Energy flexibility of office buildings -Comparison on potential in different building types

Master's Thesis Report

Written by: Ivan Kolev and Kremena Pavlova
Supervisors: Per Heiselberg and Mingzhe Liu

Date: 10.01.2017

Aalborg University

AALBORG UNIVERSITY
DENMARK

Project period: 1.09.2017-10.1.2018

Title: Energy flexibility of office buildings – Comparison on potential in different building types

Authors:

Ivan Kolev

Student no.20160149

(Signature)

Kremena Pavlova

Student no.20160143

(Signature)

Supervisors: Per Heiselberg, Mingzhe Liu

Pages report: 52

Pages appendix: 60

Synopsis

This research document is developed to assess the energy flexibility potential in office buildings in Denmark. The study focuses on ability of building thermal mass to store energy. There are office and administrative buildings currently used in the country which are erected over different periods of time. They differ in thermal properties, heat capacity of building elements, air permeability, people load, equipment load, etc. Their building energy flexibility is expected to perform differently, therefore is examined, and classified. Four main building cases are included in the research, each of them representing specifications of building structure typical for their time of erection. Different configurations of internal loads and solar gains are assigned for each case. Assessment is conducted using a novel system which has the ability to both heat and cool by using the principle of forced convection. A flexibility controller, based on electricity price, is applied to the system in order to activate the thermal mass of chosen structures. Evaluation of investigated building models is done according to developed metrics.

Abstract/Preface

This master paper is a mandatory part of the fourth semester programme in Building Energy Design at Aalborg University. The objective of this research is to investigate and evaluate the performance of energy flexibility of typical Danish office building constructions dating from different periods. Studies are carried out for 4 different building cases, each of them characterized by different heating demand, thermal storage, insulation level, infiltration rate, but supplied with a same novel two-pipe heating and cooling system.Each main case is divided in 4 subcases as they differ in internal gain (people load, lighting, equipment load, solar gains).Analysis and comparison have been performed on two control strategies in order to implement evaluation methodology. This includes ability of energy shifting and grid adjustment, comfort level, economic benefits. All investigated models are tested with two controllers – a normal one called a "referent" and a "flexible" which represents the integration of energy flexible measure in the system. The flexible controller has the ability to adjust the set points for heating and cooling depending on different price levels.

Energy flexibility can be assessed by the conservation capability of buildings. There are different ways buildings can store energy with the use of hot water tanks, etc. But there is also a promising potential in using storage of the building structure, therefore this document will focus on the available thermal structural storage of different building cases. This will define the relation between thermal building properties and efficiency of energy flexibility. The results of the study will give an insight into the energy flexibility performance of each building case, by concluding what are the outcomes and shortcomings for user thermal comfort level and costs for operation of the energy system.

Acknowledgements

This project is done as a continued study of a base unpublished research conducted by the Supervisors in this project – Mingzhe Liu and Per Kvols Heiselberg called "Energy flexibility of a nearly-zero-energy building with a novel building energy system evaluated with integrated metrics". The fundament of their work is used during the process of these assessments, moreover current project can be considered as a natural follow-up of their work brought to a further direction. Many of the technical elements are either reused or inspired of the base research. For example, the prototype of their geometric model is used to create variety of building structural options in Energy +. Thermal zoning of the building is kept according to the example in their research. All investigated 16 options are analyzed and compared according to evaluation metrics included also in their labor. There are other research papers used as an inspiration for methodology approach or used technical terminology as "Energy flexibility of residential buildings using short term heat storage in thermal mass" (J.Le Dreau, and Per Heiselberg), "Phase change materials and thermal energy storage for buildings" (Alvaro de Gracia,Luisa F.Cabeza), "Energy saving potential of a two-pipe system for simultaneous heating and cooling of office buildings" (Alessandro Maccarini, Michael Wetter, Alireza Afshari, Goran Hultmark).

Table of content

1. Introduction

1.1 Background of the project

Today the need of implementation of sustainable energy solutions globally has resulted a growth of renewable energy sources and more yet to come. Increasing number of governments establish different energy policies and strategies to cut off from the diminishing natural resources- fossil fuels. Countries, for instance like Denmark has directed energy milestone to convert completely 100 percent on green energy for both energy and transport sector by 2050.In order to complete this goal, Denmark has set up several energy policy milestones: half of the electricity produced is covered by wind power by 2020, coal must be phased out from Danish power plants by 2030 and electricity and heat supply provided by renewable energy by 2035 (1). At this stage, Denmark has managed successfully to support 30 % of its total share of energy consumption with renewable energy. (2) The country is one of the leaders of wind power generation as it provides more than 5 GW of installed wind energy capacity, of which almost 1.3 GW are offshore wind turbines (2).

Consequently, the huge ‘’green transition’’ is leading to a surplus of energy that is being derived from the renewable electricity generation. Thus, problems are experienced with overloading electricity power lines creating grid/voltage instability, due to fluctuation of the available electricity production and its deviation from the actual electricity demand. Since electricity is difficult and expensive to store, a bigger attention is paid on energy flexibility improvements or in other words on finding solution to resolve the mismatch between the demanded and the produced electricity. Furthermore, energy flexibility has to improve on both electricity supply and response side and the latter puts focus on demand response (DR) of building systems.

Demand response of building electrical systems is represented of a shift in power consumption from the system in order to balance the electricity demands with available power in the grid or to respond to the supply conditions. Therefore, buildings will play huge role for energy flexibility development and one key strategy will be introducing of more “grid supportive buildings”. This means a building with integrated DR will shift its energy response according to the grid availability by using smart energy management controls .Normally, the response is dependent on the changes of electricity price. In addition, building structure can offer different energy storage capability. For example, buildings thermal mass utilization combined in the same time with HVAC system with modern automated DR control are expected to contribute to higher energy flexibility.

1.2 Problem Formulation

As it is well-known, electricity production provided by renewable sources has relatively unpredictable trend. This surplus or lack of power in grid influence the price on market. Business can benefit of the price fluctuation if they make their administrative buildings flexible and oriented to low tariff periods. Application of energy flexibility will also make their administrative centers supportive to the challenges in electricity grid. There are constructions currently used as office buildings in Denmark, which are erected over different ages. Some are quite modern, others have typical features from the middle of 20th century, there are even architectural examples dating back to the "National Romanticism" period. All these variety of building types will affect the performance of energy flexibility differently. So the focus of this master thesis and the main research question is:
What is the energy flexibility potential in office buildings from different periods of time?
The approach to the question would be set by distinguishing different building properties typical for each identified period. Once the classification of the constructions and their parameters are clarified, their energy flexibility performance will be simulated using a relevant software tool -Energy plus. Then performance of each type will be examined and compared according to evaluation metrics.

1.3 Problem delimitation

Delimitation on used control strategies

This research will not make deep investigation on optimizing the used control strategies. Basic analysis of disadvantages of current flexibility controller will be done, and ideas of optimizations will be proposed. But implementation and simulation on the suggested ideas will not be performed.

Delimitation of used HVAC system

This document includes 4 main different cases of construction types, each of them has 4 alternatives of varying internal gains: for people load, equipment load, lighting load and solar gains. In total there are created 16 investigated options with a normal/referent controller, and another 16 with a flexibility controller. All options in the research are examined with the same HVAC system – Lindab Solus Beam (See Chapter 3.1 HVAC system description). Building energy flexibility potential of the investigated options with other HVAC systems, f.e. floor heating or radiators are not considered.

Delimitation due to the used simulating software

Main focus of the research is to investigate the potential of thermal mass, and more precisely the ability to store energy in building components. There are advanced building materials called phase change materials (PCM). PCM are designed with the special purpose to accumulate energy and then release it with a higher amount by changing phase from solid to liquid. EnergyPlus is used software tool to perform simulations in this research. The software does not support implementation of PCM in models, therefore only standard building materials are used.

1.4 Research Methodology

Focuses of investigations are office buildings which have typical properties for four different periods of time- administrative buildings from 1890-1930, from 1940-1980, complying “Building regulations 2015”, and fulfilling “Building Class 2020”. Periods are distinguished in 4 different cases which differ in transmission and infiltration losses, and heat capacity of building elements. The 4 cases are combined with 2 alternatives for people load, equipment load, lighting load, and another 2 alternatives for g-values. Therefore, all cases have 4 variations resulting in total of 16 different options (see chapter 3.2 Building case studies). All options are being tested for their energy performance with and without a flexibility controller of their HVAC system. EnergyPlus is being used to perform the simulations, as it has the ability and functionality to implement the specific heating and cooling system together with the used control strategy. The building model used in simulations has the same geometrics for all cases. It is a three-storey building with total area of 2926 m2. The model has a relatively high share of 38% glazed facade area. The pitched roof typical for case 1(see chapter 3.2 Building cases) is simplified and shape is adjusted to fit the software model. Weather data file used in simulations complies for Denmark (Copenhagen). Energy flexibility of all options is tested with an archived electricity price list from 2015 (9). The results of all investigated options are evaluated and compared according to evaluation metrics presented in chapter 3.3 Evaluation metrics description.

2. Literature review

Various research papers are reviewed and analyzed before and during the development of current project. . Valuable information as a solid background is gained within the topic of energy flexibility. Approaches of other researches are investigated, together with their focuses and findings.Through-out the literature review are found inspirations or shared methods for storing energy in buildings, defined controllers used for energy storage, and methods to evaluate the efficiency over tested strategies for optimizations.

In general, energy flexibility topic is still a growing area of research. Nevertheless, the investigations within building energy flexibility are measured with a great importance. Buildings can store energy by using equipment like water tanks, batteries or the building structure itself (3).In this way they can adjust their energy demand, which can help in solving the problems with future energy grids.

There is a promising potential of the thermal mass of the building structure. Therefore, in different case studies, it is commonly evaluated how thermal structure of a building can take best advantage of fluctuating energy prices (4)

As Glenn Reynders *et al*.(4) state the investigation approach of such cases confirms for high energy cost savings when thermal mass is being activated in order to achieve optimized energy consumption profile. However, it is also mentioned that the results are highly case dependent, due to the fact the savings vary of the local energy price market and thus can be difficult to generalize conclusions.

In the research paper developed by J.Le Dreau and. P .Heiselberg (3) thermal mass storage is also being examined as an energy flexibility potential of residential buildings. For the purpose, they develop a concept for different modulations of set-point which will indicate whether the HVAC system is in charging or discharging mode. When their system is in “upward modulation”, the set-point is increased with 2K, therefore energy is being stored. “Downward modulation” is defined as a decrease of the set point with 2K, which turns the building into conservation mode, in other words releasing the heat previously stored in the thermal mass. These principle of set-point modulation of the controller are used to test the potential of energy flexibility in office buildings assessed in this paper (see chapter 3.1.1 Used control strategies). Further in the same research by Dreau and Heiselberg (3), they apply a price signal divided into three levels – corresponding to low, normal and high prices of electricity on the market. So according to the price signal, their system switches either on “upward modulation”, “downward modulation” or keeps the basic set point. To evaluate the performance of the ability of the controller to switch from high to low price levels, they use the term “a flexibility factor” (see chapter 3.3.2 Ability of energy shifting). This factor is used in current research as part of the evaluation metrics to investigate energy flexibility performance.

Also, in their study the assessment is done on two buildings with different thermal properties. It is demonstrated that level of insulation and infiltration rate have significant importance on the thermal performance of the buildings. The investigations are also oriented on different type of heat emitters-a radiator and a floor heating system .Finally, the conclusion reports for a better understanding of dynamic behavior of buildings towards flexibility strategy. The investigated modulation scenarios results in varying savings in energy cost between 3 and 10 %. It is also given a suggestion for further research to investigate energy flexibility with other types of buildings and systems for activation of thermal mass. This is where the current topic of research is inspired from.

Different methodology approaches are implemented to evaluate different research cases. For instance, Glenn Reynders *et al*.(4) use a generic quantification method of the structural thermal mass. This method considers three main dimensions of energy flexibility-size, time and cost represented by storage capacity, storage efficiency and shifting capability. Nevertheless, due to simplification of the researched model, the study investigates constant outdoor temperature and shorter period for simulations. Therefore, in the current master paper, other metrics are used to assess the flexibility performance for each building case. Those implemented in this research examine the thermal comfort, economic benefit, energy shifting and power adjustment of the grid on an annual base.

In the paper of Development of a new controller for simultaneous heating and cooling of office buildings" (5), there a few key aspects common for the current project. In this document, the research is conducted with an HVAC system which has the same distribution principle of a two pipe system used for both heating and cooling. In addition, their assessment is done for an office building. Therefore some of the parameters as internal heat loads are shared, or adjusted according to the sources used in the above mentioned research. The developed controller by Maccarini et al. (5) is designed to provide supply according to indoor air temperature. Their newly tested controller optimized energy cost with approximately 44%. For comparison the best performing option (Option 13) in current paper also registers significant savings of up to 41% by using a flexibility controller.

3.Energy flexibility research

3.1 HVAC system description

The case study involves evaluation of the energy flexibility potential of a novel building energy system that is represented by active chilled beam used for both heating and cooling. Such system is based on induction principle and the heat transfer is done by forced convection. Ventilation air is supplied with a high pressure by the diffusers of the beams located on the suspended ceiling of each thermal zone. The created low pressure underneath the unit makes the room air to induce through the coil and then this air is recirculated again through the diffuser and supplied back in the room heated or cooled, depending on the need. Ventilation ratio of primary to induction air can vary between 1:2 and 1:7, which is quite high for an active chill beam. The primary air is supplied in the unit with a set point of 18 degrees and for this purpose is pre-heated by the use of a rotary heat exchanger.

The unique HVAC system allows low temperature heating and high temperature cooling handled by the same two-pipe water loop with operating temperatures of 20-23 degrees. This will provide the possibility of reusing the thermal energy in the return water circuit, which makes the system highly efficient and will contribute to greater savings on running and commissioning costs. As well as cost for repair of the system, due to the fact there are only pipes for maintenance (f.e there are no regulation valves).

The innovative two pipes system will also provide the possibility to cool and heat in the same time the building as the system can take an advantage from the excess heat from one place and transfer it to another if there is a need for this. It is commonly met in practice, rooms facing north have need for heating while zones with south orientation might experience overheating on a sunny winter day.

