Energy Flexibility Potential of Heating and Cooling Systems of a Nearly-Zero-Energy Office Building

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Abstract

The increasing growth of renewable energy sources (RES) demands the rise of energy flexible technologies in order to facilitate and regulate the operation of a smart grid system. Demand response techniques like these allow buildings to participate and contribute to the system balancing and improve both the power grid and the performance of the building.

This master thesis aims to compare the energy flexibility potential of different heating and cooling systems of a new nearly-zero-energy office building.

Different systems have different behavior and therefore they have certain advantages and disadvantages, affecting the energy flexibility and as a result, the energy consumption of the building, as well as its indoor comfort. The three compared systems were: a novel two-pipe heating and cooling system, a radiator heating system with mechanical ventilation for cooling, and a radiant floor heating system also with mechanical ventilation for cooling.

Each model had two cases: a Reference and a Flexibility case. The Reference models had the same fixed set-points for all systems. The Flexibility models had the set-points fluctuate based on electricity price, in addition to weather predictive controls for the activation of the cooling system.

These systems were modeled using EnergyPlus and compared with Matlab, using 4 evaluation metrics. The ability of power adjustment, which is the capability of the building to adjust its power usage according to the different electricity price periods. The ability of energy shifting, which is the process of utilizing the accumulated energy in the building mass during low electricity price level, at high price level. The economic benefit, which concerns both owners and users, since it involves the yearly energy cost of the building. And lastly, the indoor thermal comfort level was analyzed.

The final results of the evaluation metrics showed that the novel two-pipe system was able to achieve higher energy savings and flexibility potential. It managed to accomplish this whilst keeping the highest thermal comfort level of all cases. The energy flexibility was realized by the excess heat transfer from warmer zones to colder ones and vice versa. The underfloor heating system also showed great potential for flexibility, as it had a greater ability of energy shifting due to being an embedded system. Although the flexible behavior of the set-points had a negative influence on the thermal comfort, even the highest decrease of all cases was not enough to be a major issue. A future study could look at different levels of set-points in order to achieve greater energy flexibility from radiator and floor heating systems.

Preface

This Master Thesis has been written at the faculty of Engineering and Science at Aalborg University during the 4^{th} semester of the education program, from September 2017 to January 2018, by three members currently enrolled in the Master Building Energy Design.

The thesis builds on simulations conducted in EnergyPlus and on meetings with the supervisors throughout the duration of the semester. For the completion of the study, special gratitude goes to our supervisors, Mingzhe Liu and Per Kvols Heiselberg for their guidance, patience and innovative ideas. Moreover, we would sincerely like to thank Lucian Iordachescu and Mihhail Samusev for all their help with some of the used software, for their aid has been valuable.

Finally, this study was conducted based on the work of Mingzhe Liu and Per Kvols Heiselberg on "Energy flexibility on a nearly-zero-energy building with a novel building energy system evaluated with integrated metrics".

Reading instructions

This report is divided into chapters that contain sections and subsections. In this way, it is easier to refer to. For each figure, table and equation that may be present in this report, there are assigned numbers with respect to the given chapter. For instance, the first figure in chapter 3 will be Figure 3.1.

Additional information, graphs and tables are placed in the appendix, which is after the bibliography list. The bibliography contains the list of literature, which is referred throughout the entire document. The citations are presented as author-year citations, also known as the Harvard method.

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Contents

1 Introduction

1.1 Intro

It has been repeatedly proven that the use of non-renewable energy sources is being detrimental to the environment, thus the need for using renewable sources (RES) has heightened. Denmark's goal in terms of energy is to use solely RES by 2050. [Energistyrelsen, 2015]

Considering this increase, energy flexibility is becoming a relevant topic currently, having in mind the stochastic nature of renewable electricity production. Since most RES depend on wind and solar energy production, the supply of electricity varies in function of the local weather conditions. This has a direct impact on the price of electricity itself, for there will be times when the RES are abundant (for example on a windy day), which will result in a surplus of electricity, hence the price will go down. The opposite happens when the RES are scarce, due to the rarity of electricity production during such periods, the price will go up. [Hurtado et al., 2017]

In this context, energy flexibility refers to the ability of shifting energy usage from periods with high electricity prices to periods with low prices or in other words, to match demand with production. [Pallonetto et al., 2016]

Buildings can store energy, which gives the possibility of shifting its demand and thus becoming energy flexible. Moreover, the fact that buildings use 38 % of the total energy use results in a potential of energy saving in the building sector.[Reynders et al., 2013]

Buildings offer different possibilities of energy storage. Structural thermal storage, through the structure of the building itself and individual units, e.g. hot water tanks or batteries. [Dreau and Heiselberg, 2016]
By storing energy during periods of high production (low prices) and using it during periods of low production (high prices), a shift in energy use is achieved. This ultimately has as outcome a reduction in the energy use of the building.

The ability of a building to shift energy depends on multiple parameters, such as structure, systems and external conditions. The systems used in the building can play a significant role in the efficiency of energy storage.

Commercial buildings especially, have the ability of reducing the energy use and present several options for demand management (matching demand with production). Most of their energy is used by the Heating, Ventilation and Air-Conditioning (HVAC) systems, which if controlled to use the building's energy storage properties will result in a reduction of the demand. [Christantoni et al., 2016]

1.2 Problem statement

How do different heat emission and cooling systems, in accordance with the thermal mass of a building, influence the ability of said building to be energy flexible? Additionally, what impact does it have on the indoor comfort?

1.3 Energy flexibility

According to the Danish National Energy Efficiency Action Plan (NEEAP), the electricity and heating supply shall be covered by renewable energy sources (RES) by the year 2035. By 2050, 100 % of all energy supply - electricity, heat, industry and transport - shall be covered by RES. Currently, solar power, wind power and biomass are used in a large scale in Denmark. In 2015, wind power generation reached 42 % of consumed electricity. This is expected to rise to 50 % by the year 2020. [Energistyrelsen, 2015]

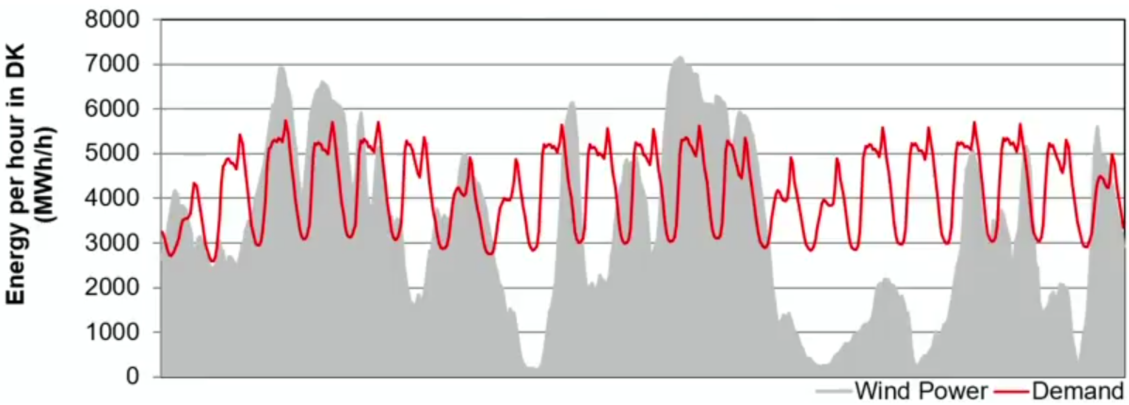

Figure 1.1: *Typical expected month in 2020 in Denmark*

The graph above shows a typical expected month in 2020. The red line shows the energy demand and the gray areas are the wind power generation. It is apparent that the power demand has quite regular daily patterns, however, the wind power generation fluctuates greatly. Some days the wind power generation is far below the demand, while during other days it is higher than the demand. This is a lot different from conventional power generation. In a conventional power plant, energy generation is always planned according to the energy demand so that they are matched.

In the case of wind energy, there is no way to control its intensity and generation periods, so a new approach is needed. That is to control the energy demand in order to match the generation. This is called demand flexibility, which is to match the instantaneous energy generation to the energy consumption.

This phenomenon also has a direct impact on the price of electricity itself. In the days when the RES are abundant the prices of electricity will go down because of the surplus. The opposite happens when the RES are not producing enough, when the prices will go up. [Hurtado et al., 2017]

In this context, energy flexibility refers to the ability of shifting energy usage of the buildings from periods with high electricity prices to periods with low prices, or in other words, to match demand with production. [Pallonetto et al., 2016]

The biggest influences on building energy flexibility is the thermal mass of the constructions. The fact that buildings can store energy makes it possible to shift energy and thus achieve energy flexibility. Buildings offer different possibilities of energy storage. Structural thermal storage, through the structure of the building itself, and individual units, e.g. hot water tanks or batteries. By storing energy during periods of high production (low prices) and using it during periods of low production (high prices), a shift in energy use is achieved. This ultimately has as outcome a reduction in the energy use of the building. Moreover, the fact that buildings use almost 38 % of the total energy use in Denmark, results in potential energy savings in the building sector. Other parameters that affect buildings' performance are the HVAC systems and the user behavior. [Reynders et al., 2013]

Most buildings have the ability to become energy flexible by adjusting these parameters. The following graphs are from a test scenario from DTU, where it can be seen the energy demand during one day. By utilizing a demand - response program, the building's thermal mass and systems, the energy demand could be changed to a more flexible pattern, without peaks.

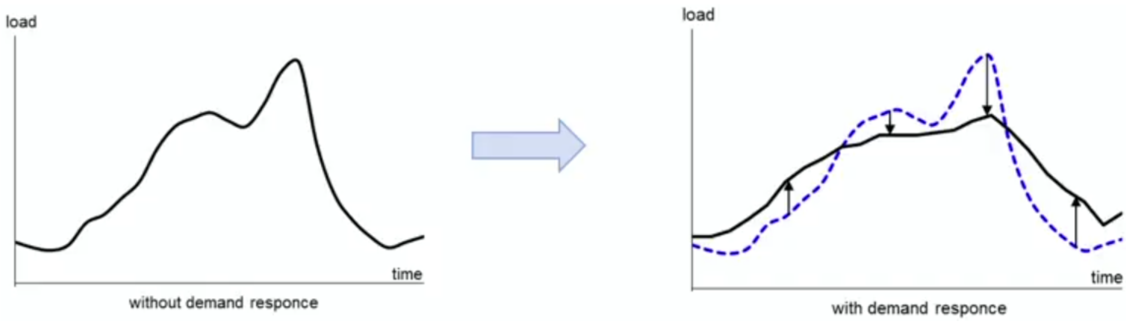

Figure 1.2: *Energy demand during a typical day. Left: Without demand response. Right: With demand response. [DTU, 2018]*

2 Methodology

This chapter describes the process of collecting and analyzing the data used for the assessment of the different systems. Additionally, the used evaluation metrics are being explained, as well as, basic information about the used software are given.

2.1 Methodology

This master thesis was focused on comparing the energy flexibility potential of different heating and cooling systems of a new nearly-zero-energy office building. To achieve this, three different systems were modeled and analyzed. A novel two-pipe system, which is a purely convective heating and cooling system. A traditional heating system using radiators, along with a central ventilation system for cooling. Finally, a radiant floor heating system with centralized ventilation for cooling.

Different systems have different behavior and thus certain advantages and disadvantages. This affects the energy flexibility and therefore the energy consumption of the building, as well as its indoor thermal comfort.

The primary research method was numerical. In order to model and analyze the energy performance, flexibility and comfort level of the different systems, a building energy simulation tool (EnergyPlus) was used. The processing of data was realized by a programming platform (MATLAB). The aim of this report was to establish new systems in EnergyPlus, whilst adjusting variables like different types of controls, schedules, temperature set-points etc. Once the characteristics of the models aligned with the expected performance, it was possible to investigate the energy flexibility and comfort level of the models, while comparing them. All extracted data from EnergyPlus was processed with MATLAB in order to get results and graphs.

More detailed and specific information about the models, variables, evaluation metrics and methods are presented in following sections of this master thesis report.

2.2 Evaluation metrics

In order to measure flexibility, certain metrics were investigated. The selected metrics to evaluate the performance of the models were:

- Power adjustment ability
- Energy shifting ability
- Economic benefit
- Comfort level

These parameters were chosen taking into consideration the impact on both the electricity grid but also the building's owners and users. These metrics were calculated under the two control strategies (Reference and Flexibility), Chapter 4, to estimate the yearly and seasonal performance of the different systems.

Power adjustment ability

This is the ability of the building to adjust power usage according to the different electricity price periods. The electricity cost fluctuates between periods of low, medium or high prices. It is desirable that the building would reduce its power consumption during times with high prices, to help release pressure of the grid. Respectively, an increase in consumption is wanted when prices are low.

The power adjustment parameter is the difference between the power of the Flexibility case (with demand-response control) and the Reference case (without the control). The cases are described in more detail in Chapter 4.

Economic benefit

The economic benefit is a relevant metric for owners and users, since it involves the energy cost of the building. When controlling the energy systems in the building according to the different electricity price periods, economic savings are achieved (smaller energy bill). This metric is calculated by taking the monthly energy consumption for a year, the monthly energy cost and the monthly energy consumption at the three price levels.

Energy shifting ability

To be able to activate the thermal mass of the building, additional heating or cooling energy has to be added by the means of demand-response control strategies. Energy is being accumulated in the thermal mass of the constructions and is ultimately being released when necessary. In the process, some of the energy will be released priorly, meaning that it will not pay back when prices are high. Hence, when additional energy is accumulated in periods of low energy price, it can be stored (energy storage). Furthermore, when the energy price is high and the extra energy that was previously stored is being used, the thermal storage can be activated (energy activation).

Comfort level

The most frequently used method of demand-response control is activating the building's thermal mass and adjusting the heating and cooling set-points. The risk in doing so is that the comfort of the indoor environment could be compromised. In order to avoid this, thermal comfort classes need to be compared. In standard EN 15251, three different comfort classes are described but only two of them are recommended, Class I and Class II. These classes introduce temperature ranges for heating and cooling and they can be seen in table 2.1.

Class	Temperature range heating	Temperature range cooling
I	21 - 23 °C	23.5 - 25.5 °C
II	20 - 24 °C	23 - 26 °C

Table 2.1: *Advised indoor temperatures*

2.3 Software description

EnergyPlus is a whole building energy simulation program that can model both energy consumption - for heating, cooling, ventilation, lighting and plug and process loads - and water use in buildings. [EP]

EnergyPlus is widely used around the world and is also an open-source platform. Because of these two factors, there are a lot of forums and other resources on-line and off-line, which can provide valuable additional assistance to possible issues that might be faced in the process of modeling the different systems.

MATLAB is a multi-paradigm numerical computing environment. A proprietary programming language developed by MathWorks. It allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces and interfacing with programs written in other languages. MATLAB combines a desktop environment tuned for iterative analysis and design processes with a programming language that expresses matrix and array mathematics directly. [mat, a] [mat, b]

3 System description

In this chapter three different heating and cooling systems are described. These systems will be modeled in EnergyPlus and will be further analyzed and compared in order to determine their influence on energy flexibility, energy consumption and indoor thermal comfort.

3.1 Novel two-pipe heating and cooling system

Depending on the geographical location of a building and the season, different oriented zones might have different needs concerning heating and cooling. While for summer and winter there is a general cooling and heating demand respectively, during spring and autumn, when external thermal loads can vary greatly, it is more common for different facades to have distinct demands. In these cases, there might be a simultaneous need for heating and cooling, making it necessary for both units to run at the same time.

Lindab introduces a novel energy system, Lindab Solus system, which consists of a two-pipe water system with common inlet temperature for both heating and cooling, by using High Temperature Cooling (HTC) and Low Temperature Heating (LTH). Through the mixing of the return water from the different zones, the outlet temperature can nearly maintain the desired inlet level, eliminating the need for heating or cooling units (boilers, chillers etc.). The system can run with an inlet temperature between 20 - 23 $°C$, depending on outdoor air temperature, for both heating and cooling demand, at the same time.

More specifically, if a south facing zone has an indoor temperature of 20 $°C$, there would be a need for cooling in part of the building, while at the same time there would be a heating demand in another part. By supplying with a constant water flow of 22 $°C$ inlet temperature, the mixing of return water could also achieve a steady return temperature of 22 $°C$ (Fig 3.1).

