energy simulations. It is important to improve the quality of energy predictions and to facilitate energy simulations that better agrees with physics and actual energy use. This is especially important since decisions regarding designs and economy are often based on the predicted energy use.

1.1. *Objectives*

This article analyses how different use patterns of household electricity affects simulated space heating demand. The aim was to focus on the principal influence from different use patterns and to address the importance of taking these patterns into account when energy simulations are performed by consultants.

2. Method

With the aim to analyse how different household electricity use patterns affect space-heating demand, simulations are the only reasonable option since it would be impossible to measure confounders in real buildings where a number of other factors influence the space heating demand on the same or a higher level. Therefore, space-heating demand of a typical modern Swedish residential apartment building was simulated with different household electricity use patterns. Space heating is the energy that the occupied space needs for keeping the desired indoor temperature. Other heating energies in buildings not presented in this study are ventilation air heating and domestic hot water heating. The household electricity use patterns were described based on measurements, and, to enhance the theoretical understanding of the problem, as arbitrary pulses of different length occurring at different times during the year and the day, respectively.

Energy simulations in practice are almost always based on one-zone calculations. The same approach was chosen in this study to match sector practice. Future work could include variations between apartments and the effect on space heating demand from the split-up in zones instead of using one zone for the building. Still, each of the actual zones will be reflected by a certain parametric set up in this study.

Parametric studies of energy use-related parameters were done to study the influence from different designs of the building on the difference between space heating demands simulated with different household electricity use patterns.

2.1. *Limitations*

Except for the approach with one-zone simulations, which means that variations between apartments were not resolved, a number of assumptions were made to keep the focus on the question on the effect on space heating from household electricity. The combination of parameters regarding user-based influences is a matter of future work.

Window airing was not considered in the simulation model since there is a lack of models and measurements on its variation over time. Airing would possibly have a clear effect on high indoor air temperatures, which occur when it is warm outdoors, but this is not analyzed.

Varying load from occupants was handled as a parameter in a parametric study due to lack of studies on such variations in Swedish residential buildings and to keep the focus on varying household electricity. Measurements of occupancy levels over time is ongoing (Bagge and Johansson 2008), which enables future studies on the topic.

Other types of bought energy not analysed in the study but which are included in the requirements of the Swedish building regulations (The National Board of Housing Building and Planning 2008), are common electricity used for example for air handling units and outdoor lighting and domestic hot water heating.

2.2. *Use patterns*

Use patterns were used based on arbitrary rectangular pulses of household electricity use, and measured data for varying household electricity use in Swedish residential buildings. The arbitrary pulses had different lengths and occurred at different times during the year and the day, respectively. These pulses were defined by the pulse width and the pulse centre point as parameters as described in Figure 1. The heights of the pulses were set so that the integral of the pulse, representing the household electrical energy, remained constant for the different pulse lengths.

The use patterns based on measurements were modelled from measurements presented by Bagge (2008) who analysed variations in use of household electricity during the year and during the day. To be able to use these measurement results more effectively in simulation code, the variation during the year was described by a sinus function based on 12 monthly mean powers as part of the yearly mean power according to Equation (1), where P_{mom} is the actual power at the time t and P_{av} is the annual average power.

$$P_{\text{mom}} = P_{\text{av}} + P_{\text{av}} \cdot 0.238 \cdot \sin\left(\frac{2\pi}{8760}t + 1.42\right) \quad [t] = h \tag{1}$$

The variation during the day was described by 24 discrete hourly ratios between the actual power and that day's mean power according to Bagge (2007), which means that the daily profile was a step function. Bagge (2007) found that the relative variation during the day, the hourly power for each hour of the day compared to that day's average power, was equal during the year despite the variations during the year. Figure 2 presents the used pattern and the measured variation during the year and Figure 3 presents the used pattern during the day.

2.3. *Simulated building*

The building used in the simulation was a theoretical building with the default configuration representative

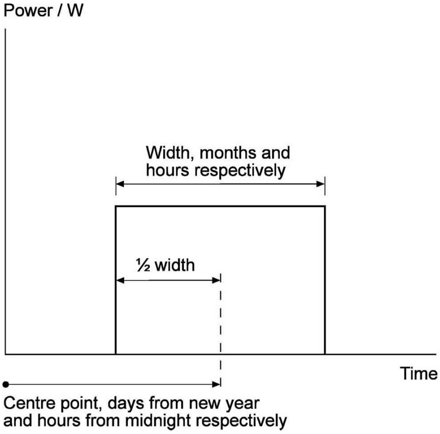

Figure 1. The description of the arbitrary pulses and the definition of 'Pulse width' and 'Centre point'. 'Hours from midnight' and 'hours' refers to pulses during different times of the day. 'Days from new year' and 'months' refer to pulses during different times of the year. The height was defined so the area, representing the annual household electricity use, was constant.

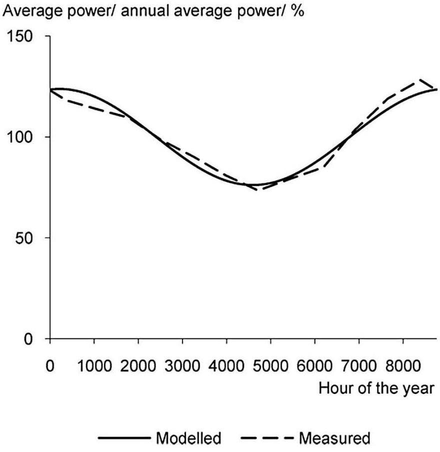

Figure 2. The measured household electricity use pattern during the year together with the modelled curve fit used in the simulations.

for buildings in Sweden built according to the Swedish building regulations (The National Board of Housing Building and Planning 2008). The theoretical building was a four storey, two stair case multi-family building containing four two bed room apartments 75 m^2 each in size on each storey. The building was 26.3 m by 12 m and each storey's height was 2.4 m. The total heated floor area was 1264 m^2. The long sides were facing north and south with an equal amount of window area. The total window area was 13% of the heated floor area. Table 1 presents the thermal transmittance and area of the different building elements. The thermal bridges were set to 72 W/K. The average thermal transmittance of the building envelope including thermal bridges was 0.32 W/($m^2 \cdot K$). The windows solar heat gain coefficient was 0.4 including possible shading effects. The total ventilation airflow was 480 l/s and the supply air temperature was 18°C and constant. The building was heated to an indoor temperature of 21°C. No cooling system was used. Air leakage through the building envelope at 50 Pa pressure difference between indoors and outdoors was 0.8 l/(s · m^2) or 1.3 ach (air changes per hour). The thermal storage capacity was 15,000 J/($m^2 \cdot K$) for an area of 1896 m^2. Internal heat gains included household electricity, 30 kWh/(m^2 · year), and one occupant per apartment with 100 W per person and 60% attendance level spread evenly. The default theoretical building was located in Malmö, southern Sweden, lat N55.6°.

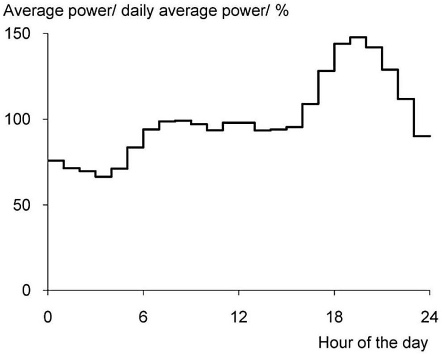

Figure 3. The household electricity use pattern during the day based on measurements.

Table 1. The area and thermal transmittance of the different building elements.

Building element	Thermal transmittance [W/($m^2 \cdot K$)]	Area (m^2)
Foundation	0.10	316
Roof	0.10	316
Walls	0.18	572
Windows	1.2	164

2.4. *Simulation tool*

Code was developed to simulate the energy use by the help of the power balance shown in Figure 4 (Johansson 2005, International Organization for Standardization 2008) to handle varying household electricity gains and parametric studies effectively. ROOM is the simulated zone. P_{trans} is the transmitted heat, P_{cap} is the heat from the first order heat capacitor with the temperature t_{cap}, P_{solar} is incoming shortwave solar radiation that heats the room and P_{vent} is the power needed to change the temperature of the supply air, t_{sa}, to the temperature of the exhaust air, t_{ex}. It is assumed that the room temperature, t_{room}, is the same as the exhaust temperature. Ventilation air heating after the supply air heat recovery was calculated but was almost the same for all cases due to the constant supply air temperature.

Leakage air was assumed to have a constant airflow rate, q_{leak}, of 5% of the airflow rate at 50 Pa pressure difference, which is reasonable for a supply and exhaust ventilation system with under balance to prevent over pressure (Torssell 2005, Johansson 2008). P_{int} refers to the load from people that was assumed to be constant, and for household electricity that was assumed to heat the indoors and vary over the day and year. $P_{support}$ is the energy needed to keep the room in balance at the desired t_{room}. Since it was assumed that there was no cooling system, $P_{support}$ could not be negative. Outdoor climate data were

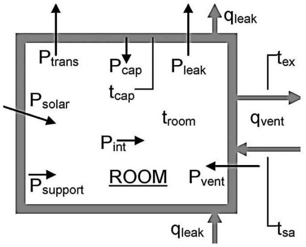

Figure 4. Power balance used in the simulation tool for the building. The air-handling unit is not shown and the energy going to it is not reported. Quantities are given in the text.

obtained from the computer program Meteonorm (Meteotest 2003), which simulates outdoor climate data for locations of the entire world.

2.5. *Simulations*

Simulations of space heating demand were performed with internal heat gains from household electricity that

- were constant
- varied during the day, according to Figure 1, with pulse widths of 1, 2, 4, 8 and 16 h, and with centre points of 0, 6, 12 and 18 h from midnight, in all combinations
- varied during the year, according to Figure 1, with pulse width of 1, 2, 4 and 8 months, and centre points of 1, 91, 182 and 273 days, in all combinations
- varied during the day, according to Figure 3 (daily variation)
- varied during the year, according to the measurements, Figure 2 (annual variation)
- varied during the year and the day (both daily and annual variations), according to the pattern in Figure 2 multiplied by the pattern in Figure 3

The simulated annual and monthly space heating demand and the annual space heating peak power for the different use patterns were compared as well as different energy-related parameter's effect on the differences between simulated space heating demands with different use patterns.

Parametric studies of the following parameters are presented

- average thermal transmittance
- window's solar heat gain coefficient
- building's thermal capacity
- average use of household electricity
- attendance level and times
- outdoor annual average temperature.

The average thermal transmittance was varied between 0 and 1 $W/(m^2 \cdot K)$ in steps of 0.1 $W/(m^2 \cdot K)$, while the thermal transmittance in the default case was 0.32 $W/(m^2 \cdot K)$. The thermal transmittance of 0 $W/(m^2 \cdot K)$ is theoretical and cannot possibly be achieved in reality. Still, in that case, there is a leakage giving a heating demand. The window's solar heat gain coefficient was varied between 0 and 1 in steps of 0.1. A solar heat gain factor of zero means that no solar heat gains are transmitted and a factor of one means that all solar heat that reaches the outside of the window is transmitted. The building's thermal capacity was varied between 0 and 200 $kJ/(m^2 \cdot K)$ in steps of 25 $kJ/(m^2 \cdot K)$. A thermal capacity of 0 $W/(m^2 \cdot K)$ is theoretical and cannot possibly be achieved in reality. The average use of household electricity varied between 0 and 10 kW in steps of 1 kW, with the default case at 4.1 kW. The household electricity power can be zero if the building is not occupied. The use pattern levels, see Figures 2 and 3, were multiplied by the average power, which means that when the household electricity is increased, the difference between the highest and lowest power during the day and the year, respectively, increases. Table 2 presents the different attendance cases studied and Table 3 gives the outdoor climates tested. Regarding attendance, cases 2, 3 and 4 represent typical times for Swedish shift work and case 5 is the default.

3. Result

Table 4 gives the result of the simulated heating demand for the default theoretical building using the different household electricity use patterns. The ventilation air heating was 1.6 kWh/m^2 for all cases and is not included in further results. Only space heating is presented. Annual space heating simulated with household electricity use that varied during the day (daily variation) was 0.5 kWh/m^2 higher compared to if it was simulated with constant electricity use.

Annual space heating simulated with household electricity use that varied during the year (annual variation) was 1.4 kWh/m^2 lower than the simulation with constant use. With household electricity that varied during the year and the day (both daily and annual variations), the annual space heating was 0.9 kWh m^2 lower. Although the absolute differences are relatively small, the difference between the annual space heating demand simulated with 'daily variation' and 'annual variation' household electricity use patterns, was 2 kWh/m^2, or 10%.

Figures 5 and 6 give the resulting annual space heating with the household electricity use varied according to the rectangular pulses shown in Figure 1. It is shown in Figures 5 and 6 that the time at which

Table 2. Attendance cases, heat gain power per apartment during attendance and attendance time.

Case	Power (W)	Attendence time
1	100	00–24
2	100	00–07 and 17–24
3	100	00–13 and 23–24
4	100	07–21
5	60	00–24
6	0	00–24

Table 3. Simulated outdoor climates and their annual average temperature used in Figure 9.

Building location	Annual average outdoor temperature (°C)	Latitude (degrees)
Karasjok, Norway	−2.52	N69.4
Kiruna, Sweden	−1.23	N67.8
Frösön, Sweden	2.53	N63.2
Umeå, Sweden	3.67	N63.8
Stockholm, Sweden	6.66	N59.3
Malmö, Sweden	8.01	N55.6
Glasgow, UK	9.41	N55.8
London, UK	10.6	N51.5
Milano, Italy	11.7	N45.4
Madrid, Spain	14.8	N40.4
Los Angeles, USA	18.1	N34.1

Malmö was default.

Table 4. Simulated space heating demand with constant, daily, annual and both daily and annual household electricity use patterns.

Case	Annual space heating (kWh/m^2)	Relative to constant (%)
Constant	18.1	100
Daily variation	18.6	102.8
Annual variation	16.7	92.4
Both annual and daily variation	17.2	95.1

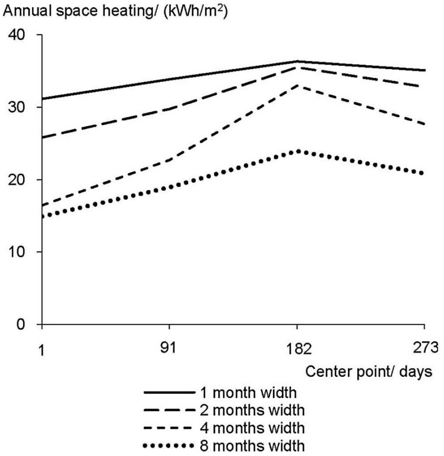

Figure 5. The annual space heating demand with internal heat load in pulses of pulse widths from 1 to 8 months, and at different centre points during the year according to Figure 1. The yearly internal heat load energy was the same for all pulse widths. A constant heat load with the same energy would result in a space heating demand of 18.1 kWh/m^2.

the pulse centre point occurs and the width of the pulse affects the space heating demand to different extent due to different outdoor climate conditions during different times of the year. When pulses are occurring during times when the outdoor temperature generally is low, during winter and nights, the space heating demand decreases. It is also shown that the space heating demand decreases with increasing pulse length. However, a pulse width of 12 months and 24 h, respectively, which is the same as the default case, results in higher space heating demand compared to internal heat gains concentrated in a pulse width of 4 and 8 months, respectively, occurring with pulse centre point on January 1st and a pulse width of 8 and 16 h, respectively, occurring with pulse centre point at midnight.

Figures 7–14 present results from simulations of space heating demand with household electricity use patterns that was constant, varied during the day (daily variation), varied during the year (annual variation) and varied during both the day and the year (both daily and annual variations), respectively. When no other design parameter is varied or nothing else is declared, the default parameters were used. The space heating simulation results with constant use are presented on the right *y*-axis in the figures. The presented differences on the left *y*-axis in the figures are the space heating demands with a certain type of use pattern of household electricity minus the corresponding value with constant use of household electricity. A positive difference means that the use pattern results in a higher space heating demand and a negative difference means that the use pattern results in a lower space heating demand. Figure 7 presents the annual space heating peak power and Figure 8 presents the monthly space heating demand. Figures 9–14 present the annual space heating demand simulated with different energy-related parameters.

For all tested parameters, see Figures 9–14, the simulated space heating demand with household electricity that varied during the day according to Figure 3, was higher when compared to simulated space heating demand with constant use. A reason for this is that the household electricity power, according to the use pattern, is lower during nights than days. During nights, the outdoor temperature is typically lower and there is no solar radiation. With household electricity varying during the year, the use pattern according to Figure 2, the space heating demand, was lower in all cases. This can be explained by the fact that

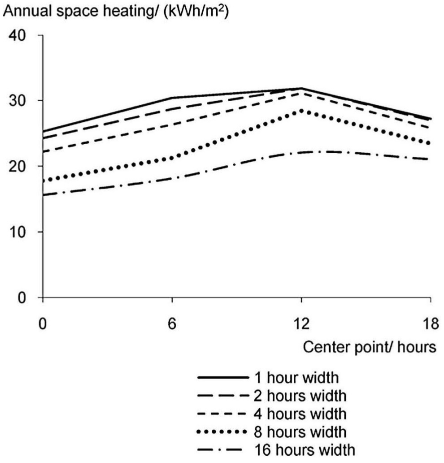

Figure 6. The annual space heating demand with internal heat load in pulses of widths from 1 to 16 h and at different centre points during the day according to Figure 1. The daily internal heat load energy is the same for all pulse widths. A constant heat load with the same energy would result in a space heating demand of 18.1 kWh/m^2.

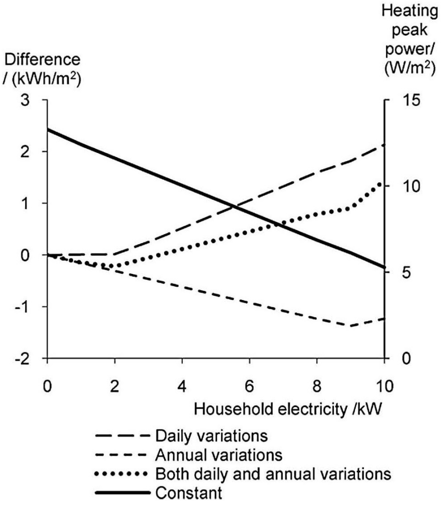

Figure 7. The annual heating peak power simulated with constant household electricity load (continuous line, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left y-axis), for varying average household electricity power.

the use of household electricity according to the use pattern is higher during winter when the outdoor temperature is lower and the solar radiation is lower, which means that the benefit from the internal load is more frequent.

When the use of household electricity was varied during both the day and the year, usage patterns according to Figures 2 and 3, the simulated space heating demand decreased in all cases compared to the simulations with constant use of household electricity. The decrease is smaller compared to the decrease with household electricity that varies during only the year. For all studied parameters, the difference between the decrease with variations during the year only and variations during both the year and the day is close to the difference between the space heating demand with use of household electricity varying over the day and the case with constant use.

The difference between the constant and the annual varying pattern in heating peak power, as well as the space heating demand, decreases negatively with increasing average household electricity according to Figures 7 and 12, but with very high average household electricity, the negative differences decrease again. This is explained by the fact that the household electricity handles a major part of the space heating need.

The monthly space heating presented in Figure 8 shows that the effects of the different use patterns are different at different times of the year. During January there is a difference of 14% between simulated space heating demand with the use patterns ‘constant’ and ‘both daily and annual variations’.

A varying thermal transmittance as in Figure 9 influences the space heating demand strongly. The difference at zero is zero because the household electricity alone handles the leakage and ventilation losses. At high thermal transmittance, the heating demand increases leading to many hours with a heating need from the heating system, leading to a slightly decreased difference at different use patterns.

When the solar heat gain coefficient is higher than 0.4, the difference of the ‘both daily and annual’ use pattern is constant while the difference of the ‘daily’ use pattern increases with higher solar heat gain coefficient, see Figure 10. This is because the building’s thermal storage capacity is effective over a day and not over a year, as seen in Figure 11 where the thermal heat storage capacity is varied. Hence, the increased heat gains from the sun at higher solar heat gain coefficients can be stored during shorter periods of time only. For

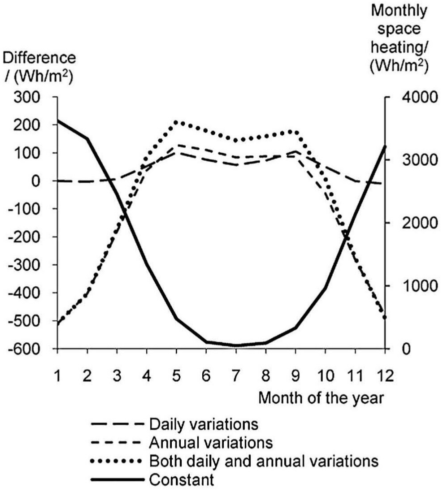

Figure 8. The monthly space heating simulated with constant household electricity load (continuous line, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left y-axis), for the different months of the year. Month 1 is January.

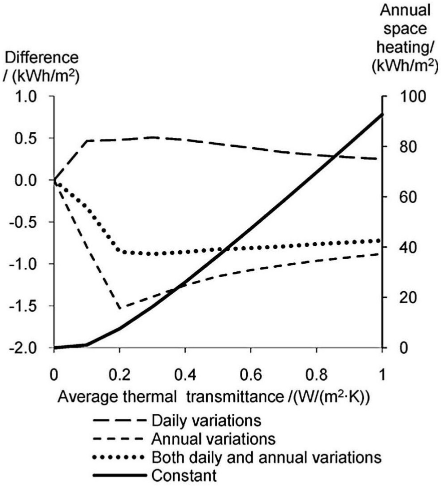

Figure 9. The annual space heating demand simulated with constant household electricity load (continuous line, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left y-axis), for varying average thermal transmittance.

high thermal storage capacities, the heat transfer limits the storage.

Figure 13 shows the simulation results from the different attendance patterns regarding the user's presence given by Table 2. Higher level of attendance means lower space heating demand, but the differences between the use patterns are rather constant.

Regarding the outdoor climate variation, shown in Figure 14, the effect from the 'annual' use pattern is small in Los Angeles due to the fact that the difference between winter and summer outdoor climate is small, which is also visible for the two climates of UK. For the other outdoor climates, the differences are rather constant. It must be noted that building design and other parameters in other countries can be different from the ones used from Swedish measurements.

4. Discussion

The results presented in Table 4 show that the simulated space heating demand and hence the total energy use is affected by the choice of household electricity use pattern. If the household electricity is described by the 'daily variation' use pattern, the simulated space heating demand will be higher and if it is described by the 'annual variation' pattern it will be lower compared to if a constant household electricity use pattern is used. The most correct procedure should be to describe the household electricity use pattern according to measurements as is done in the 'both daily and annual variations' use pattern. The use patterns 'daily variation' and 'annual variation' described in this paper were based on results from measurements in 196 apartments in Sweden (Bagge 2008), and the general characteristics of these measurements regarding variations during the day and during the year align with observations from other studies, as presented in the introduction of this paper. The simulated space heating demand with the 'both daily and annual variations' household electricity use pattern was lower compared to the constant pattern but higher than the 'annual variation' pattern.

Simulations of energy use by consultants in the building sector usually underestimate the energy use. The results from this study do not explain this. Instead, it shows the opposite. If the space heating demand is simulated with a household electricity use pattern that takes both annual and daily variations into account, the space heating demand is lower than if a constant use pattern is assumed. This gives that the difference

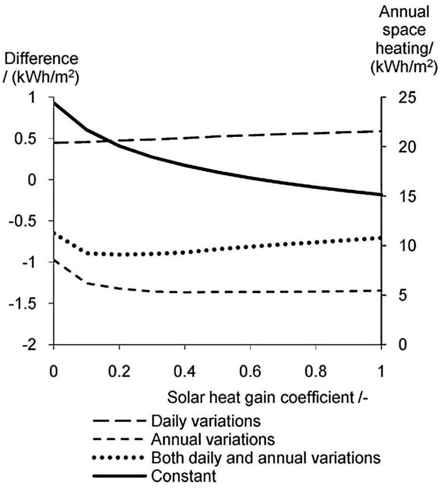

Figure 10. The annual space heating demand simulated with constant household electricity load (continuous line, refers to the right *y*-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left *y*-axis), for different solar heat gain coefficients.

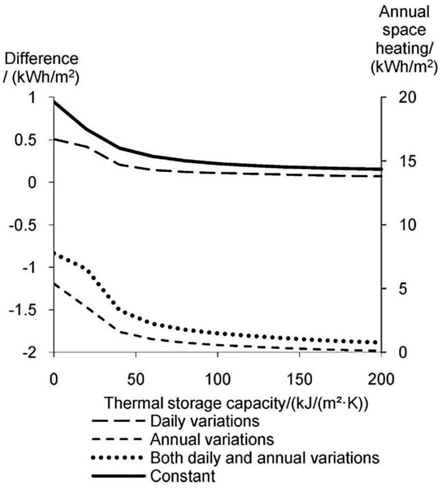

Figure 11. The annual space heating demand simulated with constant household electricity load (continuous line, refers to the right *y*-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left *y*-axis), for varying thermal storage capacity.

between measured and predicted use would be even larger. On the other hand, compensating underestimating simulated energy use by using a constant household electricity gain is not a plausible solution from the physical perspective.

The difference between the highest and lowest use during the day in December is 3.4 W/m^2 heated floor area according to the 'both daily and annual variations' use pattern. A passive house built according to the Swedish requirements (Feby 2009) will have a total heat loss of about 0.5 W/(°C · m^2) related to the heated floor area. That means that in a low energy building, the difference in household electricity use power during the day in December equals a 7°C difference in outdoor temperature. A normal day during the winter in the default outdoor climate has an amplitude in the daily outdoor temperature variation of 2°C, which means a top to bottom difference of 4°C (Harderup 1995, Johansson 2002). According to this, it is more important to have a varying household electricity use than a varying outdoor temperature. A varying outdoor temperature is commonly used in simulations in research as well as in practice and so a varying household electricity use should also be used. Regarding the parametric study, the thermal transmittance has high impact on the space heating demand. The difference between space heating demands with different use patterns have maximums at a thermal transmittance of 0.2 W/(m^2 · K). This is a common average thermal transmittance for a low energy building such as a passive house designed according to the Swedish requirements (Feby 2010). Low energy buildings that get an extensive part of the heating from household electricity are the most important to simulate properly.

The ventilation air heating is not reported in this study since it is almost constant due to the constant supply air temperature, which is the most common set up in Swedish residential buildings if there is a supply and exhaust ventilation system. The air-handling unit is not affected by the heating system in the space of the building. Exhaust only ventilation does not seem to be an alternative in the coming low energy housing so that is irrelevant to simulate. The choice of supply air temperature affects the energy use and can be subject of optimization (Johansson 2003, Engdahl and Johansson 2004), particularly in low energy housing where it is an important part of the cooling system and usually the heating system (Janson 2008, Thullner 2010). Demand controlled airflow by attendance or

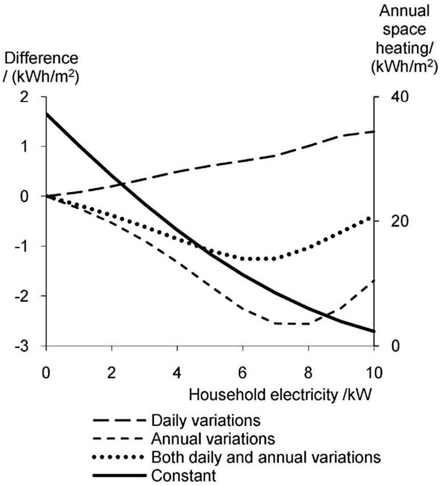

Figure 12. The annual space heating demand simulated with constant household electricity load (continuous line, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left y-axis), for varying average household electricity power. The default case was 4110 W.

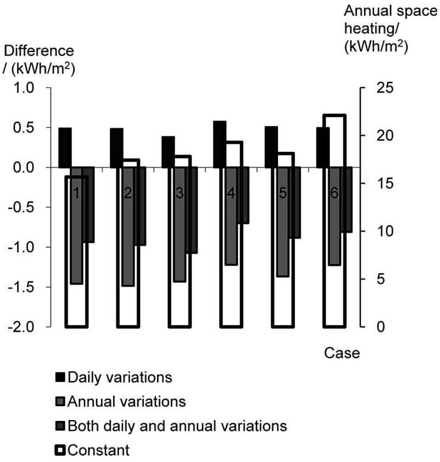

Figure 13. The annual space heating demand simulated with constant household electricity load (transparent bars, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (grey bars, refers to the left y-axis), for different attendance cases according to Table 2.

indoor temperature is another option that influences the energy simulations and makes it necessary to have good input data on the patterns of use.

Varying attendance of people over time was not modelled comprehensively in the study but in Figure 13, it can be seen that the difference between different cases of attendance schedules is approximately a third of the difference between different household electricity use patterns, which corresponds to the fact that the gain from people is approximately a third of the gain from household electricity according to the Introduction section.

The different use patterns effect on space heating should particularly be taken into account if space heating measured during a shorter period of time, e.g. during 1 month, is compared to a predicted use that did not consider household electricity use patterns. This is illustrated by the results shown in Figure 8. The largest differences occur during the winter, which is due to the higher use of household electricity during the winter as seen in Figure 2.