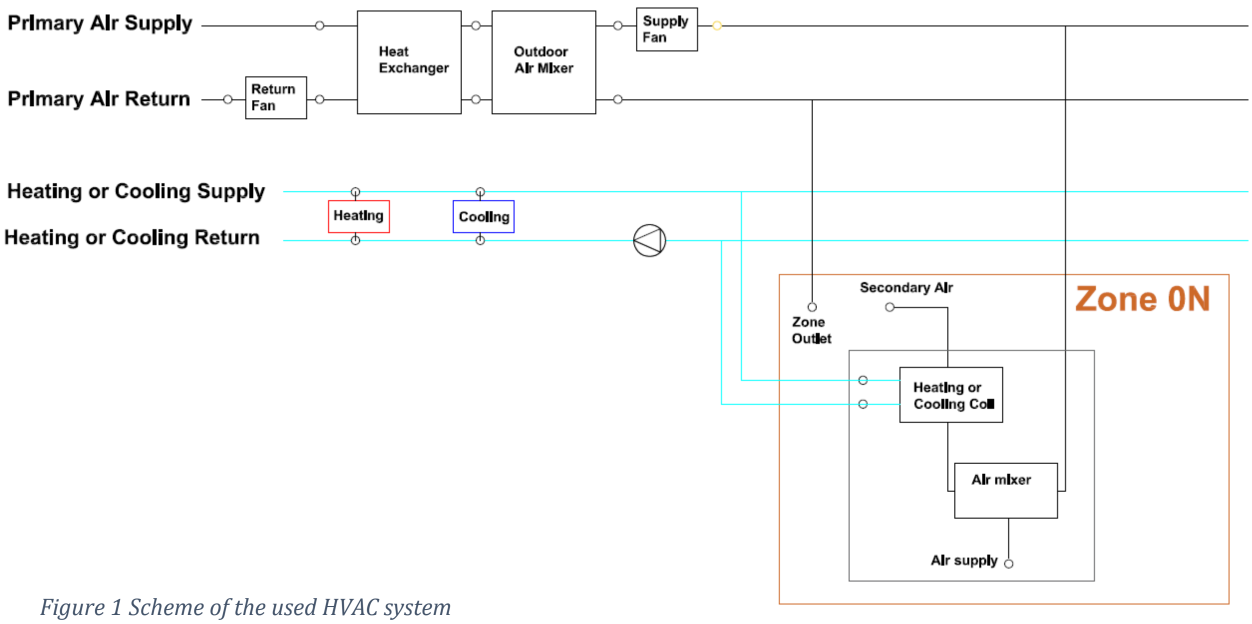


Figure 1 Scheme of the used HVAC system

3.1.1 Used control strategies

Two control strategies are carried out in order to research the energy flexibility potential of the studied building cases .The first one is a referent simple controller scenario ,which operates the HVAC system under normal conditions by only following two set points –one for occupied and another for unoccupied hours both for heating and cooling. The second control – a flexibility controller, based on more complex control algorithms provides different set points for heating and cooling depending on the electricity price. This control works by adjusting the set points of the building system to three electricity price levels- low, medium and high, which thresholds are derived from electricity price data for 2015 (9).The concept of the flexibility controller is to either increase or decrease the set points during low price electricity for heating or cooling and in this way to store energy in the thermal mass of the construction. It is expected this action will provide good thermal comfort when high price electricity is available and even though in this period the system will perform on lower power mode.

The heating set-points of the investigated controls are described in the table below.

Control strategy	Heating set-points occupied/unoccupied hours (degrees C)	Cooling set-points Occupied/unoccupied hours (degrees C)
Referent controller	20 °C/18 °C	25 °C/27 °C
Flexibility controller Low price mode (<111.5 DKK/MWh)	21 °C/19 °C	24 °C/26 °C
Medium price mode (>111.5 & <203.8 DKK/MWh)	20 °C/18 °C	25 °C/27 °C
High price mode (>203.8 DKK/MWh)	17 °C/15 °C	29 °C/31 °C

Table 1 Control strategies of the set-points for heating and cooling

3.1.2 Building thermal zones

The case building is defined by 2926 m^2 heated area and it consists of three floors. Each floor is split on northern and southern zones, due to the fact solar loads on these facades are experienced differently. The variations in solar gains on east and west located rooms as well the difference in functionality was a premise to isolate them into two separate thermal zones. Building spaces with different internal load characteristics such as the hallway areas are also divided into single zones from the rest. Therefore, in total there are 11 thermal zones present in the simulated EnergyPlus models. According to the level and orientation each building zone is represented by corresponding letter and number as seen on figure 2.

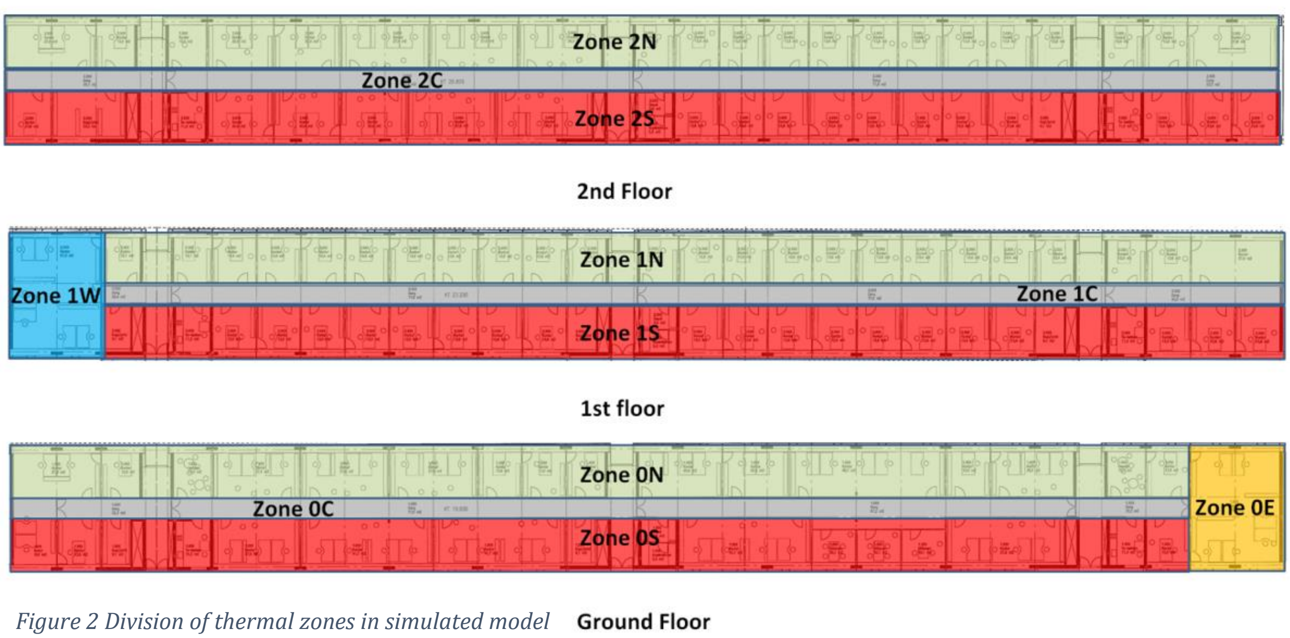


Figure 2 Division of thermal zones in simulated model

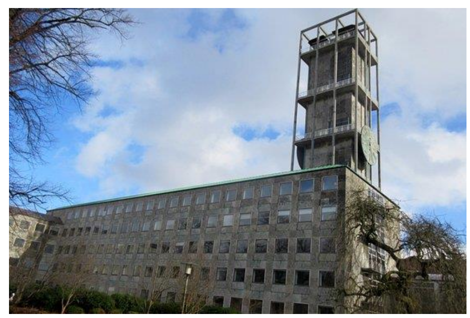
3.2 Building Case studies

Currently in Denmark, there are buildings used for office and administrative purposes constructed in different periods of time. Some of them are quite newly executed, but also there are buildings which time of original erection can be tracked back to the end of 19^{th} century. Each period specifies with its own constructing properties like air tightness, level of insulation, material use, thermal mass, etc. As those properties differ for each period, a comparison is done among them in order to investigate their response to energy flexibility, and more specifically the potential to conserve energy. In this research four main building periods are distinguished, which can be seen in the form of four cases:

1

Office Constructions:
1890-1930

2



Office Constructions:
1940-1980

3

Office Constructions:
Building Regulation 2015

4

Office Constructions:
Building Class 2020

Case 1

Figure 3 Buildings 1890-1930, Aarhus Custom House

First case represents office buildings constructed within 1890-1930. Usually those buildings are considered with high architectural and cultural value. Example of such a building is the Aarhus Custom House (Toldkammeret in Danish language) constructed in 1898, located by the harbor in Aarhus, Denmark (see figure 3). Its original purpose was to function as an office building and it was used by tax authorities until the middle of 1990s. Currently the building is exploited by other administrative institutions.

Roof

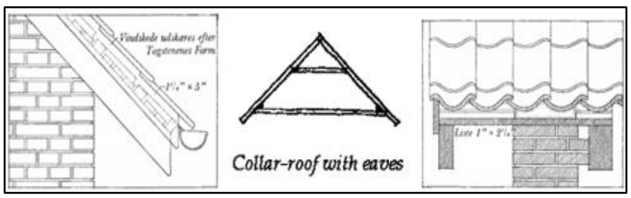


Figure 4 Collar-roof type with eaves

Roof structures belonging to case 1 are shaped as a result of the underlying wooden construction. The following roof types are typical for the period: Collar tie roofs; Collar tie with knee-brace; “Copenhagen roofs; Mansard roofs; Trussed rafter roof, “The half-Trussed” roof. Rafters in this case are dimensioned 150 x 130 mm placed each meter. Originally there is no placement of insulation in the structure, therefore transmission loss through the roof in this case is quite high. More details on roof construction can be seen on Table 2.

Construction	**Roof**		**U-value [W/m2.K] = 1.7**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Eternit corrugated plate/tile	0.03	790	1920	0.89
Wooden battens	0.038 x 0.072 c/c=0.3	1048	640	0.186
Timber rafters	0.13 x 0.15 c/c =1	1630	680	0.167
Reed board ceiling	0.025	1090	800	0.58

Table 2 Roof construction-properties

Walls

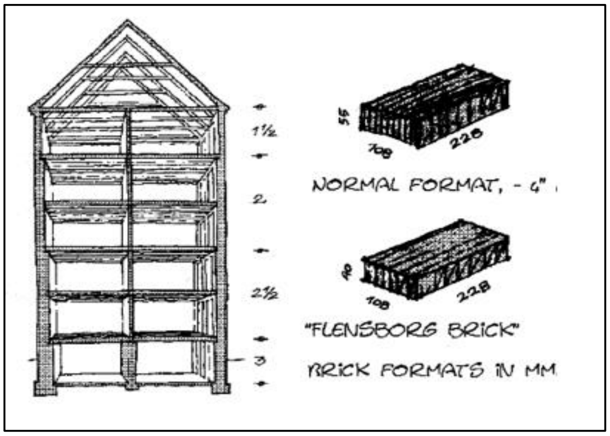


Figure 5 Brick work wall structure, brick sizes

Common practice shows external walls for this period are made of bare brick work. Plastering and decorative bands are often met, but in this research they are neglected due to the insignificant influence they might have on energy flexibility. Typically facades are made of 2 ½ -3 bricks in width and thickness decreases with half a brick for each upper floor. This results in a different transmission loss for each floor. Gables are made with a same thickness from ground to the last floor. Partition walls are no longer constructed by 1900 with timbering, therefore inner walls are considered as fully brickwork too. Details on different wall construction used in this case can be found on Table 3.

Construction	**Facade wall (ground floor)**		**U-value [W/m2.K] = 0.8**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Brick	0.652	790	1920	0.89
Construction	**Facade wall (1st floor)**		**U-value [W/m2.K] = 0.99**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Brick	0.512	790	1920	0.89
Construction	**Facade wall (2nd floor)**		**U-value [W/m2.K] = 1.24**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Brick	0.388	790	1920	0.89
Construction	**Facade wall (Gable all floors)**		**U-value [W/m2.K] = 1.24**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Brick	0.388	790	1920	0.89

Table 3 External walls construction-properties

Floors

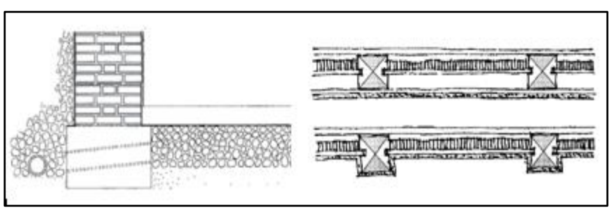


Figure 6 Ground supported floors, Upper storey partition floors

Portland cement was widely introduced to construction process after 1890. At that time, foundations and ground supported floors started being cast out of concrete. This was very important especially for ground supported floors, which had to fulfill new requirements for water tightness. Storey partitions of upper floors used to be made of light-weight constructions. Bearing elements were the timber joists placed at a distance from 0.6m to 1m. In between the joists was placed a pugging layer of around 50mm to ensure fire safety.

Construction	Storey partition			
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Wooden board	0.025	1630	680	0.167
Timber rafters	0.2 x 0.2 c/c = 1.05	1630	680	0.167
Clay pugging	0.05	900	2080	1.45
Wooden board	0.02	1048	640	0.186
Reed mats + plaster finish	0.025	1090	800	0.58
Construction	**Ground floor**		**U-value [W/m2.K] = 0.51**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Floor finish	0.02	1048	640	0.186
Concrete slab	0.1	800	2385	1.2
Gravel layer	0.2	900	2240	1.95

Table 4 Floor construction-properties

Windows

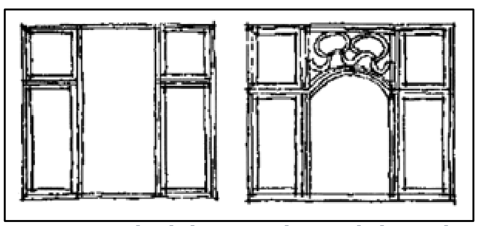


Figure 7 Frederiksberg window and Skønvirke ornamentation

Windows had typically 3 sections, as after 1890s the midsection usually was done broader without openings. This type was called “Frederiskberg “window, as for the more expensive buildings it came with “Skønvirke” ornamentation (see figure 7). What it is important for this case is the very high transmission loss, as the original structure of this window is with a single pane. This results in a U-value of up to 5.1 (see BR, 1995, chapter 8) plus unwanted condense phenomena in the heating season. Quite often the structure of this window was improved soon after original installation (renovation) by mounting additional internal casement. This led to significant improvement of transmission loss down to u-value of 2.7.

