Reducing Energy Use of an Electric Floor Heating System and analyzing Thermal Comfort and Heat Transmission when using different Control Strategies

Analysis of a bathroom in a residential building located in Gävle, Sweden

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Abstract

The main purpose of this research was to investigate a possibility of reducing energy use in a bathroom equipped with an electrical floor heating system. Electricity is an expensive mode of heating, but can be very cheap and easy in installation and maintenance, especially when comparing to a water based underfloor heating system. That's why its popularity is raising amongst houseowners. Changing heating controller is a simple and cheap way of reducing energy use in the case of an electrically operated heating system. For this purpose three different controllers: ON-OFF, proportional-integral (PI) and PI linked to a schedule adjusted to occupancy were investigated in this paper. Main method used to analyze energy consumption and thermal comfort provided by control strategy was the building energy software IDA Indoor Climate Energy (ICE) 4.6. All results were a direct product of those simulations and the applied conditions. Three testrooms were constructed all with very different building structures to analyze the effects of thermal transmittance (U-Value) on energy use. Results showed that thermal comfort was best provided by PI regulator and PI linked to a timer during scheduled occupancy. The least satisfying results gave the ON-OFF. Energy use can be lowered by 8%, 15% or 28% when switching from ON-OFF to a timed PI controller. This means there is a potential of reducing energy by almost a third in an current households bathroom by simply switching to a newer more adaptive controller strategy. An even higher saving of 48% is achievable when lowering U-Value by additional insulation of an external wall (assuming the bathroom has just one external wall) and changing to a scheduled PI regulator.
Preface

This thesis is submitted as a fulfillment of requirement for completing a bachelors degree of science with major in energy systems at the University of Gävle. The work was done in the spring of 2014. The text was solely written by the author, however theory is based on the research of others.
Writing this thesis was challenging but I learned a lot in specific about building energy software. I hope this knowledge and experience will be helpful in my later work life.
I would like to thank my supervisor Mathias Cehlin for supporting and guiding me all along the way. His guidance helped me in all the time of research and writing of this thesis.
Further I wish to express my gratitude to the company SWECO in specific to Peter Hansson who was so kind to provide me with a thematic I could write about and giving me valuable feedback.
1. Introduction

1.1 Background

The threat of global warming puts many countries under pressure of reducing energy use and CO2 emission. Fossil fuels contribute to global warming and so the use of them must be minimized. Sweden has the lowest share of fossil fuels which is about 35% (see Figure 1) within the International Energy Agency (IEA) Countries, which are Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Republic of Korea, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States.

Nowadays electricity production is almost CO2 free in Sweden, since hydro and nuclear power can account up to 92% of total annual electricity generation (International Energy Agency 2008) (see Figure 2).

![Energy-Related CO2 Emissions per GDP in Sweden and in Other Selected IEA Countries, 1973 to 2010](image)

* * excluding Luxembourg and Norway throughout the series, as forecast data are not available for these countries.


Figure 1: CO2 Emission in Sweden and other IEA countries 1973 to 2010 (International Energy Agency 2008)
The Figure below shows the Swedish energy consumption by sector in 2007. "These were published on p. 54/55 in the report ‘Energy in Sweden 2008’ by Swedish Energy Agency (Energimyndigheten)” (Phineas 2009). The numbers are compared to values from 2010 and show just slight variations. These variations are affected by temperature conditions, as for example a colder winter results into a higher energy demand for heating.
Sweden has the second largest space heating requirements in the IEA, due to the cold climate, low population density and long transportation ways (International Energy Agency 2008). Therefore it is essential to reduce energy use and increase efficiency of heating systems in the space heating sector.

The main heating supply arrives from district heating network and private heat pumps. 77% of all apartments are heated by district heating (International Energy Agency 2008). The rest of housing may be heated by i.e. heat pumps and electrical heating systems. Most commonly used are radiators, but within the last 20 years applications of floor heating systems have increased significantly. 30% to 50% of all residential buildings in Germany, Austria and Denmark are equipped with floor heating. First commercialized floor heating systems were introduced 1930 by Lyod Wright in the United States. Europe followed shortly in the mid 60s using metal pipes to distribute hot water below the floor surface. Due to a lack of knowledge regarding sufficient house insulation, floor heating got a bad reputation, because of the high temperatures needed to compensate the high heat losses.

With time floor heating systems were improved, nowadays plastic pipes of PEX-type are mainly used (Olesen 2002). A few decades later floor heating is used in many countries, mainly Germany, Switzerland, Austria and the Nordic countries for its energy saving potential and indoor comfort (Jing et al. 2010).

The traditional floor heating system utilizes a "wet system", which distributes low temperature water within pipes cast in 6 to 30 cm below screed or concrete. This though results into a thermally "heavy" floor, which is very cost intensive in installation and slower in reaction when adjusting room temperature (Danfoss Heating Solution 2011). An electrical heating system instead is very easy to install and usually directly below the floor surface material around 2 cm. An electrical floor heating system can be installed on almost any floor construction and is very fast adaptable to change room temperature. This ensures a room temperature that is significantly closer to the desired temperature compared to a heavy wet heating system (Danfoss Heating Solution 2011).

Anyhow there are some disadvantages using electrical floor heating. One of them is that it is comparably expensive to use electricity for heating and that not all electricity comes from renewable resources. This makes it even more important to reduce energy use. One way is to apply new modern controllers like Proportional Integral (PI) instead of ON-OFF thermostats. A step further is to couple the controller to a schedule so a comfortable indoor temperature is just supplied when occupants are actually residing in the room. This way one avoids heating up a room unnecessarily in the night or during the day when all occupants are for example at work.

Studies have been done investigating green scheduling, simulations strategy analysis and individual room control methods (e.g. Olesen 2001, Good et.al 2005). This previous studies though all researches a water based floor heating system and therefore also involves some research about efficient heat pumps. None of those research papers examines electrical infloor heating with the possibility of energy reduction by turning the heating system off during for example the night. One paper found using electrical floor heating discussing the prospect of peak power reduction by better load management (Truong et.al 2012). Other scientific articles propagate a new floor substance called phase change material (PCM) (Lin et.al 2004 and Mazo et. al 2012) to reduce energy use. This material has properties of storing heat and therefore could be charged during off peak hours when using an electrical floor heating system. There was no research found examining the possibility of using an electrical floor heating system linked to occupancy for a more efficient and less energy consuming heating strategy.
1.2 Aims and Objectives

The aim and objectives of this paper are summarized into the following points:

- *Investigating the possibility of minimizing energy use through control strategy in a bathroom using an electrical floor heating system*

- *Analyzing the effects of different control strategies on thermal comfort*

- *Visualizing heat transmission through building components*

1.2.1 Limitations

The research aim and objectives are subject to limitations. Achieving the aims, simulations with a building energy software were run and specific conditions applied. The simulation was conducted with climate conditions found in the city of Gävle in Sweden. Certain default values, as for leakage and thermal bridges were used from the software's resources. Certain factors like air velocity, humidity and vertical air temperature difference were neglected, since they cannot be modeled or have very little impact on the result. Establishing thermal comfort can be very extensive, therefore decisive aspects were reduced to operative and floor surface temperatures. 
2. Method

2.1 Introduction

Primary method used in this paper is a building energy simulation program. The one chosen to be used in this paper is IDA Indoor Climate and Energy (ICE) 4.6. It is used to produce all results for each individual model and its different boundary conditions. To build realistic models it was necessary to collect information about building envelopes, ventilation rates and of course floor heating systems by scientific articles from databases like www.sciencedirect.com, several electronic sources and a book. These informations were used to provide a better knowledge of the system and to explain why certain settings or conditions were used in IDA.