As household electricity-related products such as cold appliances, washing machines, and electronic devices are replaced by more energy efficient alternatives the household electricity will decrease given that the number of products and operating times are not increased. Figure 12 illustrates how the space heating is affected by increasing or decreasing household electricity. If the default household electricity use, 30 kWh/(m^2 · year), is reduced by 50%, the annual use of household electricity is decreased by 15 kWh/(m^2 · year) while the annual space heating demand is increased by 9 kWh/(m^2 · year). The result is that the actual energy saved is only 6 kWh/(m^2 · year) or 40% of the decrease in household electricity use. If there was a heating demand, the year around the increase in space heating would equal the decrease in household electricity. With the outdoor climate used, there is not a heating demand the year around. The result indicates that the heating season is approximately half a year, which is reasonable considering the building characteristics. If the space heating energy is from renewable sources, an increased space heating demand might be beneficial if the electricity comes from non-renewable sources. If environmental questions are to be considered, it is probably better to compare the decrease in CO_2 emissions rather than comparing only the energy savings. Considering economy, electricity is often more expensive than heat. On the other hand, it can be believed that the efficiency of an indoor electric

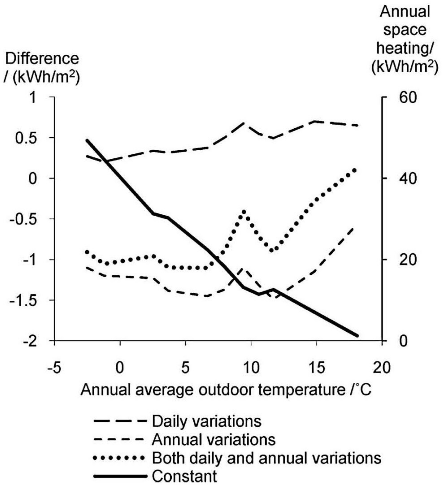

Figure 14. The annual space heating demand simulated with constant household electricity load (continuous line, refers to the right y-axis) and the difference of daily, annual and both daily and annual use patterns, respectively (dashed lines, refers to the left y-axis), for different outdoor climates with varying annual average outdoor temperatures according to Table 3.

appliance is 100% or very close to it. Typical heating systems have lower efficiencies, either it is district heating or a furnace, which means that more energy has to be bought to heat the house by the heating system than by the electrical appliances.

5. Conclusions

This study has shown that the variation in household electricity is not negligible when energy use simulations or power demand simulations are performed, particularly for low energy buildings. Although the differences between the simulated annual space heating demands with different household electricity use patterns are relatively small, this is not a reason for assuming a constant use of household electricity in simulations. In practice, in the building sector there is no data to use and a lack of software that handles these variations. Therefore, there is a need for software where it is easy to use different relevant patterns of input data, and more measurements on these variations are needed, particularly for residential buildings. Furthermore, there is a need for more research on other parameters that vary over time not addressed in this study, such as window airing and attendance patterns. Cooling and the resulting indoor climate simulations are also a matter of future research. To be able to make the right decisions regarding energy efficient measures and designs, there is a need to study how the household electricity use characteristics develop over times longer than a year as new products are entering the market and homes.

Acknowledgements

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PAPER 2
AP 2

Johansson D, Bagge H and Lindstrii L, Measurements of occupancy levels in multi-family dwellings – Application to demand controlled ventilation, Submitted to Energy and Buildings 2011.

Measurements of occupancy levels in multi-family dwellings – Application to demand controlled ventilation

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ABSTRACT

The occupancy level of dwellings is an important parameter to know to determine the energy efficiency, energy use and indoor air quality, especially in low-energy buildings where the user-related energy uses, such as household electricity and domestic hot water heating, are significant parts of the energy balance in a building. For residential buildings, there is a lack of occupancy level data, which also needs to be resolved over time, in a way so that both short term and long term variations can be described. As a part of an ongoing study, occupancy levels were measured in 18 apartment buildings containing 342 apartments in total with readings every 30 minutes during more than a year. Averages and standard deviations of occupancy level, and variation in occupancy during the year, week and day respectively are presented. The results show a highly varying occupancy level over time, which indicates the potential of demand controlled ventilation in dwellings.

KEYWORDS

Occupancy level, demand controlled ventilation, dwellings, residential

1 INTRODUCTION

The occupancy level of dwellings is an important parameter to know to determine the energy efficiency, energy use and indoor air quality, especially in low-energy buildings where the user-related energy uses, such as household electricity and domestic hot water heating, are significant parts of the energy balance in a building. A high occupancy level probably results in a higher use of household electricity and domestic hot water heating but should reduce the use of space heating due to higher internal heat gains, given that the heating control system works properly, and that the ventilation air change rate is sufficient, so that window airing is not needed to maintain the indoor air quality. To verify a building's energy performance, it is of interest to know the occupancy level and how the occupancy level varies during different times of the day, the week and the year. These variations can indicate the usefulness of demand controlled ventilation in dwellings. Constant ventilation airflows in mechanically ventilated dwellings are designed for maximum occupation, which is probably not the case during all hours of the year. This implies that dwellings are over-ventilated at times of less than maximum occupation which might result in higher than necessary energy use for heating and ventilation.

According to the Swedish building regulations [1], demand controlled ventilation is accepted in residential buildings on condition that the ventilation airflow can be individually controlled for each apartment with a minimum of 0,10 $l/(s \cdot m^2)$ related to floor area when there are no occupants in the apartment and a minimum of 0.35 $l/(s \cdot m^2)$ related to floor area when the apartment is occupied.

The concentration of CO_2 is often used to control demand controlled ventilation [2]. CO_2 producing processes in dwellings are, for example, the metabolism of occupants and pets, decaying organic substances, such as kitchen garbage, and combustion processes, such as the burning of candles. The authors of reference [3] report typical indoor air CO_2 concentrations between 500 and 1500 ppm for mechanically ventilated dwellings, and stress that the concentrations are seldom constant and should be evaluated accordingly. The researchers in reference [4] monitored CO_2 concentrations in the living rooms of 19 dwellings in Finland during one week. The average CO_2 concentration was 570 ppm and varied between 350 and 900 ppm in the different dwellings. Peak concentrations were about 1200 ppm and generally the highest concentrations were measured during the night when the occupants were at home.

People spend up to 90 % of their time indoors [5]. The researchers in reference [6] studied occupational and energy patterns for 158 families living in the outskirts of Athens, using questionnaires. Occupancy rate patterns during the day were described for different family members and typical families, and activity patterns for different electrical appliances are presented. According to [7], the reported occupancy density in 386 Swedish apartments, based on questionnaires, was 2.1 persons per apartment and varied between averages of 1.9 and 2.5 in the studied properties.

Recommended occupation density according to reference [8] for use in energy simulations for Swedish conditions are, for a single room apartment, 1.42 persons and for a two bed room apartment 2.18 persons and an attendance time of 14 hours per day. The average dwelling area per person in Sweden during 2009 was 57 m^2 for all dwelling types and 50 m^2 for multi-family dwellings [9]. These values are very low compared with the studied occupancy density in Hong Kong [10] that was about 12 m^2 usable floor area per person, which illustrates that occupancy characteristics have to be studied locally and that results are not necessary representative for other locations.

Even if some studies on occupancy levels in housing are available, they are few, and they usually did not give results over longer periods, and they do not combine occupancy levels with other energy and moisture related issues in housing. Therefore, the researchers in reference [11] started a holistic study of energy use and indoor climate, including measurements of household electricity use, domestic hot water use, indoor temperature, indoor relative humidity, and CO_2 with readings every 30 minutes during more than a year in several Swedish multi-family buildings at four different locations, from lat 55.6° to lat 67.9°. This paper presents the part of the results on occupancy levels and an application to demand controlled ventilation. Moisture results are presented in [12] and [13].

1.1 Objectives

The aim of this study was to measure the occupancy level in multi-family dwellings based on the CO_2 concentration of the indoor air, to present averages and standard deviations of occupancy level, and to study the variation in occupancy during the year, week and day respectively. Another aim was to apply the measured occupancy to a life cycle cost analysis of demand controlled ventilation, including initial costs for construction and running costs for energy and maintenance, to compare it with a constant airflow system.

2 METHODS

2.1 Measured and calculated parameters and definitions

By taking measurements in the exhaust air of residential buildings, a large number of apartments could be included in the study at a reasonable cost, compared with taking measurements in every individual apartment. On the other hand, it is not possible to find distributions between apartments inside a certain residential building or distributions between different rooms in an apartment. Measurements of CO_2 were carried out every 30 minutes to make it possible to obtain daily and weekly time distributions as well as daily and weekly spans. Measurements were carried out during at least one year, to obtain annual time distribution and to be able to evaluate the method during different outdoor conditions.

Occupancy levels were calculated based on the measured CO_2 concentrations, indoors and outdoors, and the ventilation airflow. The ventilation airflow was constant and taken from commissioning measurements. The production of carbon dioxide can be described by Equation 1 where C_p is the carbon dioxide production in l/s, C_{in} is the carbon dioxide volume concentration in the exhaust air, and C_{out} is the carbon dioxide volume concentration in the outdoor air and q is the ventilation airflow of the building in l/s including leakage. It is assumed that there is no buffering. The effect of buffering and time lags will be a matter for future analysis. If a single person produces c_p l/s carbon dioxide indoors, Equation 2 gives the equivalent number of persons, n, in the building. C_p can be corrected for other producing or reducing sources in the building. This gives the equilibrium state of occupancy, as there is a transient build up and a transient decay time. Due to the linearity, the average will be described by Equation 2. The error is a time lag in the occurrence of occupancy.

$$C_p = (C_{in} - C_{out}) \cdot q \qquad (1)$$

$$n = \frac{C_p}{c_p} \tag{2}$$

Since the metabolic rate varies with activity level, age, sex and weight, an average c_p has to be determined. Reference [14] gives values per body weight for adults, as an average of men and women, as 0.17 l/(s·kg) while sleeping, 0.26 l/(s·kg) while sitting and 0.30 l/(s·kg) while standing. The researchers in reference [15] analysed carbon dioxide generated by children, based on reference [16]. Children produce 1.74 times as much CO_2 as adults per kg body mass. The average weight of adult Swedes, if it is assumed that there are equal numbers of men and women, is 74.5 kg [17]. For the estimation of c_p, it was assumed that people spend 14 h a day in their homes [8]. It was assumed that 8 h were spent sleeping, 4.5 h sitting and 1.5 h standing. If it is assumed that children on average weigh half as much as adults, and 83 % of the population are adults, the average c_p became 15.0 l/h. It would be possible to try to vary c_p over the day, but that would introduce several uncertain parameters.

In this paper, the occupancy level is generally shown as the absolute occupancy level, O_a, i.e. the number of persons per apartment area, which is abbreviated to p/m^2. In the analysis, the word 'span' is used to describe the difference between a maximum and minimum value during a certain period of time. Daily span means the highest 30-minute occupancy level reading minus the lowest 30 minute occupancy level reading during a 24-hour calendar day period. Weekly span means the highest minus the lowest daily average occupancy level during a calendar week, Monday to Sunday.

2.2 Measuring equipment and possible errors

The measurement sensors were placed in the central exhaust close to the exhaust fan before possible heat recovery coils. The indoor carbon dioxide sensors were calibrated every 6 months. The manufacturer, SenseAir, stated the error of the carbon dioxide sensor as ± 30 ppm ± 3 % of the reading with a repeatability error of ± 20 ppm ± 1% of the reading, but to reach this accuracy, the sensor must be calibrated. It is probable that the error corresponds to the total error due to the rather long times between calibrations, if absolute values are of interest. If variations during periods of a week or less are of interest, the relevant error is most probably the repeatability error. At a measured value of 700 ppm, this means ± 51 ppm and ± 27 ppm respectively. At outdoor values of approximately 400 ppm, this means ± 42 ppm and ± 24 ppm respectively. Logger errors were small in comparison, ± 2.5 % of the reading according to the manufacturer Onset, with an almost zero repeatability error. The airflow measurements can have a typical error of ± 10 % with a repeatability of ± 5 % [18]. For daily and weekly variations it is probable that the error corresponds to the repeatability, which gives a probable occupancy level error of ± 8.7 %. For annual variations and seasonal variations, the probable occupancy level error becomes ± 17 %. It was not stated whether the CO_2 sensor error was related to indoor temperature, that was fairly constant, or relative humidity, that varied more, or other dust/matter? present in the indoor air. It was assumed that the errors were random.

Measuring in the total exhaust air of a building means that it is not possible to know the distribution inside or between apartments. It only gives the airflow weighted point values at the exhaust devices. On the other hand, measuring in a single room does not give information about an entire apartment or the entire building. It is believed that the representation of the apartment is plausible.

Other CO_2 producing processes beside the metabolism of the occupants were unknown when the occupancy level was studied. On the other hand, these processes also need ventilation, which means that their effects could plausibly correspond to the ventilation need. The same can be argued about the internal heat gains.

Besides constant mechanical exhaust ventilation, the kitchen stove air in the studied buildings was also led through the same ducts as the rest of the exhaust air. Exhaust air was, in general, taken from bathrooms and kitchens, and outdoor air inlets were located in bedrooms and living rooms.

Buildings are exposed to air leakage due to wind and buoyancy that changes the air in the apartments in addition to the mechanical ventilation. The actual air change rate could be measured with tracer gas methods but it would be expensive to do this continuously during a whole year and not realistic, if many buildings are to be included. On the other hand, this error is minimized in buildings with mechanical exhaust air only. This will lead to a lower indoor pressure, which reduces the exfiltration, resulting in reduced air change from leakage. Typically, the leakage is decreased by a factor of 5 compared with a building with balanced ventilation [19]. If a building has a mechanical exhaust air system and an airtightness of 0.8 $l/(s \cdot m^2$ surrounding walls) at 50 Pa testing pressure, a constant airflow rate of $1\ \% \cdot 0.8\ l/(s \cdot m^2)$ can be assumed in normal conditions in the south of Sweden [19]. If 1.4 m^2 surrounding area per 1 m^2 floor area is assumed, 0.011 $l/(s \cdot m^2$ floor) is added to the mechanical ventilation. This can be corrected for in the analysis but is small compared to a normal ventilation airflow such as stipulated in the former Swedish building regulations [20]. These require a ventilation airflow of 0.35 $l/(s \cdot m^2$ floor), which corresponds to an air change rate of 0.5 h^{-1} at an interior room height of 2.4 m.

If people in the buildings open windows, the air change rate increases dramatically [21]. That could mean that during the summer period, the measured values are only valid close to the exhaust devices. In all studied buildings the central exhaust duct included exhaust air from common spaces such as staircases and storage rooms and hence the measured values are the average values for the whole ventilated volume inside the building.

2.3 Data analysis

The variations in occupancy levels on a yearly, weekly and daily basis were analysed. The variations during the year are presented as monthly averages. The weekly variations were calculated as the difference between a specific day's average measured value and the corresponding weekly average. Variations during the day were calculated as the difference between each 30 minute measured value and the corresponding daily average measured value. The variations during the day were calculated for weekdays and weekends respectively. The presented variations during a week and a day provid the typical daily and weekly profiles, with information about time of day and the weekly peaks, and when increases and decreases typically occur.

The method for calculating variations during the week and the day means that the difference between the highest and the lowest value in the presented variations will be smaller than the defined average span, if the maximum or minimum occurred at different times of the days or weeks respectively. Even if the resulting variation is smaller than the logger error, the logger error was believed to be random and did not occur at certain times of the day or week. To give the magnitude of the variations, the daily and weekly spans were calculated.

2.4 Application to demand controlled ventilation

An application where the knowledge about occupancy levels is important is the economical and energy benefit from a demand controlled ventilation system. Each ventilation system can either have a constant airflow (CAV) or a variable airflow (VAV). One idea behind having a variable airflow rate is to decrease the airflow at lower occupancy levels, ventilating when there is a need for it only. Variable airflow ventilation based on the demand for air only is sometimes called Demand Controlled Ventilation (DCV), and can be used to decrease the amount of energy used to heat and cool the supply air and to move the supply and exhaust air. However, a variable airflow ventilation system has higher installation and maintenance costs than a system with constant airflow. Life cycle costs (LCC) for different ventilation systems in a theoretical multi-family dwelling, both with and without variable airflow based on the occupancy level, were calculated to judge the economical benefit of a demand controlled system.

The life cycle costs of the heating and ventilation systems were simulated using a computer program for life cycle costs of indoor climate systems, ProLive [19]. It takes into account the initial costs for buying and installing components using a power demand calculation as well as energy costs, maintenance costs, repair costs and costs for space loss due to system components. In the costs, hydronic heating and connection to district heating is included. Costs are based on Swedish prices from Sektionsfakta [22], which is a known cost database for the building sector. ProLive uses Swedish costs in SEK excluding VAT (25% value added tax). 1 SEK ≈ 0.15 US$ ≈ 0.11 € as of 2011-02-01. Outdoor climate is obtained from the computer program Meteonorm [23]. Life cycle costing means here that future costs are discounted to their present day value, the net present value, by the use of a discount rate of interest. In this example, the price of heat was set to 0.6 SEK/kWh and the price of electricity was set to 0.8 SEK/kWh (both exclusive of VAT) to correspond to costs in 2003. The discount interest rate was assumed to be 1% for electricity, 2% for heat and 3% for other costs representing a real price increase for heat and even more for electricity. An annual cost of 800 SEK/m^2 related to floor was assumed for space loss. A 40 year calculation period was used. The scrap value and scrapping costs were assumed to be zero.

The input data for the building assumed no cooling, hydronic radiators for heating and four storeys. Assumed data for the building are given by Table 1. The outdoor climate data is from Stockholm, Sweden.
Table 1 gives the apartment areas, the window areas, the heat transmission areas and the number of people per apartment. The rooms with supply devices are the rooms that are not kitchens or bathrooms. Exhaust devices are located in the kitchens and in the bathrooms. It was assumed that there were two exhaust devices for each apartment, except for the four-room apartments where it was assumed that there were three exhaust devices. The building was assumed to be a medium weight construction.

Table 1. Data for the theoretical multi family dwelling used in the application example.

Storey height	3 m	Internal load presence		3 W/m^2
Building width	12 m	Internal load abscence		2 W/m^2
Total floor area	2080 m^2	Heat recovery efficiency		0.8
Room temperature	22°C	Heat plant efficiency		0.9
Heat transmittance	0.365 W/(m^2·K)	Solar rad. trans., SGHC		0.4
Supply air temperature	18°C	Leakage at 50 Pa		0.8 l/(s·m^2)
No. of rooms/apartment	1 room	2 rooms	3 rooms	4 rooms
No. of apartments	8	8	8	8
No. of persons/apartment	1	2	3	4
Window area	3 m^2	6 m^2	8 m^2	9 m^2
Apartment area	30 m^2	50 m^2	80 m^2	100 m^2
Heat transmission area	34.2 m^2	57.0 m^2	91.2 m^2	114 m^2

In Sweden, the requirement for ventilation airflow is currently 0.35 l/(s·m^2), where the area refers to the floor area [1]. If nobody is in the building, a third of this value, 0.12 l/(s·m^2), was used in the study to account for material pollution.

The systems included in this study were, an exhaust ventilation system (E) with air inlets at the windows in the rooms that were not kitchens or bathrooms, and a supply and exhaust ventilations system with heat recovery (SEH) with ceiling diffusers for supply air. Constant airflow and variable airflow were simulated. In the case of the variable airflow rate system, an airflow control damper (two for the supply and exhaust system) and an occupancy detector for 766 SEK were assumed to be included for each apartment, corresponding to an IR occupancy sensor and its installation. The occupancy detector could be a manually operated switch inside each apartment which would be cheaper, or a mixed gas sensor that would have approximately the same price. That means that the airflow was varied for the entire apartment and not for each room in each apartment. The analysis of appropriate sensors for demand controlled ventilation in dwellings is a matter of future research, but it is believed that both moisture and occupancy must be part of the control.

The relative occupancy level, O_r, is the ratio between the actual number of people in the building at a certain time and the number of people the building is designed for. In this study, it was assumed that O_r was constant over the year to simplify calculations. It was assumed that the designed airflow of 0.35 l/(s·m^2) was needed when $O_r = 1$ and that it was reduced linearly to a third, 0.12 l/(s·m^2), at $O_r = 0$, which is close to what is allowed in Sweden, 0.10 l/(s·m^2). The occupancy level also influences both the internal load from people and the internal load, excluding load from people according to Table 1.

3 RESULTS

The measured average occupancy level and corresponding standard deviations are presented for outdoor temperatures less than and higher than the yearly average outdoor temperature respectively, according to [24], for the different buildings in Table 2. The measurement period lasted for one year, starting during the summer and autumn of 2008 and continuing until the summer and autumn of 2009. Figure 1 shows the monthly average occupancy level. Figure 2 shows the duration of the occupancy levels at the different locations and the average level. Figures 3 and 4 show the weekly and daily variations. In these graphs, the deviation from the average is given. Figures 5 and 6 show the durations of weekly and daily spans.

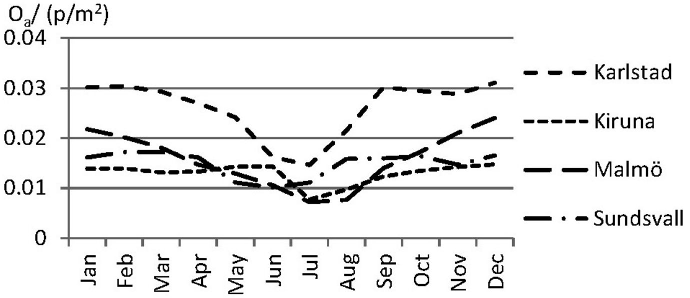

Figure 1. Monthly average occupancy levels at the different locations. The values shown are average values of all buildings at a specific location.

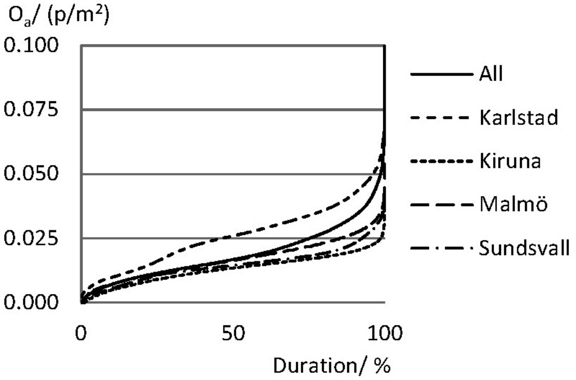

Figure 2. The duration of occupancy. The values shown are all the values of all buildings at a specific location. The 'All' curve is based on all the values of all buildings together.

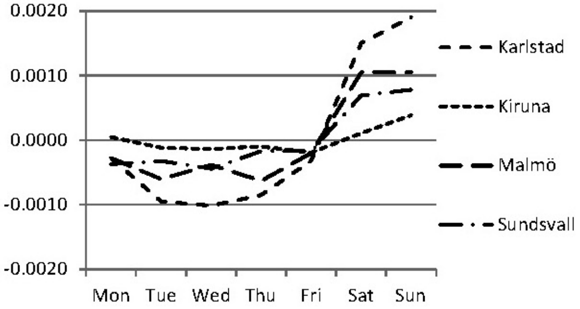

Figure 3. The variations in occupancy level during the week. ΔO_a is the average of (daily average minus weekly average). The values shown are average values of all the buildings at a specific location.

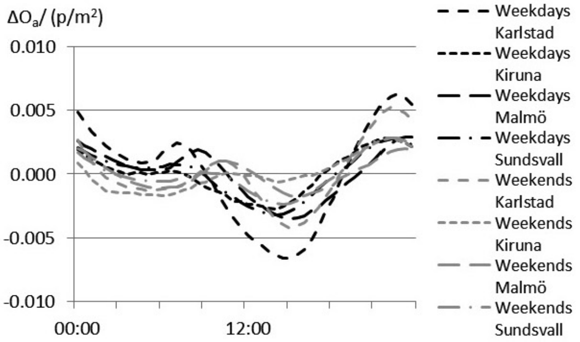

Figure 4. Variations in occupancy level during the day, presented for weekdays and weekends respectively. ΔO_a is the average of (30 minute reading minus daily average). The values shown are average values of all buildings at a specific location.

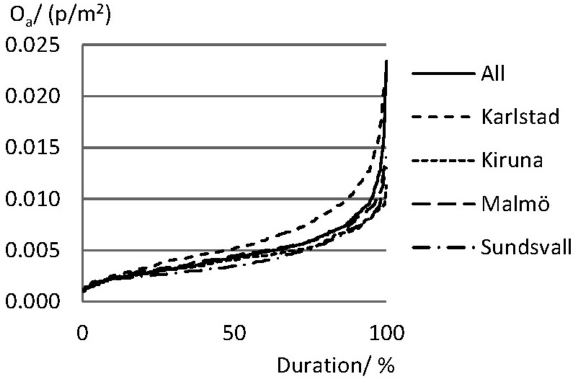

Figure 5. The duration of the weekly span.

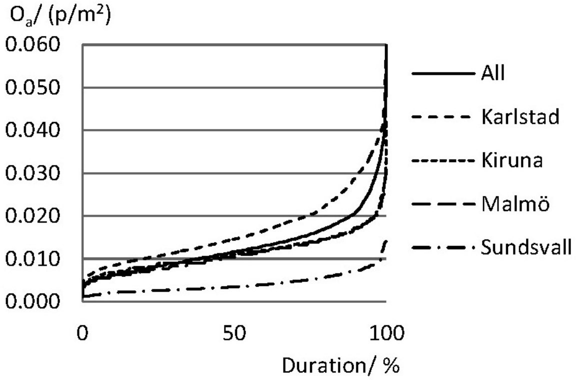

Figure 6. The duration of the daily span.

Table 2. Data showing number of apartments (Apt.) and buildings (Bld.) and the apartment floor area, averages and standard deviations, σ, of occupancy level, O_a, at the different locations at different outdoor temperatures, T, at or below the yearly averages of outdoor temperature and of outdoor temperatures higher than the yearly average outdoor temperature, T_{Avg}, and average occupancy levels for the whole measurement period.

Location	Number of Bld.	Number of Apt.	Apt. Floor area/ m²	T_{Avg}/ °C	O_a /(p/m²) ($T \le T_{Avg}$)	σ /(p/m²) ($T \le T_{Avg}$)	O_a /(p/m²) ($T > T_{Avg}$)	σ / (p/m²) ($T > T_{Avg}$)	O_a / (p/m²)
Karlstad	6	165	11443	5.5	0.030	0.006	0.023	0.008	0.026
Kiruna	4	42	2792	-1.7	0.014	0.004	0.013	0.005	0.013
Malmö	4	72	4920	8.2	0.020	0.005	0.011	0.006	0.015
Sundsvall	4	63	4800	3.6	0.017	0.004	0.013	0.006	0.015
Average					0.020	0.005	0.015	0.006	0.017

In all the studied buildings, the average occupancy levels were higher at outdoor temperatures less than the average outdoor temperature, 0.020 persons/m^2, compared with the average occupancy level at outdoor temperatures higher than the average outdoor temperature, 0.015 persons/m^2, which was expected due to, for example, increased window airing and subsequent higher total air exchange rates, and possibly more time spent outdoors during summer. The occupancy level per apartment at outdoor temperatures less than the average outdoor temperature was on average 1.4 persons per apartment and varied between 0.9 and 2.1 persons per apartment at the different locations.

The variations during the year, week and day, Figures 1, 3, and 4, had equal characteristics for all locations. The variations in monthly mean values during the year were considerable for most locations, see Figure 1. The difference between summer and winter month average occupancy levels were between 0.005 and 0.015 persons/m^2 at the different locations, with higher occupancy levels during the winter months than in summer. During summer, window airing is believed to be used to control indoor temperature and this affects the measured occupancy levels as discussed in the methods section. The monthly average occupancy levels measured in Kiruna were more or less constant during the year. Kiruna is located at Lat 67.9°, which is above the Arctic Circle, and hence the outdoor temperatures are relatively low compared with those at the other studied locations, which would reduce the need for window airing to maintain the desired indoor temperature.

It is reasonable to believe that the occupancy level would be higher during weekends, compared with weekdays, which was also indicated by the measurement results according to Figure 3. The differences between the weekdays are small compared with the differences between weekdays and weekends. According to Figure 5, the average span in daily average occupancy level during a week was 0.005 persons/m^2 which means that a typical weekend day has a 0.005 persons/m^2 higher occupancy level than a typical weekday.

During weekdays, the occupancy had minimums around 06:00 and 15:00, and maximums around 8:00 and 22:00, see Figures 4. During weekends, the morning maximum occurred about two hours later which is believed to be due to later morning habits during weekends, when people generally do not work or go to school. The difference in occupancy is highest between the minimum at 15:00 and the maximum at 22:00. According to Figure 6, the average daily span was 0.013 persons/m^2 which means that during a typical day, the occupancy level measured at 22:00 is 0.013 persons/m^2 higher than the occupancy level measured at 15:00.

3.1 Demand controlled ventilation in multi-family dwellings

Figure 7 gives the respective resulting life cycle cost and energy cost for the simulated theoretical multi-family dwelling as a function of the relative occupancy level, O_r. Litterature indicates tha O_r is close to 60 %. From this, it is shown that, based on life cycle cost, the best multi-family dwelling has a supply and exhaust ventilation system with heat recovery and variable airflow. A lower O_r means reduced average internal heat load which increases the need for heating but if the airflow is reduced at the same time, this increase is dampened or turned to a decrease.