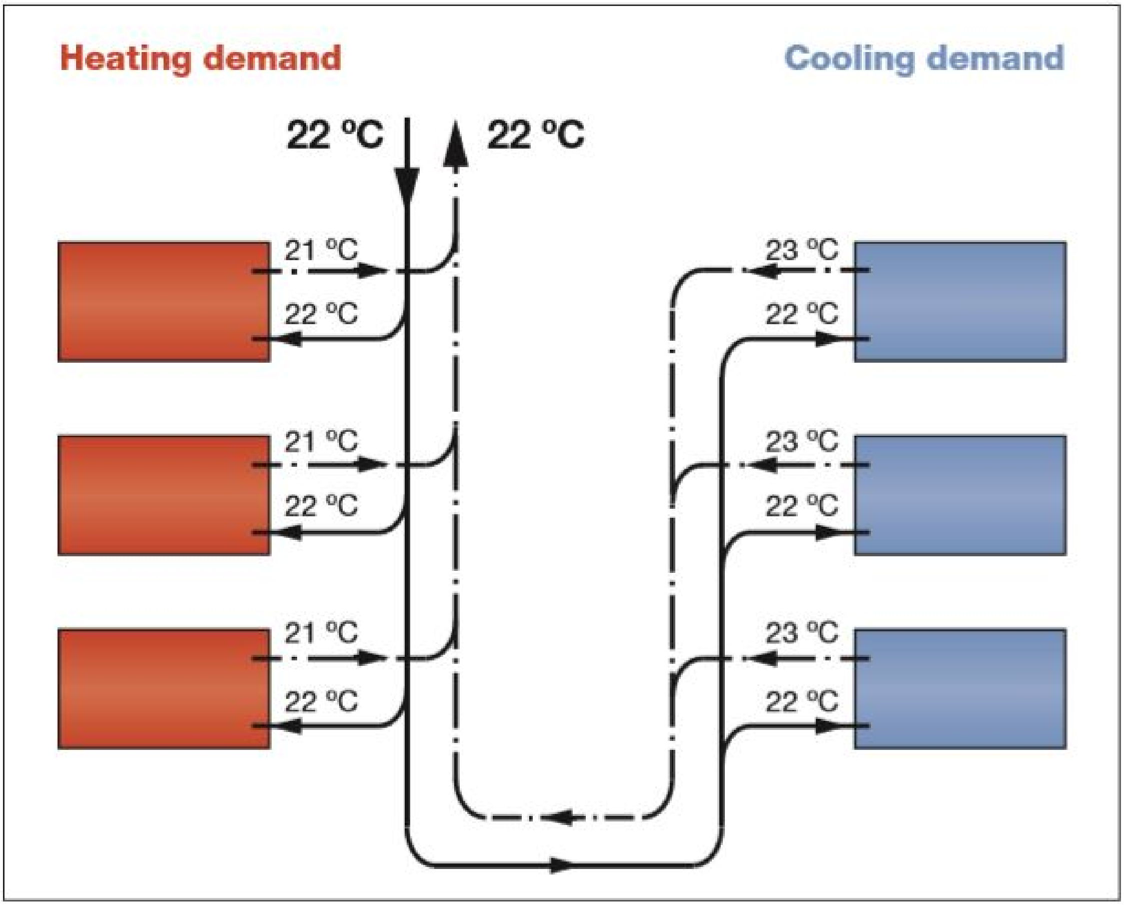

Figure 3.1: *Water temperature for Spring Autumn. 50% cooling, 50% heating need. [Lindab, 2016]*

In order for the system to be efficient, it is necessary to maintain a constant flow throughout the entire system. Only a small amount of energy is required to keep the temperature steady. As a result, energy balance is achieved in the building by transporting accumulated heat to colder areas. The reduction of water flow results in decrement of energy transfer between the rooms, which consequently decreases the system's efficiency.

Additionally, the constant flow throughout the entire system eliminates the need for control valves, actuators or controllers in the different areas, while temperature sensors and thermostats are redundant, apart from a temperature control for the entire system, installed in the technical room. As a result, the absence of valves and dampers reduces the pressure losses, which can lead to the use of smaller pumps.

Furthermore, the low velocities of the inlet air reduces the risk of draft in the occupied area, achieving optimal air distribution. At the same time, the relatively low temperature of the induced air causes small temperature difference with the room air, avoiding stratification problems.

The components of a Lindab Solus System are the following:

- Cooling unit
- Heating unit
- Free cooling unit (optional)
- Solus beams
- Water pipe system

Generally, the heating and cooling capacity is determined by the temperature difference between the water circuit and the room air temperature. The higher the temperature difference, the higher the capacity. Given that with this system the temperature difference is very low, the coil's efficiency has to be very high in order to compensate for the small temperature difference and deliver the desired high capacity and reach the same output effect.

Finally, free cooling can be achieved at higher outdoor temperatures since high temperature cooling is used. As a result, the number of days when free cooling is possible is increased significantly.

[Lindab, 2016]

3.2 Radiator heating system

A radiator heating system is a hydronic heating system. Hydronic heating systems have been used for hundreds of years and are quite simple in principle. A hydronic heating system uses water (or a water-based liquid) to transfer thermal energy from where it is produced (like a heat pump) to the space where it is needed, through convection and radiation (using heat emitters like radiators).

Using water as a medium for heat transfer, makes hydronic systems highly suitable for heating systems. Water is available in abundance, it is nontoxic, nonflammable and has higher heat storage capabilities of many materials. In comparison to using air as a medium, the specific heat capacity of water in $kJ/(kgK)$ is about 4 times greater than air, while the density is about 1.000 times higher, at 980 kg/m^3, whereas for air is 1.2 kg/m^3. Water is thus around 4,000 times better than air at transporting heat flow.

A radiator heating system consists of three parts, namely:

- **heat source**: e.g. a boiler, heat exchanger or the like, as well as various equipment.
- **distribution**: i.e. piping and other equipment that ensure proper distribution of the hot water.
- **consumption**: which consists of the heat emitters (like radiators) that emit the heat to the room.

Which **heat source** a heating system will use, can be specified by several things, like personal preference, availability, local or state regulations.

A hydronic systems' **distribution** system may be divided into several general piping arrangement categories:

- One-pipe
- Two-pipe direct return
- Two-pipe reverse return (sometimes also called three-pipe)
- Four-pipe

The one-pipe system is characterized by a simple piping loop, as there are no separate pipes for supply and return. In this layout, the same water passes several radiators, which makes the water colder and colder as it progresses further in the piping system.

The two-pipe system is characterized by having separate piping for supply and return. This means, among other things, that all radiators get water with virtually the same temperature. The two-pipe system can be arranged in two different layouts: with direct return or with reverse return. The direct return system takes the shortest route back to the source, while the reverse return is arranged so that each flow path (supply + return) is of similar length and flow resistance.

The main advantage with the reverse return is that because both supply and return flow resistances are roughly equal (since the flow paths are the same), the system is essentially self-balanced. See Figure 3.2.

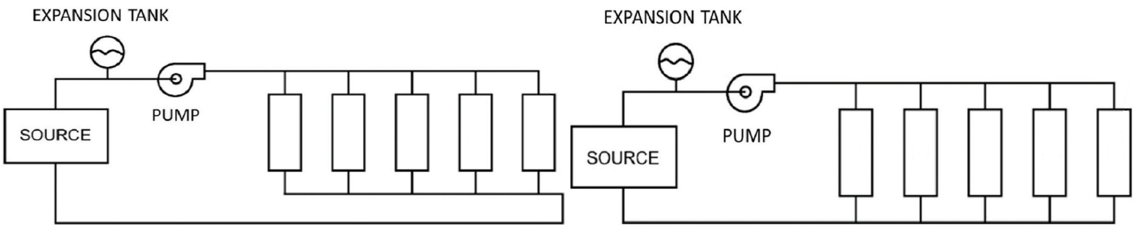

Figure 3.2: *Two-pipe system. Left: reverse return, right: direct return. [Crall, 2018]*

A four-pipe system (two supply and two return) is basically two two-pipe systems working together, which makes it possible to have hot and chilled water during intermediate seasons. This makes it possible to heat and cool at the same time.

The **consumption system** consists of the heat emitters that have to heat up the rooms of the building, as well as the heat exchangers included in any related systems, such as ventilation and DHW systems.

There are many different kinds of heat emitters which differ from each other in several ways, for example, distribution of heat emitted by radiation and convection, heat storage capacity, the surface temperature, integration possibilities and hydraulic properties.

The choice of heat emitters depends on the technical, architectural and economic issues of each project. The technical issues involve the temperature set of the heating system, flow rate and heat output of the emitters' characteristics. The architectural parameters include the appearance of the heat emitters in accordance to the architectural design, style etc. The economic issue is the balance between installation, running and maintenance cost. [Byggeforskningsinstitut, 2000] [Doninelli, 1993]

3.3 Radiant floor heating system

Radiant panel heating is also a hydronic type of heating system. The radiant panel is made of numerous pipes or tubes, that are uniformly distributed along the area of the panel. These pipes are filled with water, heated at 35-40 $°C$. Due to the higher temperature of the water compared to the temperature of the construction element, heat is being transmitted from the water to the construction, which subsequently transfers it to the room, heating up the space.

There are different radiant heating systems depending on their location. Such, a radiant system can be placed on the walls, ceiling or floor of a room. In this paper, only a radiant system embedded in the floor, commonly referred to as floor heating system, will be investigated.

The constructions of a floor heating system differ and there are numerous possibilities. For example, the pipes containing hot water can be placed directly in the slab or they can be on top of the slab, in a layer of screed. Both examples can be seen below. Typically, the floor slab is insulated from underneath to prevent heat from radiating downwards. This can differentiate for each specific case due to the placement of the slab itself in the building.

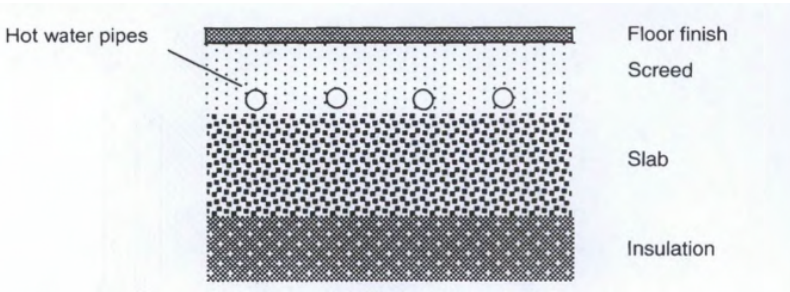

Figure 3.3: *Floor heating construction with pipes in the screed layer [Siegenthaler, 2012]*

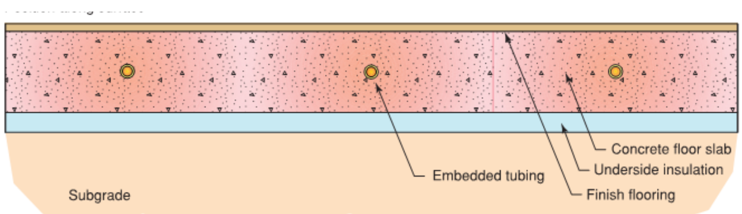

Figure 3.4: *Floor heating construction with pipes placed in the slab [Siegenthaler, 2012]*

The placement of the pipes is also a variable when it comes to floor heating systems. The distance between the pipes, their size and pattern arrangement are parameters which if changed alter the outcome and efficiency of the system. There are various patterns in which the piping can be done, like spiral or serpentine. Generally, pipes near exterior walls have a fluid temperature higher than pipes centrally located. That is to overcome higher losses that occur in those areas, by increasing the heating output. When there is no wall facing outwards, the heating output is designed to be uniformly distributed along the area of the floor.

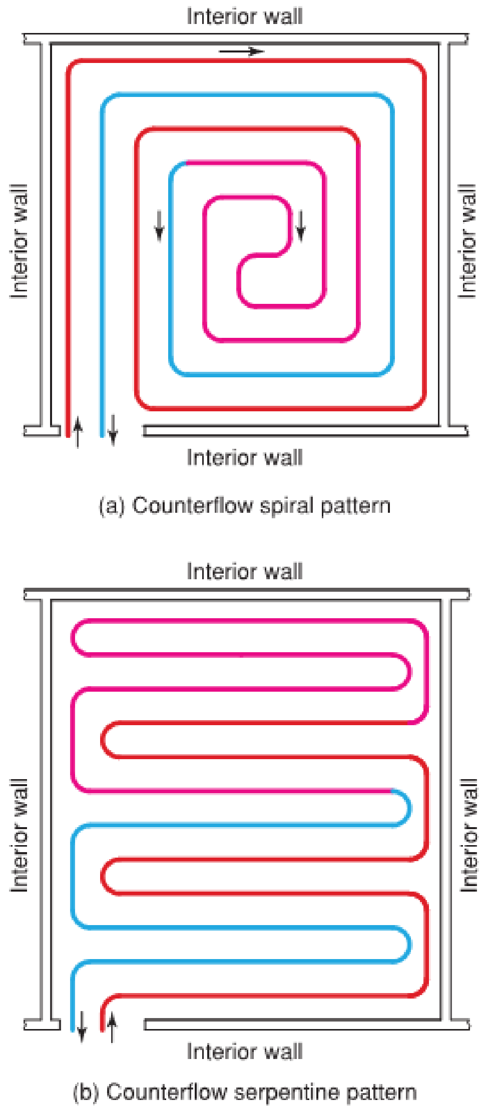

Figure 3.5: *Floor heating different layout patterns [Siegenthaler, 2012]*

4 Model Description

In this chapter, the simulated models in Energy Plus will be described in detail and schematic diagrams will be presented for the different systems.

4.1 Building Model Description

The created model is a simplified version of the new Aarhus Municipality office building. It is the first nearly zero-energy office building in Denmark and it was built in 2012. The building is located in the southwestern part of Aarhus, at Grønlandsvej 1, Viby. It consists of 3 floors and a basement. It is oriented towards North with a deviation of 30 degrees.

In the EnergyPlus model, only 3 floors have been designed, resulting to a total area of 2924.1 m^2. In Figure 4.1, the plans of all modeled floors are shown, with the marked thermal zones. In Table 4.1, the areas of each thermal zone are given.

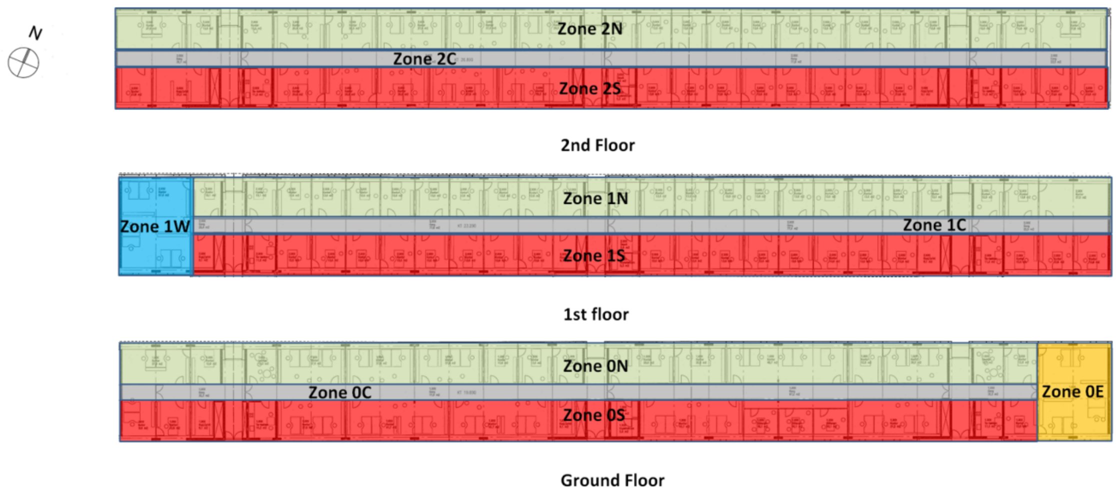

Figure 4.1: *Floor plans and thermal zones*

Zone	0C	0N	0S	0E	1W	1C
Area $[m^2]$	146.88	362.61	362.61	102.60	51.30	155.52

Zone	1N	1S	2C	2N	2S
Area $[m^2]$	383.94	383.94	164.16	405.27	405.27

Table 4.1: *Thermal zones' areas*

The internal walls of each zone have not been modeled as vertical surfaces; instead, their properties have been added as internal thermal mass, by the total surface area being exposed to the zone air.

The internal gains from people load, lighting and electrical equipment, as well as the used schedules are simulated to depict the operation of an office building. In the Appendix A.4 are presented all used schedules.

The selection of materials for the modeled constructions intended to approach the actual structure of the building's components. In the Appendix A.1 are presented detailed tables with the materials for each element, along with their properties. For the shading of the building are assumed exterior horizontal blinds.

The simulation has been realized using a weather file for Copenhagen, while the site's terrain has been selected to match the urban environment. In Figure 4.2 are presented the weather data and electricity price throughout an entire year. The data is taken for year 2015, as a reference year.

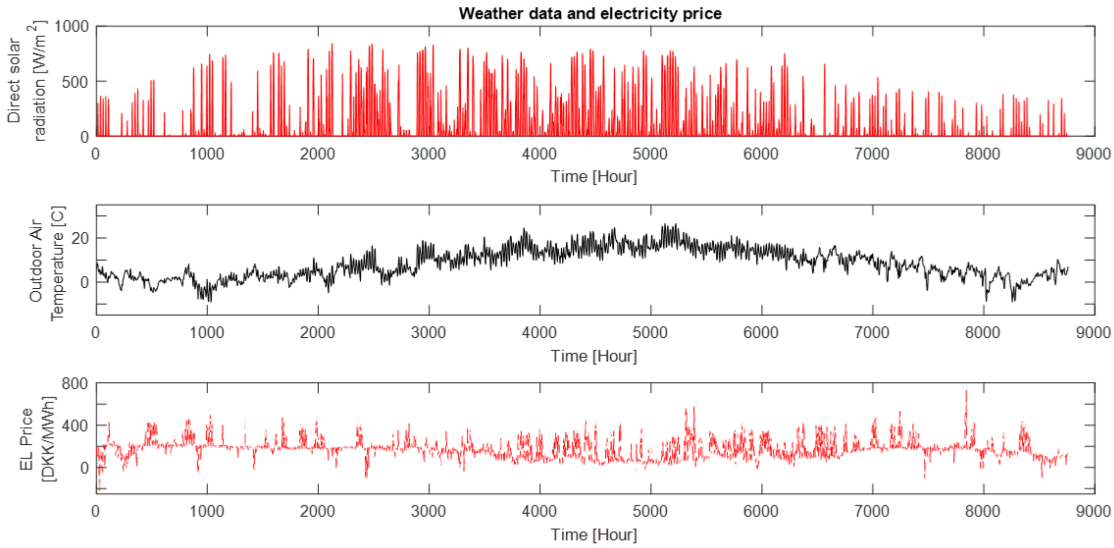

Figure 4.2: *Weather data (Outdoor temperature & Solar radiation) of Copenhagen and electricity price of Denmark in 2015*

Natural ventilation is scheduled to be automatically activated during non-occupied hours when the operative temperature exceeds 23 °C. The design flow rate values for infiltration and natural ventilation are presented in Table 4.2.

