LICENTIATE THESIS

# On the Effect of Occupant Behavior and Internal Heat Gains on the Building's Energy Demand

A case study of an office building and a retirement home

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The picture on the cover depicts an office building and a multi-purpose building being constructed in the new city district Ebbepark in the city of Linköping, Sweden. Source: The author's own picture.

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# Abstract

About 12% of the greenhouse gas emissions and 40% of the total energy use in the EU derive from buildings. User behavior, construction, and HVAC systems have a significant impact on a building's energy use. If a building is to be energy-efficient it is important to understand how all these parameters are connected. This study is motivated by the need to decrease the energy use in buildings to reach the goals of energy use and greenhouse gas emissions.

In this study, measurements of indoor climate and electricity use, together with time diaries was used to create input data for an energy simulation model of a retirement home. A parametric study was conducted to simulate how energy demand was affected by changes in five different parameters in an office building. Also, two different energy-efficiency indicators were used to see how indicators can affect the perceived energy-efficiency of buildings.

A high amount of airing and low electricity use had the most impact on the heating demand in the retirement home, and electricity use had the highest impact on the heating and cooling demand in the office building. The model of the retirement home using data gathered on-site had 24% higher energy use than the model using standard user input data. In the office building, energy demand for heating and cooling could be lowered by 12-31% by lowering the electricity use by 30% compared to standard user input data.

For office buildings, the most important thing to lower heating and cooling energy demand seems to be lowering the electricity use. Using today's standard user input data does not correspond well to using on-site gathered data in a retirement home and it is therefore important to develop the standard user input data further. The indicator $kWh/m^2$ seems to promote buildings with low occupancy. This could lead to buildings being utilized in an inefficient way. The indicator $kWh/m^2$ should either be replaced or combined with an indicator that also considers occupancy.



**Keywords:** building energy simulation, energy efficiency indicators, occupant behavior, energy performance, internal heat gains, building energy demand

# Sammanfattning

Runt 12% av utsläppen av växthusgaser och 40% av den totala energianvändningen i EU kommer från byggnader. Brukarbeteende, konstruktion och HVAC-system har signifikant påverkan på en byggnads energianvändning. Om en byggnad ska bli så energieffektiv som möjligt är det viktigt att förstå hur dessa parametrar hör ihop. Denna studie motiveras av behovet att minska energianvändning i byggnader för att nå målen för energianvändning och utsläpp av växthusgaser.

I denna studie användes mätningar av inomhusklimat och elanvändning, tillsammans med tidsdagböcker, för att skapa indata till en energisimuleringsmodell av ett ålderdomshem. En parameterstudie genomfördes för att simulera hur energibehovet påverkades av ändringar i fem olika parametrar i en kontorsbyggnad. Två olika indikatorer för energieffektivitet användes, för att se hur olika indikatorer påverkar hur en byggnads energieffektivitet uppfattas.

Hög grad av vädring och låg elanvändning hade störst påverkan på värmebehovet i ålderdomshemmet. I kontorsbyggnaden påverkades det värme- och kylbehovet mest av elanvändningen. Modellen av ålderdomshemmet där data insamlad på plats användes, hade 24% högre värmebehov än modellen som använde standardiserade brukarindata. Det totala energibehovet för värme och kyla i kontorsbyggnaden kunde sänkas med 12-31% genom att sänka elanvändningen med 30% jämfört med standardiserade brukarindata.

Det viktigaste för att få ner värme och kylbehovet i kontorsbyggnader verkar vara att sänka elanvändningen. Att använda dagens standardvärden för brukarindata överensstämmer inte väl med att använda data insamlad på plats för ett ålderdomshem. Det är därför viktigt att vidareutveckla standardiserade brukarindata. Indikatorn kWh/m$^2$ verkar främja byggnader med låg beläggning. Detta skulle kunna leda till att byggnader utnyttjas på ett ineffektivt sätt. Indikatorn kWh/m$^2$ skulle därför behöva ersättas eller kombineras med en indikator som även beaktar byggnadens beläggningsgrad.

**Nyckelord:** energisimulering, indikatorer för energieffektivitet, brukarbeteende, energiprestanda, interna värmelaster, byggnaders energibehov

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# List of Papers

This thesis is based on the following papers, which are referred to in the text by Roman numerals.

**Paper I**
Carlander, J., Trygg, K., & Moshfegh, B. (2019). Integration of Measurements and Time Diaries as Complementary Measures to Improve Resolution of BES. *Energies* 12(11): doi: 10.3390/en12112072

**Paper II**
Carlander, J., Moshfegh, B., Akander, J., & Karlsson, F. (2020). Effects on Energy Demand in an Office Building Considering Location, Orientation, Façade Design and Internal Heat Gains – A Parametric Study. *Energies* 13(23): doi: 10.3390/en13236170

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# 1. Introduction

## 1.1 Background

EU has set a goal that by 2030 its greenhouse gas (GHG) emissions should be lowered by at least 40% compared to 1990, have a share of at least 32% renewable energy, and at least 32.5% improvement of energy efficiency [1]. In 2018 the residential and commercial/institutional sector accounted for about 12% of the EU's total GHG emissions [2]. Of the EU´s total energy use, buildings accounted for about 41% [3], while the residential sector accounted for 26.1% and the service sector for 14.2% [4]. In Sweden there are almost three million residential buildings, approximately 120,000 buildings for public service, and approximately 60,000 office buildings [5]. In 2019, the residential and service sector in Sweden used 147 TWh, which was 40% of Sweden's total energy use [6]. The residential sector used 87 TWh and the service sector used 47 TWh, which are 59% and 32% respectively of the total energy use of Sweden's residential and service sector in 2018 [6]. The remaining energy use in the sector derives from agriculture, forestry, construction and fishing.

District heating has been increasing steadily since the 1970s in Sweden, but the increase has recently begun to flatten out. It is the primary source for heating and heating of domestic hot water (DHW) in Sweden for residential, office and other service buildings. The total energy use for heating and DHW within this sector was about 80 TWh, where district heating comprised about 46 TWh in 2018 [7]. Single-family houses needed 30.6 TWh, multifamily buildings 26.8 TWh, and offices and other service buildings used 21.7 TWh of the total energy use for heating and DHW [7]. District heating is the dominant form of heating in multifamily buildings, offices and other service buildings while in the single-family house category, electrical heating dominates. During 2018, the main fuel source for district heating was biofuels with a share of 62% of the production. The same year, the share of heat pumps was 8%, natural gas, coal and petroleum products together was 8%, and other fuels which contain combustible waste corresponded for 15% of the production [8].

In Sweden today, a building's energy efficiency is most often measured in kWh/m$^2$, annually, hence called kWh/m$^2$, and is also the measure of the maximum allowed energy use of buildings legislated by Boverket (National Board of Housing, Building and Planning). Boverket sets all building legislation in Boverket's construction regulations (BBR), which is frequently updated. In the latest edition of BBR, which is called BBR 29, the allowed energy use for new facilities, which includes office buildings and retirement homes, was lowered from 80 kWh/m$^2$ to 70 kWh/m$^2$, see [9]. How to calculate the energy use of a building was also changed in recent years from calculating the specific energy use (i.e., purchased energy) of the building, to calculating a primary energy number (reflecting on primary energy use). Primary energy is energy that has not undergone any engineered conversion process (and is in essence a natural resource). Energy sources such as solar, wind, water, biomass and geothermal energy count as renewable primary energy sources while oil, coal, natural gas

and uranium count as non-renewable sources of primary energy. When calculating primary energy use according to BBR, the energy use is divided into four categories: heating, cooling, DHW, and energy for operation of the building, such as fans, pumps, heating cables, and control and monitoring systems. The energy use from each of these categories is then multiplied by a weighting factor depending on the energy carrier, for instance, district heating has a factor of 0.7, and electricity, fossil oil and fossil gas have a factor of 1.8 [9]. There is also a geographic factor for heating that depends on the location of the building within Sweden. This is to compensate for the differences in temperature and daylight hours between the different parts of Sweden, so that a building situated in the north is allowed to have slightly higher energy use for heating than a building located in the south of Sweden [9].

A building's energy demand is dependent on several different factors. Among these are a building's thermo-physical properties, technical construction details, outdoor climate, and the maintenance and quality of its HVAC system [10,11]. It is however not only construction choices that affect a building's energy demand, but user behavior and internal heat gains (IHGs) also has a significant impact [10–13]. IHGs is caused by equipment that is used in the building, solar radiation, and the people occupying the building. The level of IHGs is also connected to the occupants' behavior since the more people that are present and the longer they are present, the more heat will be emitted. More people also often implies more electrical appliances, at least in offices where they most probably have one computer each, all of which generate heat that contributes to the IHGs. For these reasons, buildings are in some cases designed to minimize solar heating, to avoid having an unnecessarily high cooling demand. This is often done by implementation of some form of solar shading, but some buildings also have an architectural design which in itself prevents solar heat gains. However, in countries with colder climate and widely differing amount of daylight through the year such as Sweden, it is also important to construct buildings so that heat does not leak out through the building body, which often means having thicker insulation layers in the building envelope, and windows with low *U*-values. These two aspects can be quite contradictory, since in one case heat is prevented from entering the building and in the other, heat is prevented from leaving the building. The higher the IHGs the lower the heating need, but the cooling need will often be higher as a result, if comfort cooling is available in the building. When designing new office buildings, energy demand is often simulated with a Building Energy Simulation (BES) software [14]. However, there are often great discrepancies between the simulated energy demand and the actual energy demand of the finished building [14]. These discrepancies are called the "energy performance gap" [15–17]. Some of the differences between simulated and actual energy demand can be traced to occupants' behavioral patterns [18]. These patterns are often hard to predict [18]. Therefore, when simulating, behavioral patterns are often modelled as repeating schedules which occur in the same way on a daily basis.

When estimating a building's energy efficiency, the most common indicator used in Sweden is kWh/m$^2$. Apart from kWh/m$^2$ there are many other indicators for measuring energy efficiency in buildings. In [19], the authors use six different indicators on five different case buildings, showing that energy efficiency indicators play a key role when designing buildings. They conclude that while kWh/m$^2$ is very precise to measure the technical properties of a building during the design phase, it does not perform well when space efficiency and occupancy are considered in the building's operation phase. Different indicators have different impacts on how energy efficiency is perceived in a building [19].

The present study is motivated by the need to further reduce energy use in new and existing offices and service buildings by investigating what effects user behavior and IHGs have on a building's energy demand. It is also motivated to further improve energy efficiency in new and existing offices and service buildings, by shedding light on how indicators for energy efficiency play a key role in how energy efficiency is perceived. These issues are paramount to deal with, if we are to reach both national and EU goals for GHG emissions, energy efficiency and use of renewable energy. It is also necessary if the United Nations (UN) goals for sustainable development are to be reached.

## 1.2 Aim and research questions

The aim of this thesis is to show:

- how occupant behavior and different levels of IHGs can affect energy demand in public and office buildings in Sweden,
- how different levels of IHGs can affect design and construction choices in new public and office buildings in Sweden,
- how energy demand is affected by using standard values for user input data in BES, compared to using real and/or probable future values,
- and how energy efficiency can be perceived differently by the use of different indicators, when changes in IHGs and occupant behavior occur.

The study objects of the thesis are an existing retirement home and a planned office building, both located in the city of Linköping, Sweden. The aim of the thesis will also be to discuss how we should account for different IHGs and occupant behavior in future modelling of buildings. It will also discuss if changes should be made to the indicators of energy efficiency used today and what effect that might have on future building projects.

The above-mentioned research aims will be addressed by investigating the following research questions.

1 How does user behavior and different levels of IHGs affect energy demand in a retirement home and an office building in Sweden?
2 How is energy demand affected in a retirement home and an office building in Sweden, when using empirical and/or probable future values of IHGs and behavior compared to today's standard values?
3 How is energy efficiency perceived when using two different indicators, if changes in IHGs and user behavior occur in a retirement home and an office building in Sweden?

Table 1 indicates which papers address the three research questions.

Table 1. Description of which papers handle the three different research questions in the thesis.

| Research questions (RQ) | 1 | 2 | 3 |
|---|---|---|---|
| Paper I | X | X | |
| Paper II | X | X | X |

Paper I does not explicitly cover research question 3, but new calculations using both indicators have been carried out and are included in this thesis.

## 1.3 Description of research journey

This licentiate thesis is the product of a cooperation between the corporate research school Reesbe and the municipally owned real estate company Sankt Kors. Reesbe stands for Resource Efficient Energy Systems in the Built Environment and is a corporate research school which is a collaboration between Gävle University, Mälardalen University, Dalarna University, and different companies in the energy and real estate sector. The purpose of Reesbe is to analyze the interplay between supply and use of energy in the district heating field and find solutions that in the long run and from a systems perspective give lower costs, lower resource use, reduced climate and environmental impact, better indoor environment when constructing new buildings or renovating, and an increased share of solar energy [20]. The municipally owned real estate company Sankt Kors has a mission to promote development and growth in Linköping, Sweden [21]. They are mainly focused on providing creative corporate environments for start-ups and expanding businesses [22]. Sankt Kors's collaboration with Reesbe research school is supposed to give them information on how to develop new city districts that are energy-efficient and environmentally friendly with a focus on office buildings. The research is supposed to highlight driving forces and obstacles for implementation of energy-efficient solutions in city district development and end up in a checklist that can be followed in future building projects to have as energy efficient buildings as possible. This begins by highlighting problems connected to energy use that arise in building projects and then finding solutions and giving examples of how to overcome these problems.