2.2 Building Energy Simulations (BES)

Enquiring energy performance of a building is usually very complex and difficult to obtain. Therefore building energy simulations softwares examine the dynamic interaction of heat, light and mass (air and moisture) within a building. This is done to predict and investigate energy and environmental performance as it is dependent to climate, occupants and heating system, ventilation and air conditioning (HVAC). Generally building energy modeling is described as "the process of creating a computer-based analytical simulation that provides a way to predict the performance a virtual building, including its comfort, energy consumption and efficiency, and life cycle costs" (Eisenhower 2012). Building simulations are very important tools because of their significant role in reducing energy consumption of buildings. They are cost inexpensive compared to time consuming experiments, allow simulations of various energy alternatives and it gives one the opportunity of testing and optimizing a building before it is actually built. Some examples of what a building energy simulation can accomplish is given below:
- Sizing of equipment needed to provide desired thermal condition
- Establish how different equipment and design elements interact
- Optimize a building design or operation strategy
- Perform real-time simulation
(Eisenhower 2012)

Nowadays there are many simulation tools available, this paper made use of the most common software used in Scandinavian countries which is IDA Indoor Climate and Energy (ICE) 4.6.

2.2.1 IDA Indoor Climate and Energy (ICE) 4.6

IDA ICE 4.6 is a simulation tool that simulates a building performance in regard to energy consumption and thermal indoor climate. It can model a building with its systems and controllers to produce an accurate result regarding lowest energy use and optimal thermal comfort. All resulting data has been compared well with measured data and therefore can create precise results. The programs transparency gives users the opportunity to check all underlying equations and change all variables to produce an even more realistic detailed dynamic building performance (EQUA-IDA Indoor Climate and Energy 2014).
Possibilities offered by using IDA ICE are therefore realistic HVAC and plants incorporation, complex control strategies and description of building envelope. Possible outcomes may be data showing CO₂ levels, heat fluxes, temperatures, air quality, energy and all these can be individually produced for every hour of a year or as a total annual result.

2.2.2 Limitations in IDA ICE
Using BES software involves always limitations. In this particular case using IDA ICE the limitations involve i.e. a uniform air temperature distribution. This means that the air temperature is calculated to be at any point in the room the same. This for example excludes down draft from windows, which is known to be one of the bigger issues using floor heating in a room with large or single and double glazed window areas. Infiltration and wind pressure coefficient were used from default settings in IDA, which is supposed to consist of common mean values, but can be effecting the results if changed to different measured values.

2.4 Validation
Articles found on the database-searchportal sciedirect were peer reviewed and therefore can be trusted, as well as the referenced book. Information which was collected from other websites may be corrupted even though that the content was compared to other online sources. Simulating a building performance using a computer program involves errors, since the real case complexity exceeds the programs capability. Due to those simplifications had to be made. For a more detailed description of possible errors and flaws in IDA ICE it is advisable to read the IDA ICE CIBSE-Validation Report (2007) or refer to the software websites recommended validation reports (see EQUA-IDA Indoor Climate and Energy Validation and Certification 2014).
3. Theory

3.1 Thermal Comfort

Certain requirements and properties need to be taken into account when providing an acceptable thermal comfort which is described as “that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 2009, chapter 9). The main parameters for providing a comfortable thermal environment are air temperature and mean radiant temperature. The combination of those two gives the so called operative temperature (Oleson B.W. 2002).

It is common to use Fanger's comfort index, which is a function of predicted percentage of dissatisfaction (PPD) and a predicted mean vote scale (PMV) to evaluate thermal conditions. Fanger's index takes into account all attributes influencing the thermal sensation on an occupant like air and surface temperatures, draughts and humidity’s. (Although air speeds cannot be simulated with IDA and therefore is not taken into account). PPD can be chosen as a resulting output for IDA, but since it gives unrealistic values for this research problem it will not be used in future reference.

Instead a main focus was made on operative temperature and floor surface temperature for evaluation of thermal comfort. Recommendation for operative temperatures at head height in a residential bathroom is min 20 °C, floor surface temperature shall be between min 16° and max 27° C (Boverket 2012, p.206) where optimal floor temperature is 24°C. The figure below shows the percentage of dissatisfaction caused by too warm or too cold floors for occupants wearing light indoor shoes. It is favourable to maintain floor temperature at a level that the percentage of dissatisfaction is below 10 %.

![Figure 4: Local thermal discomfort caused by warm and cold floors (Olesen and Parsons 2002)](image)

However the thermal sensation also strongly depends on clothing and activity of the residents. Wearing jeans and a t-shirt gives an approximate clothing level (clo) of 0.5. Depending on the activity level the human body emits heat which is measured in metabolic rate (met) where 1 met equals 58 W/m². Two tables can be found in the appendix I which show a more detailed numeration of clothing- and activity levels. If
using a well insulated building heat emitted by occupants can have significant impact on the heat balance and therefore energy use of the heating system. Another factor determining thermal comfort is draft. Draft can be caused by too high ventilation rates, leakages or large windows with high U-values. Usually cold draft from surfaces is compensated by radiators placed beneath them. Using floor heating imposes a risk of cold draft. However it can be determined if a radiator is needed. Resulting air velocities from surfaces stand in relation to window height, U-value and outside temperature. Assuming an indoor temperature of 21°C gives a max acceptable air speed of 0.18 m/s. If now a outside temperature of -12°C is assumed following figure was established by Olesen (2002).

![Figure 5: Downdraft from cold surfaces (Olesen 2002)](image)

3.2 Building Physics

Heat transfer is known as the process of which energy is transported through a building structures of different temperatures. There are three modes of heat transfer: Conduction, Radiation and Convection. Conduction means heat is being transferred through the vibration of molecules in the material. Thermal radiation is a result of temperature difference between bodies. This mode can even propagate in a vacuum and does not require a material medium. Thermal radiation makes out the greatest part of heat supplied by floor heating the rest is due to conduction. Convection is due to the flow of a fluid, mostly air or water in building physics (Hagentoft 2003 p.4). One dimensional (1D), steady state heat conduction is expressed simplified by the law of Fourier:

\[ q = -\lambda \Delta T \]

![Figure 6: One dimensional, steady state heat flow through a material](image)
where heat flow is denoted by \( q \) [W/m\(^2\)] and thermal conductivity which is specific for each material by \( \lambda \) [W/mK].