	Infiltration (all zones)	**Natural Ventilation (per zone)**
$[m^3/s * m^2]$	0.00004	0.0012

Table 4.2: *Infiltration & Natural ventilation*

Finally, the zone thermostat set-point temperatures for heating and cooling, during occupied and unoccupied hours are presented in Table 4.3, for the two different cases (Reference and Flexibility).

		Heating Set-point (occupied/ unoccupied)	**Cooling Set-point (occupied/ unoccupied)**
R		20/ 18 °C	25/ 27 °C
F	Low Price (<111.5 DKK/MWh)	21/ 19 °C	24/ 26 °C
	Middle Price (>111.5 & <203.8 DKK/MWh)	20/ 18 °C	25/ 27 °C
	High Price (>203.8 DKK/MWh)	17/ 15 °C	29/ 31 °C

Table 4.3: *Office room heating and cooling set-points for "Reference" and "Flexibility" case, during occupied and unoccupied hours.*

For the Flexibility case, the activation of cooling is additionally controlled by the direct solar radiation level and outdoor air temperature. Therefore, during low electricity price, cooling is being activated if the direct solar radiation is above 500 W/m^2 and the outdoor air temperature is above 20 °C, at any time during the following 24 hours.

4.2 Novel two-pipe heating and cooling system

This novel building energy system combines low-temperature heating and high-temperature cooling, with a two pipe system that can supply heating and cooling to different zones of the building, simultaneously. The model comprises two loops, an air and a water loop. Outdoor fresh air is supplied in the zone through an active beam, after being preheated by a rotary heat recovery unit, with a set-point of 18 °C. The active beam unit consists of a heating/ cooling coil, which is connected to the water loop, an air mixing chamber and nozzles. The primary air enters the air mixing chamber through the nozzles, resulting in a low-pressure zone. Thus, secondary air is induced from the room in the mixing chamber, after passing through the heating/ cooling coil. The outdoor air fraction for the outdoor air mixer is set to 100% during occupied hours in order to assure the supply of fresh, non-contaminated outdoor air. The water loop is connected to the district heating and cooling network. In Figure 4.3 is depicted a schematic diagram of the system.

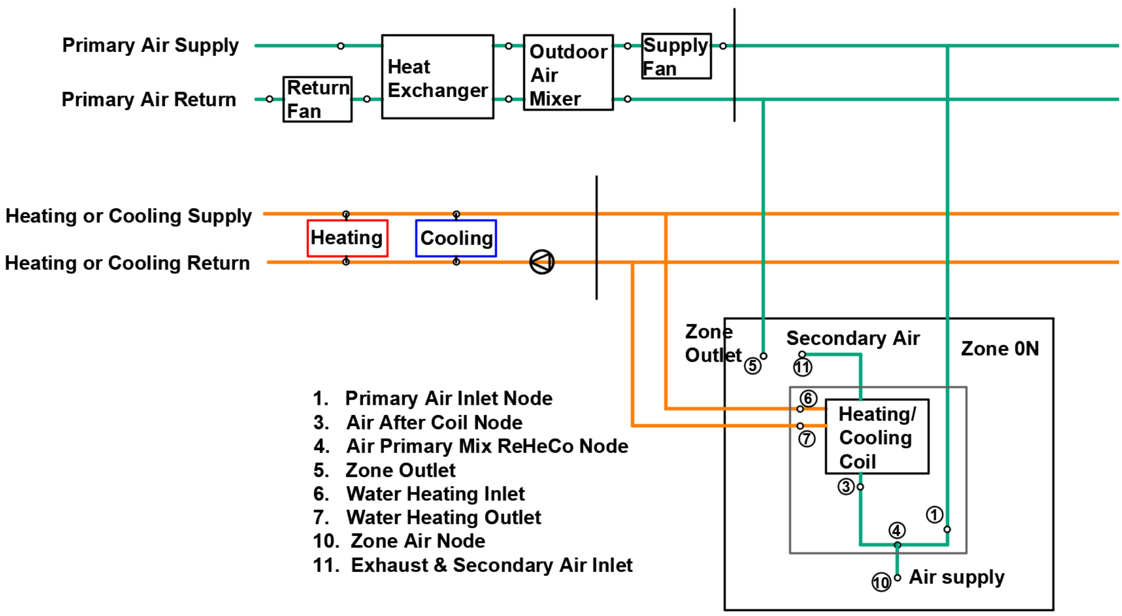

Figure 4.3: *Schematic diagram of Lindab Solus system*

The supply water temperature entering the coil of each zone is regulated based on three components. The return water temperature and the difference between the set-points for heating and cooling and the minimum and maximum measured temperatures of all zones, respectively. The resulting temperature of the water loop is set close to the room temperature (22 °C). As a result, the system can use the excess heat from warm zones to heat up colder areas, and vice versa. Additionally, the air supply temperature is set to 18 °C for heating and 23 °C for cooling.

4.3 Radiator Heating and Mechanical Ventilation System

The second modeled system is a radiant - convective heating system, using hot water radiators and a mechanical ventilation system to provide fresh air supply and cooling, when necessary. The selected radiators are baseboard type radiators, connected to the hot water loop. The air loop is sized to cover the needs of the entire building for fresh air supply, while it is equipped with a cooling coil which can cover the need of cooling during the warm months of the year. The air is supplied directly to each zone through a single duct air terminal unit with no recirculation or air mixing. The air terminals are scheduled to be activated during office hours. Both water loops are connected to the district heating and cooling network. Figure 4.4 presents a schematic diagram of the system.

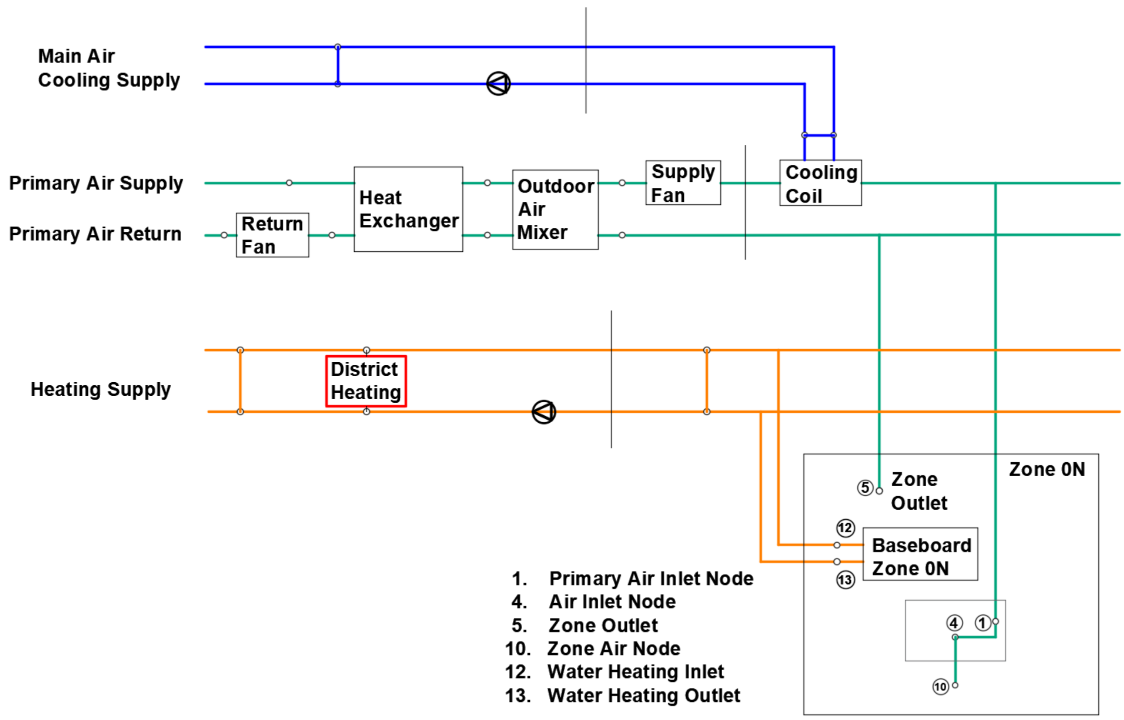

Figure 4.4: *Schematic diagram of radiator heating and mechanical ventilation system*

The system is controlled to be activated when the averaged outlet air temperature from all zones exceeds the set-point limits of heating and cooling.

4.4 Radiant Floor Heating and Mechanical Ventilation System

The last model is an underfloor heating system, using low supply hot water temperature. The layout and control of the whole system is very similar to the system with radiators that is described above. However, the construction of the floors had to be slightly variated in order to match the structural needs of this system; that is that 3 *cm* of insulation had to be added below the concrete slab in order to prevent heat loss to adjacent spaces. The water pipes have been located in the middle of the concrete slab. The exact construction elements and material parameters are presented in Appendix A.2. A schematic diagram is presented in Figure 4.5.

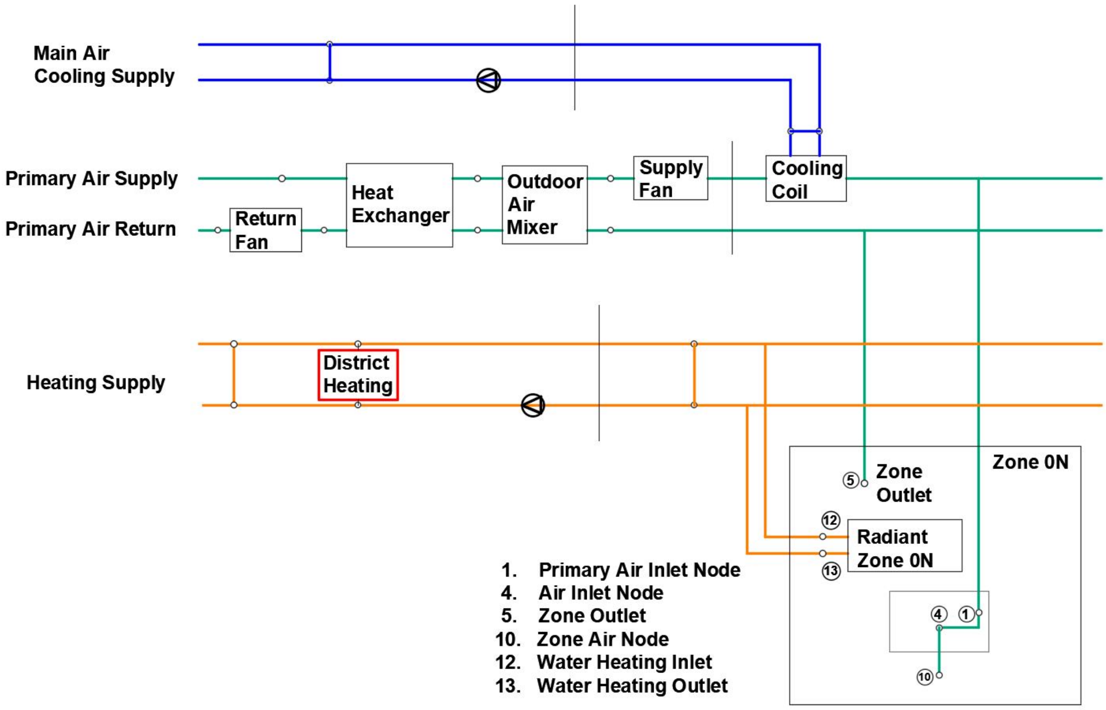

Figure 4.5: *Schematic diagram of radiant floor heating and mechanical ventilation system*

5 Results

In this chapter, the performance of all the models will be presented. The extracted data from the simulations will be displayed in graphs and the different models will be analyzed. Every system will be presented separately for both Reference and Flexibility case and comparison of the two cases will be conducted. Finally, all different systems will be compared in order for conclusions about their performance and energy flexibility potential to be drawn.

5.1 Novel two-pipe system

5.1.1 Reference

The following graphs were chosen to illustrate a week in winter (Week 12) and summer (Week 31), respectively, of the zone operative temperatures. It can be observed that generally, the temperatures of all zones is kept within the heating and cooling set-points (HS, CS) for occupied and non-occupied hours, with the exception of a couple of zones (2S, 1S).

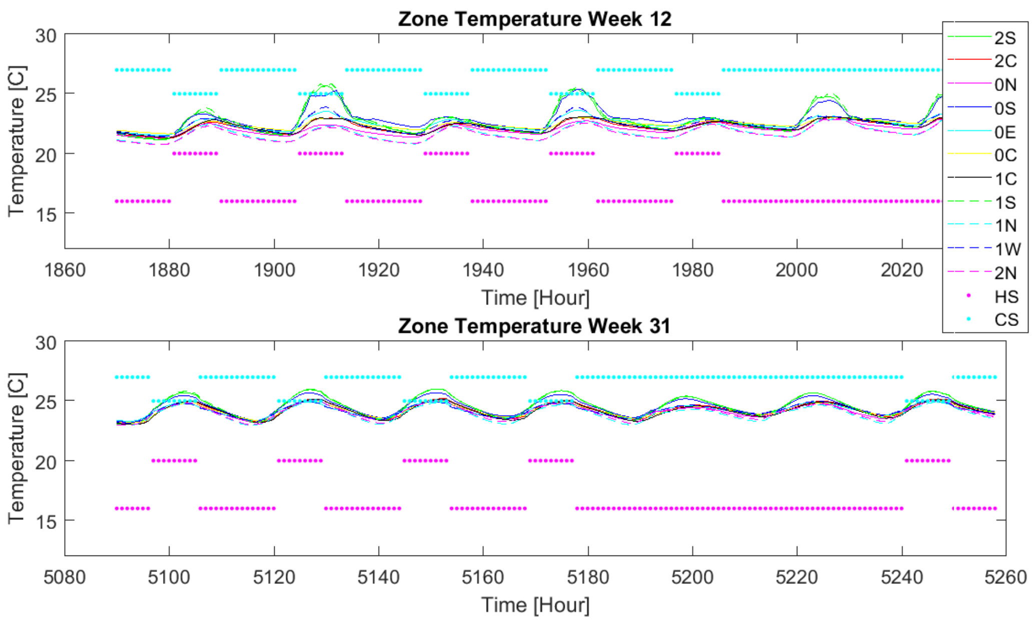

Figure 5.1: *Two-pipe system. Zone temperatures during winter and summer for Reference case.*

The system is activated by comparing the highest and lowest zone temperatures to the set-points and when they are exceeded, as in week 12 (zones 2S and 1S), the return water temperature of the coil will be adjusted in order to achieve the desired outcome. Since the cooling set-point of 25 $°C$ has been surpassed, cooling is activated; which correlates to the next figure.

In Figure 5.2 are presented the temperatures of primary air inlet temperature - Node 1, secondary air (or recirculated air) - Node 11, coil outlet air temperature - Node 3, as well as water coil supply and return temperatures, Water Demand Inlet and Water Demand Outlet.

The activation of cooling, both in week 12 and 31 is demonstrated by the lower temperature of the supply water (Water Demand Inlet) compared to the return water (Water Demand Outlet). This means the system has registered the need and is providing water at a lower temperature to cool the space. Consequently, the temperature of Node 3 is also lower than the one of Node 11. Additionally, the temperature of Node 1 has a steady pattern which follows the office schedule hours. During occupied hours, the supply air temperature is set to 18 $°C$, which is the set-point of the heat exchanger. During non occupied hours, the outlet air mixer is deactivated and the zone air is circulating in the air system. On the other hand, in the course of summer, week 31, the same pattern can be observed with the difference that Node 1 has a constant temperature since the heat exchanger is deactivated.

