ENERGY FLEXIBILITY OF A LARGE-SCALE OFFICE BUILDING: INFLUENCE OF OCCUPANCY AND FLOW VARIATION OF A TWO PIPE ACTIVE BEAM SYSTEM FOR SIMULTANEOUS HEATING AND COOLING

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Synopsis

This research document has been developed to assess the influence of occupancy and flow variation of a two-pipe system for simultaneous heating and cooling on the energy flexibility of a large-scale office building.

A baseline model is compared with a flow reduction case, an occupancy variation case, and a model with both changes implemented. For each of the mentioned cases three different control strategies are also evaluated. A referent controller with fixed setpoints, a flexibility controller based on electricity price levels and a 24 hours horizon weather predictive controller used for cooling purposes.

The results are analyzed according to four metrics for energy flexibility described in the thesis.

ABSTRACT

The thesis at hand is a mandatory part of the fourth semester master program in Building Energy Design at Aalborg University. The research's objective is to investigate and evaluate the influence of occupancy variation and flow reduction on a two-pipe system for simultaneous heating and cooling, in a large-scale office building; and how performance of energy flexibility is affected by these variations. Studies are carried out in order to determine the range of flow and occupancy variations, and four main cases are established including the baseline model. For each case three control strategies are implemented and a total of 12 cases are simulated using EnergyPlus software. The results will show that occupancy variation has a clear impact on the performance of the two-pipe system, and a 15% flow reduction actually improves the energy savings with no considerable effect on thermal comfort. From the control algorithms analyzed a control strategy based on electricity price levels will be proven to give the best results.

AKNOWLEDGMENTS

The project at hand is inspired and tries to continue the work of an unpublished research conducted by Per Kvols Heiselberg and Mingzhe Liu called "Energy flexibility of a nearly-zero-energy building with a novel building energy system evaluated with integrated metrics".

Their work is used as a fundament for exploring new research directions and many of the technical elements, including the prototype EnergyPlus model are reused and adjusted to the needs of the research.

TABLE OF CONTENTS

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND OF THE PROJECT

Many of the last decade problems have pushed the world towards renewable energy sources. Reasons as pollution, climate change and energy insecurity are just a few examples why more and more governments have adopted stringent policies to change from fossil fuels to renewable energy resources. Denmark wishes to be one of the European leaders in the "green transition" and as such set clear goals to use only green energy by 2050 for the public transport sector and provide electricity and heating only from renewable resources by 2035.

The shift to "green" does come with several issues regarding the power grid stability as the main electricity generators are wind turbines. The climatic fluctuations therefore are felt in the availability of electricity in the grid. The imbalance between the grid supply and consumer demand can lead to overloading the grid (if the demand is low and energy availability is high) or to high electricity price if the grid cannot meet the demand. Efforts are made to solve the current problems from both supply and demand side.

As the building stock accounts for approximatively 40% of the energy demand there is am overgrowing research field aimed at reducing the energy use and improving the energy flexibility of the buildings. More advanced control algorithms have been created for the buildings HVAC systems (as demand-response and predictive controllers) and innovative systems have been developed.

One such system is a two-pipe active beam system developed by Lindab, used simultaneous for heating and cooling that has the capability of transferring heat from one building zone to others.

1.2. PROBLEM FORMULATION

A two-pipe system for simultaneous heating and cooling works by forced convection and induction of the room air through the heating/cooling coil of the air terminal. The system has the benefit of using high temperature cooling and low temperature heating with an operational working fluid temperature range of 20 to 23^{0}C.

Several researches have been done to the present day evaluating the capabilities of this system. However, all researches found investigate the system at a nominal water flow of 0.038kg/s. The producer specifies that a constant water flow must be provided through all the loops of system as there are no regulation valves present. This remark is understood spatially and not temporal.

Moreover, as “working remotely” has become incorporated in today’s culture it is believed that the actual occupancy schedules used for design and operational simulations need a closer attention as they do not reflect the present reality.

The research question of this thesis is:

How does flow and occupancy variation influence the energy flexibility potential of a newly build office building?

To approach the problem at hand research on existing documentation is done, relevant cases are created, and energy flexibility potential is investigated trough simulated models in EnergyPlus software and analysis of relevant evaluation metrics.

1.3. PROBLEM DELIMITATION

Since EnergyPlus treats control options from the demand to the supply side of the defined systems, and due to the simplifications done to model of the plant, it is not understood, at the time of writing this thesis, how to set one control variable to control all the 11 heating/cooling coils; as setting different flow at the circulation pump will unbalance the system. Therefore, evaluation on dual variable control strategies will not be made.

1.4. RESEARCH METHODOLOGY

Different literature is researched for inspiration. Evaluation metrics of energy flexibility are chosen and described. Investigations on choosing a secondary flow to be variated from the baseline conditions are done and the reduced flow is chosen based on thermal comfort limits. An occupancy variation schedule is created based on literature findings to simulate a presence/absence scenario. Different combinations of flow variation, occupancy variation and three control algorithms are simulated, and results evaluated according to the energy flexibility metrics and presented.

CHAPTER 2. LITERATURE REVIEW

As, to the present time, there has not been found any literature regarding the flow variation of a Solus system, this chapter investigates the available researches found on the topics of energy flexibility, energy saving potential of two-pipe systems and occupancy level influence on heat transmission among building zones.

2.1. EVALUATION METRICS AND SOLUS SYSTEM

Energy flexibility has become an important research area as the shift from conventional fossil fuels to renewable energy resources trend comes with new challenges, in the sense that the available energy in the grid and its price fluctuates dependent on the climatic conditions. Therefore, it is important that building energy systems come to meet this fluctuation by becoming more flexible in terms of energy consumption.

Various researches have been made to the present day regarding the energy flexibility of buildings, systems and the metrics used to describe the flexibility potential, as building can store energy into the building's structure or more innovative systems than traditional ones (radiators, floor heating etc.) can accommodate the grid demand without jeopardizing the indoor comfort.

In their research paper, J.Le Dreau and P. Heiselberg evaluate energy flexibility potential of residential buildings with different thermal mass and different heating/cooling systems (radiators, floor heating, natural and mechanical ventilation). The research is focused on the existing Danish building stock and the results are evaluated at whole building level without looking into particular differences between the systems.

For this purpose, a simple controller was developed that modulates the temperature set-points between "upward modulation"- increasing set-points with 2K, and "downward modulation"-decreasing set-points with 2K. This type of simple control is used as the refence case in the current study and it is presented in detail in chapter 3.4. Control strategies.

To evaluate the energy flexibility potential, a "flexibility factor" metric is used, metric that will be used for evaluation also in the current research and is described in chapter 3.5.3. Ability of energy shifting. Their research shows a promising potential of the thermal mass of a building structure to take advantage of the grid variation. It is concluded in their research that as the autonomy of low insulated buildings is short compared to passive buildings, different control strategies should be implemented as the simple control algorithm can lead to overheating, in the second case, due to the high time constant of the building. [1]

Glenn Reynders et al. [2] use the “power shifting capability” performance indicator to evaluate the active demand response of a system, defined as *“the relation between the change in heating power and the duration that this shift can be maintained before the thermal comfort is jeopardized”.*

This indicator adapted for the current research and renamed “ability of grid adjustment” is presented in detail in chapter 3.5.4. Ability of grid adjustment/power difference.

Maccarini et al. have extensively researched the Solus two-pipe system and published their findings in different research papers. In *“Energy saving potential of a two-pipe system for simultaneous heating and cooling of office buildings”*, by comparing a two-pipe system with a traditional four pipe system it was concluded that *“the two-pipe system was able to use less energy thanks to three effects: useful heat transfer from warm to cold zones, higher free cooling potential and higher efficiency of the heat pump.”* [3] The savings are between 12 to 18% of total annual energy.

Different control strategies of the two-pipe system have been also investigated by Maccarini et al. with energy savings of 44% for a typical winter and typical summer day. Using first a simple control method of turning on/off the water loop 2 hours before/after the occupancy time in a two-zone office building, the supply water temperature has a linear dependency on the outdoor air. The more advanced controller will track the room air temperature and adjust the supply water temperature accordingly in order to satisfy the heating/cooling needs based on the equation described below.

“$Tsup = Tret + khea - kcoo$” where:

Tret -is the return water temperature;

khea and kcoo are offsets defined to adjust the return water temperature based on the evaluation of room air temperature and set-points. [4]

This control algorithm is implemented in the current research as the refence controller.

2.2. OCCUPANCY INFLUENCE

As most of the researches based on simulation investigations set as default a full load occupancy to emphasize system behavior or energy storage capabilities of the thermal mass, research is made to determine the importance of occupancy level on energy consumption.

The occupancy level influence on an active beam two-pipe system has been researched by Maccarini et al. for different climate zones. In order to generate different occupancy levels, a simple probabilistic model was developed in Modelica language and simulations run at different occupancy probabilities. Results for the Copenhagen climatic conditions show that at 100% occupancy the annual energy use for heating is 2,1kWh/m^2 and 17,7kWh/m^2 for cooling. When the occupancy level is set at 20% the annual energy use is 18kWh/m^2 for heating respective 0,2kWh/m^2 for cooling. [5] This result highlights the influence that the occupancy level has on the energy consumption.

In his PhD research, Jie Zhao distinguishes between the “active role” that occupants play in a building as using equipment, turning on or off lights, and the “passive role”. While the first treats occupants as disturbances, the second defines occupants as generators of heat and CO_2 that have high influence on the HVAC energy consumption. [6]

During his research he implements a case study in an open plan office where occupancy level data are collected over 49 working days. He concludes that in a typical week, occupancy rates for Monday and Thursday follow the average weekday occupancy rate, while Tuesday and Wednesday have the highest occupancy rates. The lowest occupancy rates is Friday and, during the working schedule, at lunch break (12-13:00) with an occupancy rate of 41.43%.

The findings from literature review serve as inspiration for this thesis and are implemented to the best considered extent in the current research.

CHAPTER 3. ENERGY FLEXIBILITY RESEARCH

3.1. BUILDING DESCRIPTION

The Energy Plus model used for investigations in this thesis is based on one administrative building of Aarhus commune, situated at Grøndalsvej 1, DK -8260 Viby J, Aarhus.

Figure 1 Aarhus Kommune, Grøndalsvej 1

Although the building is referred to as a “nearly zero energy building”, in the documentation submitted for revise, an energy frame calculation done by Grontmij AS in May 2011 using BE10 calculation tool states that the building complies with the energy requirements of a low energy building class 2015.