Multilayered structures in series can be handled with the help of a resistance network in the case of 1D and steady state flow. The resistance parameter for each material becomes:

\[
R = \frac{d}{\lambda}
\]

where resistance stands for \( R \) [m\(^2\) K/W] and heat flow comes to:

\[
q = \frac{(T_+ - T_-)}{R_1 + R_2 + R_3}
\]

with \( q \) [W/m\(^2\)] (Hagentoft 2003 pp.15-18).

Heat flow \( q \) can be rewritten as:

\[
q = U \ast (T_+ \ast T_-)
\]

where \( U \) [W/m\(^2\) K] is the thermal transmittance of the wall and is defined as:

\[
U = \frac{1}{R_{se} + \sum_{i=1}^{N} R_i + R_{sl}}
\]

with \( R_{se} \) [m\(^2\) K/W] and \( R_{sl} \) [m\(^2\) K/W] as external and internal surface resistance which accounts for both convective and long wave radiation between the surrounding and the wall surface. As standard values 0.04 m\(^2\)K/W and 0.13 m\(^2\)K/W are normally used as \( R_{se} \) and \( R_{sl} \) respectively (Hagentoft 2003 p.57).
3.3 Building recommendations

Using a floor heating system in a building has different requirements than using an average radiator network. First of all as a thumb rule it is recommended to insulate the ground below the cellar or the slab on the ground with at least 250 mm of insulation. Using floor heating most efficiently requires a small resistance above the floor heating pipes but a large resistance beneath them. Therefore materials which have good insulation properties should never be layered above a floor heating system.

If the floor heating system now works as planned the air temperature should be decreased. Otherwise energy use will always be larger than using radiators. The amount of ground insulation determines how much the indoor temperature can be decreased.

Also floor surface material regulates the length of heating demand during a year. If for example tiles are used as surface material, the floor might feel cold if floor heating is not in operation, this will increase the period of heating demand.

An advantage of radiators is that they can prevent the so called down draft. Air cools down at the window surface and flows along the wall down to the floor. When installing floor heating systems it is therefore recommended to use windows with a U-Value of 1 W/m²K (Energimyndigheten, Konsumentverket, Formas & Boverket).

Wall and floor construction standards and suggestion can be found on the website www.isoover.se. The structures mentioned on the website are partly used in the IDA model.

3.4 Heating Controllers

To regulate the heating output of a floor heating system a controller is needed. The two most common devices used are proportional-integral (PI) and ON-OFF controller. It is one of the simplest regulators since it just can regulate between on and off. PI therefore is one of the most widely used algorithm control applications. It adjusts more flexible to change in heating demand. Further it controls heating output to be anything between 0 and 100%. This gives a more constant room temperature. ON-OFF thermostats are designed to let the temperature drop by one or two degrees before they turn on again. PI instead can supply all the time heat at a low power, which will not make the temperature drop as much.

Figure 8 shows a control diagram for both ON-OFF (a) and PI (b) over time.
3.5 Parallel wall layers (Calculations)

In IDA ICE 4.6 it is just possible to build wall layers in series. Therefore parallel wall constructions need to be remodeled beforehand to fit the input requirements. A materials property is defined by heat conductivity ($\lambda$) [W/m,K], density ($\rho$) [kg/m$^3$] and specific heat ($c_p$) [J/kg,K]. These factors determine i.e. its thermal resistance ($R$) [m$^2$,K/W] and the overall heat transfer coefficient ($U$) [W/m$^2$,K]. The following calculations used in this paper will form a new material, which is a mix of the two parallel components. The resulting mix will have different values for heat conductivity ($\lambda$), density ($\rho$) and specific heat ($c_p$). This material further then can be used as one homogenous substance in IDA.

Following figure shows an example of a parallel floor structure which was used to establish the new mix material. Material b has properties $\lambda_b$, $\rho_b$ and $c_{p,b}$. Material a therefore follows with $\lambda_a$, $\rho_a$ and $c_{p,a}$.
Defining new material properties:

\[ \lambda_{\text{new}} = \frac{x_1}{X} \cdot \lambda_b + \frac{x - x_1}{X} \cdot \lambda_a \] (1)

\[ \rho_{\text{new}} = \frac{x_1}{X} \cdot \rho_b + \frac{x - x_1}{X} \cdot \rho_a \] (2)

\[ c_{p \text{ new}} = \frac{x_1}{X} \cdot c_{p b} + \frac{x - x_1}{X} \cdot c_{p a} \] (3)
4. Model Description

4.1 Introduction

To accomplish a more accurate result the testroom (bathroom) was divided into models A, B and C. All models were set up with different properties, which similar can be found in current residential buildings in Sweden. Models A and B show an apartment building with two storey’s and a basement. Model C refers to a newly build single family home without cellar. However some properties and boundary conditions were set for all room models to be the same. A further description of these follows.

4.2 Climate and Location

The test rooms were situated in a suburban area in the city of Gävle in Sweden. The climate data was taken from the national climate institutions Sveriges meteorologiska och hydrologiska institut (SMHI) records. The climate file describes the mean of the years from 2009 to 2013. A graph showing dry bulb temperature, duration diagram and sun radiation for a whole year is attached in appendix III.

4.3 Room size

The test room had a floor size of 5 m\(^2\) (2 m x 2.5 m) and a height of 2.6 m. The glass measurements of the window (optional) were 0.7 m x 0.5 m. The door was located on the opposite wall of the window. All bathroom measurements are shown in figure 10.
4.4 Ventilation

For this paper it was assumed that all testrooms were equipped with an exhaust ventilation device subtracting a constant air volume of 10 L/s (recommended by Boverket 2011, p.63). Supply air is most likely to be provided through the door and therefore from the other adjacent rooms. To simplify this in the simulation a supply ventilation terminal was added, feeding the bathroom with 20°C air at a pace of 10 L/s. The energy used for ventilation will be neglected in the results.

4.5 Heat loads and schedules

To perform a realistic simulation, occupants and light has to be included. These factors have significant impact on the heat balance for a well insulated building. The occupants residing in the room were clothed with light indoor clothes (e.g. long pajamas) at 0.4 (± 0.4) clo and 1 met activity level, which is equal to a rested sitting position. There was always just one person at a time in the bathroom and the schedule for occupancy was estimated for a family which is from Monday to Friday between 8 and 16 o’clock not at home. The busiest time was in the early morning hours and after 16 until 22 o’clock. The light had a power output of 50 Watt and was turned on just during occupancy. The schedules can be found in appendix II.