The research originated from a new building project in the city of Linköping where a new city district called Ebbepark is being planned and built. Ebbepark is located within the central parts of Linköping, right between the University and the inner city, and is supposed to become a city within the city. What this means is that Ebbepark will become a city district that will contain office buildings, public buildings, and residential buildings. There will be 750 new apartments, a school and other public facilities, and 75,000 $m^2$ of new office space and corporate environments [23]. The vision of Ebbepark is that it should be a bold, caring, and "smart" part of Linköping, and there are three keywords that all development in Ebbepark should revolve around: *Dare*, *Share*, and *Care*. With its closeness to Linköping University and its researchers, the vision is that collaborations will spring from meetings between researchers, corporations, residents, and visitors to Ebbepark, which can lead to new ideas, innovations and solutions contributing to sustainability. This is how the word *Dare* fits into the picture. The thought behind the word *Care* is that Ebbepark should be a brave and caring environment where city life pulsates throughout the day and everything is easily available. There should be pleasant boutiques, shops, restaurants with a "green" profile, community service that meets daily needs, cultural experiences, and events, as well as opportunities for socializing, relaxation, and exercise, both in Ebbepark and the nearby recreational forest area Vallaskogen. The word *Share* derives from the thought that within Ebbepark there should be sharing of equipment, vehicles, and premises, as well as sharing ideas and experiences. There should also be a clear will to take mutual responsibility within Ebbepark.

The public building studied in this project was a retirement home. It was the case studied in Paper I and was chosen as it was already part of an ongoing research project, which was a collaboration between the real estate company Riksbyggen and Linköping University, where the author of this thesis was already involved through an advanced course at the university. The aim of that research project was to evaluate a new method where time diaries and measurements were used to analyze and model occupant behavior in terms of schemes incorporated into a BES model to evaluate behavior influence on energy use. The aim was also to find suitable renovation measures for the retirement home. It focused on mapping the energy use of the building and how the residents used the building. This was done by:

- conducting measurements of indoor environment and electricity use
- let residents keep a time diary
- conducting interviews
- let the residents answer a questionnaire on how they perceived the indoor climate and indoor environment
- and using building energy simulations.

Paper II studies an office building which is planned by Sankt Kors. The building has a special design for its façade where the east and west facing walls are "saw-toothed" if seen from above, which means that the windows are oriented

in another direction than the façade plane to reduce solar heat gains. The windows are oriented towards the northeast and northwest, whereas the rectangular building body has its largest façades directed in the east and west directions (see Figure 1). Since the author of this thesis had gained substantial knowledge about energy simulations from the previous study (Paper I), the author was brought in by Sankt Kors to investigate which angle on the "saw-toothed" façade would yield the lowest solar heat gains. It turned out that the higher the angle was, the lower the cooling demand became. However, the heating demand increased by almost the same amount as the cooling demand decreased, leaving the total energy demand for heating and cooling almost unchanged. This then led to the author starting to conduct a more in-depth study of the building to see if there were any differences if the location were changed, how differences in internal heat gains mattered, if the orientation made a difference and how a regular "straight" façade would do. This investigation led to the writing of Paper II. Another question was also if such an intricate façade design lowers the energy demand enough to be economically sustainable, but this will not be answered in this thesis.

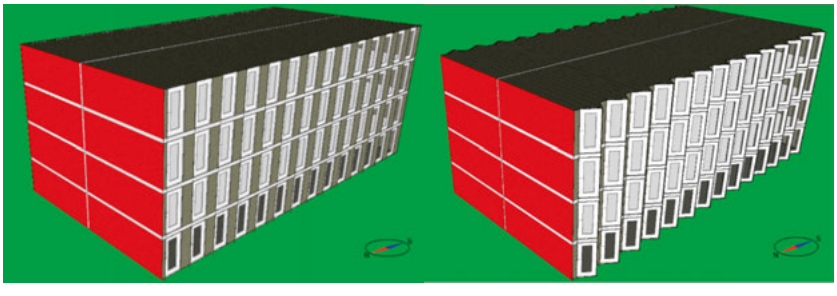

Figure 1. On the left is the model of the office with a straight facade, on the right is the model with a saw-toothed facade. The wall marked in red represents the reference surface directed towards north in the figure.

Both these studies have been vital in gaining insight and knowledge for the remainder of the research project, not only through the results they have produced but also because the author has gained insights in the building sector, how it works and where potential drivers and obstacles are and can arise.

## 1.4 Research methods

The research methods used in this thesis will be described briefly in this section, and in more detail in section 3. Methods.

*Measurements*
Measurement is a very broad method which can basically include measurements of anything. In this thesis, measurements on a real building were used as a method of gaining data to compare with results from building energy simulation. The measurements consisted of temperature, $CO_2$ level, and electricity use among others.

*Time diaries*
Time diaries are used to describe and analyze the relationship between location, activities, and movement of individuals and the method originates from the research field of time geography [24–26]. In this study it was used to understand how residents of a retirement home used the building, and more specifically to connect behavior affecting energy use to the previously mentioned measurements.

*Building Energy Simulation*
BES is a method in which a building's energy demand can be simulated with the aid of computer software. BES is often used in planning stages in projects for new buildings and/or when testing different solutions for renovation and retrofitting of existing buildings. There are many different energy simulation software programs on the market and in this study the software IDA-ICE /Indoor Climate and Energy) was used. IDA-ICE is not only an energy simulation software but also simulates the indoor climate, hence the name indoor climate and energy. Included in the term indoor climate for IDA-ICE is indoor temperature, relative humidity and comfort indices PPD and PMV.

*Validation*
Validation is a very important step within BES if the study is of an existing building. Within BES there are three basic approaches to validation of a simulation model: analytical validation, peer comparison, and empirical/realistic validation [27,28]. In this study, validation was done according to empirical/realistic validation.

*Data collection*
The data for this thesis was collected through logged measurements of temperature, electricity use, and $CO_2$ levels. It was also collected with time diaries and on-site readings of energy use for space heating and ventilation. Drawings were used as a data source for the building construction and design.

*Parametric study*
A parametric study is a study where parameters for evaluation are designated, a parameter range is set, design constraints are specified, and then the results of each parameter variation are analyzed. In this thesis a parametric study was performed to see how the energy demand of a new office building was affected by variations in several different parameters including IHGs, location, orientation, and solar shading.

## 1.5 Research process

The following section describes how the different methods were used to answer the research questions (RQ) of the thesis, first a short description of the studied buildings is presented.

The retirement home which was studied consists of a total of 99 apartments in five buildings. In the main building there is a canteen as well as several spaces for group activities and a couple of offices for the staff. It was built in 1983 and has not undergone any renovations since. Out of the 15 apartments in the studied building, residents from 11 of them participated in the study and data about their age, civil status and working status can be found in Table 2.

Table 2. Gender, age, civil status, and working status of the residents in the retirement home.

| Description | Facts |
|---|---|
| Gender | Female (8), Male (5) |
| Age | 58-94 (mean 85, median 78) |
| Civil status | Single (9), married (4: two couples) |
| Retired/working | 11/2 |

The studied office building is a four-story office building in the planning stage. It is supposed to house about 300 staff, a canteen, and some larger conference rooms. The most distinctive feature of the building is probably its façade design which on the east and west side is going to look saw-toothed from above. The windows on the east and west side are located on the side of the "teeth" that are pointing northwest and northeast, to lower the amount of solar heat gains. There will also be fins sticking out from the "teeth" to further prevent solar heat gains.

To answer the research questions in this thesis, all the methods described in section 1.4 were used. A BES model was important to answer the research questions, and the models used were created in the following way. When creating the model of the retirement home, drawings and on-site measurements were used, and to get the IHGs as close to reality as possible, time diaries and logged measurements from the residents' apartments were used. The time diaries and logged measurements were combined to make detailed schedules for occupancy, electricity use, and airing in the BES model. To make sure that the building model was a good representation of the real building, the model was validated by comparing results from the simulation with results from the measurements. Almost the same process was followed for the planned office building, but in this case, the input data could not be gathered on-site since the building does not exist yet. The building was therefore modelled according to drawings and data from the building project.

To be able to answer RQ1, changes were made to the input values of IHGs and occupancy. For the retirement home, two different settings for the IHGs were simulated and the results of energy demand were compared. For the model of the new office building, a larger parametric study was conducted. The IHGs were divided between occupancy and electricity use and the parameter values were then varied between ranges set for them. The simulated results from each different case of IHGs were then compared.

RQ2 could be answered by making cases for both models where standard values of IHGs and occupancy gathered from Sveby (Standardize and Verify Energy performance in Buildings) [29,30] were used. The results from the simulations using these standard values were then compared to the other simulated cases to see what differences occurred.

When the results of energy demand from all the simulated cases in the office building had been gathered, the results were converted into two different indicators for energy efficiency. The same was done with the two models of the retirement home. To answer RQ3, the results was compared using two different indicators.

## 1.6 Delimitations

This thesis and its papers are set within a Swedish context, meaning among other things that the standard values for user input data in BES are limited to Swedish data, and location of the building in Paper II is limited to different locations in Sweden. The thesis focuses on energy demand of buildings which are presumed to be located within a district heating system and therefore does not include any other ways of heating and/or cooling. The system boundary of this thesis is the buildings themselves and does not include the surrounding energy system. Climate files for the building simulations are from typical years for the office building and from the same year as the measurements were conducted in the retirement home and does not consider future climate changes.

## 1.7 Overview of included papers

*Paper I: Integration of Measurements and Time Diaries as Complementary Measures to Improve Resolution of BES*

In Paper I, a retirement home was studied to see how the occupants' behavior affected the energy demand of the building. In order to understand how the occupants "live within" the building, they were requested to keep a time diary for seven days where they wrote down what they were doing, with whom, where they were, what equipment they used, and what time it was. During this seven-day period, measurements of temperature, electricity use, and $CO_2$ levels were logged in the apartments and heating demand was logged for the city block. The time diaries were compared to the measurements where it could be seen how behavior such as opening windows and doors, and having visitors affected the temperature and $CO_2$ levels, and how electricity use changed when the occupants used different household appliances. Interviews were also conducted with the participants to clarify certain things and to add more data about their daily activities. To see how their behavior affected the energy demand of the building, two different models of the building were made in the BES software IDA-ICE, one called BES-ref with standard values for airing, electricity use and occupancy, and one where schedules for the same activities had been created according to the time diaries and logged measurements called BES-

v.2. The simulation results of energy use from the two models were then compared on three different levels, building level, apartment level, and room level, to see how they differed.

The studied retirement home is in the city of Linköping in Sweden and contains what in Sweden is called assisted living accommodation. Assisted living in this case means that the residents of the building rent their own apartments which are equipped with safety alarms so they can call for assistance if incidents happen, and there are two healthcare providers that operate in the building, one publicly and one privately owned. In total, the building complex has 99 apartments where 35 are assisted living accommodation, and it also contains a home for people suffering from dementia. The building complex consists of five buildings, one large where three buildings are connected via walkways and two smaller detached buildings. In the study, time diaries, measurements, and interviews were conducted in one of the detached buildings, where the residents of 11 out of 15 apartments took part in the study. Most residents in the building complex are over 65 years old, and the age span of the study was 58–94 years old with a mean age of 85.

*Paper II: Effects on energy demand in an office building with potential future internal gains*
In Paper II, a new office building that is planned in Linköping, Sweden was studied to see how different amounts of occupancy and internal gains, as well as different location, orientation and façade design affected the energy demand. How the building's energy efficiency was perceived with two different indicators was also studied. Two different models were created in IDA-ICE and both were simulated with eight different levels of internal gains, two different settings for time spent in the building by occupants, two different levels of number of occupants, three different locations (Luleå, Linköping, and Malmö), eight different orientations (N, NW, W, SW, S, SE, E, NE), and with or without solar shading in the form of blinds. The two models differed in their façade design, one was modelled as the planned building with a façade designed to lower solar heat gains so that the cooling need is decreased by having it angled in a saw-toothed way seen from above, and the other was modelled with a simple straight façade (see Figure 1).

## 1.8 Co-authors' statement

*Paper I: Integration of Measurements and Time Diaries as Complementary Measures to Improve Resolution of BES*
The research and paper were planned by the author of this thesis together with Associate Professor Kristina Trygg. Research design and development of the methodology was conducted as a collaboration between the author of this thesis and Associate Professor Patrik Rohdin. Kristina Trygg was responsible for the time diaries and interviews as well as contributing the texts about these two methods in the methods section of the paper. Measurements were conducted

by the author of this thesis together with research engineer Jakob Rosenquist. Creation of the building model, simulations on it in the software IDA-ICE as well as analysis of the results were performed by the author of this thesis. Who thereby have main authorship of the paper and also responsibility for research design, methodology, investigation and visualization. Professor Bahram Moshfegh supervised the work and together with Associate Professor Jan Akander contributed guidance and comments on the text, and Kajsa Ellegård was the project manager.

*Paper II: Effects on energy demand in an office building with potential future internal gains*

The study was planned by the author of this thesis together with Professor Bahram Moshfegh and Associate Professor Jan Akander. Main author (author of this thesis) was responsible for research design, methodology, investigation and visualization. The two simulation models of the building were created and simulated in the software IDA-ICE. The data was processed by the author of this thesis, who also performed the analysis of the results. Professor Bahram Moshfegh and Associate Professor Jan Akander supervised the work, and also contributed guidance and comments on the text together with Doctor of Technology Fredrik Karlsson.