Only part of the whole building was used for the Energy Plus model and the geometry was modified for simplicity purposes. The thermal envelope of the model is identical with the thermal envelope of the respective building and its components presented in the table below:

Component	U-value [W/m^2 K]
Roof	0,07
Ground floor	0,07
Partitions	0,091
Facades	0,098
Windows	0,9 (g_{value}=0,4)

Table 1 Thermal envelope components U-values

The infiltration rate is set to 0.5 l/s/m2 of the heated floor at a pressure difference of 50 Pa. Internal heat gains are set to 4W/m^2 for lighting, 6W/m^2 for electric equipment and the occupancy is 0,057143 persons/m^2, corresponding to 4W/m^2 internal heat load from occupants. The working hours are defined as from 9am to 5pm.

For a detailed documentation of these values please see Appendix 1: Extract of BE10 energy calculation.

As Energy Plus already has weather data files available for most of world cities, the climatic conditions for Copenhagen, Denmark have been downloaded from https://energyplus.net/weather-region/europe_wmo_region_6/DNK%20%20 and used for simulations.

3.2. BUILDING THERMAL ZONES

The simulated building model has a heated floor area of 2926m^2 divided into three levels (0, 1 and 2). Each floor is respectively split into northern and southern zones (N and S), as solar gains differ from south to north, and a central zone (C) corresponding to the access corridor. Areas with different functionality as landscape office and meeting room are isolated into separate thermal zones corresponding also to the cardinal directions their windows fare facing (1W and 0E); as these zones experience unique solar gains in the model.

There are, in total, 11 thermal zones represented below in Figure 2.

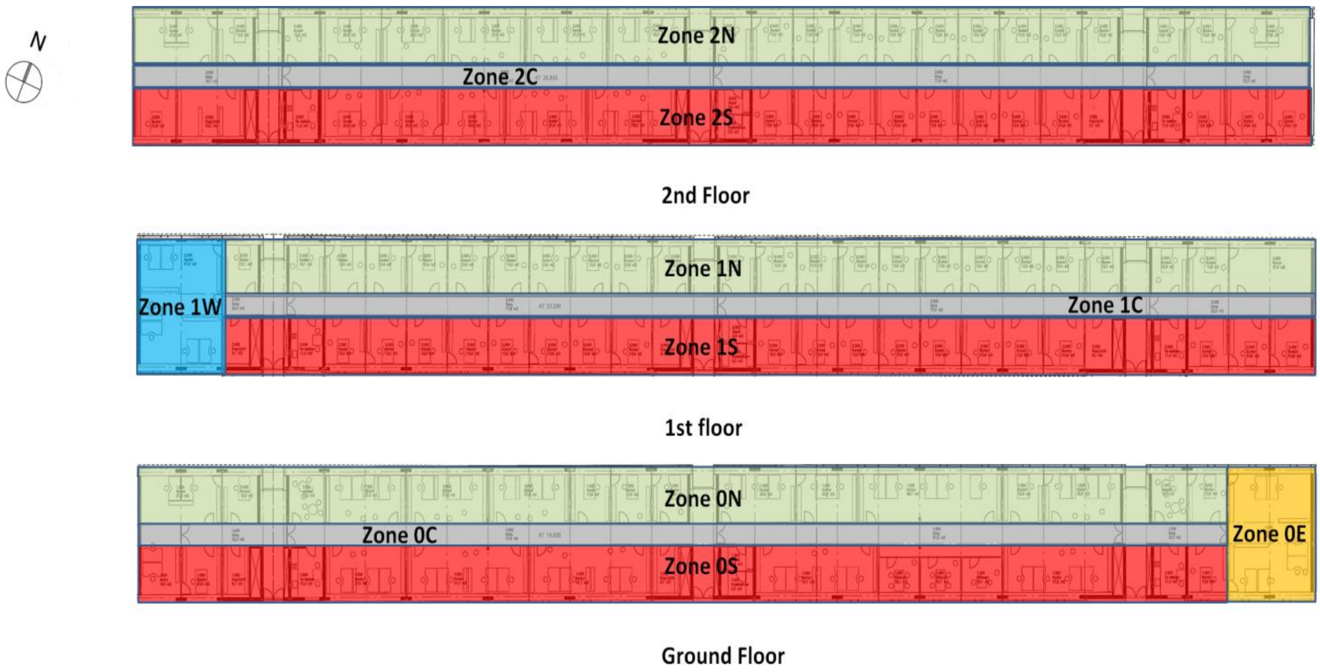


Figure 2 Division of thermal zones of the simulated model

3.3. HVAC SYSTEM DESCRIPTION

The HVAC system servicing each thermal zone is a novelty building energy system that uses active chilled beams for both heating and cooling. The system is based on the induction principle as the ventilation air is supplied to the zones with high pressure by the active beams diffusers. This creates a low-pressure zone underneath the unit terminal that will have as effect a forced induction of the zone air in the mixing plenum of the active beams, trough the heating/cooling coil where the air is exchanging thermal energy with the water medium of the coil. Trough forced convection, the air is afterwards supplied back to the respective zone.

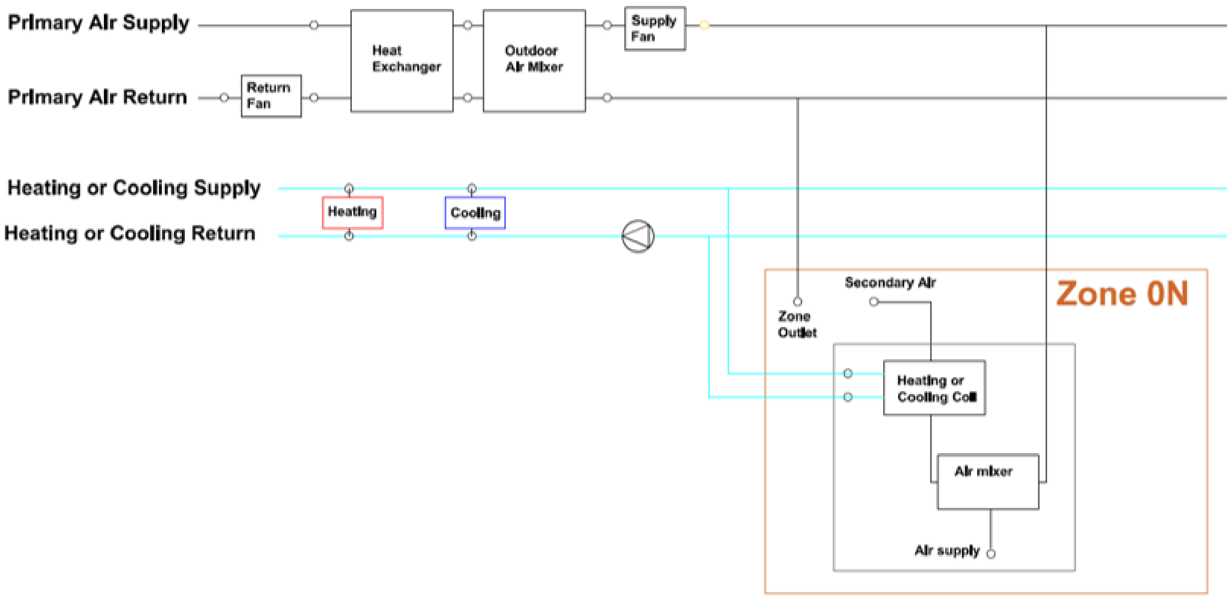


Figure 3 Schematic of the HVAC system

The primary air, defined here as the outdoor air entering the mixing plenum of the active beams, is supplied at a set-point of 18°C. To achieve this temperature setpoint, the outdoor air is preheated/precooled by the use of a rotary heat exchanger with 0,85 efficiency and two coils; one for heating and one for cooling after the heat exchanger in the air loop of the system. The ventilation unit is serviced by a constant volume fan with an efficiency of 0,8 capable of producing a total air flow of 13m^3/s as the ventilation requirement is 0,002m^3/s per m^2. The heating and cooling coils of the ventilation unit have separate water loops serviced by district heating respective cooling but for the purpose of this thesis have no evaluation relevance.

The novelty of this system is represented by the use of a “Solus system” developed by Lindab/AB. The Lindab solus active beam allows for low temperature heating (LTH) and high temperature cooling (HTC) by using a two-pipe delivery system of the heating/cooling medium, with water loop operating temperatures of 20-23°C at inlet and 21-23°C at outlet. Due to this, the same active beam is used for heating and cooling as compared to conventional four-pipe system. This system also allows for the possibility of heat transfer within the buildings zones, as heat excess from one zone is transferred to zones in need of heating. For example, a north facing zone may have a heating need while a zone oriented south is experience overheating due to solar gains in a typical sunny winter day.

As the zones described in the previous subchapter have fairly big areas, for simplification, the number of active beams servicing the building have been reduced to one active beam per thermal zone and dimensioned accordingly in the simulation model. It has been estimated that one active beam is capable of servicing 27m^2 of floor area, with a constant solus beam water flow of 0,12142kg/s for each real water loop.

The table below presents the conversion:

				Values per simplified beam	
level	**zone**	**Area[m^2]**	**actual number of active beams**	**Air flow [m^3/s]**	**Water flow [kg/s]**
0	0C	146.88	6	1.4688	0.660525
	0S	362.61	14	3.6261	1.630672
	0N	362.61	14	3.6261	1.630672
	0E	102.6	4	1.026	0.461396
1	1C	155.52	6	1.5552	0.69938
	1S	383.94	14	3.8394	1.726594
	1N	383.94	14	3.8394	1.726594
	1W	51.3	2	0.513	0.230698
2	2C	164.16	6	1.6416	0.738234
	2S	405.27	15	4.0527	1.823
	2N	405.27	15	4.0527	1.823

Table 2 Lindab Solus active beams conversion

3.4. CONTROL STRATEGIES

Three control strategies are used during the research for this thesis. The first type of control, known hereafter as the referent controller (R), uses two simple sets of temperature set-points to operate the HVAC system. For the occupied hours, the heating and cooling set-points of the zones are 20 and 25 °C. For the unoccupied hours, the set-points are 18 respectively 27 °C.

In other words, if the zone temperature falls below 20 °C, the controller signals the main cooling/heating coil of the heating/cooling water loop (Solus system) to increase the temperature at the inlet node of the demand side of the loop in order to meet the desired zone temperature set-point. As there are 11 thermal zones, the control algorithm evaluates the minimum temperature of all zones for heating, and the maximum temperature of all zones respective.