Construction	Window	U-value [W/m2.K]= 2.7	g-value = 0.4;0.8
Layers:	1.Clear glass 6mm	2.Air gap 10 mm	3. Clear glass 6 mm

Table 5 Windows properties

Case 2

Figure 8 Building type 2 (source in Reference chapter)

Second case will illustrate the construction conditions of administrative buildings erected in the period 1940-1980. Typical for those buildings is the increased implementation of concrete instead of brickwork. Also, the window area on façades tends to increase as the glazing production was improved and industrialized. Example of an administrative building from that period is the Aarhus town hall, officially inaugurated in 1941 (see figure8). Also, there are many constructed buildings from that period, which original purpose was residential. Some of those with attractive location in city centers gradually converted into office buildings, where small and bigger companies found convenient approach to their clients. This is why some of the presented components in this case are also common for residential housing.

Roof

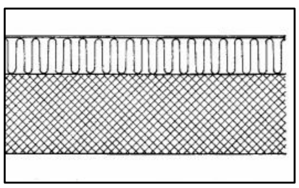


Figure 9 Flat light-weight concrete roof

At the beginning of the period (1940-1980), roofs turned to be lower than before, but still made of light construction. In some cases bearing timber elements were replaced by iron T-beams. New thing about the roof component is the use of insulation. In the second half of the century, lower timber roofs were gradually replaced by flat light-weight concrete roofs.

Construction	**Roof**		**U-value [W/m2.K] =0.45**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Bitumen felt	0.002	1000	1700	1
Insulation	0.07	1210	29	0.038
Concrete deck	0.15	800	2385	1.2
Gypsum ceiling	0.002	1090	800	0.58

Table 6 Roof construction-properties

Walls

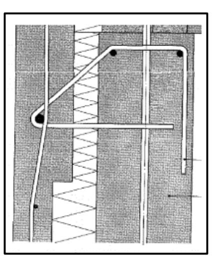


Figure 10 Concrete external wall

Concrete turned to be recognized as material not just for foundations and basement walls, but also used on facades. Walls are being constructed the same thickness in all floors. The old method to change the inner thickness of an external wall is no longer popular, as this causes challenges to vertical pipelines and wiring. Thermal properties of the wall component are taken in consideration, as an insulation layer finds place in the structure. In regard to internal walls, majority of them are still masonry.

Construction	External wall (Façade and gable)		U-value [W/m2.K] =0.46	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Concrete	0.06	900	2240	1.95
Insulation	0.07	800	32	0.039
Concrete	0.15	900	2240	1.95

Table 7 External wall construction- properties

Floors

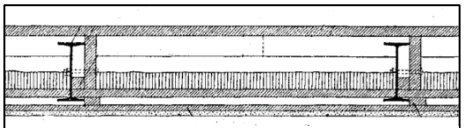


Figure 11 Light-weight floor with iron beams

Storey partitions were constructed as light-weight till around 1950s on wooden beams. Often iron beams were included in the bearing structure when there was a need of increasing the load capacity. The basic structure of the storey partition in this case is quite similar to the one from case 1. The same counts for the ground supported floor.

Construction	Storey partition			
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Floor finish wooden board	0.025	1630	680	0.167
wooden beam	0.13 x 0.03 c/c 0.6	1630	680	0.167
Clay pugging	0.05	900	2080	1.45
Steel beam	NP18 c/c 0.6	504	8050	50.2
Air gap	0.025	1004	500	3.75
Wooden board	0.02	1630	680	0.167
Gypsum/plaster finish	0.025	1090	800	0.58
Construction	**Ground floor**		**U-value [W/m2.K] = 0.49**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Screed	0.02	840	1856	0.72
Concrete slab	0.1	800	2385	1.2
Sand layer	0.2	710	1520	1.1
Gravel layer	0.1	900	2240	1.95

Table 8 Floor construction-properties

Windows

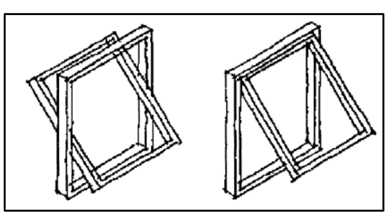


Figure 12 Windows Case 2

Windows were quite vulnerable part of the construction in regard to preventing heat loss over the years. Double glazing, also known as thermal glazing was invented in 1940. The idea of trapping 10 mm air in between two layers of glass decreased the U-value of this components down to 2.7. Later on when the technology improved, windows from this period could achieve U-value of 2.

Construction	Window	U-value [W/m2.K] = 2	g-value = 0.4;0.8
Layers:	1.Thermal glass 6mm	2.Air gap 13 mm	Thermal glass 6 mm

Table 9 Windows properties

Case 3

Figure 13 NNIT data center in Bægsværd, Denmark

Buildings which comply "Building Regulations 2015" characterize with strict requirements on thermal properties, building air-tightness, consumption of energy use, fire safety, etc. NNIT is one of the leading IT companies in Denmark, who has built a new data center in Bagsværd fulfilling BR15 (see fig.13). The center is extraordinary safe, as it is expected to last for at least 50 years. Also, it is considered as one of the most energy efficient data centers in the world.

Roof

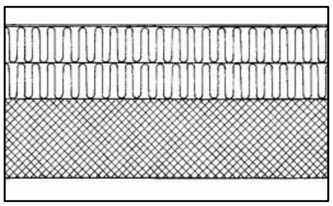


Figure 14 Concrete roof structure

TTS beams, hollow core decks or light-weight concrete elements could be a choice for bearing structure of the roofs in this case. The one, chosen in the assessment, is a concrete element, thus to simplify the simulation and to provide more uniform thermal mass, compared to a hollow-core structure.

Construction	**Roof**		**U-value [W/m2.K] = 0.17**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Bitumen felt	0.004	1000	1700	1
Polystyrene insulation	0.195	1200	100	0.037
Concrete slab	0.18	800	2385	1.2
Air space	0.45	1004	500	3.75
Plaster board	0.026	1000	881	0.2

Table 10 Roof construction-properties

Walls

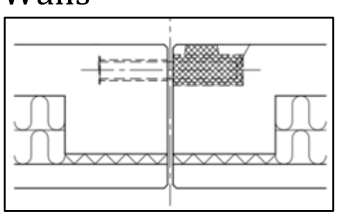


Figure 15 Pre-fabricated external wall element

It is a common practice that a lot of the building components typical for administrative buildings at this time are prefabricated. Sandwich elements are mostly used as external walls, because of good price, quality, and very short time for execution. This practical choice is preferred by many companies when establishing or extending their office area.

Construction	External wall (Façade and gable)		U-value [W/m2.K] = 0.25	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Concrete front layer	0.06	900	2240	1.95
Mineral wool insulation	0.145	800	32	0.037
Concrete front layer	0.15	900	2240	1.95
Plasterboard	0.014	1000	881	0.2

Table 11 Wall construction-properties

Floors

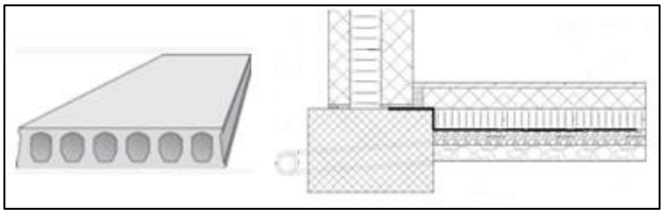


Figure 16 Storey-partition and ground floor

A basic structure of a storey partition is usually made of hollow core decks. Depending on design and distribution line of installations, there can be suspended free space above the hollow core (suspended floor), or beneath it – suspended ceiling. In this research, free space of 400 mm forms the suspended ceilings as part of the storey partition. Ground supported floor has to fulfill a high thermal requirement, and protection considerations in terms of moisture and hazardous gases.

Construction	Storey partition			
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Screed	0.03	840	1856	0.72
Concrete slab	0.18	800	2385	1.2
Ceiling air space	0.4	1004	500	3.75
Ceiling insulation	0.045	800	100	0.037
Plaster board	0.026	1000	881	0.2
Construction	**Ground floor**		**U-value [W/m2.K] = 0.17**	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Screed linoleum	0.03	840	1856	0.72
Concrete slab	0.15	800	2385	1.2
Polystyrene insulation	0.15	1210	29	0.037
Sand layer	0.1	710	1520	1.1
Gravel layer	0.1	900	2240	1.95

Table 12 Floor construction-properties

Windows

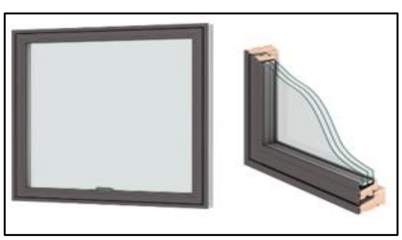


Figure 17 Triple- glazed windows

Windows complying BR15 case have to fulfill requirements for energy demand, light transmittance, in some cases fire and health safety. After invention of thermal glazing, this technic was improved by increasing the casement from double to triple, or trapping gas instead of just air in between glazing layers.

Construction	Window		U-value [W/m2.K] = 1.4		g-value= 0.4;0.8
Layers:	1.Glass 6 mm	2.Argon 13 mm	3.Glass 6 mm	4.Argon 13 mm	5.Glass 6 mm

Table 13 Windows properties

Case4

Figure 18 Aarhus Kommune, Grøndalsvej 1

A fundamental difference between requirements of "Building Regulations 2015" and "Building Class 2020" is the requirement for significant reduction of energy supply for heating, ventilation, cooling, domestic hot water, and lighting per m^2 of heated floor area. But in this assessment for energy flexibility, the focus is set on transmission loss properties typical for each case. Even though thermal requirements of building envelope between BR15 and Class2020 are quite similar, these options are compared because each insignificant change either in component properties or infiltration rate might result in a major difference of energy flexibility performance. Especially when those changes are done on very sensitive buildings due to the high air-tightness or thick insulation levels of different building components. Example for this case is taken by one of the administrative buildings of Aarhus commune, located at Grøndalsvej 1 in the second biggest city of Denmark (see fig.18). The mentioned building is rated as "nearly zero energy building", which does not necessary mean it complies with Building class 2020, despite the possibility is quite high. But in this assessment it is used as an inspiration to do an investigation including a building option which fulfills requirements for Class 2020. The building components part of the building envelope in this case have the same structure as those from "Case 3", but different thickness of insulation and load bearing layers. Therefore, it will be examined if components with higher U-values than those in "Case 3" have different and noticeable influence on building energy flexibility. Also, another key factor taken into consideration here, is the requirement for infiltration rate of just 0.5 l/s/m^2 of the heated floor at a pressure difference of 50 Pa.

Roof

Construction	Roof		U-value [W/m2.K] = 0.07	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Bitumen felt	0.001	1000	1700	0.5
Stone wool	0.45	800	16	0.0039
Concrete slab	0.27	800	2400	2.1
Air space	0.45	1004	500	3.75
Plaster board	0.014	1000	881	0.2

Table 14 Roof construction-properties

Walls

Construction	External wall (Façade and gable)		U-value [W/m2.K] = 0.11	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Cement plate	0.015	1500	2000	0.35
Polyurethane thermo panel	0.21	1400	40	0.023
Concrete front layer	0.2	800	2400	2.1
Plasterboard	0.014	1000	881	0.2

Table 15 Wall construction-properties

Floors

*Storey partitions are the same as in Case 3

Construction	Ground floor		U-value [W/m2.K] = 0.07	
Material	Thickness [m]	Cp [J/Kg.K]	ρ [kg/m3]	λ [W/m.K]
Wood	0.01	1048	640	0.186
Concrete	0.27	800	2400	2.1
Stone wool	0.5	800	16	0.039
Asphalt	0.001	1000	1700	0.5