4.6 Building and Construction

The following figures shall give a better perception of the building modules used for the simulations. They show enlarged the building compositions for walls and floors and the location of the simulated model. The following construction details were simplifications, they do not represent a detailed and realistic building composition. In this paper just materials which had effect on heat balance were taken into account. Figure 11 shows an older apartment building, which was additionally insulated to lower heat transmission. Figure 12 displays a newly built family house which is built after current building standards. The roof to the attic was build with a 50 cm thick insulation layer for all models adjacent to the attic. It was assumed that this cost effective and easy measure was undertaken for even the older apartment building. The electric heating pipes were laid into a 20 mm thick light weight concrete layer. In the simulation the heating source was situated 20 mm beneath the floor surface. More detailed descriptions can be found in the following subsections. The most important part of the simulation in IDA ICE 4.6 are the U-Values which are a result of the building structure. The figure shows the components and materials while the table below displays the resulting U-Values for the structures used. U-Values are based on material layers in series, which are assembled by IDA. Parallel structures were calculated manually into one material mix (calculation process described in 3.4 Parallel wall layers (Calculations)) and then used in IDA as input. The calculation procedure is described in detail in appendix IV. Some typical thermal bridges which were used in all simulation are shown in appendix V.
Figure 11: Two storey apartment building showing models A and B

Table 1: U-values of walls and floors used in simulation for model A and B

<table>
<thead>
<tr>
<th></th>
<th>Model A</th>
<th></th>
<th>Model B</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall (internal)</td>
<td>Floor (internal)</td>
<td>Ceiling ((^{(2)}))</td>
<td>Wall (external)</td>
<td>Floor (internal)</td>
<td>Roof</td>
</tr>
<tr>
<td>U-Value [W/m²K]</td>
<td>0.499</td>
<td>0.178</td>
<td>0.229</td>
<td>0.515</td>
<td>0.229</td>
<td>0.07</td>
</tr>
</tbody>
</table>

\(^{(1)}\) Calculation procedure for mix materials can be found in appendix IV

\(^{(2)}\) Ceiling has the same construction as internal floor over a heated living area (see Model B internal floor for structure details)
Figure 12: Newly build single family house after Swedish building standards showing model C

Table 2: U-values of walls and floors used in simulation for model C

<table>
<thead>
<tr>
<th></th>
<th>Model C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>U-Value [W/m²K]</td>
<td></td>
</tr>
<tr>
<td>Wall (external)</td>
<td>0.149</td>
</tr>
<tr>
<td>Floor (external)</td>
<td>0.186</td>
</tr>
<tr>
<td>Roof</td>
<td>0.07</td>
</tr>
</tbody>
</table>

(1) Calculation procedure for mix materials can be found in appendix IV
4.6.1 Model A
This model was located inside a house surrounded by heated living areas and above a cellar with constant temperature of roughly 15 °C. The floor was a light building structure consisting of wood joists and a 220 mm layer of insulation between the logs. All walls were internal and had the same building composition.

4.6.2 Model B
Model B had one wall with a window exposed to the outdoor environment. The wall was directed east. All other walls were internal and adjacent to occupied living spaces. The window consisted of 2 glass with an according U-Value of 2.9 W/m²K. The roof was insulated by 50 cm and the floor consists of wooden logs with noise insulation of 95 mm in between.

4.6.3 Model C
In this model the room was located in a newly build house. The window was of 3 glass with U-Value of 1.9 W/m²K and directed east. The roof was like in model B insulated with 50 cm insulation material. The house foundation was standing on ground consisting of soil. For simulations the soil temperature at 1 m below ground surface was 10°C all year long.

4.7 Heating system and control
An electric radiant floor heating systems was applied into the IDA model. It covered the whole floor area and had a power rating of 100 W/m². The heating system was operated by a controller. The controller was set to maintain a temperature of 21°C. To compare the results of different controlling strategies, a time controlled heating strategy and the two most common heating controllers were used for comparison. The PI Control and a ON-OFF Control were applied for this cause. Using IDA ICE makes it possible to construct an individual controller scheme, which is seen below.

The reason for using a PI controller coupled to a time schedule instead of an ON-OFF was simply because it can regulate the temperature better. It can maintain a certain temperature and can gradually heat up the floor after a longer period of no operation (for example in the night).

For each model the schedule needed to be changed to adapt to the new boundary conditions. The schedule was designed for an extreme winter day to ensure a sufficient heat supply at any time of the year. For further reference this day is called synthetic winter day with dry bulb temperatures of min -24°C and max -17°C. The design day temperatures were taken from SMHI as a mean of extreme winter cases throughout a couple of years. The design day was chosen to be on a working day, i.e. a day between Monday to Friday. This is important since the heat loads from occupants and lightning differs from the weekend.
Figure 13: PI-controller linked to a schedule (controller scheme)
5. Results

5.1 Energy use of different controllers

The simulations were conducted throughout one typical heating period in Sweden which goes from 15th September to 15th April of the following year. Table 3 shows the resulting energy use for one heating period in Sweden using different control strategies. In case A the ON-OFF used no energy, because the room was constantly supplied by 20°C air from other rooms. The temperature in the testroom needed to sink at least by 2°C below the setpoint temperature (21°C) for the ON-OFF to start up. Therefore the ON-OFF controller never received a signal to turn on, since the temperature was never going to fall below 20°C.

Table 3: Energy consumption of different controllers for models A, B and C for a simulation period from 15 sep to 15 apr (7 months)

<table>
<thead>
<tr>
<th>Model</th>
<th>ON-OFF (kWh)</th>
<th>PI (kWh)</th>
<th>PI+Schedule (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td>0</td>
<td>152</td>
<td>142</td>
</tr>
<tr>
<td>Model B</td>
<td>414</td>
<td>422</td>
<td>352</td>
</tr>
<tr>
<td>Model C</td>
<td>332</td>
<td>349</td>
<td>238</td>
</tr>
</tbody>
</table>

Conducting from those results a saving potential for the PI Controller with a schedule can be acquired. Saving potential was obtained by comparison to the cheapest alternative shown. Conclusively in model A energy use can be reduced by 6%, in model B by 15% and in model C by 28% when using a PI controller in connection with a schedule.

Further energy can be reduced by a better insulated home. Model B represented a poor insulated house while model C showed a modern relatively low energy carving building. Comparing the results of model B to C, energy can be saved by 19.9% in the case of using an ON-OFF, 17.3% for PI and 32.4% using PI+Schedule. This means a total energy saving of 47% can be achieved by first upgrading to a better control system and then by extra insulating a building.