# 2. Background and related research

A building's energy use is dependent on several different factors, including the building's energy systems, local and regional/national energy systems, how the building is constructed and how the people living or working in the building use it. It is also important to know how to measure a building's energy efficiency, since different indicators can show different results. Using one indicator for energy efficiency might make the building seem very energy efficient, while using another might give contradictory results. Multiple indicators can be used to describe energy efficiency from different perspectives.

## 2.1 Energy and climate goals

Sweden's energy politics is based on the same three pillars as the energy cooperation within the EU. These three pillars are to combine security of energy supply, competitiveness, and ecological sustainability [31]. The goals for 2030 in Sweden are that emissions of GHGs should be 63% lower compared to 1990, emissions from domestic transport (not including air traffic) should be 70% lower compared to 2010, and the energy use should be 50% more efficient compared to 2005 [32]. Sweden shall have 100% renewable electricity production by the year 2040 [32]. No later than 2045, Sweden shall have net zero emissions and at least 85% of the reduction in emissions shall occur in Sweden [32]. In comparison, the EU has the following goals for 2030: Lower the emissions of GHG by 40% compared to 1990; lower the energy use by 32.5% through better energy efficiency; 32% of the total energy use shall derive from renewable energy; the share of renewable energy within the transport sector shall be 14%; and the interconnection of the installed electricity production in all member countries shall be at least 15 % [32].

## 2.2 Sustainable development goals

The UN adopted 17 sustainable development goals (SDGs) (see Figure 2) in 2015 with the agenda "Transforming our world: the 2030 Agenda for Sustainable Development" [33]. The SDGs with their 169 target goals are supposed to be a roadmap to achieve a better and more sustainable future for all [34], and are meant to stimulate action to the year 2030 within areas of critical importance for humanity and the planet [33]. Among the SDGs we find goals such as no poverty, zero hunger, gender equality, affordable and clean energy, sustainable cities and communities, responsible consumption and production, promotion of sustainable economic growth, climate action, and peace and justice [33,34]. The UN states that all 17 SDGs are dependent on each other, and it is important that they are all achieved by 2030. The work in this thesis is most closely connected to the three following SDGs.

Figure 2. The United Nations Sustainable Development Goals. Source https://www.un-brussels.org/the-sustainable-development-goals-sdgs/

*SDG 7-Affordable and Clean Energy*

This goal includes targets to ensure access to affordable, reliable and modern energy services, substantially increase the share of renewable energy in the global energy mix, and to double the global rate of improvement in energy efficiency [33]. There are also targets to enhance international cooperation to facilitate access to research and technology of clean energy, as well as to promote investment in energy infrastructure and clean energy technology [33]. As can be seen, the Swedish and EU goals of energy mentioned in section 2.1. are closely linked to this SDG.

*SDG 11-Sustainable Cities and Communities*

Among the targets for this goal is to ensure access to adequate, safe and affordable housing and basic services for all. Provide access to safe, affordable, and sustainable transport systems for all. Strengthen efforts to safeguard the world's cultural and natural heritage and reduce the adverse per capita environmental impact of cities. To support least developed countries in building sustainable and resilient buildings. To substantially increase the number of cities and settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, and resilience to disasters [33].

*SDG 13-Climate Action*

The goal of urgent action to combat climate change and its impacts is broken down in five targets:

- Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
- Integrate climate change measures into national policies, strategies and planning.

- Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.
- Implement the commitment of developed countries to raise 100 billion dollars annually to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation
- Fully operationalize the Green Climate Fund through its capitalization as soon as possible.
- Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island states [33].

## 2.3 Sweden's building stock

New buildings in Sweden have to be built according to regulations set by the National Board of Housing, Building and Planning (Boverket). These regulations have become more and more rigorous over the years following the oil crisis in the 1970s, especially when it comes to regulations of heat recovery, thermal insulation, and airtightness which can be seen in reference [35]. To reduce a building's energy use and to create a better indoor climate, today's building techniques focus on airtightness, insulation, moisture, ventilation and minimization of thermal bridges [36]. The total energy use in Sweden was 373 TWh and of this the building sector used 147 TWh in 2018 [6]. In the statistics from Energimyndigheten (the Swedish Energy Agency) [6] the building sector includes households, public services and other services, agriculture, forestry, fishing, and construction. In 2016 Sweden had about 120,000 buildings connected to social functions, and around 60,000 buildings containing some sort of business activity [5]. The public service and other services sub-sector stood for approximately 32% of the sector's total energy use in 2018 [6] which is about 47 TWh.

## 2.4 Energy performance gap

The energy performance gap is the difference between simulated/calculated energy use and real energy use of a building [15–18]. There can be several causes for an energy performance gap. There can be construction mistakes, improper adjusting of equipment, excessive simplification in simulation models, and/or occupant behavior, where occupant behavior is believed to be the greatest cause of the energy performance gap by many researchers and governmental institutions [15–18].

## 2.5 Energy use affected by behavior of occupants

Page et al. [37], conclude the following five active behaviors that affect energy use in a building:

- use of lighting and solar shading,

- use of HVAC systems and set-points,
- use of hot water,
- use of appliances
- and use of openings.

They also mention the production of metabolic heat, but as a "passive" behavior. All these things that occupants do in a building will affect the final energy demand of the building and it is therefore important to understand the relationship between the occupants' energy use behavior and the building [11,38,39]. According to Harish and Kumar [40], the key sources of energy use in buildings are lighting, electrical devices and HVAC systems that the occupants are able to adjust themselves to manage their own visual and thermal comfort. The variations in these systems adjusted/controlled by the occupants can cause significant variations in a building's energy demand [40]. In an office building, staff usually follows certain behavioral patterns when they arrive at work, when they leave, and what they do, but their workdays can vary a lot. One day they might be seated at their workstation all day and the next they might be in meetings all day (or meeting at other locations), one day they might heat their lunch in a microwave and the next they might go out for lunch. The staff might also respond to thermal discomfort in the office by opening or closing windows and/or curtains, changing the settings on the thermostat or the air conditioning, and all these changes in behavioral patterns will affect the building's energy use in one way or another. There is also an increasing trend of working from home, especially during the ongoing COVID-19 pandemic, which in that case means that some staff won't even be in the building. One problem therefore lies in how to account for these changes when constructing new buildings. In this thesis, occupant behavior refers to occupants' interaction with building systems in order to control the indoor environment, their use of electrical appliances, and their presence in the building.

## 2.6 BES and modelling of internal gains and occupant behavior

In new building projects in Sweden where BES is used, internal gains and occupant behavior are most often modelled as schedules which repeat over the weekdays. According to Sveby, an office employee is in the office nine hours per day, five days a week, and 50 weeks per year [29]. There is supposed to be one office employee per every 20 $m^2$, and the operation electricity use of the building should be 50 kWh/$m^2$, year [29]. Sveby is an organization that among other things provides reports on standardized user input data. Their user input data can be and are widely used in building projects in Sweden if other data is not available. There are however more ways of modelling behavior than simply making schedules. In a few studies, [41,42], the authors created load profiles of occupancy and electricity [41], and electricity and DHW use [42] from time use survey (TUS) data. Richardsson et al. [41] conclude that the simulated output correlated very closely to the original data from the TUS and that it is very effective and computationally efficient to create electricity use profiles from

such data. Widén et al. [42] conclude that their model makes realistic reproductions of electricity demand and load distributions compared to available measurement data and that "the overall energy-use pattern found in measured data is well described by the model, while magnitudes sometimes deviate". Other studies that have used TUS data for similar purposes are [43,44], where [43] developed a high spatial resolution model of energy use in residential buildings down to zone level using TUS data from the US, and [44] made a probabilistic occupancy model with the help of Belgian TUS data.

## 2.7 Indicators of energy efficiency in buildings

Which indicator that is chosen for measuring energy efficiency in a building, plays a large role in how energy efficient said building is perceived to be. Therefore, it is vital to understand how to measure the energy efficiency in the building operation phase in order to encourage the right efficiency measures [19]. It is important to comprehend the interplay between occupancy, space efficiency, and energy efficiency in an office building to be able to understand the building's energy efficiency [19]. The most common indicator for measuring a building's energy efficiency according to the literature review of this study is kWh/m$^2$ and year, also called specific energy consumption (SEC). Many previous studies use this indicator and among these are [45–49]. Far fewer studies use indicators where occupancy and space use are included and among these studies are [50,51]. Most studies are also more focused on technical characteristics of the buildings or their technical systems. The problem with only using kWh/m$^2$ is that it omits the issue of occupancy and space efficiency [19]. If a building is more space efficient and has a higher occupancy, the less energy efficient it can seem using kWh/m$^2$, since the building's floor area remains the same but the components of energy use that are dependent on the number of users are higher [52,53]. Houvila et al. [19] used six different indicators for measuring energy efficiency in buildings in their study; kWh/m$^2$, kWh/npersons (*nperson* = number of occupants), kWh/hpers (*hpers* = sum of the number of hours that each building occupant spends in the building during the year in question), kWh/m$^2$*hpers, kWh/m$^2$*o ($o$ = average presence of the occupants during normal working hours 8-17 and normal workdays, where $0 \leq o \leq 1$), and kWh/m$^2$*u ($u = (nt_{avg})/(A/a_{ref}*t_{ref})$, where $n$ is the actual number of people using the space, $t_{avg}$ is the average number of daily hours present per person, $A$ is the total studied area, $a_{ref}$ and $t_{ref}$ are normalizing factors, where $a_{ref}$ is the amount of space per person available in a typical office setting and $t_{ref}$ represents normal working hours). The energy use of five different buildings was then calculated using these six indicators and the results were compared to see how the difference in occupancy and internal gains affected the perceived energy efficiency. They concluded that different indicators have different impacts on the results showing the efficiency. They also state that the indicator SEC is very useful in the design phase, when only estimations can be made of the actual number of occupants, and it is also useful for comparing technical solutions at this stage. It is also easy to calculate and to compare with other buildings since there are a lot of documented cases where this indicator

has been used [19]. The indicator kWh/npersons is very easy to calculate and it is illustrative when space efficiency is considered and the area of the building is fixed as it most often is in existing buildings [19]. However, neither kWh/npersons nor kWh/hpers consider the area of the building, which makes them poor choices when comparing technical aspects of a building. Nonetheless, kWh/hpers is a good indicator for both occupancy and space efficiency [19]. The indicator kWh/$m^2$*hpers takes both occupancy and the space used into account but the problem is that it exponentially overestimates the effect of the space and person hour efficiency [19]. Houvila et al. [19] continue to conclude that kWh/$m^2$*o does not take space efficiency into account, but highlight the relative occupancy, and the disadvantage is that in some cases even 100% occupancy is not optimal. They finally conclude that kWh/$m^2$*u is the only indicator that takes both relevant aspects into account, but that it is rather difficult to calculate for existing buildings since data of real time occupancy is hard to get.

# 3. Methods

Both studies included in this thesis are case studies where whole Building Energy Simulation (BES) has been used as method among other methods. In the first paper, a cross-disciplinary research approach was used. The authors of Paper I come from different fields of research and used different methods such as time diaries, which originate in the field of time geography, as well as measurements and energy simulations, which is more of a technical approach. These different methods were then combined to gain better understanding of the studied object and hence the results from the study.

## 3.1 Field measurements and data collection

The measurements conducted in Paper I were measurements of indoor climate, energy use, and electricity use. Indoor climate was measured using logged measurements in each of the participating residents' apartments where $CO_2$ levels and indoor temperature were logged with a time resolution of five minutes. Indoor temperature was also measured in the stairwells and other common areas. Electricity use was logged for each participating apartment with a resolution of five minutes and collected for the other three apartments at a weekly interval with the resident's consent. Weekly electricity use was also collected for the building and the entire retirement home. Energy use for space heating and DHW was measured for the entire city block as there were no separate meters for the apartments or different buildings. All measurements carried out in the retirement home can be seen in Table 3. Residents in 12 out of 15 apartments in the studied building agreed to have measurements conducted in their apartment.

Besides measurements, construction data was also gathered for the two studied buildings (Paper I and II). Construction data for the retirement home was gathered both from drawings and on-site observations. For the office building, no on-site observations could be made since the building is only in the planning stage, so construction data was gathered from drawings. The data consisted of, among other things, measurements of the building envelopes and interior, thicknesses and materials of walls, roofs, windows, U-values, etc.