Table 16 Floor construction-properties

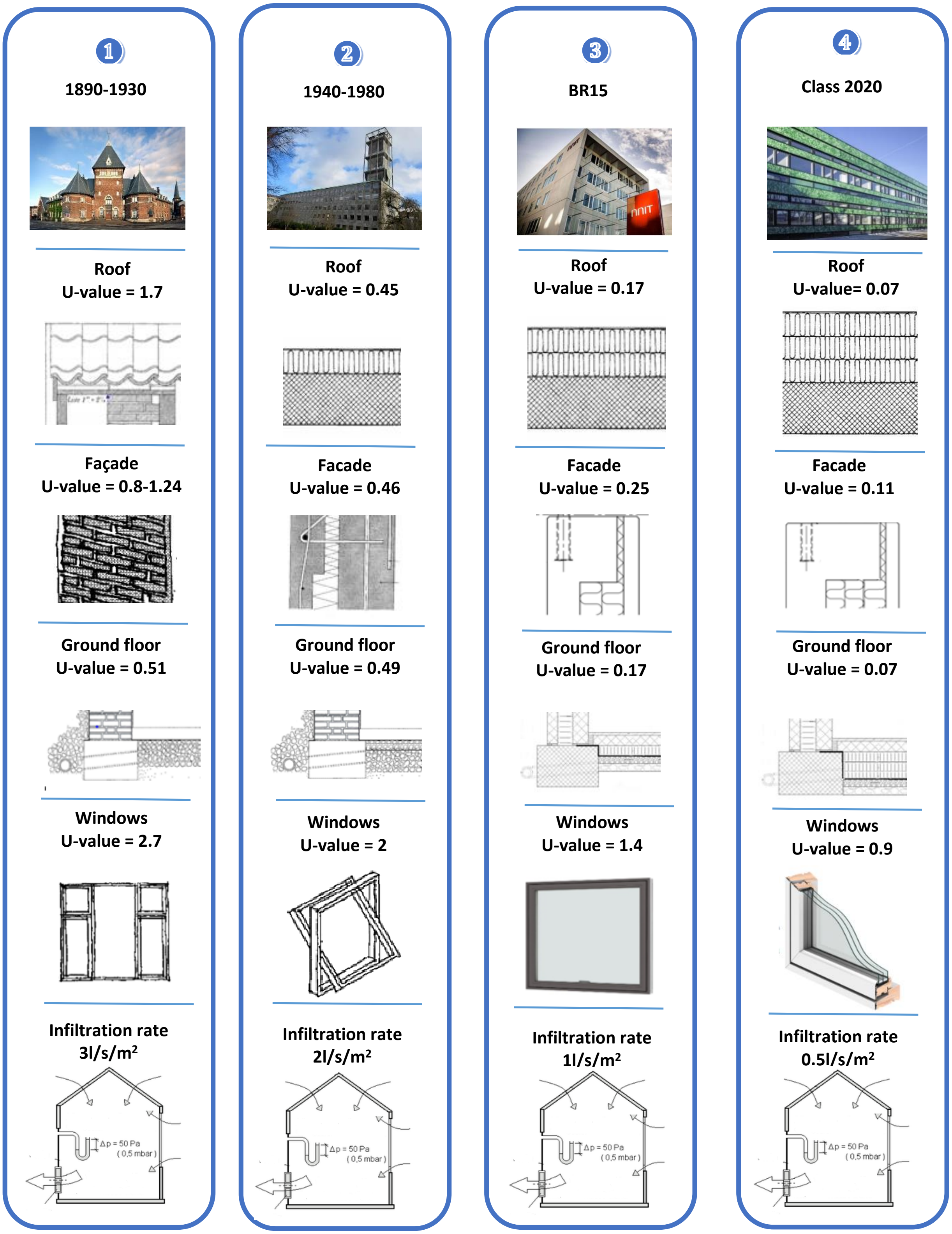
Windows

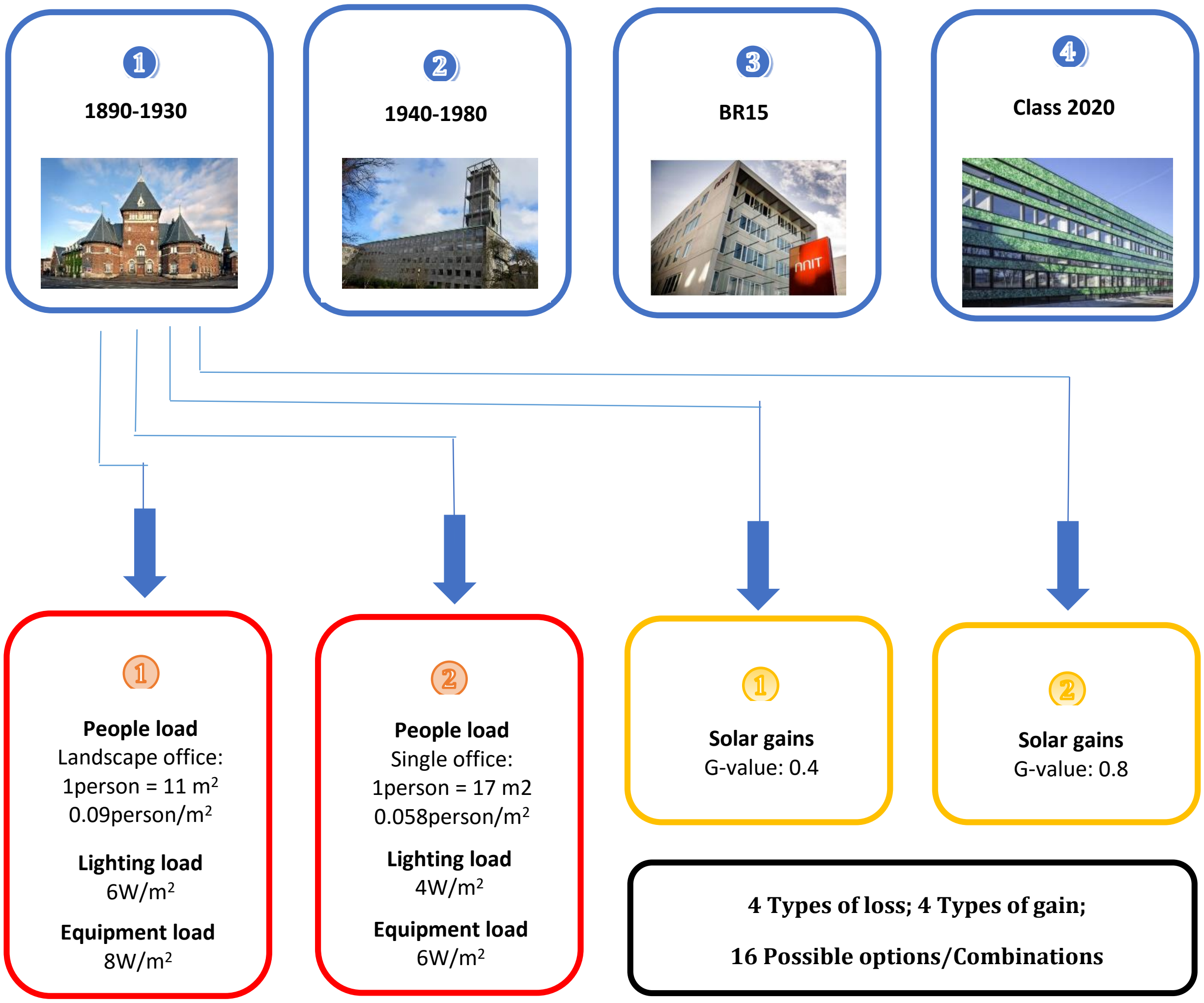
Construction	Window		U-value [W/m2.K] = 0.9		g-value= 0.4;0.8
Layers:	1.Glass 3 mm	2.Argon 13 mm	Glass 3 mm	4.Argon 13 mm	5.Glass 3 mm

Table 17 Windows properties

All construction cases are combined with configurations representing two alternatives for internal gains (people load, lighting load, equipment load) and another two alternatives for solar gains. Solar gains variation would be among two numbers: g-value = 0.4, and g-value 0.8. Generally g-value represents the transmittance of solar radiation through glazing pane. But these two options of solar gains will actually indicate a façade with lower and higher glazing area. As due to the alternatives of people load, they will represent an office area with higher density of occupants, which is typical for landscape offices. Respectively the lower density is accounted for administrative buildings having primarily single offices. In landscape offices typically the working area is higher and requires more space with sufficient illuminance level, which should fulfill DS700. Therefore, it is assumed lighting load and equipment load would be increased in the landscape density load. Numbers of office workers per m^2, lighting, and equipment loads are inspired by building model prototype described in "U.S. Department of Energy Commercial Reference Building Models of the National Building Stock (7).

Summary of Building Cases





Construction type (blue) - 1
Internal load type (red) - 1
Solar gain type (yellow) - 1

1. possible option: 1+1+1
2. possible option: 1+1+2
3. possible option: 1+2+1
4. possible option: 1+2+2

5. possible option: 2+1+1
6. possible option: 2+1+2
7. possible option: 2+2+1
8. possible option: 2+2+2

9. possible option: 3+1+1
10. possible option: 3+1+2
11. possible option: 3+2+1
12. possible option: 3+2+2

13. possible option: 4+1+1
14. possible option: 4+1+2
15. possible option: 4+2+1
16. possible option: 4+2+2

3.3 Evaluation metrics description

3.3.1 Thermal comfort

When evaluating energy flexibility potential in different building structures, one of the main parameters of investigations is thermal comfort. When applying energy flexibility strategy, it is expected a decrease of energy demand for high electricity price periods. However, at the same time indoor thermal comfort might be jeopardized and therefore assessment of this evaluation metrics must be done accordingly.

Normally, office workers are considered to have sedentary activity level of 1.2 met. Thermal environment for occupants with this activity can be divided in three comfort classes for heating and cooling season according to *EN Standard 15241 2007-Indoor environmental input parameters and assessment of energy performance of buildings, people.*

office building sedentary activity 1,2 met	Category	Heating season clothing level 1 clo	Cooling season clothing level 0,5 clo
	I	21-25 degrees	23,5-25,5 degrees
	II	20-25 degrees	23-26 degrees
	III	18-25 degrees	22-27 degrees

Table 18 Thermal comfort classes considerations, EN 15241 2007

The thermal comfort results for this study ($F_{comfort}$) are given in percentage (%) on an annual base for each referent and flexibility option. The data is derived from the equation:

$$F_{comfort} = \frac{\int H \text{ class } II}{\int H \, office}$$, where

$H_{class\ II}$ are the hours when Class II is achieved including the hours for comfort Class I

H_{office} is represented by total occupied working hours, which is estimated to 2340 h per year as the working schedule is from 08.00 to 17.00

Class II is categorized for validation of achieved thermal comfort in thermal zones in new buildings and renovations according to ISO 15241. Therefore focus of the assessment is put on this thermal comfort class.

Class I High level of expectation and is recommended for spaces occupied by very sensitive and fragile people with special requirements like handicapped, sick, very young children and elderly persons.
Class II Normal level of expectation and should be used for new buildings and renovations
Class III an acceptable, moderate level of expectation and may be used for existing buildings.

Table 19 Comfort class definitions, EN 15241 2007

3.3.2 Ability of energy shifting

Flexibility factors are analyzed, in order to determine what the achieved level of energy flexibility is for each simulated model. They have been also investigated by J.Le Dreau al. Heiselberg (3).

The metric is described by the ability of the system to adjust its output during high and low price electricity periods and by this providing flexibility to the grid. Therefore, flexibility factors are established by the following equation:

$$\text{Flexibility factor} = \frac{\int \text{qheating\&cooling low price}\ dt - \int \text{qheating \&cooling high price}\ dt}{\int \text{qheating\&cooling low price}\ dt + \int \text{qheating\&cooling high price}\ dt}$$

Coefficients of energy shifting are calculated for all investigated building options with flexibility controller and then compared. Buildings with high flexibility factors suggest for ability of using more power for heating/cooling during low price electricity and less electricity for heating/cooling when high price energy is present.

3.3.3 Ability of grid adjustment/power difference

A key feature of energy flexibility is the power adjustment ability of a certain building type according to fluctuating electricity prices. This metric reveals the actual power adjustment of a building using a flexible controller in comparison to a normal/referent one. The flexible controller is designed to respond for each price level (low, medium and high) with a different set point modulation. With this controller, power supply will increase at lower price, thus heat would be stored in thermal mass. When the price is high, the flexible controller will decrease the heating set point, therefore the supplied power would be lower. When the price is within its medium levels, flexible controller will supply the same power as the normal controller during occupied hours. Normal or also known as "referent" controller maintains always the same comfort level during working hours, which means the set point changes based only on occupied and non-occupied time. As the two controllers have different operational strategies, one based on price levels, the other on working schedule, then they will consume different power. Registered hourly power difference between the two controllers will show the ability of power adjustment for the flexible controller (see equation No 1). This assessment is done by distinguishing 8 different price thresholds (see table 20). So the power supply difference between a referent and a flexible option can be seen for each threshold level. The evaluating metric is presented for a period of one year, therefore the power difference can be observed over heating and cooling seasons.

$P_{difference} = P_{flexibility} - P_{reference}$ (equation 1)

$P_{diferrence}$ - hourly power supply to the building with flexibility control

$P_{reference}$ - hourly power supply to the building with a referent control

	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 20 Price levels are determined before start of the project and used as follow up of a base research

3.3.4 Economic benefit

As long as Danish energy policy is to become 100% free of conventional fuels, then sources like wind-mill power generators will become of a great importance. In this case, wind will be a key factor to determine not only the produced energy, but also the price on electricity market. Quite often excess and lack of electricity production will make the price variate. One of the main reasons to assess energy flexibility in buildings is to evaluate the potential in saving by taking the advantage of fluctuating price. By adjusting the heating and cooling systems being active primarily when the price is low, this will result in lower electricity bills on a long term. In this research, the energy cost is calculated on yearly base, using the following formula:

$C = \int (Q \cdot P_{EL}) dt$ where:

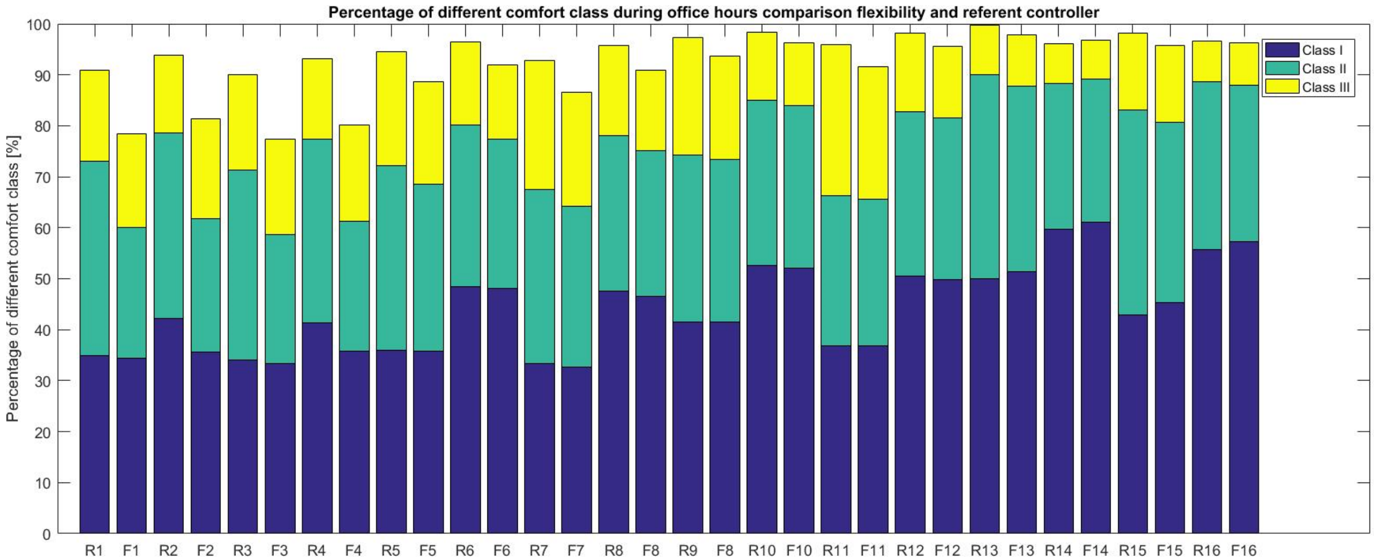
C – Energy cost for heating and cooling
Q – Annual energy consumption
P_{El} – Electricity price

To perform the estimation, two variables are needed. Annual energy consumption for each option will be found from energy plus simulations. Electricity price variation is extracted from an online market platform (https://www.nordpoolgroup.com) for a period of one year. Archived price data is taken for 2015 (9), as this will be the sample to perform in the assessment.