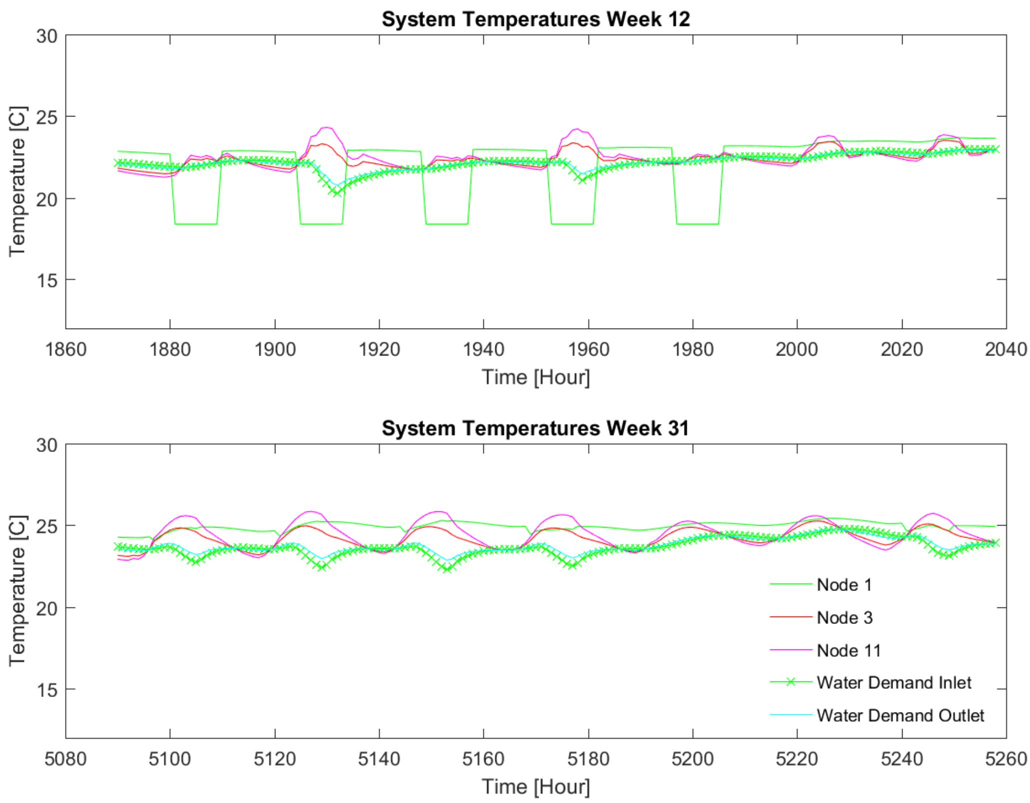

Figure 5.2: *Two-pipe system. System temperatures during winter and summer for Reference case.*

In Figure 5.3, a heating scenario is represented. This is based on the temperature of the water supply being higher than the one of the return. The fact that the temperature of the air node after the coil is higher than the one of the exhaust air, backs up this statement. Even though the set-point is maintained in the presented zone, it is to be remembered that the system is activated by the minimum and maximum temperature of all zones and a uniform supply water temperature is provided to all coils. In this case, it was the temperature in zone 1N that was below 20 °C.

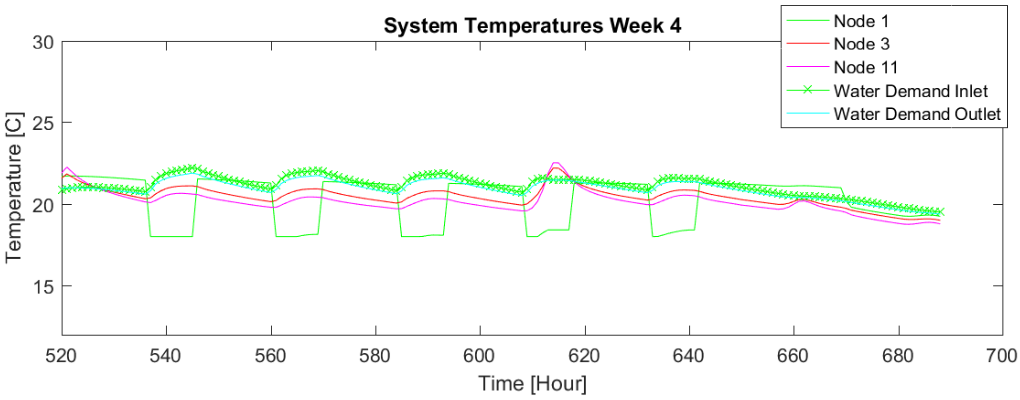

Figure 5.3: *Two-pipe system. System temperatures during winter for Reference case.*

In terms of energy use, a large share of the total energy consumption is accounted for the fan, which is represented by the green bar in Figure 5.4. It is though expected for such a system, since both the act of heating and cooling are achieved by means of the ventilation system. The values of energy use are 4.17 kWh/m^2, 3.14 W/m^2 and 8.76 W/m^2 for heating, cooling and fan, respectively.

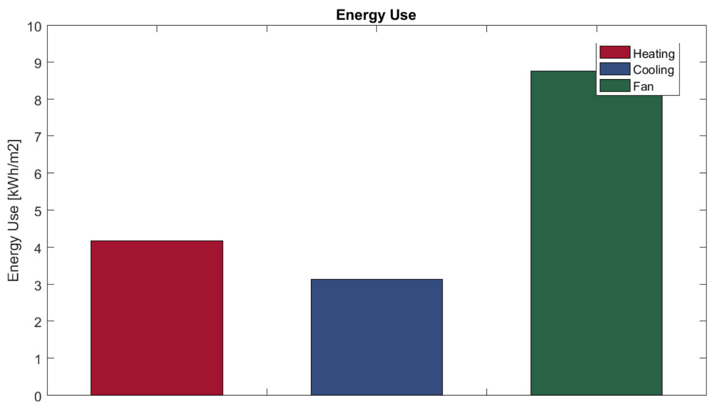

Figure 5.4: *Two-pipe system. Energy use for heating, cooling and fan for Reference case.*

5.1.2 Flexibility

The Flexibility case of this model performs similarly to the Reference case, with no major difference in terms of zone temperatures, apart from the additional set-points for the different levels of electricity price. The activation of cooling process occurs in the same way as in Reference case, with the exception that Flexibility introduces a new control for cooling. When electricity price is low, if the direct solar radiation is above 500 W/m^2 and the outdoor air temperature is above 20 $°C$ during the next 24 hours, cooling is being activated.

Analyzing figure 5.5, it can be observed that by introducing the new control strategy, the energy consumption for cooling has decreased (2.70 W/m^2). Energy consumption for heating has also decremented slightly (3.83 W/m^2), even though it is not as much as the one of cooling, while the fan uses the same amount of energy as before.

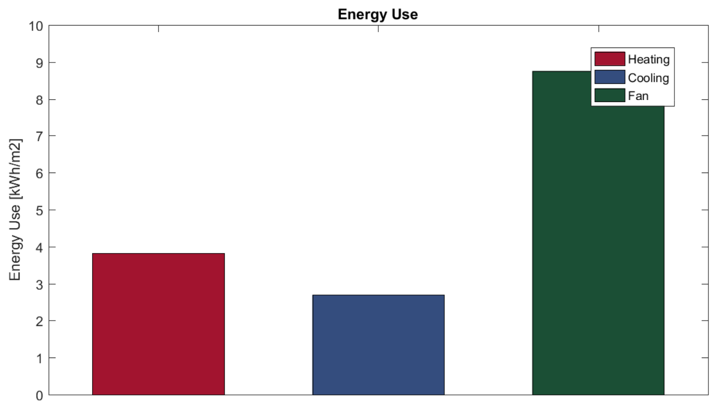

Figure 5.5: *Two-pipe system. Energy use for Flexibility case.*

5.1.3 Compare

Ability of power adjustment

The following graphs are based on the calculation of the power difference between Flexibility and Reference case:

$$\text{Power difference} = \text{Power Flexibility} - \text{Power Reference [kW]}$$

Figure 5.6 shows the power difference for different price levels during the entire year. For the energy flexibility control to be activated, the power difference should be positive (white) during low level prices and negative (black) during high price periods. During high electricity prices the power used in the Flexibility model is less than in the Reference model (<0, black), while for low electricity price it spends more power (>0, white). The gray color represents zero power difference between the cases. During summer period, the Flexibility case model increases the consumption of low price electricity, due to the implemented control strategies, while during winter period, the Flexibility case model decreases the energy consumption during high price level, due to the adjusted set-points. During summer period, cooling is not triggered by the weather conditions, as there is no high need for cooling in the Danish climate, but by the low electricity price level.

Figure 5.7 shows the ability of the system to adjust its power usage according to the 8 price levels. When the prices are low (levels 1-2), the power difference is at its highest. This shows that the Flexibility model is performing as expected and will use more energy when the prices are low. During medium prices (levels 3-6), the power difference is around 0, meaning that the energy used is about the same for both models. Finally, during high prices (levels 7-8), the opposite of the low price periods occurs. The power difference is negative, which means that the flexible model uses less energy at these prices.

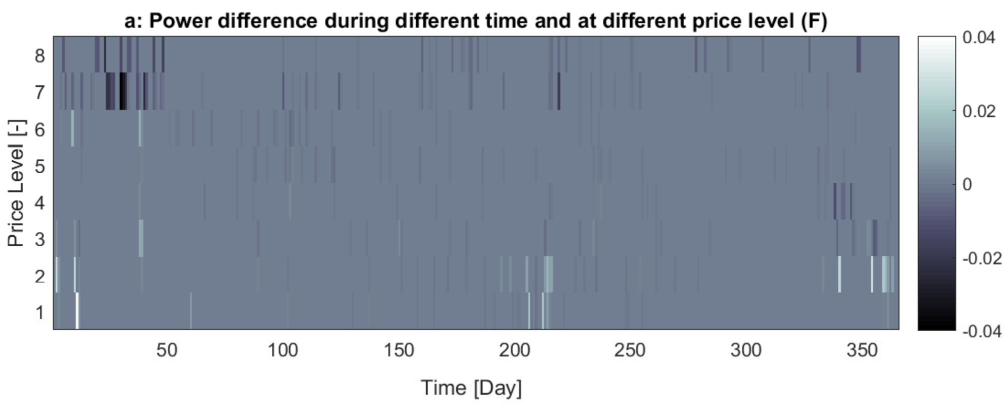

Figure 5.6: *Two-pipe system. Power difference between Flexibility and Reference case at different time of the year and within different price level.*

Figure 5.7: *Two-pipe system. Ranges of hourly power difference of Flexibility case withing different price level.*

Ability of energy shifting

As mentioned previously, a big part of the energy flexibility is due to the energy stored in the building's construction during heat accumulation. By using more energy when the prices are low, it is possible to store more energy that will be released during periods of high prices. Using this process of storage and activation leads to energy savings.

Figure 5.8 shows the shifted energy consumption between the Reference and Flexibility case. With dark blue are presented the activated periods of energy storage (during low electricity prices). With light blue are the inactivated periods of energy conservation (during high electricity prices). With green is shown the energy consumption during medium prices where no activation occurs. Finally, with yellow is the total energy consumption.

The figure shows high consumption difference during activated and inactivated periods. During low prices it is 0.37 kWh/m^2 for the Reference case and rises to 0.65 kWh/m^2 for Flexibility. The consumption in the inactivated periods goes from 0.53 kWh/m^2 all the way to almost null consumption. Nothing changes in period of medium prices with a consumption of 0.92 kWh/m^2 for both cases. Lastly, the total consumption is at 1.8 kWh/m^2 for the Reference case and decreases to around 1.6 kWh/m^2 for Flexibility. The decrease is mainly caused by the very low consumption during the inactivated periods (high prices).

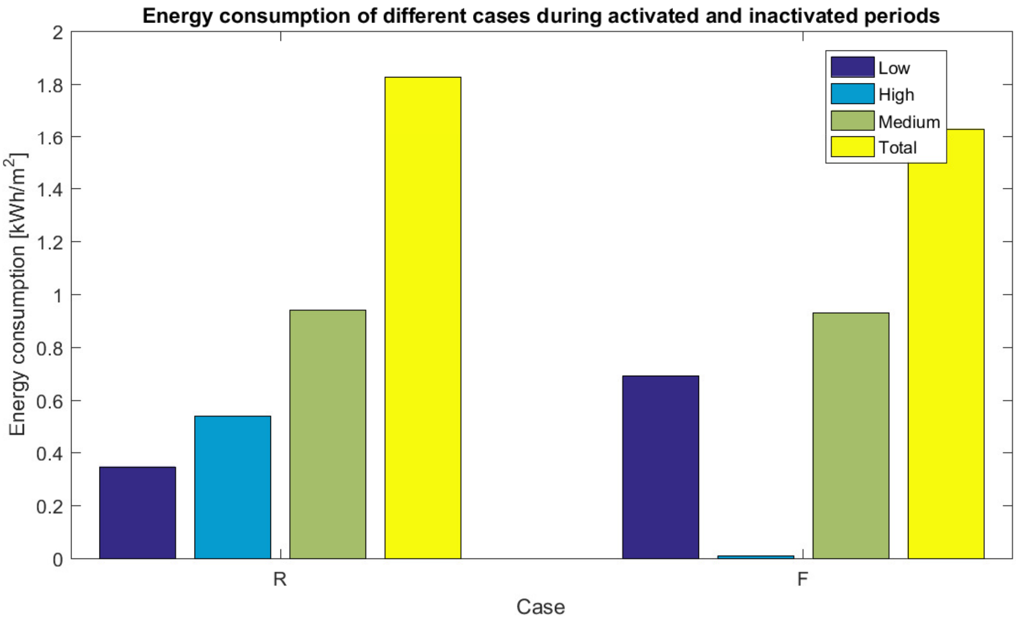

Figure 5.8: *Two-pipe system. Energy consumption of different cases during activated and inactivated periods.*

Economic benefit

Figure 5.9 shows the economic benefit. Graph (a) shows the monthly energy consumption in kWh/m^2. Graph (b) shows the monthly energy cost in DKK/m^2, and lastly, graph (c) presents the energy consumption at each of the 8 price levels in kWh/m^2. The blue bars present the Reference case, while the yellow the Flexibility.

In graph (a), it can be observed that the Flexibility model has a lower energy consumption than the Reference model in all but two months, July and December. Furthermore, the energy cost is a lot lower, which means that the consumed energy is during low electricity price. The Flexibility model's percentage of yearly savings is 34.9 %. This is also supported by graph (c), where it can be observed that more energy is consumed during electricity price level 1 and 2, while there is almost no consumption for level 7 and 8. For the medium price level, the consumption is about the same as the Reference model.

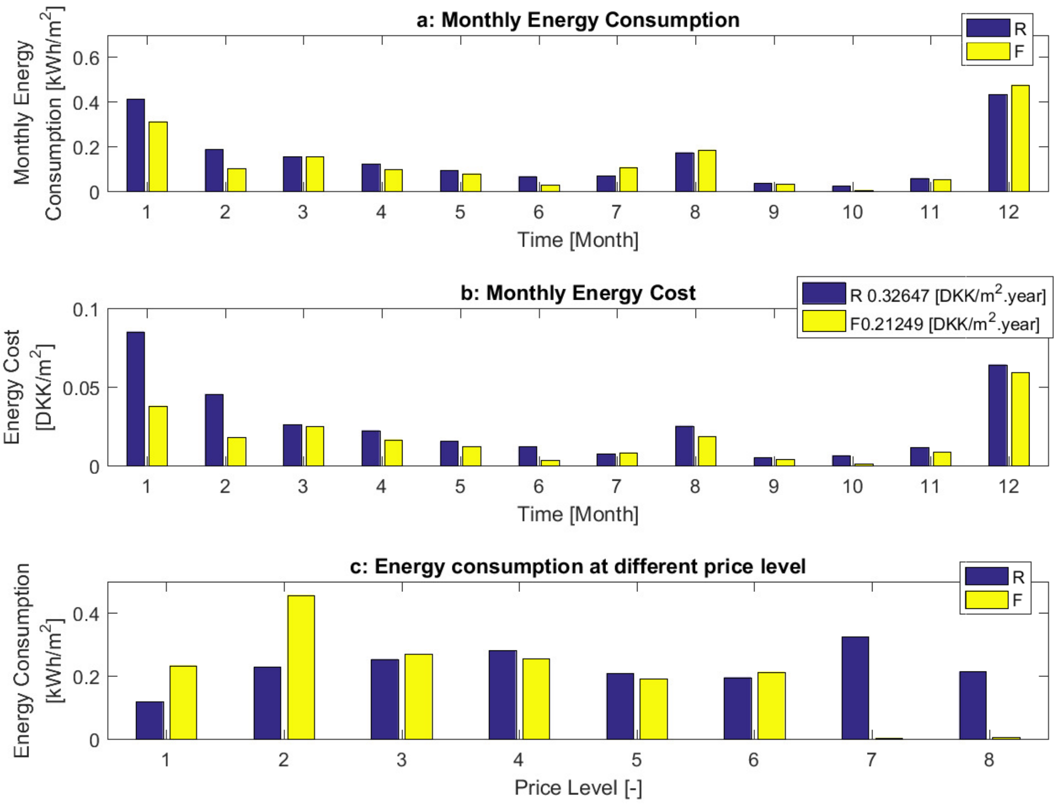

Figure 5.9: *Two-pipe system. Monthly energy cost and energy consumption of different price levels of different cases. a: Monthly energy consumption of different cases. b: Monthly energy cost of different cases. c: Energy consumption at different price levels of different cases.*

Total energy consumption

In Figure 5.10 is presented the total energy consumption in kWh/m^2, divided into heating and cooling consumption, for the two cases. As it can be observed from the graph, the energy consumption for cooling has decreased considerably, while the heating energy use has lowered slightly. The total amount for Reference is at 1.83 kWh/m^2 and decreases at 1.63 kWh/m^2 for Flexibility.