Table 3. Measurements at the retirement home (city block Räknestickan), time resolution and time span, as well as which measurement equipment was used.

| Measuring type | Measuring Equipment | Area | Time resolution | Timespan |
|---|---|---|---|---|
| **District heating** | Meter at the city block's central heating plant | Entire city block (one measuring point) | weekly | 2 months |
| **Domestic hot water use and temperature** | Meter at the city block's central heating plant | Entire city block (one measuring point) | weekly | 2 months |
| **Domestic cold-water use** | Meter at the city block's central heating plant | Entire city block (one measuring point) | weekly | 2 months |
| **Facility electricity** | Electricity meter | Entire city block (six measuring points) | weekly | 2 months |
| **Apartment electricity** | Electricity meter | Ekholmsvägen 106 (15 apartments) | weekly | 2 months |
| **Total electricity** | Eliq | Entire city block (incoming electricity for each facility and for the central ventilation. 5 measuring points in total) | Every 5 minutes | 1 week |
| **Momentary Total electricity** | Fluke 41B Power harmonics analyser + Universal Technic current clamps | Entire city block (incoming electricity for each facility and for the central ventilation. 5 measuring points in total) | - | - |
| **Momentary temperature** | Swema3000 | Stairwells, ventilation outlets | - | - |
| **Logged temperature** | Tinytag Plus2 | 12 apartments | Every 5 minutes | 1 week |
| **Logged apartment electricity** | Eliq | 12 apartments | Every 5 minutes | 1 week |
| **Relative humidity** | Tinytag view2 Temp and RH logger | 12 Apartments | Every 5 minutes | 1 week |
| **$CO_2$** | Tinytag $CO_2$ | Dining hall + 12 apartments | Every 5 minutes | 1 week |
| **Energy use from apartment ventilation** | Everflourish power meter EMT707CTL | Ventilation unit in one apartment | 1 week | 1 week |
| **Momentary ventilation flows** | Swema3000 | Outlets on roof + measured on central ventilation system | - | - |
| **Building envelope tightness** | Retrotec DM32 Blower door | 1 apartment | - | - |

## 3.2 Time diaries

Time diaries are a method commonly used to describe and analyze the relationship between location, activities, and movement of individuals. A time diary differs from a normal diary in the way that it describes an individual's life for a period of time in a more or less systematic way. It was developed within the field of time geography and in several studies within this field has been

used to study how everyday life affects energy use with a time geographic approach (e.g., References [24–26]). Time diaries often begin to show a pattern of a person's movements between the dwelling, workplace, shops they visit, and when they visit family and friends. It also helps in understanding how long these activities go on and how they contribute to structuring an individual's life. When using time diaries, researchers are often looking for specific activities that they want the respondent to write down which are related to the study's objective. It might be that they want to know when they use hot water, when and for how long they have their windows opened, when they cook, go outside, etc., but in the end, it is the respondent who decides what gets entered in the diary. When a respondent keeps a time diary, they often become more aware of their actions and activities, which can make them reflect more about their everyday life and help them explain why they do certain things. A time diary can come in both paper and digital format, where the digital format often comes as an app to the cell phone or the activities are recorded on the computer [54]. The digital format is often less time-consuming for the researcher and for the respondent, but some respondents feel more secure with writing by hand [12,54].

In the case of this study, the participants felt more secure writing their diaries by hand instead of using a digital format. As previously stated in section 3.1 the residents from 12 apartments agreed to have measurements conducted in their apartment. Of these 12 households, 11 agreed to also keep a time diary, the 12$^{th}$ resident stating difficulty to write due to poor eyesight as a reason for not wanting to keep a time diary. They kept a time diary for the same seven-day period as the measurements of indoor climate were conducted in their apartment. In the time diary they were asked to fill in what they were doing (activity), at what time the activity took place (time), where they were (place), if they were by themselves or with someone (with whom), if they used any electrical appliances, and as a final note they could add their own comments.

## 3.3 Building Energy Simulation and validation

Whole Building Energy Simulation is a method for analyzing a building's energy demand and/or indoor climate based on a variety of input data. It can be used in building projects to predict future energy demand on a planned building or to see how renovation or retrofitting of a building will affect the energy demand. BES is most often seen as the best approach for estimating energy use in new building projects [14]. Within the field of energy simulation today, there are many discussions about uncertainties in input data and how it affects the output, where occupant behavior is seen as one of the biggest "disturbances/uncertainties". The more accurate the input is, the more accurate the output will be [12]. These uncertainties can lead to quite high discrepancies between the simulated results and real energy use in a building [14], contributing to the performance gap of a building [15,40].

For both studied buildings in this thesis, the whole Building Energy Simulation software IDA-ICE version 4.8 has been used as a tool to estimate energy demand and indoor climate. IDA-ICE is a dynamic BES software, where comfort indices, thermal conditions and building performance can be estimated [55]. IDA-ICE has been tested and validated. In IEA's Task 34, IDA-ICE was validated with test cell measurements. It has also been validated according to CEN standards EN 15255-2007, 15265-2007 [56], and 13791 [57], as well as ASHRAE Standard 140-2004 [58].

Two models were created for the retirement home in Paper I. One called BES-ref which used standard user input data, and one called BES-v.2 which used user input data gathered on-site. For BES-v.2, schedules for electricity use, airing, and occupancy were created according to the time diaries and measurements for each apartment and implemented into the simulation model. An empirical/realistic validation was done for BES-v.2. To validate BES-v.2, the simulation results of temperature and $CO_2$ for each apartment were compared to the measurements of temperature and $CO_2$ from the respective apartment. When the simulated results of temperature and $CO_2$ corresponded to the measurements, the model was considered validated. To achieve the same response in temperatures and $CO_2$ levels in the model as in the measurements, calibration of the schedules for airing, electricity use, and occupancy was made. The electricity use in the model was simply put in as a schedule with the same power [W] and time as the measurements and was compared with the total electricity use for the entire week to see that the right level was achieved. BES-ref used the same validated model as BES-v.2 as a base, but instead of using empirical data for user input data it used standard user input data from Sveby. The validation process can be seen in Figure 3.

In the case of the office building, the validation could not be empirical/realistic since the building is only in the planning stage. The model was therefore seen as validated by relying on the software IDA-ICE to do correct estimations. As previously stated, IDA-ICE has been validated several times throughout its history.

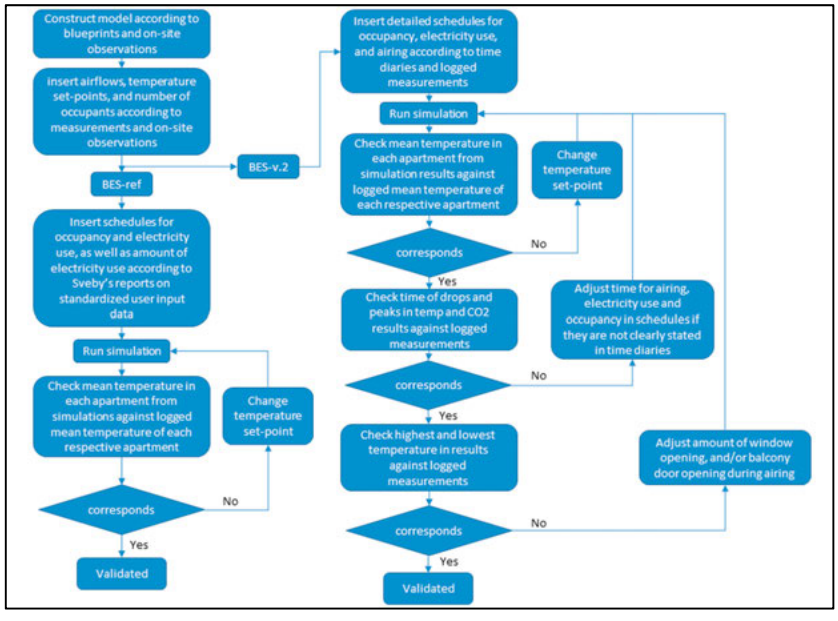


Figure 3. Validation process of BES-ref and BES-v.2.

## 3.4 Parametric Study

A parametric study was used for the model of the office building to see how different variables affected the heating and cooling demand of the building. The variables that were changed were occupancy, electricity use, solar shading or no solar shading, façade design, and location and orientation of the building. Occupancy was set as either 0.05 persons/m$^2$ or 0.035 persons/m$^2$ as well as having two different schedules of time spent in the building. The first schedule was to represent regular office hours, 9 h/day 5 days/week 50 weeks/year. The second schedule was made to represent an office that is also utilized during evening and weekends. This schedule has occupancy from 8-22 during weekdays and 12-22 on weekends and vacation. During weekday evenings (17-22) the number of occupants is 0.025 persons/m$^2$, and during weekends and vacation the number of occupants is 0.0125 persons/m$^2$. Electricity use followed the occupancy. All different cases of internal heat gains were named B1-B8 (see Table 4). Solar shading was either implemented as blinds with a control called sun, which means that the blinds are drawn when the solar heat against the window reaches 100W/m$^2$, or the building used no solar shading. The building without solar shading was called C1 and the building with solar shading was called C2. The façade design was changed between two types: façade type A1 had the saw-toothed façade and type A2 had a regular straight façade (see Figure 1). The three different locations investigated were Luleå, Linköping, and Malmö. The different orientations were N, NE, E, SE, S, SW, W, and NW. Combining all different variables created 768 different simulations.

Values and designation of the different variables can be seen in Table 5 and what is included in the eight different cases of IHGs can be seen in Table 4.

Table 4. Different values for internal heat gains used in the models. Lighting and equipment do not include electricity use of the ventilation system.

| Name | Occupancy (occupants/m$^2$) | Electricity | Lighting and equipment (kWh/m$^2$ × year) | Heat from occupants (kWh/m$^2$×year) | Total (kWh/m$^2$×year) |
|---|---|---|---|---|---|
| B1 | 0.05 workdays | Standard | 50.0 | 11.3 | 61.3 |
| B2 | 0.05 workdays | Low | 35.0 | 11,3 | 46.3 |
| B3 | 0.035 workdays | Standard | 35.0 | 7.9 | 42.9 |
| B4 | 0.035 workdays | Low | 24.4 | 7.9 | 32.3 |
| B5 | 0.05 workdays + extended | Standard | 70.4 | 15.8 | 86.2 |
| B6 | 0.05 workdays + extended | Low | 49.2 | 15.8 | 65.0 |
| B7 | 0.035 workdays + extended | Standard | 55.3 | 12.4 | 67.7 |
| B8 | 0.035 workdays + extended | Low | 38.5 | 12.4 | 50.9 |

Table 5. The variation of the variables used in the parametric study except internal heat gains which can be seen in Table 4. Blinds are drawn when solar heat against the windows reach 100W/m$^2$.

| Façade | | Location | Window shading | | Orientation |
|---|---|---|---|---|---|
| **Description** | **Designation** | **Description** | **Description** | **Designation** | **Description** |
| Saw-toothed | A1 | Linköping | No Shading | C1 | 0˚ (N) |
| Straight | A2 | Luleå | Blinds | C2 | 45˚ (NE) |
| | | Malmö | | | 90˚ (E) |
| | | | | | 135˚ (SE) |
| | | | | | 180˚ (S) |
| | | | | | 225˚ (SW) |
| | | | | | 270˚ (W) |
| | | | | | 315˚ (NW) |

# 4. Case studies

The study objects of the thesis are an existing retirement home and a planned new office building, both located in the city of Linköping, Sweden. A detailed description of the two studied buildings is presented in this section.

The first studied building is a single building within a city block called Räknestickan. Räknestickan consists of a total of 99 apartments, placed in five buildings. Thirty-five of these apartments are so-called assisted living where the residents have their own safety alarms, and two healthcare providers operate in the block. The studied building is one of the five buildings in the block and contains 15 apartments, equally placed on three floors. The block was built in 1983 and has not undergone any renovation or retrofitting since. In a study of the same city block made by the author of this thesis and a fellow student prior to the study in Paper I, a questionnaire regarding indoor climate and indoor environment was sent out to the residents. The answers from the questionnaire pointed towards problems with the ventilation system, and in this block, each apartment has its own air handling unit. Many of the residents did not know how to operate the air handling unit or did not even know that they had it [59]. The air handling unit in each apartment was of FTX[1] type, with an electrical heating coil where the residents could control the temperature of the inflowing air. The main heating system in the building and the apartments was waterborne radiators with supply from district heating. The studied building of the retirement home as well as the model can be seen in Figure 4 and technical and location data can be found in Table 6.

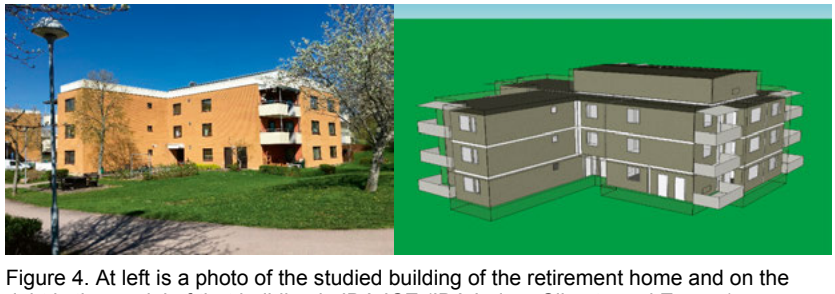

Figure 4. At left is a photo of the studied building of the retirement home and on the right is the model of that building in IDA-ICE (IDA Indoor Climate and Energy)

[1] FTX ventilation means mechanical supply and return with heat recovery.