5.2 Heat flow through building structures

In the following table heat flow through the building structure and heat supply are shown. The values were mean values throughout a period of 24h of a synthetic winter day with dry bulb temperatures of min -24°C and max -17°C. The heating system was set to supply heat at a power rating of max 100 W/m² with PI as controller, since it keeps the temperature of 21 °C almost constant over time.

Figure 14 and 15 visualize the results found in table 4. Table 4 shows mostly mean values of power supply and heat losses but also maximum power rating of the electrical heating system.
Table 4: Mean heater power and mean heat losses through building components for a synthetic winter day using PI control

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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Floor</td>
<td>Roof/Ceiling</td>
<td>window</td>
</tr>
<tr>
<td>Model A</td>
<td>28.5</td>
<td>96.2</td>
<td>21.9</td>
<td>6.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Model B</td>
<td>134</td>
<td>305</td>
<td>124</td>
<td>9.2</td>
<td>12.5</td>
</tr>
<tr>
<td>Model C</td>
<td>120</td>
<td>496</td>
<td>103</td>
<td>16.6</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Heater power describes the power consumption of the electrical floor heating system, while the floor surface heat flux is the actual heat coming into the room. The difference of values between heater power and surface heat flux was either lost to the ground below or used to heat up the floor structure. For example in model C the heater used power of 120 W, but just heat of 103 W entered the room. The difference is 17 W, but since just 16.6 W was lost to the ground the rest of 0.4 W was used to heat up the floor structure. Basically the figure shall show simplified the heat entering the room from the floor up (marked blue) and the heat losses through the floor down (marked green).

The largest amount of heat lost through the building structures appeared both in external wall and through the window in Model B. Model B was set to be a badly insulated building and therefore was expected to have the highest heat losses. Besides external wall and window, internal walls were the next major contributor of total heat transmission through the building envelope.
Figures 16 and 17 show the heater power supply and the transmission through the floor for a whole synthetic winter day (24h) respectively. During occupancy the electric floor heating system was not in operation since the room has been preheated beforehand to 21°C and the heat load emitted from occupants, lightning and solar radiation was enough to keep up the setpoint temperature during occupancy. The high peak at around hour 24 can be explained by the low temperature in the night and lack of solar radiation and internal loads.

In figure 17 the graph describing heat losses fluctuates between positive and negative values. Negative characters represent heat losses through the ground, whilst positive values embody heat which is supplied to the room by the floor structure, which behaves as a thermal storage. Not all heat supplied by the electrical floor heating system entered the room, some was lost and a fraction was used to heat the structure, which in reverse emitted this thermal stored heat when the heating system supplied less than 100 W or 20 W/m².
Figure 16: Heating supply power [W] for a synthetic winter day using PI control in model C

Figure 17: Heat losses [W] through the floor for a synthetic winter day using PI control in model C
5.3 Operative temperatures

Figures 18, 19 and 20 show operative temperatures in the testrooms for models A, B and C respectively. The results were obtained by running simulations for a synthetic winter day. To achieve a comfortable indoor climate it was defined that indoor temperatures shall be optimally 21°C and max 22°C at head height, so at 1.6 m above floor surface. A collection of figures regarding operative and surface temperatures during a whole heating period can be found in appendix VI.

In model A the testroom controlled by ON-OFF did not achieve a min temperature of 21°C during occupancy. Temperatures varied from 20.3°C to 21.4°C. Meanwhile the other two controllers differed by just max 0.2°C during occupied hours and max 0.5°C during the rest of the day. They supplied the room during occupancy with at least 21.1°C and max 21.9°C.

In the next simulation for model B, temperatures fluctuated notably. Looking at the ON-OFF graph its operation strategy between ON and OFF is clearly visible in the temperature variation. The most steady graph is shown for the PI controller. It moved between min 21°C and max 21.3°C at all times. Large disparities occurred using a PI regulator connected to a schedule. In this case temperatures dropped during unoccupied hours to 18.7°C, but during presence of occupants degrees moved between 21.1°C and 21.6°C.
In model C all three controllers followed roughly the same path. In the morning hours, between 5am and 8am, temperatures for all controllers varied by 1.2°C and in the afternoon, between 16pm and 22pm, by 0.9°C. In the morning all heaters exceeded the limit of 22°C, in the afternoon ON-OFF dropped below 21°C to 20.5°C and PI overstepped the max temperature setpoint by 0.1°C.
5.4 Floor surface temperatures

Floor surface temperatures were obtained as the operative temperatures at one synthetic winter day, the results are shown in figures 21, 22 and 23. The best thermal sensation of floor temperature varies between 19°C and 27 °C with optimal temperature fluctuating around 24 °C. In model A the ON-OFF controlled system supplied floor temperatures of around 20.5°C. PI moved between values of 21.4°C and 22.3°C. Temperatures varied noticeably using PI and schedule. During occupant hours degrees changed between min 21.6°C and max 23.4°C with lowest measured temperature of 20.6°C outside the occupied time.

\[\text{Figure 21: Floor surface temperatures for model A during a synthetic winter day}\]

In the bad insulated testroom surface temperatures changed greatly over time. Like in the operative temperature simulations before, the lowest temperature change occurred when using PI regulator, anyhow due to the high heat losses the temperature variation in this case were very high for all 3 controllers. In the morning the lowest measured floor temperature lied at 23.4°C and highest at 27.6°C. In the afternoon PI and PI+Schedule provided quite constant values around 24.9°C (+/- 0.7).
In the following figure both PI and PI+Schedule have just relatively small fluctuations. Mean surface temperature for PI+Schedule was ca. 21.7°C for PI ca. 23.5°C. Temperatures for ON-OFF controlled system varied from 22°C to 26°C, but stayed fairly constant throughout occupancy with a max difference of 1°C.
6. Discussion

Nowadays energy consumption of buildings come down to roughly one third of the total energy used. The main consumers are heating systems especially in northern countries like Scandinavia, where the mean annual air temperature can be around 4°C like in the example of the city of Gävle in Sweden. This means there is a high demand on energy efficient and optimized heating systems. In general using electricity for heating is cost expensive and cannot guarantee that it comes from renewable sources. Therefore it is recommended to switch to a water based heating system driven by a heat pump when living in a house or district heating in an apartment. Many houseowners though want to upgrade their property by installing floor heating since it can provide a better thermal sensation in comfort than radiators. When doing so, a "wet" system demands preferably a concrete ground and a higher room height, since the floor will be thickened by roughly 20cm. Hence an electrical floor heating becomes much more attractive, due to its easy installation on any ground material. Consequently it becomes important to try to reduce energy consumption and heat losses of an electrical heated floor. This can be already easily done by choosing a smart control strategy. Energy can be reduced by almost a third (28%) in a well insulated building when switching to a more adapted control and 15% in a badly insulated building. The difficulty by changing control in a house with high heat losses (e.g. model B) is that when turning off the electrical heater, heat dissipates very fast through external constructions and therefore the heating system needs to operate a much longer time and higher power rating to establish again a comfortable indoor climate. Figures 19 and 22 show very clearly that operative and surface temperatures vary greatly throughout the day. Mostly in the case of using ON-OFF or PI+Schedule controllers. When floor surface temperatures change very quickly in a short period of time it can put stresses on surface and ground materials and cause cracks and loosening of floor covering and therefore impose a risk for moisture problems in the structure. For this reason it might be a better solution to introduce radiators in the case of the poorly insulated buildings or to increase insulation. From graph 15 derives that model B has just higher heat losses through the external wall and window, thus these are the components which needs to be additionally insulated or replaced. Although replacing windows has a very long payoff time and might not be essentially necessary to reduce energy significantly in this case, since the window is of such a small size. In this model lowering the U-Value of the external wall from 0.5 W/m²K to 0.15 W/m²K will already have a large impact on energy use.