		Office Room Heating Set-point(occupied hour/unoccupied hour)	**Office Room Cooling Set-point(occupied hour/unoccupied hour)**
Rerefence (R)		20 °C/18 °C	25 °C/27 °C
Flexibility 1 (F1)	Low Price (<111.5 DKK/MWh)	21 °C/19 °C	24 °C/26 °C
	High Price (>203.8 DKK/MWh)	17 °C/15 °C	29 °C/31 °C
	Middle Price (>111.5 & <203.8 DKK/MWh)	20 °C/18 °C	25 °C/27 °C
Flexibility 2 (F2)	Low Price (<111.5 DKK/MWh) Cooling is activated if direct solar radiation is above 500 W/m2 and outdoor air temperature is above 20 °C at any time in the next 24 hours.	21 °C/19 °C	24 °C/26 °C
	High Price (>203.8 DKK/MWh)	17 °C/15 °C	29 °C/31 °C
	Middle Price (>111.5 & < 203.8 DKK/MWh)	20 °C/18 °C	25 °C/27 °C

Table 3 Control strategies

For the second control strategy (F1), the control algorithm uses three sets of temperature setpoints corresponding to three electricity price levels as described in the table above. If the electricity price falls under the low-price level, it can be observed that the heating set-points are increased to 21 °C/19 °C for heating and 24 °C/26 °C for cooling. When the electricity price exceeds the high-price threshold then the heating set-points are decreased to 17°C/15°C for heating and 29°C/31°C for cooling. This method ensures that when the price is low the system will store energy in the thermal mass of the building and when the price is high the systems energy consumption is limited and the stored energy is released.

The third control algorithm (F2) introduces a simple prediction in the sense that if the outdoor air temperature and the direct solar radiation are above 20°C and 500 W/m^2, respectively, in the time horizon of 24 hours, then cooling is activated to reduce energy consumption as it is expected that the solar gains and the air temperature exiting the ventilation unit are enough to keep the desired set-points during the low-price electricity level.

It can be observed that the control algorithms are built on top of each other from the simple referent controller to the “Flexibility 2” named controller, ensuring a gradually increase on the complexity of the system control in order to achieve higher system flexibility.

3.5. EVALUATION METRICS DESCRIPTION

3.5.1. THERMAL COMFORT

In the evaluation of energy flexibility potential of buildings, of great importance is the thermal comfort parameter from the indoor environment quality parameters. By applying different energy flexibility strategies -different types of control and different heating medium flows through the heating and cooling plant loop of the Solus system (in the present case)- a decrease in energy demand is expected with more complex strategies implemented. Nevertheless, there is a trade-off between the energy savings and the indoor thermal comfort. As with better energy saving there will always be a reduction of the overall thermal comfort of the respective building, there is a need to evaluate the operative temperatures and analyze the overall thermal comfort levels.

For the building occupants, office workers, with a sedentary activity level of 1,2 met and clothing levels of 0,5 clo for heating season respectively 1 clo for cooling season, the thermal environment is divided into four comfort classes according to “DS/EN Standard 15251-Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics”.

Type of building or space	**Category**	**Temperature range for heating °C** **Clothing ~ 1,0 clo**	**Temperature range for cooling °C** **Clothing ~ 0,5 clo**
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms) Sedentary activity ~1,2 met	I	21,0 – 23,0	23,5 - 25,5
	II	20,0 – 24,0	23,0 - 26,0
	III	19,0 – 25,0	22,0 - 27,0
	IV	Outside category III	Outside category III

Table 4 Thermal comfort classes according to DS/EN 15251/2007

Category	Explanation
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Figure 4 Description of the applicability of the categories used DS/EN 15251/2007

The thermal comfort metric ($F_{comfort}$) is calculated for all referent and flexibility options in accordance with *DS/EN Standard 15251,* as an area weighted value with the following equation:

$F_{comfort}$ [%] $=\frac{\sum Zone\ H\ class\ II * A\ zone}{A\ building * H\ office}$, where:

Zone H class II -the hours of class II achievement for a zone,
A zone -respective zone area,
A building -building total area,
H office -yearly total occupied working hours (2340h).

For a detailed description of the methodology please see Appendix 2: Thermal comfort metric calculation.

3.5.2. ECONOMIC BENEFIT

On a long term, the Danish energy policy is to use 100% renewable energy sources and renounce the conventional fuels. From the worldwide common used renewable energy sources- solar, wind, geothermal… Denmark bases this conversion on wind power generators, as wind is the most available resource. As wind speed varies greatly, so the availability and price of electricity will vary. For the end user of a building, it is important to take advantage of the potential savings of the energy use of the building as this will have a direct impact on the end users' economy. Controlling the heating and cooling systems to be generally active when the electricity price is low, or by slightly lowering the energy consumption and still be able to maintain a similar indoor thermal comfort, will result in a lower electricity bill.

For this reason, the economic benefit metric is defined as the product of the annual energy consumption and the electricity price:

C $=\int (Q * Pel)dt$ where:

C- is the energy cost for heating and cooling;

Q -is the annual energy consumption in hourly rates;

Pel- is the hourly energy price.

The electricity price is extracted from https://www.nordpoolgroup.com online market platform for the year 2015 and the hourly energy consumption is a simulated result of the Energy Plus models.

3.5.3. ABILITY OF ENERGY SHIFTING

The ability of energy shifting metric represents the capability of the system to adjust its output depending on the grid signals. It has been also investigated by P. Heiselberg and J.Le Dreau et.al [1] and presented here accordingly.

At a low level of electricity price, when the grid has a surplus of energy as the demand is not high, the system should enter a "heat storage mode" and increase/decrease the heating/cooling setpoints. When the electricity price is high due to the grid not being able to satisfy the demand, the system should enter a "heat conservation mode", consequently decrease the heating setpoint and increase the cooling setpoint.

In order to analyze the efficiency of an adaptable system, the flexibility factor (Fflex) is defined as the difference of the energy used for heating/cooling when the electricity price is low, and the energy used for heating/cooling when the price is high over time; divided by the sum of these two parameters:

$$\text{Fflex}=\frac{\int Qheating\ and\ cooling\ low\ price\ dt-\int Qheating\ and\ cooling\ high\ price\ dt}{\int Qheating\ and\ cooling\ low\ price\ dt+\int Qheating\ and\ cooling\ high\ price\ dt}$$

As it can be observed from the metric equation, if there is no heating or cooling during high electricity prices the metric has a value of 1, and if the system only works at high prices the value is -1. Therefore, high flexibility factors suggest that the system can use more energy for heating/cooling at low electricity price levels.

It must be noted here that the flexibility factor is dependent on the signal from the grid-electricity price and climatic conditions. Therefore, trough the simulated cases of this research, same climatic conditions and electricity price distribution over the year 2015 are used.

3.5.4. ABILITY OF GRID ADJUSTMENT/POWER DIFFERENCE

Perhaps the most important feature of energy flexibility is the ability of a certain facility to adjust its power consumption according to the grid offer. This metric measures the actual power adjustment of a building by comparing the power consumption of the building's systems using a simple referent controller and a flexible one. As the flexible controllers are designed to respond to the different electricity price levels by adjusting the temperature setpoints, the power consumption would increase at low price and decrease at when the electricity price exceeds the high price threshold. At the defined medium price levels, the flexible controllers will allow the system to accommodate the same power consumption as the simple referent controller. Overall the controllers will have different influences on the systems power consumption as their operational algorithms differ- one is based on a working schedule with occupied/ non-occupied hours (referent controller), the others based on electricity price levels (flexibility1 and flexibility2).

In order to evaluate this metric, eight price levels are defined for the electricity price and the power difference between the referent and flexibility controllers are evaluated for each price level.

The electricity price levels are defined in the table below and the hourly power difference is calculated as:

$P_{difference} = P_{flexibility} - P_{reference}$ where:

$P_{flexibility}$ - is the hourly power supply to flexibility control building systems;

$P_{reference}$- is the hourly power supply to referent control building systems;

and the data is taken from the respective cases simulations results.

	Price level	Percentile [%]	Price threshold [DKK/MWh]
Low	1	0-12.5	75.7
	2	12.5-25	111.5
Medium	3	25-37.5	155.1
	4	37.5-50	176.7
	5	50-62.5	188.4
	6	62.5-75	203.8
High	7	75-87.5	245.1
	8	87.5-100	744.2

Table 5 Price levels

As the simulation results are given for an entire year on an hourly basis, this metric vill also be evaluated over the period of one year thus showing the power difference over both cooling and heating seasons.

3.6. BUILDING CASE STUDIES

3.6.1. FLOW VARIATION

As mentioned before, in the HVAC system description subchapter, the EnergyPlus model uses a simplified model of the heating/cooling two-pipe system. The active beam terminal and loops have been reduced to one theoretical terminal per thermal zone and recalculated accordingly. See table 3.2: Lindab Solus active beams conversion for reference. As the EnergyPlus method of calculation is from the demand side to the supply side, the flow cannot be varied at the pump as the first terminal in the loop will use the maximum flow permitted thus unbalancing the system.

In order to find an optimal variation of the heating/cooling plant water flow, simulations are run at different flows, by reducing the flow with 15% for each simulation from the referent case.

Zone	Referent flow [kg/s]	85%[kg/s]	70%[kg/s]
0S	1.631	1.386	1.141
0N	1.631	1.386	1.141
0E	0.461	0.392	0.323
1W	0.231	0.196	0.161
1C	0.699	0.594	0.490
1S	1.727	1.468	1.209
1N	1.727	1.468	1.209
2S	1.823	1.550	1.276
2N	1.823	1.549	1.276
2C	0.738	0.627	0.517
0C	0.661	0.561	0.462
total flow to the pump	12.929	11.023	9.052

Tabel 6 Analized flows

The accepted flow is the minimum flow at which the indoor comfort is still considered acceptable. Deviations from the criteria are accepted if the thermal parameter (operative temperature) in the zones" is *not more than as example or 5 % of occupied hours a year outside the limits of the specified category".* This amounts to 108 hours per year outside category III. [7]

From the simulations results it can be seen that the indoor thermal comfort metric has a low variation with an overall metric reduction of 1.37% at 85% flow and 3.36% for the second case when compared to the referent metric.