Table 6. Technical data of the modelled building in paper 1

| **Location Data** | | | | | |
|---|---|---|---|---|---|
| **Country** | Sweden | | | | |
| **City** | Linköping | | | | |
| **Longitude** | 15.53 E | | | | |
| **Latitude** | 58.4 N | | | | |
| **Annual mean temperature** | 6.8˚C | | | | |
| **Building** | | | | | |
| **Model floor area** | 1366.2 $m^2$ ($A_{temp}$) | | | | |
| **Floor area apartments** | 1131.7 $m^2$ | | | | |
| **Model volume** | 3370.1 $m^2$ | | | | |
| **Model ground area** | 427.2 $m^2$ | | | | |
| **Model envelope area** | 1770 $m^2$ | | | | |
| **Window/envelope** | 5.5 % | | | | |
| **Average U-value** | 0.42 W/$m^2$K | | | | |
| **Number of apartments** | 15 | | | | |
| **Common area (stairwell, entrance and storage)** | 234.5 $m^2$ | | | | |
| **Time constant** | 201 h | | | | |
| **DVUT** | -13˚C | | | | |
| **$Q_{tot}$** | 1036 W/K | | | | |
| **Building envelope** | | | | | |
| | **Area [$m^2$]** | ***U* [W/$m^2$K]** | ***U*A* [W/K]** | | |
| **Walls above ground** | 775.38 | 0.25 | 197.54 | | |
| **Roof** | 427.88 | 0.18 | 75.86 | | |
| **Floor towards ground** | 427.20 | 0.45 | 191.56 | | |
| **Windows** | 97.81 | 1.91 (incl. frame) | 186.81 | | |
| **Doors** | 38.06 | 0.25 | 9.61 | | |
| **Windows** | | | | | |
| **Direction** | **Area [$m^2$]** | **Glazing** | ***g*-factor** | | |
| **N** | 21.32 | 3-pane | 0.68 | | |
| **E** | 26.97 | 3-pane | 0.68 | | |
| **S** | 23.63 | 3-pane | 0.68 | | |
| **W** | 25.89 | 3-pane | 0.68 | | |
| **Construction** | | | | | |
| **External wall 1** | Brick 87mm | Air gap 23mm | Gypsum 9mm | Insulation 170mm | Gypsum 13mm |
| **External wall 2** | Wood 20mm | Air gap 16mm | Gypsum 9mm | Insulation 120mm | Concrete 160mm |
| **External wall 3** | Wood 20mm | Air gap 16mm | Gypsum 9mm | Insulation 120mm | Gypsum 13mm |
| **External wall 4** | Brick 87mm | Air gap 23mm | Insulation 120mm | Concrete 160mm | |
| **Internal wall** | Concrete 160mm | | | | |
| **Internal floor** | Concrete 200mm | Floor coating 5mm | | | |
| **External slab** | Concrete 250mm | Floor coating 5mm | | | |
| **Roof 1** | Wood 25mm | Insulation 250mm | Concrete 200mm | | |
| **Roof 2** | Wood 25mm | Insulation 10mm | Aluminum 1mm | | |

As previously described, the building in Paper II is designed to lower the cooling demand by having a "saw-toothed" façade shape. Sankt Kors has stated that all their upcoming buildings should reach at least the grade of Silver in the environmental grading system Miljöbyggnad [60,61]. The building is therefore designed and modelled with a building envelope that has state-of-the-art insulation levels concerning energy efficient buildings in Sweden, and an FTX type ventilation system with a heat exchanger efficiency of 80%. The fans in the ventilation system were set on a fixed speed depending on the number of occupants. These are not the only things that are important to achieve a high grade in Miljöbyggnad, which has 15 different indicators such as daylight factor, indoor climate both winter and summer based on PPD levels, energy use, share of renewable energy, etc. [60,61] Technical and location data of the model can be found in Table 7.

Table 7. Technical and location data of the modelled office building

| **Location data** | | | |
|---|---|---|---|
| | **Linköping (Sweden)** | **Luleå (Sweden)** | **Malmö (Sweden)** |
| **Longitude** | 15.53 E | 22.13 E | 13.37 E |
| **Latitude** | 58.4 N | 65.55 N | 55.52 N |
| **Annual mean outdoor temperature** | 6.6 ˚C | 2.6 ˚C | 8.2 ˚C |
| **Winter outdoor design temperature** | -16.4 ˚C | -26.8 ˚C | -11.9 ˚C |

| **Building** | | |
|---|---|---|
| | **Angled façade** | **Straight façade** |
| **Model floor area** | 2308 $m^2$ | 2308 $m^2$ |
| **Model volume** | 7155 $m^3$ | 7154 $m^3$ |
| **Model ground area** | 585.1 $m^2$ | 585 $m^2$ |
| **Model envelope area** | 2647.2 $m^2$ | 2422.7 $m^2$ |
| **Window/envelope** | 19.0 % | 20.8 % |
| **Average *U*-value** | 0.22 W/($m^2$·K) | 0.22 W/($m^2$·K) |
| **Number of floors** | 4 | 4 |
| **Building heat loss coefficient** | 592.33 W/K | 526.5 W/K |
| **Airtightness** | 0.3 L/(s ext. surf.) @50 Pa | 0.3 L/(s ext. surf). @50 Pa |

| **Building envelope** | | | | |
|---|---|---|---|---|
| | **Angled façade** | | **Straight façade** | |
| | Area ($m^2$) | *U* (W/($m^2$·K)) | Area ($m^2$) | *U* (W/($m^2$·K)) |
| **Walls above ground** | 981.59 | 0.13 | 757.3 | 0.13 |
| **Roof** | 577.0 | 0.10 | 576.9 | 0.10 |
| **Slab on ground** | 585.1 | 0.12 | 585.0 | 0.12 |
| **Curtain wall total** | 503.4 | 0.36 | 503.4 | 0.36 |
| **Glazing of curtain wall** | 201.6 | 0.70 | 201.6 | 0.70 |
| **Closed part curtain wall** | 301.8 | 0.13 | 301.8 | 0.13 |

| **Thermal bridges** | | | | |
|---|---|---|---|---|
| | **Angled façade** | | **Straight façade** | |
| | *U·A* (W/·K) | % of total transmission | *U·A* (W/·K) | % of total transmission |
| **Thermal bridges** | 158.08 | 26.7 | 124.2 | 23.6 |

| **Construction** | | | | |
|---|---|---|---|---|
| | Material | Thickness (m) | Material | Thickness (m) |
| **External wall** | Concrete | 0.26 | Insulation | 0.27 |
| **Slab on ground** | Concrete | 0.20 | Insulation | 0.20 |
| **Roof** | Concrete | 0.20 | Insulation | 0.35 |

| **Ventilation system** | |
|---|---|
| Heat exchanger efficiency | 0.8 |
| Supply air flow rate | 1.3 L/(s*$m^2$) |
| Return air flow rate | 1.3 L/(s*$m^2$) |

# 5. Results

The results are presented in three different sections divided according to the three research questions.

*How does user behavior and different levels of IHGs affect energy demand in a retirement home and an office building in Sweden?*

*Retirement home*
When reading the time diaries, it could be seen that the residents of the retirement home were at home for long periods of the day, approximately 20 h/day and person. It was also clear from reading the time diaries that they aired their apartments quite often. An excerpt from one resident's time diary can be seen in Table 8. When comparing the entries in the diary in Table 8 with the measurements from the same apartment and the same date, which can be seen in Figure 5, one can see that there are certain activities that influence the measurements more than others. For instance, the resident opens the balcony door to let out the cats which can clearly be seen affecting both temperature and $CO_2$ levels at around 8:30, 13:30, 20:30, and one last time at around 22:00. The measurements of this apartment and the time diary were done in November, where the mean temperature was 5.5□ in 2014, which meant this behavior led to quite high heat losses, thus increasing the heating demand of the building. There are also activities that lower the heating demand. These activities are for instance cooking or having guests over. As can be seen in Table 8, the resident has a guest over at 13:45, and the resident also cooks at around 17:00. Looking at the measurements in Figure 5, one can see that around 13:45 the temperature and $CO_2$ level start to increase. This is a direct result from the guest being present. The cooking can be seen directly in the measurements as a spike in electricity use, which also leads to an increase in temperature.

Table 8. A transcript from one of the time diaries for one day. The gray posts can clearly be seen having an impact on the measurements in seen Figure 5.

| Time | Activity | Place | With whom | Electrical appliances | Comments |
|---|---|---|---|---|---|
| 07.30 | Waking up, turns on radio | Bedroom | Alone | Radio | |
| 08.15 | Turns off radio, gets out of bed | Bedroom | Alone | Radio | |
| 08.16 | Turns on radio, feeds the cats, makes tea | Kitchen | Alone | Water boiler 4 min, radio | |
| 08.22 | Showers and gets dressed | Bathroom | Alone | | |
| 08.30 | Hangs out linens on the balcony | Balcony/ Living room | Alone | | |
| 08.30-08.50 | Balcony door open | | | | cats wanted to be out |
| 08.45 | Makes breakfast, eats breakfast | Kitchen | Alone | Lamp, micro (4 min) | |
| 09.20 | Brushes teeth | Bathroom | Alone | Electrical toothbrush | |

| | | | | | |
|---|---|---|---|---|---|
| 09.30 | Takes in the linens and makes the bed | Balcony/ Bedroom | Alone | | |
| 09.35 | Turns off the radio | Kitchen | | Radio | |
| 09.35-12.00 | Not at home | out | | | |
| 12.00 | Home again, turns on radio, washes hands, puts groceries in fridge | Kitchen | Alone | Radio | |
| 12.10 | Making copies and laminating | Bedroom/kitchen | Alone | Copying machine, laminator | |
| 12.20 | At computer, talking on the phone | Bedroom | Alone | Computer, cell phone | |
| 12.42 | Heats and eats food, does dishes | Kitchen | Alone | Micro (3 min) | |
| 13.05 | Empties litter box, vacuums | Bathroom | Alone | Lamp, Vacuum cleaner | |
| 13.10 | Vacuuming | Kitchen, living room, bedroom | Alone | Vacuum cleaner | |
| 13.25 | Turns on lamps in windows | Kitchen, living room | Alone | Lamps | |
| 13.26-13.40 | Lights lantern | Balcony | Alone | | Balcony door open. Cats outside |
| 13.40 | Calls hair salon | Kitchen | Alone | Cell phone | |
| 13.45 | Has a guest at home, has coffee, talks, gets help with computer | | Friend | Computer, water boiler (4 min) | Very nice with good company |
| 16.10 | Turns off radio and kitchen lamp | Kitchen | Alone | | |
| 16.10 | Went for a walk | out | | | Nice with a walk |
| 17.00 | Turns on radio, starts to make dinner | Kitchen | Alone | Radio, stove (17-19) | |
| 17.15 | Copying | Bedroom | Alone | Copying machine | |
| 17.25 | Does the dishes | Kitchen | Alone | Lamp | |
| 17.40 | Goes through the mail | Kitchen | Alone | Lamp | |
| 18.00 | Turns off radio, turns on floor lamp, watches TV | Living room | Alone | TV, radio, lamp | |
| 19.00 | Eats, does dishes, cleans stove | Kitchen | Alone | | |
| 19.00-19.45 | Charges cell phone | | | Cell phone | |
| 20.05 | Watches TV | Livingroom | Alone | TV | |
| 20.15-22.00 | Watches TV | Living room | Alone | TV | Puts on thick socks |
| 20.40-20.46 | Balcony door open | | | | Cats wanted out |
| 22.00 | Empties litter box, washes hands | Bathroom | Alone | | |
| 22.03 | Puts out lantern | Balcony | Alone | | Balcony door open 22.03-22.09 |
| 22.04 | Makes the bed | Bedroom | Alone | | |
| 22.20 | Brushes teeth | Bathroom | Alone | Electric toothbrush | |
| 22.25 | Goes through some papers | Kitchen | Alone | | |
| 22.59 | Gets ready for bed | Bathroom | Alone | | |
| 23.15 | Turns off all lights and goes to bed | | Alone | | Finally in bed |

In the logged measurements of $CO_2$ levels, temperature and electricity use it could clearly be seen that certain patterns emerged for each household. However, there was not much difference between holidays and regular weekdays as it usually is in a household where the residents either work or go to school. Measurements from one day in one apartment can be seen in Figure 5.

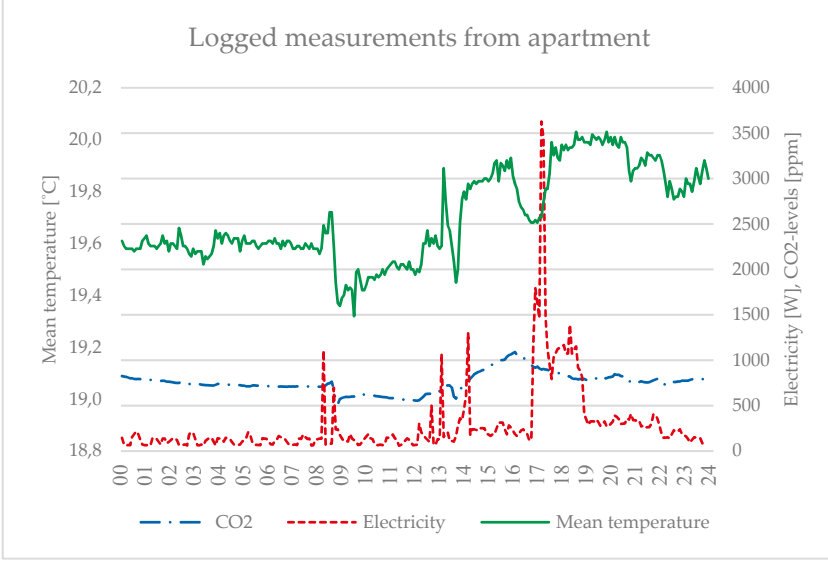


Figure 5. Logged measurements of temperature, $CO_2$, and electricity from the same apartment and day as the time diary shown in Table 8.

The time diaries together with the measurements gave a clear picture of what activities affected the indoor climate and electricity use, and in what manner. The behavior-related effects on heating demand in the studied retirement home were mostly due to airing. According to the simulations, heat losses due to airing accounted for 8 kWh/m$^2$, year. The residents had an electricity use from lighting and household appliances of approximately 20 kWh/m$^2$, year.