Simulations showed that by lowering U-Values from model B to model C, energy can be saved by 19.9% in the case of using an ON-OFF, 17.3% for PI and 32.4% using PI+Schedule regulation. Conducting from all mentioned results above a total energy saving of 47% can be achieved by changing control strategy to PI+Schedule and lowering U-Values of the structure.

However there is another alternative of reducing energy when installing electrical floor heating systems. There is an option of using a thermal mass or phase change materials (PCM) to "store" heat. This gives an opportunity to "charge" the floor during the night at off-peak hours with low electricity prices. That though requires a well insulated ground and overall building. Therefore this can be an additional opportunity to reduce costs in the case of model C.
According to the results mentioned above energy can be reduced significantly by using different control strategies and building structures, but how does that influence or compensate thermal comfort and -sensation?

Major parameters establishing thermal comfort are operative temperature, floor temperature, air velocity, humidity and vertical air temperature difference. In this paper just operative and floor temperatures were taken into consideration. Air velocities and vertical air temperature difference cannot be simulated with IDA, but can cause local discomfort. Therefore this would be an important factor to investigate in another paper using a more advanced simulation tool. Humidity can be simulated but was neglected, since humidity just changes significantly during a very short period of time, e.g. showering and is removed very vastly through the exhaust ventilation terminal.

During occupancy operative temperatures moved within the given rage of 21°C to 22°C with Pi and PI+Schedule regulator, in model C slightly above 22°C in the morning. ON-OFF did not provide sufficient temperature during any of the simulations. Operative temperatures fluctuated from 20°C to over 22°C during occupancy.

The lowest operative temperature measured 18.7°C was obtained by PI+Schedule controller in model B during non occupancy. Like mentioned above heat dissipates fast in a poorly insulated building through external walls when the heater is not operating. Although it does not influence the thermal comfort on an occupant during the scheduled occupancy hours, it will however cause a large perceived dissatisfaction if an occupant enters outside the theoretical schedule. Occupancy hours is an estimation, but can and will vary greatly in a residential building if people having for example holidays or free days or just come home earlier from work. Consequently it is not desirable that temperatures drop below 20°C at any time.

Satisfying floor surface temperatures (19°C-27°C) were reached by all models using any controller. The closest to achieve a floor temperature of 24°C during occupancy came the PI Controller, followed by PI+Schedule and last ON-OFF. These results are based on measurements of the floor surface which was in these simulations bare concrete. Simulation results may or will be different when using realistic floor coverings, like tiles or linoleum which is commonly promoted in bathrooms. This will influence not only surface temperature but also surface heat flux and therefore energy use.

As a consequence the weakness of this paper accounts to simplifications, limitations of the simulation tool and very specific boundary conditions which cannot be applied to any building.

On the contrary this research gives a broad picture of energy consumption using a certain heating system and how this is affected by building construction and its influence on indoor comfort. Further it gave a deeper insight of the program IDA ICE and its performance abilities and limitations.
7. Conclusion

Conducting from the results obtained following conclusions in regard to research aim and objectives can be drawn and summarized:

*Investigating the possibility of minimizing energy use through control strategy in a bathroom using an electrical floor heating system*

- Energy can be reduced by 6% in model A, in model B by 15% and in model C by 28% when using a PI controller in connection with a schedule.
- A total saving of 47% can be achieved by lowering U-Value of external walls from 0.5 W/m²K to 0.15 W/m²K and changing control strategy from ON-OFF to PI+Schedule. 
- Due to large surface temperature variations in model B it was recommended to use PI control or change to radiators if external wall insulation is not increased.

*Analyzing the effects of different control strategies on thermal comfort*

- PI regulator kept temperatures most constant over time.
- ON-OFF control failed in all simulations to keep operative temperatures within acceptable values.
- PI+Schedule achieved satisfying thermal comfort during occupancy, but outside the scheduled hours temperatures varied widely.

*Visualizing heat transmission through building components*

- The largest amount of heat lost through the building structures appeared in external wall and through the window in Model B.
- see figure 15
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Moosberger, S. 2007, *IDA ICE CIBSE-Validation Test of IDA Indoor Climate and Energy version 4.0 according to CIBSE TM33, issue 3*, Hochschule für Technik+Architektur Luzern, Schweiz.


Appendix

Appendix I - Clothing and metabolic rate

Table 5: Typical metabolic heat generation for various activities
(ASHRAE 2009, chapter 9.6)