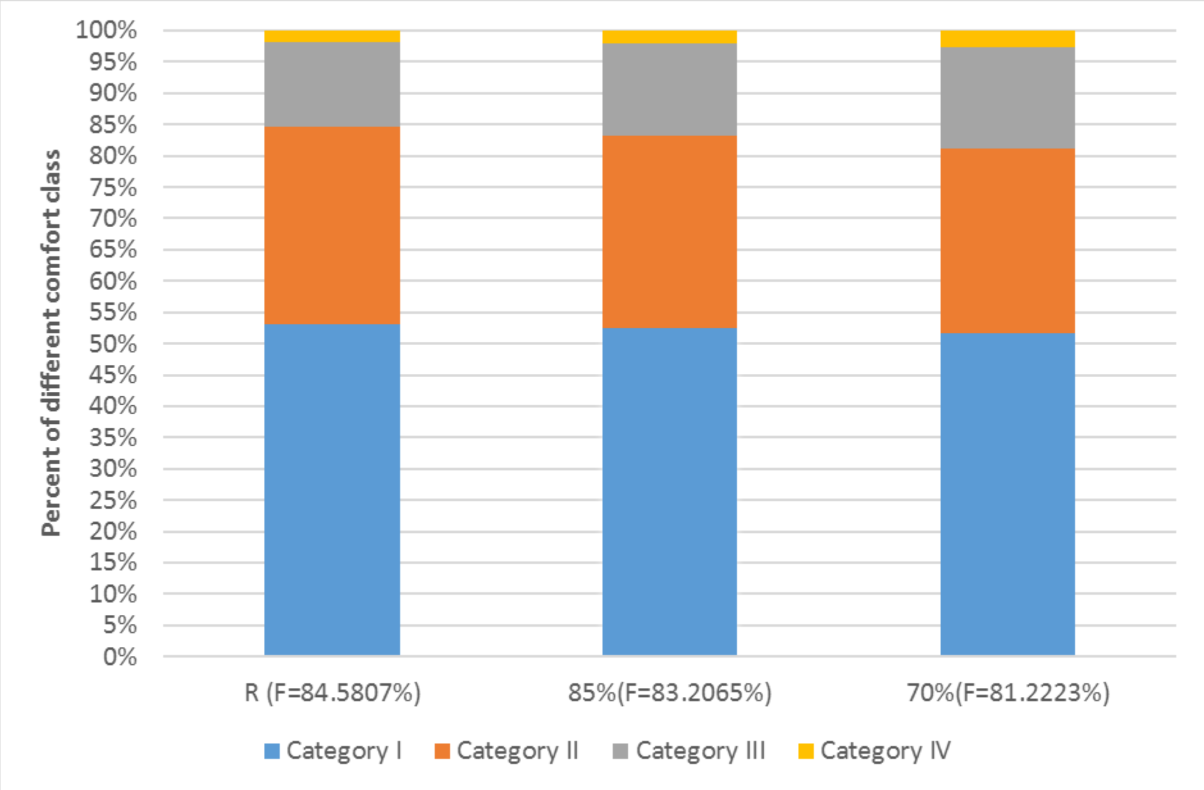


Figure 5 Comfort metric for the referent case at different Solus system water flows

The number of hours where the operative temperature is situated in category I falls with 1.3% for the first case and 2.7% for the second; and for category II with 2.2% and 6.1% respectively. For category III and IV the second case (with a flow reduction to 70% from the reference) has the highest increase with 19 and 49.5%. At a more detailed evaluation it can be seen from the tables below that by reducing the flow with 30%, the north oriented zones have a high number of hours outside category III with zone 2N exceeding the 108 hours limit. Generally, the thermal comfort of the first case (85% flow) follow close the values or the referent case and it is chosen for further evaluation in this research.

Zone	2S			2C			2N		
	R	85% flow	70% flow	R	85% flow	70% flow	R	85% flow	70% flow
Category I	1497	1474	1454	1117	1104	1066	1013	998	985
Category II	2102	2079	2040	2059	2032	1979	1723	1678	1599
Category III	2275	2275	2272	2327	2326	2318	2292	2274	2236
Category IV	65	65	68	13	14	22	48	66	**109**

Table 7 Numbers of hours of each thermal comfort category for level 2 zones

Zone	1C			1S			1N			1W		
	R	85% flow	70% flow	R	85% flow	70% flow	R	85% flow	70% flow	R	85% flow	70% flow
Category I	1112	1083	1052	1430	1426	1416	1011	1004	985	1417	1376	1363
Category II	2059	2030	1990	2023	2001	1970	1766	1715	1637	2205	2179	2161
Category III	2327	2321	2318	2258	2256	2250	2291	2280	2238	2331	2331	2328
Category IV	13	19	22	82	84	90	49	60	**102**	9	9	12

Table 8 Numbers of hours of each thermal comfort category for level 1 zones

Zone	0C			0S			0N			0E		
	R	85% flow	70% flow	R	85% flow	70% flow	R	85% flow	70% flow	R	85% flow	70% flow
Category I	1147	1129	1104	1487	1465	1455	1092	1083	1070	1452	1417	1384
Category II	2094	2070	2043	2088	2068	2037	1979	1937	1895	2230	2209	2191
Category III	2331	2331	2326	2298	2297	2294	2323	2317	2305	2334	2332	2331
Category IV	9	9	14	42	43	46	17	23	35	6	8	9

Table 9 Numbers of hours of each thermal comfort category for level 0 zones

By comparing the Solus system circulation pump electrical consumption and heating/cooling energy used on a yearly basis between the referent and 15% flow reduction cases, the results show that a reduction of 6.278 MWh is achieved. As expected, the energy used for heating and cooling the flow medium increases but as the increase amounts to 0.78 MWh per year for heating and cooling; it can be concluded that a flow reduction of 15% shows promising results.

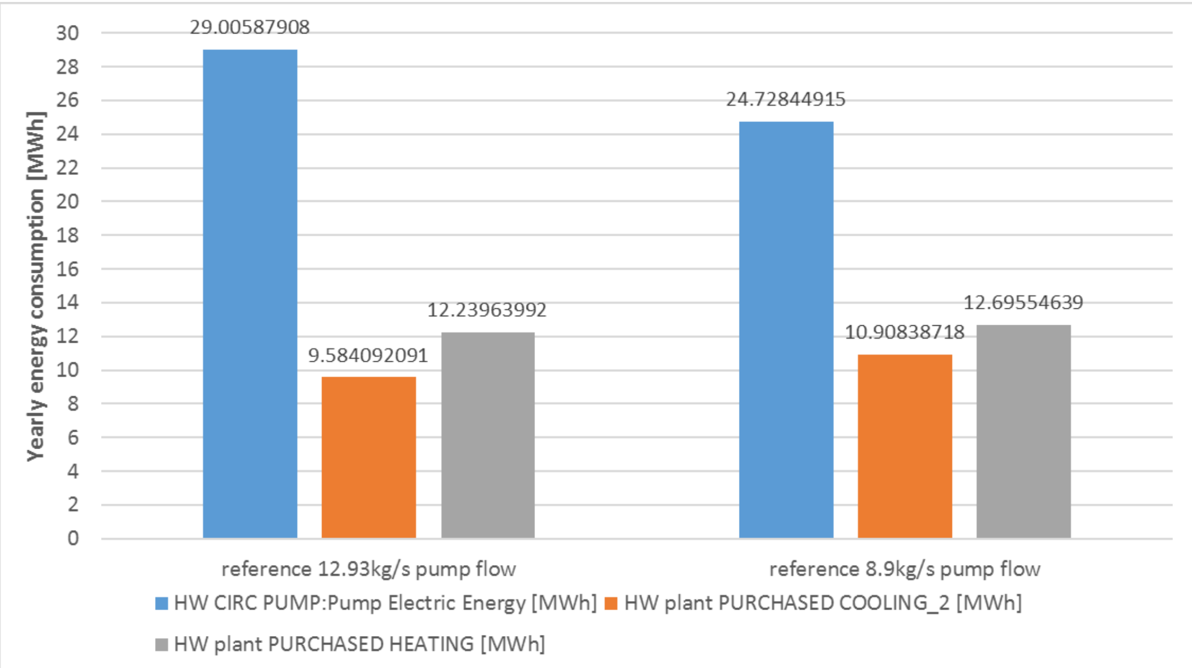


Figure 6 Solus system plant energy consumption comparison

3.6.2. OCCUPANCY VARIATION

As mentioned in the literature review chapter, occupants ”passive role” have a considerable impact on the overall HVAC and heating/cooling plant system. To asses how the occupancy level influences energy flexibility of office buildings, and if at a flow reduction of 15% from the baseline value the system is still capable to mentain an acceptable indoor thermal comfort without significant changes in energy consumption, patterns of presence/absence are created to reproduce situations in which people are present or not in the thermal zones. The same probabilistic model used by Maccarini et al. [5] is used, but adapted for the whole building.

From the baseline full occupancy of 0.057143 persons/m^2 for the entire building the following changes are implemented:

- The occupancy of zones 0C, 1C and 2C is set to an occupancy of one person durring the working hours as they are corridors and in reality never they will have an constant occupancy of 9 persons;
- For each of the remaning zones an ocupancy probability is set every hour and compared to a set of random generated real numbers between 0 and 1 for every possible occupant . If the set probability is higher that the random number, the occupant is in the zone, and if lower he is absent. The sampeling is done every hour for one week. As sugested by Jie Zhao [6] the occupancy probabilities are highest on Tuesday and Wednesday (with an hourly probability decreasing from 100% to 70% during the day), average for Monday and Thursday (decreasing form 90% to 60%) and lowest on Friday (with a daily variation from 70% to 40%). During lunch break (12:00 to 13:00) the occupancy probability is set to 50% for all days.
- The weekly generated occupancy schedules are identical trough all the weeks of the simulated year.

The generated occupancy schedule is presented in the figures bellow and implemented in the EnergyPlus simulation files as a Schedule: File for all zones.