*Office building*

In office buildings behavior such as airing through opening of windows is not usually a problem and this study has focused on occupancy and use of equipment, and not on specific behaviors of staff when they are in the office. But if one considers working from home and/or using the office building later in the evening as a behavior, one can see that this sort of behavior has a distinct impact on the heating and cooling demand of an office building.

The highest total energy demand is seen when both occupancy and electricity use are high, as in case B5, where the building is used for longer periods of the day ad electricity use is high. When comparing case B5 using solar shading and a straight façade to the case with the lowest total energy use in each city, the following differences are obtained: In Malmö the total heating and cooling

demand is 52% lower in case B8 than case B5, in Linköping it is 44% lower in case B4 than case B5, and in Luleå it is 31% lower in case B3 than case B5.

*How is energy demand affected in a retirement home and an office building in Sweden, when using empirical and/or probable future values of IHGs and behavior compared to today's standard values?*

*Retirement home*
As stated earlier, it could be seen in the time diaries that the residents of the retirement home were home quite a lot. The residents were home for approximately 20 h/day, which gives a difference of plus 6 h/day compared to standard values for a normal Swedish household, where people are at home for 14 h/day. Despite being at home for longer periods of time, they used less electricity than the average Swedish household. The residents had an electricity use of approximately 19 kWh/m$^2$ instead of 30 kWh/m$^2$, which is the standard value. The reason for the residents being home longer periods of the day is most likely due to the fact that many of them have retired so they do not go to work anymore. The reason for them using less electricity is probably because they own fewer electrical appliances than the "younger" population of Sweden. It can also be because they were taught growing up that one should try to save electricity, and/or that they simply want to save money by not using unnecessary amounts of appliances and for instance always turning off the lights when leaving a room.

It could clearly be seen that the model with the schedules based on time diaries and logged measurements, called BES-v.2, had higher energy use than the building where standard values were used, called BES-ref. It was also clear that much of this difference came from a higher degree of airing, which was implemented in BES-v.2 according to the time diaries and measurements. Energy losses due to airing were about 8 kWh/m$^2$ in BES-v.2 according to the simulations, which is twice as high as the standard values of user input data for households [30]. The total energy use for space heating was 24% higher in BES-v.2 compared to BES-ref. How the model's energy demand and electricity use was affected on building level can be seen in Table 9.

Table 9. Energy use on building level for both models of the retirement home and comparison between the two.

| | BES-ref [kWh] | BES-v.2 [kWh] | Difference BES-ref to BES-v.2 |
|---|---|---|---|
| **Heating from radiators (DH)** | 48545 | 58345 | 20% |
| **AHU heating (electrical)** | 3432 | 6357 | 85% |
| **Total energy for space heating** | 51976 | 64702 | 24% |
| **Energy loss due to airing** | 5464 | 10865 | 99% |
| **Household electricity (input)** | 34092 | 20659 | -39% |

On apartment level the differences were quite high between BES-v.2 compared to BES-ref. There were also large differences between the individual apartments, especially in BES-v.2. The apartment with the largest difference in airing losses compared between BES-ref and BES-v.2 had a difference of 42.6 kWh/m$^2$, where BES-ref had losses of 4.3 kWh/m$^2$ and BES-v.2 had losses of 46.9 kWh/m$^2$. In that particular apartment, the residents always had the bedroom window slightly opened during the night all year round. The apartment with the largest difference in total energy demand had a difference of 170%. It should be said that this apartment had very low energy use from the beginning due to the resident keeping a low indoor temperature so the difference in total was 21.6 kWh/m$^2$, where BES-v.2 had the highest demand with 34.3 kWh/m$^2$. The apartment with the largest difference in energy demand for space heating between BES-ref and BES-v.2 in absolute numbers had a difference of 48.5 kWh/m$^2$, and once again it was BES-v.2 that had the highest demand.

*Office building*

When comparing energy demand between cases using standard values for user input data, represented by IHGs case B1, with cases using probable future IHGs, represented by case B2-B8, there are some distinct differences between the locations. In Luleå, energy demand for heating and cooling when using IHGs case B1 end up in the middle of all scenarios (see Figure 6). In Linköping and Malmö, energy demand for heating and cooling when using IHGs case B1 becomes the second highest compared to the other scenarios (see Figure 6). One aspect that is the same for all locations is that the cooling demand is always the second highest across all scenarios when using standard values for user input data (B1). The only case of IHGs that has a higher cooling demand than B1, is B5, which uses standard values together with an extended occupancy (see Table 4 for description of the different cases). In Table 10, energy demand for heating and cooling for case B1 is compared to energy demand for heating and cooling of the other cases of IHGs. All the compared cases in Table 10 have the straight façade and use solar shading.

Case B5, B6, B7, and B8 represent scenarios where the office is utilized during more hours of the week, such as evenings and weekends. In Luleå, every case with occupancy during evenings and weekends (B5, B6, B7, B8) generates a higher energy demand for heating and cooling than case B1, while in Linköping and Malmö it is only case B5 that generates a higher energy demand for heating and cooling than B1.

The results in Table 10 show that by using less electricity but keeping a standard occupancy, represented by case B2, energy demand for heating and cooling could be lowered by 12% in Luleå, 25% in Linköping, and 31% in Malmö. Case B2 represents a future scenario where we have more energy-efficient office equipment but keep the same occupancy as today. B3 represents a scenario where more people work from home, but the office equipment has not become more energy-efficient, and compared to B1 the energy use is still lower. This is since there is less occupancy, there is also less IHGs from office equipment, even if the equipment has not become more energy efficient. If B1 is compared to case B4, which represents a scenario where staff works more

from home (less occupancy) and the office equipment is more energy efficient, the energy demand for heating and cooling in Malmö is 39% lower in case B4, in Linköping it is 32% lower, and in Luleå it is 11% lower.

Table 10. Energy demand for heating and cooling for all cases of internal gains compared to case B1, which uses standard input data. All results are from the model with a straight facade and solar shading.

| | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 |
|---|---|---|---|---|---|---|---|---|
| **Malmö** | | | | | | | | |
| Difference compared to B1 | - | -31% | -33% | -39% | +21% | -30% | -27% | -42% |
| Heating+Cooling [kWh/year] | 68499 | 47193 | 45723 | 41610 | 82882 | 47958 | 49930 | 39452 |
| **Linköping** | | | | | | | | |
| Difference compared to B1 | - | -25% | -27% | -32% | +21% | -19% | -17% | -29% |
| Heating+Cooling [kWh/year] | 75875 | 56523 | 55073 | 51054 | 92424 | 61456 | 63265 | 53792 |
| **Luleå** | | | | | | | | |
| Difference compared to B1 | - | -12% | -12% | -11% | +27% | +8% | +8% | +6% |
| Heating+Cooling [kWh/year] | 84119 | 74225 | 74195 | 74911 | 107044 | 90458 | 90900 | 89296 |

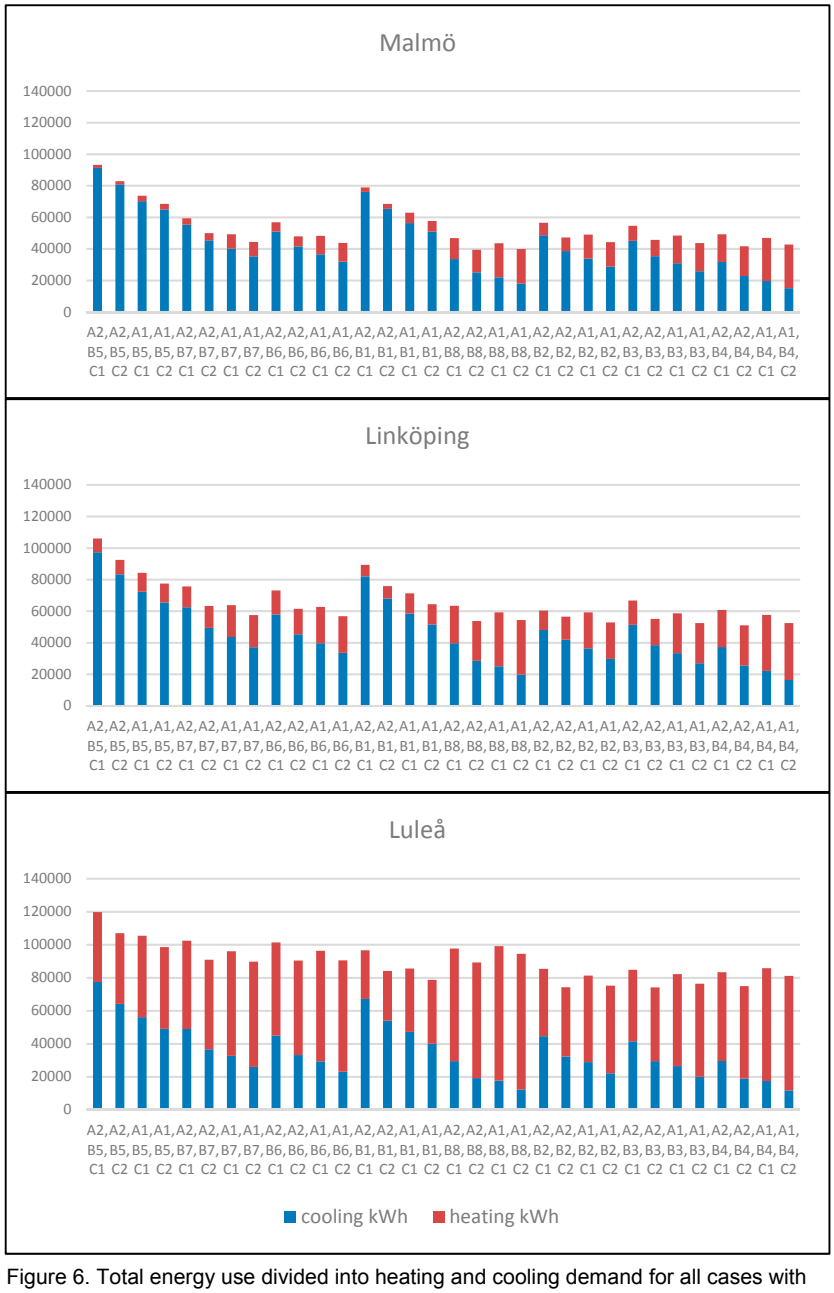


Figure 6. Total energy use divided into heating and cooling demand for all cases with the reference surface facing north. Internal heat gains (B1–B8) are in order from highest to lowest (left to right) for each location. A1 is angled façade and A2 is straight façade. C1 is without blinds and C2 is with blinds.

*How is energy efficiency perceived when using two different indicators, if changes in IHGs and user behavior occur in a retirement home and an office building in Sweden?*

The most widely used indicator for measuring energy efficiency in buildings in Sweden is kWh/m$^2$ and year, hence abbreviated to kWh/m$^2$. In this study the indicator kWh/(m$^2$ × hpers) and year, hence abbreviated to kWh/m$^2$*hpers, has been used to compare how energy-efficiency can be perceived differently by using different indicators.

*Retirement home*

When comparing BES-ref with BES-v.2 the results are that BES-ref is perceived as the most energy efficient when kWh/m$^2$ is used as indicator (see Table 11). If kWh/m$^2$* hpers is used as indicator, BES-v.2 is perceived as the most energy efficient (see Table 11). As previously described, BES-ref uses Sveby's standard of occupancy in residential buildings which is 14 h/day per person and BES-v.2 uses actual occupancy hours gathered in the study, which shows that the residents are at home approximately 20 h/day and person.

Table 11. Comparison between Bes-ref and Bes-v.2 for both indicator kWh/m$^2$ and kWh/m$^2$*hpers

| | BES-ref kWh/m$^2$ | BES-v.2 kWh/m$^2$ | BES-ref kWh/m$^2$*hpers | BES-v.2 kWh/m$^2$*hpers |
|---|---|---|---|---|
| Heating from radiators (DH) | 35,5 | 42,7 | $39*10^{-5}$ | $32*10^{-5}$ |
| AHU heating (electrical) | 2,5 | 4,7 | $2,7*10^{-5}$ | $3,6*10^{-5}$ |
| Total energy for space heating | 38 | 47,4 | $41*10^{-5}$ | $36*10^{-5}$ |
| Energy loss due to airing | 4 | 8 | $4,3*10^{-5}$ | $6,1*10^{-5}$ |
| Household electricity (input) | 25 | 15,1 | $27*10^{-5}$ | $11*10^{-5}$ |

*Office building*

If kWh/m$^2$ is used as indicator, it can be seen in Figure 7-9 that in all cities that the cases with low IHGs can be perceived as more energy efficient. However, it is not the case with the absolute lowest IHGs, case B4, that can be perceived as the most energy efficient. In Malmö it is the case with internal gains B8, which has the fourth lowest IHGs, in Linköping and Luleå it is the case with the third lowest internal gains, B2 that can be perceived as the most energy efficient. As can be seen in Figure 7-9, the cases that can be perceived as the most energy efficient when using the indicator kWh/m$^2$*hpers are now the cases using B6 as IHGs for all cities. B6 have the third highest IHGs and have low electricity use and high occupancy with extended hours. When using kWh/m$^2$*hpers, one can also see that the IHGs case with the fewest occupancy hours, case B3, is perceived as the least energy efficient in Linköping and Luleå, while in Malmö it is case B1 that is perceived as the worst, closely followed by case B3. Case B4 has the lowest occupancy hours and the lowest total IHGs of all cases and is perceived as the third worst in Malmö and Linköping and the second worst in Luleå.