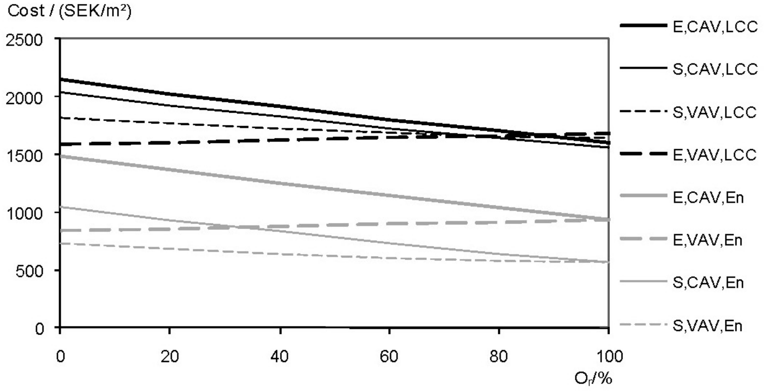

Figure 7. Life cycle cost (LCC) and energy cost (En) per floor area for the theoretical multi-family dwelling. E stands for exhaust ventilation, S for supply and exhaust ventilation with heat recovery, CAV for constant airflow and VAV for demand controlled ventilation.

4 DISCUSSION AND CONCLUSIONS

The variations during the year, week and day were systematic for all studied parameters and similar for all studied locations and the spans were of considerable magnitude. Measurements need to be performed during longer periods of time, if average values are to be obtained. If occupancy level is to be measured as an instantaneous value, the effect due to the variations should be taken into account. Results from shorter measurement periods might not be representative for other periods during a year, week or day. Since the values presented are average values from many apartments, the spans within a single apartment or a single room can be expected to be higher.

The overall problem when determining the relative occupancy level is to measure the maximum design occupancy level. It could be based on, as in the examples below, studies of living patterns. The problem is that occupancy levels change with time, and it is difficult to determine if a person who lives in an apartment is actually registered there and how 'regularly' he or she lives there. Maximum occupancy level can be based on the design of the ventilation airflow, but that does not need to be connected to how many people who can actually be in a building. Number of beds is an alternative, but there can be guest beds, and if there are, the ventilation should possibly not be designed for occasional extra guests. The same problem is not encountered in offices and classrooms, where the seats can be counted and the designed ventilation airflow should correspond to that number. Another way is to compare the average with the maximum level, or a high percentile. For example, the location average is close to a third of the highest level at each location respectively. The location average divided by the location 97 % percentile is between 50 and 53 %.
The absolute occupancy level, O_a, does not depend on the design values. The average occupancy level per apartment according to this study was 1.4 persons per apartment, which, combined with the occupancy density of 2.1 persons per apartment reported by [7], would indicate that the average occupancy level was about 68 %.

Low-energy buildings are designed to utilize internal heat gains from, for example, household electricity and occupants and thereby the need for bought space heating is reduced. To accurately design low-energy buildings, it is therefore important to know the characteristics of the internal loads. Regarding occupants, this research presents an average difference of 0.013 persons/m^2 between the highest and lowest occupancy level during the day, according to Figure 8. Assuming heat gains of 100 W per person means that the average difference in heat gain from occupants during the day is 1.3 W/m^2. A passive house built according to the Swedish requirements [25] will have a total heat loss about 0.5 W/(°C·m^2) related to the heated floor area. That means that in a low energy building, the difference in occupants′ heat gains during the day is equivalent to a 2.6 °C difference in outdoor temperature. A normal day during the winter in a south Swedish outdoor climate has an amplitude in the daily outdoor temperature variation of 2 °C, which means a top to bottom difference of 4 °C [26]. According to this, varying internal heat gain from occupants is of an equivalent magnitude to the variations in outdoor temperature, which should be taken into consideration when predicting energy performance of buildings. A varying outdoor temperature is commonly used in simulations in research, as well as in practice, and this should also be the case when it comes to the varying internal heat gain from occupants.

User-related energy uses such as household electricity and domestic hot water heating, are most probably dependent on the number of occupants. Verifications of these energy uses would benefit from comparison not only to building characteristics, for example, floor area or number of apartments, but also with the number of occupants. It should be of interest to carry out these comparisons on different timescales and use them as feedback. An extreme increase in use of domestic hot water from one month to another, or from one year to another, might be explained by an increase in occupancy level. These comparisons are normally not possible to make due to the lack of measurements of occupancy levels in buildings.

The variations obtained in this study, with constant ventilation airflow in the studied buildings, shows a highly varying occupancy level over time, which indicates the potential of demand controlled ventilation in dwellings. This is an issue for future analysis. The application of demand controlled ventilation in a theoretical multi-family dwelling located in Stockholm, Sweden, shows clear benefits from a life cycle cost perspective at the measured occupancy levels. The prices of components and sources of energy change with time. Updated prices would give even faster payback times, as energy prices have increased more than other costs. More research into how to design and install demand controlled ventilation in dwellings in a correct way, to ensure both low energy use, moisture safety and a good indoor climate, is needed.

The measurement study took into account more parameters than occupancy levels, and future research will combine these parameters and look at possible relationships between the parameters and differences between locations. This study provides data on occupancy in multi-family dwellings in Sweden, shown as annual, weekly and daily variations. Together with other data, this can contribute to improving simulations and design.

ACKNOWLEDGEMENT

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PAPER 3
AP 3

Bagge H, Useful solar heat gains and combined air leakage and window airing heat losses in residential buildings – Multi parameter linear regression analysis, Submitted to Applied Energy 2011.

Useful solar heat gains and combined air leakage and window airing heat losses in residential buildings – Multi-parameter linear regression analysis

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Abstract

Multi-parameter linear regression was used to quantify useful solar heat gains and combined air leakage and window airing heat losses in residential buildings. The analysis was based on one year of measured data on daily use of heating in nine properties and their corresponding outdoor climates. Modern residential buildings often have large glazed areas and solar heat gains often represent a large part in the energy balances calculated by energy simulation tools. It is of interest to be able to verify the useful solar heat gains in actual buildings during operation. The same applies for air leakage heat losses. It is an important feature of a low energy building to have as little air-leakage as possible. The studied buildings had yearly average quantified useful solar heat gains of 13 kWh/m^2 heated floor area and quantified combined air leakage and window airing heat losses of 27 kWh/m^2. The quantification of useful solar heat gains and combined air leakage and window airing heat losses can be used to verify the energy efficiency of a building and the agreement with predicted values, and improve the quality of feedback to all involved in the building process regarding the actual building's performance during operation.

Nomenclature

A_H	Heated floor area, interior floor area of heated volumes, excluding garage	m^2
A_w	Window area	m^2
A_{wN}	Window area facing North	m^2
A_{wE}	Window area facing East	m^2
A_{wS}	Window area facing South	m^2
A_{wW}	Window area facing West	m^2
$T_{o.d.avg}$	Daily average outdoor temperature	°C
$G_{d.acc}$	Daily accumulated global radiation	Wh/m^2
$W_{d.\ avg}$	Daily average wind speed	m/s
Q_{USHG}	Useful solar heat gains	kWh
Q_{ALHL}	Combined air leakage and window airing heat losses	kWh
$Q_{USHG,\ 1}$	Useful solar heat gains, plausible	kWh
$Q_{ALHL,\ 1}$	Combined air leakage and window airing heat losses, plausible	kWh
$Q_{USHG,\ 2}$	Useful solar heat gains, principal	kWh
$Q_{ALHL,\ 2}$	Combined air leakage and window airing heat losses, principal	kWh
$Q_{d.H}$	Daily use of heating	kWh
Q_{SH}	Daily use of space heating	kWh
NWY	Normal weather year	

1 Introduction

To design a building that fulfils requirements regarding low energy use, it is crucial to perform energy simulations of the building in question during the design process and the simulations must represent the building during operation [1]. Research on the agreement between predicted and actual use of space heating in residential buildings in Sweden shows that measured use of energy for space heating during operation exceeds the predicted by between 50% and 100% even in low-energy buildings [1, 2, 3, 4]. There is a need to develop methods that analyses a buildings energy use and provides feedback to all involved in the building process regarding the actual buildings performance during operation and the agreement with predictions and assumptions during the design process.

Requirements regarding energy use are often set as annual use. That means that to verify whether a building fulfills requirements, it should be enough just to measure the annual energy use. However, more time resolved measurements and measurements of more energy end uses can increase the quality of the verification and give more feedback regarding the buildings performance.

Modern residential buildings often have a high percentage of window area in relation to heated floor area and solar heat gains often represent a large part in the energy balances calculated by energy simulation tools. A huge amount of solar heat gains will enter the building through the windows. Even if a certain amount of heat gains enter the building through the windows, it is not clear to what extent it will be useful. Whether or not the solar heat gains are useful and decrease the space heating demand depends on the building as a system, the building technique and the heating and ventilation systems, and their interactions with its occupants. It is of interest to be able to analyze how much solar heat gains actually affect the use of space heating in residential buildings during operation. The same applies to air leakage. It is an important feature of a low-energy building to have as little air leakage as possible and this is crucial in order to ensure a good indoor climate, moisture safety and sustainability. Higher wind speeds generally increase the air leakage and hence increase the energy use due to the greater volume of air that has to be heated to the room temperature. Increased air leakage might increase draughts, which the occupants might compensate for by choosing a higher indoor temperature. Window airing, which might be a way of compensating a poorly functioning mechanical ventilation system, will affect the energy use in the same way as described above.

Quantification of useful solar heat gains and energy use due to air leakage and window airing in buildings during operation would improve the quality of a number of parameters. These include the verification of a building's energy use, the assessment of the energy efficiency of a building, the feedback to architects, designers and construction workers and the verification of results from calculations and simulations.

In earlier studies [5, 6], linear regression analysis has been used to study the correlation and relation to different parameters of a building's energy use. Monthly measured energy use and multivariate analysis have been used to investigate the influence on the energy use of different building-specific parameters [7]. This paper presents a method that uses multi-parameter linear regression analysis based on daily measurements of energy use and outdoor climate to quantify useful solar heat gains and combined air leakage and window airing heat losses.

1.1 Objectives

Multi-parameter linear regression was used to analyze one year of measured data on daily use of heating at nine properties and their corresponding outdoor climates.
The aim of this study was to:

- Describe the use of heating as a function of outdoor temperature, global radiation and wind speed
- Quantify the useful solar heat gains
- Quantify the combined air leakage and window airing heat losses
- Compare useful solar heat gains and combined air leakage and window airing heat losses to window area and orientation of window areas at the studied properties.

1.2 Limitations

The weather parameters were measured in the same city as the studied properties but a few kilometres away. The studied properties are located right next to the sea, which is not the case of the corresponding weather station. Generally, it is believed that the wind speeds are somewhat higher at the studied properties than shown by the measurements.

The global radiation measurements do not give any information as to whether it is a day with sunshine from a clear sky or if it is overcast, since the global radiation is the sum of direct solar radiation and diffuse sky radiation. By using daily accumulated global radiation some information is lost. For example, during late spring, the day has many more daylight hours than a day in December. In December, sunshine from a clear sky during the few hours of daylight might equal the amount of daily accumulated global radiation during an overcast day with more daylight hours. However, the diffuse sky radiation can also be useful in the building. Days with high global radiation due to direct solar radiation might have high outdoor temperatures during the day while the night might have low outdoor temperatures due to the clear sky.

The daily average values are measured from 00:00 hours to 24:00 hours. This means that heat gained by the building during the day might do the building a favour the following day. Another alternative would have been to measure the day from sunrise to sunrise but the time of sunrise changes during the year and the ‘day’ would then not have 24 hours.

2 Method

In 2001, multi-family dwellings were built in nine properties in Västra hamnen, Malmö, Sweden, latitude N56. Several well-known Swedish architects were involved in designing the buildings, hence they reflect modern architecture. Data regarding the buildings is presented in section 2.5. Prior to their inauguration, the buildings were displayed at the international housing exhibition Bo01. The housing exhibition had an ecological and sustainability focus and hence all buildings were supposed to be energy efficient. A measurement program was set up to monitor the energy use of the buildings. This study was based on daily measurements of heating during 2005 in the different properties.

2.1 Multi-parameter linear regression analysis

Multi parameter linear regression analysis was used to describe the use of heating as a function of outdoor temperature, global radiation and wind speed based on the measured parameters $Q_{d.H}$, $T_{o.d.avg}$, $G_{d.acc}$ and $W_{d.avg}$. The software SPSS [8] was used for the analysis. The analysis included days that had $T_{o.d.avg}$ between 0 °C and 10 °C. Constants for the regression equation 1 were obtained for three different sets of outdoor climate parameters:

- Set 1: $T_{o.d.avg}$, $G_{d.acc}$, and $W_{d.avg}$
- Set 2: $T_{o.d.avg}$ and $G_{d.acc}$
- Set 3: $T_{o.d.avg}$

$$Q_{d.H} = m_1 + x_1 \cdot T_{o.d.avg} + x_2 \cdot G_{d.acc} + x_3 \cdot W_{d.avg} \qquad [1]$$

Equation 1 has x_3 as zero when used with parameter set 2 and, x_2 and x_3 as zero when used with parameter set 3. The constants for the regression equations and the corresponding R^2-values are presented for the different sets of parameters and the different properties. The regression equations describe how the building and its technical systems work as a whole in conjunction with its occupants during different conditions. During certain conditions, the heat gains balance the heat losses and there is no demand for space heating. However, if the measured heating is used for both space heating and domestic hot water heating, there will be a heating demand the year around. This use should be more or less constant in relation to the outdoor conditions. If a building's use of space heating depended only on the outdoor temperature, there would be a perfect correlation between heating and outdoor temperature, which can only be obtained in theory. If such a relationship existed, it would mean that the building could not make use of heat gains, given that the heat gains are not constant the year around, which is most certainly not the case with solar heat gains. Besides weather, the occupants will affect the energy use depending on how many people live in the building, their presence, how much household electricity and domestic hot water they use and what indoor temperature they want. The occupants will also affect the energy use depending on how much they ventilate the apartment through open windows and how solar shading is used. This could be called energy-related behavior and its effect on space heating is included in the regression equations. The R^2-values for the regression equations with different outdoor climate parameter sets are compared to determine what set of parameters best describes the use of space heating. The model that has the highest R^2-value is the "best" [8].

2.2 Space heating, useful solar heat gains and combined air leakage and window airing heat losses

The regression equations determined according to section 2.1 and the outdoor climate parameters $T_{o.d.avg}$, $G_{d.acc}$ and $W_{d.\,avg}$ during a normal weather year, NWY, for Malmö according to Meteotest [9] was used to calculate the annual use of space heating, Q_{SH}, for each property respectively. Daily use of space heating was calculated as $Q_{d.H}$ minus the average daily use of domestic hot water heating, according to [10]. Daily use of space heating was set to zero if $Q_{d.H}$ was less or equal to the daily use of domestic hot water heating.

Useful solar heat gains, Q_{USHG}, and combined air leakage and window airing heat losses, Q_{ALHL}, were calculated as the difference between Q_{SH} during a NWY and Q_{SH} calculated with reduced $G_{d.acc}$ and $W_{d.\,avg}$ respectively according to equations 2 and 3.

$$Q_{USHG} = Q_{SH}{}^{*} - Q_{SH}{}^{**} \qquad [2]$$

$Q_{SH}{}^{*}$: Space heating calculated according to equation 1 with outdoor climate parameters $T_{o.d.Avg.}$, $G_{d.acc.}$and $W_{d.Avg.}$ as during a NWY.

$Q_{SH}{}^{**}$: Space heating calculated according to equation 1 with outdoor climate parameters $T_{o.d.Avg.}$, and $W_{d.Avg.}$ as during a NWY and reduced $G_{d.acc.}$.

$$Q_{ALHL} = Q_{SH}{}^{*} - Q_{SH}{}^{**} \qquad [3]$$

Q_{SH}^{*}: Space heating calculated according to equation 1 with outdoor climate parameters $T_{o.d.Avg.}$, $G_{d.acc.}$and $W_{d.Avg.}$ as during a NWY.

Q_{SH}^{**}: Space heating calculated according to equation 1 with outdoor climate parameters $T_{o.d.Avg.}$, and $G_{d.acc.}$ as during a NWY and reduced $W_{d.Avg.}$.

A building that utilizes solar heat gains will have a negative Q_{USHG} which means that Q_{USHG} decreases the energy use and a building that has air leakage heat losses will have positive Q_{ALHL} meaning that Q_{ALHL} increases the energy use.

2.3 Window area and orientation

Multi parameter linear regression analysis was used to study the Q_{SH}, Q_{USHG} and Q_{ALHL} relationships to window area and orientation. The software SPSS [9] was used for the analysis. Regression equation 4 describes the energies as functions of A_w/A_H. Regression equation 5 describes the energies as a function of A_{wN}/A_H, A_{wE}/A_H, A_{wS}/A_H and A_{wW}/A_H.

$$Q = m_2 + y_1 \cdot \frac{A_w}{A_H} \qquad [4]$$

$$Q = m_3 + z_1 \cdot \frac{A_{wN}}{A_H} + z_2 \cdot \frac{A_{wE}}{A_H} + z_3 \cdot \frac{A_{wS}}{A_H} + z_4 \cdot \frac{A_{wW}}{A_H} \qquad [5]$$

2.4 Outdoor climate

Figures 1 to 6 show the weather parameters $T_{o.d.avg}$, $G_{d.acc}$ and $W_{d.\,avg}$ during 2005 and a NWY according to [9]. The average outdoor temperature was 8.9 °C during 2005 compared to 8.5 °C during a NWY. The corresponding average daily global radiations were 2813 Wh/m^2 and 2713 Wh/m^2 and the corresponding average wind speeds were 3.2 m/s and 4.8 m/s.

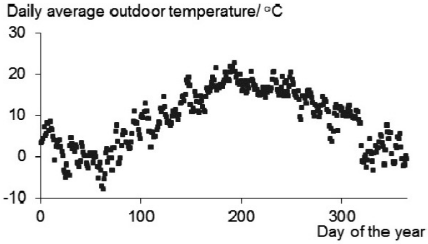

Figure 1. Daily average outdoor temperature in Malmö during 2005.

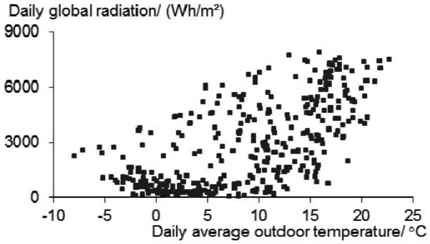

Figure 2. Daily accumulated global radiation as a function of daily average outdoor temperature in Malmö during 2005

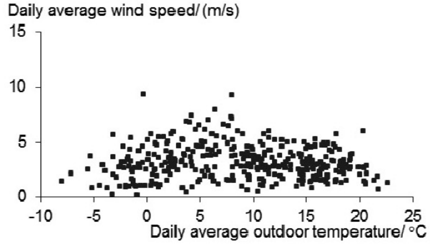

Figure 3. Daily average wind speed as a function of daily average outdoor temperature in Malmö during 2005.

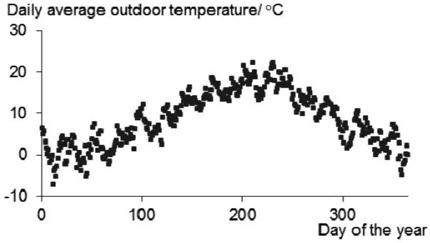

Figure 4. Daily average outdoor temperature in Malmö during a NWY.

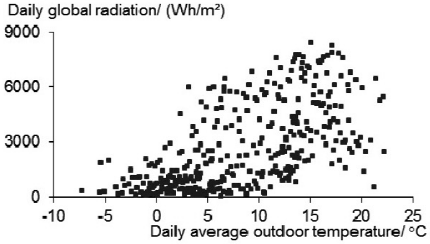

Figure 5. Daily accumulated global radiation as a function of daily average outdoor temperature in Malmö a NWY.

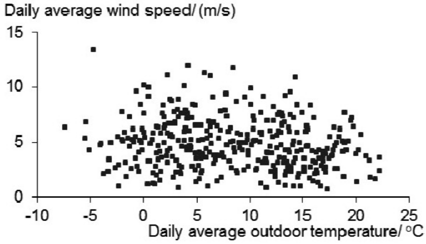

Figure 6. Daily average wind speed as function of daily average outdoor temperature in Malmö a NWY.

2.5 The examined properties

The buildings at the studied properties were erected during 2000 and 2001. Generally, there was a high-rise building of five stories and a row of? terraced houses in each property. The building techniques used and the characteristics of the buildings in the examined properties have been described by [4; 11]. Table 1 presents data for the buildings in the examined properties regarding number of apartments and area. Properties 1, 5 and 8 had commercial space. In Property 1 there were two clothes shops, at Property 5 a coffee house and at Property 8 two restaurants and a clothes shop.

All properties except Properties 5 and 8 used hydronic radiators while Properties 5 and 8 used hydronic under floor heating. Property 7 used both hydronic radiators and hydronic under floor heating. All properties except Properties 7 and 8 used electronic comfort heaters in bathrooms. All buildings except Properties 2 and 6 used mechanical exhaust ventilation. Properties 1, 3, and 5 used exhaust air heat pumps that supplied space heating. In Properties 2 and 6 each apartment had its own air handling unit consisting of supply and exhaust air fans and a heat pump. The heat pump prioritised heating the domestic hot water and then heated the supply air. In Property 9, the supply air to the garage was extract air from the apartments.

Figure 7 shows window area per heated floor area and orientation of the window area in the different properties. Window area includes both frame and glazed area. Seven of the nine properties studied had a greater proportion of their window areas facing west than other directions. Properties that had large window areas facing west were typically placed where they had a view of the sea in that direction. These properties had no buildings or other obstacles in front of their west façades.

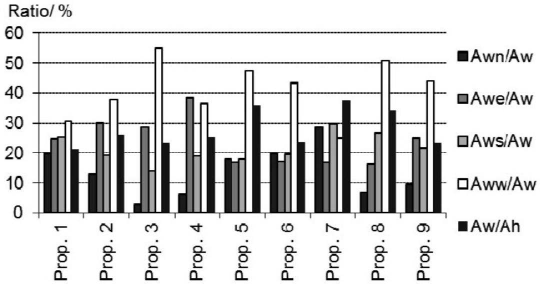

Figure 7. Window area per heated floor area and orientation of the window area in the properties.

Table 1. Data regarding the number of apartments in the buildings and the different floor areas of interest.

	Apartments in the high-rise building	Apartments in the terraced house	Total heated floor area /m²	Heated floor area excluding garage, A_H /m²	Apartment floor area /m²
Prop. 1	37	4	7550	5463	4001
Prop. 2	9	2	1570	1445	1242
Prop. 3	16	7	4749	3546	2002
Prop. 4	15	5	4075	2623	1657
Prop. 5	23	-	6251	3115	2656
Prop. 6	8	3	1750	1739	1309
Prop. 7	27	-	4322	3467	2667
Prop. 8	21	1	3772	2437	2686
Prop. 9	13	5	3366	2390	1621

3 Results and Discussion

3.1 Multi-parameter linear regression

Table 2 presents the constants for the regression equations according to equation 1 and the corresponding R^2-values for the studied properties respectively. In all cases the significance was zero. For all properties the R^2-value increased with increased number of parameters in the regression analysis which means that Q_{SH} has better correlation to $T_{o.d.avg}$ and $G_{d.acc}$ than to just $T_{o.d.avg}$ and better correlation to $T_{o.d.avg}$, $G_{d.acc}$ and $W_{d.\ avg}$ than to $T_{o.d.avg}$ and $G_{d.acc}$. On average, the R^2-value increased by 0.22 when all three weather parameters are included in the regression analysis compared with $T_{o.d.avg}$ only. This indicates that the addition of global radiation and wind speed improves the prediction of space heating than when outdoor temperature alone is used. For regression equations based on $T_{o.d.avg}$, $G_{d.acc}$ and $W_{d.\ avg}$, the R^2-value is on average 0.89, higher than 0.9 in six cases out of nine and higher than 0.77 for all cases, which indicates that these three weather parameters describe a great part of the use of heating during the heating season.

3.2 Useful solar heat gains and combined air leakage and window airing heat losses

Useful solar heat gains and combined air leakage and window airing heat losses were calculated according to equation 2 and 3. It can be questioned whether equation 1 with constants according to Table 2 is representative for $G_{d.acc}$ and $W_{d.\ avg}$ that are close to or equal to zero since the data that they are based on does not contain a zero value of $G_{d.acc}$ and $W_{d.\ avg}$. Regarding air leakage, the temperature difference between indoors and outdoors and the buoyance will create air leakage also at wind speeds of zero. However, if it is assumed that extrapolations of the effect from $G_{d.acc}$ and $W_{d.\ avg}$ are accurate down to zero, setting the parameter of interest to zero should give a more principal value of the energies. Hence, useful solar heat gains and air leakage heat losses were calculated for two different conditions. The first provide more plausible values, calculated with the outdoor climate parameter of interest set to monthly minimums according to Table 3. The second provide principal values, calculated with the outdoor climate parameter of interest set to zero.

- $Q_{USHG,\,1}$ calculated with reduced $G_{d.acc}$ according to Table 3.
- $Q_{USHG,\,2}$ calculated with $G_{d.acc}$ as zero.
- $Q_{ALHL,\,1}$ calculated with reduced $W_{d.\,avg}$ according to Table 3.
- $Q_{ALHL,\,2}$ was calculated with $W_{d.avg}$ as zero.

Table 4 shows calculated values of Q_{SH}, $Q_{USHG,\,1}$, $Q_{USHG,\,2}$, $Q_{ALHL,\,1}$, $Q_{ALHL,\,2}$ and their averages, medians and standard deviations. As expected, $Q_{USHG,\,2}$ and $Q_{ALHL,\,2}$ were higher than $Q_{USHG,\,1}$ and $Q_{ALHL,\,1}$. $Q_{USHG,\,1}/A_H$ was on average -12.8 kWh/m^2 while $Q_{USHG,\,2}/A_H$ was -17.5 kWh/m^2. $Q_{ALHL,\,1}/A_H$ was on average 23 kWh/m^2 while $Q_{ALHL,\,2}/A_H$ was 28.5 kW h/m^2. There is a high variation in the energies between the properties, which is illustrated by relatively high standard deviations and the ratio between averages and standard deviations not being higher than two in any of the cases. $Q_{ALHL,\,1}$ and $Q_{ALHL,\,2}$ are on average more than twice as high as $Q_{USHG,\,1}$ and $Q_{USHG,\,2}$. This might indicate that it is more important to improve air tightness of the building envelope than promote access to solar heat gains to achieve low energy use. The solar heat gains are only available during parts of the day while the wind is present at all times of the day.

Table 2. Constants for the regression equation 1 with different sets of outdoor climate parameters and corresponding R^2-values.

	Parameter set	m_1	x_1	x_2	x_3	R^2
Prop. 1	1	1713	-165,4	-0,07	77,2	0,79
	2	1992	-158,1	-0,09	-	0,75
	3	1931	-179,3	-	-	0,69
Prop. 2	1	525	-31,5	-0,04	32,6	0,91
	2	653	-29,5	-0,05	-	0,81
	3	597	-39,3	-	-	0,52
Prop. 3	1	1126	-78,5	-0,084	25,7	0,86
	2	1219	-76,1	-0,09	-	0,85
	3	1158	-97,3	-	-	0,66
Prop. 4	1	986	-57,7	-0,038	29,0	0,93
	2	1091	-55,0	-0,045	-	0,89
	3	1060	-65,6	-	-	0,77
Prop. 5	1	1587	-139,6	-0,11	137,2	0,78
	2	2084	-126,6	-0,146	-	0,67
	3	1985	-160,9	-	-	0,53
Prop. 6	1	625	-41,0	-0,033	20,4	0,95
	2	699	-39,0	-0,039	-	0,91
	3	673	-48,1	-	-	0,75
Prop. 7	1	2749	-150,9	-0,107	105,2	0,94
	2	3130	-141,0	-0,134	-	0,87
	3	3040	-172,5	-	-	0,72
Prop. 8	1	2629	-133,5	-0,092	90,0	0,90
	2	2955	-125,0	-0,115	-	0,83
	3	2877	-152,1	-	-	0,70
Prop. 9	1	1231	-66,8	-0,079	35,6	0,93
	2	1360	-63,5	-0,088	-	0,90
	3	1300	-84,3	-	-	0,66

Table 3. Monthly minimums of $G_{d.acc}$ and $W_{d.\,avg}$ during a NWY in Malmö.

	jan	feb	mar	apr	maj	jun	jul	aug	sep	okt	nov	dec
$G_{d.acc}$/(Wh/m^2)	73	368	828	669	1263	987	1392	515	808	201	118	87
$W_{d.avg}$/(m/s)	1.0	1.5	1.1	5.1	0.8	1.0	1.0	1.0	0.7	1.3	0.8	1.1

Table 4. Calculated annual use of space heating, useful solar heat gains and combined air leakage and window airing heat losses.

	Q_{SH}/A_H /(kWh/m^2)	$Q_{USHG,\,1}$ /A_H /(kWh/m^2)	$Q_{ALHL,\,1}$ /A_H /(kWh/m^2)	$Q_{USHG,\,2}$ /A_H /(kWh/m^2)	$Q_{ALHL,\,2}$ /A_H /(kWh/m^2)
Prop. 1	31.4	-3.3	11.4	-4.5	14.3
Prop. 2	83.3	-16.1	25.5	-22.1	31.4
Prop. 3	58.1	-9.7	31.0	-13.4	37.7
Prop. 4	51.4	-7.1	12.3	-9.6	15.3
Prop. 5	87.9	-12.8	40.8	-17.8	50.1
Prop. 6	68.2	-9.2	12.7	-12.6	15.9
Prop. 7	151.0	-17.4	35.1	-23.7	43.5
Prop. 8	213.1	-26.0	46.8	-34.2	58.0
Prop. 9	75.5	-16.8	16.2	-23.6	20.2
Average	93.0	-12.7	27.0	-17.2	33.3
Median	75.7	-11.2	28.2	-15.6	34.6
Std. dev.	56.2	6.6	12.9	8.7	15.8

Table 5. Constants for the regression equations 4 and 5 and corresponding R^2-values.