<table>
<thead>
<tr>
<th>Activity</th>
<th>W/m²</th>
<th>met*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resting</td>
<td>40</td>
<td>0.7</td>
</tr>
<tr>
<td>Sleeping</td>
<td>45</td>
<td>0.8</td>
</tr>
<tr>
<td>Reclining</td>
<td>60</td>
<td>1.0</td>
</tr>
<tr>
<td>Seated, quiet</td>
<td>70</td>
<td>1.2</td>
</tr>
<tr>
<td>Standing, relaxed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Walking (on level surface)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 km/h (0.9 m/s)</td>
<td>115</td>
<td>2.0</td>
</tr>
<tr>
<td>4.3 km/h (1.2 m/s)</td>
<td>150</td>
<td>2.6</td>
</tr>
<tr>
<td>6.4 km/h (1.8 m/s)</td>
<td>220</td>
<td>3.8</td>
</tr>
<tr>
<td>Office Activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reading, seated</td>
<td>55</td>
<td>1.0</td>
</tr>
<tr>
<td>Writing</td>
<td>60</td>
<td>1.0</td>
</tr>
<tr>
<td>Typing</td>
<td>65</td>
<td>1.1</td>
</tr>
<tr>
<td>Filing, seated</td>
<td>70</td>
<td>1.2</td>
</tr>
<tr>
<td>Filing, standing</td>
<td>80</td>
<td>1.4</td>
</tr>
<tr>
<td>Walking about</td>
<td>100</td>
<td>1.7</td>
</tr>
<tr>
<td>Lifting/packing</td>
<td>120</td>
<td>2.1</td>
</tr>
<tr>
<td>Driving/Flying</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Car</td>
<td>60 to 115</td>
<td>1.0 to 2.0</td>
</tr>
<tr>
<td>Aircraft, routine</td>
<td>70</td>
<td>1.2</td>
</tr>
<tr>
<td>Aircraft, instrument landing</td>
<td>105</td>
<td>1.8</td>
</tr>
<tr>
<td>Aircraft, combat</td>
<td>140</td>
<td>2.4</td>
</tr>
<tr>
<td>Heavy vehicle</td>
<td>185</td>
<td>3.2</td>
</tr>
<tr>
<td>Miscellaneous Occupational Activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooking</td>
<td>95 to 115</td>
<td>1.6 to 2.0</td>
</tr>
<tr>
<td>Housecleaning</td>
<td>115 to 300</td>
<td>2.0 to 3.4</td>
</tr>
<tr>
<td>Seated, heavy limb movement</td>
<td>130</td>
<td>2.2</td>
</tr>
<tr>
<td>Machine work</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sawing (table saw)</td>
<td>105</td>
<td>1.8</td>
</tr>
<tr>
<td>light (electrical industry)</td>
<td>115 to 140</td>
<td>2.0 to 2.4</td>
</tr>
<tr>
<td>heavy</td>
<td>235</td>
<td>4.0</td>
</tr>
<tr>
<td>Handling, 50 kg bags</td>
<td>235</td>
<td>4.0</td>
</tr>
<tr>
<td>Pick and shovel work</td>
<td>235 to 280</td>
<td>4.0 to 4.8</td>
</tr>
<tr>
<td>Miscellaneous Leisure Activities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dancing, social</td>
<td>140 to 255</td>
<td>2.4 to 4.4</td>
</tr>
<tr>
<td>Calisthenics/exercise</td>
<td>175 to 235</td>
<td>3.0 to 4.0</td>
</tr>
<tr>
<td>Tennis, singles</td>
<td>210 to 270</td>
<td>3.6 to 4.0</td>
</tr>
<tr>
<td>Basketball</td>
<td>290 to 440</td>
<td>5.0 to 7.6</td>
</tr>
<tr>
<td>Wrestling, competitive</td>
<td>410 to 505</td>
<td>7.0 to 8.7</td>
</tr>
</tbody>
</table>
Table 6: Garment insulation values (ASHRAE 2009, chapter 9.9)

<table>
<thead>
<tr>
<th>Garment Description</th>
<th>$I_{clo}$</th>
<th>Garment Description</th>
<th>$I_{clo}$</th>
<th>Garment Description</th>
<th>$I_{clo}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underwear</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men’s briefs</td>
<td>0.04</td>
<td>Long-sleeved, flannel shirt</td>
<td>0.34</td>
<td>Long-sleeved (thin)</td>
<td>0.25</td>
</tr>
<tr>
<td>Panties</td>
<td>0.03</td>
<td>Short-sleeved, knit sport shirt</td>
<td>0.17</td>
<td>Long-sleeved (thick)</td>
<td>0.36</td>
</tr>
<tr>
<td>Bra</td>
<td>0.01</td>
<td>Long-sleeved, sweat shirt</td>
<td>0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T-shirt</td>
<td>0.08</td>
<td>Trousers and Coveralls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full slip</td>
<td>0.16</td>
<td>Short shorts</td>
<td>0.06</td>
<td>Dresses and skirts</td>
<td>0.14</td>
</tr>
<tr>
<td>Half slip</td>
<td>0.14</td>
<td>Walking shorts</td>
<td>0.08</td>
<td>Skirt (thin)</td>
<td>0.23</td>
</tr>
<tr>
<td>Long underwear top</td>
<td>0.20</td>
<td>Straight trousers (thin)</td>
<td>0.15</td>
<td>Long-sleeved skirt</td>
<td>0.33</td>
</tr>
<tr>
<td>Long underwear bottoms</td>
<td>0.15</td>
<td>Straight trousers (thick)</td>
<td>0.24</td>
<td>Long-sleeved skirt (thick)</td>
<td>0.47</td>
</tr>
<tr>
<td>Footwear</td>
<td></td>
<td>Coveralls</td>
<td>0.49</td>
<td>Sleepwear and Robes</td>
<td></td>
</tr>
<tr>
<td>Ankle-length athletic socks</td>
<td>0.02</td>
<td>Double-breasted (thin)</td>
<td>0.48</td>
<td>Sleeveless, short gown (thin)</td>
<td>0.18</td>
</tr>
<tr>
<td>Calf-length socks</td>
<td>0.03</td>
<td>Sleeves</td>
<td>0.10</td>
<td>Sleeveless, long gown (thin)</td>
<td>0.29</td>
</tr>
<tr>
<td>Knee socks (thick)</td>
<td>0.06</td>
<td>Suit jackets and vests (lined)</td>
<td>0.36</td>
<td>Short-sleeved hospital gown</td>
<td>0.31</td>
</tr>
<tr>
<td>Panty hose</td>
<td>0.02</td>
<td>Double-breasted (thin)</td>
<td>0.42</td>
<td>Long-sleeved, long gown (thick)</td>
<td>0.46</td>
</tr>
<tr>
<td>Sandal thongs</td>
<td>0.02</td>
<td>Double-breasted (thick)</td>
<td>0.48</td>
<td>Long-sleeved pajamas (thick)</td>
<td>0.57</td>
</tr>
<tr>
<td>Slippers (quilted, pile-lined)</td>
<td>0.03</td>
<td>Sleeveless vest (thin)</td>
<td>0.10</td>
<td>Short-sleeved pajamas (thin)</td>
<td>0.42</td>
</tr>
<tr>
<td>Boots</td>
<td>0.10</td>
<td>Sleeveless vest (thick)</td>
<td>0.17</td>
<td>Long-sleeved, long wrap robe (thick)</td>
<td>0.69</td>
</tr>
<tr>
<td>Shirts and Blouses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sleeveless, scoop-neck blouse</td>
<td>0.12</td>
<td>Sweaters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short-sleeved, dress shirt</td>
<td>0.19</td>
<td>Sleeveless vest (thin)</td>
<td>0.13</td>
<td>Long-sleeved, short robe (thick)</td>
<td>0.48</td>
</tr>
<tr>
<td>Long-sleeved, dress shirt</td>
<td>0.25</td>
<td>Sleeveless vest (thick)</td>
<td>0.22</td>
<td>Short-sleeved, short robe (thin)</td>
<td>0.34</td>
</tr>
</tbody>
</table>

*Thin* garments are summerweight; *thick* garments are winterweight.  