4. Results

4.1 Thermal comfort

The results are used to determine whether flexibility options can offer adequate indoor thermal environment. For this purpose all 16 building flexibility options are compared to their relative referent options as shown on the graph below.



Graph 1 Thermal comfort overview of all referent and flexibility control options

The overall view of the simulated data reveals the old constructions provide lower thermal comfort in flexibility options.

It has to be noticed, that thermal comfort covered by the mentioned flexibility cases is decreased up to 17 % compared to the referent scenario cases. This is estimated to 398 hours of insufficient thermal comfort per year. However, such tendency can be observed only for building cases 1 and 2.These buildings are defined with higher transmission losses and infiltration rate. The analysis implies the heating and cooling system with the flexibility controller cannot compensate for the poor thermal response of these building typologies. The set-points modulations of the flexibility controller are apparently quite inadequate for high heating demand building structures. Consequently, all of the above mentioned characteristics are the causes for the decreased comfort.

While on the other hand, in building Case 4, where very low heating demand is present (for more info about construction see chapter 3.2 Building cases.), a better thermal comfort is obtained in flexibility options .Indication for this is the almost even comfort in Class II between a referent and a flexibility option. According to the investigations, it becomes clear that Comfort Class I is being even slightly increased between 1 and 3 %. In this construction scenario, apparently, the discharge energy is not fully released before the charging modulation period starts again and this could be the reason for the optimized thermal comfort.

Due to improved thermal envelope, heat from internal gains and activated thermal mass is trapped for longer time within building spaces and not lost to the outside. Conservation potential is additionally enhanced in the options with higher internal gains , which contribute to increased comfort as represented on graph 1.

There is an insignificant difference of the thermal indoor environment in building case 3.The accomplished thermal comfort for all classes is nearly the same for both referent and flexibility options. Building loads are represented by relatively moderate heating demand, lower heat transmission coefficients, and infiltration level. The transition between old and newer construction types becomes evidently obvious on the results graph 1 in which the big deviation in comfort between referent and flexibility options is eliminated. Hence, it can be concluded, this type of construction provide the minimum thermal response which will not violate thermal comfort when flexibility controller is integrated.

4.2 Ability of energy shifting - flexibility coefficients

The summary of the flexibility coefficient results are compiled and then presented on the table below.

Building typology	Options No.	Flex.factors F cases	Flex.factors R cases
Case 1 1890-1930	Opt1	0,69667	-0,48136
	Opt2	0,75913	-0,41502
	Opt3	0,66631	-0,49629
	Opt4	0,73125	-0,42322
Case 2 (1940-1980)	Opt5	0,85812	-0,56483
	Opt6	0,93851	-0,44557
	Opt7	0,83168	-0,58165
	Opt8	0,91988	-0,46944
Case 3 (BR2015)	Opt9	0,99735	-0,52533
	Opt10	1	-0,33599
	Opt11	0,98879	-0,55217
	Opt12	0,99929	-0,42088
Case 4 (Class 2020)	Opt13	0,99778	-0,50608
	Opt14	1	-0,13582
	Opt15	0,97864	-0,53059
	Opt16	1	-0,1671

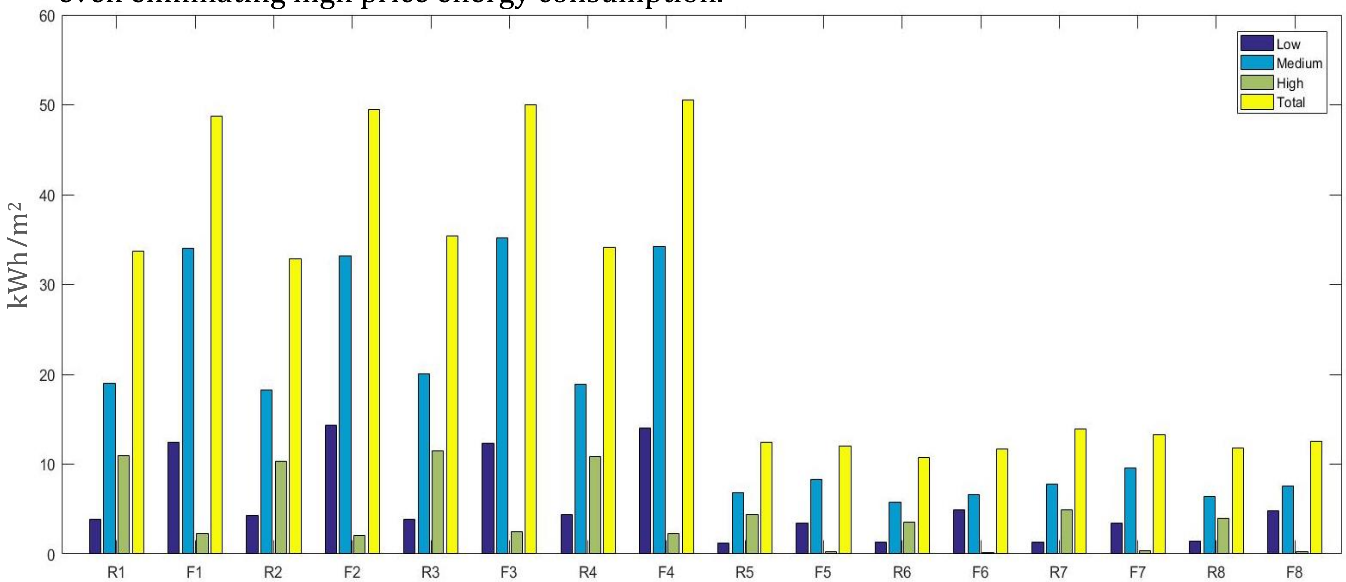
Table21 Flexibility factors for all referent and flexibility options

In the options where flexibility coefficients are higher than 0 and closer to 1, it is indicated less consumption of high price electricity and in the ones where factors are equal to 1 is specified that no high price electricity is used at all.

Respectively, when the coefficients are below 0 and closer to -1, it is determined that more of the energy is spent during high price period. Such coefficients are observed for all referent cases.

When values are equal to 0, the options are characterized with similar energy usage for heating/cooling in high and low prices period.

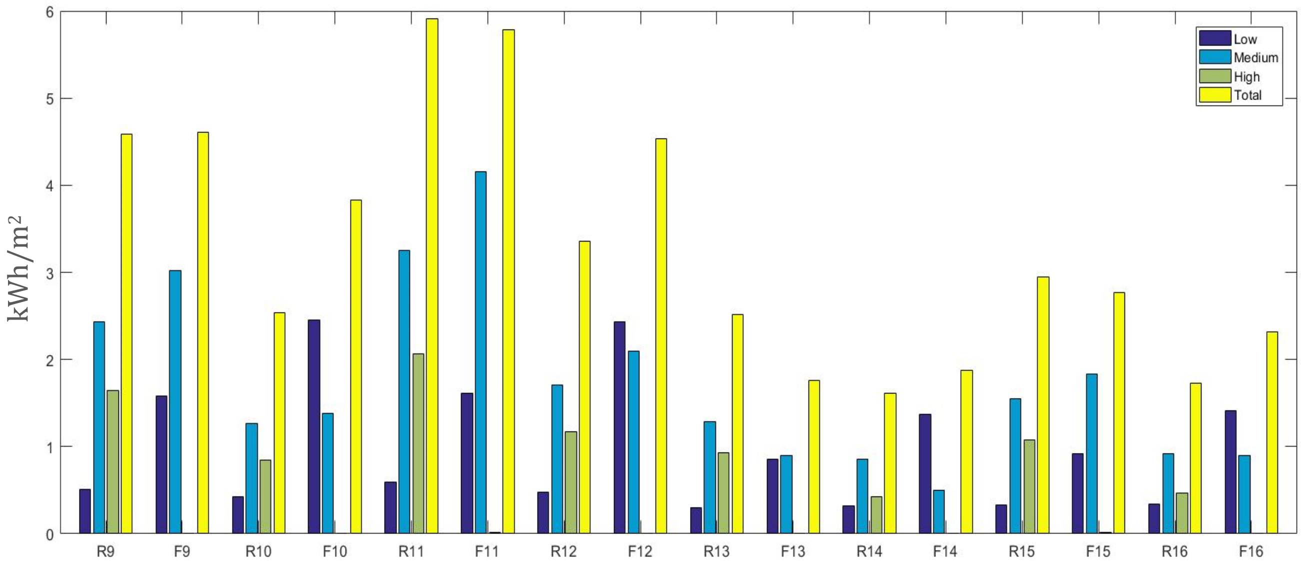
In general, lower coefficients are observed in old construction options in flexibility cases. However, the flexibility factors are becoming bigger in building case 2, but evidently higher in building case 3 and 4 (see table 2).The latter confirms for better utilization of thermal mass due to improved building envelope in the optimized construction cases. Naturally, this contributes to relatively low total electricity consumption and ability of decreasing and even eliminating high price energy consumption.



Graph 2 Flexibility factors comparison of referent and flexibility options from 1 to 8

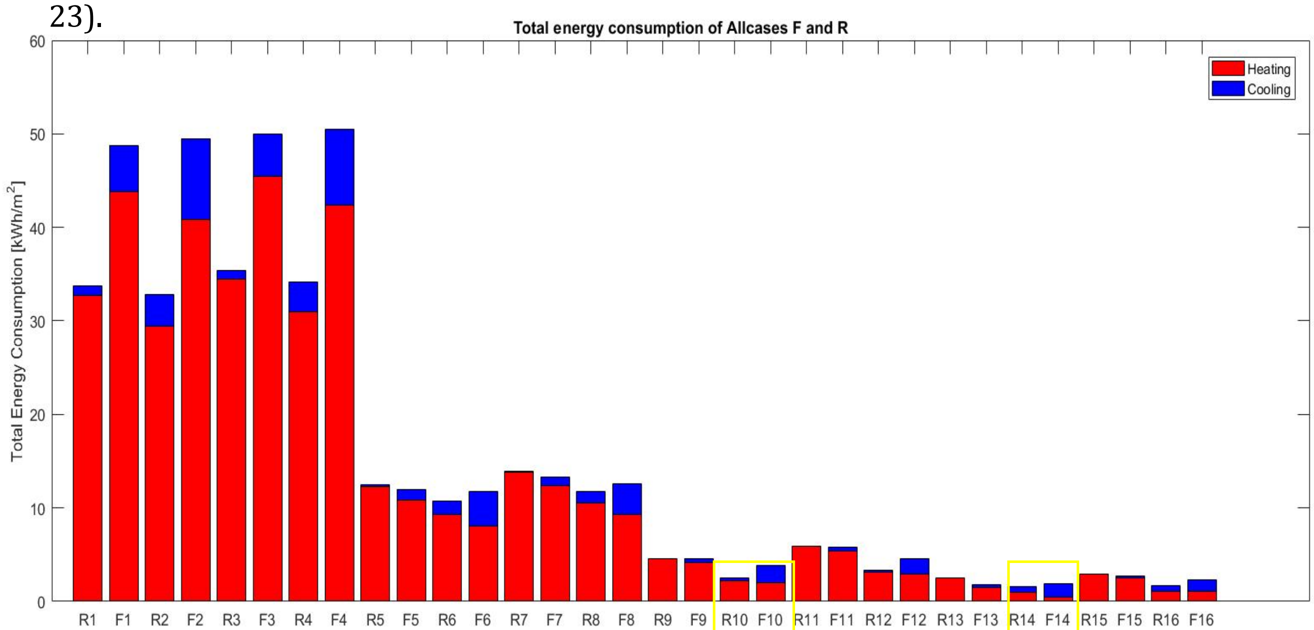
A closer look over results graph no 2. verifies the perceived tendency of energy shifting that the flexibility controller tends to work efficiently from building case 2 (Option 5-8).It is registered that approximately 80 to 90 % of high price energy consumption is decreased in flexibility cases compared to referent ones. While the low and mainly medium price energy usage is increased in flexibility options, but still resulting in savings of el price per kWh/m2 per year compared to referent (see chapter 4.4 Economic benefit, table 23).

As for the buildings with lower heating demand (case 3 and 4), the high price energy usage is completely excluded from the flexibility options as shown on graph 3. The higher thermal performance of these building options is due to increased level of insulation and reduced infiltration rate. It is noticeable, the energy shifting potential is at its optimum in options 10 and 14,respectiviely building types 3 and 4 (high solar and internal gains).These options demonstrates no electricity consumption at high price levels, high energy usage during low price periods and minimized as possible medium price electricity utilization as seen on graph 4.