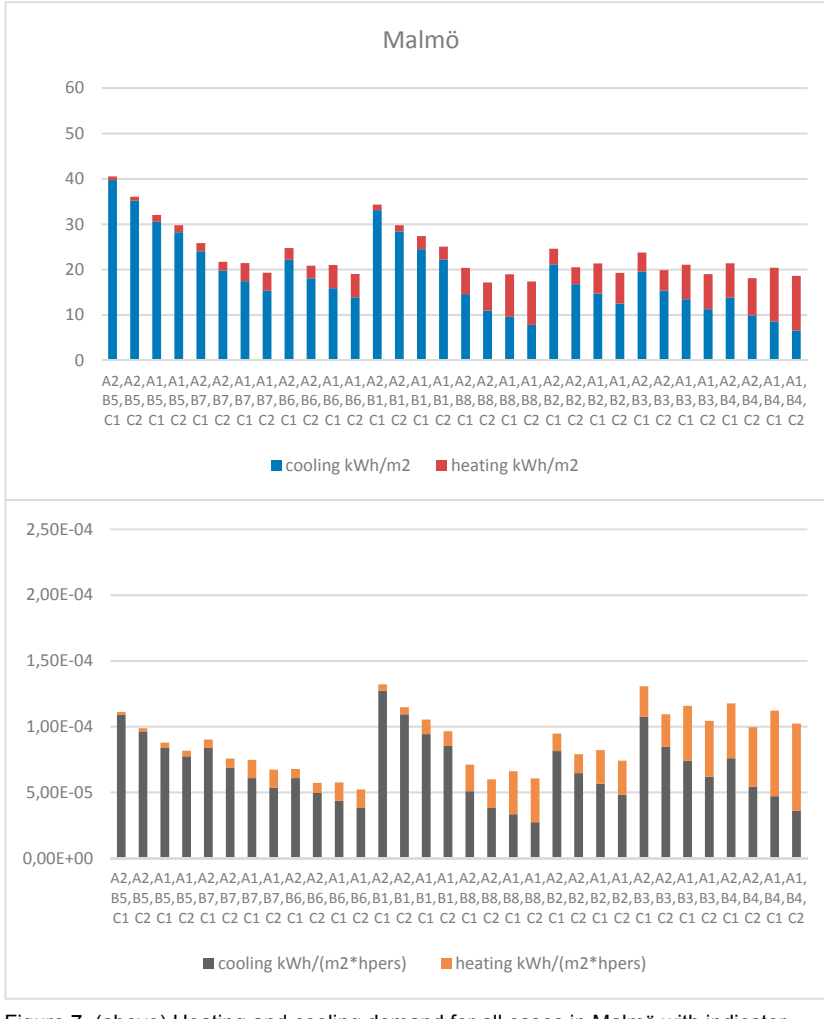


Figure 7. (above) Heating and cooling demand for all cases in Malmö with indicator kWh/m$^2$, year, (Below) heating and cooling demand with indicator kWh/(m$^2$*hpers), and year. Internal heat gains cases B1–B8 are ordered from highest to lowest (left to right). A1 is angled façade and A2 is straight façade. C1 is without blinds and C2 is with blinds. Detailed description of the designations on the X-axis can be found in Table 4 and 5.

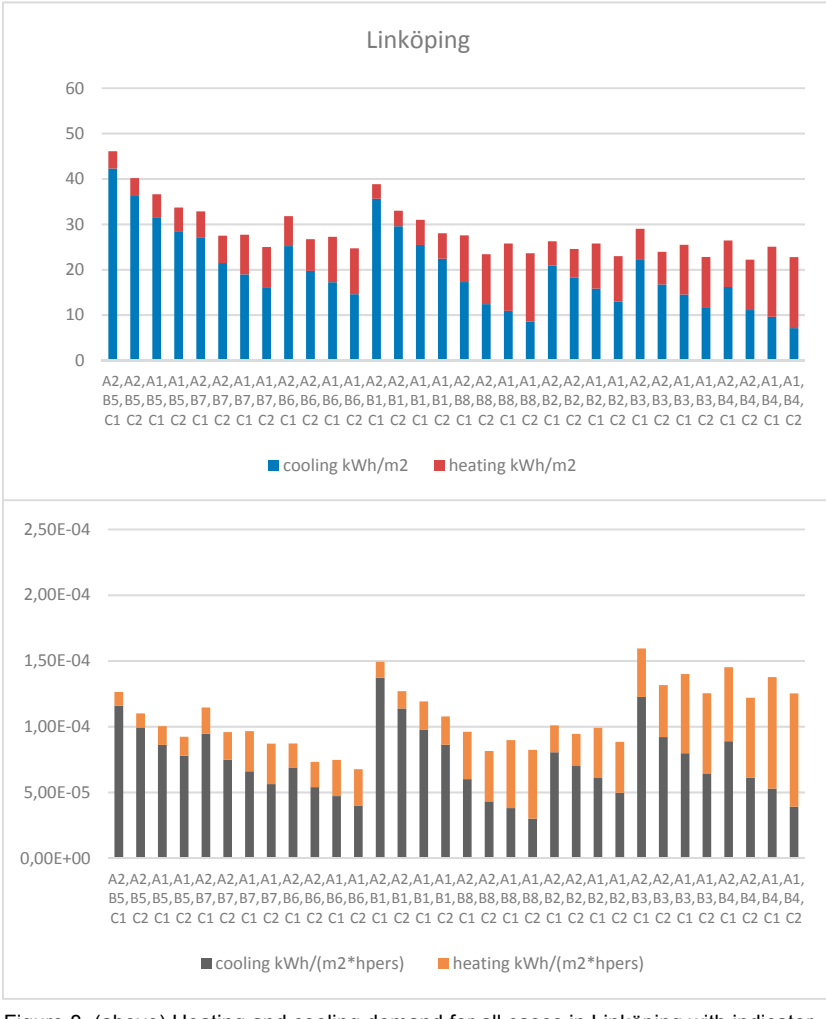


Figure 8. (above) Heating and cooling demand for all cases in Linköping with indicator kWh/m$^2$, year, (Below) heating and cooling demand with indicator kWh/(m$^2$*hpers), and year. Internal heat gains cases B1–B8 are ordered from highest to lowest (left to right). A1 is angled façade and A2 is straight façade. C1 is without blinds and C2 is with blinds. Detailed description of the designations on the X-axis can be found in Table 4 and 5.

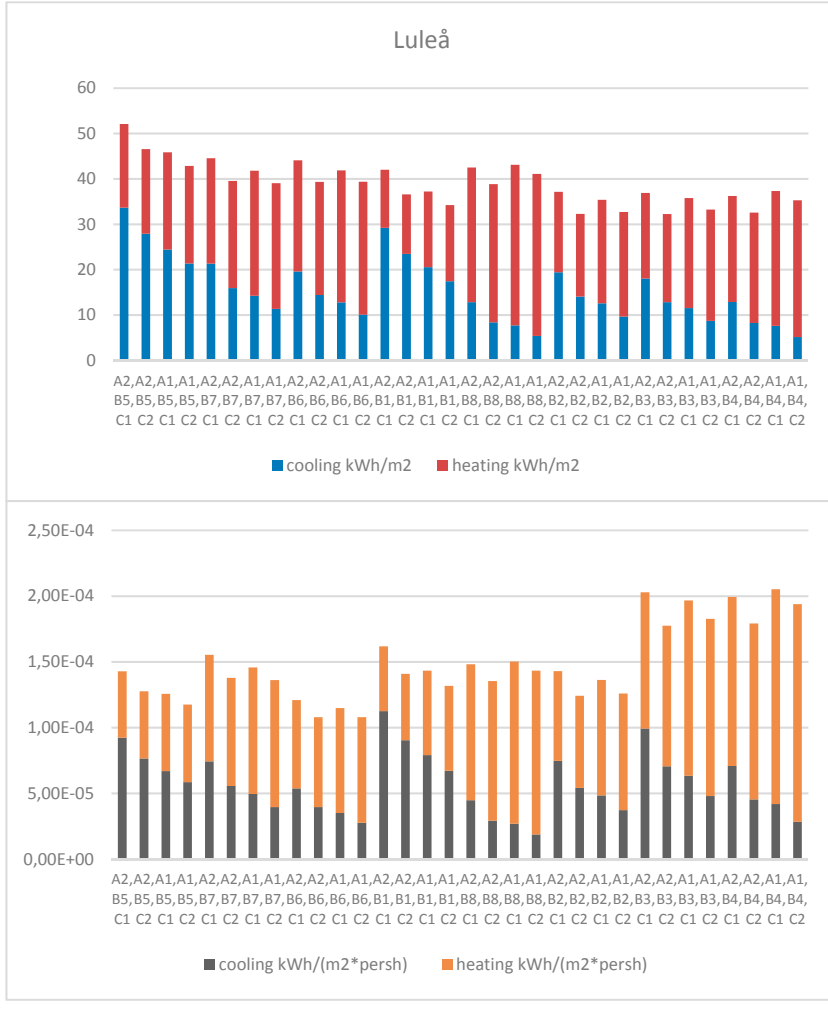


Figure 9. (above) Heating and cooling demand for all cases in Luleå with indicator kWh/m2, year, (Below) heating and cooling demand with indicator kWh/(m2*hpers), and year. Internal heat gains cases B1–B8 are ordered from highest to lowest (left to right). A1 is angled façade and A2 is straight façade. C1 is without blinds and C2 is with blinds. Detailed description of the designations on the X-axis can be found in Table 4 and 5.

# 6. Discussion

As can be seen in the results, user behavior and internal heat gains have a high impact on energy demand both in a retirement home and in an office building in Sweden. A brief overview of the results from the office building show that by decreasing the electricity use and keeping standard occupancy, the energy demand could be reduced by 12–31% depending on location. According to the results for the retirement home, energy losses due to airing was approximately twice as high as the standard values suggests. This could indicate that the standard values need to be adjusted. The high amount of airing in the retirement home seems to be due to two factors. The first factor is that the ventilation system in the apartments is from 1983, has not been maintained as it should be, and does not provide an acceptable air quality which leads to extra airing. The results from the questionnaire of indoor climate and indoor environment conducted in the previous study made it clear that many residents perceived the air as being of poor quality. The second factor is that this kind of airing behavior is something that many of the residents in the retirement home had grown up with and were used to do in their previous homes. A common practice in Sweden, according to the interviews with the residents, was to air your home twice a day by opening windows and doors, even during colder periods of the year. This should not be needed in a building with an FTX type ventilation system. After interviewing the participants, it was also clear that they had received little to no information about their ventilation system from the landlord, which meant that they had almost no knowledge of how it worked. The ventilation system was also located behind a heavy wooden panel, which for an elderly citizen would be very hard to move when it is time to change filters or to adjust the heat from the electrical heating coil. One could argue that it would be beneficial both for the landlord and the residents, if the residents had received more information from the landlord about their ventilation system, and that the landlord changes filters when the time comes. In order to lower the heating demand of the building, the best measure would probably be to replace the ventilation systems with a newer central mechanical ventilation system with heat recovery that hopefully would make the air quality better. This together with informing the residents how the system works and that airing in the manner that they are used to, may not be necessary with that sort of ventilation system, would probably reduce the heating need.

In an office building there are other issues regarding occupant behavior and there is also often a cooling demand, which is uncommon in regular residential buildings in Sweden. As the results show, the cooling demand is not affected very much whether the building is located in the southern or northernmost part of Sweden. This could lead to the conclusion that cooling demand for this building is mainly affected by internal heat gains and not affected much by outdoor climate in Sweden. On the other hand, the results show that heating demand is affected to a higher degree by location in Sweden. If looking at the results from one location at a time, energy for heating and cooling is mostly affected by how high the internal gains are, which is dominated by heat from

electrical appliances. In an office building, the use of electrical appliances is strongly related to the staff, since staff use computers, copying machines, microwaves for heating lunch, etc. This should mean that the less staff, the less energy demand and electricity use. However, in the results we can see that when the IHGs get very low, the total energy demand (excluding electricity use) starts to increase, which is due to the increased heating demand. One must also consider the fact that a building with low occupancy has fewer people utilizing the energy delivered to the building, which could be seen as a waste of energy. As stated in the results, the IHGs yielding the lowest heating and cooling demand are case B8 in Malmö and case B2 in Linköping and Luleå. All of these cases of IHGs have low electricity use, B8=38.5 kWh/m$^2$ and B2=35 kWh/m$^2$, and rather high occupancy, B8=12.4 kWh/m$^2$ and B4=11.3 kWh/m$^2$. This leads to the conclusion that there should be an optimum for every building to strive for when it comes to internal heat gains in order to have as energy efficient building as possible. In building projects, it should therefore be good practice to investigate what level of internal heat gains the building should aim for in the use phase, taking occupancy and electricity use into consideration, in order to have as low energy demand as possible. This is instead of how it is today, when in the beginning of a project, standard values for occupancy and electricity use are used as input in calculations and/or simulations, and it is only in later stages that more accurate input for occupancy and electricity use is used. In early stages of a building project, it is of course difficult to know how many people will be working in the building and how they will use the offices, but if it is decided early on in the building project what the optimal internal heat gains are for the specific building, the rest of the design can use that as a base. For example, instead of designing a building and then using standard user input data for the energy simulations/calculations, a quick study could be done with a range of different IHGs to see what level of IHGs, including heat from occupants and electrical appliances, yields the least energy demand for the building in terms of heating and cooling. Then, in the following steps of the design phase, designers will know how many people the building should be designed for. However, in order for this to work and be usable in building projects calculations and/or simulations must be easy to do, so maybe the standard values for IHGs should be per person instead of per m$^2$ as it is today. Of course, this could easily be translated from today's standard values, but in order to make it easier for the people doing the energy calculations, IHGs could be stated in kWh/pers directly in the standards. The IHGs of case B1 is the case using standard values for user input data. When looking at the results we can see that if we would apply the process described above in the design phase and design the building to hold the number of people using the amount of electricity as in IHGs case B8 in Malmö, the sum of energy demand for heating and cooling could be decreased from 22 to 14 kWh/m$^2$ if comparing the building with the same façade design, solar shading, and orientation. If the same comparison is done in Linköping, but between IHGs case B1 and B2, the sum of energy demand for heating and cooling can be decreased from 14 to 9 kWh/m$^2$. However, in Luleå the sum of energy demand for heating and cooling is only decreased from 6.5 to 5 kWh/m$^2$ between IHGs case B1 and B2, which

has much to do with the higher heating need in Luleå. This means that for a building located in the northern parts of Sweden the standard values for IHGs are actually quite good from an energy demand point of view, while in the more southern parts of Sweden it would be better to design the building for other IHGs.