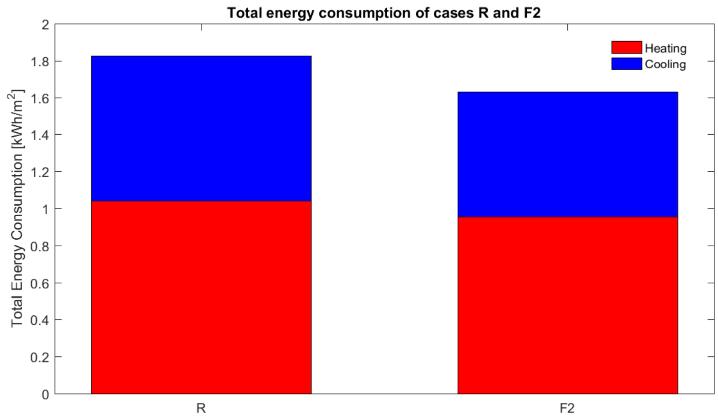

Figure 5.10: *Two-pipe system. Total energy consumption of Reference and Flexibility case, for heating and cooling.*

Comfort level

For the Flexibility model, comfort Class I is slightly decreased while Class III is marginally increased. Since the total energy consumption for heating remains almost the same for both cases, it can be concluded that the comfort level is decreased due to cooling activation. The Reference model is within Class II 80.34 % of time, while Flexibility achieves 78.68 %, which correlates to 39 hours less time while the comfort level is within Class II. However, it can be concluded that the comfort level is still satisfying.

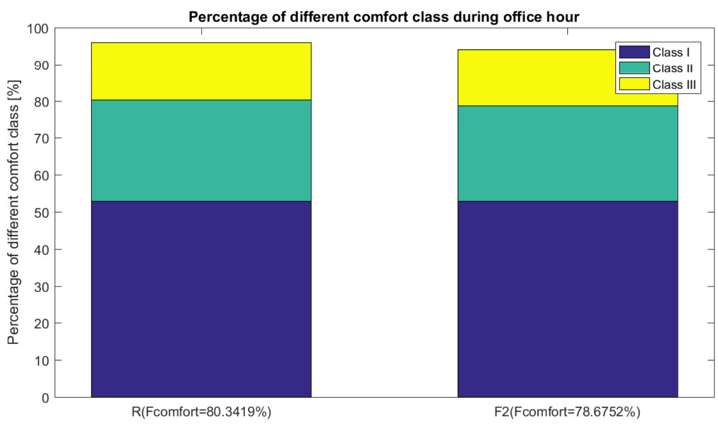

Figure 5.11: *Two-pipe system. Percentage of different comfort classes for different cases.*

5.2 Radiator Heating and Mechanical Ventilation System

5.2.1 Reference

Figure 5.12 presents the operative temperatures in all zones, as well as the set-points for the cooling and heating systems (CS, HS). The systems are activated based on the average of all zone temperatures. The graph shows that, generally, they are kept within the set-points. During summer, the set-points are exceeded slightly during occupied hours, for most days of the presented week. In these days, the cooling is activated.

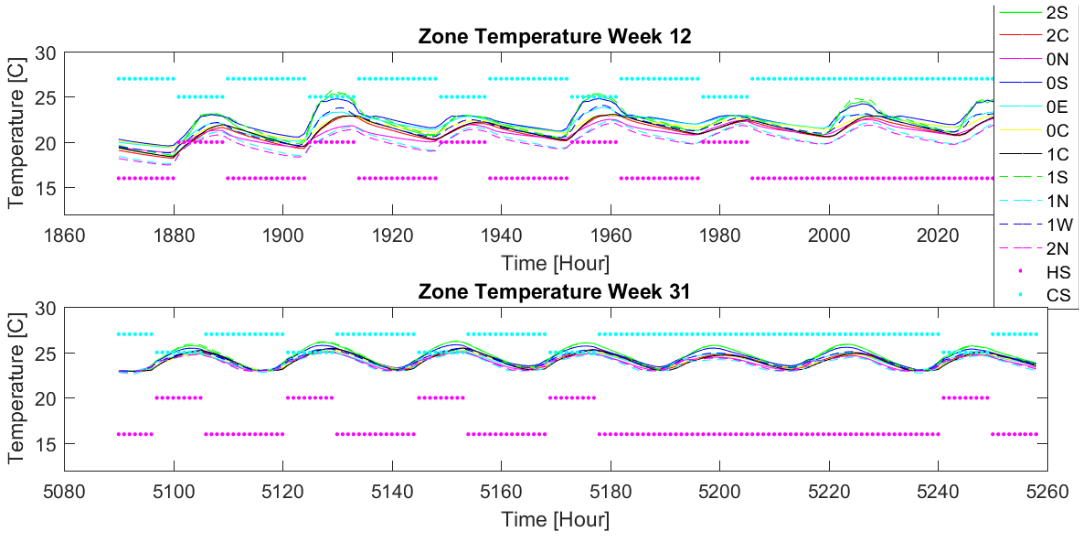

Figure 5.12: *Radiator system. Zone temperatures during winter and summer for Reference case.*

The next graphs shows the temperatures for supply and return air, as well as the outdoor air temperature, during a week in winter (Week 12) and one in summer (Week 31).

During occupied hours, the temperature of the Zone Equipment Inlet, is higher than the Outdoor Air temperature and equal to 18 $°C$, which is the set-point for the heat exchanger. During unoccupied hours, it matches the Zone Equipment Outlet temperature, due to the recirculation of the indoor air in the air system and through the outdoor air mixer (same performance as the two-pipe system). During summer period and occupied hours, it can be observed that the Outdoor Air temperature is higher than the Zone Equipment Inlet temperature, proving that the cooling coil is activated. This can also been confirmed by the Zone Equipment Outlet temperature, exiting the zones, that rises above the set-point, resulting to the activation of cooling.

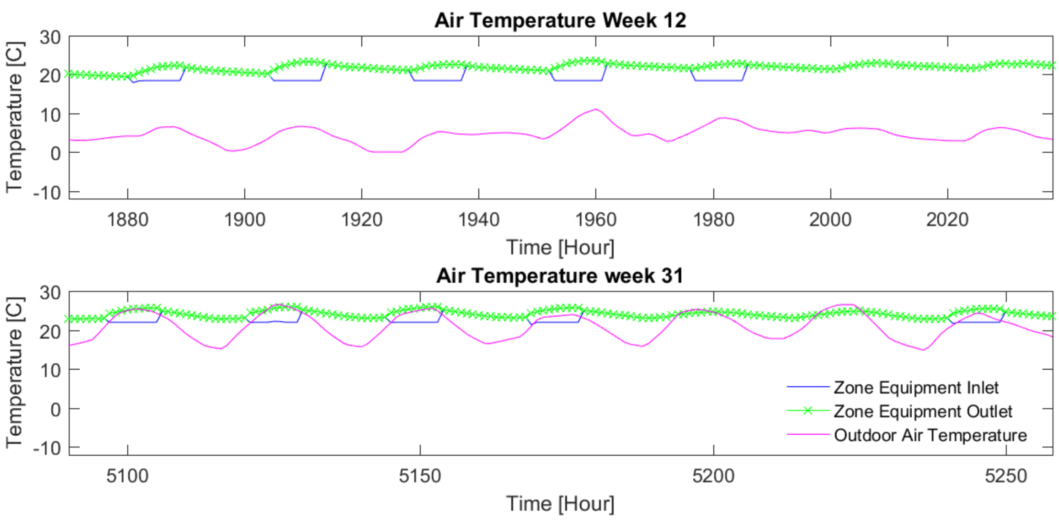

Figure 5.13: *Radiator system. Air temperatures during winter and summer for Reference case.*

The energy consumption for heating (red bar), cooling (blue bar), and the air handling unit fan (green bar) are presented in the following graph, for the second system. The heating consumption is 4.52 kWh/m^2, the cooling is 0.27 kWh/m^2, and the fan consumes 1.76 kWh/m^2. It is worth mentioning that for this system the energy consumption for cooling is noticeably smaller compared to the consumption for heating, as well as compared to the first system. This is caused by the cooling activation schedule (summer period), compared to the first system that cooling can be triggered at any moment during the entire year.

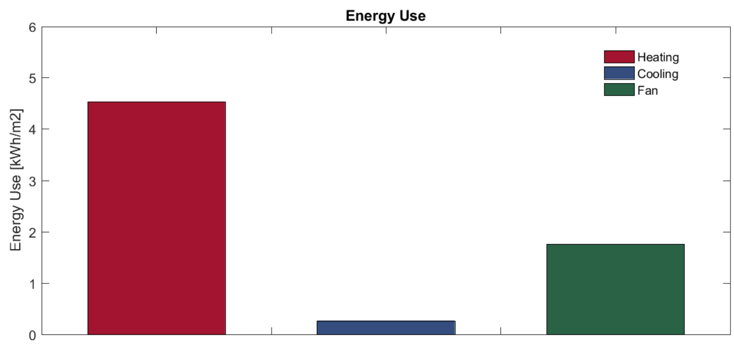

Figure 5.14: *Radiator system. Energy use for heating, cooling and fan for Reference case.*

5.2.2 Flexibility

The operative zone temperatures are similar between the two cases. However, the set-points are different since they are adjusted to the electricity prices, fluctuating between low and high.

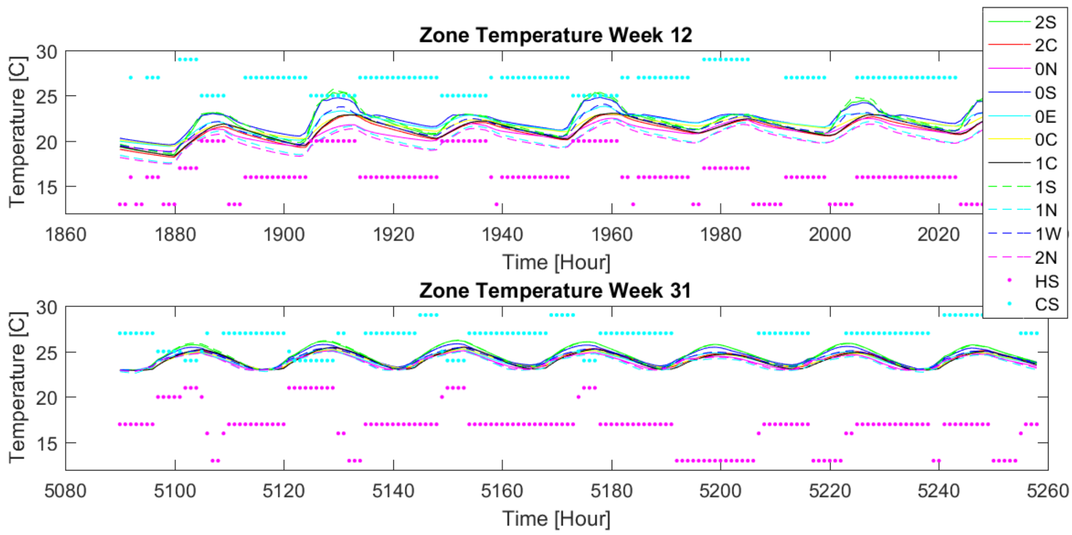

Figure 5.15: *Radiator system. Air temperatures during winter and summer for Flexibility case.*

The heating consumption is 4.24 kWh/m^2, the cooling is 0.24 kWh/m^2, while the fan consumes 1.76 kWh/m^2. Compared to the Reference model, heating and cooling energy usage is deceased while the fan has the same usage.

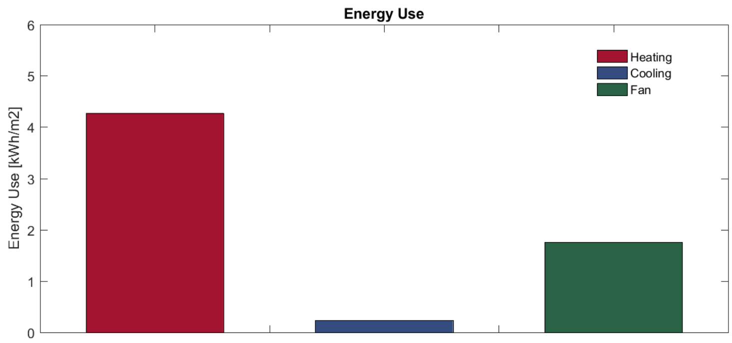

Figure 5.16: *Radiator system. Energy use for heating, cooling and fan for Flexibility case.*

5.2.3 Compare

Ability of power adjustment

Graph (a) presents negative power difference predominantly in the winter season and at the two highest levels of electricity price. This confirms that the Flexibility case uses less power than the Reference during times of high price level. This is further supported in graph (b), which also illustrates that Reference has a higher power usage at the highest price levels. However, there is no power regulation shown during the summer period.

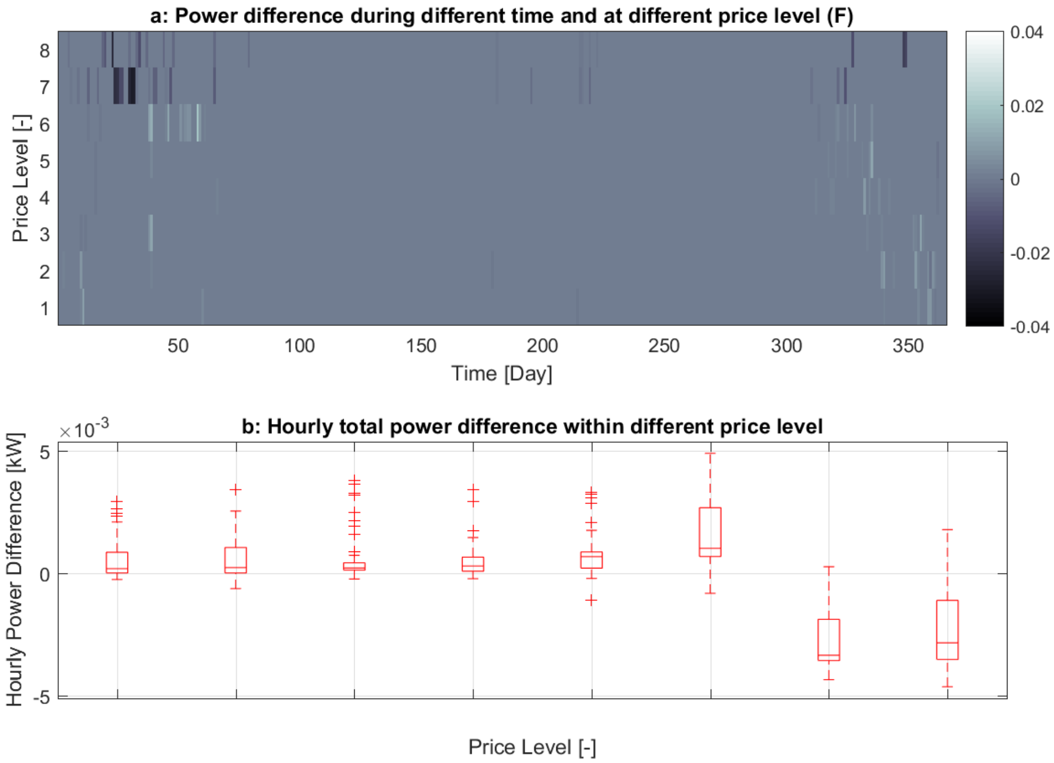

Figure 5.17: *Radiator system. Power difference between Flexibility and Reference case at different time of the year and within different price level.*

Ability of energy shifting

A better overview can be obtained from Figure 5.18, of the overall energy consumption of the two cases, which is the sum of Figure 5.19 at different price levels. It can be better observed that the total energy consumption is lower for Flexibility, while for medium price level it spends more. Additionally, Flexibility consumes visibly less energy during high price periods. Unforeseeable, the energy usage for Flexibility is only slightly higher than Reference.

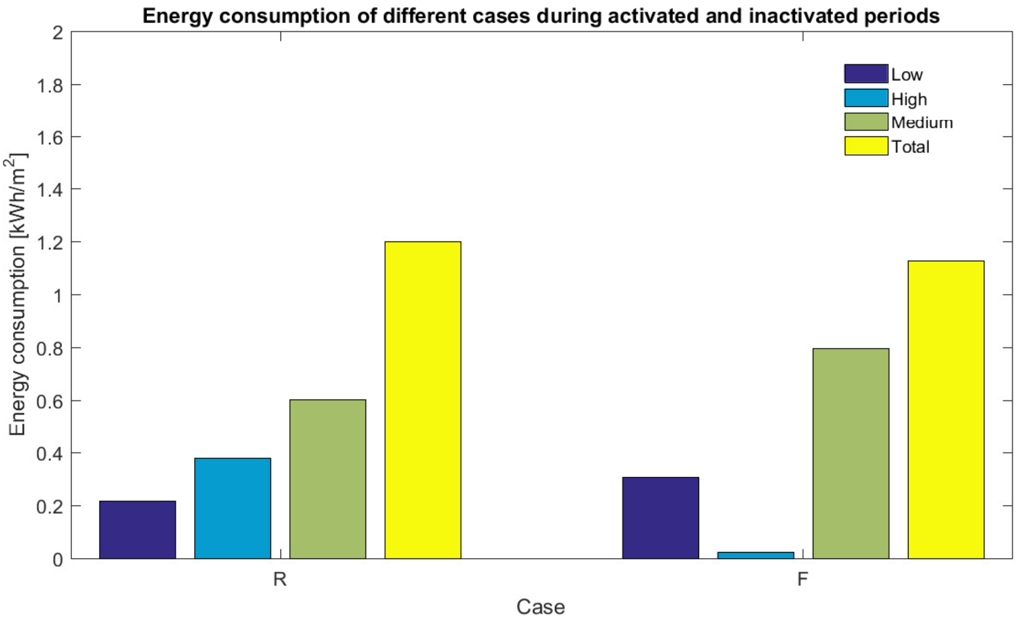

Figure 5.18: *Radiator system. Energy consumption of different cases during activated and inactivated periods.*

Economic benefit

For the radiator models, the Flexibility case works as expected, using less energy than the Reference case during high price periods and more when prices are low. As shown in the following graphs, throughout certain months (April-June, September and October), there is no energy consumption since there is no cooling demand. In the periods of high price, the Flexibility model uses very little energy compared to the Reference one. On the other hand, it uses more when prices are in the middle category. As intended, the model uses more energy during low prices, though in a smaller measure than planned. The difference between Reference and Flexibility is small.