Graph 3 Flexibility factors comparison of referent and flexibility options from 9 to 16

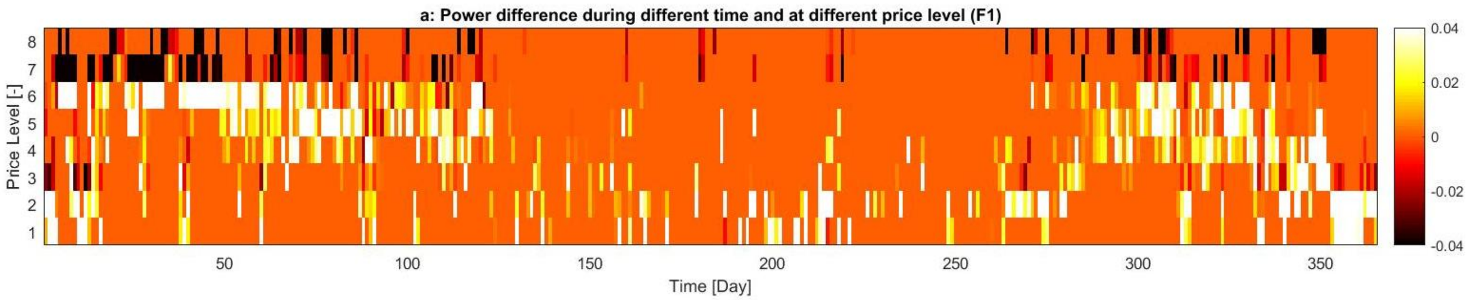
In addition, the mentioned options use the highest amount of low price electricity among their construction case variations (option 10 scores highest consumption during low el. price in case 3 and option 13 scores highest low el. price in case 4).The reason for this performance is that both options are characterized with high solar gains (more information refer to see chapter 3.2 Building case studies, ,page 27),which in combination with highly insulated and airtight building envelope leads to overheating. The high cooling load of these options can be justified from graph no 4, where cooling need accounts for more than half of the total energy consumption. In spite of this fact, savings of energy costs are still present for both options on an annual base compared to their referent options (see table 23).



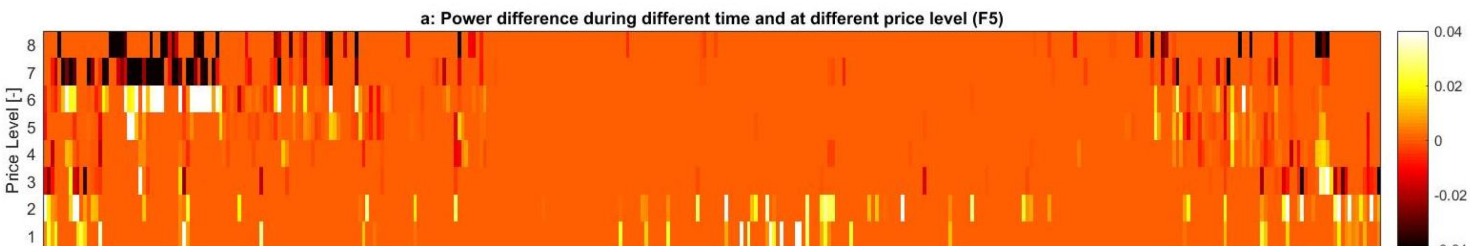
Graph 4 Annual energy consumption for heating and cooling for all building options

4.3 Ability of power (grid) adjustment

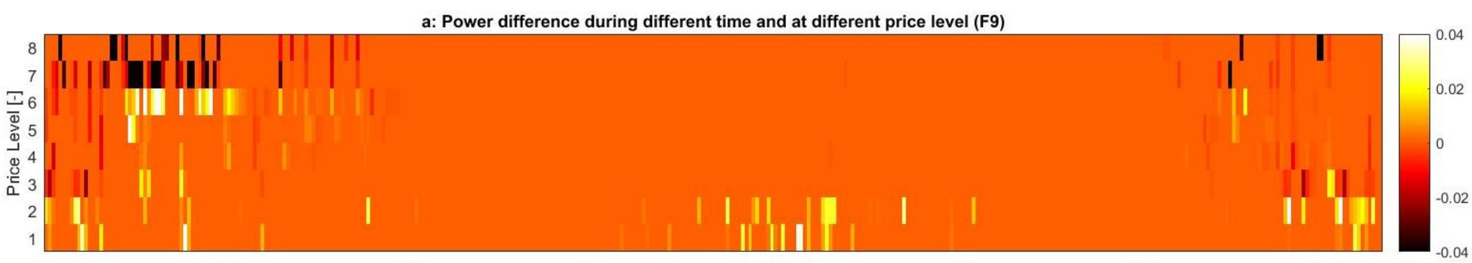
Graph 4 shows the results for total hourly consumption for both heating and cooling on yearly base. All assessed options are presented with a normal controller and a flexible one. Options from 1 to 4 represent building type from Case 1. Those options register significantly more consumption than all the rest. Reasons can be found in the high transmission and infiltration losses typical for the case. Furthermore, all flexibility options consume more energy than their relative referent options. Apparently higher modulation set points are achieved quite challenging. Buildings from 1890-1930 have very poor ability to trap generated heat. Storing energy in thermal mass by increased set point comes together with a lot of heat waste. Also, it is visible the high influence of solar gains. Options 2 and 4 have windows with higher g-value. This reflects to big amount of energy spent on heating, and more on cooling over the year. Case 2 sums up the options from 5 to 8. Here the difference in consumption between referent and flexibility options are much smaller, but still noticeable. As the trend for this case shows that in options 5 and 7, which have lower solar gains, the referent controller uses higher amount of energy yearly. And for options 6 and 8, the higher energy use annually is for the flexibility controller. The situation in case 3 and 4 is quite similar, as the trend for rest of options is the same. The difference in cases 3 and 4 is the advantage of the higher building class. The better thermal properties of the building components in case 4 results in smaller amount of energy spent on heating and cooling on annual base.
Graphs 5, 6, 7, and 8 show the power difference between a flexibility and a referent controller for options 1, 5, 9, and 13. Common for these options is they have the same people load, lighting load, equipment load, and solar gains but they all belong to different cases.



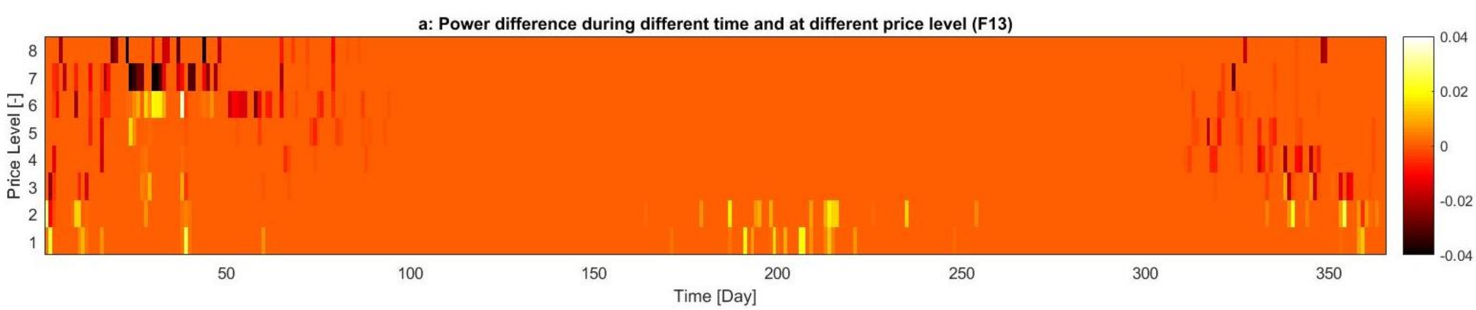
Graph 5 Option 1 (Office building from 1890-1930), Power difference between a flexible and a referent controller



Graph 6 Option 5 (Office building from 1940-1980), Power difference between a flexible and a referent controller



Graph 8 Option 9 (Office building complying BR2015), Power difference between a flexible and a referent controller



Graph 7 Option 13 (Office building complying Building Class 2020), Power difference between a flexible and a referent controller

On most of the figures is clearly visible the boundary condition between price level 6 and 7. This is where the threshold for expensive electricity price is set at 203.8 DKK/MWh. As price levels 7 and 8 belong to the expensive fee above 203.8 DKK/MWh, the flexibility controller tries to adjust and minimize the power consumption. This is why power difference at these price levels is negative compared to a referent controller. It can be seen the power difference at price levels 7 and 8 is highest for Case 1.For rest of cases is registered a steady decrease of the power difference in the same price levels as the lowest is achieved in Case 4. This corresponds with the decreasing demand for energy consumption seen on graph 4. Generally, lower energy consumption for different options, goes together with smaller difference between a referent and a flexibility controller. In the beginning of the year on graph 5 there are two yellow bars indicating that the flexibility controller spends more energy in price level 7.This shows lack of ability to adjust to power grid.

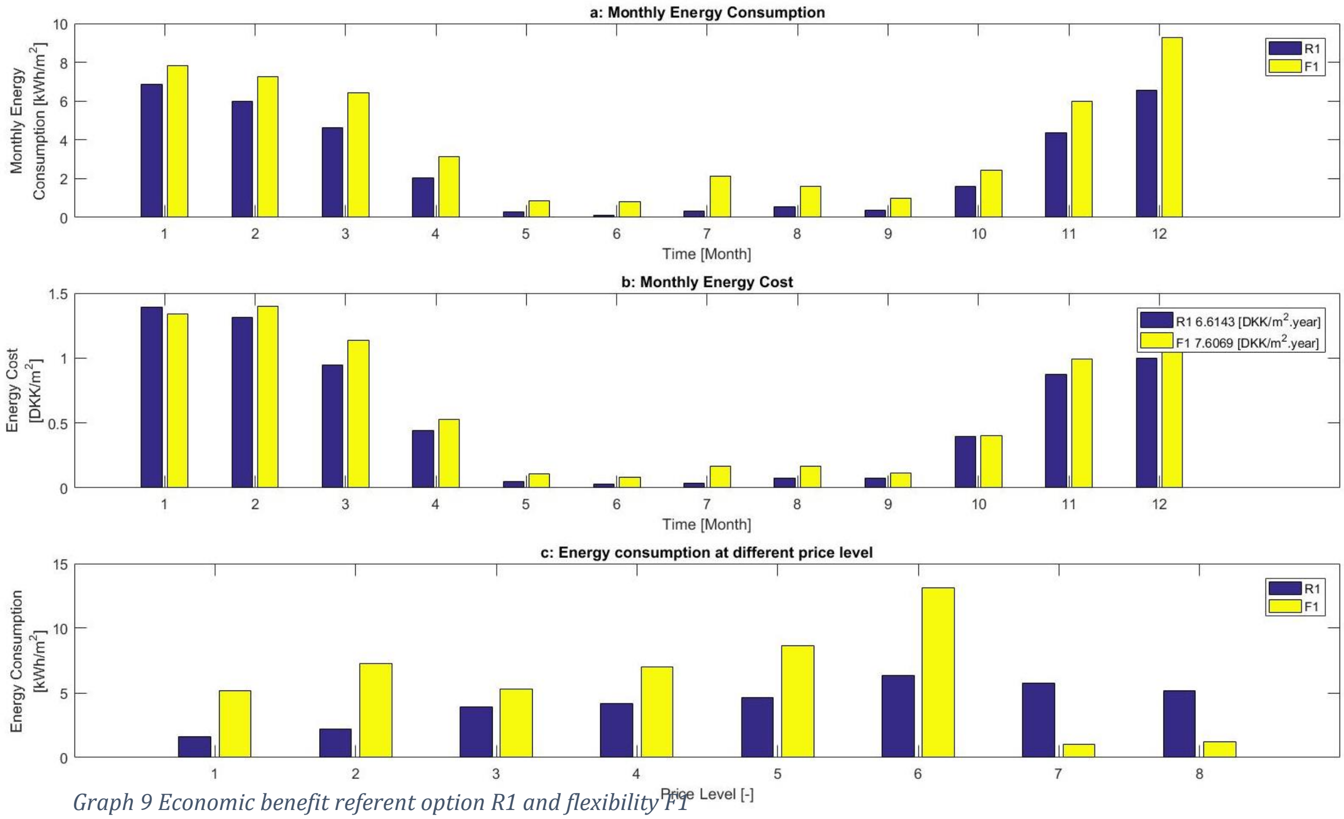
Price level 6 is the higher boundary for medium price. For the cases with relatively high thermal losses through the building envelope (case 1 and 2), it is observed that the power used by flexibility controller in price level 6 is much higher compared to the referent one. Reasons for that can be found in the situations when the flexibility controller adjusts from a high to a medium price period. It will need to compensate with additional output the increase of set point modulation with 2 C°. The "leakier" a building is in terms of energy, the higher power difference will be registered for this situation in price level 6.

On the other hand, price level 3 is a lower boundary for a medium price level. Here is the situation where it can be seen mostly the benefit of the released heat previously stored in thermal mass. This will happen when the flexibility controller switches from a low price period to a medium. Thus, it will make the power difference negative between a flexibility and a referent option, which is marked on graphs in darker colors. This occurs mostly during the heating season for all of the above presented graphs.

Price levels 1 and 2 are clearly indicating the ability of a flexibility controller to use more power than a referent one. In case 1 this ability is used mostly, due to the short conservation time the building has, and also the high dependence of outdoor conditions. On Fig. 5, there is a negative power difference during summer period in price level 1, which represents poor power adjustment.