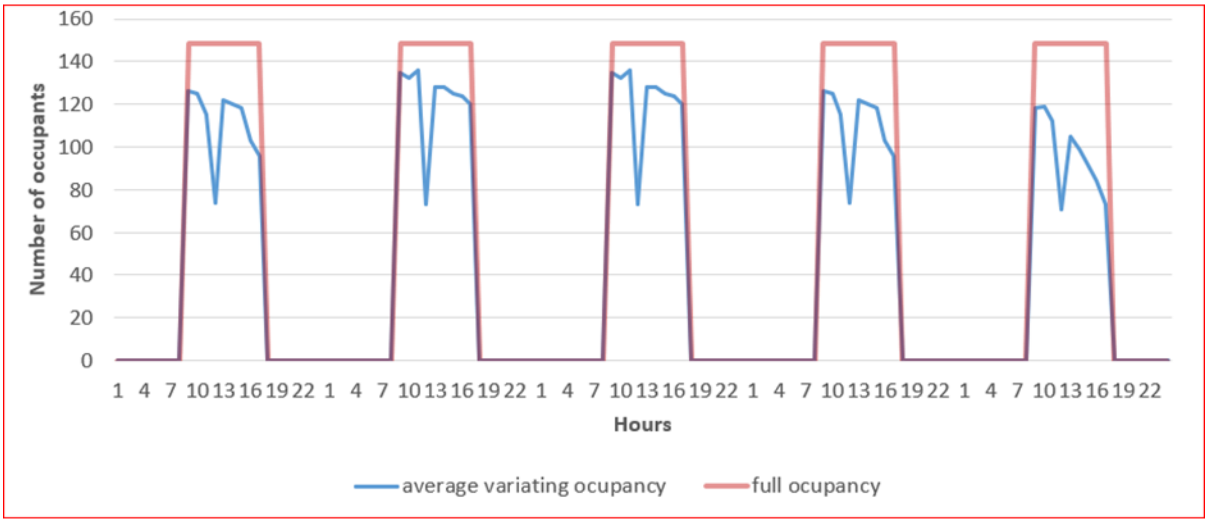


Figure 7 Comparison between baseline occupancy and occupancy variation

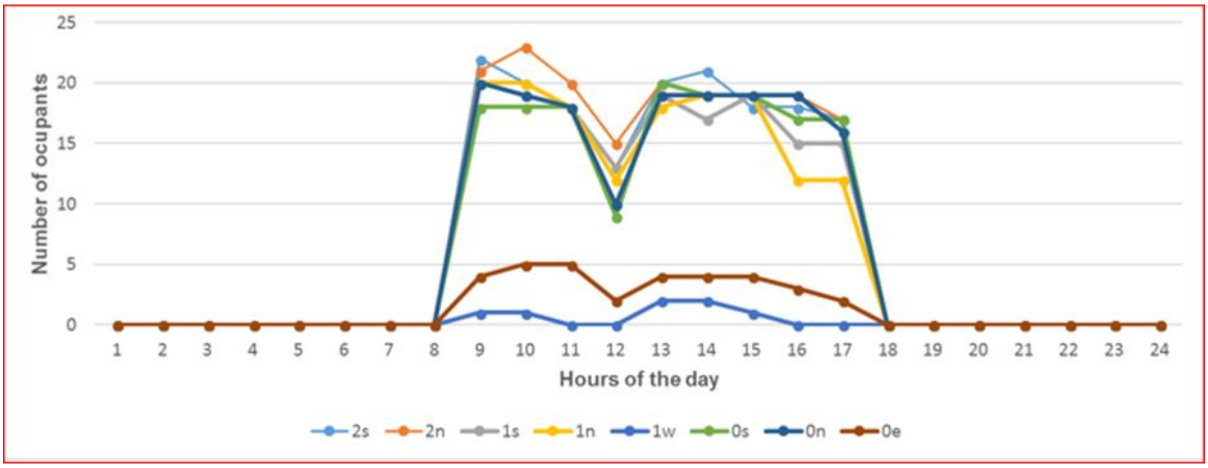


Figure 8 Occupancy variation for Monday and Thursday

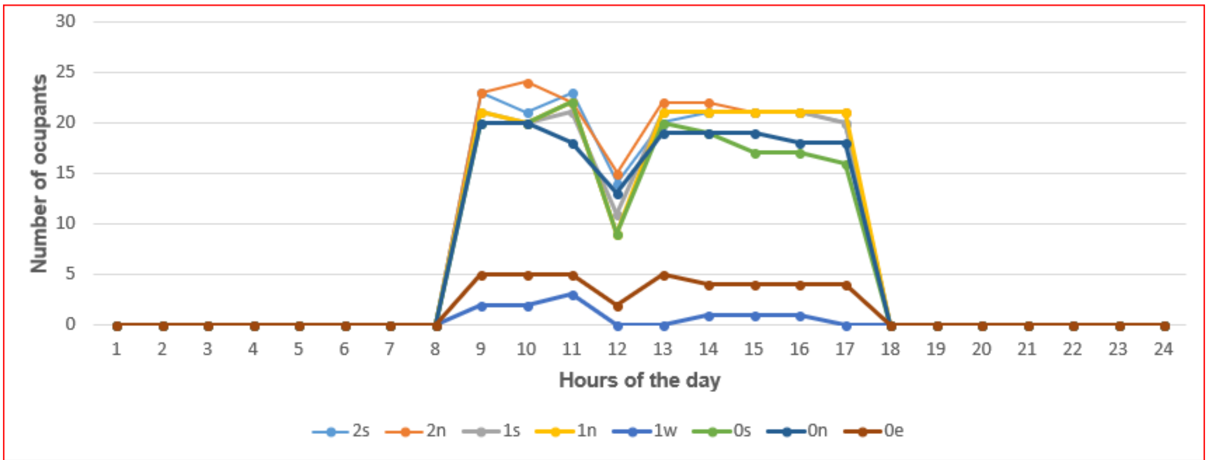


Figure 9 Occupancy variation for Tuesday and Wednesday

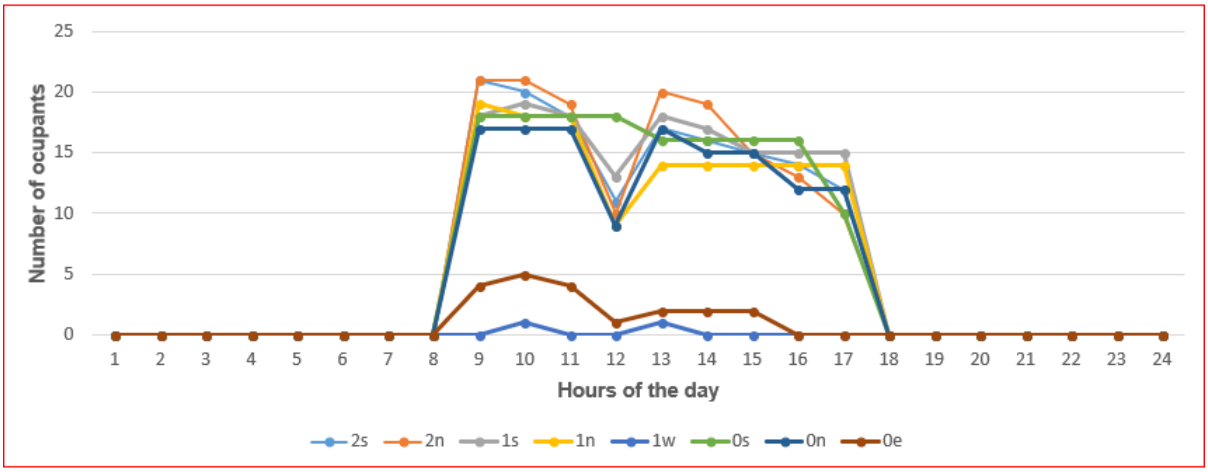
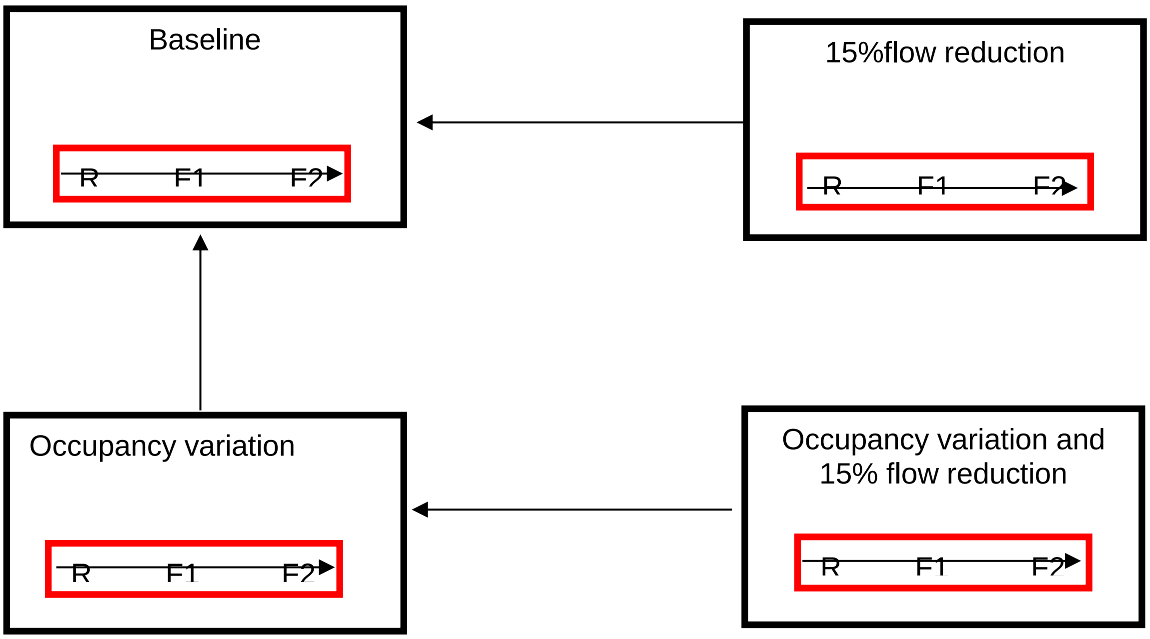


Figure 10 Occupancy variation for Friday

3.6.3. CASES TO BE ANALIZED

By combining the 15% flow reduction with the occupancy variation, three main cases are developed to be compared with the baseline named. Furthermore, each of these four cases have three type of contollers described in subchapter 3.4 Control strategies. It total there are 12 variations to be evaluated and compared. A cross comparison is effectuated between the main cases but also for each case the performance of each control alghorithm is evaluated.



For ease of notation, for each variation there is assigned a ”code name”. Troughout the thesis the variations can be refered to with the full name or by the above mentioned code.