Dependent variable	R^2	m_1	m_2	y_1	z_1	z_2	z_3	z_4
$Q=Q_{SH}$	0.52	120.3		7.25				
$Q=Q_{USHG,\,2}$	0.42	11.6		-1.02				
$Q=Q_{ALHL,\,2}$	0.70	-44.2		2.53				
$Q=Q_{SH}$	0.90		-41.1		-802.1	-703.2	2626.8	377.2
$Q=Q_{USHG,\,2}$	0.71		3.8		120.5	73.5	-335.3	-86.7
$Q=Q_{ALHL,\,2}$	0.85		-29.4		111.7	-70.43	400.4	281.5

3.3 Window area and orientation

Table 5 shows the calculated energies Q_{SH}, $Q_{USHG,\,2}$ and $Q_{ALHL,\,2}$, according to Table 4, and their correlations to window area and window areas in certain orientations and the constants for regression equations 4 and 5. The regression analysis of the energies and window areas, and energies and window areas in certain orientations, are based on a relatively limited sample and the conclusions should be interpreted with the limited sample in mind. The R^2-values are relatively high for correlations especially between Q_{SH} and window areas in certain orientations, and $Q_{ALHL,\,2}$ and window areas in certain orientations. The correlation between $Q_{ALHL,\,2}$ and window areas in certain orientations is stronger than the correlation between $Q_{USHG,\,2}$ and window areas in certain orientations, which is also the case regarding the corresponding energies' correlations to A_w/A_H. This might be due to air leakages being common around windows and the use of window airing increasing with increasing window area causing more solar heat gains that might result in high indoor temperatures. Q_{SH} increases with increasing window area, which is expected since windows have much higher transmission losses than walls and the increase in $Q_{USHG,\,2}$ with increasing window area is small in relation to the increase in Q_{SH} according to Table 5. According to the results in Table 5, the increase in $Q_{USHG,\,2}$ with increased window area is rendered negligible by the more than twice as high increase of $Q_{ALHL,\,2}$. Comparing the air leakage heat losses in different buildings with their respective measured air-tightness is an area for future research.

4 Conclusions

Multi-parameter linear regression analysis was used to describe the use of space heating as a function of outdoor temperature, global radiation and wind speed. Based on the regression analysis, useful solar heat gains and combined air leakage and window airing heat losses were quantified. These quantifications can be used to verify the energy use of a building and the agreement with predicted values. A divergence here calls for an investigation to clarify whether the predicted useful solar heat gains and air leakage and window airing heat losses were erroneous or whether the building technique used and the technical systems were not working correctly. Compared with using annual use of energy only, to verify energy use, quantification of useful solar heat gains and combined air leakage and window airing heat losses should improve the understanding of a building's energy efficiency. It should also improve investigations regarding discrepancies and improve the quality of feedback to all involved in the building process regarding an actual building's performance during operation.

In the studied buildings, the use of space heating had a relatively strong correlation to window area and even more to window areas in a certain orientation, which was also the case regarding useful solar heat gains and combined air leakage and window airing heat losses, which all increased with increased window area. Although useful solar heat gains increased with increased window area, the use of space heating increased several times more for the same increase in window area. This is probably because windows have much lower insulation performance than walls and that air leakage and window airing heat losses increased more than twice as much as useful solar heat gains for the same increase in window area. This implies that a moderate window area would support energy efficiency.

The presented method can be used to study the air leakage heat losses before and after air-tightness improvements of existing buildings and verify whether and by how much the improvements affect the use of space heating, which can improve the reliability of cost-effectiveness estimations. It would be of interest to study the use of heat at a city level with respect to its correlation to climate parameters according to the method presented in this paper, which could improve forecasting and implementation of renewable energies in the system.

Acknowledgment
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ENERGY USE IN MULTI-FAMILY DWELLINGS – REQUIREMENTS AND VERIFICATION

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ABSTRACT

Energy use at nine properties containing 200 apartments erected during 2001 located in the south of Sweden has been studied. Before obtaining a building permit, the developers had to present calculations that proved that their building's energy use fulfilled specific requirements. The energy use was measured and compared to the requirements regarding energy use and predicted energy use. Despite of the specific goal of the projects, resulting total energy use varied by a ratio of three between the lowest and the highest and only one property out of nine fulfilled its goal. This stresses the importance of higher quality energy predictions, clear requirements, verifications and appropriate legal options to ensure that buildings achieve low energy use.

1. INTRODUCTION

The building industry is facing a great challenge. Energy efficiency has to be significantly improved in new, as well as existing buildings in order to reduce CO_2 emissions. This calls for actions from all involved in the building process, from architects and designers to construction workers and operation managers.

During 2001, the international housing exhibition Bo01 was held in Malmö, in the south of Sweden. This housing exhibition had an ecological and sustainability focus and the area was supposed to be self supporting in regards to energy with 100% being locally supplied renewable energy. There was also supposed to be an annual balance of energy supply and energy use at the area (Lövehed, 2005). To achieve this balance, all buildings were designed to use a maximum of 105 kWh/m^2 energy annually including space heating, domestic hot water, common electricity and household electricity (Quality Programme Bo01, 1999). The developers used different techniques to achieve the restrictions regarding energy use. Before receiving a building permit, the developers had to submit calculations that proved that their building's energy use was predicted to be less than 105 kWh/m^2. The Quality programme (1999) requires that the energy used at the properties were measured during two years after inauguration. The results from the measurements are presented with the intention of helping decision makers during the building process and to be a source of feedback to the building industry.

2. STATE-OF-THE-ART REVIEW

2.1 Reduction of greenhouse gas emissions

Sweden has to reduce the greenhouse gas emissions by 17%, excluding sectors included in the carbon emission trading system, before 2020 in relation to 2005 in order to meet the goal of reducing EU's greenhouse gas emissions by 20% before 2020 (Commission of the European Communities, 2008).

The Directive[25] on energy end use efficiency and energy services states that the energy use should be at least 9% more efficient by 2016 in relation to the time period 2001 to

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[25] Directive 2006/32/EC of the European Parliament and of the Council on energy end-use efficiency and energy services and repealing Council Directive 93/76/EEC, *Official Journal of the European Union.*

2005. According to the Directive, the mitigation of CO_2 and other greenhouse gas emissions will be reduced if the efficiency of energy end use is improved.

The energy use in the sector dwellings and service that consists of residential buildings, commercial buildings excluding industrial buildings, service buildings, agriculture, street lighting, sewage and power stations stands for 36% of the total energy use in Sweden. Within this sector, 87% is used in residential and commercial buildings for space heating, domestic hot water heating and operation of installations. (Swedish Energy Agency, 2006)

According to Klimatberedningen (2008) there is a need for more powerful means of control in the Swedish building regulation that should also include renovation, if the EU climate goals should be possible to achieve.

2.2 Regulations and requirements in Sweden

According to the Swedish building regulations (The National Board of Housing, Building and Planning, 2008), residential buildings must not use more than 110 kWh/m^2 in the south and 130 kWh/m^2 in the north regions of Sweden, for bought energy including space heating, domestic hot water heating and electricity for operating the building. Within two years after the inauguration, the energy use must be measured during at least one year to verify that the requirement regarding energy is attained. In addition to this, there are many initiatives for energy efficient buildings in Sweden. The Bygga Bo project represents collaboration between companies, municipalities and the government (Glaumann *et al*, 2008). The project aims to promote development towards a sustainable building- and property sector. The projects have classification of buildings, new and existing, based on different environmental factors. Regarding energy use, the project defines three different levels. Level A, B and C corresponding to annual bought energy less than 110, 135 and 171 kWh/m^2 including space heating, domestic hot water heating and electricity for operating the building.

The Swedish specification of requirements for a passive house (Forum för energieffektiva byggnader, 2007a) have recommended a highest annual bought use of energy excluding household electricity, 45 kWh/m^2 in the south and 55 kWh/m^2 in the north. However the specifications require that the installed power for space heating shall not exceed 10 W/m^2 in the south half of Sweden and 14 W/m^2 in the north half. In buildings that have a heated floor area less than 200 m^2, the installed power shall not exceed 12 W/m^2 and 16 W/m^2 respectively.

The Swedish specification of requirements for a mini energy house only exists as a preliminary document (Forum för energieffektiva byggnader, 2007b). The document recommends that the highest annual total use of bought energy excluding use of household electricity shall be 45 kWh/m^2 in the south and 55 kWh/m^2 in the north. The total annual bought energy is calculated with a formula that favors district heating and biomass fuel meaning that a building that uses these can have a higher energy use and still fulfill the requirements. The specifications require that the installed power for space heating shall not exceed 15 W/m^2 in the south half of Sweden and 19 W/m^2 in the north half. In buildings that have a heated floor area less than 200 m^2 the installed power shall not exceed 17 W/m^2 and 21 W/m^2 respectively.

'Miljöbyggprogram syd' (Malmö Stad, 2008) is a program developed by the municipalities of Lund and Malmö, Sweden in cooperation with Lund University. Regarding energy use, the program defines three different levels: A, B and C. For residential buildings level A corresponds to a 'passive house', level B corresponds to a 'mini energy house' and level C corresponds to the requirements regarding energy use in the Swedish building regulations.

2.3 Predicted and measured energy use

To design a building that fulfils the requirements regarding energy use in the Swedish building regulations, it is crucial to perform energy simulations of the building in question during the building process (Bagge, 2007). The simulations must represent the building during operation and the calculated result shall be verified within two years after the inauguration by measurements of the energy use in the actual building during operation. According to Elmroth (2002) it is too common that measured energy use exceeds predicted use. Elmroth refers to a number of residential buildings in Stockholm, Sweden, built during the 1990s that have measured energy use exceeding the predicted by 50 to 100%.

Lindén (2006) studied the energy use at a housing area built in 2001 in Stockholm, Sweden. The buildings were designed to use no more than 60 kWh/m² annually, including all electricity. During operation, none of the buildings fulfilled that goal. Lindén concludes that the energy restriction set to 60 kWh/m² was impulsive and not based on what could be achieved in reality. Nilsson (2003) studied the energy use in the multi-family dwellings built for the housing exhibition Bo01 after the first year of operation. The use was about 50% higher than predicted. This was partly because an energy simulation program that was not appropriate for the actual buildings was used. (Bagge *et al*, 2006)

Karlsson *et al* (2007) studied energy use in passive houses built in Lindås, Sweden. The measured energy use during operation was 50% higher than the use predicted during the design phase. According to Karlsson *et al* this is partly due to higher indoor temperature and less efficient heat exchangers than predicted. Elmroth *et al* (2005) studied energy use in an energy efficient single family house in Malmö, Sweden. The measured total energy use agreed very well with the predicted use. However, the use of household electricity was higher and the use of space heating was lower compared to the predicted use. Karlsson *et al* (2007) stresses the importance of accurate input data for energy simulations. The building users' behaviour is very important in low energy buildings and also the hardest to model according to Karlsson *et al*.

2.3 Measured user related energy end uses

Energy related building user behaviour is, for example, use of household electricity, use of domestic hot water, occupancy rate and window airing. Time resolved data on these parameters are needed to perform accurate simulations of energy use (Bagge and Johansson, 2008a). Tso and Yau (2003), Riddell and Manson (1995), Capasso *et al* (1994) and Paatero and Lund (2006) studied the daily use patterns of household electricity in different projects in Japan and Europe during time periods of different length varying from 22 days to one year. Common for the different projects was that there were generally two peaks during the day, one during the morning or noon and one during the evening.

Papakostas *et al* (1995) monitored domestic hot water heating in four apartment buildings in a Solar Village in Greece. Average domestic hot water use patterns by day of the week were analysed. During weekdays, the patterns showed equal characteristics. There was one peak during the evening and one at noon. During weekends the peaks appeared earlier and the use was more uniform. Vine *et al* (1987) monitored domestic hot water use in four apartment buildings in San Francisco. During a typical day, there was a peak in use during the morning and another peak in the evening. Different usage patterns were observed for weekdays and weekends.

Lech *et al*. (1996) measured the amount of time spent indoors and Papakostas and Sotiropoulos (1997) studied occupational and energy patterns for 158 families living in the outskirts of Athens, using questionnaires. Occupancy rate patterns during the day were described for different family members and typical families, and activity patterns for different electrical appliances are presented.

There seems to be a lack of Swedish building user related data, showing both annual and daily variations, particularly for many parameters that can be correlated, including many apartments. Based on this shortage Bagge and Johansson (2008a; 2008b) started a study of household electricity use, domestic hot water use, indoor temperature, moisture production and CO_2 production with hourly measurements. Preliminary results show that the studied parameters have peaks at the same times during the day.

2.3 Decisions during the building process

Johansson (2005b; 2007b) discusses life cycle costing from the perspective of the energy use of a building and its climate system. It was shown that the life cycle cost can be decreased by the right system choice (Johansson, 2007a; 2008a) and optimisation (Johansson, 2005a; Johansson, 2008b). At the same time, in almost all cases, an optimisation means that the energy use is decreased since the commonly used level of energy related measures is low.

Nässén *et al* (2008) interviewed eleven persons who had experience from energy issues in the Swedish building sector including public authorities, construction and housing companies, architects and consultants. Nässen *et al* raised the question of the absent incentive to reduce life cycle costs of buildings when the building companies acts as their own client and sell directly to the housing market. According to one answer this is not a problem "since any client would simply stick to the energy performance which is defined by the building standards". The most common basis for decisions on energy efficiency investments in new buildings was, according to the interviews, the standard in the building regulations and most clients focus on minimising initial investment costs rather than life cycle costs.

Wijk *et al* (2005) sent a questionnaire to 345 random picked households that were prospective investors in a single family house. The response rate was 83%. According to the answers in the questionnaire, 57% preferred lower operation costs over lower investment cost.

3. RESEARCH PROJECT

3.1 Project description and objectives

The objective of this research project was to study the measured energy use in the multi-family dwellings built for the housing exhibition Bo01. This shows whether or not the different properties fulfilled the requirement regarding energy use in the Quality programme (1999) after the first years of use. The key values concerning energy use provided can be used to critically examine different designs and systems, and results from calculations. Energy use for space heating, domestic hot water heating, assimilation of solar heat gains, common electricity and household electricity is presented to give input that helps designers of buildings to fulfill requirements concerning low energy use.

3.2 Research methodology

When energy use in buildings is to be analyzed, the only method with reasonable accuracy is measurements of the physical parameters in a positivistic research approach. It would be interesting to combine these measurements with a hermeneutic approach with for example interviews and questionnaires for the building users, but in this research project, the focus has been limited to measurements. The energy use measurements were outlined before this research project was formed. The energy use and outdoor climate data were collected hourly. Data about the buildings, their construction and technical systems, were collected from the developers. To be able to analyze the energy use, a number of models and assumptions based on other studies and theories were used (Bagge, 2007).

4. RESEARCH RESULTS AND INDUSTRIAL IMPACT

4.1 Measured energy use

All the developers designed the buildings to achieve the same goal concerning energy use. The measured total energy use varied with a ratio of three between the lowest and the highest use during operation. The measured use was higher than the predicted in all but one case. Only one out of nine properties, fulfilled the requirement in the Quality program (1999), with total annual energy use below 105 kWh/m² heated floor area. Three properties used more than 190 kWh/m² annually, five properties used between 110 kWh/m² and 140 kWh/m² and one used 100 kWh/m². The total average annual energy use of all properties was 157 kWh/m² during 2005. Table 1 presents the average, lowest and highest use of; district heating, domestic hot water heating, common electricity and household electricity.

Table 1. Average, lowest and highest measured annual use.

Energy use (kWh/m²)	**Average**	**Lowest**	**Highest**
District heating	104	58	234
Domestic hot water heating*	23	19	25
Common electricity	20	6	52
Household electricity	35	22	47

*Domestic hot water heating is a part of District heating

The three properties that had the highest total energy use have three particular characteristics. They were the three properties with the highest window area in relation to heated floor area, they all had under floor heating as primary heat distribution system and they had the highest use of district heating.

The two properties that had the highest use of heat did not have any kind of exhaust air heat recovery. These properties had the highest and the third highest window area in relation to the heated floor area and under floor heating as the primarily heat distribution system. This indicates that a combination of the three characteristics; under floor heating, large window area and no heat recovery might be unfavorable from an energy use perspective.

The average use of district heating at properties that used under floor heating as primary heat distribution was 173 kWh/(m²·year) compared to 70 kWh/(m²·year) at properties that used radiators. The average use of district heating at properties without ventilation heat recovery was 145 kWh/(m²·year) compared to 72 kWh/(m²·year) at properties with ventilation heat recovery.

All the examined properties have a large ratio of windows in relation to heated floor area, varying between 22% and 38%. During the design phase, the useful solar heat gains were predicted to between 35% and 50% of the annual total heat losses. The measured annual useful solar heat gains was on average 14 kWh/m² and varied between 3 kWh/m² and 22 kWh/m² at the different properties. On average, the useful solar heat gain was 17% of the annual use of district heating.

4.2 Same function, different systems

A building that appears to have a low use of heating might have that because the domestic hot water was heated by, for example, electricity. This is the case at two properties where the domestic hot water was heated in each apartment by an exhaust air heat pump included in an air handling unit run by household electricity. These properties also had relatively low use of common electricity since each apartment had its own air handling unit run on household electricity.

Persson (2005) reported that electrical under floor heating and towel dryers in bathrooms could increase the use of household electricity by 2000 kWh annually per apartment. The difference between average annual use of household electricity at the Bo01 properties with and without electrical heaters in bathrooms run by household electricity was 2100 kWh per apartment. At properties with air handling units run by household electricity and electrical heaters in bathrooms, the annual use was on average 1300 kWh higher per apartment compared to the average use at properties with electrical heaters in bathrooms. At the properties that had the highest use of district heating, one reason for the high use might be that towel dryers and under floor heating in bathrooms were heated by district heating. These properties have lower use of household electricity compared to the other properties where towel dryers and under floor heating in bathrooms were run by household electricity.

To be able to analyze the energy use of a building, the entire picture of the different types of energy is needed. When it comes to money and environmental impact, different types of energy is also usually valued differently. It is apparent that it is not possible to rate a building with only one parameter regarding energy use.

4.3 Different use at different times

At places where the outdoor climate varies during the year, the use of space heating will also vary since it depends on the outdoor temperature. The use of space heating will be largest during the winter and lowest during the summer. Other types of energy use such as use of household electricity and use of domestic hot water were also different at different times of the year.

During December, the measured use of household electricity was almost twice as high compared to the use during July. The variations during the day were also high. All properties had daily household electricity variations with common characteristics. The use was least during the night, increased during the morning and was constant during the afternoon where after there was a peak during the evening. During weekends, the use increased later during the morning compared to weekdays. The use was higher during the afternoon during weekends compared to weekdays.

Assuming a constant use of household electricity in energy simulations of residential buildings can result in incorrectly calculated space heating since excess heat from the household electricity is an important internal heat gain, especially in low energy buildings.

The variation in use of domestic hot water heating had equal characteristics as the use of household electricity. At all properties there were two peaks during the day. However, during weekends these peeks were not as high as during weekdays. The first and largest peak occurred during morning and the second peak during the evening. The peaks occurred at about the same time as the peaks in use of household electricity.

4.4 Implementation and exploitation

The Swedish building regulations requires that predicted energy use shall be verified by measurements in the actual building. According to the Swedish building regulations, it is recommended that safety factors are used to assure that the energy use during operation aligns with the predicted use (The National Board of Housing Building and Planning, 2008). No guidelines regarding the safety factors are given in the building regulations. The energy predictions for the examined properties were executed by consultants that make energy predictions on a regular basis. Yet the actual energy use was much higher than predicted. Several other studies have found equal differences between measured and predicted energy use. If these results are representative, a safety factor of at least two should be appropriate to ensure that the actual energy use does not exceed the predicted energy use. However, a safety factor that high is unrealistic and pinpoints the necessity of better knowledge for the designers and the construction workers. It is of greatest concern to have energy simulations done carefully and with suitable input data and critical examination of the results to get realistic predictions. The construction work needs to be carefully done so the buildings' different elements and technical systems match the design data.

5. CONCLUSIONS

To enable a detailed analysis of a buildings energy use and to find reasons for deviations between calculated and measured energy use, the measurements of energy use need to have a high time resolution and they need to be divided into suitable end uses of energy. This was partly done at the examined properties but not enough. It was, for example, not possible to split domestic hot water from space heating, and in many cases, common electricity or household electricity was apparently a part of the heating system without separate meters.

The result stresses the importance of a detailed analysis of the energy use in order to rate a building or a property. Studying just a few parameters, for example use of heating and common electricity, might result in an inappropriate rating of the energy use.

A specific goal concerning total energy use in the newly built multi-family dwellings resulted in a ratio of three between the lowest and the highest total energy use during operation and only one property out of nine that fulfilled the goal. This result stresses the importance of higher quality of energy predictions to enable design of buildings that fulfils requirements for low energy use, regardless whether the deviation is due to insufficient usage of energy use simulation tools, unqualified consultants or imperfect construction work.

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PAPER 5
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Use of Household Electricity – Measurements and Analysis

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1. Introduction

When optimising the design of a low energy house, it is of great importance to know what amount of household electricity is likely to be used and how it varies over the year and during the day in order to understand the internal load pattern. A total of 145 apartments in seven multi-family dwellings were examined regarding the use of household electricity. The buildings are located in Malmö in the south of Sweden and were built during 2001. All houses were designed to use no more than 105 kWh/m^2 annual total bought energy including space heating, domestic hot water heating, household electricity and common electricity.

Elmroth et al[1] studied energy use in an energy efficient house in Sweden. The measured annual use of household electricity was 4150 kWh or 30 kWh/m^2. Wall[2] studied energy use in energy-efficient terrace houses. The measured annual use of household electricity was 32 kWh/m^2. Lindén[3] studied the energy use at a housing area built in 2001 in Stockholm, Sweden. The buildings had a restriction to use no more than 20 kWh/m^2 electricity annually, including all electricity. The annual use of household electricity during 2005 was 27 kWh/m^2. It is not clear if the use is per heated floor area including or excluding garage area.

Tso and Yau[4] studied the daily consumption patterns of household electricity in about 1500 households in Hong Kong. The use was about the same during a 24 hour period except for a large peak in the evening. No noticeable difference was found between the patterns for weekdays and weekends. The use was higher during summer compared to winter due to the use of air-conditioning to cool the apartments. Riddell and Manson[5] studied power usage patterns of domestic consumers in New Zealand. It was found that mid morning and early evening peaks displayed the same trends. Capasso et al[6] monitored the electricity use in 95 households in Milan. The daily average load profile showed a smaller peak at eight o'clock in the morning and a bigger peak at eight o'clock in the evening. The use was least around five o'clock in the morning. After the morning peak the use stayed at a higher level compared to the use during the night. Paatero and Lund[7] monitored use of household electricity in 702 households in Finland. The variations during the day have a large peak around eight o'clock in the evening during both weekdays and weekends. The use increased during the morning but there was no peak. Between mornings and evenings, the use was higher during weekends compared to weekdays.

Bagge et al[8] interviewed consultants who ran energy simulations of buildings. The consultants seldom simulated the variations in use of household electricity over the day and the year although they were aware that there were variations. This was because no data regarding the variation was available and most energy simulation programs for buildings were not adapted for input data that varied during the day and the year.

Bagge et al[9] simulated energy use in buildings and assumed that the use of household electricity varied over the year. The result showed that the calculated heating demand was reduced about 10% in well insulated buildings if the household electricity was assumed to vary compared to if a constant use was assumed.

1.1 Method and limitations

The household electricity use was measured at 7 properties, containing 145 apartments. Hourly readings were used to analyse the variation in use during the day and monthly averages was used to analyse the variation during the year. The variation is presented as the monthly mean power in percentage of the yearly mean power. Due to the variation in use during the year, the daily use will be different at different times of the year. Bagge[10] found that the relative variation during the day was equal during the year. The variations during the day are presented as hourly power for each hour of the day compared to that day's average power, expressed as percentage of the daily mean power. The presented profiles are mean values of all days during 2005.

The use was measured at the property level, which means that the measured values are the sum of the use in the apartments at the property. The individual inhabitants' behavior will have a greater affect on the total use at properties with fewer apartments. No consideration was given to holidays occurring on a week-day.

1.2 The studied properties

The energy use in the studied properties has been monitored since 2001. The measurements and analysis of the total energy use is presented in Bagge[10]. The properties are grouped into type 1, 2 and 3 properties based on different installations being supported by household electricity. At the type 1 properties, properties 5 and 6 containing 49 apartments and 8094 m^2 heated floor area, the household electricity does not support any heating and ventilation installations. At the type 2 properties, properties 2, 3 and 7 containing 61 apartments and 3184 m^2 heated floor area, the household electricity supports electrical heaters in bathrooms. Persson[11] reported that electrical heaters in bathrooms could increase the use of household electricity by 2000 kWh annually per apartment. At the type 3 properties, properties 1 and 4 containing 22 apartments and 3184 m^2 heated floor area, the household electricity supports apartment located air handling units with fans for supply and exhaust air and a heat pump that recovers heat from the exhaust air and heats the supply air and the domestic hot water as well as electrical heaters in bathrooms.

2. Result

Figure 1 presents the annual use of household electricity per heated floor area during 2005.

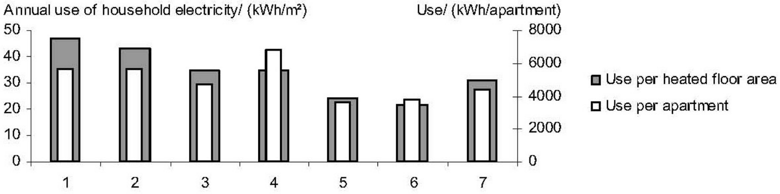

Figure 1. Annual use of household electricity per heated floor area, garage area excluded, and per apartment.

The use during 2005 was on average, 35 kWh/m^2 with the highest use being 47 kWh/m^2 and the lowest was 22 kWh/m^2. At the type 1 properties, the average use was 23 kWh/m^2 or 2800 kWh per apartment. At the type 2 properties, the average use was 36 kWh/m^2 or 4900 kWh per apartment. At the type 3 properties, the average use was 45 kWh/m^2 or, 6200 kWh per apartment.

Figure 2 presents the variation in use during the year at all properties respectively and the mean variation based on all properties.

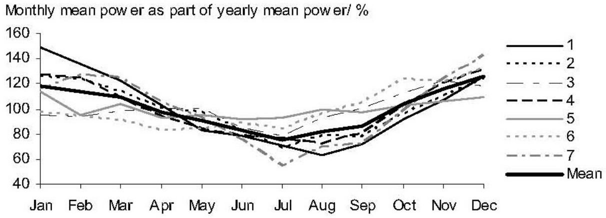

Figure. 2. The monthly variations in the use of household electricity at the different properties and the mean variation.

At all properties, the household electricity use was higher during the winter compared to the use during the summer. According to the mean variation based on all properties, the use varied between 75% and 130% of the yearly mean power. Norén[12] and Sandberg[13] have found similar variations. The variations in use differ to some extent between the properties. This can partly be explained by different technical solutions. For example, household electricity was used for fans and heat pumps in the individual apartments at the type 3 properties.

Figure 3 presents the daily variations at the type 1, 2 and 3 properties during weekdays and weekends respectively.

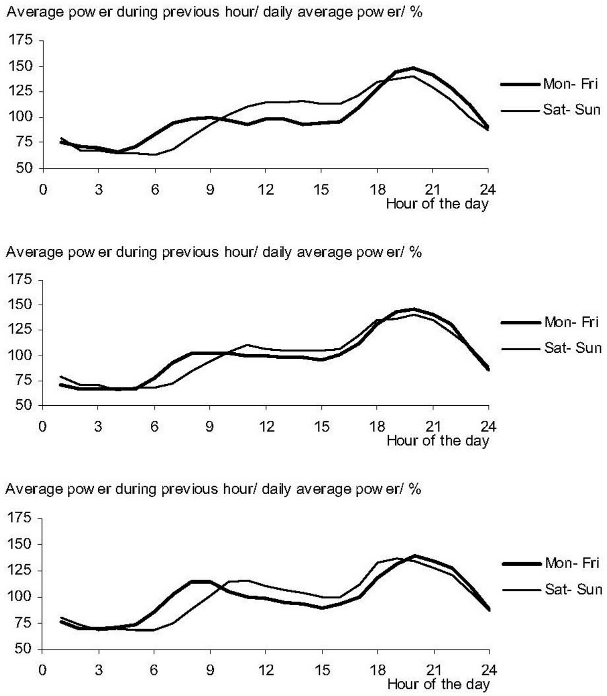

Figure 3. The variation in use of household electricity during the day, presented for Monday to Friday and Saturday to Sunday respectively at the type 1, 2 and 3 properties.

All properties had daily household electricity profiles with common characteristics:

- the use was least during the night
- increased during the morning where there was also a small peak
- was about constant during the day and afternoon
- increased during late afternoon
- reached a maximum at eight or nine

During weekends, the use increased later during the morning compared to weekdays. The use was higher during the afternoon during weekends compared to weekdays. At the type 3 properties the peak during mornings is more accentuated than at the other properties.

3. Discussion and conclusions

Compared to the result from other studies[1-3], the average use per heated floor area in this study, 35 kWh/m^2, was higher. The use varied between 22 and 47 kWh/m^2 at the different properties. If electrical heaters in bathrooms or air handling units are supplied by household electricity, the use of household electricity increase noticeably. The daily use patterns presented in this study showed similar characteristics to the variations found in literature[5-8].