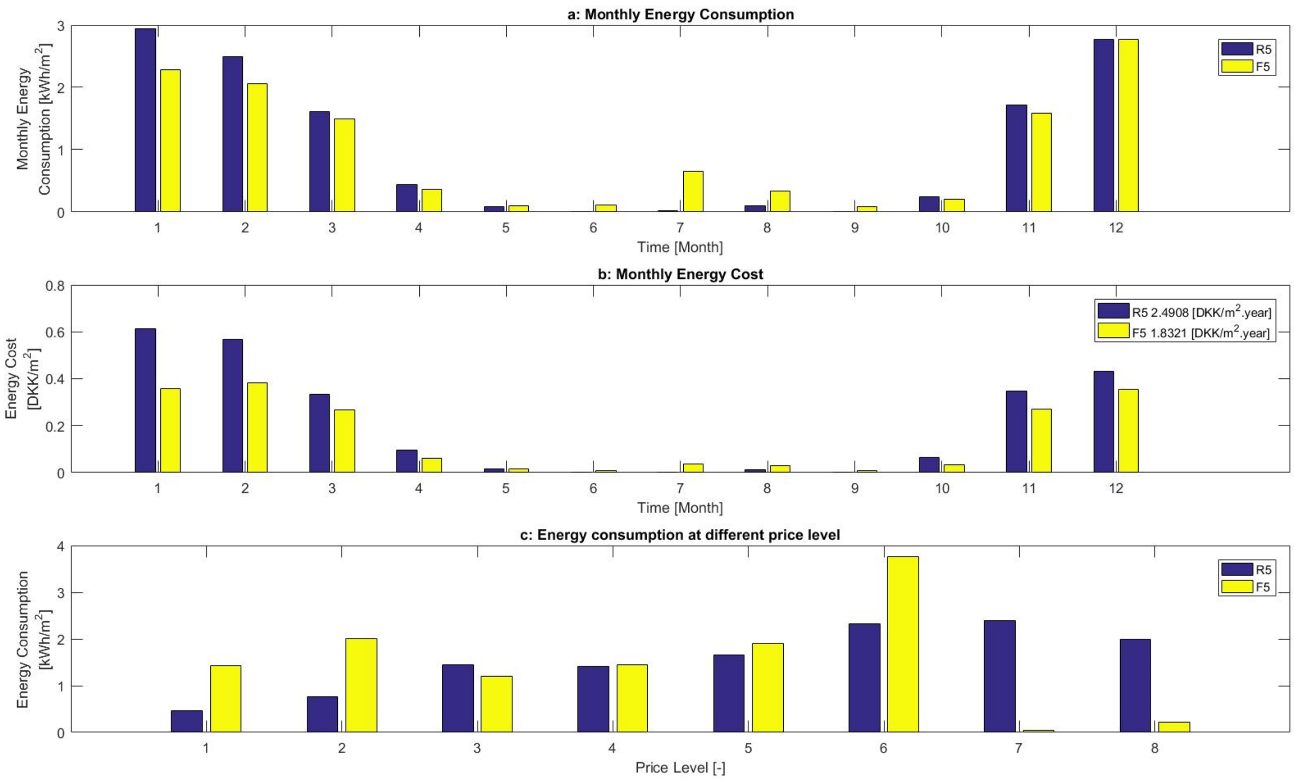
It is clearly seen that the power difference is in favor for a flexibility controller when the options are of high building class (cases 3 and 4). The ability of power adjustment is more optimal for these buildings, as the conservation time is longer compared to other cases (discharge mode of energy in thermal mass).

4.4 Economic benefit



Graph 9 Economic benefit referent option R1 and flexibility F1

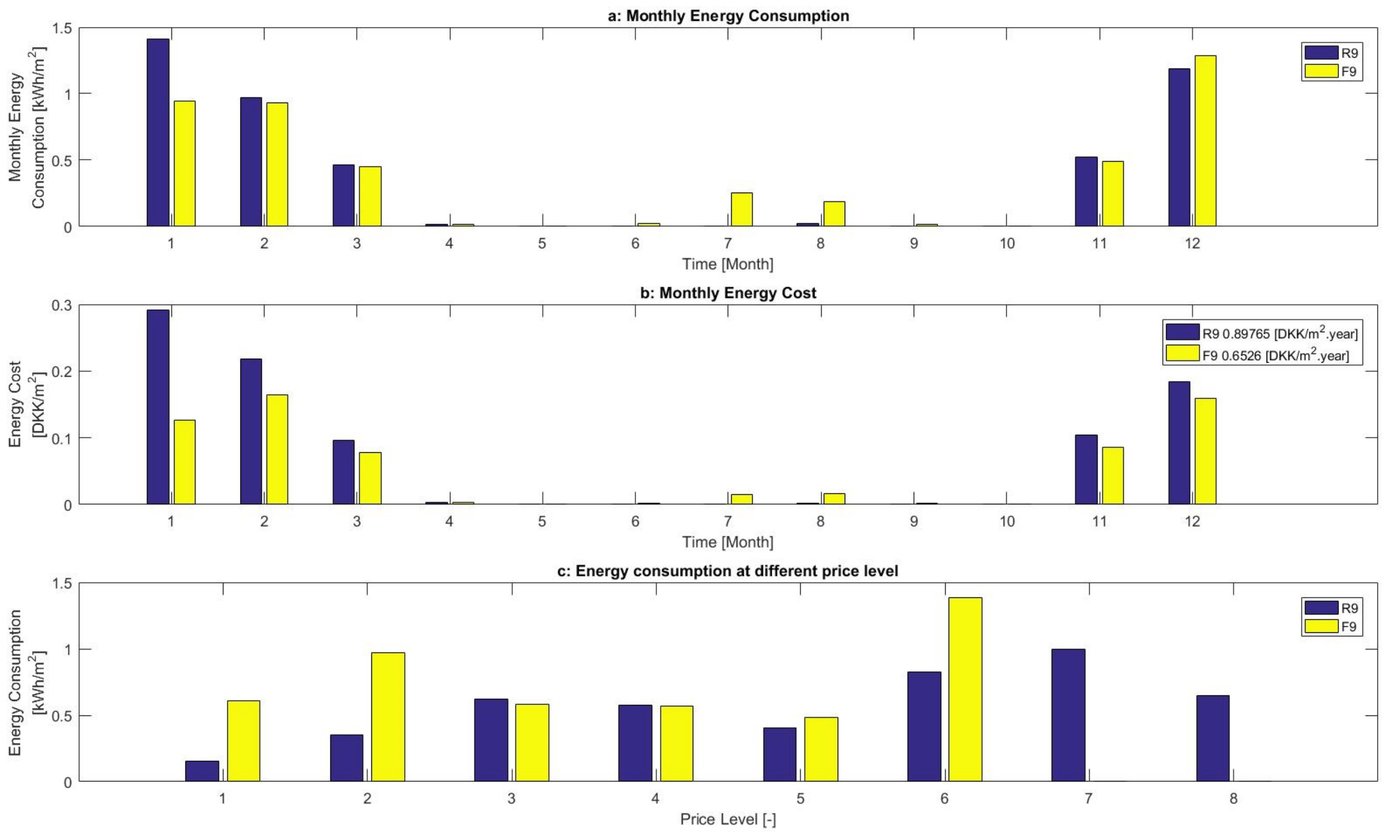
Graph 9 represents the economic comparison between option 1 with (marked as F1) and without (marked as R1) a flexibility controller. It is observed that the desired effect of cheaper energy cost on yearly base is not achieved. Actually the flexibility option registers 13% increase of the electricity bill annually. Reasons can be the very high transmission and infiltration losses typical for this case. Buildings from the period 1890-1930 have relatively high thermal mass but the lack of insulation could not make them trap the heat. Therefore increasing the set point during charging mode in the flexibility option is very expensive. Graph 10 shows the economic situation for Case 2, represented by option 5.



Graph 10 Economic benefit referent option R5 and flexibility F5

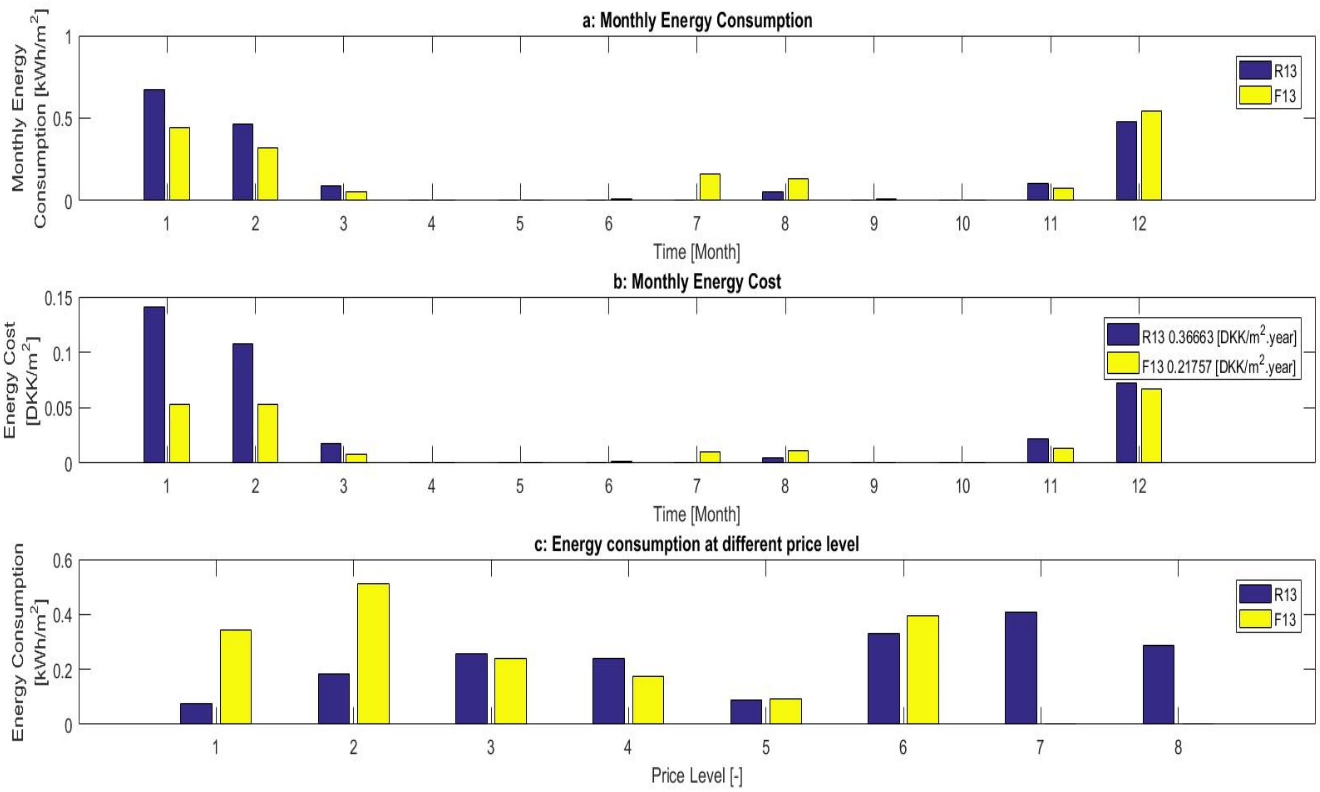
The first impression is unlike option 1, here in the beginning of the year (months 1, 2 and 3), energy consumption used by flexibility controller is significantly lower. The end of year (months 10, 11 and 12), which is actual start of a new heating season, energy consumption between two controllers is used almost evenly. So the reason for this energy performance difference between the beginning and end of the year should be found in price levels. It is understood the electricity prices at the beginning of 2015 are higher, therefore flexibility controller works at lower modulation set point. As due to the last months of the year, price levels stimulate the flexibility controller to work more often on higher power mode.

Graph 11 shows “option 9”, part of Case 3. The tendency of the flexibility controller to use lower amount of energy during heating season is kept, just at it is in previous case. Exception is just December, where apparently the prices are quite low. During many of the months, (f.e. February, March, November), energy consumption between two types of controllers is almost even. The small difference is caused by the higher thermal properties of the buildings representing “Case 3”. Generally if energy demand for a building is low, then a possible difference of energy consumption between two types of controllers would be relatively low as well. What is of a significant difference here is the energy cost in favor of the flexibility controller, and this is mostly seen in December. Despite the more energy consumed at that time, cost spent on energy is lower, and this is due to ability of this building to take advantage of the low prices. As to the cooling season, all of the discussed options so far indicate flexibility controller uses not just more power during this period, but also spends higher costs. Reason for this performance should be found in the price trend line during summer period, which is low on yearly base. As the flexibility controller functions in a quite simple manner by following the price, whenever there are attractive electricity fees in a roll, the controller will keep a charging mode more often, even though it might not be necessary.



Graph 11 Economic benefit referent option R9 and flexibility F9

Graph 12 shows the best performing option with flexibility controller in terms of economic benefit. Except the cooling season, all the rest of the time flexibility controller uses significantly lower amount of energy at a noticeable lower price compared to a referent controller. Reason should be found in the very high quality of the case representing buildings complying Class 2020. The air permeability of the building is very low, and this is of quite high importance when the heating transfer method of the HVAC system is by convection. Second, the transmission loss through the building envelope is very low, and this helps the building to exploit the heat released from internal gains for longer periods. By that the conservation time is extended due the increased ability to trap heat.



Graph 12 Economic benefit referent option R13 and flexibility F13

For most of the options is achieved a reasonable comfort level despite differences in the building properties among cases (see chapter 4.1 Thermal comfort). The above economic benefits are discussed without taking into consideration the investment costs, but just the operational ones. In order to make a thorough evaluation of the benefit, there should be an investment calculation showing the initial price for each case. As heat demand differs for each building type, then HVAC systems with different capacity will have to maintain the indicated thermal comfort (see graph 1) at presented annual operation costs. The implemented system used for heating and cooling is "Solus Active Beam" supplied by Lindab. This product is provided in various sizes, as the bigger ones will offer higher heating ability. In this research, estimation about needed number of beams is done for a unit with the highest possible length – 3.75m. In addition, static nozzle pressure and volume of primary air flow should be defined in order to estimate the heating capacity of the selected unit by following the Lindab manual of the product. It was estimated that for a thermal zone of 405.27 $m^{2,}$ having heat demand of 12395.6 W and a ventilation flow rate requirement of 0.81 m^2/s are needed 15 units. Each unit has a heat output capacity of 838W including the ability to induce room air up to 7 times compared to primary air. Same estimation is done for the identical zone in all building cases, and the results are presented in Table 22. Price per unit beam, or any kind of forming a price was not provided by the Lindab, thus clear estimation of investment cost and payback time could not be done.

	Case 1 Thermal zone 2S	Case 2 Thermal zone 2S	Case 3 Thermal Zone 2S	Case 4 Thermal zone 2S
Demand [W]	38685	27928	18546.7	12395.6
Number of units	47	34	23	15
m2/per 1 unit	8.62	11.92	17.62	27

Table 22 Table 6 Number of beam units necessary to maintain ventilation and heat demand requirements in Zone 2S

Relative conclusion is made that situation in "Case 1" is quite unacceptable as 47 units to maintain a thermal zone of 405.27 m^2 is not just high in financially terms, but could be quite challenging to implement the beams with such a frequency, so they function according to expectations. Numbers for "Case2" are under question whether the initial investment would come for a reasonable price. It is assumed "Case 3" probably shows acceptable result, as one beam will be able to maintain 17.62 m^2 of the chosen thermal zone. Here in this investment classification, 1st place is for "Case 4" way in front of the rest, by being able to maintain 27 m^2 per beam of total area in Thermal zone 2S.