	Referent controller	**Flexibility 1 controller**	**Flexibility 2 controller**
Baseline	R	F1	F2
15% flow reduction	AR	AF1	AF2
Occupancy variation	BR	BF1	BF2
Occupancy variation and 15% flow reduction	CR	CF1	CF2

Table 10 Description of the variations to be analyzed

CHAPTER 4. SIMULATION RESULTS

4.1. THERMAL COMFORT

Thermal comfort is a subjective metric in the sense that it addresses the end user of the facility. To evaluate how the thermal indoor environment responds to flow variation, different occupancy levels and control strategies, the results are compared between all possible variations.

All simulated options register a decrease in the comfort factor if compared to the referent case with the simple controller. If comparing the baseline cases with the “flow variation” the comfort factor is reduced with 1.37%, 1.08% and 1.16% for the referent, flexibility1 and flexibility2 controllers. On the other hand, the occupancy variation presents a reduction of 1.88%, 1.87% and 1.8% from the baseline. This suggests that, for a flow reduction of 15%, a better thermal comfort is achieved than for an occupancy variation of 10 to 29% from the full baseline occupancy.

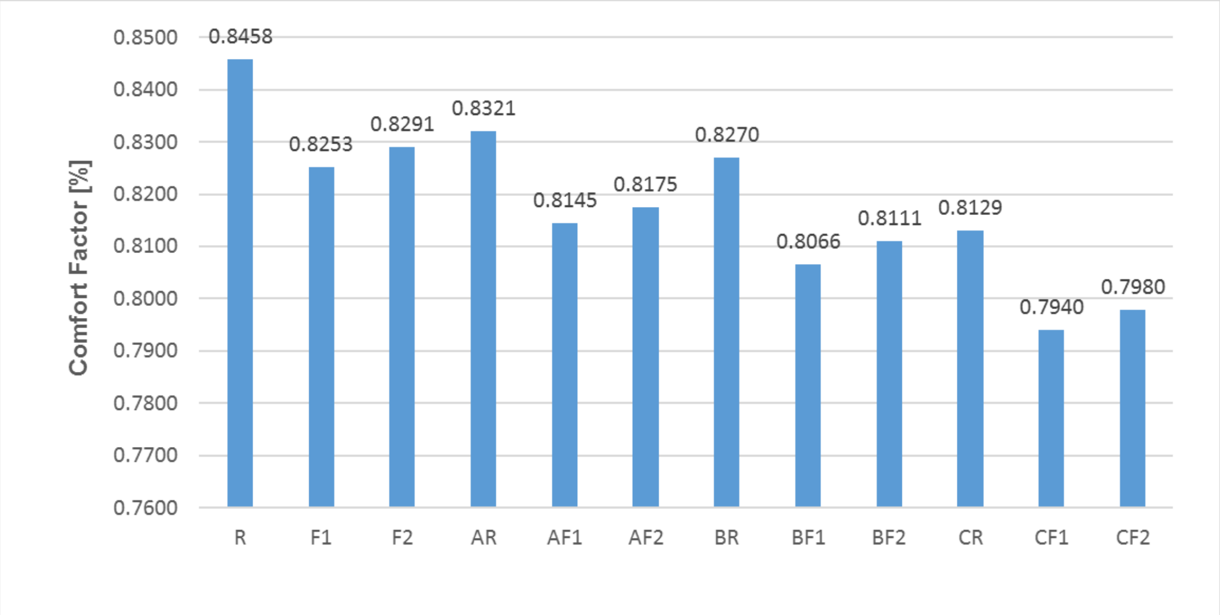


Figure 11 Comfort factor for all variations

When looking at the percentage of hours in a certain comfort class, generally, category I has an increased number of hours with superior control algorithms. Due to the predictive control method implemented, the number of hours in category II increases also when “flexibility 2” control is compared to “flexibility1” for all variation. At a cross-comparison, the number of hours for category II are decreased with only 27 hours with only 10 hours increase for category IV per year between “flexibility 2” and “flexibility 2 with flow reduction”; while the differences are 42 hours for category II and 11 hours for category IV between “flexibility 2” and “flexibility 2 occupancy variation”.

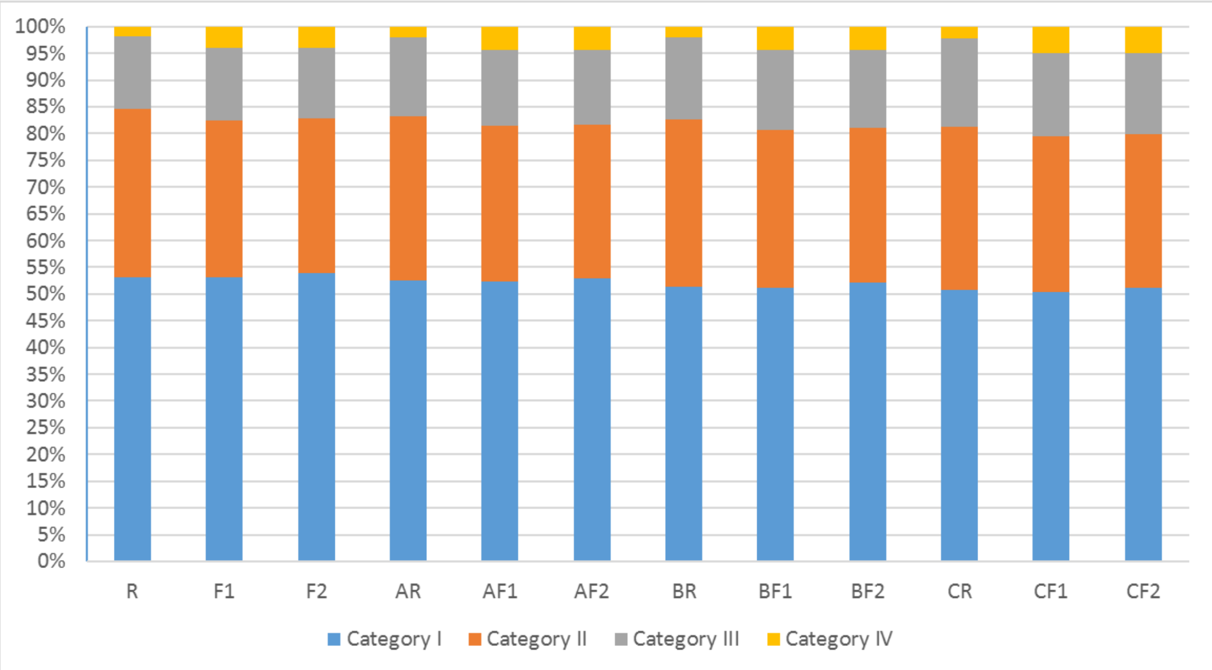


Figure 12 Percentage of different comfort classes during office hours

The worst result is achieved by “flexibility 1 with occupancy and flow variation” with 1858 hours for category II and 117 hours for category IV.

	R	F1	F2	AR	AF1	AF2	BR	BF1	BF2	CR	CF1	CF2
Category I	1243	1241	1260	1227	1223	1241	1202	1197	1221	1186	1179	1199
Category II	1979	1931	1940	1947	1906	1913	1935	1887	1898	1902	1858	1867
Category III	2298	2246	2247	2292	2237	2237	2295	2236	2236	2287	2223	2224
Category IV	42	94	93	48	103	103	45	104	104	53	117	116

Table 11 Number of hours for each comfort class and case

Two conclusions can be made from the results evaluation. First, it is possible to reduce the flow with at least 15% from the nominal value without compromising the thermal comfort. This is mostly due to the capability of the system to transfer heat between the building’s different thermal zones. Second, it can be argued that, as the system works through forced convection, the occupancy level has a greater effect on the systems performance than with traditional HVAC systems.

4.2. ECONOMIC BENEFIT

Results presented in the figure below show that the economic benefit is improved with the use of advanced controllers as the yearly energy costs are reduced. The lowest costs are achieved by "flexibility2" controller in all cases. The maximum cost reduction of this controller is achieved for the occupancy variation case, with a cost fall of 0.14718Dkk/m^{2}year, and the minimum for the baseline case. "Flexibility 1" controller presents a maximum reduction of 0.17179 0.14718Dkk/m^{2}year for the baseline case and a minimum of 0.0748Dkk/m^{2}year for the flow variation case.

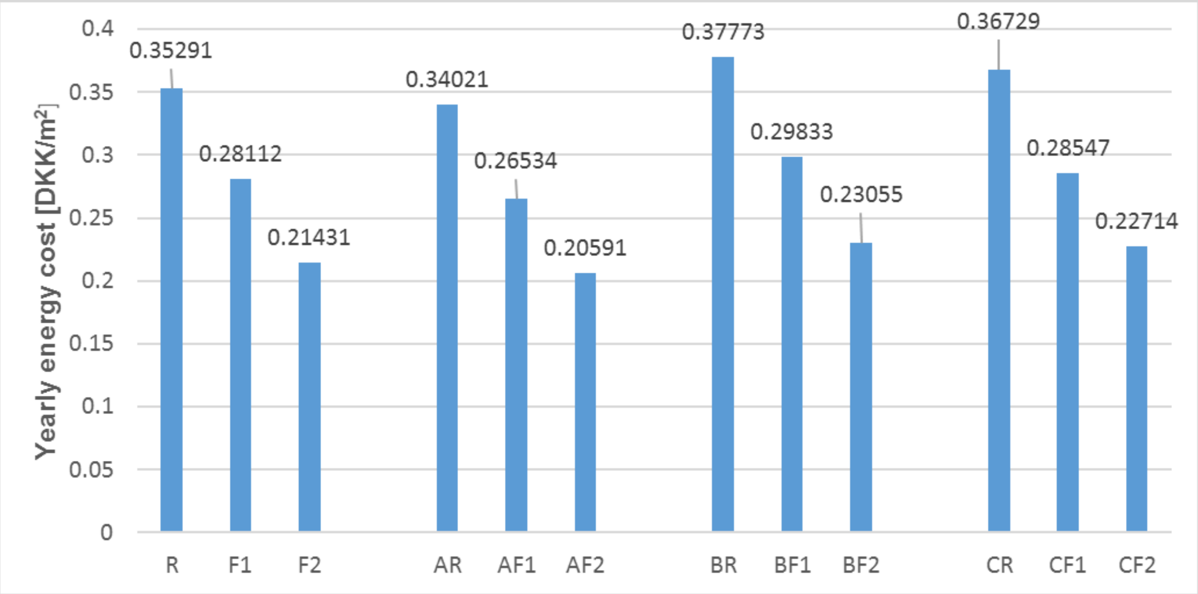


Figure 13 Energy cost for all cases

An in-depth analysis is effectuated in terms of energy consumption, energy cost and energy consumption at different price levels; on a monthly distribution. Controller" Flexibility1" consumes more energy than the "referent" controller for months of March, May to September, and December. However, this extra energy consumption is done at the lowest price levels, therefore the energy cost is lower except for the summer months. On a yearly basis the energy cost is reduced from 0.36739 to 0.28547 DKK/m^2 per year. The higher costs in the cooling season is attributed to a higher electricity cost at the grid and extra energy consumption used for cooling.