$1$ clo = 0.155 (m²·K)/W  

*Knee-length
Appendix II - Occupant and light schedule

Figure 24: Occupant schedule

Figure 25: Light schedule
Appendix III - Mean climate values of Gävle from 2009 to 2013

Figure 26: Mean dry bulb temperature [°C] for Gävle from 2009 to 2013

Figure 27: Duration diagram of mean dry bulb temperature[°C] for Gävle from 2009 to 2013
Figure 28: Direct sun radiation [W/m²] for Gävle from 2009 to 2013

Figure 29: Diffuse sun radiation [W/m²] on hot surface for Gävle from 2009 to 2013
Appendix IV - Calculations for parallel wall structures

Composing a new mixed material consisting of two substances layered in parallel requires

Table 7: Thermal properties of various materials used in building structure

<table>
<thead>
<tr>
<th>Thermal properties</th>
<th>Insulation</th>
<th>Wood</th>
<th>Air</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ [W/m,K]</td>
<td>0.036</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>ρ [kg/m³]</td>
<td>20</td>
<td>500</td>
<td>1.2</td>
</tr>
<tr>
<td>cₚ [J/kg,K]</td>
<td>750</td>
<td>2300</td>
<td>1006</td>
</tr>
</tbody>
</table>

Figure 30: External and internal wall construction (view from top) used in model A, B and C as well as floor construction used in model A and B

Defining properties of new material mix (insulation mix consisting of insulation and wooden logs) by using equations (1), (2) and (3):

(1) \[ \lambda_{\text{new}} = \frac{x_1}{x} \cdot \lambda_b + \frac{x-x_1}{x} \cdot \lambda_a = \frac{45}{600} \cdot 0.14 + \frac{600-45}{600} \cdot 0.036 = 0.043 \text{ W/m,K} \]

(2) \[ \rho_{\text{new}} = \frac{x_1}{x} \cdot \rho_b + \frac{x-x_1}{x} \cdot \rho_a = \frac{45}{600} \cdot 500 + \frac{600-45}{600} \cdot 20 = 56 \text{ kg/m}^3 \]

(3) \[ c_{p\text{ new}} = \frac{x_1}{x} \cdot c_{p_b} + \frac{x-x_1}{x} \cdot c_{p_a} = \frac{45}{600} \cdot 2300 + \frac{600-45}{600} \cdot 750 = 866 \text{ J/kg,K} \]
Defining properties of new material mix (*air mix* consisting of air and wooden logs) by using equations (1), (2) and (3):

\[
\lambda_{\text{new}} = \frac{X_1}{X} \cdot \lambda_b + \frac{X - X_1}{X} \cdot \lambda_a = \frac{45}{600} \cdot 0.17 + \frac{600 - 45}{600} \cdot 0.036 = 0.046 \text{ W/m.K}
\]

\[
\rho_{\text{new}} = \frac{X_1}{X} \cdot \rho_b + \frac{X - X_1}{X} \cdot \rho_a = \frac{45}{600} \cdot 1.2 + \frac{600 - 45}{600} \cdot 20 = 18.6 \text{ kg/m}^3
\]

\[
c_{p_{\text{new}}} = \frac{X_1}{X} \cdot c_{p_b} + \frac{X - X_1}{X} \cdot c_{p_a} = \frac{45}{600} \cdot 1006 + \frac{600 - 45}{600} \cdot 750 = 769 \text{ J/kg.K}
\]

**Table 8: New thermal properties of mix materials used in IDA simulation**

<table>
<thead>
<tr>
<th>New thermal properties</th>
<th>Insulation mix</th>
<th>Air mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$ [W/m.K]</td>
<td>0.043</td>
<td>0.046</td>
</tr>
<tr>
<td>$\rho$ [kg/m$^3$]</td>
<td>56</td>
<td>18.6</td>
</tr>
<tr>
<td>$c_p$ [J/kg.K]</td>
<td>866</td>
<td>769</td>
</tr>
</tbody>
</table>
Appendix V - Thermal Bridges used in Simulations

<table>
<thead>
<tr>
<th>Thermal bridges</th>
<th>None</th>
<th>Good</th>
<th>Typical</th>
<th>Poor</th>
<th>Very Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall / internal slab</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.05 W/K/(m joint) (total for both adjacent zones)</td>
</tr>
<tr>
<td>External wall / internal wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 W/K/(m joint) (total for both adjacent zones)</td>
</tr>
<tr>
<td>External wall / external wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.08 W/K/(m joint) (total for both adjacent zones)</td>
</tr>
<tr>
<td>External windows perimeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 W/K/(m perim)</td>
</tr>
<tr>
<td>External doors perimeter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 W/K/(m perim)</td>
</tr>
<tr>
<td>Roof / external walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.09 W/K/(m joint)</td>
</tr>
<tr>
<td>External slab / external walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.14 W/K/(m joint)</td>
</tr>
<tr>
<td>Balcony floor / external walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.2 W/K/(m joint)</td>
</tr>
<tr>
<td>External slab / internal walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 W/K/(m joint) (total for both adjacent zones)</td>
</tr>
<tr>
<td>Roof / Internal walls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 W/K/(m joint) (total for both adjacent zones)</td>
</tr>
<tr>
<td>External walls, inner corner</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 W/K/(m joint) (negative number)</td>
</tr>
<tr>
<td>Total envelope area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0 W/K/(m^2 envelope)</td>
</tr>
</tbody>
</table>

*Figure 32: Values of thermal bridges used for all simulations*
Appendix VI - Results of operative and surface temperatures from 15sep-15apr

Model A

Figure 33: Model A operative temperatures for heating period when using ON-OFF control

Figure 34: Model A operative temperatures for heating period when using PI control
Figure 35: Model A operative temperatures for heating period when using PI+Schedule control

Figure 36: Model A surface temperatures for heating period when using ON-OFF control
Figure 37: Model A surface temperatures for heating period when using PI control

Figure 38: Model A surface temperatures for heating period when using PI+Schedule control
Model B

Figure 39: Model B main temperatures for heating period when using ON-OFF control

Figure 40: Model B operative temperatures for heating period when using PI control
Figure 41: Model B main temperatures for heating period when using PI+Schedule control

Figure 42: Model B surface temperatures for heating period when using ON-OFF control
Figure 43: Model B surface temperatures for heating period when using PI control

Figure 44: Model B surface temperatures for heating period when using PI+Schedule control
Model C

Figure 45: Model C main temperatures for heating period when using ON-OFF control

Figure 46: Model C main temperatures for heating period when using PI control
Figure 47: Model C main temperatures for heating period when using PI+Schedule control

Figure 48: Model C surface temperatures for heating period when using ON-OFF control
Figure 49: Model C surface temperatures for heating period when using PI control

Figure 50: Model C surface temperatures for heating period when using PI+Schedule control