To make accurate energy calculations, the variation in use of household electricity, during the day and the year should be taken into account. This is significant when modern low energy buildings are designed since excess heat from household electricity is a major heating source. The presented yearly and daily load patterns can be used to simulate internal heat gins from household electricity when energy calculations for low energy buildings are executed.

The variations in use over the year calls out for caution when household electricity use measured at different times of the year are compared. If no respect is taken to the variations over the year, there might be large errors if household electricity measured during a shorter period is used for estimating the annual use.

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Indoor Hygrothermal Conditions in Multifamily Dwellings—Measurements and Analysis

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ABSTRACT

In order to design a building envelope that provides for a healthy indoor climate and sustainability, both energy and moisture simulations are needed. Decisions during the building process often are based on results from simulations of energy and moisture. Accurate simulations call for comprehensive input data regarding indoor temperature and indoor moisture supply. Simulations for residential buildings lack the necessary data, a deficit that must be resolved over time in a way that allows both short and long term variations to be described. As a part of an ongoing study, these parameters were measured in 18 apartment buildings containing 325 apartments in total. The parameters were measured at the building level through measurements in the exhaust air of the ventilation system, which provided average values for the apartments. Measurements of the outdoor temperature and relative humidity enabled calculations of moisture supply, which is defined as the difference between indoor vapor content and outdoor vapor content. The parameters were monitored every 30 minutes for one year. The buildings were located in Sweden between latitude N56° and N67°. Examples of results are data on averages, distributions between houses, and variations and spans during the day, during the week, and throughout the year. The presented data can help to improve simulations of indoor climate and energy use in residential buildings, which will make building envelope design decisions more appropriate.

INTRODUCTION

In the building industry, it is necessary to perform calculations regarding energy use and moisture levels in different parts of the construction process to ensure that a building will be sustainable and healthy. The indoor temperature will affect the use of space heating, and the moisture levels will affect deterioration of materials and growth of microorganisms. To accurately predict energy use and moisture levels, input data are needed o simulate energy use and indoor climate and to verify results from simulation programs.

Measurements on indoor temperatures and relative humidity have been made. Kalamees et al. (2006) presented a thorough literature review regarding moisture supply, which is defined as indoor vapor content minus outdoor vapor content. In previous studies, indoor climate was only studied for shorter periods. Holgersson and Norlén (1984) presented measured indoor temperatures in multifamily dwellings. Indoor temperatures were measured in the living rooms between March and May. The average indoor temperature was 21.8°C, and it varied between 20.2°C and 23.8°C.

Indoor temperature and relative humidity were measured in 1800 single-family houses and apartments in multifamily buildings in Sweden (Boverket 2009). Measurements were carried out in 15 minute intervals during two weeks in each house or apartment. The two-week measurement period started between October 2007 and May 2008, depending on location, which resulted in measured data origins from different measurement periods. The average indoor temperature, relative humidity, and moisture supply in multifamily dwellings were 22.3°C, 30%, and 1.22 g/m^3, respectively. Distributions between buildings are presented but not distributions during the measurement periods.

Kalamees et al. (2006) measured indoor humidity loads in 100 bedrooms and 79 living room in 101 single-family

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detached houses during 2002 and 2004. During periods with outdoor temperatures at or below 5°C, the average moisture supply was 1.8 g/m^3; during periods with outdoor temperature over 5°C, the average moisture supply was 0.5 g/m^3. The difference between bedrooms and living rooms was small. Moisture supply figures of up to 4 g/m^3 are given for use in moisture design of dwellings (Nevander and Elmarsson, 1994).

Kalamees et al. (2009) studied the span between the maximum and minimum daily indoor temperature, relative humidity, and vapor content based on hourly measurements during one year in master bedrooms and living rooms in 170 detached houses in Finland. The average amplitudes during summers and winters were 0.9°C and 1.0°C, 6% and 6%, and 1.5 and 1.3 g/m^3, respectively. Standards regarding hygrothermal conditions, such as EN 13788 (2001) and EN 15026 (2007), do not give any information regarding variations during the day and the week.

Elmroth (2002) calls attention to that it is too common that measured energy use exceeds predicted use. Bagge and Johansson (2009) highlighted several projects where the measured use exceeded the predicted by 50% to 100% although energy efficient goals during the planning. Karlsson et al. (2007) studied energy use in passive houses built in Sweden. The measured energy use during operation was 50% higher than the use predicted during the design phase. This was partly due to higher indoor temperature and less efficient heat exchangers than predicted. Karlsson stressed the importance of accurate input data for energy simulations. The building users' behavior is very important in low-energy buildings and also the hardest to model according.

According to the literature, there are large deviations between predicted and measured energy use in residential buildings during operation, and deviations may be suspected for predicted and measured moisture conditions in buildings during operation. Kalamees et al. (2009) studied the dampening effect of hygroscopic materials and concluded that there was a considerable difference between simulated and measured values. Simulations are often executed with conditions that are not common in real buildings, and, for example, the difference in quality of workmanship is hard to take into account in simulations. Page et al. (2008) argued that although simulation models are developed to represent the physics of the building more and more accurately, the model of the inhabitants' behavior is too simplified, which leads to errors in predictions. According to Rode and Grau (2008), whole building hygrothermal simulations show that the amplitudes of indoor humidity can differ significantly, depending on whether the moisture buffering effect of building materials is included.

As buildings become more energy efficient through reduced thermal transmission and reduced ventilation heat loss, building users' energy-related behavior will have a greater effect on the buildings' total energy use. The thermal transmission is reduced by use of highly insulated climate envelopes, which might increase the risk of moisture damage if the constructions are not appropriately designed. The design of moisture-safe constructions are carried out using simulation tools. To ensure correct simulation results, appropriate data are needed on indoor hygrothermal conditions, since differences between indoor and outdoor conditions are the driving forces behind moisture and heat transport.

Conclusively, there seems to be a lack of building user-related data that show both variations during the year and the day, particularly for many parameters that can be correlated, including many apartments. Therefore, Bagge and Johansson (2008a; 2008b) began a study on household electricity use, domestic hot-water use, indoor temperature, indoor relative humidity, moisture supply, moisture production, CO_2 production, and occupancy with readings every 30 minutes for more than a year in 18 multifamily dwellings composed of 325 apartments. This paper presents results for indoor temperature, relative humidity, and moisture supply.

METHODS

Measured and Calculated Parameters and Definitions

By measuring the exhaust air of residential buildings, as opposed to measuring for each individual apartment, a large number of apartments could be included in the study at a reasonable cost. On the other hand, it is not possible to measure distributions between apartments inside a certain residential building or between different rooms in an apartment. The measured parameters related to this paper are temperatures in the central exhaust duct and outdoors, and relative humidity in the central exhaust duct and outdoors. Moisture supply can be calculated using these parameters. Measurements were performed every 30 minutes to make it possible to obtain daily and weekly time distributions as well as daily and weekly spans. Outdoor temperature and outdoor relative humidity were bought from the Swedish Meteorological and Hydrological Institute, which monitors outdoor climate conditions every three hours. All parameters were measured during at least one year to obtain annual time distribution and to evaluate the methods during different outdoor conditions.

Moisture supply, v_{ms}, is defined as the difference between indoor and outdoor vapor content. Vapor content is defined as the mass of water vapor per volume of mixture of water vapor and air. Saturation vapor content, v_{sat}, as a function of air temperature, t, was calculated according to Equation 1, with an error less than 0.07 g/m^3 compared to tabled data presented by Nevander and Elmarsson (1994).

$$v_{sat} = 4.7815706 + 0.34597292 \cdot t + 0.0099365776 \cdot t^2 + 0.00015612096 \cdot t^3 + 1.9830825 \cdot 10^{-6} \cdot t^4 + 1.5773396 \cdot 10^{-8} \cdot t^5 \tag{1}$$

In the analysis, the word "span" is used to describe the difference between a maximum and minimum value during a certain period of time. Daily temperature span means the highest 30 minute temperature reading minus the lowest 30 minute temperature reading during a 24 hour period. Weekly temperature span means the highest minus the lowest daily average temperature during a calendar week, Monday through Sunday.

Studied Cases and Their Location

The buildings studied are presented in Table 1. All the buildings used mechanical exhaust-air ventilation. The measurement periods, the yearly average outdoor temperature, and the number of hours at or below the average outdoor temperature at the different locations are presented in Table 2.

Measuring Equipment and Possible Errors

Temperatures are measured using loggers with a specified error of ±0.35°C. Based on general experience, the specified error for these devices seldom exceeds ±0.2°C. Relative humidity is measured using the same loggers, and relative humidity error is given to 2.5% absolutely. The loggers were calibrated before measurements in order to decrease the number of possible errors.

The lack of measurements for single rooms leads to problems knowing if a measured value is the airflow weighted average value for an entire apartment or only the airflow weighted point value at the exhaust device. On the other hand, measuring in a single room does not give information on the entire apartment. It is believed that the measurements represent the conditions in the apartment. The measured values for indoor temperature and relative humidity include the possible effects of moisture buffering and heat storage of the building and of movables, such as furniture, paintings and books. An important task in this study was to determine the airflow rate that changed air in the buildings. In addition to mechanical ventilation systems, buildings are exposed to leakage due to wind and buoyancy, which also change air in apartments. The actual air change rate could be measured with tracer gas methods, but this would be expensive to do annually and unrealistic if many buildings are to be included. On the other hand, the error caused by neglection of air change due to wind and buoyancy has been minimized by using buildings with mechanical exhaust air only, which leads to a larger under pressure inside the building that reduces exfiltration and, consequently, air change from leakage. Typically, the leakage is decreased by a factor of 5 compared to a building with balanced ventilation (Johansson 2005). If a building has mechanical exhaust and an air tightness of 0.8 L/(s·m^2 surrounding walls) at 50 Pa testing pressure, a constant airflow rate of 1%·0.8 L/(s·m^2) can be assumed in normal conditions (Johansson 2005). If the surrounding area is assumed to be 1.4 m^2 per 1 m^2 floor area, 0.011 L/(s·m^2 floor) is added to the mechanical ventilation. This can be corrected for in the analysis but is small compared to the former Swed-

Table 1. Buildings Studied

Location	Building	Year Erected	Number of Apartments	Number of Stories
Karlstad	1	2005	23	4
	2	2005	22	4
	3	1964	34	9
	4	1964	36	9
	5	1940	24	2
Kiruna	1	1963	9	3
	2	1963	9	3
	3	1963	12	3
	4	1963	10	3
	5	1963	11	3
Malmö	1	1971	24	8
	2	1971	16	8
	3	1971	16	8
	4	1971	16	8
Sundsvall	1	1969	12	3
	2	1969	18	3
	3	1969	18	3
	4	1969	15	3

Table 2. Measurement Periods, Yearly Average Outdoor Temperature, and Number of Hours of Outdoor Temperature at or below the Average at Different Locations

Location	Start Date	End Date	Average Outdoor Temperature, C°	Hours at or below Average Temperature, h
Karlstad	2008-06-12	2009-07-07	5.5	4089
Kiruna	2008-07-05	2009-08-19	–1.7	3749
Malmö	2008-10-10	2009-11-23	8.2	3872
Sundsvall	2008-09-05	2009-09-29	3.6	4336

ish building regulation (Boverket 2002) that requires a ventilation airflow rate of 0.35 L/(s·m^2 floor). In addition to exhaust ventilation in buildings studied, kitchen stove air was transported through the same ducts as the rest of the exhaust air. Exhaust air was in general taken from bathrooms and kitchens, and outdoor air inlets were located in bedrooms and living rooms.

If people inside the buildings open windows, the air change increases dramatically (Nordquist 2002). This could mean that during the summer period the measured values for moisture are only valid close to the exhaust devices.

The measured indoor temperature can include errors if, for example, it is measured in the central exhaust duct, if the ducts are not insulated, or if ducts are located in cold spaces. These things are visible in buildings or on construction drawings. Cold air can also be drawn into the system via leakage in the exhaust duct system, which may result in inaccurate airflow rate measurements. Measured temperatures and relative humidity are not presented where exhaust ducts were partly located outside the climate envelope, for example on unheated attics. Measured temperatures were found to be considerably affected by attic temperature. The temperatures measured in the main exhaust duct were assumed to be the average indoor temperature of the apartments in buildings where exhaust ducts were located inside the climate envelope. In all buildings studied, the central exhaust duct included exhaust air from common spaces, such as staircases and storage rooms, so the measured values are the average values for the whole ventilated volume inside the building.

Analysis

The variations in indoor temperature, relative humidity, and moisture supply during the year, week, and day were analyzed. Variations during the year are presented as monthly averages. The weekly variations were calculated as the difference between a specific day's average measured value and the corresponding weekly average. Variations during the day were calculated as the difference between each 30 minute measured value and the corresponding daily average measured value. Variations during the day were calculated for weekdays and weekends, respectively. Variations are presented as averages of these differences for the whole year and for the seasons—winter, spring, summer, and autumn, respectively. Winter is defined as December through February, spring as March through May, summer as June through August, and autumn as September through November. The variations presented give typical daily and weekly profiles with information on at which time of day and week peaks, increases, and decreases typically occur.

The method for calculating variations during the week and day means that the difference between the highest and the lowest value in the variations presented will be smaller than the average span defined if the maximum or minimum occurred at different times of the day or week, respectively. Even if the resulting variation is smaller than the logger error, the logger error is believed to be random and did not strike at certain times of the day or week.

Daily and weekly spans were calculated to give the magnitude of the variations. Daily spans were calculated as the difference between the highest and lowest values during a day, and weekly amplitudes were calculated as the difference between the highest and lowest daily average value during a week.

RESULTS

The indoor temperature, moisture supply, relative humidity, and corresponding standard deviations are presented for outdoor temperatures less than and higher than the yearly average outdoor temperature, according to Nevander and Elmarsson (1994) in Tables 3 and 4, respectively.

Figures 1 through 3 present the variations during the year, Figures 4 through 7 present the variations during the week, and Figures 9 through 14 present the variations during the day. Tables 5 and 6 present the average span of variations during the week and during the day. Figure 8 presents the duration of the weekly span, and Figure 15 presents the duration of the daily span.

DISCUSSION AND CONCLUSIONS

The average indoor temperature during periods with outdoor temperature less than the yearly average was 22.21°C, which agrees with results from other studies. The average indoor relative humidity was 34% and the average moisture supply was 2.14 g/m^3, which are both higher than reported averages from other studies (see Tables 3 and 4). This might be due to the measurement methods of other studies, which measured in bed rooms and living rooms. In these other studies, moisture generation in bathrooms and kitchens might not be part of the full measured values since residential ventilation is designed for flow paths from bed rooms and living rooms to kitchens and bathrooms. Measuring in the central exhaust air should give a better interpretation of the conditions inside the climate envelope. Boverket's (2009) average is based on averages from a measurement period of two weeks beginning between October and May. If measurement period start times were not evenly distributed between October and May, there could be an over- or underestimation due to variations throughout the year, as presented in Figures 2 and 3, which means Boverket's data is not directly comparable to the results of this study.

Analysis of the variations during the year, week, and day gives information on the typical characteristics of indoor temperature, relative humidity, and moisture supply. Variations during the year and day (see Figures 9, 11 and 13) shared characteristics for all locations, while variations during the week (see Figures 4 through 7) seem to have no common characteristics. It was believed that indoor temperature would be higher during weekends the on weekdays due to an expected higher occupancy level. Variations during the year were considerable, especially for moisture supply and indoor relative humidity, but

Table 3. Average and Standard Deviation of Indoor Temperature, Moisture Supply, and Indoor Relative Humidity for Outdoor Temperatures at or below the Yearly Average Outdoor Temperature

Location	Building	Indoor Temperature, C°		Relative Humidity, %		Moisture Supply, g/m^3	
		Avg	σ	Avg	σ	Avg	σ
Karlstad	1	22.5	0.38	34.5	3.90	3.09	0.69
	2	22.1	0.52	34.3	4.22	2.86	0.62
	3	22.6	0.40	33.3	4.38	2.87	0.61
	4	22.4	0.39	30.7	4.68	2.27	0.59
	5					2.33	0.64
	Average	22.4	0.42	33.2	4.30	2.77	0.63
Kiruna	1					2.08	0.63
	2					1.81	0.62
	3					1.62	0.59
	4					1.31	0.51
	5					1.92	0.56
	Average					1.75	0.58
Malmö	1	22.7	1.10	34.0	5.25	2.25	0.73
	2	21.9	0.91	33.4	5.16	1.80	0.68
	3	21.7	1.00	35.4	5.11	2.03	0.65
	4	22.0	1.24	33.8	5.35	1.89	0.68
	Average	22.1	1.06	34.1	5.22	1.99	0.69
Sundsvall	1					2.40	0.72
	2					1.59	0.63
	3					2.33	0.72
	4					1.92	0.61
	Average					2.06	0.67

the variations for relative humidity are believed due to outdoor climate variations. Monthly mean values for indoor relative humidity (see Figure 2) were highest during the summer months and lowest during the winter months; moisture supply (see Figure 3) was lowest during the summer months and highest during the winter months. The monthly average indoor temperatures (see Figure 1) were higher during the summer months and on a fairly constant level during the rest of the year.

The difference in average moisture supply during cold and warm periods of the year (i.e., winter and summer) agreed with results from Kalmees et al. (2006). During the day, the indoor temperature was at minimum around 06:00 and at maximum around 19:00 (see Figures 9 and 10). The increase in temperature during the day may be due to solar heat gains, and the maximum value in the evening might be due to increased internal heat gains from household electricity that peaks at the same

Table 4. Average and Standard Deviation of Indoor Temperature, Moisture Supply, and Indoor Relative Humidity for Outdoor Temperatures over the Yearly Average Outdoor Temperature

Location	Building	Indoor Temperature, C°		Relative Humidity, %		Moisture Supply, g/m^3	
		Avg	σ	Avg	σ	Avg	σ
Karlstad	1	24.4	1.70	44.6	6.11	2.15	1.24
	2	24.1	1.50	44.7	6.37	1.98	0.98
	3	23.7	1.32	45.4	7.08	1.85	1.00
	4	23.2	1.24	45.00	7.85	1.53	0.97
	5					1.55	1.12
	Average	23.9	1.44	44.9	6.85	1.88	1.05
Kiruna	1					0.82	0.83
	2					0.67	0.81
	3					0.39	0.81
	4					0.32	0.72
	5					0.86	0.74
	Average					0.61	0.78
Malmö	1	23.7	1.43	48.5	4.88	1.40	0.92
	2	23.5	1.58	47.5	4.74	1.07	0.93
	3	23.2	1.49	49.4	4.73	1.22	0.86
	4	23.1	1.43	49.1	5.45	1.17	0.88
	Average	23.4	1.48	48.6	4.95	1.22	0.90
Sundsvall	1					1.36	0.92
	2					0.73	0.94
	3					1.46	0.96
	4					1.22	0.91
	Average					1.19	0.93

time as temperature (Bagge 2008). During the night there are usually less internal heat gains from household electricity and no solar heat gains, which might explain the minimum in the morning. As people begin their morning practice, internal heat gains increase. Indoor relative humidity typically decreased during the night, with a minimum at around 06:00, after which it increased and remained relatively constant during the day (see Figures 11 and 12). During summer, the indoor relative humidity was constant during the night and increased during the morning to a maximum at around 10:00, after which it decreased to a minimum at 18:00. During summer, window airing is suspected of being used to control indoor temperature, which affected the measured relative humidity and moisture supply as discussed in the "Methods" section of this paper. The variation in moisture supply during the day had the same general characteristics as the indoor relative humidity, except during summer where the moisture supply decreased during the night and had a negative spike around 06:00, after which it

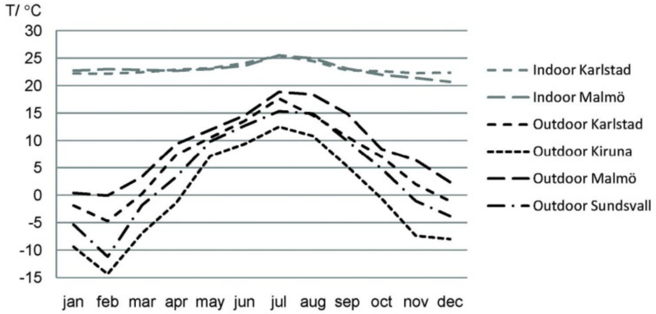

Figure 1 *Monthly average indoor and outdoor temperatures, T, at the different locations during the measured period. Indoor temperatures are average values of all buildings at a specific location.Depending on the start date of the measurement period, the presented monthly averages are from different years.*

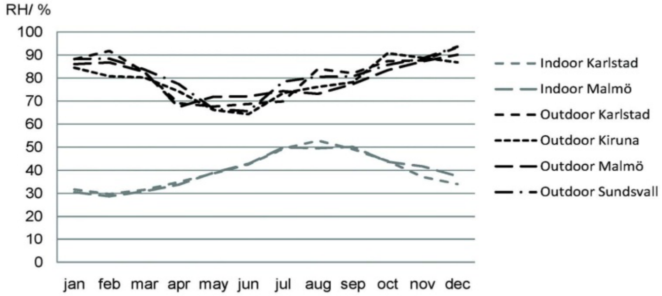

Figure 2 *Monthly average relative humidity, RH, indoors and outdoors at the different locations during the measurement period. Indoors are average values of all buildings at a specific location. Depending on the start date of the measurement period, the presented monthly averages are from different years.*

increased and remained at a constant level during the afternoon, decreased during the evening, and increased around midnight (see Figures 13 and 14). Generally, for all studied parameters, the increase during mornings begins later during weekends compared to weekdays, which most certainly is due to occupants waking later in the morning on weekends. Computer simulation tools for energy use and hygrothermal conditions in buildings often give the user the option to define different indoor conditions during weekdays and weekends, respectively. Results from this study show there were not greater differences in average indoor temperature, indoor relative humidity, and moisture supply between weekdays and weekends as compared to differences for random days.

Weekly and daily variations were small compared to the possible equipment errors. It is believed that the equipment errors are random, but if there were a systematic error, it may have influenced the average variations. It is difficult to acquire information on the types and causes of equipment errors, particularly for humidity measurements. The result on spans of daily and weekly variations shows that an arbitrary day's or week's variation is far higher than the equipment error, which indicates reasons other than equipment errors for the resulting variations (see Figures 8 and 15 and Tables 5 and 6).

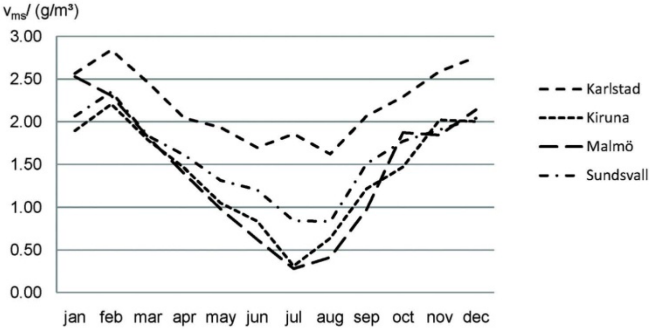

Figure 3 *Monthly average moisture supply indoors and outdoors at the different locations during the measurement period. Indoors are average values of all buildings at a specific location. Depending on the start date of the measurement period, the presented monthly averages are from different years.*

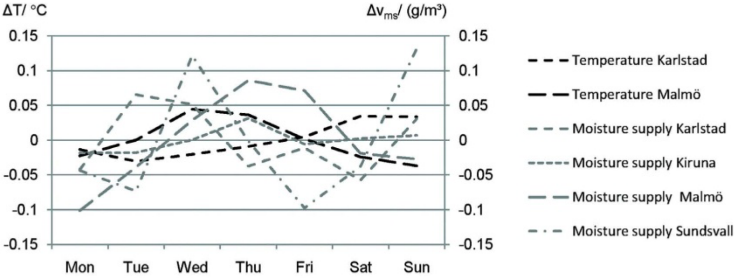

Figure 4 *The variations in indoor temperature and moisture supply during the week. ΔT and Δv_{ms} are the average of (daily average minus weekly average). The presented values are average values of all buildings at a specific location.*

The average daily span—the average difference between the highest and the lowest measured value during a day—of indoor temperature, relative humidity, and moisture supply was 0.58°C, 5.9%, and 1.91 g/m^3. The average weekly span—the average difference between the highest and the lowest daily average during a week—was 0.66°C, 7.1%, and 1.32 g/m^3. The magnitude of both daily and weekly spans indicates measurements need to be performed during longer periods of time if average values are to be obtained. Since the values presented are average values of many apartments, the spans within a single apartment or a single room can be expected to be higher.

Variations during the year and during the day were systematic for all studied parameters and equal for all studied locations, and the span of all studied parameters were of considerable magnitude. If any of the studied parameters is to be measured as an instantaneous value, the effect from the variations during the year, week, and day should be taken into account. If a material located inside the climate envelope is to be studied with regard to moisture, the variations and spans presented should be considered, since they may cause the material to be humidified or dehumidified during different times and, hence, cause hysteresis in the sorption.

ACKNOWLEDGMENTS

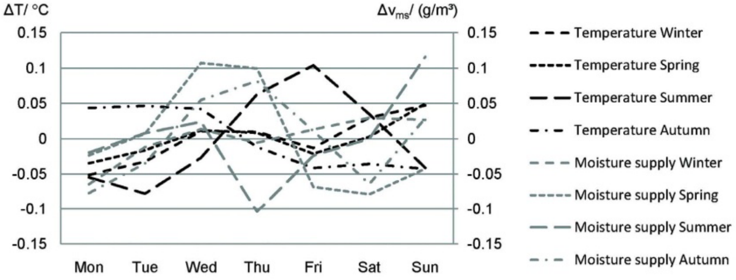

Figure 5 *The variations in indoor temperature and moisture supply during the week for different seasons. ΔT and Δv_{ms} are the average of (daily average minus weekly average). The presented values are average values of all buildings of all locations.*

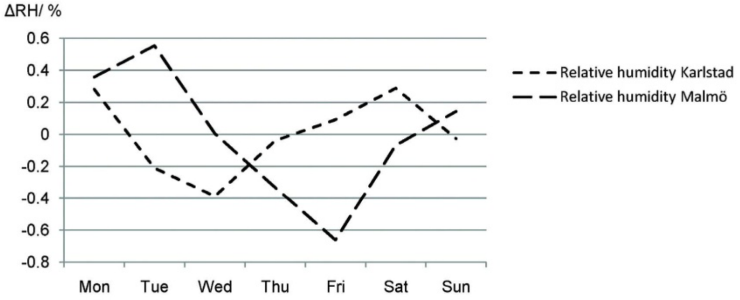

Figure 6 *The variations in relative humidity during the week. ΔRH is the average of (daily average RH minus weekly average RH). The presented values are average values of all buildings at a specific location.*

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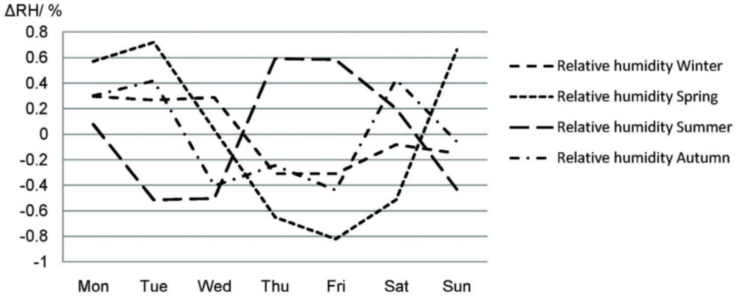

Figure 7 *The variations in indoor relative humidity during the week for different seasons. ΔRH is the average of (daily average RH minus weekly average RH). The presented values are average values of all buildings of all locations.*

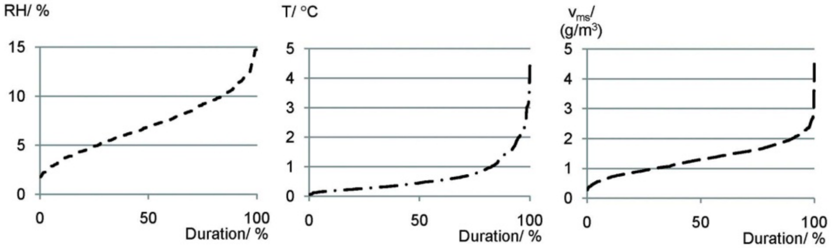

Figure 8 *The duration of the weekly span of temperature, T_{span}; relative humidity, RH_{span}; and moisture supply, v_{ms_span} respectively. The presented values are average values of all locations.*

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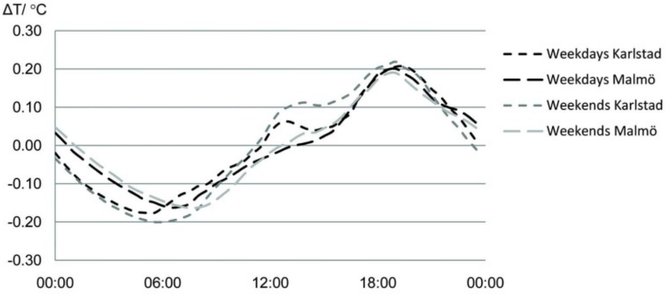

Figure 9 *Variations in indoor temperature during the day, presented for weekdays and weekends respectively. ΔT is the average of (indoor temperature minus daily average indoor temperature). The presented values are average values of all buildings at a specific location.*

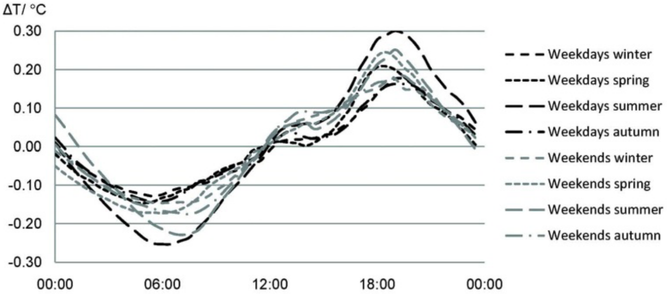

Figure 10 *Variations in indoor temperature during the day for different seasons, presented for weekdays and weekends, respectively. ΔT is the average of (indoor temperature minus daily average indoor temperature). The presented values are average values of all locations.*

Kalamees, T., M. Korpi, J. Vinha, and J. Kurnitski. 2009. The effect of ventilation systems and building fabric on the stability of indoor temperature and humidity in Finnish detached houses. *Building and Environment* 44:1643–50.