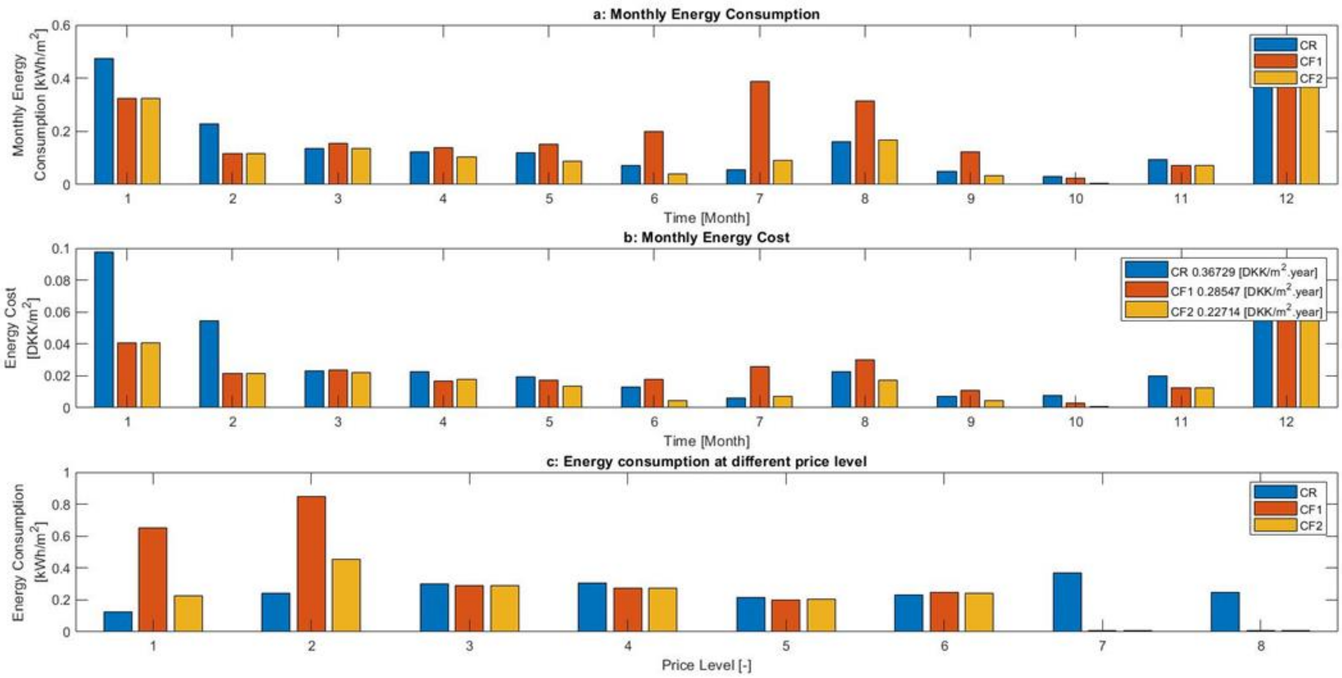


Figure 14 Economic benefit detailed for occupancy plus flow variation case

As these results are consistent throughout the simulated cases, for the graphical representation of all the variations please see Appendix 3: Economic benefit graphical results.

From the graphical representation of the results it can be concluded that "Flexibility2" out-performs the other controllers.

The results are compared between different cases to better analyze the effect of flow and occupancy reduction. The cost difference is compared for all types of control, between baseline and flow variation, baseline and occupancy variation, flow variation and occupancy plus flow variation cases. As it can be seen from the tables bellow, there is a decrease of annual energy cost when the heating/cooling plant flow is reduced by 15% and an increase when the occupancy varies from the baseline full occupancy. When applying the same 15% plant flow reduction to the variating occupancy case, the cost difference becomes positive again suggesting that the system can provide superior economic benefit with flow reduction even for different occupancy rates.

	Cost difference between baseline and flow variation cases [DKK/m²year]	Decrease of annual energy cost [%]
Reference controller (R)	0.0127	3.60%
Flexibility1 (F1)	0.0158	5.61%
Flexibility2 (F2)	0.0084	3.92%

Table 12 Cost difference between baseline and flow variation cases

	Cost difference between baseline and occupancy variation cases [DKK/m²year]	Decrease of annual energy cost [%]
Reference controller (R)	-0.02482	-7.03%
Flexibility1 (F1)	-0.01721	-6.12%
Flexibility2 (F2)	-0.01624	-7.58%

Table 13 Cost difference between baseline and occupancy variation cases

	Cost difference between occupancy variation and occupancy+flow variation cases [DKK/m²year]	Decrease of annual energy cost [%]
Reference controller (R)	0.01044	2.76%
Flexibility1 (F1)	0.01286	4.31%
Flexibility2 (F2)	0.00341	1.48%

Table 14 Cost difference between occupancy variation and occupancy+flow variation cases

Controller "flexibility 1" has the best performance overall with a decrease of annual energy cost of 5.61% (F1-AF1cases), 4.31% (BF1-CF1 cases), and an increase of only 6.12% (F1-BF1 cases). This proves that just a general comparison, as the one at the beginning of the subchapter, can be misleading.

4.3. ABILITY OF ENERGY SHIFTING

As described in the first part of this thesis, to analyze the ability of the system to shift its energy consumption from high to low price levels, the flexibility factors are calculated for each case and presented in the table below:

	R cases Flex Factor	F1 cases Flex Factor	F2 cases Flex Factor
Baseline	-0.21419	0.9914	0.97999
Flow variation	-0.22208	0.98649	0.96996
Occupancy variation	-0.22937	0.98428	0.9639
Occupancy and flow variation	-0.24953	0.97882	0.95394

Table 15 Flexibility factors for all cases

The flexibility controllers, for all cases, have a factor above 0.95 which indicates that the system's energy consumption is shifted mostly to low price periods as a factor equal to 1 represents no energy consumption during high price periods. For the referent controllers, the factor variates between -0.21 and -0.25 indicating an energy consumption during high price periods three times higher than for low price periods. It is observed that there is an enormous improvement on the ability of the system to shift his energy use when flexibility control options are implemented. The predictive controller "Flexibility2" has better flexibility factors than "Flexibility1" but this pales in comparison with the difference from the referent controllers.

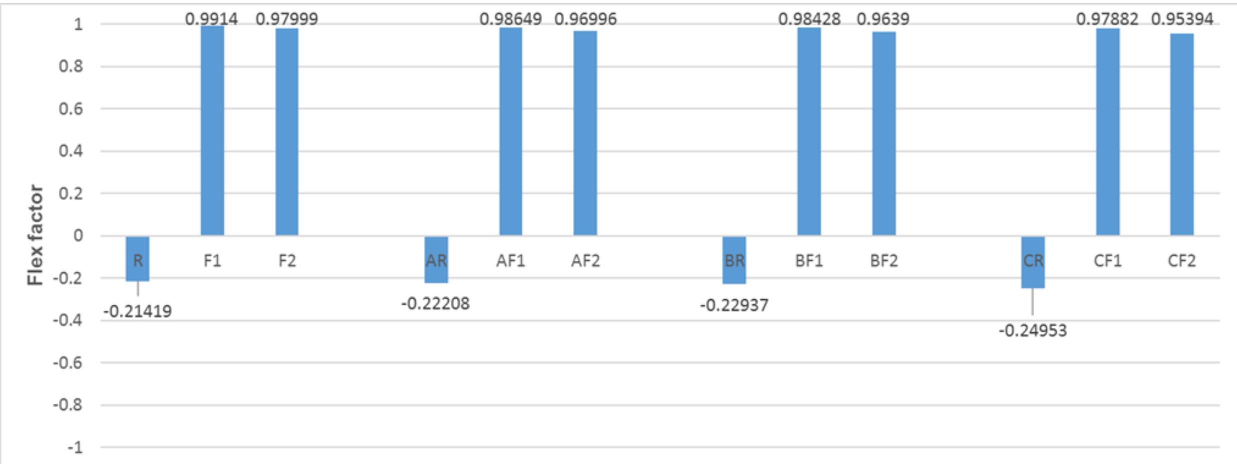


Figure 15 Flexibility factors for all cases comparison

A cross comparison analysis between the variations reveals that the flexibility factors differences (between baseline-flow variation and occupancy variation-flow variation) are of 10^{-2} order. In practice this is basically equal to 0.

In what concerns the energy consumption for heating and cooling, throughout the variations, the system consumes more energy, when the control algorithm corresponds to “flexibility1” controller. This increase of energy used for cooling is attributed to high solar gains on the south thermal zones and it is resolved with the implementation of control algorithm “flexibility2” that activates cooling depending on future climatic conditions.