By summing the monthly costs from graph (b) for an entire year, it can be calculated that the Flexibility model has a saving of 25.7 % in relation to the Reference case.

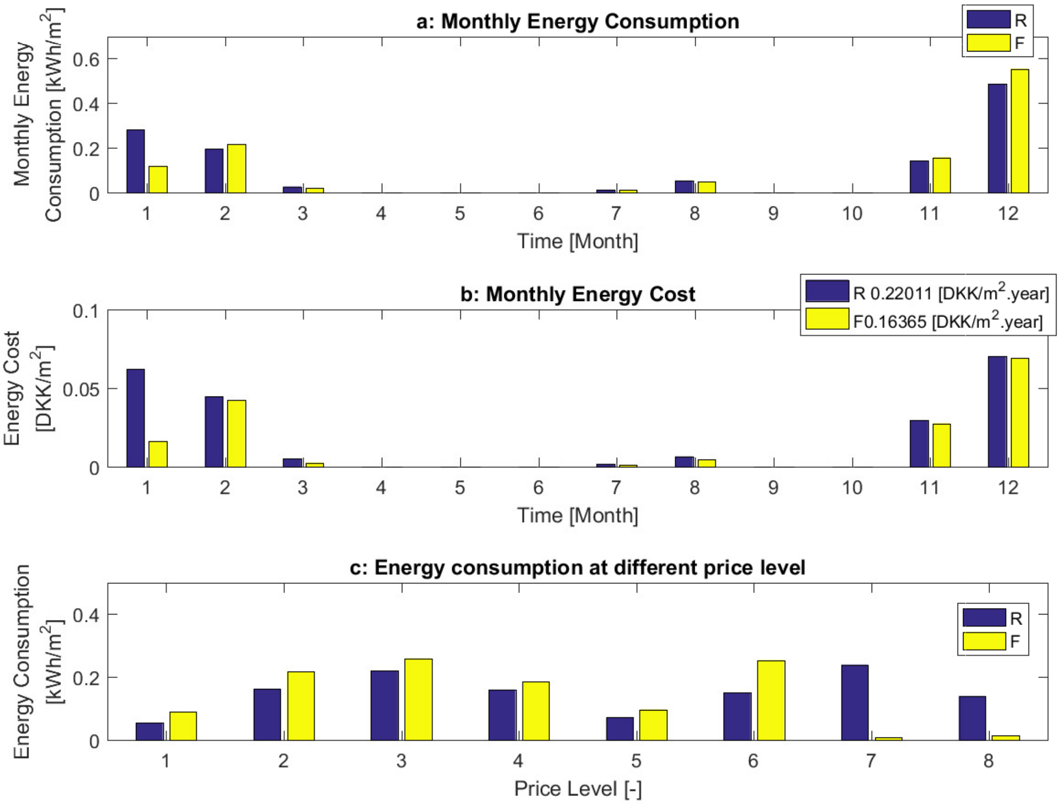

Figure 5.19: *Radiator system. Monthly energy cost and energy consumption of different price levels of different cases. a: Monthly energy consumption of different cases. b: Monthly energy cost of different cases. c: Energy consumption at different price levels of different cases.*

Total energy consumption

It is noticeable in Figure 5.20 that there is a very small difference in the energy used for cooling between the two cases. On the other hand, heating is decreased more in the case of Flexibility. This relates to the first graph (Fig. **??**) where flexibility was achieved in the course of winter. Thus, it can be concluded that energy wise, Flexibility performs better than Reference and manages to shift more energy, though the comfort level should likewise be taken into consideration.

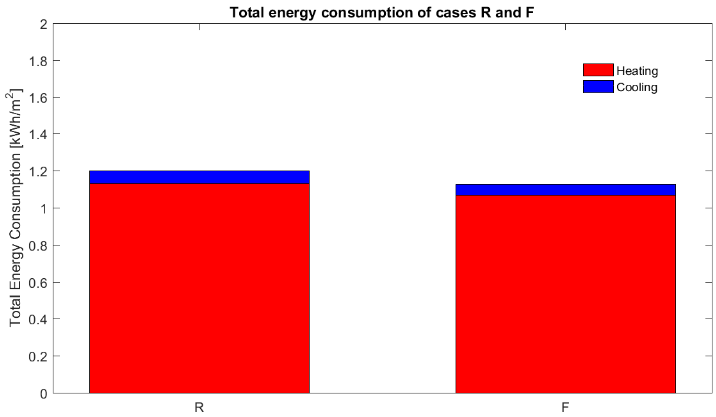

Figure 5.20: *Radiator system. Total energy consumption of Reference and Flexibility case, for heating and cooling.*

Comfort level

The Reference case presents a higher percentage of comfort, that being 69.19 % during occupancy time, while Flexibility shows 67.61 %. Even though Flexibility has a decreased percentage of comfort this is only 1.58 % and it correlates to 45 hours, in class II, less than Reference. Regardless of the fact that the comfort level is lower in Flexibility, it is deemed sufficient and not detrimental to the users.

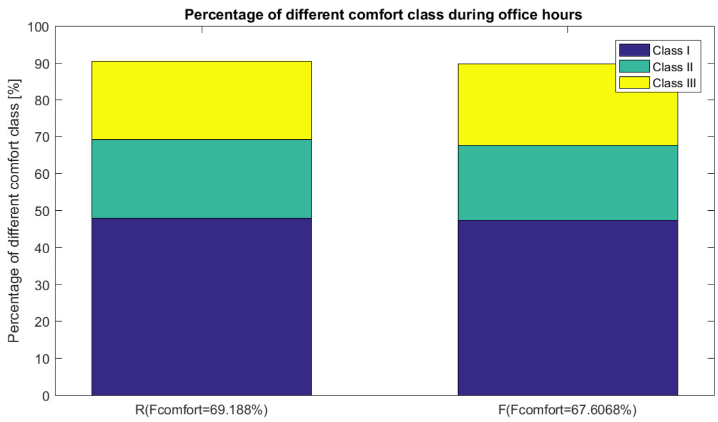

Figure 5.21: *Radiator system. Percentage of different comfort classes for different cases.*

5.3 Radiant Floor Heating and Mechanical Ventilation System

The behavior of the radiant system is very similar to that of the radiator system, given that the layout is exactly the same, with just a few modifications to match the system's needs. In Appendix A - A.3 are presented more graphs concerning the system's performance, for both Reference and Flexibility cases.

5.3.1 Reference

In Figure 5.22 are depicted the supply and return water temperatures for both the cooling coil and the hot water loop, for one week during the winter (Week 3) and one during the summer period (Week 30). In the graphs, it can be seen that the water supply temperature is constant, while the return temperature fluctuates, depending on the heating or cooling needs. In Week 3 only heating is activated, while in Week 30 is only the cooling coil.

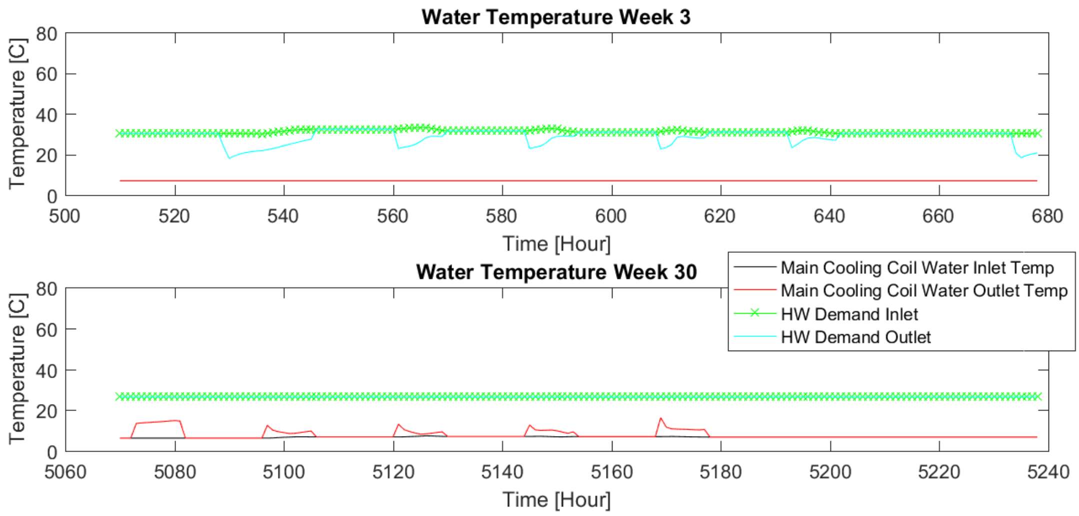

Figure 5.22: *Radiant system. Water temperatures of the cooling coil and the hot water loop during winter and summer for Reference case.*

In Figure 5.23 are given the energy use values in kWh/m^2 for heating, cooling and the fan for the Reference case of the radiant system. It is worth mentioning that the heating energy consumption (4.5 kWh/m^2) is significantly higher compared to the one for cooling (0.22 kWh/m^2). As stated for the radiator system, this is explained by the control strategy that sets the operation of heating and cooling only during winter and summer periods, respectively. During most of the summer period, the outdoor temperatures are not high enough to turn on cooling.

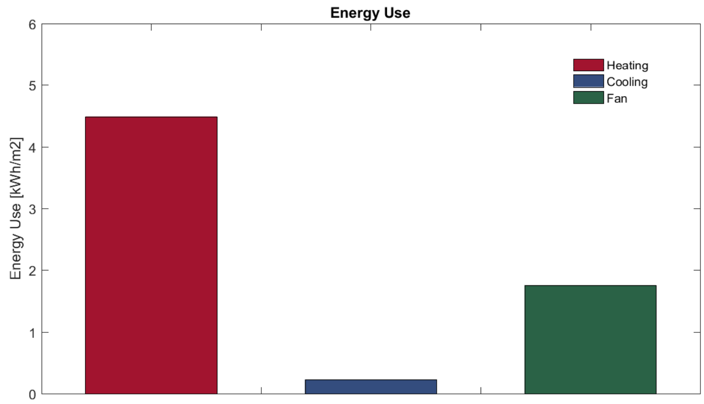

Figure 5.23: *Radiant system. Energy use for heating, cooling and fan for Reference case*

5.3.2 Flexibility

Correspondingly, for the Flexibility case, the energy use reaches the values of 3.8 kWh/m^2, 0.19 kWh/m^2 and 1.8 kWh/m^2, for heating, cooling and fan consumption, respectively. As expected, the heating consumption has dropped noticeably compared to the Reference model, while the energy use decrease for cooling is insignificant and the fan consumption is the same.

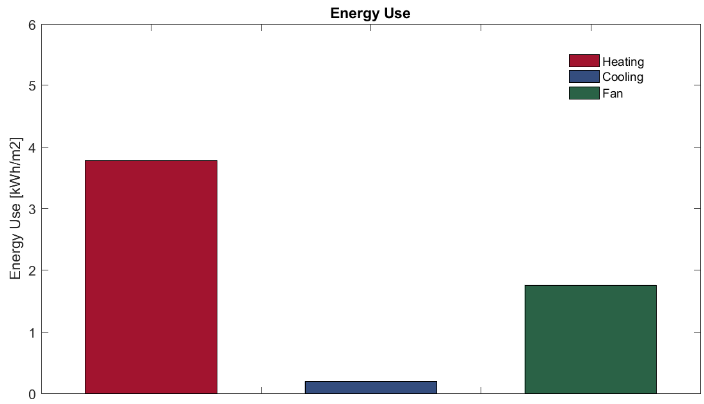

Figure 5.24: *Radiant system. Energy use for heating, cooling and fan for Flexibility case.*

5.3.3 Compare

Ability of power adjustment

It can be observed that for high price level, the power difference between the Reference and Flexibility case is negative during the heating season, meaning that the Flexibility model is consuming less energy, relating to the control strategy. However, during low price periods the released power is equal for both cases, while for medium price level, the Flexibility case has an increased power output. These observations are supported by both graphs.

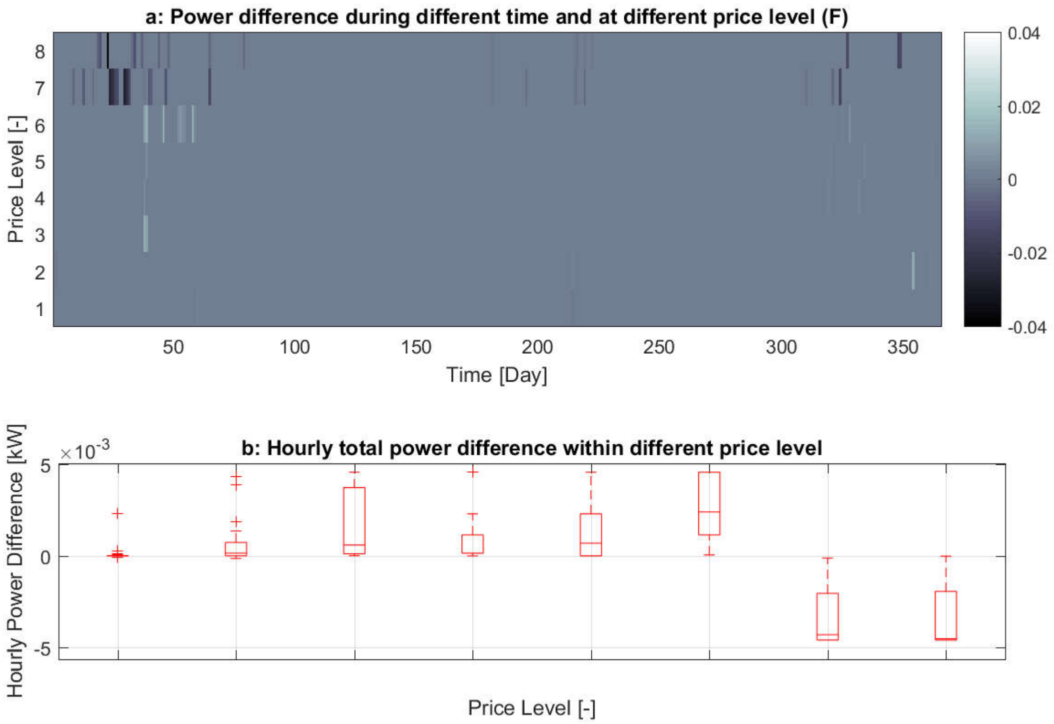

Figure 5.25: *Radiant system. Power difference between Flexibility and Reference case at different time of the year and within different price level.*

Ability of energy shifting

The ability of energy shifting can be studied easier in Figure 5.26 where is presented the total energy consumption for different electricity price levels. Summing up, the total energy consumption is smaller for the Flexibility case, while it is decreased greatly during high price level. However, the used energy is not increased significantly during low price periods, meaning that the control of energy Flexibility has been partially achieved.

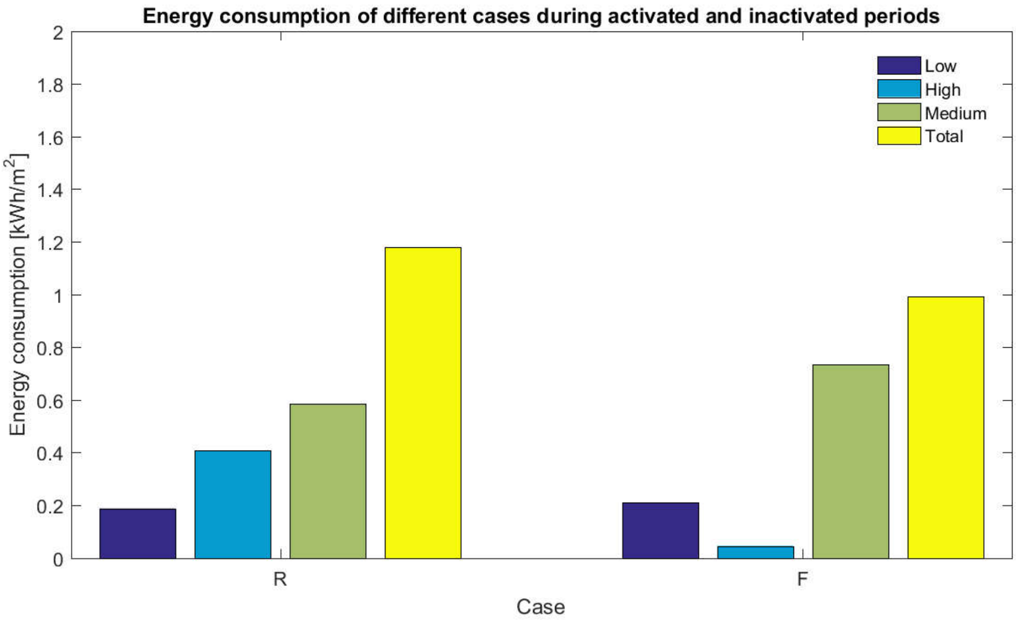

Figure 5.26: *Radiant system. Energy consumption of different cases during activated and inactivated periods.*

Economic benefit

As it can be observed more clearly from the following set of graphs, even though the Flexibility case model has a very small energy consumption during high level price periods, during medium level is higher than the Reference case, while for low electricity price is not as high as expected. At this point, it can be assumed that the increased energy consumption during medium price periods could be caused by the fail of energy storing during low electricity price. Furthermore, it is worth mentioning that like the radiator heating system, there is minimum energy consumption during the cooling season. Finally, by applying energy flexibility strategies, yearly savings of 32.3 % can be achieved, compared to the Reference case.