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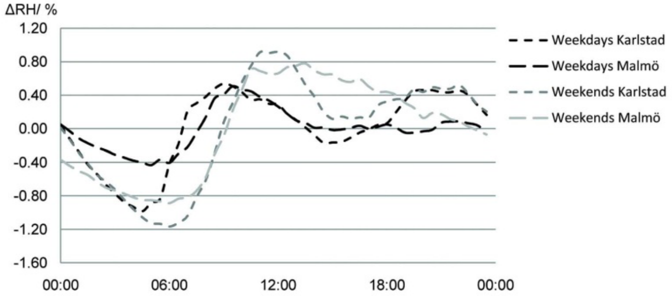

Figure 11 *Variations in relative humidity during the day, presented for weekdays and weekends, respectively. ΔRH is the average of (RH minus daily average RH). The presented values are average values of all buildings at a specific location.*

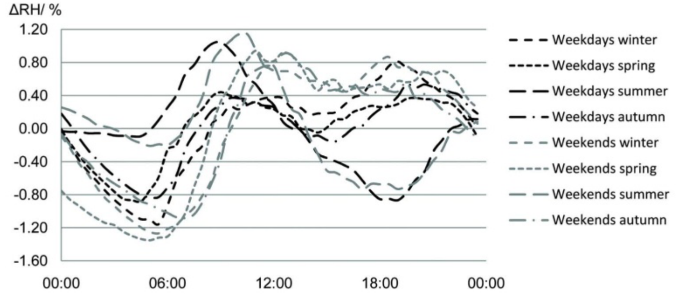

Figure 12 *Variations in relative humidity during the day for different seasons, presented for weekdays and weekends, respectively. ΔRH is the average of (RH minus daily average RH). The presented values are average values of all locations.*

Rode, C., and K. Grau. 2008. Moisture bufferings and its consequence in whole building hygrothermal modeling. *Journal of Building Physics* 31(4):333–60.

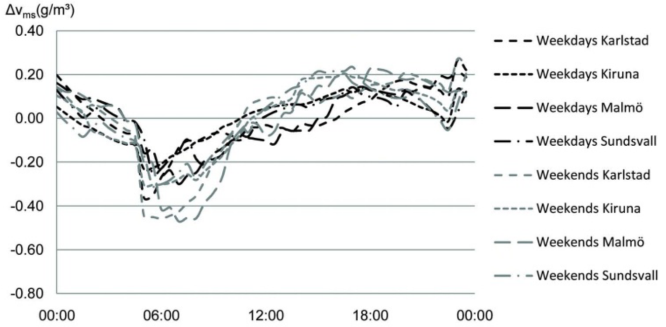

Figure 13 *Variations in moisture supply during the day, presented for weekdays and weekends, respectively.* Δv_{ms} *is the average of (*v_{ms} *minus daily average* v_{ms}*). The presented values are average values of all buildings at a specific location.*

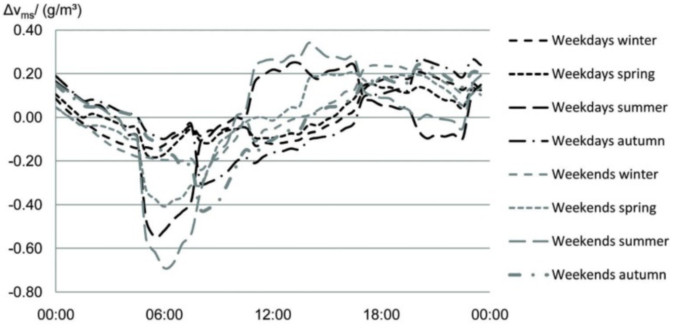

Figure 14 *Variations in moisture supply during the day for different seasons, presented for weekdays and weekends, respectively.* Δv_{ms} *is the average of (*v_{ms} *minus daily average* v_{ms}*). The presented values are average values of all locations.*

Table 5. Average Span and Standard Deviation During the Week for Whole Year and Seasons, Respectively

Period	Indoor Temperature, C°		Relative Humidity, %		Moisture Supply, g/m^3	
	Average	σ	Average		Average	σ
Year	0.66	0.62	7.1	2.9	1.32	0.51
Spring	0.49	0.40	5.0	2.0	1.23	0.48
Summer	0.51	0.33	6.3	2.3	1.15	0.43
Autumn	1.25	0.94	9.0	2.8	1.56	0.55
Winter	0.48	0.31	7.7	2.5	1.29	0.49

Table 6. Average Span and Standard Deviation During the Day for Whole Year and Seasons, Respectively

Period	Indoor Temperature, C°		Relative Humidity, %		Moisture Supply, g/m^3	
	Average	σ	Average		Average	σ
Year	0.58	0.30	6.9	2.6	1.91	0.91
Winter	0.50	0.20	4.9	1.7	1.35	0.57
Spring	0.58	0.28	5.6	2.0	1.74	0.77
Summer	0.76	0.39	7.2	3.5	2.47	0.99
Autumn	0.51	0.23	5.6	2.2	1.95	0.82

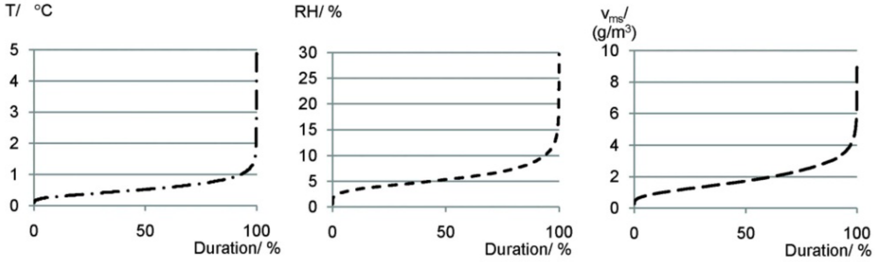

Figure 15 *The duration of the daily span of temperature, T_{span}, relative humidity, RH_{span}, and moisture supply, v_{ms_span}, respectively. The presented values are average values of all locations.*

PAPER 7
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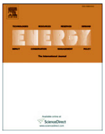

Measurements of household electricity and domestic hot water use in dwellings and the effect of different monitoring time resolution

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ABSTRACT

The use of household electricity and domestic hot water has been measured for 72 apartments in an apartment building located in the south of Sweden. The measurements were carried out with samples every 6 s, a tenfold increase in resolution compared to available published data, during a measurement period of five days, in the winter season, including a weekend. The influence of the time resolution on the distribution of data was analysed by integrating the 6 s data to represent longer logging intervals. Extreme values, especially the high values, are shown to be reduced if the time interval is increased. The maximum household electric power was 50% higher at a 6 s resolution compared to 60 s and the corresponding difference for domestic hot water flow was 40%. Daily variations has to be considered for photovoltaic installations and solar thermal collectors, energy simulations of buildings need at least hourly data and all kind of power design in a building or its services benefits from much more resolved data.

1. Introduction

1.1. Background

Recent demands on verification of actual energy use, combined with a need for more precise design of buildings to accomplish a better performance, puts the focus on what is relevant to measure and how often. In low energy buildings, the user behaviour is important for calculating energy use and power need. Variation over time is an important parameter both regarding integrated annual energy use and the power design of buildings and specific building components. Also, data with sufficient time resolution is helpful when diagnosing and troubleshooting buildings. This paper analyses how the time resolution influence the measurements of household electric power and domestic hot water flow.

According to the recast of the Energy Performance of Buildings Directive [1] of the European Union, from 2020 all new buildings within the Union have to be almost zero energy buildings and energy should to a large extent come from renewable energy sources. This applies to buildings owned or occupied by public authorities starting 2018. To achieve nearly zero energy use, buildings will most likely have to be designed as zero energy buildings, defined as a building 'where, as a result of the very high level of energy efficiency of the building, the overall annual primary energy consumption is equal to or less than the energy production from renewable energy sources on site' [2]. Renewable energy sources on site can for example be solar thermal collectors and photovoltaics. The solar thermal collectors can provide heat for domestic hot water heating as well as space heating and solar photovoltaics can provide electricity for use in households. To design a building that achieve low energy use it is of great importance to know the characteristics of the household electricity and domestic hot water use [3,4]. The use of household electricity and domestic hot water is strongly influenced by the user behaviour and increasingly so as the space heating portion of the total energy use decreases in energy efficient buildings. Equally, it is crucial to know these characteristics in order to successfully design solar collector systems for domestic hot water heating and solar photovoltaic systems for household electricity [5,6].

The researchers in Ref. [7] studied the daily use patterns of household electricity in about 1500 households in Hong Kong taking two hourly samples for a week. The energy use was about the same during a 24-h period except for a large peak in the evening. No noticeable difference was found between the patterns for weekdays and weekends. The use was higher during summer compared to winter due to the use of air-conditioning to cool the apartments. Ref. [8] monitored the electricity use in 95 households

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in Milan by logging measurements made every 15 min over nine months. The average daily load profile showed a small peak at eight o'clock in the morning and a large peak at eight o'clock in the evening. The least use was found around five o'clock in the morning. After the morning peak, the energy use stayed at a higher level compared to the energy use during the night. Ref. [9] monitored the use of household electricity in 702 households in Finland by logging hourly measurements over a one year period. The variations during the day showed a large peak around eight o'clock in the evening during both weekdays and weekends. The use increased during the morning but there was no well defined peak. Daytime, the use was higher during weekends compared to weekdays. Ref. [10] studied the variations during the day and year of household electricity for 145 apartments located at seven properties in Sweden by logging hourly measurements over one year. The energy use during the winter was higher compared to the summer. The energy use during the year varied between 75% and 130% of the annual mean. Other studies have found similar variations [11,12]. The variations during the day had common characteristics at the seven studied properties [10]. The use was the least during the night, increased during the morning to a small peak and was almost constant during the day and afternoon. During late afternoon it increased and reached a maximum at eight to nine o'clock. During weekends, the peak appeared later during the morning compared to weekdays. The use was higher during the afternoon during weekends compared to weekdays.

The seven properties studied by authors in Ref. [10] used an annual average of 35 kWh/m^2 (4 W/m2) with the highest use being 47 kWh/m^2 (5.4 W/m^2) and the lowest 22 kWh/m^2 (2.5 W/m^2). The authors in Ref. [13] studied energy use in an energy efficient house in Sweden. The measured annual use of household electricity was 4150 kWh or 30 kWh/m^2 (3.4 W/m^2). Ref. [14] studied energy use in energy efficient terrace houses. The measured annual use of household electricity was 32 kWh/m^2 (3.7 W/m^2). The authors in Ref. [15] studied the energy use at a housing area built in 2001 in Stockholm, Sweden. The annual use of household electricity during 2005 was 27 kWh/m^2 (3 W/m^2).

The researchers in Ref. [16] monitored domestic hot water use in four apartment buildings in a Solar Village in Greece and described hourly consumption patterns based on 30-min averages. The use was higher during weekends than during weekdays. The use during different seasons was studied and it was found that during spring, the use could be 100% higher than during the summer season. This was partly explained by a higher temperature of the cold incoming water. Average domestic hot water use patterns by day of the week were analysed. During weekdays, the patterns showed equal characteristics. The highest peak in use was between eight and ten o'clock in the evening and the second highest peak around one o'clock in the afternoon. During weekends the peaks appeared earlier and the use was more uniform. Ref. [17] monitored domestic hot water use in four low-income apartment buildings in San Francisco based on integrated hourly values from six months of measurements. Each building had a solar-assisted domestic hot water system. During a typical day, there was a peak in energy use during the morning and another peak in the evening. These peaks were related to bathing, cooking and dishwashing. Different usage patterns were observed for weekdays and weekends. During weekends a very large peak occurred during the middle of the day. Ref. [6] investigated how people used domestic hot water by asking 271 people living in 92 households to keep time diaries with a 5-min resolution. This data was compared to that of user profiles used in solar heating simulation tools. It was found that user profiles did not match the investigated users.

The authors in Ref. [5] studied the domestic electricity load of eight homes in England based on data recorded with a time resolution of 1 min. They also examined the effects of time averaging over longer time intervals. Two of the homes were studied in detail. One of these had the lowest measured demand and one had, what was considered to be, a typical demand. During a weekday in December the house with the typical demand had a base load of about 0.5 kW with morning and evening peaks of up to 4 kW with a 1-min resolution and 2 kW with a 30-min resolution. The base load during the night and during the afternoon was the same. The highest load during the measurement period was 8.8 kW at a 1-min resolution and 3.1 kW at a 30-min resolution. Ref. [18] studied what impact time averaging had on the statistical analysis of domestic photovoltaic systems. As part of this, household electric power in 13 homes, six detached houses and seven apartments, was monitored with a 10-min resolution. The household electric power during four summer weeks was examined regarding descriptive statistics. The differences between maximum and minimum powers and the standard deviation at time resolutions of 10 min and 1 h, respectively, were found to be considerable. On average, the maximum power at the 10-min resolution was about six times higher compared to the 1-h resolution and the minimum power at the 1-h resolution was, on average, twice as high compared to the power at the 10-min resolution.

The researchers in Ref. [19] monitored domestic water use in ten households, of which four were apartments, over nine months with a 10-min time resolution. Over a period of three weeks, a time resolution of less than 1-min was used. The daily domestic hot water use per person and day in apartments was, on average, 45 l. It was found that between the individual households, the use of water varied extensively from day to day. During the measurement period, 18% of the hot water volume was used at wash basins, 38% in kitchen sinks and 44% in bathtubs and showers. More than half of the occasions lasted for less than 1 min.

It is important, for several reasons related to energy use, to measure the behavioural data behind the use of household electricity and domestic hot water. It is also important to find a reasonable time resolution for measuring this data. Based on the studied literature, a time resolution of shorter than one minute should be appropriate. A shorter time resolution means that actual maximum powers and flows can be resolved and that variations over time will be more detailed. On the other hand, more data must be saved and managed, which requires more advanced equipment. Therefore it is of interest to analyse the benefits of data with higher resolution and to determine what is lost, from a statistical perspective, when using lower resolution data.

1.2. Objectives and limitations

The aim of this study was to:

- Measure the household electricity and domestic hot water use for an apartment building during a 5 day period while including the weekend, in the winter season monitoring every 6 s to give a tenfold increase in resolution compared to published data.

Table 1
Type of apartments. The number of rooms includes bed rooms and a living room but excludes kitchen and washrooms. All apartments had a kitchen and a washroom; the four-room apartments had an additional washroom.

Number of rooms/-	Number of apartments/-	Apartment area/m^2
1	8	32
2	8	60
2	16	63
3	32	76
4	8	93

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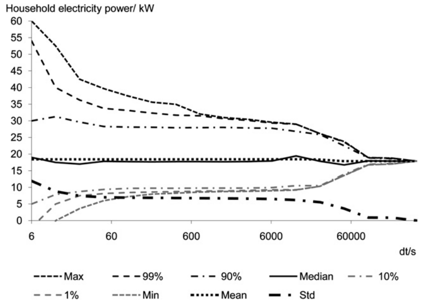

Fig. 1. Different statistical characteristics of the household electric power for intervals ranging from 6 s to 393,216 s in multiples of 6 s by 1, 2, 4, 8, …, 65,536.

- Analyse the influence of the time resolution on the distribution of data by integrating the 6 s data to represent longer logging intervals.

Measurements were made during the winter season. In the winter season, it is known that the values of both parameters are higher than the expected annual average. Measurements were made in one apartment building not in individual apartments since the main focus was on the supply system and the whole building simulation problem. More buildings would give more statistically descriptive data of the parameters, which was not the focus of this study. Annual variations could not be analysed and is a matter for future research. Variations and distribution patterns of single apartments are also other areas of future research.

2. Method

According to the literature review, both diary notations and measurements have been used to study time resolution and variation over time of user behaviour in buildings. In this study, where a 6 s resolution was of interest, diaries would not be applicable. Therefore, measurements were made by installing equipment that could logg every 6 s. The data loggers measured the use of the total building electric power and water flow for the household electricity and domestic hot water respectively. A measurement period of 5 days was selected randomly to include a weekend.

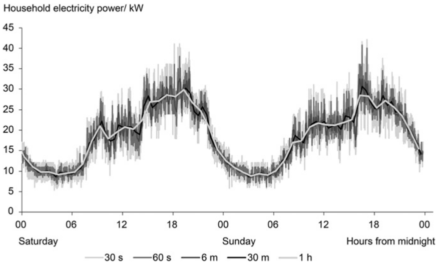

Fig. 3. The household electric power during Saturday through Sunday for different time intervals ranging from 30 s to 1 h.

2.1. Measurements

Use of household electricity and domestic hot water was measured for five days, Wednesday through Sunday, 14–18 January 2009, in a residential building in Malmö in the south of Sweden at latitude N56°. The building was erected in 1971 and consists of 72 apartments. The building was eight stories high and had four stairwells. Table 1 presents the apartment characteristics.

The one-, two- and three-room apartments had one bathtub, one washbasin, one WC, and a kitchen sink. The four-room apartments had one bathtub, two wash basins, two WC's, and a kitchen sink. According to the Swedish building code, the flow at hot water outlets should be 0.3 l/s for bathtubs and 0.2 l/s for all other hot water outlets. The total hot water flow sum for the building becomes 52 l/s which according to Author in Ref. [20] suggests a required minimum flow of 2.3 l/s of domestic hot water for the entire building.

2.2. Measurement equipment and experimental error analysis

Measurement equipment was installed to monitor the use of electricity and domestic hot water. The use of household electricity was obtained as the difference between the measurements taken from two meters. These meters gave one pulse for each 50 Wh. The use of domestic hot water was obtained as the sum of measurements from two flow meters in parallel. The meters had a start flow of 0.011 l/s. The maximum error at flows less than 0.083 l/s was ±5% and at flow higher than 0.083 l/s, the maximum error was ±2%. A single dripping outlet might have a flow less than the meter start

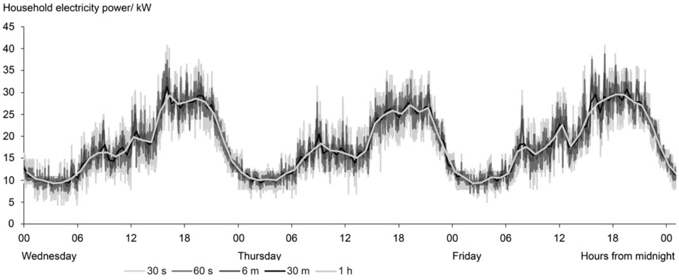

Fig. 2. The household electric power during Wednesday through Friday for different time intervals ranging from 30 s to 1 h.

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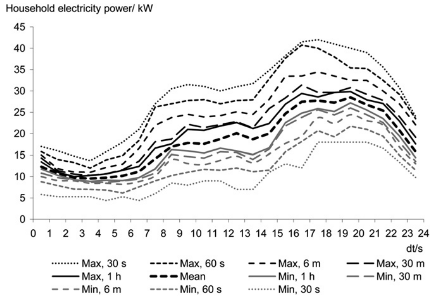

Fig. 4. The average household electric power for the measurement period presented for each clock hour of the day and the maximum and minimum at different intervals ranging from 30 s to 1 h. For example, the values at 8 are based on all data between 07 and 08 in the morning all the measured days. With 1 h resolution, it means one data per day, 5 in total, while it is much more data with 30 s resolution.

flow which means that possible dripping hot water outlets are not registered unless the total flow relating to dripping exceeds the start flow. If the aim is to study the users' use of tap hot water, dripping taps are not of interest since this depends on the hot water outlets and not on the user. However, if hot water heating is studied, dripping hot water should be considered since even a small leakage will result in a large volume over time.

A data logger measured and stored counted pulses from the meters during set 6 s intervals. The meters give a puls when the meter energy or water volume has changed by the quantity of it's resolution. That means that up to one pulse during an interval might have been accumulated during the prior interval, or intervals if there are intervals with no registered pulses. In addition, during an interval, up to one pulse might be registered on the following intervals. For example a sequence of one interval with one logged pulse, four intervals with no logged pulses followed by one interval with two logged pulses means that one of these two pulses might have been accumulated during the four intervals with no logged pulses and the interval before these. If there are n pulses logged during an interval, $(n-1)$ pulses have for sure occurred during the interval while one pulse might have been accumulated during the current interval and intervals before this until and including an interval that has one or more registered pulses.

Table 2
Different statistical characteristics of the household electric power for intervals ranging from 30 s to 1 h.

Household electricity power/kW		Wed	Thu	Fri	Sat	Sun	All
Mean		18.19	17.63	19.06	18.81	18.37	18.41
Std.	30 s	7.40	6.42	7.55	7.61	7.11	7.25
	60 s	7.12	6.10	7.30	7.33	6.86	6.97
	6 min	6.95	5.92	7.11	7.16	6.67	6.79
	30 min	6.82	5.82	6.92	7.02	6.55	6.66
	60 min	6.73	5.74	6.84	6.91	6.48	6.57
Max.	30 s	40.80	35.00	40.80	41.00	42.00	42.00
	60 s	37.35	33.00	38.80	38.00	40.75	40.75
	6 min	33.50	30.00	34.47	32.50	32.50	34.47
	30 min	31.38	27.68	30.78	30.30	30.73	31.38
	60 min	29.40	27.20	29.64	29.86	28.55	29.86
99%	30 s	34.80	32.02	35.44	35.50	35.00	34.80
	60 s	33.42	30.00	34.12	33.50	33.00	33.14
	6 min	31.80	28.42	33.01	31.97	31.59	31.96
	30 min	30.40	27.27	30.24	29.88	30.22	30.56
	60 min	29.23	27.05	29.60	29.56	28.50	29.61
90%	30 s	28.80	27.00	29.60	30.00	28.00	28.80
	60 s	28.80	26.50	29.40	29.00	27.00	28.20
	6 min	28.34	26.17	29.30	28.31	26.87	28.00
	30 min	27.98	26.05	28.45	28.45	26.56	27.98
	60 min	27.89	25.76	28.40	27.90	26.76	27.86
Median	30 s	17.00	16.80	18.00	18.00	18.19	17.80
	60 s	17.00	16.73	18.00	18.50	18.93	17.85
	6 min	16.83	16.46	17.86	18.94	19.55	17.69
	30 min	17.03	16.55	18.01	18.69	20.15	17.86
	60 min	16.50	16.64	17.68	19.89	20.18	17.60
10%	30 s	9.80	10.14	10.00	9.50	9.38	9.90
	60 s	9.80	10.00	9.80	9.36	9.00	9.50
	6 min	9.66	10.34	9.99	9.58	9.37	9.75
	30 min	9.80	10.29	10.21	9.64	9.41	9.76
	60 min	10.06	10.33	10.61	9.77	9.47	9.81
1%	30 s	6.20	8.00	7.80	7.20	7.20	7.20
	60 s	7.70	9.00	8.50	8.03	7.80	8.05
	6 min	8.77	9.28	8.95	8.65	8.50	8.71
	30 min	9.25	9.59	9.27	8.99	8.81	9.02
	60 min	9.31	10.01	9.33	9.22	8.92	9.08
Min.	30 s	4.40	6.00	5.00	5.30	5.80	4.40
	60 s	7.10	8.00	7.00	6.85	6.15	6.15
	6 min	8.51	9.00	8.54	8.46	8.20	8.20
	30 min	9.20	9.43	9.24	8.66	8.66	8.66
	60 min	9.25	10.00	9.28	9.16	8.88	8.88

The measured pulses have been corrected according to the method described above with the assumption that the pulse of uncertain origin is distributed evenly between the current interval and the intervals before, until and including the first interval that has a logged pulse or pulses. This means that after the correction

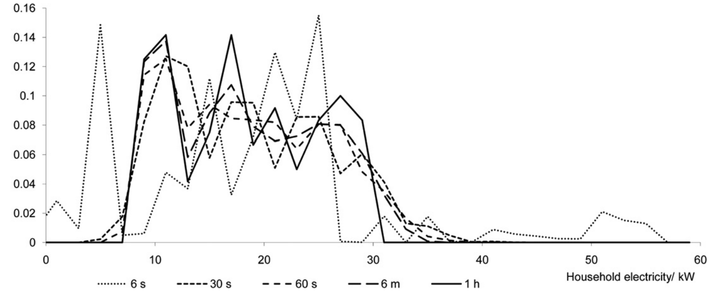

Fig. 5. The relative frequency of household electric power for different intervals ranging from 6 s to 1 h.

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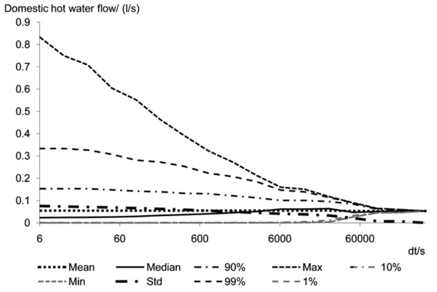

Fig. 6. Different statistical characteristics of the domestic hot water flow for intervals ranging from 6 s to 393,216 s in multiples of 6 s by 1, 2, 4, 8, ..., 65,536.

Table 3
Household electricity energy during the measurement period and the energy and average power per apartment and per apartment area.

	Energy/ kWh	Energy/(kWh/ apartment)	Energy/ (kWh/m^2)	Power/ (W/apartment)	Power/ (W/m^2)
Wednesday	437	6.1	0.089	253	3.7
Thursday	423	5.9	0.086	245	3.6
Friday	457	6.4	0.093	265	3.9
Saturday	451	6.3	0.092	261	3.8
Sunday	441	6.1	0.090	255	3.7
Average	442	6.1	0.090	256	3.7

there will be no intervals with zero pulses. The use of household electricity and domestic hot water were calculated as average power and flow during the interval respectively. Regarding household electricity, it is reasonable to assume that the use will never be zero at any time due to use of refrigerators, freezers and equipment on standby. However, it is also reasonable that the use of domestic hot water can be zero at times, for example during night, if there are no leaking water taps. Only intervals just before or after an interval with zero pulses will be affected by the correction. The household electric peak powers and domestic hot water peak flows were not affected by the correction since the peaks occurred during intervals that have intervals with logged pulses both before and after. Since this method gives the average power and flow during the interval, the actual peak value during an interval can be higher than the average value but not lower.

The theoretical highest error of overestimated household electricity can be shown to be less than 2/3 pulses during an interval and the theoretical highest error of underestimating can be shown to be less than 4/3 pulses, due to the set up where the household electricity use is a difference between 2 m. The theoretical highest error of overestimated domestic hot water flow is less than 2 pulses during an interval and the theoretical highest error of underestimating is less than 2/3 of a pulse. As the time of the interval increases, the relative effect of this error decreases since each pulse is spread over a longer time.

In the actual data set, at 6 s time intervals, maximum possible over correction of household electricity was 0.67 pulses and the maximum possible under correction was 1.17 pulses. The 90 percentile of the corrections was 0.37 pulses and the 10 percentile was 0.52 pulses. The maximum possible over correction of domestic hot water at 6 s time interval was 2 pulses and the maximum possible under correction was 2/3 pulses. The 90 percentile of the corrections was 0.50 pulses and the 10 percentile was 0.33 pulses.

After the correction, the lowest household electric power at the 6 s intervals was 0.125 pulses. The lowest domestic hot water flow after the correction was 0.00083 pulses. As mentioned, in the actual data set, the maximum power and maximum flow occurred during intervals that have intervals with logged pulses both before and after and hence are not affected by the correction.

3. Results

Based on the number of logged and corrected pulses, and the corresponding time of the interval, the average power and flow during the interval was calculated. Longer time intervals were calculated by summing pulses over multiples of the logged 6 s intervals.

The median, 99, 90, 10 and 1 percentile and standard deviation was studied for different time intervals, while the average was the same as expected. The result is presented for individual days during the measurement period as well as for the whole measurement period.

3.1. Household electricity

Fig. 1 presents different statistical characteristics of the household electric power for different time intervals ranging from 6 s to 393,216 s (4.6 days). The intervals are in multiples of 6 s. The maximum value and the 99 percentile are almost the same at intervals longer than 600 s (10 min). The same applies for the minimum and the 1 percentile. At intervals longer than 24,576 s

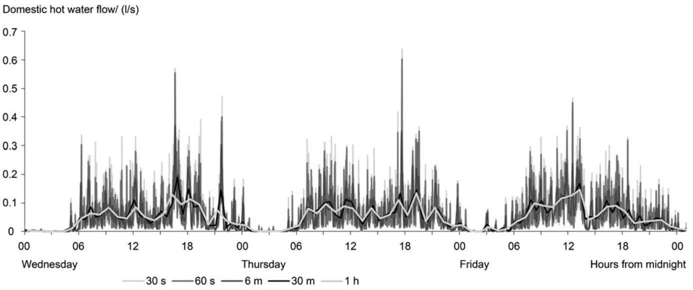

Fig. 7. The domestic hot water flow during Wednesday through Friday for different time intervals ranging from 30 s to 1 h.