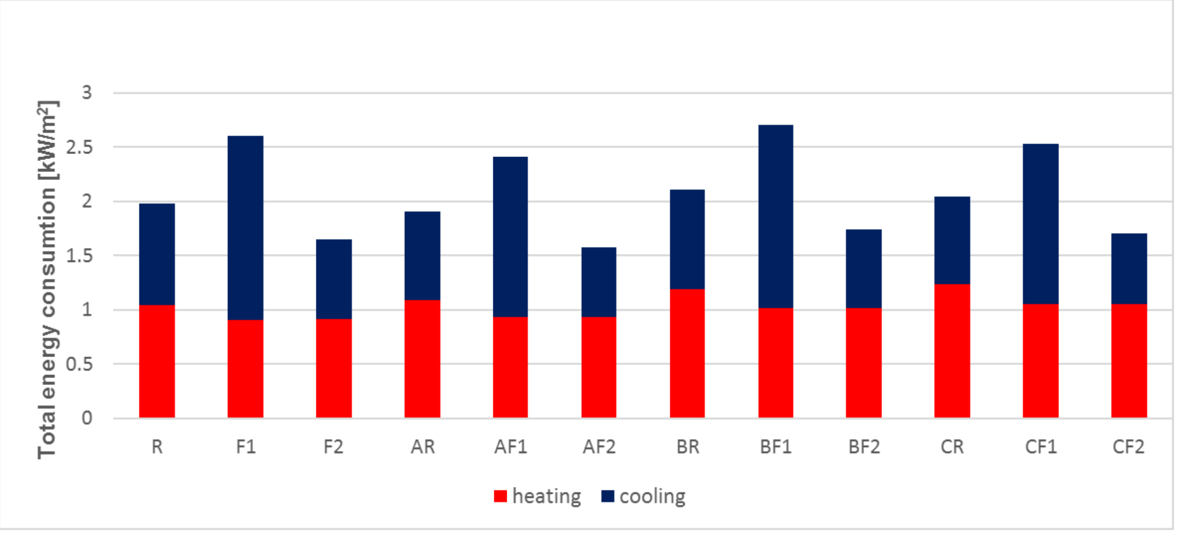


Figure 16 Yearly values for heating/cooling plant energy use

Furthermore, it is evaluated how a 15% flow reduction influences the heating/cooling plant total consumption (R/F1/F2 compared to AR/AF1/AF2 and BR/BF1/BF2 compared to CR/CF1/CF2). Results show that in the cases of flow reduction there is a small increase of energy use for heating but generally the overall consumption is lower than in the cases where the flow is kept at its nominal value. This is due to an actual reduction of energy used for cooling as at lower flows there is an increase of thermal energy transfer between the water medium and the zones air.

It must be underlined here that this factor does not consider the plant system circulation pump’s energy reduction in the cases when the flow is reduced with 15% and actual results may almost certain prove an increase ability of energy shifting than the ones presented here.

4.4. ABILITY OF GRID ADJUSTMENT/POWER DIFFERENCE

The power difference between the flexibility and their respective referent controllers is investigated for all the cases. As described before in sub-chapter 3.6.3 Case studies, all variations have the same lighting and equipment load, same solar gains and the same thermal properties of the building's envelope. The results show no difference in the ability of grid adjustment on a cross comparison between the four main cases as this metric investigates the ability of the building to store and release energy in its thermal mass. The variations investigated in this thesis (flow and occupancy variation) have a minimal, close to no effect, on the power difference when evaluated on a yearly basis. As this effect can be hard to visualize, maybe more in-detail evaluations (on a daily occupancy interval basis) methods are needed to evaluate the power difference. For a full graphical representation of the results please see Appendix 4: Power difference results.

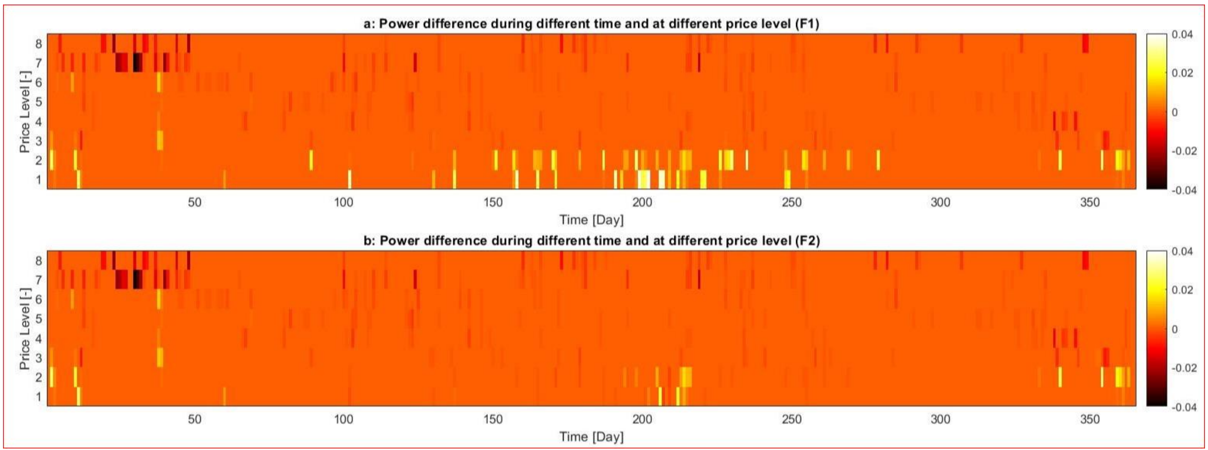


Figure 17 Power difference between referent and flexibility controllers for all cases

On a comparison between the different types of controllers, at the boundary condition for the high price level (between price levels 6 and 7), the power difference has negative values as both flexibility controllers minimize the power consumption. This effect is highly visible during the first part of the year corresponding to the heating season. During most of the year "flexibility1" controller manages to register more hours of positive power difference at low price level (price levels 1 and 2) that "flexibility2". The predictive nature of "flexibility2" controller has a negative effect on the grid adjustment as cooling is activated when the outdoor air and direct solar radiation exceed 20 °C and 500W/m2 on a 24 hours prediction horizon.

4.5. SUMMARY OF RESULTS

The main findings of the investigations are compiled in this subchapter to present a holistic overview of the findings.

First, by evaluating the overall system behavior when the occupancy is reduced from the baseline case with 10 to 29%, it can be concluded that, even at a small to moderate occupancy variation the systems energy consumption is affected with a total cost increase of 7.58% for “flexibility 2” controller. The thermal comfort is reduced with 2% but this deviation is considered to be acceptable.

It can be argued at this point that the system is more sensible to “people load” than traditional heating/cooling systems as it works by convective heating/cooling, inducing the zone air in the mixing plenum of the ventilation terminal through its coil.

		R	F1	F2
Flexibility factor [-]	occupancy variation	-0.22937	0.98428	0.9639
	baseline	-0.21419	0.9914	0.97999
Thermal comfort Category II [%]	occupancy variation	83%	81%	81%
	baseline	85%	83%	83%
Plant energy consumption for heating and cooling [kWh/m^2 year]	occupancy variation	2.10	2.70	1.74
	baseline	1.98	2.60	1.65
Energy cost savings (occupancy variation-baseline) [%]		-7.03%	-6.12%	-7.58%

Tabel 16 Results summary- occupancy variation compared with baseline

When comparing the 15% flow reduction variation with the baseline case results show a negligible decrease of flexibility factors for all the control algorithms indicating a stability in the ability of energy shifting. The thermal comfort metric is reduced with 2% from the baseline to a minimum of 81% corresponding to “flexibility 1” controller. The total energy consumption of the two-pipe system, excluding the energy use of the circulation pump, is reduced with a maximum value of 0.19 kWh/m^2 per year also in the case of “flexibility 1” controller with energy savings of 5.31%.

		R	F1	F2
Flexibility factor [-]	15% flow reduction	-0.22208	0.98649	0.96996
	baseline	-0.21419	0.99140	0.97999
Thermal comfort Category II [%]	15% flow reduction	83%	81%	82%
	baseline	85%	83%	83%
Plant energy consumption for heating and cooling [kWh/m^2 year]	15% flow reduction	1.90	2.41	1.57
	baseline	1.98	2.60	1.65
Energy cost savings (15%flow reduction-baseline) [%]		3.6%	5.31%	3.92%

Tabel 17 Results summary- 15%flow reduction compared with baseline

Similar results are found when the same 15% flow reduction is applied over the occupancy variation. The maximum energy savings amount to 4.31% with a decrease in plant energy consumption of 0.170.19 kWh/m^2 per year. Therefore, it can be concluded that the plant flow reduction has positive effects even when applied over a reduction in occupancy.

		R	F1	F2
Flexibility factor [-]	occupancy variation	-0.22937	0.98428	0.9639
	Occupancy variation and 15% flow reduction	-0.24953	0.97882	0.95394
Thermal comfort Category II [%]	occupancy variation	83%	81%	81%
	Occupancy variation and 15% flow reduction	81%	79%	80%
Plant energy consumption for heating and cooling [kWh/m^2 year]	occupancy variation	2.10	2.70	1.74
	Occupancy variation and 15% flow reduction	2.04	2.53	1.70
Energy cost savings (occupancy variation and 15%flow reduction-baseline) [%]		2.76%	4.31%	1.48%

Tabel 18 Results summary- occupancy variation compared with occupancy variation and 15%flow reduction

CHAPTER 5. CONCLUSION AND SUGESTIONS FOR FURTHER REASERCH

The aim of this study was to evaluate how energy flexibility of a newly build office building, serviced by a two-pipe system active beam used both for heating and cooling, is influenced by occupancy level variation, flow reduction of the heating/cooling medium, and different control strategies. For this purpose, in the first part of the thesis energy flexibility metrics are presented and investigations have been made, inspired by the reviewed literature, on the occupancy variation and flow reduction strategies. The occupancy variation has been generated using a simple probabilistic model inspired by Maccarini et al. [5] and occupancy probabilities in accordance with the investigation findings of Jie Zhao [6].

The minimum flow was chosen by repetitive simulations of the baseline model with different flows, until the number of hours, when the indoor thermal comfort is outside the temperature range of category II, exceeds 108 in accordance with "DS/EN Standard 15251-Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics".

Three main building cases are chosen (15% flow reduction, occupancy variation and occupancy variation with 15% flow), and combined with the baseline case and three different control strategies. In total 12 building model options are established and simulated in EnergyPlus energy simulation software.

In the second part the simulation results are analysed, and cross compared between the main variation cases but also locally to see how different control algorithms influence the evaluation metrics for each main case.

Throughout the thesis it has been proven that occupancy levels have an important impact on the two-pipe system functionality and the 15% flow reduction is able to reduce the energy consumption without considerable sacrifice on the thermal comfort. The flow reduction was also able to account for the occupancy variation and set back the metrics close to the baseline value. In what concern control, the best strategy with this system has been proven to allow the building to store energy in the thermal mass during low electricity prices and use the stored energy during high prices levels. The simple prediction algorithm is outperformed by it.

The power difference metric has proven inconclusive to the research of this thesis as it addresses more the heat storage capabilities of the building. The ability of energy shifting has been proven robust with very small differences in the four main variations. However, it has to be underlined that the results do not take into account the energy savings of the circulation pump in the flow reduction cases and it is predicted that in reality the system is able to perform better.

Further research is recommended as to integrate flow reduction as a control possibility together with the temperature set-points. It is believed that in the cold season on a sunny day, a flow reduction cam better mitigate the temperature difference between the south and north oriented zones and save energy while doing so.

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LIST OF FIGURES AND TABLES

APPENDICES