Table 23 summarizes the economic benefit results among all options. All options in "Case 1" give a clear indication that implementing a flexibility control will not contribute to any optimizations, but it will actually increase the costs. This is why decrease of energy costs percentage in their fields in the table are actually marked with minus, to demonstrate the opposite effect. As to the rest of the options included in cases 2, 3 and 4, they all register optimization on energy costs using the flexibility controller. A more detailed view of their results shows that least decrease is achieved for the options which have higher g-value of the windows (Options 10, 12, 16). This is due to the overheating caused by solar gains, and increased energy spent on cooling especially during summer period. Options with a configuration of higher people load and small g-value contribute most to energy flexibility. It is assumed that high people load as internal gain extend the conservation time in a way so it does not challenge thermal comfort, as it is challenged by high solar gains. Option 13, which complies building class 2020, stresses the attention with the most significant saving of 41% of energy cost annually.

		Cost referent controller R1 [DKK/m2 yearly]	Cost flexibility controller F1 [DKK/m2 yearly]	Cost difference R - F	Decrease of annual energy cost in %
Case 1 1890-1930	Opt1	6.6143	7.6069	-0.9926	-13%
	Opt2	6.3161	7.4792	-1.1631	-16%
	Opt3	6.9718	7.8701	-0.8983	-11%
	Opt4	6.5895	7.7119	-1.1224	-15%
Case 2 (1940-1980)	Opt5	2.4908	1.8321	0.6587	26%
	Opt6	2.0553	1.5782	0.4771	23%
	Opt7	2.7958	2.0786	0.7172	26%
	Opt8	2.27	1.7572	0.5128	23%
Case 3 (BR2015)	Opt9	0.89765	0.6526	0.24505	27%
	Opt10	0.47476	0.40855	0.06621	14%
	Opt11	1.159	0.8596	0.2994	26%
	Opt12	0.64098	0.53631	0.10467	16%
Case 4 (Class 2020)	Opt13	0,3666	0.21757	0.14903	41%
	Opt14	0,21884	0.17479	0.04405	20%
	Opt15	0.57738	0.39209	0.18529	32%
	Opt16	0.30601	0.23905	0.06696	22%

Table 23 Economic benefit of operation costs in All 16 options

4.5 Summery of the results

According to the performed yearly dynamic simulations and analyses over the different building typolgies ,it can be generally concluded that the highest energy flexibility is accomplished in the buildings with high thermal performance- Case 3 and 4. The better thermal structure affirms for a greater ability to provide necessary conditions for energy flexibility. Additionaly, the thermal comfort is preserved, and even slightly improved in the building class 2020-Case 4, particulary for comfort Class I. The savings from the annual energy costs are varying for each option of the mentioned cases. However, it is investigated a significant increase of savings on energy cost per m2 per year in opt 13 - 41% (see table 12). Consequently, high ability of energy shifting from high to low price electricity is observed in the same cases with evidently high flexibility coefficients.

As for the buildings with poorest thermal performance -Case 1, flexibility controller did not performed as expected.The flexibility approach here is considered as inadequate for a building with such thermal characteristics.The reason for this is the jeopertized thermal comfort ,a decrease of 13-17 % for Class II or 304-398 hours of insufficient thermal comfort. The yearly energy consumption is highly influenced and the cost for electricity jumped with 13 to 16 % in comparison with the referent case. There are also low flexibility factors, which suggest for lower efficiency of this controller.

In building Case 2, the thermal comfort is decreased by approximately 3%. On the other hand, this control application can bring high savings of up to 26% from the yearly electricity consumption costs per m^2. After all, insignificant differences in comfort can be neglected if the running costs of the building system are prioritized.This case demonstrates fair energy flexibility factors, but only in options with higher internal gains.

Building options	Options	Thermal comfort Class II (%)		Annual energy cost for heating and cooling (DKK/ kWh per m2)		Energy cost savings (%)	Flexibility factors
		R	F	R	F		
Case 1 (1890-1930)	Opt1	73.03	60	6.6143	7.6069	-13%	0.69667
	Opt2	78.67	61.79	6.3161	7.4792	-16%	0.75913
	Opt3	71.23	58.71	6.9718	7.8701	-11%	0.66631
	Opt4	77.3	61.19	6.5895	7.7119	-15%	0.73125
Case 2 (1940-1980)	Opt5	72.22	68.5	2.4908	1.8321	26%	0.85812
	Opt6	80.17	77.30	2.0553	1.5782	23%	0.93851
	Opt7	67.43	64.23	2.7958	2.0786	26%	0.83168
	Opt8	78.11	75.08	2.27	1.7572	23%	0.91988
Case 3 (BR 2015)	Opt9	74.23	73.67	0.89765	0.6526	27%	0.99735
	Opt10	85.08	84,01	0.47476	0.40855	14%	1
	Opt11	66.28	65.59	1.159	0.8596	26%	0.98879
	Opt12	82.73	81.58	0.64098	0.53631	16%	0.99929
Case 4 (Class 2020)	Opt13	88.11	87.86	0,3666	0.21757	41%	0.99778
	Opt14	88.37	89.19	0.21884	0.17479	20%	1
	Opt15	83.11	80.64	0.57738	0.39209	32%	0.97864
	Opt16	88.63	88	0.30601	0.23905	22%	1

Table 24 Final results

5. Suggestions on further research

5.1 Control optimizations

According to the research results, the investigated control strategy combined with a novel building system is successful mainly in buildings with good thermal performance. The most optimum options are represented by the higher energy class buildings with high internal gains. They offer highest ability to shift energy from high to low energy prices by providing the best adaptability to the grid. Moreover, from economical point of view, these options resulted in energy cost savings on an annual base. Therefore, it can be concluded the performance of the energy flexibility controller is quite sufficient.

In spite of the effectiveness of this controller, there are several drawbacks that must be taken into consideration. Generally, the achievements of the tested controller will vary due to the fact the electricity price trend differs from one year to another. The available power from the grid will be different throughout entire year and therefore a fluctuating tendency will be difficult to predict. Consequently, it might result in a big offset from the varying energy prices, which will lead to inadequate performance of the HVAC system

This study has been conducted based on electricity price of 2015 (9) and the set points of the system are adjusted to eight price thresholds (can be seen on table 20). The latter is determined by splitting the annual electricity fluctuations into eight price levels in order to simplify the controller algorithms. In this way the control is adapted to the particular yearly conditions of electricity variations. Nevertheless, such approach creates a risk for the system to work insufficiently, if electricity price does not fall within expected price frames. In order to fix this, a calibration of new price thresholds for the energy system will be necessary. However, it might be time and money consuming to monitor the parameters as the available energy prices are only provided for 24 hours ahead. Neglecting this concern, a proposal could be made that the electricity price thresholds for the control are determined for a shorter period of time. It is expected this will improve the control precision by responding updated recent price levels.

Furthermore, the analyses of electricity data of 2015 revealed tendency of low price electricity mostly during the summer months (see Appendix IV Economic benefit) Respectively, high energy consumption is registered over the same period of time, which leads to excessive energy expenditure (see Appendix IV Economic benefit). This brings to a conclusion that the ‘’storing modulation‘’ is often activated when might not be necessary, e.g even when thermal mass is fully charged for the chosen set-point.

As mentioned example earlier, during low price period, the thermal mass is being charged in order to provide best thermal comfort, which means a much higher output is used by the system and accordingly this causes higher energy consumption and higher cost for energy per m2. The control follows electricity prices no matter, if it is desired. This can be determined as a weak point of this control strategy and another approach for more optimized controller can be further investigated.

Therefore, second suggestion for optimization is to limit the controller's work on high capacity e.g. in low price periods when there is no need for heating or cooling. For this purpose, another variable except of the electricity price can be monitored to activate the system. For example, outdoor conditions such as temperature and wind speed can be more reliable parameters to follow in order to switch the system to a charging mode. This will help in optimizing controller's performance in terms of saving energy consumption and respectively cost for it, while providing sufficient indoor thermal comfort.

The sample for a boundary condition for activation of flexibility controller on low price mode is suggested as:

- heating season: low price heating only when outdoor temperature is below10 degrees and wind speed higher than 6 m/s
- cooling season: low price cooling only when outdoor temperature is above 20 degrees

If the conditions are not met, then the system will perform according to the specified set-points for medium and high price levels as shown on table 1 (3.1.1 Used control strategies)

The scope of possible savings and comfort class achievements with the improved control strategy can only be confirmed after series of simulations. In this sense, precise boundaries of the optimized controller in regard to wind speed and outdoor temperature can be found through simulations, in case it shows actual results.

5.2 Suggestion to research flexibility potential on other types of buildings

Main aim of this research was to keep the current geometrics of the building when investigating different structural properties due to time limitation. This gives some restrictions in regards to other types of administrative buildings, which could present different perspective on energy flexibility. For example office buildings with a ceiling height of more than 5 meters (town halls type), or structures shaped as towers, primarily made of glass, steel and columns as bearing elements. It is known that overall shape of a building influence its thermal properties, therefore it could be assumed it might affect the potential in energy conservation.

5.3 Suggestion to research flexibility potential with other types of HVAC systems

Another direction of a possible further research is to investigate how different HVAC systems would influence the energy flexibility potential on administrative buildings representing structures from different ages. As “Solus active beam” uses a convectional way to transfer heat, this makes it quite vulnerable for structures with relatively high infiltration rate. Therefore a system having higher percentage of a radiant heat transfer probably would be able to store higher amount of energy in the thermal mass of a building with relatively high air permeability of the building envelope. Also, it would be interesting to compare energy cost of a same building structure whether it will have similar saving cost using “Solus active beam” or other alternative heating system.

6. Conclusion

The aim of this study is to evaluate the energy flexibility potential of typical office buildings, represented by various construction options. The building options are tested with a novel building energy system combined with flexibility and referent control strategies . The assesment is carried out by the use of several evaluation metrics-thermal comfort,economic benefit,ability of power shifting and adjustment to the the grid.

In the first part of the project, suggested constructions are defined by different thermal properties such as level of insulation, airtightness, thermal mass, etc. In total, there are established 16 options derived from 4 different building cases constructed in different periods of time.The wide range of observed models is an attempt to depict an actual picture of the variaty of buildings in Denmark -non-renovated and recently constructed . Afterwards, all 16 options are simulated with two different control strategies –a flexibility and a referent,which resulted in 32 EnergyPlus models. In the second part, the data from the referent and flexibility options are compared and analyzed in order to extract final results and plot graphs . The overview of the buildings response towards the investigated energy flexibility strategy is presented on table 24.

To summirize, a two pipe heating and cooling system with a flexibility control strategy based on electricity prices is profitable mainly for higher energy building classes (Buildings complying BR15 and Class 2020). Such buildings in a combination with high internal gains,which is normally the case for office buildings –(high equpement ,people and lighting load) can contribute for relatively high savings in energy cost for heating and cooling annually. Contraly, high solar gains influences negatively the sensitive structures from Cases 3 and 4. This leads to increased energy consumption spent on cooling, which reduces the economic benefits. Results on applied flexability strategies for Case 2 are not satisfying, despite there are some optimistic achievements. General concerns here are in regards to the huge HVAC capacity needed to maintain sufficient comfort. A possible high investment cost might come with long unreasonable payback time. Levels of investigated energy flexibility potential in non-renovated buildings typical for Case 1 are evaluated not just low, but even much worse compared to referent conditions.

7. References list

(1) Out Future Energy, The Danish Government, 2011

(2) The Danish Energy Model, Danish Energy Agency,2015

(3) Energy flexibility of residential buildings using short term heat storage in thermal mass" ,Le Dreau,Per Heiselberg,2016

(4) Generic characterization method for energy flexibility: Applied to structural thermal storage in residential buildings,Glenn Reynders,Jan Dirken,Dirk Saelens ,2017

(5) Energy saving potential of a two-pipe system for simultaneous heating and cooling of office buildings" (Alessandro Maccarini, Michael Wetter, Alireza Afshari, Goran Hultmark,2016

(6) Phase change materials and thermal energy storage for buildings" ,Alvaro de Gracia,Luisa F.Cabeza,2015

(7) U.S. Department of Energy Commercial Reference Building Models of the National Building Stock ,Deru,Michael,Kristin Field,Daniel Studer,Kyle Benne,Brent Griffith,PaulTorcellini,Bing Liu,2011).

(8) EN 15251-2007 - Indoor environmental input parameters for design and assessment of energy performance of buildings,2007

(9) Electricity price data 2015, https://www.nordpoolgroup.com/historical-market-data/.

(10) Danish Building Regulations 2015 (BR15),2015

(11) Danish Building Regulations, 1995

(12) Danish Standard 418 Calculations of heat loss from buildings, 2011

(13) BPS Publication – 100,Ernest Muller, Horsens Polytechnic ,1996

(14) BPS Publication – 101, Horsens Polytechnic,1997

(15) BPS Publication -102 Horsens Polytechnic,1997-1998

(16) *BPS Publication -103, Ernest Muller, Horsens Polytechnic,1996*

(17) *Figure 3 Reference: http://taekker.dk/*

(18) *Figure 4 Reference: http://danskbyggeskik.dk/*

(19) *Figure 5 Reference: BPS Publication-101*

(20) *Figure 6 Reference : BPS Publication – 100*

(21) *Figure 7 Reference: BPS Publication – 102*

(22) *Figure 8 Image: https://www.tripadvisor.dk/*

(23) *Figure 9 Image: http://danskbyggeskik.dk*

(24) *Figure 10 Image: http://danskbyggeskik.dk*

(25) *Figure 11 image: Reference: http://danskbyggeskik.dk*

(26) *Figure 12: Reference: BPS Publication 102*

(27) *Figure 13 Reference: http://www.tjri.com/da/Kontor-bolig*

(28) *Figure 14 Reference: http://danskbyggeskik.dk*

(29) *Figure 15 Reference: http://spaencom.dk*

(30) *Figure 16 Reference: https://expan.dk/*

(31) *Figure 17 Reference: http://velfac.dk/*

(32) *Figure 18 Reference: http://www.byggeplads.dk/*

8. Appendices