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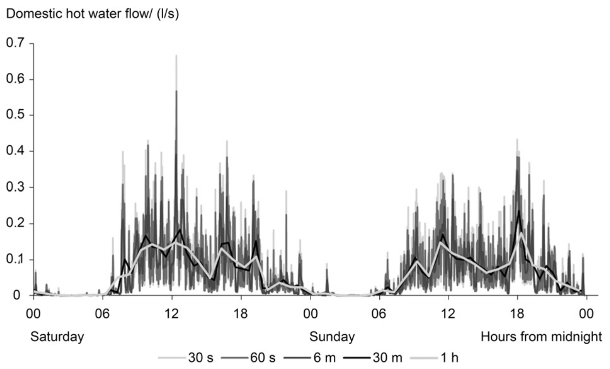

Fig. 8. The domestic hot water flow during Saturday through Sunday for different time intervals ranging from 30 s to 1 h.

(about 7 h) the 90 percentile aligns with the maximum and the 10 percentile aligns with the minimum. At time intervals less than 6000 s the figures relates to variations during the day. At intervals longer than 6000 s, the variations during the day are starting to be diminished. At intervals longer than 60,000 s the figures relate to variations between days. The median value is slightly less than the average value except for 6 s intervals and 49,152 s intervals (about 14 h). The standard deviation decreases going from 6 s intervals to 60 s intervals and is almost constant between 60 s and 12,288 s (about 3.5 h) intervals and then decreases.

Figs. 2 and 3 present the household electric power during the measurement period and Fig. 4 presents the average household electric power based on the whole measurement period for each hour of the day and the maximum and minimum values for each hour at different intervals ranging from 30 s to 1 h. The electric power use during night was on average about 10 kW, from morning through early afternoon 16 kW and during late afternoon and evenings 26 kW. The plotted electric power visualizes the decreasing peak power at longer intervals. The peak during Thursday morning is 32 kW and the peak during Thursday evening is 35 kW at 30 s intervals while the corresponding peaks at 1 h intervals are 18 kW and 27 kW. The 30 s intervals evening peak is 10% higher than the morning peak while the 1 h evening peak is 50% higher than the morning peak. During periods of low electric power use, typically during night, the span between highest and lowest values at 30 s intervals is about 7 kW and during periods of high use, typically during evenings, about 20 kW. At 60 s interval these spans decreases to about 3 kW and 12 kW, and at 6 min intervals 2 kW and 5 kW. At 30 min and 1 h intervals, the use is more or less smooth during the day. The characteristics of the 1 h intervals power is in accordance with published data. The power during the night is believed to mostly relate to standby of equipment, refrigerators and freezers. Refrigerators and freezers operate intermittently which can explain the span between highest and lowest measured values during the night.

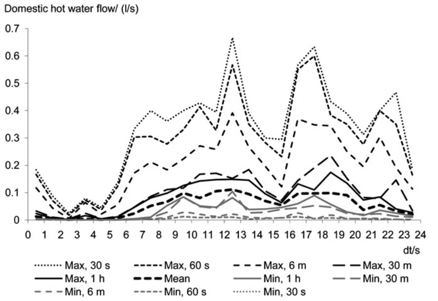

Fig. 9. The average domestic hot water flow for the measurement period presented for each hour of the day and the maximum and minimum for each hour at different intervals ranging from 30 s to 1 h.

Fig. 5 describes the frequency of household electricity for different time intervals. The graph is based on counts of occurrence of data, split into 2 kW intervals. With a 6 s time resolution, the few occurring peaks are based on the few number of discrete pulses possible from the electricity meters during the 6 s interval. A conclusion from the graph is that there was probably no power failure longer than 30 s. Below 30 kW, the distribution is rather rectangular.

Table 2 presents different statistical characteristics of the household electric power for intervals ranging from 6 s to 1 h. Table 3 presents the household electricity energy and average power during the different days of the measurement period. The household electricity energy and average power was more or less the same during the different days of the measurement period. The average power was least during Thursday and highest during Friday with a difference of 1.4 kW between the two. The standard deviation increased with shorter intervals. The difference between the standard deviation at 30 s intervals and 1 h intervals was on average 0.7 kW. Generally the maximum increases with shorter intervals and the minimum decreases with shorter intervals. The same applies for the 99th and 90th percentile and the first and tenth percentile respectively. However, due to the distribution of the household electric power, see Fig. 6, the percentiles and the median can, in some cases, increase and decrease in contradiction to what is described above [5]. The difference between the maximum at 30 s intervals and 1 h intervals was on average 12 kW and the corresponding differences at the 99th and the 90th percentile were 5 kW and 1 kW. The difference between the minimum at 30 s intervals and 1 h intervals was on average 4.5 kW

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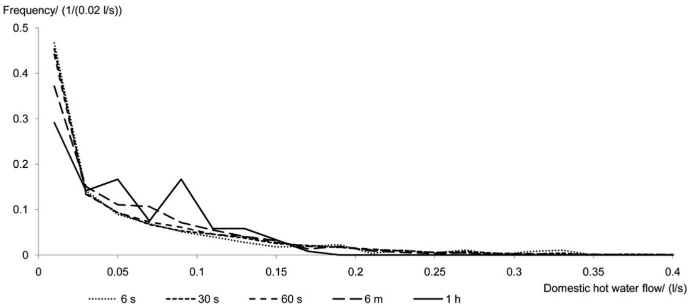

Fig. 10. The frequency of domestic hot water flow for different intervals ranging from 6 s to 1 h. Part 1, 0–0.4 l/s of 0–0.9 l/s.

and the corresponding differences at the 99th and the 90th percentile were 2 kW and 0.1 kW.

3.2. Domestic hot water

Fig. 6 presents different statistical characteristics of the domestic hot water flow for different time intervals between 6 s and 393,216 s (4.5 days). The intervals are in multiples of 6 s. The median is less than the average value except for the intervals of 6144, 12,288 and 24,575 s. The median increases up to intervals of 6144 s (about 1.5 h). The standard deviation decreases with longer intervals. The maximum value and the 99th percentile are almost the same at intervals longer than 24,576 s (about 7 h) and the 90th percentile at intervals longer than 49,152 s (14 h). The minimum, first percentile and tenth percentile are almost the same except at intervals of 24,576 and 49,152 s (about 7 h and 14 h) where the 10th percentile is slightly higher.

Figs. 7 and 8 shows the domestic hot water flow during the measurement period. Fig. 9 presents the average domstic hot water flow based on the whole measurement period for each hour of the day and the maximum and minimum for each hour at different intervals ranging from 30 s to 1 h. The plotted flow visualizes the decreased peak flow at longer intervals. During the night between one and five o'clock, the flow is close to zero. There are large differences between the peaks during the days of the measurement period for 30 and 60 s intervals while longer intervals have less difference between the daily peaks. There are no obvious general characteristics of the use during the day except a local minimum during the afternoon at 2 pm and 3 pm for all days except Thursday.

Figs. 10 and 11 show the relative frequency of the domestic hot water flow based on counts of data with 0.02 l/s interval. The result is split into two graphs to make the values at high flow visible. The origin from rather few discrete pulses with short time resolutions is visible, and it is also shown that the most probable flow is or is close to 0, which is reasonable to get, especially during nights.

Table 4 presents different statistical characteristics of the domestic hot water flow for intervals ranging from 6 s to 1 h. Table 5 presents the domestic hot water volume during the different days of the measurement period. The average domestic hot water flow was 0.055 l/s and the average daily volume was 4733 l. The difference between the highest use, Saturday, and the lowest use, Wednesday, was 0.011 l/s or 984 l. On average, the median decreased with shorter intervals and was lower than the average flow for the analysed cases. The standard deviation increased with shorter intervals. The difference between the standard deviation for the 30 s intervals and 1 h intervals was on average 0.027 l/s. Generally the maximum increased with shorter intervals and the minimum decreased with shorter intervals. The same applies for the 99th and 90th percentile and the 1st and 10th percentile respectively. The difference between the maximum at 30 s intervals and 1 h intervals was on average 0.46 l/s and the corresponding differences at the 99th and the 90th percentile were

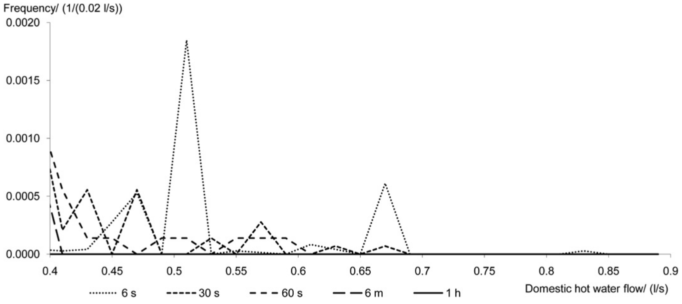

Fig. 11. The frequency of domestic hot water flow for different intervals ranging from 6 s to 1 h. Part 2, 0.4–0.9 l/s of 0–0.9 l/s.

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Table 4
Different statistical characteristics of the household electric power for intervals ranging from 30 s to 1 h.

Domestic hot water flow/(l/s)		Wed	Thu	Fri	Sat	Sun	All
Mean		0.050	0.052	0.054	0.062	0.056	0.055
Std.	30 s	0.068	0.064	0.065	0.081	0.072	0.070
	60 s	0.065	0.062	0.063	0.079	0.070	0.068
	6 min	0.057	0.052	0.052	0.070	0.062	0.059
	30 min	0.044	0.039	0.042	0.057	0.053	0.048
	60 min	0.037	0.037	0.041	0.053	0.049	0.044
Max.	30 s	0.57	0.63	0.47	0.67	0.43	0.67
	60 s	0.55	0.60	0.45	0.57	0.38	0.60
	6 min	0.37	0.35	0.24	0.39	0.34	0.39
	30 min	0.19	0.15	0.17	0.18	0.24	0.24
	60 min	0.13	0.13	0.15	0.15	0.17	0.17
99%	30 s	0.31	0.28	0.27	0.34	0.32	0.31
	60 s	0.28	0.25	0.26	0.33	0.29	0.30
	6 min	0.21	0.22	0.22	0.27	0.27	0.26
	30 min	0.17	0.14	0.15	0.18	0.21	0.18
	60 min	0.13	0.13	0.14	0.15	0.17	0.15
90%	30 s	0.14	0.13	0.14	0.18	0.16	0.15
	60 s	0.14	0.13	0.14	0.17	0.15	0.15
	6 min	0.13	0.11	0.13	0.15	0.13	0.13
	30 min	0.10	0.10	0.11	0.15	0.11	0.12
	60 min	0.09	0.09	0.11	0.13	0.11	0.12
Median	30 s	0.023	0.026	0.028	0.024	0.025	0.025
	60 s	0.024	0.028	0.030	0.027	0.027	0.027
	6 min	0.034	0.041	0.040	0.034	0.037	0.037
	30 min	0.048	0.050	0.046	0.044	0.052	0.047
	60 min	0.049	0.051	0.040	0.050	0.053	0.049
10%	30 s	0.00076	0.0012	0.0012	0.00078	0.00038	0.00089
	60 s	0.00076	0.0012	0.0012	0.00078	0.00038	0.00092
	6 min	0.00075	0.0012	0.0013	0.00081	0.00038	0.00092
	30 min	0.0016	0.0022	0.0034	0.0011	0.0006	0.0015
	60 min	0.0014	0.0023	0.0058	0.0014	0.0021	0.0016
1%	30 s	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	60 s	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	6 min	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	30 min	0.00043	0.00089	0.00083	0.00030	0.00038	0.00035
	60 min	0.00042	0.00128	0.00093	0.00047	0.00043	0.00036
Min.	30 s	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	60 s	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	6 min	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	30 min	0.00035	0.00068	0.00068	0.00030	0.00038	0.00030
	60 min	0.00035	0.00118	0.00071	0.00030	0.00040	0.00030

Table 5
Domestic hot water volume during the measurement period. Total volume and volume per apartment and per apartment area.

	Volume/l	Volume/(l/apartment)	Volume/(l/m^2)
Wednesday	4333	60.2	0.88
Thursday	4473	62.1	0.91
Friday	4697	65.2	0.95
Saturday	5318	73.9	1.1
Sunday	4846	67.3	0.98
Average	4733	65.7	0.96

0.16 l/s and 0.031 l/s. The difference between the minimum at 30 s intervals and 1 h intervals was on average 0.00030 l/s and the corresponding differences at the 99th and the 90th percentile were 0.000060 l/s and 0.00076 l/s.

4. Discussion and conclusions

The different levels of time averaging used in the study show what gets lost by measuring rapidly varying parameters related to buildings, such as household electric power and domestic hot water flow. Extreme values, especially on the high side, disappear if the time interval is increased. Still, this study has been limited to integrating meter technology. With momentarily based meters, even more information could be lost. With the integrating meters used, the average is correct as far as the precision of the meter goes. In that case, if the question is to verify an annual average household electricity use, it is enough with a time resolution of 1 year. If it is of interest to sort out annual variations which are most important for annual energy use calculations, and for energy supply system load analysis, at least one reading per month is necessary. This is also of interest for energy systems that is stored over time in the magnitude of some days, like large water tanks, or for systems where the supply power varies strongly with the year. Another application would be to design the orientation of solar collectors to minimize the need for accumulating systems.

If daily variations must be considered, such as for photovoltaic and solar collectors, energy calculations need at least hourly data. However, all kinds of power design in a building or its services benefit from much more resolved data. The limit of 6 s in this study was set for practical reasons to be able to handle quantity resolution and the amount of logged data, but there is no proof shown that it is enough. The maximum for both parameters increase when the resolution goes from 12 s to 6 s. The maximum household electrical power, with respect to the described pulse management and the meter errors is at least the given one, but it is not known what happens during the 6 s interval. In this analysis, it has also been assumed that registered pulses are evenly spread within the time span of the resolution, which is an assumption. It is reasonable that a water tap is used for at least 6 s at a time. Literature indicates that it is less than one minute. Regarding electrical appliances, the same can be believed except for starting powers of electric motors, of which there are likely not many connected to the electrical system of a household. This study does not take that problem in to account, since it would require millisecond resolution. Electrical fuses in the building's main power installation should need in the magnitude of 6 s to break, but that analyses is a matter of future research. Common electricity and elevators are also subjects of future research since elevators seem, by far, to have the highest single electric power need in an apartment building.

The problem with higher time resolution is the amount of resulting data which sets the practical limit for what is possible to measure in practice. To calculate the energy balance of a building, there are also parameters that changes slowly and do not necessitate high time resolution such as indoor and outdoor temperature. Measurements over a longer time period would give more information on maximum values. The highest measured hot water flow at a 6 s interval was 0.83 l/s which is much lower compared to the required flow of 2.3 l/s, calculated according to Ref. [20]. However, the flow might have been higher during the 6 s measurement interval and during a buildings life span. Higher flows would certainly occur if the domestic hot water system's designed maximum flows were not the limiter.

With integrating meters, it is not possible to increase both quantity of samples and time resolution. Practical meters, particularly regarding water flow, have limited dynamic range. They should handle very low flows as well as the design flow and give information on both, and usually they are also used and approved for billing purposes. There are also budget restrictions resulting in compromises. With a 6 s interval, there were at the most 9 pulses per interval for electricity and 5 pulses for domestic hot water, which means that a numerical error is added to the maximum value. With longer time averaging intervals, the dynamic resolution increases. More sophisticated software to log extreme values would be interesting to test. There is a need for logger equipment that handles much more data and can be used in practice. For research purposes larger amounts and more detailed measurements should be made to verify and develop design practice both regarding the

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two parameters studied here in as well as other parameters. To analyse distributions between apartments and parts of apartments or houses would also be of interest to be able to make statistically based guidelines for system design.

The household electricity use patterns align well with the characteristics reported by references. The average household electric power was 3.7 W/m^2 which agrees quite well with literature. The average use of 10 kW during night equals 2 W/m^2 or 140 W/apartment. When a house is designed according to the Swedish requirements for a passive house, internal heat gains of a maximum of 4 W/m^2 is allowed when the design heating load is calculated [21]. The design heating load probably occurs during night when there are no solar heat gains and the outdoor temperature is typically lower [22]. There is a difference of 2 W/m^2 between the internal heat gains according to Ref. [21] and the average measured household electric power during night. Except from household electricity, internal heat gains might be from people and if the people are assumed sleeping, during night, heat gains from one person can be about 80 W. If heat gains from people shall make up the 2 W/m^2 difference there has to be one person per 40 m^2 which is considered reasonable.

As household electricity related products such as refrigerators, washing machines, and electronic devices are replaced by more energy efficient alternatives the household electricity use will decrease given that the number of products and operating times are not increased. On the other hand, it can be assumed that high power devices such as washing machine heaters or hair dryers will still have the same, rather high, electric power need which means that the ratio between the extreme values and the average will be even higher. Implementation of energy efficient products can, on the other hand, decrease the absolute variations in household electricity in the low part of the frequency graph because there is an increasing amount of appliances that runs automatically.

The difference between the highest and lowest household electric power during a day was about 8 W/m^2 floor area measured at 6 s intervals and 4 W/m^2 floor area measured at 1 h intervals. A passive house built according to the Swedish requirements [21] will have a total heat loss of about 0.5 W/(°C m^2) in relation to the heated floor area. That means that in a low energy building, the difference in household electric power during a day according to the measurements corresponds to between 8 °C and 16 °C difference in outdoor temperature depending on the time interval of the measurements. For a normal day during the winter in typical south Swedish outdoor climate, there is a difference between top and bottom values of 4 °C [22,23]. According to this comparison, it is more important to have a varying household electricity use than a varying outdoor temperature in energy and power simulations of dwellings. A varying outdoor temperature is commonly used when doing simulations in research as well as in practice. Similarly should a varying household electricity be used. According to Ref. [24], consultants seldom take the daily variations of household electricity use into account when performing energy simulations.

The pattern of the variations of the domestic hot water flow is weak compared to [25] measurements in Malmö over much longer time. The ratio between the maximum flow and the average flow is high, which corresponds to the generally used theory on frequency distribution of several water taps based on binomial distributions. It is noticeable in Fig. 10 how fast the relative frequency drops with higher flow. High flows occur very seldom. The distribution should be of interest for the design of sewage heat exchangers as well as solar collectors. The design of water supply components can help from the results of this approach but it is not known if the maximum flow is limited by the design or the user's behaviour. It is also not as crucial to handle the maximum flow of water as it is for electricity where voltage drop must be avoided.

The study has given insights in the area of time resolution of data of the apartment building user related parameters household electricity and domestic hot water use. It has been shown that hourly data is not adequate when designing components and supply systems, even if it might be sufficient when performing annual energy calculations. The limited amount of buildings and the limited time span of the measurements do not allow for statistically comprehensive descriptive data. However future measurements in combination with existing literature will hopefully establish guidelines.

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PAPER 8
AP 8

Bagge H, Johansson D, Lindstrii L, Indoor hygrothermal conditions in Swedish residential buildings – Measurements and standards, Submitted to Building and Environment 2011

Indoor hygrothermal conditions in Swedish residential buildings – measurements and standards

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Abstract
To be able to design a building with healthy indoor climate and sustainability, both energy and moisture simulations are needed. Accurate simulations call for comprehensive input data regarding user related parameters, such as indoor temperature, relative humidity and ventilation airflow rate. As a part of an on-going study, indoor temperature and indoor moisture conditions have been measured in 18 Swedish residential buildings containing in total 325 apartments located between latitude N56° and N67°. The parameters were measured at the building level, through measurements in the exhaust air of the ventilation system, providing average values of the apartments. The parameters were monitored every 30 minutes during one year. Indoor temperature, moisture supply and indoor relative humidity were studied as functions of the outdoor temperature and compared to corresponding parameters in EN 13788 and EN 15026. A proposal for indoor hygrothermal classes are presented based on the measured data and its statistical characteristics.

Keywords: Indoor temperature, relative humidity, moisture supply, indoor climate, indoor climate classes

1 Introduction

In the building industry, it is necessary to perform calculations regarding energy use and moisture levels to ensure that a building will be sustainable and healthy. During the design phase, simulations are used to ensure that different constructions will meet design criteria, also construction type and materials might be chosen based on the simulation results. Simulations are used not only during the design phase but also when a moisture damage or energy related problem is assessed. [1] The indoor temperature will affect the use of space heating and the conditions inside a construction, and moisture levels together with temperature will affect deterioration of materials and growth of microorganisms. The relative humidity will affect the perception of indoor climate. Heat, air and moisture simulations (HAM) are an important area, crucially needed to produce low energy buildings when margins are low. Even if a lot of progress has been made recently regarding numerical models and computing speed, correct results also require correct boundary conditions. Therefore, to make accurate predictions on energy use, indoor climate and moisture levels, adequate input data are needed in order to simulate energy use and indoor climate and verify results from simulation programs.

According to [2] and [3], design of the thermal envelope is in most cases done with assumed constant indoor conditions that does not relate to the actual conditions according to measurements. The indoor climate conditions should reflect local regional conditions and dynamics. To assess the performance of a buildings thermal envelope and possible mould growth it is important to have accurate indoor boundary condition data that are based on measurements [3].

Indoor temperature is typically the main thermal comfort parameter assessed in both calculations and measurements although other parameters such as operative temperature and different thermal comfort variables might be more reliable although not as easily measured and simulated. In Swedish residential buildings, a sufficient indoor temperature is maintained by a heating system and a control system given that enough heating power is installed. The control system can be more or less advanced and hence appropriate. The indoor temperature during the heating season affects thermal and ventilation heat losses and hence the energy use. Outside of the heating season the indoor temperature is determined by the outdoor temperature, internal heat gains and solar heat gains. Cooling is typically not used in Swedish residential buildings. At high outdoor temperatures the indoor temperature can be controlled to some extent by airing and solar shading.

Indoor moisture conditions are usually measured as relative humidity. If both indoor and outdoor temperature and relative humidity are measured, the moisture supply can be calculated. The moisture supply is defined as the difference between the indoor and outdoor vapour content. In calculations the indoor moisture conditions are described by indoor relative humidity or moisture supply. For a given moisture supply, the indoor temperature determines the indoor relative humidity. Both indoor temperature and relative humidity affects the perceived indoor air quality. In dwellings, there are usually no technical systems that controls the indoor moisture conditions as is the case with indoor temperature during the heating season. The moisture level can be controlled by use of demand controlled ventilation airflows. In older buildings without mechanical ventilation systems, moisture triggered fans are sometimes installed in bathrooms.

When consultants or researchers perform practical calculations, it is not realistic to measure input data for every case. Standards describing the indoor temperature and moisture load enable a way to provide input data for simulations. EN 13788 [4] and EN 15026 [5] are examples of such standards and describes the indoor hygrothermal conditions. EN 13788 describes the indoor temperature and the moisture supply in different classes as functions of the outdoor temperature. EN 15026 describes the indoor temperature and the indoor relative humidity, in a normal and a high class, as functions of the outdoor temperature. It is important for practical reasons that these standards describe realistic input data with realistic distributions depending on what simulations and risk analyses that will be performed.

Measurements on indoor temperatures and relative humidity have been made. [1] presented a thorough literature review regarding moisture supply, which is defined as the indoor vapour content minus the outdoor vapour content. Common for the previous studies was that the indoor climate had only been studied for shorter periods. [6] presented measured indoor temperatures in multi-family dwellings. The indoor temperatures were measured in the living rooms between March and May and was on average 21.8°. Indoor temperature and relative humidity were measured in 1800 single family houses and apartments in multi-family buildings in Sweden [7]. Measurements were carried out during two weeks in each house or apartment with measurements every 15 minutes. The two week measurement period started between October 2007 and May 2008 depending on location meaning that the measured data origins from different measurement periods as well as geographic locations. The average indoor temperature, relative humidity and moisture supply in multi-family dwellings were 22.3˚C, 30% and 1.22 g/m^3. Distributions between buildings are presented but not distributions during the measurement periods or the relation to the outdoor temperature. Some shortcomings are that they only measured during the heating season, and even if they would have started measurements during the whole year, it is not clear if their measurement period starting times were evenly distributed between October and May. There might be an over or under estimation due to the variations over the year as presented by [8] which means that the data from [7] are not directly comparable to the results from this study. [1] measured indoor humidity loads in 100 bedrooms and 79 living room in 101 single family detached houses during 2002 and 2004. During periods with outdoor temperatures at or below 5˚C, the average moisture supply was 1.8 g/m^3, and during periods with outdoor temperature over 5˚C, the average moisture supply was 0.5 g/m^3. The difference between bedrooms and living rooms was small. Moisture supply figures of up to 4 g/m^3 are given for use in moisture design of dwellings [9].

[10] Calls attention to the problem that it is too common that measured energy use exceeds predicted use. [11] highlighted several projects where the measured use exceeded the predicted by 50 % to 100 % despite of explicit energy efficient goals during the planning. [12] studied energy use in passive houses built in Sweden. The measured energy use during operation was 50% higher than the use predicted during the design phase. This was partly due to higher actual target indoor temperature and heat exchangers being less efficient than predicted. [12] stressed the importance of accurate input data for energy simulations. The building users' behaviour is very important for the performance of low energy buildings and also the hardest to model according to [12].

According to the literature there are large deviations between predicted and measured energy use in residential buildings during operation and it might be suspected that the same applies for predicted and measured moisture conditions in buildings during operation. [13] studied the dampening effect of hygroscopic materials and concluded that there were considerable differences between simulated values and measured values. Simulations are often executed with conditions that are not typical for real buildings and for example variations in the quality of workmanship are hard to take into account in simulations [14]. [15] argued that although simulation models are developed to represent the physics of the buildings more and more accurately, the model of the inhabitants' behaviour is too simplified which leads to errors in predictions. According to [16], whole building hygrothermal simulations show that the amplitudes of indoor humidity can be significantly different depending on whether the moisture buffering effect of building materials is included or not.

As buildings are getting more and more energy efficient through reduced thermal transmission and reduced ventilation heat loss, the building's users energy related behavior will have a greater effect on the buildings total energy use. The thermal transmission is reduced by use of highly insulated climate envelopes which however might increase the risk of moisture damage if the constructions are not appropriately designed and built. The design of moisture safe constructions are carried out using simulation tools and to ensure correct results from simulations there is a need for appropriate data on the indoor hygrothermal conditions since driving forces for moisture and heat transport are the differences in the conditions between indoors and outdoors. The outdoor climate is often described by many parameters on an hourly scale based on several years of measurements.

In conclusion, there seems to be a lack of building user related data, especially data obtained during longer periods from many apartments with high time resolution, particularly for many parameters that can be correlated to each other. Therefore, a study on household electricity use, domestic hot water use, indoor temperature, indoor relative humidity, moisture supply, moisture production, CO_2 production and occupancy with readings every 30 minutes during more than a year in 18 multi-family dwellings comprising 325 apartments was done [17, 18]. This paper presents results relating to indoor temperature, relative humidity and moisture supply.

1.1 Objectives and limitations

To be able to provide the building research and building sector with more data on the user behavioral hygrothermal parameters of buildings, particularly for conditions in Swedish apartment buildings, the objectives of this study was to

- Measure indoor and outdoor temperatures and relative humidity in some apartment buildings at different locations in Sweden during a year to get examples on Swedish hygrothermal conditions with annual variations
- Analyze indoor temperatures, indoor relative humidity and moisture supply in Swedish residential buildings.
- Compare the results of these measurements with European standards on indoor hygrothermal conditions typically used in simulations
- Propose adaptations of standards based on the measured data beeing an example of Swedish hygrothermal conditions

Measurements were performed in buildings on four locations spread over Sweden, which means that it was realistic to find relationships between location and result. The architecture and the surroundings were not analyzed. It is not analyzed what confounders could disturb the generalization of the result or what could be matched for. Therefore the result of this rather limited set up has to be seen as a descriptive part adding to more measurements performed in literature. On the other hand, building user's behavior is believed to change over time so it is difficult to know the applicability of older studies. More research is needed regarding measurements of representative data.

The measured objects were apartment buildings, not houses, selected based on availability and technical systems suitable for measurements in the central exhaust duct system to be able to increase the number of apartments included in the average. The problem with central measurements is the lack of possibility to analyze conditions in or distributions between apartments or single rooms. Window airing was not measured or analyzed. Effects from moisture buffering and effects from air exchange efficiencies were also not analyzed in this study.

2 Method

Measurements were performed during one year in 18 Swedish apartment buildings including 325 apartments on a central level of each building by putting the equipment in the central exhaust. The measurements were compared to the description of indoor temperature and moisture supply in EN 13788 and to the description of indoor temperature and indoor relative humidity in EN 15026. Based on these standards and the measurement results, descriptions of indoor hygrothermal conditions according to the measurements were made based on a combination of a qualitative and quantitative method.

The measurement periods for the different buildings, the yearly average outdoor temperature based on [9] and the number of hours at or below the average outdoor temperature were according to Table 1. Characteristics of the studied buildings are presented in Table 2. All the buildings used mechanical exhaust air ventilation.
Readings were made every 30 minutes enabling analyses of daily, weekly and annual variations presented by [8]. Simulation programs usually simulate using hourly time steps. The full year measurement also enables comparisons with the standards that take into account a whole year's outdoor climate. Even if the generalization based on the rather small measurement sample should be made with caution, distribution over time and between buildings is of high interest for risk analyzes.