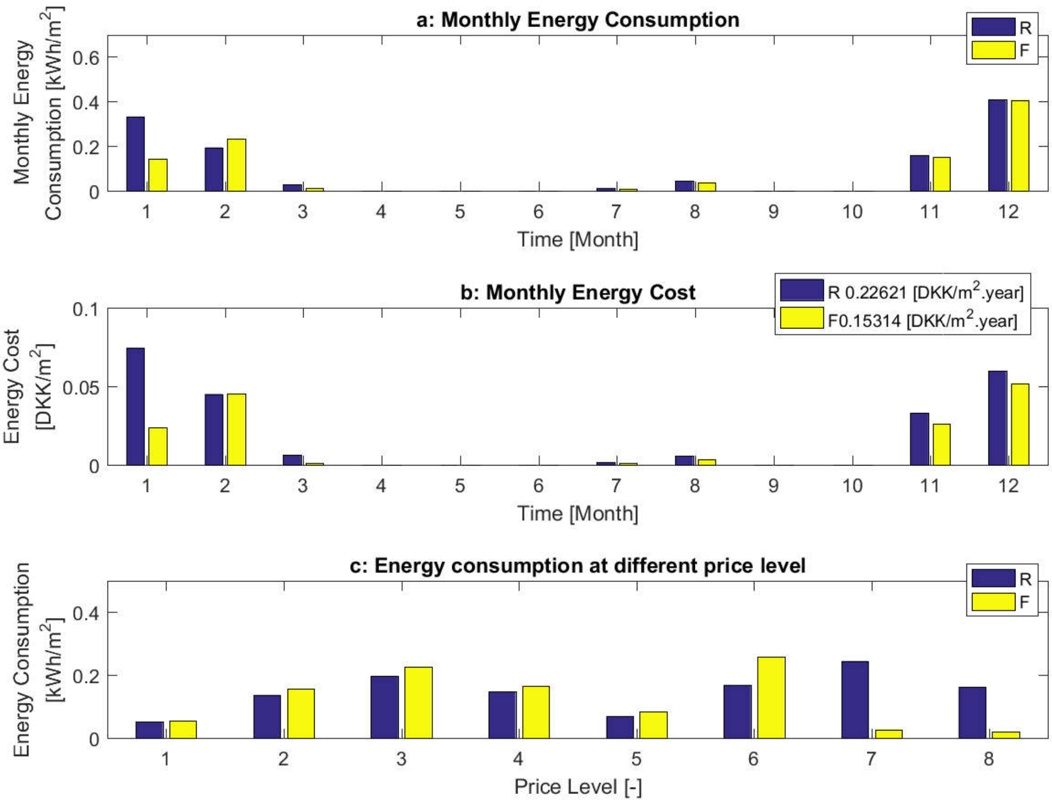

Figure 5.27: *Radiant system. Monthly energy cost and energy consumption of different price levels of different cases. a: Monthly energy consumption of different cases. b: Monthly energy cost of different cases. c: Energy consumption at different price levels of different cases.*

Total energy consumption

Looking at the total energy consumption for heating and cooling, it can be concluded that the energy flexibility of the system is due to the decrease of power for heating, while cooling is barely affected. However, this comes as no surprise since the energy consumption for cooling is very small, resulting in small possibility of energy storing.

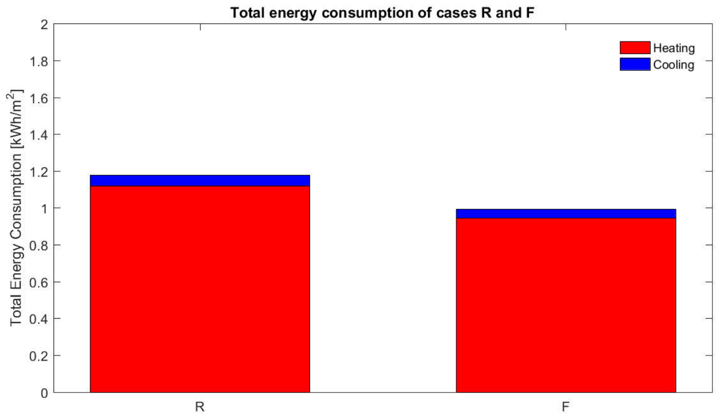

Figure 5.28: *Radiant system. Total energy consumption of Reference and Flexibility case, for heating and cooling.*

Comfort level

Finally, the performance of a system cannot be assessed without taking into consideration the comfort level. In this case, the control of the energy flexibility manages to decrease the total energy consumption, without jeopardizing the thermal comfort. In Figure 5.29 can be observed that the percentage of the total time within Class II is 71.24 % for Reference case and 68.50 % for Flexibility, resulting in 73 hours less in Category II compared to Reference case.

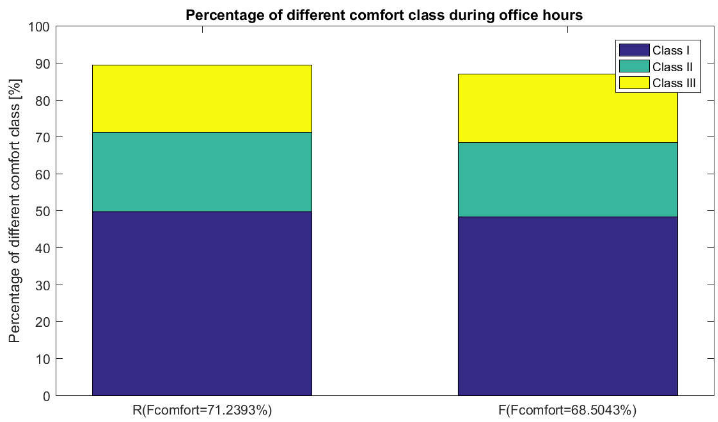

Figure 5.29: *Radiant system. Percentage of different comfort classes for different cases.*

5.4 Comparison of all systems

Figure 5.30 presents the total energy consumption for all 3 models, for both Reference (R) and Flexibility (F) cases. The total consumption is divided into the energy used for heating and cooling. Even though Model 1 has higher total energy consumption compared to the other models, the amount used for heating is higher for models 2 and 3, while the consumption for cooling is significantly smaller for both of them. As it can also be noticed in the previous sections (5.1.3, 5.2.3, 5.3.3), the reduced cooling need of models 2 and 3 is connected to the low outdoor temperatures, even in the middle of the summer period.

In general, the novel two-pipe heating and cooling system has a different performance compared to the other systems. This is due to the fact that the system's set-up, operation and control are quite distinct to models 2 and 3. The control of the Lindab Solus system allows for heating and cooling to be activated at any moment during the year. On the other hand, for the other two systems, heating and cooling is scheduled to be activated only during winter and summer season, respectively. Additionally, for models 2 and 3, the activation of heating and cooling is based on the average outlet temperature from all zones, in contrast to the first system that is controlled based on the maximum and minimum calculated temperature of the whole building.

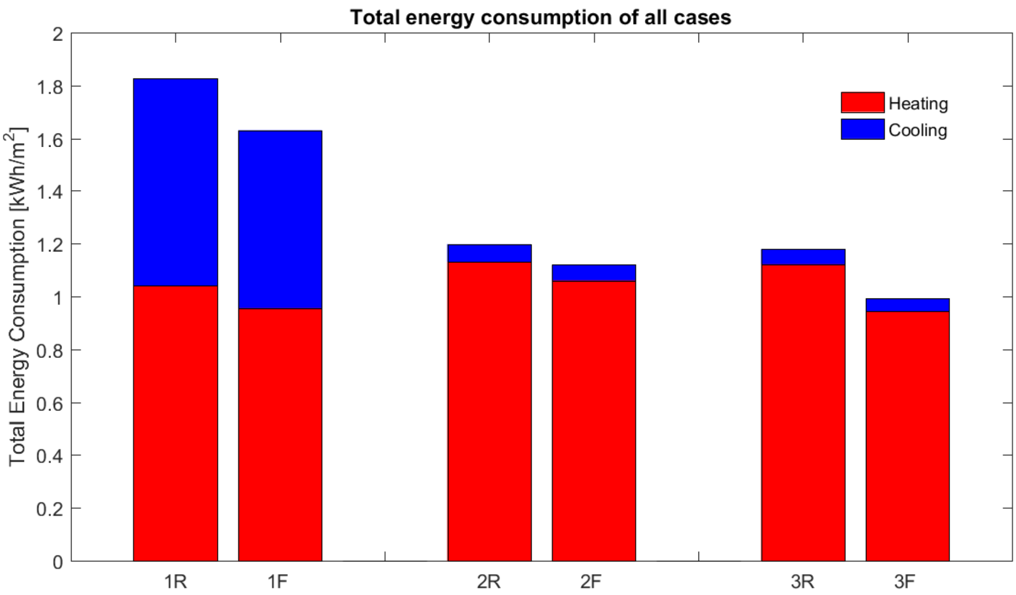

Figure 5.30: *Comparison of all systems. Total energy consumption of Reference and Flexibility case, for heating and cooling.*

In the following tables are presented the levels of energy consumption [kWh/m^2] for all different cases, as well as the calculated percentage [%] difference between R and F cases for each model.

		Total	Heating	Cooling
R	**Model 1**	1.83	1.04	0.79
$[kWh/m^2]$	**Model 2**	1.20	1.13	0.07
	Model 3	1.18	1.12	0.06
F	**Model 1**	1.63	0.96	0.67
$[kWh/m^2]$	**Model 2**	1.12	1.06	0.06
	Model 3	0.99	0.94	0.05
[%]	**Model 1**	10.7		
	Model 2	6.51		
	Model 3	15.84		

Table 5.1: *Energy consumption of all models and both cases (R, F); percentage of difference between R and F case.*

As it can be seen, the underfloor heating system has the highest energy saving percentage (15.84 %) compared to the novel two-pipe system (10.70 %) and the radiator system (6.51 %). However, in order to come to conclusions about the systems' general energy saving and flexibility potential it should also be taken into consideration the electricity price level of the periods when the energy was consumed.

In the following Figure is presented the energy consumption of the 3 models, for the flexibility case, for the 3 different price categories (low, high and medium), as well as the total amount.

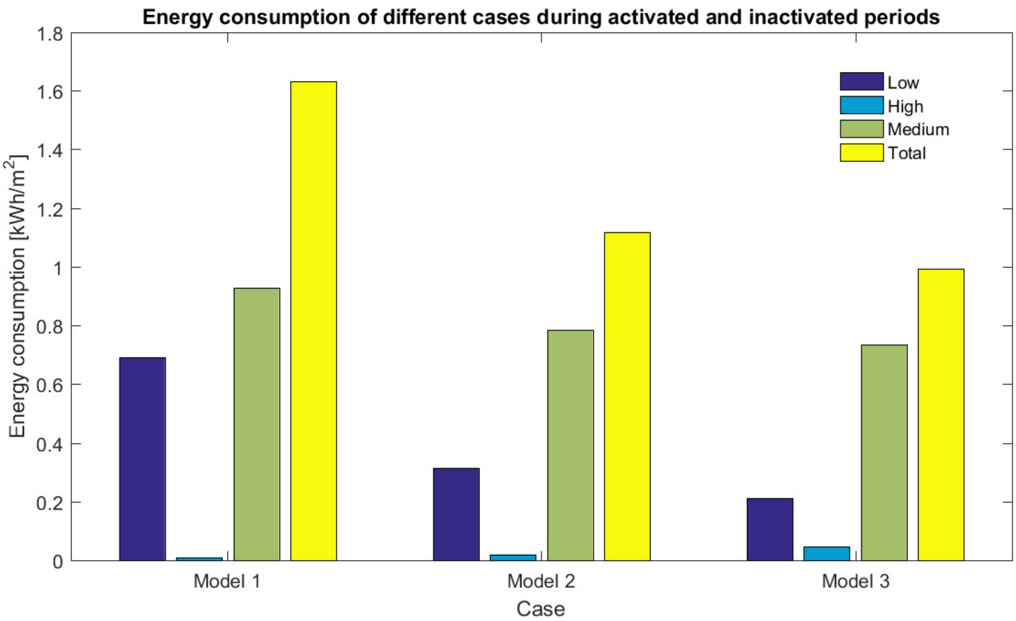

Figure 5.31: *Comparison of all systems. Energy consumption of different cases during activated and inactivated periods, for Flexibility case.*

In the following table are presented the energy consumption values for all cases.

	Low	High	Medium	Total
Model 1	0.69	0.01	0.92	1.63
Model 2	0.31	0.02	0.78	1.12
Model 3	0.21	0.04	0.73	0.99

Table 5.2: *Energy consumption of all models for Flexibility case, for different price level periods*

It can be noticed that Model 1 uses the highest amount of low price energy, while the consumption of high price energy is minor. Respectively, Model 2 seems to consume a higher amount of low price and lower amount of high price electricity, compared to Model 3. However, a clear conclusion for the flexibility potential of the different systems cannot be drawn from this graph, since they are not provided the exact electricity price levels. Consequently, in the following graph is shown the total energy cost $[DKK/m^2 year]$ of all models and cases.

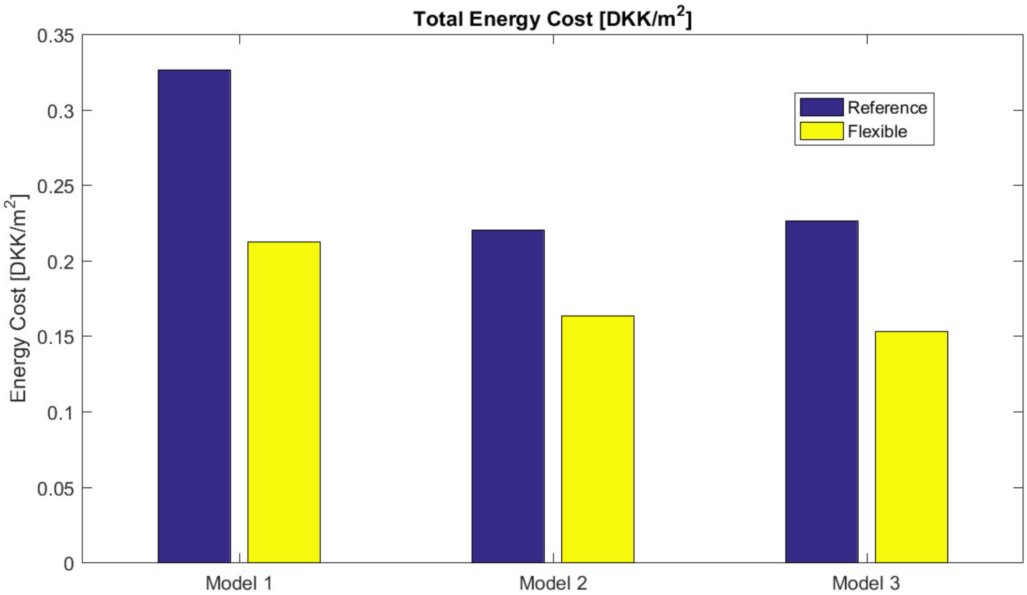

Figure 5.32: *Comparison of all systems. Energy cost for both cases (R, F).*

From the calculated yearly savings of energy cost it can be concluded that the two-pipe system has the highest potential of energy saving, with a percentage of 34.92 %, while the floor heating system achieves a percentage of 32.30 % and the radiator heating system saves up to 26.71 %.

As far as comfort level is concerned, Model 1 achieves the highest percentage of time of thermal comfort within Class II for both cases, while models 2 and 3 achieve similar percentages. The percentage of time within class II decreases 1.67 % (39 h) for Model 1, 1.54 % (45h) for Model 2 and 2.74 % (73 h) for Model 3.