Comparing the results from the two models of the retirement home BES-ref, which uses standard values, and BES-v.2, which uses empirical data as input, shows that using the standard values for user input data cannot accurately predict real energy use in the building. The BES-ref model underestimates the needed energy for space heating and compared to BES-v.2 it shows a heating demand of 24% less. This is probably due to the fact that the standard values for user input data are gathered and developed from regular Swedish homes, and not specifically housing with elderly residents. In this study it could be seen, as previously described, that the residents are at home longer periods of the day, use less electricity, and air a lot more than the regular population in Sweden. Since all these behavioral aspects affect the energy use in a building, standard values for more types of buildings should therefore be developed to decrease the energy performance gap. By the time this is written, Sveby has user input data for office buildings, schools, and residential buildings. The author of this thesis suggests that user input data should also be developed for retirement homes and also other kinds of public buildings. One thing that needs to be addressed is that when the younger generations of today grow old, they will probably not act the same way as elderly people today. As stated before, some of the residents at the retirement home said in interviews that the reason they aired was because they had been taught to do so and did it in their previous homes. This is a practice which, according to the author, is not as widespread among younger generations. This means that these user input data must be regularly updated so that better predictions of energy use can be made in building projects. They are regularly updated today but the author of this thesis would claim that they are not updated often enough.

Here is one difference between office buildings and residential buildings. When residential buildings are planned it is difficult to anticipate how many or how few people that will live in the building. This means that in a building project for a residential building, it is most convenient to use the standard values for user input data, and from that try to design as efficient a building as possible. On the other hand, when planning an office building, the real estate owner, or businesses using the building could have more to say about how many people should be allowed to use the building and could therefore try to find the “optimal” internal heat gains for the building as described above.

One thing that has not been addressed so far in this discussion is the choice of method and how it can be developed. This study has been done mainly with energy simulations. In the case with the retirement home, it was conducted on an existing building where much input data could be gathered on site. There are always uncertainties in collected data, and this is also the case in this study. There is the accuracy of measuring equipment used, in some cases the occupants had moved the measuring equipment to other locations in the rooms of

their apartments, and how accurate the residents' logs are in the time diaries. There are also other uncertainties, such as accuracy of drawings, U-values, measurements of airflows, material parameters etc. Then there is also the validation of the model, and in this case, it was not possible to validate against energy use since the central heating plant was connected to the entire block and not the single building investigated. This meant that validation had to be made against indoor temperature and $CO_2$ level. In retrospect it would have been very good to also be able to validate against energy use. Despite these uncertainties, the results are indicative and does have significance. When it comes to the office building no measurements were made since the building is only in the planning stage. What could be argued however is how well the different cases of IHGs correspond to real-life scenarios. Are they predicative of future scenarios or will we use buildings in a completely different way?

One thing that could have a large impact on the results, is if the model were to have individual office rooms instead of office landscapes. If this were the case, it is very likely that the cooling demand would increase, which would impact the results. In the author's opinion, the method of using time diaries together with measurements is a great way to find behavior affecting energy use, at least in residential buildings. It can also be used to create more accurate building energy simulations of existing buildings and to develop better standard values for user input data. The method is however very time consuming which is an obstacle for it to be used in the building industry. If it could be developed so that it is less time consuming it could open up the use for it within the industry.

When comparing energy efficiency with two different indicators we can see that when using kWh/m$^2$, it is more beneficial to have less internal gains, and when using kWh/m$^2$*hpers, it seems to be more beneficial to have a high occupancy and low electricity use in order to get as low cooling and heating demand as possible in the building. The indicator kWh/m$^2$ does not take into account the actual use of the building and therefore it almost only depends on the technical aspects of the building, such as U-values, glazed areas, ventilation and heating system. This means that if the internal gains are low, less cooling will be needed, and the total energy demand will be low, unless the IHGs are so low that the heating demand start to increase more than the cooling demand is decreased. According to this study, this only happens in the cases with the lowest internal gains. When it comes to kWh/m$^2$*hpers it considers both the technical aspects of the building and also the occupancy. The results show that when using this indicator, IHGs case B6 is perceived as the most energy efficient in all three cities. Case B6 has the third highest IHGs in the study, having high occupancy but low electricity use. Cases B3 and B4, which have the two lowest IHGs, become the worst from an energy efficiency point of view when using kWh/m$^2$*hpers in Linköping and Luleå, closely followed by B1 in Linköping, while in Malmö B1 is the worst closely followed by B3 and B4. B1 uses the standard values for user input data while B3 has less occupancy but normal electricity use and B4 has low occupancy and low electricity use. This means that it is perceived as good practice to have either prolonged hours of

use in the building or more people working in the building. The building could be seen as more area-efficient and also more energy efficient, since the delivered energy is utilized by more people. One problem with this indicator however, as stated by [19], is that it exponentially overestimates the effect of the space and person hour efficiency. Regardless of this the author believes that it would be good if some sort of indicator that includes occupancy hours was used instead of just kWh/$m^2$ in the future so that a measure of space efficiency and the utilization of delivered energy was taken into consideration. One thing that must not be forgotten is how a higher occupancy affects the building in terms of wear and tear. Can there be a way for real estate owners to gain anything from increasing the use of a building or will there just be more expenses due to higher maintenance costs? Another thing that can also be discussed is if we were to spend more time outside of our homes during evenings or weekends, for instance in an office building which is let out for some other activity during these times. Then the energy that is delivered to our homes will not be utilized in the same amount, which in that case might render our homes to be seen as less energy efficient. When this paper is written, there is an ongoing pandemic of COVID-19. This has led to a lot of people working from home instead of going to their offices. When data of energy use from office buildings can be gathered for 2020, we might see a decrease of energy use there if the owners have actively decreased heating and cooling needs since almost no one has been in the buildings. The question is, will we see more people working from home even after the pandemic is over? It has been the trend for some time that people are working more from home even before the pandemic and now people have also been forced to learn how to use digital tools for meetings and other work-related things, which makes it even easier to work from home. If this comes to pass, we might need to have buildings that are more adaptable in our use of them. Adaptable ventilation systems, adaptable heating and cooling systems, easy to change layout depending on the number of employees, etc. But maybe everything does not come down to the buildings themselves in order to have energy efficient buildings. We who use them might also have to become more adaptable, put on that extra sweater when we are feeling cold instead of just complaining about the indoor temperature, and draw the blinds when it gets a little too hot or the sun shines on our screens.

# 7. Conclusions

Conclusions of this thesis is presented in three sections divided by the research questions.

*How does user behavior and different levels of IHGs affect energy demand in a retirement home and an office building in Sweden?*
In the retirement home in this study, three behavior patterns have been identified as affecting heating demand the most. These are airing, using less electricity than the average population, and being at home for longer periods of the day than the average population. Staying at home and using less electricity is linked to the internal gains, and in this case the results show that even though the residents are at home for longer periods of the day than the average population, the heat from the residents is not enough to make up for the heat loss due to airing and the lower heat emitted from electrical appliances.

According to the results in this study, the factor that affects energy demand the most in an office building is electricity use, which is closely linked to occupancy, both of which affect the IHGs. The case that had the highest IHGs also yielded the highest total energy demand for heating and cooling in all three investigated cities. The most effect from lowering the IHGs can be seen in Malmö, which is the most southern of the three cities.

*How is energy demand affected in a retirement home and an office building in Sweden, when using empirical and/or probable future values of IHGs and behavior compared to today's standard values?*
Comparing the model that used standard user input data, Bes-ref, with the one that used actual input data gathered through measurements and time diaries in the retirement home, Bes-v.2 showed that standard user input data does not correspond well to how people living in retirement homes act. The standard user input data should therefore be developed for more different types of buildings than they are today.

In the office building the comparison was made between a case using standard user input data and several different cases of possible future IHGs. The results show that much can be gained simply by decreasing the electricity use for office equipment and lighting. So, decreasing electricity use is not only good in itself, but it also has a positive effect on the overall energy demand.

*How is energy efficiency perceived when using two different indicators, if changes in IHGs and user behavior occur in a retirement home and an office building in Sweden?*
When using the Swedish standard indicator for energy efficiency, $kWh/m^2$, in the retirement home, Bes-ref was perceived to be the most energy efficient. This was despite Bes-v.2 having lower electricity use. Since there is no cooling

in the building, the low electricity use affects the heating demand in a negative way since it gives off less IHGs. However, when the indicator was changed to kWh/($m^2$*hpers) which includes hours of use, Bes-v.2 was perceived as the most energy efficient. This is an effect of the increased occupancy hours when using the empirical input data for the model.

When using kWh/$m^2$ in the office building, the cases with low IHGs are perceived as more energy efficient. However, if using kWh/($m^2$*hpers), the cases with low IHGs and primarily low occupancy hours, are perceived as the least energy efficient. Nonetheless, it is not the cases with the highest IHGs that are perceived to be the most energy efficient with this indicator, but it is case B6, which has the third highest IHGs. This is because B6 has high occupancy, regular office hours plus evenings and weekends, but low electricity use.

*General conclusions*

For new office buildings it should be of highest priority to have as low electricity use as possible to bring down the internal heat gains and, in this way, lower the cooling and total energy demand. The author would also recommend that quick parametric studies using different levels of internal heat gains be conducted in the project stage of new office buildings. This could help to decide how many people the office should be designed for. In the retirement home there is a large offset in the simulated results when using standard user input data compared to using user input data gathered on-site. This would suggest that standard user input data cannot be used for a retirement home and that the user input data must be developed further. As of today, there are standard user input data for office buildings, schools, and residential buildings. These need to be extended to include more different types of buildings, such as retirement homes. It is also important that these standards are continuously updated since our behavior changes over time. For instance, it is highly unlikely that the next generation to come to a retirement home will act in the exact same way as those that are there now. Also, technology changes over time too. For instance, LED lighting should be considered in Sveby's standardized user input data, since the technology made a huge entry into the market just after Sveby came out with their first versions of default values. The question of which indicator for energy efficiency should be used must be further investigated, since kWh/$m^2$ seems to promote buildings with low occupancy due to low occupancy often meaning low electricity use and therefore low internal heat gains. Low occupancy could mean that buildings are not utilized in an efficient way and should therefore be considered inefficient. Exchanging or combining kWh/$m^2$ with an indicator which also takes occupancy into consideration is therefore recommended.

# 8. Further work

As stated in section 1.3 the overall research project is supposed to highlight driving forces and obstacles for implementation of energy-efficient solutions in city district development. To reach the overall goal, three more studies have been planned. The first study will investigate drivers and obstacles for implementation of energy efficient innovations in new building projects. Hopefully this will shed light on both issues and good examples in the process of building projects, so that the obstacles can be avoided, and the good examples reused and/or developed further in future building projects. The second study will be on indicators of energy efficiency, but instead of looking at a building level, the study will look at indicators on a city district level. The third study will be a systems analysis on a city district level. Calculating and simulating different energy solutions for a city district, and also possibly study power demand, and how peaks in power demand can be decreased in a city district like Ebbepark. If there can be energy exchange between different buildings such as offices and residential buildings, it might be possible to cut power peaks in the local energy system.

To study what would happen if the model of the office building was modelled with individual office rooms instead of open office landscapes, would also be of interest. Running the same simulations as in Paper II will probably yield a higher cooling demand. The increased cooling demand might change which case of IHGs will be the most energy efficient. Combining that study with Paper II could give useful knowledge on the difference in energy demand between using open office landscapes and individual offices.

The author of this thesis would also claim that it should be of importance to investigate if electricity use deriving from staffs and occupants in buildings should be included in the Swedish legislations of energy use, and in that case how.

How a high amount of airing and low electricity use affects a building's energy system, is dependent on the surrounding energy system and what sort of energy carriers that are used for heating and electricity. A future study could investigate the effect on energy and power demand depending on choices of operating strategy and occupant behavior, and also how this affects a building's GHG emissions. By using average values for GHG emissions in Sweden, the conclusion is that it is better with high electricity use and a low heating demand than vice versa. However, considering problems with power demand and a systems view on electricity and district heating in power and heating systems, other conclusions might be drawn.

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**Papers**

Associated papers have been removed in the electronic version of this thesis.
For more details about the papers see:
http://urn.kb.se/resolve?urn=urn:nbn:se:hig:diva-35507