Table 1. The Measurement Periods and the Yearly Average Outdoor Temperature and the Number of Hours of Outdoor Temperature at or Below the Average at the Different Locations

Location and latitude	Start date	End date	Average outdoor temperature, C°	Hours at or below Avg. temp., h
Karlstad, 59°	2008-06-12	2009-07-07	5.5	4089
Kiruna, 67°	2008-07-05	2009-08-19	-1.7	3749
Malmö, 56°	2008-10-10	2009-11-23	8.2	3872
Sundsvall, 62°	2008-09-05	2009-09-29	3.6	4336

Table 2. Characteristics of the studied buildings

Location	Building	Erected year	Number of apartments	Number of stories
Karlstad	1	2005	23	4
	2	2005	22	4
	3	1964	34	9
	4	1964	36	9
	5	1940	24	2
Kiruna	1	1963	9	3
	2	1963	9	3
	3	1963	12	3
	4	1963	10	3
	5	1963	11	3
Malmö	1	1971	24	8
	2	1971	16	8
	3	1971	16	8
	4	1971	16	8
Sundsvall	1	1969	12	3
	2	1969	18	3
	3	1969	18	3
	4	1969	15	3

2.1 Measured and calculated parameters and definitions

By making measurements in the exhaust air of residential buildings, a large number of apartments could be included in the study at a reasonable cost and effort, compared to measuring in every individual apartment. On the other hand, it is not possible to find distributions between apartments inside a certain residential building or distributions between different rooms in an apartment. The measured parameters related to this paper were: temperatures in the central exhaust duct and outdoors, and relative humidity in the central exhaust duct and outdoors. From these parameters, the moisture supply can be calculated. Outdoor temperature and outdoor relative humidity were aquired from the Swedish Meteorological and Hydrological Institute, who monitors outdoor climate every 3 hours.

Moisture supply, v_{sup}, is defined as the difference between the indoor vapour content and the outdoor vapour content. The vapour content is defined as the mass of vapour, water as gas, per volume of mixture of vapour and air. The saturation vapour content, v_{sat}, as a function of the air temperature, t, was calculated according to Equation 1 with an error less than 0.07 g/m^3 compared to tabled data presented by [9] [19].

$$v_{sat} = 4.7815706 + 0.34597292 \cdot t + 0.0099365776 \cdot t^2 + 0.00015612096 \cdot t^3$$
$$+ 1.9830825 \cdot 10^{-6} \cdot t^4 + 1.5773396 \cdot 10^{-8} \cdot t^5$$
$$(1)$$

When the results are compared to the standards, and when new proposed standards are presented, two-dimensional frequency graphs are used. In these graphs, the relative frequency is given as a grayscale based on counting data in intervals of 2.4 °C for the outdoor temperature and 0.8 °C for the indoor temperature, hence the unit of the relative frequency of 1/(0.8·2.4 °C^2), for the indoor temperature graph. For the moisture supply graph, the y-axis gives the moisture supply split in 0.8 g/m^3, giving the unit 1/(2.4·0.8 °C·g/m^3). For the indoor relative humidity graph , the y-axis gives the relative humidity split in 3.6 %, giving the unit 1/(3.6 · 2.4 %·°C). The area integral of these graphs on relative frequency with respect to these units is 1. The graphs indicate the number of annual hours with a certain indoor temperature or moisture supply respectively at an arbitrary outdoor temperature. It is also shown how common certain outdoor temperatures were. The choice of outdoor temperature as a depending variable was based on the construction of the EN standards where this assumption is used. Other depending variables were not analyzed or tested for, but an example of a reasonable relationship could be indoor temperature versus global shortwave incoming solar radiation.

The comparison of measured data to the given EN standards was made qualitatively based on visual comparison of the standard lines drawn in the relative frequency graphs. In the literature, there are examples on quantitative methods for making classes in the standards [1]. The risk with a quantitative method is that extreme data is not considered. In this study, a combination of qualitative interpretation in the frequency graphs combined with data on distributions were used for proposing new adapted standards with the same depending variable as the EN standards. The proposed standards were based on the distribution of data and are intended to describe different levels of extremes in the measured data. For moisture supply, it is common to only describe high extremes, but also low extremes were given in the proposals to be able to, for example, calculate the risk of very low indoor relative humidity in an arbitrary location in Sweden. The outdoor temperature at the studied locations defines the outdoor temperatures for which the proposed standards are valid. Close to the low and high limits respectively of the outdoor temperature, there are not very many measured values which mean less statistical confidence than at more frequent outdoor temperatures. Therefore, the values at low and high outdoor temperatures in the proposed standards have in some cases been chosen by qualitative method.

Buffering effects or influence over time from, for example, a moisture load on mould growth cannot be taken into account because the frequency graphs does not show the order in time of data points. For example, an extreme high value of indoor relative humidity can probably occur for a short time without causing a high risk of mould growth. In a frequency graph like the one presented in this paper, the total area of existing data depends on frequency of samples. The analysis of time influence is an interesting matter for future research and how to do it depends on the aim of the moisture design.

2.2 Measurement equipment and possible errors

Temperatures are measured with data loggers with a specified error of ±0.35°C. Generally, the experience from using these devices is that the error is seldom more than ±0.2°C. The relative humidity is measured with the same data loggers. The relative humidity error is given to ±2.5% absolutely. The data loggers were calibrated before the measurements started regarding temperature and relative humidity to decrease the possibility of combined errors due to the fact that the error of the difference can be much higher.

The lack of measurements in single rooms in each apartment lead to problems with knowing if a measured value is the airflow weighted average value of the entire apartments, or only the airflow weighted point value at the exhaust devices. On the other hand, measuring in a single room does not give information on the entire apartment. It is believed that the representation of the apartment is plausible. For example, during the summer the indoor temperature in a room with windows facing south will probably be much higher compared to a room with windows facing north. If the indoor conditions were measured in individual rooms, the orientation of these rooms would affect the results and in order to assess the whole building conditions, measurements should be made in all rooms of the building which would limit the possible number of buildings at a set measurement budget.

The measured indoor temperature and relative humidity data includes the possible effects from moisture buffering and heat storage of the building and the movables, such as furniture, paintings and books. Buildings are exposed to air leakage due to wind and buoyancy that changes the air in the apartments in addition to the mechanical ventilation. The actual air change rate could be measured with tracer gas methods but it would be expensive to do it annually and not realistic if many buildings are to be included. On the other hand, this error is minimized in buildings with mechanical exhaust air only. It leads to a lower indoor pressure which reduces the exfiltration which decrease air change from leakage. Typically, it is decreased by a factor of 5 compared to a building with balanced ventilation [20]. If a building has mechanical exhaust and an air tightness of 0.8 $l/(s\cdot m^2$ surrounding walls) at 50 Pa testing pressure, a constant airflow rate of $1\%\cdot 0.8\ l/(s\cdot m^2)$ can be assumed in normal conditions for south Sweden [20]. If it is assumed 1.4 m^2 surrounding area per 1 m^2 floor area, 0.011 $l/(s\cdot m^2$ floor) is added to the mechanical ventilation. This can be corrected for in the analysis but is small compared to a normal ventilation airflow such as the former Swedish Building regulation [21] that demands a ventilation airflow of 0.35 $l/(s\cdot m^2$ floor). Exhaust air was, as general, taken from bathrooms and kitchens, and outdoor air inlets were located in bedrooms and living rooms.

When windows in the building are opened, the air change increases dramatically [22]. That could mean that during the summer period, the measured values regarding vapour content are only valid close to the exhaust devices.

The indoor temperature can have errors when measured in the central exhaust duct, due to the ducts not being insulated and located in unheated spaces. These things were checked for visibly in the buildings and through construction drawings. There can also be leakage in the exhaust duct system that causes cold air to be drawn into the system and the airflow rate measurements to become wrong. In buildings where the exhaust ducts were partly located outside the climate envelope, typically unheated attics, the temperatures measured are not presented. The same applies for relative humidity since it is directly influenced by temperature. The measured temperatures were found to be considerably affected by the temperature in the attic. The temperatures measured in the main exhaust duct were assumed to be the average indoor temperature of the apartments in buildings where the exhaust ducts were located inside the climate envelope. In all studied buildings the central exhaust duct included exhaust air from common spaces such as staircases and storage rooms and hence the measured values are the average values for the whole ventilated volume inside the building.

3 Results

The indoor temperature, moisture supply, relative humidity and corresponding standard deviations are presented for outdoor temperatures less than and higher than the yearly average outdoor temperature according to Table 2, in Table 3 and Table 4 respectively.

Table 3. Average and Standard Deviation of Indoor Temperature, Moisture Supply and Indoor Relative Humidity for Outdoor Temperatures at or Below the Yearly Average Outdoor Temperature

Location	Building	Indoor temperature, C°		Relative humidity, %		Moisture supply, (g/m^3)	
		Avg	σ	Avg	σ	Avg	σ
Karlstad	1	22.5	0.38	34.5	3.90	3.09	0.69
	2	22.1	0.52	34.3	4.22	2.86	0.62
	3	22.6	0.40	33.3	4.38	2.87	0.61
	4	22.4	0.39	30.7	4.68	2.27	0.59
	5					2.33	0.64
	Average	22.4	0.42	33.2	4.30	2.77	0.63
Kiruna	1					2.08	0.63
	2					1.81	0.62
	3					1.62	0.59
	4					1.31	0.51
	5					1.92	0.56
	Average					1.75	0.58
Malmö	1	22.7	1.10	34.0	5.25	2.25	0.73
	2	21.9	0.91	33.4	5.16	1.80	0.68
	3	21.7	1.00	35.4	5.11	2.03	0.65
	4	22.0	1.24	33.8	5.35	1.89	0.68
	Average	22.1	1.06	34.1	5.22	1.99	0.69
Sundsvall	1					2.40	0.72
	2					1.59	0.63
	3					2.33	0.72
	4					1.92	0.61
	Average					2.06	0.67

Table 4. Average and Standard Deviation of Indoor Temperature, Moisture Supply and Indoor Relative Humidity for Outdoor Temperatures Over the Yearly Average Outdoor Temperature

Location	Building	Indoor temperature, C°		Relative humidity, %		Moisture supply, (g/m³)	
		Avg	σ	Avg	σ	Avg	σ
Karlstad	1	24.4	1.70	44.6	6.11	2.15	1.24
	2	24.1	1.50	44.7	6.37	1.98	0.98
	3	23.7	1.32	45.4	7.08	1.85	1.00
	4	23.2	1.24	45.00	7.85	1.53	0.97
	5					1.55	1.12
	Average	23.9	1.44	44.9	6.85	1.88	1.05
Kiruna	1					0.82	0.83
	2					0.67	0.81
	3					0.39	0.81
	4					0.32	0.72
	5					0.86	0.74
	Average					0.61	0.78
Malmö	1	23.7	1.43	48.5	4.88	1.40	0.92
	2	23.5	1.58	47.5	4.74	1.07	0.93
	3	23.2	1.49	49.4	4.73	1.22	0.86
	4	23.1	1.43	49.1	5.45	1.17	0.88
	Average	23.4	1.48	48.6	4.95	1.22	0.90
Sundsvall	1					1.36	0.92
	2					0.73	0.94
	3					1.46	0.96
	4					1.22	0.91
	Average					1.19	0.93

The four moisture classes of EN 13788 are shown in Figure 2 together with the measured moisture supply. Moisture 'Class 1' aligns well with the most frequent measured moisture supplies. At outdoor temperatures below 0 ˚C, EN 13788 describes the moisture supply as constant which, according to the measurements, seems appropriate. The decrease in moisture supply with increased outdoor temperature is clearly seen in the measured moisture supply frequency plot. At outdoor temperatures higher than 20 ˚C the EN 13788 moisture supply is constant and zero. There is a large variation in moisture supply, between -3 and 10 g/m^3, at outdoor temperatures higher than 10 ˚C. Moisture 'Class 2' and 'Class 3' describes less frequent moisture conditions for outdoor temperatures less than 0 ˚C according to the frequency plot. But, the inclination of the moisture classes between 0 and 20 ˚C do not align with the frequency plot and frequent moisture supplies are higher than even the highest moisture class.

Figure 3 and 4 presents the measured results and EN 15026. The increase in indoor relative humidity is clearly seen in the measured data. According to the measurements, the increase of relative humidity with increased outdoor temperatures has a slightly higher inclination compared to EN 15026. None of the levels 'Normal' and 'High' aligns with the most frequent relative humidity according to the measurements which are lower than the 'Normal' level. At 0 ˚C, the difference between the measured mean value and the 'Normal' level is about eight percent relative humidity which is close to the difference between the moisture levels 'Normal' and 'High'. The measurements exceed the 'High' level only at very few occasions. The very high relative humidity and moisture supply at outdoor temperatures around 16 ˚C relates to a few values measured in one of the buildings when the fan was not running.

The indoor temperature described according to EN 15026 is approximately 2 ˚C less than the most frequent measured indoor temperature for outdoor temperatures up to 10 ˚C. The increase in indoor temperature with increased outdoor temperature is clearly seen in the measured indoor temperature frequency plot. Compared to EN 15026, the measurements indicates that the increase starts at around 7 ˚C instead of at 10 ˚C and the inclination of the EN 15026 line is almost twice as high compared to the inclination indicated by the measured indoor temperatures. EN 13788 describes the indoor temperature as a constant value equal for all outdoor temperatures which is not appropriate for outdoor temperatures higher than 7 ˚C according to the measurements.

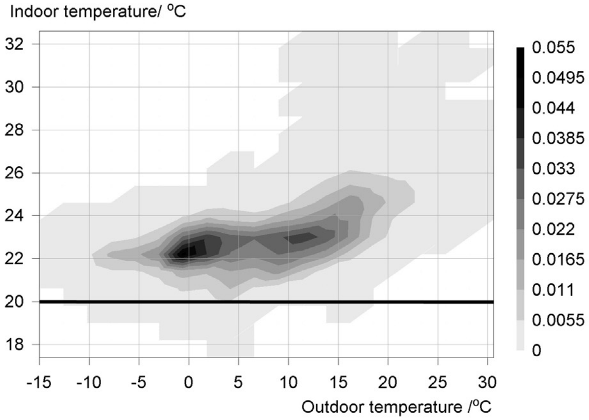

Figure 1. Relative frequency in the unit 1/(0.8°C · 2.4°C) of indoor temperature and outdoor temperature for all the studied buildings, compared to EN 13788.

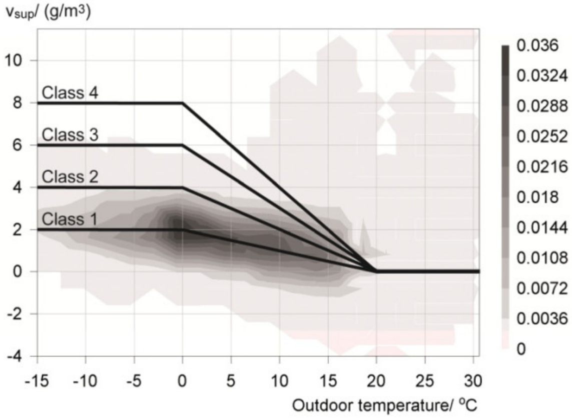

Figure 2. Relative frequency in the unit 1/(2.4 °C· 0.8 g/m³) of indoor moisture supply and outdoor temperature, compared to EN 13788.

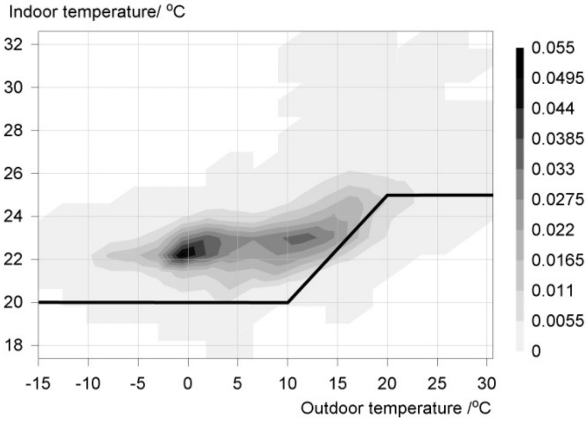

Figure 3. Relative frequency in the unit 1/(0.8°C·2.4°C) of indoor temperature and outdoor temperature, compared to EN 15026.

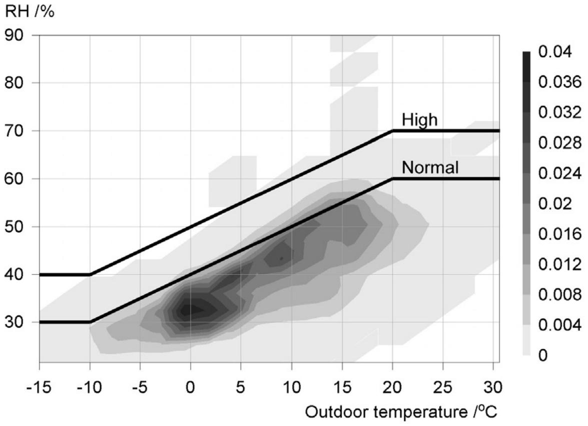

Figure 4. Relative frequency in the unit 1/(3.6% · 2.4°C) of relative humidity indoor and outdoor temperature, compared to EN 15026.

4 Proposal of new hygrothermal classes for measured Swedish conditions

Figures 5 through 7 presents the proposed standards for indoor temperature, moisture supply and indoor relative humidity as functions of the outdoor temperature.

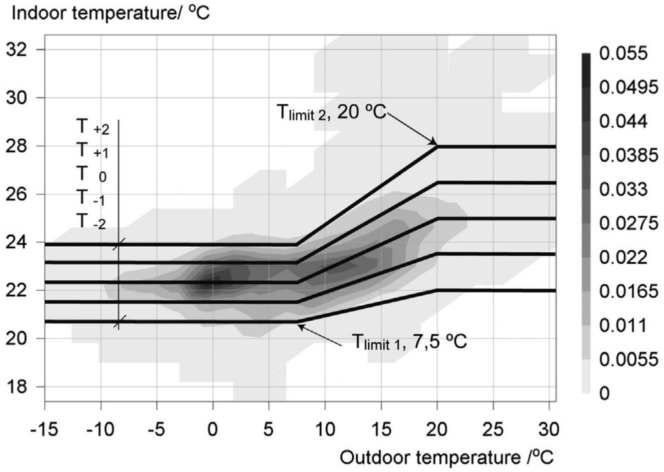

Figure 5. Relative frequency in the unit 1/(0.8°C·2.4°C) of indoor temperature and outdoor temperature for all buildings and a proposal of five temperature classes.

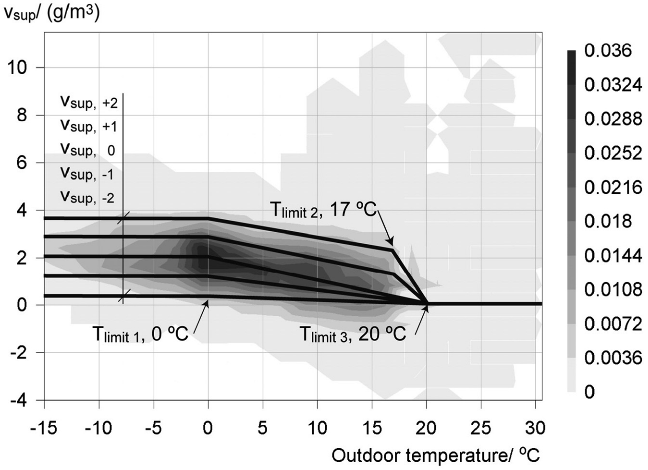

Figure 6. Relative frequency in the unit 1/(2.4 °C· 0.8 g/m³) of indoor moisture supply and outdoor temperature for all buildings and five proposed moisture classes.

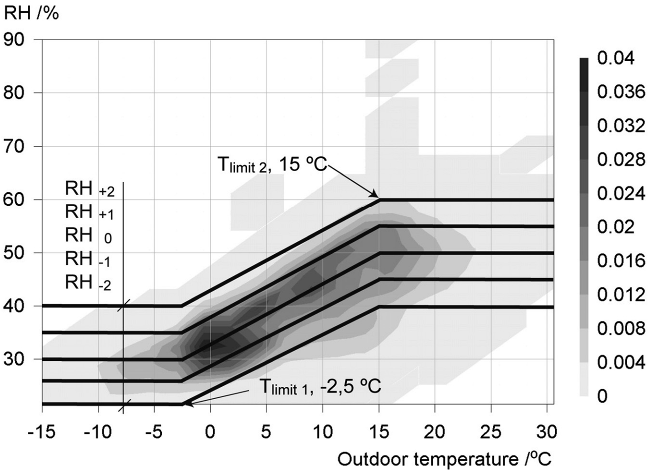

Figure 7. Relative frequency in the unit 1/(3.6% · 2.4°C) of relative humidity indoor and outdoor temperature and five proposed moisture classes.

Table 5. Indoor temperatures at the temperature limits according to Figure 5.

Class	T_{indoor} at $T_{limit\ 1}$/ °C	T_{indoor} at $T_{limit\ 2}$/ °C
+2	23.8	28
+1	23.05	26.5
0	22.3	25
-1	21.55	23.5
-2	20.8	22

Table 6. Moisture supply at the temperature limits according to Figure 6.

Class	v_s at $T_{limit\ 1}$/ (g/m^3)	v_s at $T_{limit\ 2}$/ (g/m^3)	v_s at $T_{limit\ 3}$/ (g/m^3)
+2	3.4	2.3	0.0
+1	2.7	1.5	0.0
0	2.0	0.3	0.0
-1	1.3	0.2	0.0
-2	0.6	0.1	0.0

Table 7. Relative humidity at the temperature limits according to Figure 6.

Class	RH_{indoor} at $T_{limit\ 1}$/ %	RH_{indoor} at $T_{limit\ 2}$/ %
+2	40	60
+1	35	55
0	30	50
-1	25	45
-2	20	40

Figure 5 and Table 5 presents a proposal of temperature classes adapted according to the measured data. An average temperature class T_0 and two high, T_{+1} and T_{+2}, and two low temperature classes, T_{-1} and T_{-2}, were constructed. At outdoor temperatures below 7.5˚C, T_0 is 22.3˚C and constant. This is based on the average indoor temperature at outdoor temperatures below the yearly average outdoor temperature as presented in Table 3. T_{+1} and T_{+2} at outdoor temperatures below 7.5˚C were set as one and two standard deviations, 0.75˚C according to Table 3, higher than T_0. T_{-1} and T_{-2} were chosen to be one and two standard deviations lower than T_0. At outdoor temperatures above 20˚C, T_0 is 25˚C and constant, based on the indoor temperature frequency plot and EN 15026. The higher and lower temperature classes were based on the standard deviation at outdoor temperatures above the yearly average outdoor temperature, 1.5˚C, as presented in Table 4. The breakpoint outdoor temperatures, 7.5˚C and 20˚C, and the linear relations between them were chosen based on the frequency plot. The inclination of the lines that describes the different temperature classes at temperatures between the break point temperatures differ due to different standard deviations used at outdoor temperatures below 7.5˚C and above 20˚C. The increase in inclination with increasing temperature class is in accordance with the frequency plot.

In Figure 6 and Table 6, proposed moisture supply classes are presented together with measured data. An average class $v_{sup,\ 0}$, two high classes, $v_{sup,+1}$ and $v_{sup,\ +2}$, and two low classes, $v_{sup,\ -2}$ and $v_{sup,\ -2}$, were constructed. At outdoor temperatures below 0˚C, all classes are considered constant. $v_{sup,\ 0}$ is 2.0 g/m^3 which is the average moisture supply according to Table 3 at outdoor temperatures below the yearly average outdoor temperature. At outdoor temperatures higher than 20˚C, all classes are zero and constant based on the frequency plot and EN 13788. At outdoor temperatures less than 0˚C, $v_{sup,\ +1}$ and $v_{sup,\ +2}$ are one and two standard deviations, 0.7 g/m^3 according to Table 3, higher than $v_{sup,\ 0}$ and $v_{sup,\ -1}$ and $v_{sup,\ -2}$ are two standard deviations less than $v_{sup,\ 0}$. $v_{sup,\ 0}$, $v_{sup,\ -2}$ and $v_{sup,\ -2}$ decrease linearly between the break point temperatures 0˚C and 20˚C. $v_{sup,\ 0}$ is the same as the 'Class 1' of EN 13788 for all outdoor temperatures. $v_{sup,\ +1}$ and $v_{sup,\ +2}$ decrease linear between the break point temperatures 0˚C, 17˚C and 20˚C. The break point temperatures and the inclinations were chosen based on the frequency plot. The two step inclination of $v_{sup, +1}$ and $v_{sup, +2}$ were chosen in order to include the frequent high moisture supplies at outdoor temperatures between 17°C and 20°C without giving high moisture supply at outdoor temperatures above 20°C.

Figure 7 and Table 7 presents the indoor relative humidity as a function of the outdoor temperature for five different classes. At outdoor temperatures less than -2.5°C and higher than 15°C, the indoor relative humidity is described as constant. RH_0 is 30% relative humidity at outdoor temperatures below -2.5°C and 50% relative humidity at outdoor temperatures above 15°C. At outdoor temperatures between the break point temperatures the relative humidity increases linearly with increasing outdoor temperature. These values were chosen based on the frequency plot. RH_{+1} and RH_{+2} are one and two standard deviations, 5% according to Table 3 and 4, higher RH_0 and RH_{-1} and RH_{-2} are one and two standard deviations less than RH_0. The levels of RH_0 below $T_{limit\,1}$ and above $T_{limit\,2}$ were chosen based on the frequency plot.

5 Discussion and Conclusions

The average indoor temperature during periods with outdoor temperature less than the yearly average outdoor temperature was 22.3°C according to the measurements which agrees with results from other studies. The average indoor relative humidity was 34 % and the average moisture supply was 2.14 g/m^3 which are both higher than reported averages from other studies, see Table 3 and 4. This might be due to the measurement methods where other studies have measured in bed rooms and living rooms. Due to that, the moisture generation in bathrooms and kitchens might not be part of the measured values in its full since residential ventilation is designed for flow paths from bed rooms and living rooms to kitchens and bathrooms. Because of this, measurements made in the central exhaust air should give a better estimation of the conditions inside the climate envelope, even if this study does not give information on distributions between different apartments.

According to literature, it is common that indoor hygrothermal conditions are assumed constant in heat, air and moisture simulations. This might be appropriate if there are systems that control temperature and moisture around the year. This is however not the case in residential buildings in Sweden. Cooling is very seldom used and moisture control is not used on apartment or building level. The use of cooling in apartments in cold climates should be avoided for the purpose of lowering the energy use in the built sector.

EN 13788 and EN 15026 do not describe any distribution parameters. When heat air and moisture simulations of designs are carried out it is of interest to know the average conditions but also the probability of extreme conditions. This is addressed in the proposed standards where there are two classes higher and two classes lower in addition to the average class. The difference between the individual classes is 1 standard deviation. The higher classes are of interest if a safety factor is desired in the design of for example an exterior wall and the lower classes are of interest for example when the risk of uncomfortable indoor air conditions due to low relative humidity is assessed. It should be stressed that combinations of extreme indoor temperature classes and extreme moisture classes might give unreasonable high indoor relative humidity or moisture supplies. It is important to have a comprehensive view of the particular design investigated before choosing indoor temperature and moisture class to use in simulations.

The indoor temperature in the EN standards are 2 °C lower compared to the presented measurements. In Sweden it is generally accepted that indoor temperatures in multi-family residential buildings are a few degrees above 20 °C. In spite of that, 20 °C has often been used as the set point temperature in energy calculations. This is probably one reason to why measured use of energy is generally is higher than predicted. Another reason might be the heating control system. To work properly, the heating control system should make use of internal heat gains and solar heat gains by decreasing the supplied space heating when other heat sources are available and thereby maintaining the desired indoor temperature. The measurements show that during the heating season the indoor temperature is not constant. For example, at an outdoor temperature of 0 °C, the indoor temperature has been up to 25 °C which might be due to that the heating control system cannot respond fast enough to heat gains. Indoor temperatures up to 26 °C have been measured in individual apartments at outdoor temperatures down to 2 °C [23]. These are probably indoor temperatures higher than desired and a result of can be that users open windows which causes heat that could be stored to get lost. A heating control system that accurately can handle both low and high heating powers and assimilate fast varying heat gains can reduce the energy use in both existing and new buildings. It seems like the energy simulation tools used in practice do not take the characteristics of the heating control system into account as results from the simulation tools often gives a constant indoor temperature during the heating season, which would be the case if the heating control system works ideally. Also the indoor moisture conditions affect the energy use and should be taken into consideration in energy simulations. If ventilation air heat exchangers are used, the energy efficiency rate of the heat exchanger is defined by the temperature and moisture conditions of the indoor and outdoor air.

Possible moisture recovery in the ventilation system must be considered. Recently, problems have been shown caused by moisture recovery in rotating ventilation heat exchangers [24]. For certain indoor hygrothermal conditions this can result in unstable removal of moisture with increasing relative humidity and moisture damage risks as result. Rotating ventilation heat exchangers have a high temperature efficiency and effectively reduce the energy use but in order to work properly they need to be analyzed regarding risk of moisture feedback and the consequences this might bring. Prior studies of indoor moisture conditions have only studied the conditions in living rooms and bed rooms. Consequently, the results from these studies should have lower moisture levels compared to this study that takes the moisture conditions in the whole ventilated volume into account. The air that enters the ventilation heat exchanger is not only from living rooms and bed rooms but from the whole ventilated volume that also includes for example bathrooms and kitchens. Hence, if moisture recovery in rotating ventilation heat exchangers is to be assessed, results from prior studies might not be sufficient while this study should present adequate values.

Consideration regarding what should be a sufficient safety margin compared to the possible economic consequences needs further research. A high safety margin might produce a very rugged construction but probably also a very expensive one. If a lower safety margin introduces a risk of damage, that if it occurs is cheap to repair and of no health risk to the occupants, it might actually be more beneficial than a too high safety margin from a life cycle perspective

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