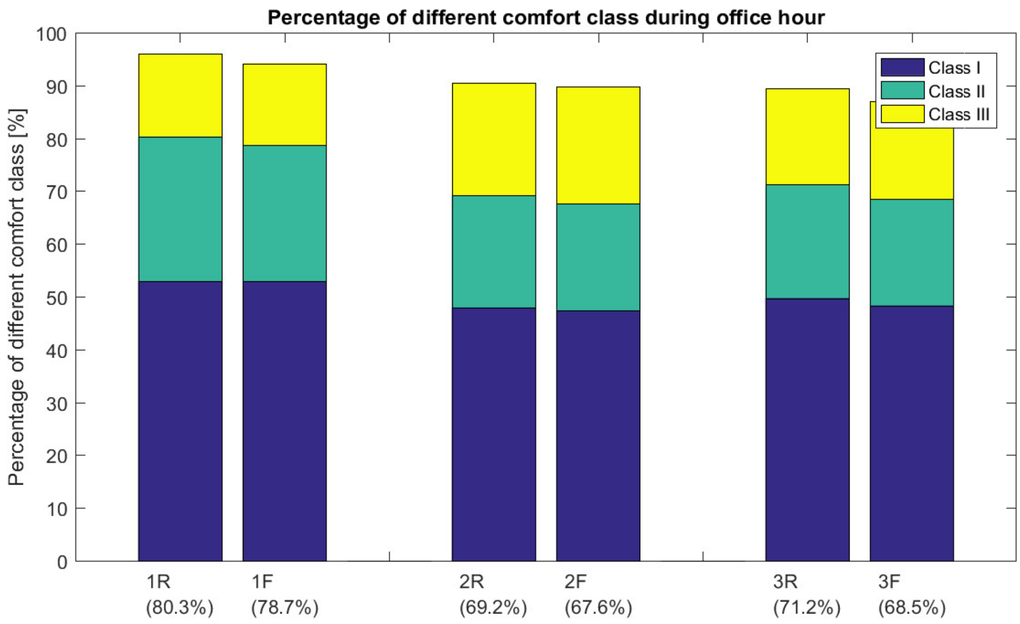

Figure 5.33: *Comparison of all systems. Percentage of different comfort classes for both cases (R, F).*

5.5 Discussion

Summing up, the novel two-pipe system is able to achieve higher energy savings and manage greater flexibility level compared to the other systems. This is accomplished due to the excess heat transfer from warmer zones to colder ones and vice versa. Moreover, the decided flexibility control aims to regulate cooling activation based on direct solar radiation and outdoor air temperature. This part of the control does not affect significantly models 2 and 3, given that the energy consumption for cooling is trivial. As far as models 2 and 3 are concerned, as expected, the system with underfloor heating achieves more significant energy savings compared to the system equipped with radiators. The activation of the system's high thermal mass results in decrease of energy consumption.

6 Conclusion

This study aims to evaluate the performance and energy flexibility potential of different heating and cooling systems on a case office building. The analyzed systems are a novel two-pipe heating and cooling system, a radiator heating system with mechanical ventilation for cooling and a radiant (underfloor) heating system with mechanical ventilation for cooling, as well. The evaluation metrics used to weigh the systems' performance are the ability of power adjustment, economic benefit, the ability of energy shifting, the total energy consumption and thermal comfort level. All these parameters affect the operation of the systems in terms of energy flexibility and should be taken into consideration for their assessment.

Summing up, from the conducted analysis, the following conclusions can be drawn:

- Both heating and cooling are activated during the entire year for the novel two-pipe system, while for the other two models, the activation of heating and cooling is restricted per season. This is due to the operation of the novel system that is activated based on the minimum and maximum temperatures of all zones, which leads to the necessity of decreasing the supply air temperature at any moment throughout the year.
- The two-pipe system has the highest energy saving potential (34.9 %), followed by the underfloor heating system (32.3 %), while the radiator system has the lowest savings (25.7 %). The high ability of Model 1 to adjust its energy consumption is due to the fact that it can utilize the heat from warm areas in the colder ones. Additionally, the regulation of energy consumption for cooling has a significant impact on the total energy savings. Further, the percentage of savings for the floor heating system is also quite high. The high thermal energy storage of the system in its structural mass can increase its energy flexibility.
- As expected, the modification of set-points will have an impact on the thermal comfort level. The percentage of time within accepted comfort level classes decreases 1.67 % for Model 1, 1.54 % for Model 2 and 2.74 % for Model 3, reaching 94.19 %, 89.7 % and 87.01 %, respectively.

Ultimately, a general estimation of the systems' potential for energy flexibility can be drawn from this study. Nevertheless, further investigation and adjustment of the applied control strategies to the individual system's needs would be necessary in order to form a more complete conclusion. It would be of great interest to conduct supplemental research of their performance by introducing new predictive control methods.

Bibliography

EnergyPlus website. URL https://energyplus.net/.

MATLAB wiki. URL https://en.wikipedia.org/wiki/MATLAB.

MATLAB website. URL https://www.mathworks.com/products/matlab.html.

Byggeforskningsinstitut, Statens, 2000. *Sbi 175 Varmeanled vand som medium*.

Christantoni, D., Oxizidis, S., and Flynn, D., 2016. Implementation of demand response strategies in a multi-purpose commercial building using a whole-building simulation model approach. *Energy and Buildings*.

Crall, Christopher P., 2018. *Direct and reverse return*. URL https://insulation.org/io/articles/understanding-thermal-systems-hydronic-heating-and-cooling-systems/.

Doninelli, Mario, 1993. *Design principles of hydronic heating systems*.

Dreau, J. Le and Heiselberg, P., 2016. Energy flexibility of residential buildings using short term heat storage in the thermal mass. *Energy*.

DTU, 2018. *DTU website*. URL www.dtu.dk.

Energistyrelsen, 2015. *Danish Climate and energy policy*.

Hurtado, L. A., Rhodes, J. D., and Nguyen, P. H., 2017. Quantifying demand flexibility based on structural thermal storage and comfort management of non-residential buildings: A comparison between hot and cold climates. *Applied Energy 195*.

Lindab, 2016. *Lindab Solus System*, 2016.

Pallonetto, F., Oxizidis, S., and Milano, F., 2016. The effect of time-of-use tariffs on the demand response flexibility of an all-electric smart-grid-ready dwelling. *Energy and Buildings 64*.

Reynders, G., Nuytten, T., and Saelens, D., 2013. Potential of structural thermal mass for demand-side management in dwellings. *Building and Environment 64*.

Siegenthaler, John, 2012. *Modern Hydronic Heating For Residential and Light Commercial Buildings*.

A Appendix

A.1 Constructions

Construction element	Materials	e [mm]	Cp [kJ/kgK]	ρ [kg/m^3]	λ [W/mK]
Opaque partition walls	Plasterboard	50	1	881	0.2
Ground floor	Wood	10	1.048	640	0.186
	Concrete	270	0.8	2400	2.1
	Stone wool	500	0.8	100	0.038
	Asphalt	1	1	1700	0.5
Floor slab	Plasterboard	14	1	881	0.2
	Concrete	270	0.8	2400	2.1
	Wooden floor	10	1.048	640	0.186
Transparent partition walls	Glass panels	10	0.9	2600	0.8
Slab	Plasterboard	10	1	881	0.2
	Concrete	160	0.8	2400	2.1
	Carpet	5	1.8	283	0.06
External walls	Plasterboard	14	1	881	0.2
	Concrete	200	0.8	2400	2.1
	Polyurethane thermo-panel	210	1.4	40	0.023
	Cement plate	15	1.5	2000	0.35
Roof	Plasterboard	14	1	881	0.2
	Concrete	270	0.8	2400	2.1
	Stone wool	450	0.8	100	0.038
	Asphalt	1	1	1700	0.5

Table A.1: *Constructions reference case*

Construction element	Materials	e [mm]	Cp [kJ/kgK]	ρ [kg/m^3]	λ [W/mK]
Floor slab	Wooden floor	10	1.048	640	0.186
	Concrete	270	0.8	2400	2.1
	Polyurethane thermo-panel	30	1.4	40	0.023
	Plasterboard	14	1	881	0.2

Table A.2: *Constructions flexibility case*

Glazing properties	
g-value [-]	0.49
Light transmittance coefficient [-]	0.71
U-value [W/m^2K]	0.64

Table A.3: *Glazing characteristics*

A.2 Schedules

Schedule	Setpoints	Seipoints unoccupied
Main air outlet temperature cooling	22 °C	-
Main air cold water	7 °C	-
Heat recovery air supply	18 °C	-
Office room heating setpoint	20 °C	16 °C
Office room cooling setpoint	25 °C	27 °C
Hot water	65 °C	-

Table A.4: *Schedules*

A.3 Graphs

A.3.1 Two-pipe system

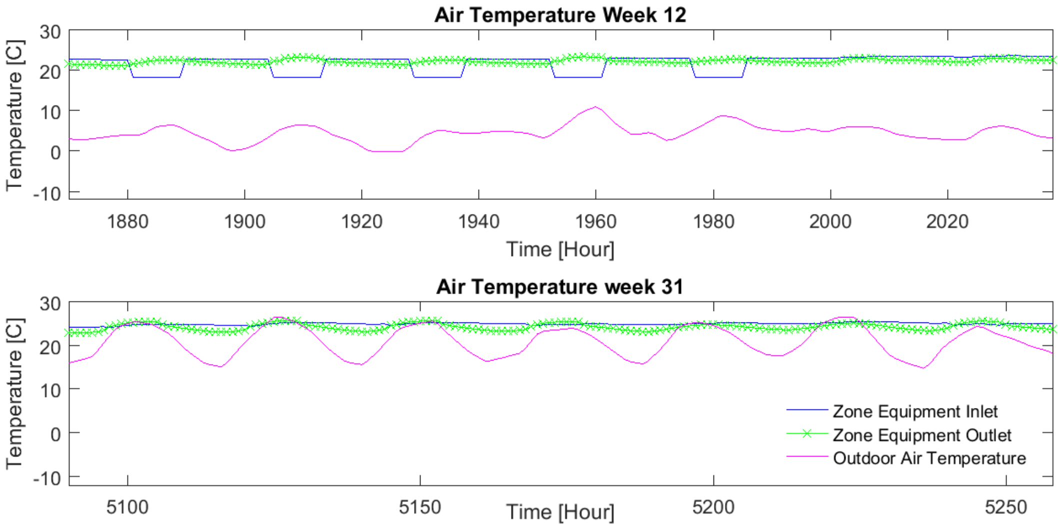

Figure A.1: *Air temperatures during winter and summer of the two-pipe system. Reference case.*

A.3.2 Radiator system

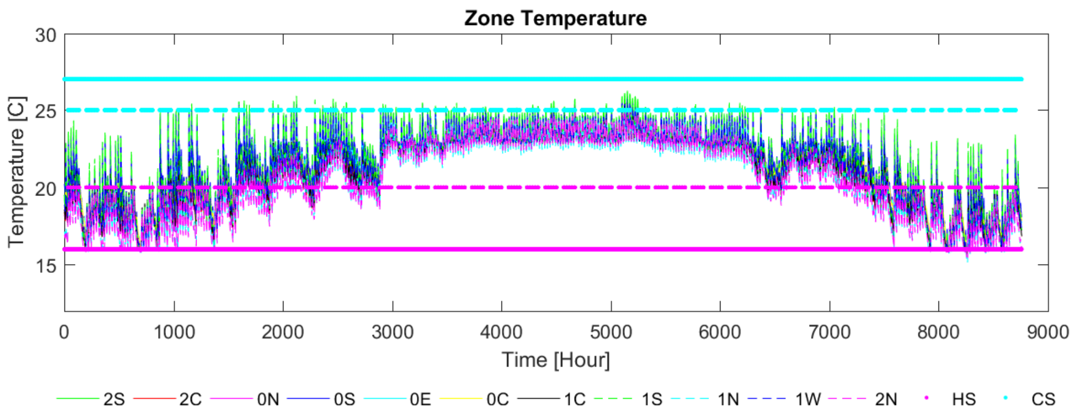

Figure A.2: *Zone temperatures, whole year, of the radiator system. Reference case.*

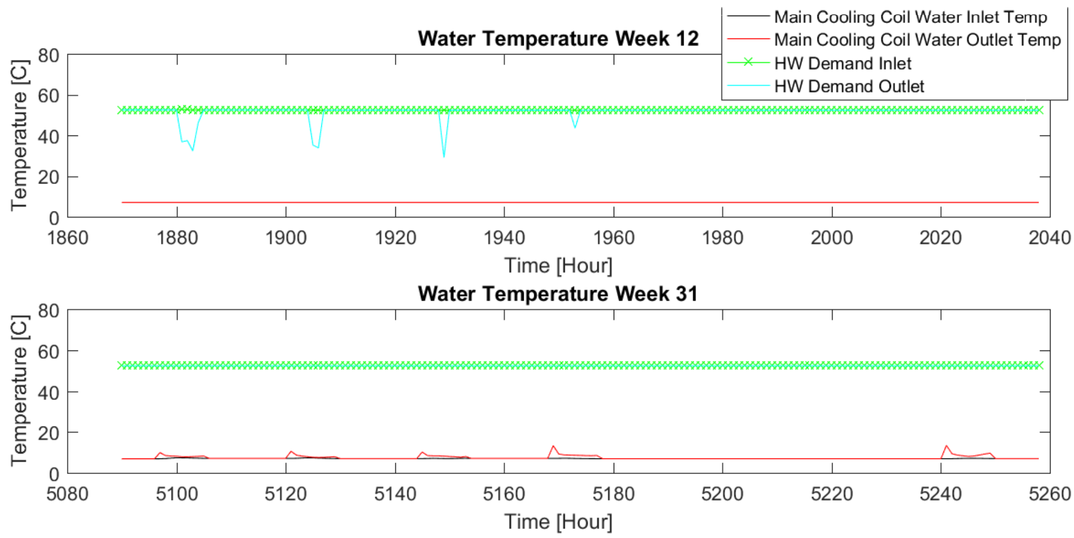

Figure A.3: *Water temperatures of the cooling coil and the hot water loop during winter and summer of the radiator system. Reference case.*

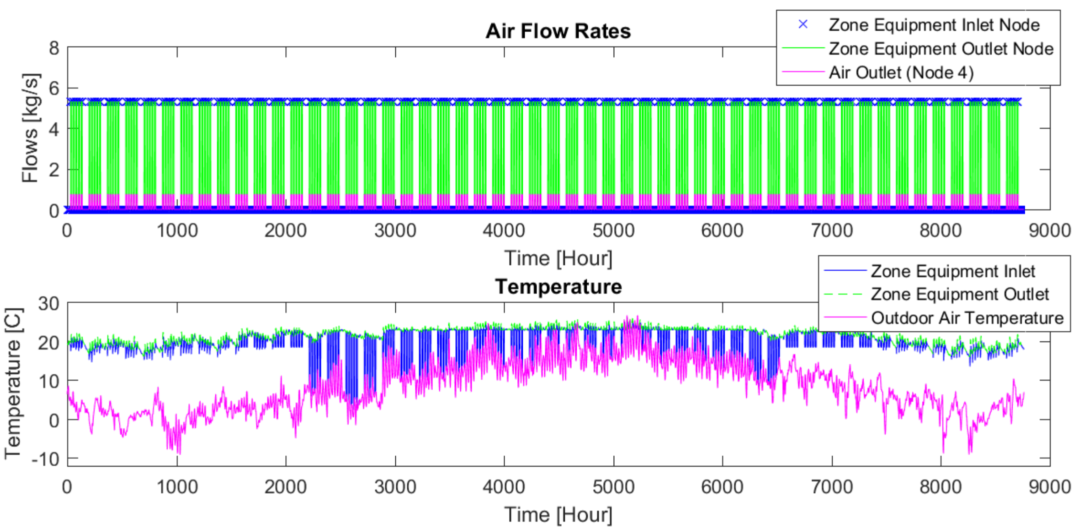

Figure A.4: *Air flow and temperatures, whole year, of the radiator system. Reference case.*

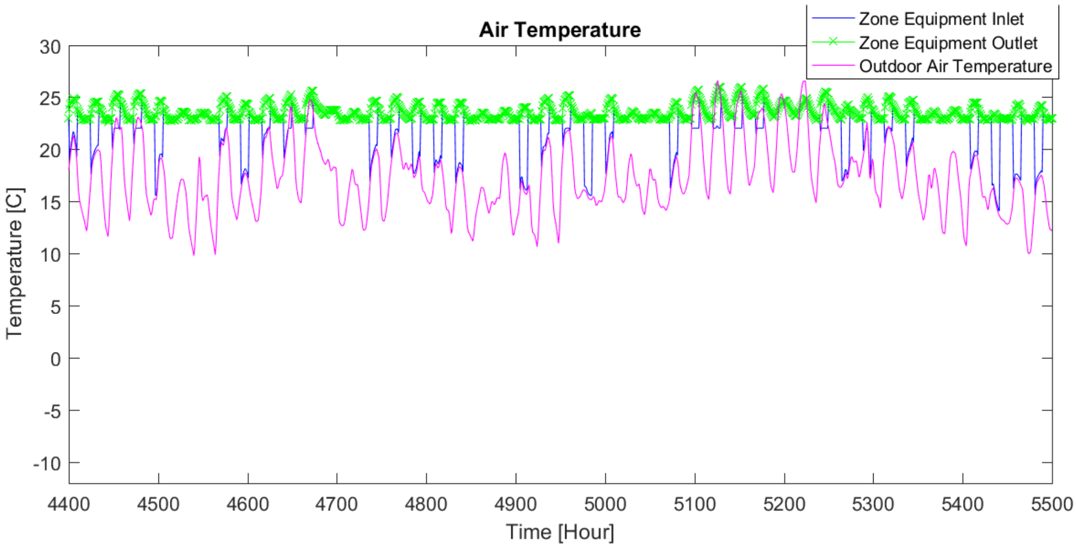

Figure A.5: *Air temperatures during summer of the radiator system. Flexibility case.*