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Development of model based control of building services by use of weather forecast

Energy optimization through operational excellence in Danish building stocks

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Preface

This report is the final result of my master thesis in building technology. This work for the master thesis was conducted throughout the period October 2013 - March 2014. at the Technical University of Denmark (DTU), Department of Civil Engineering, Section for Building Physics and Services, under supervision of Professor Svend Svendsen and PhD student Lies Vanhoutteghem. The weighting of this thesis is 30 ECTS-points.

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Abstract

The project aims to develop and investigate a concept suitable for continuous commissioning of low-energy buildings based on model-based predictive control. The purpose of the concept is to use predictive control to generate a control strategy for the building installations in order to ensure the predicted energy consumption while maintaining a required indoor environment.

In general the function of this continuous commissioning through model-based predictive control concept based on the guidelines described in EN13790 – (calculation of the energy consumption for demonstration of the energy frame), is to create a solution to all the cases of modern low-energy buildings that do not perform as intended in terms of energy consumption and indoor environment.

The developed concept consists of a simulation model, which is able to generate a control strategy for the heating and cooling of a modern low-energy building. The software analyses the thermal development of the building and calculates how to regulate this development in the most energy efficient way, in order to ensure that the operative indoor temperature is compliant with the DS/EN 15251.By means of the predictive control it is possible to document that the building performs as predicted.

A comparison and analysis of the weather data for 2011 revealed that in general the weather forecast underestimated the temperature by 0.5°C and overestimated the solar irradiance by 39W/m^2.

Based on the simulation results it was concluded that MPC does not provide large direct energy savings (4%) compared to the original control. Furthermore it was revealed that the MPC strategy could provide a slightly better indoor environment with less overheating hours compared to the original control strategy. Simulation revealed that inaccurate forecasts did not always have a huge impact on the indoor thermal environment and energy consumption because the set points did not always change as a result of the error.

Throughout tests in a preliminary study several issues regarding the usability of the concept were uncovered. It was concluded that in order for model-based predictive control to be used for continuous commissioning it is essential to implement user behavior. Furthermore the importance of integrated control that ensures that all involved systems are controlled in accordance to similar set points was uncovered. Finally it was uncovered that the concept most likely would not provide large direct energy savings however the concept can provide huge savings in form of detection of control errors.

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1 Introduction

1.1 Background

Decreasing amounts of fossil fuels available combined with increased CO_2 emissions and climate change is the main cause that the Kyoto agreement was concluded in 1998. The agreement commits the EU to reduce greenhouse gas emissions and prevent further global warming. Through the agreement EU has undertaken the responsibility to reduce greenhouse gas emissions to 80-95% below 1990 levels by 2050. [1]

According to Danish Statistic [2], buildings represent approximately 30 % of the total Danish energy consumption thereby emitting large quantities of CO_2. The majority of the energy consumption is for heating, electricity and water.

In an attempt to solve this problem several initiatives have been launched. On a European level, an *Energy Performance of Buildings Directive* (EPBD) was drawn up to impose requirements for building energy performance. The latest directive adopted on 19 May 2010 stipulates the requirement that new buildings built from 2020 must have a "nearly zero-energy" consumption. A nearly zero-energy building (nZEB) is defined as a building with a very high-energy performance and with an energy consumption consisting almost entirely of renewable sources [3]. The energy performance of buildings in terms of energy use for space heating and cooling can be documented by means of methods described in EN ISO 13790 [4] or similar.

A drafting of declarations regarding the energy consumption of buildings is only meaningful if it is coupled with a drafted declaration regarding the associated indoor environment. This aspect is amongst others described in detail in the European standard EN 15251 [5] which includes various criteria for design of a building's indoor air quality. This aspect is extremely important since the modern Western man spends on average 90% of his time indoors [6]. This means that the overall goal of this process is to create energy efficient homes that can provide the necessary environment, as humans need to thrive.

The latest version of the Danish climate and energy strategy [7] was launched in August 2013 (see figure 1-1). It requires that by 2035, all buildings will be heated with renewable heat alone. In 2050 the entire electricity should also be covered by renewable sources. Furthermore, requirements to the buildings energy frame for residential and non-residential buildings are presented in the Danish building regulations. They must obey respectively 20 and 25 kWh/m^2 in 2020 [7].

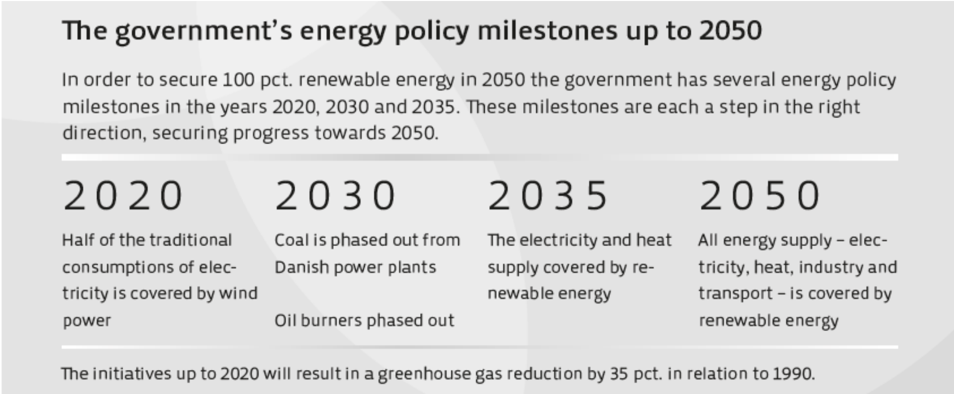

Figure 1-1 - The Danish government energy policy milestones up to 2050 [1]

It is obvious that the whole industry needs to be more efficient. It is also apparent that alternative forms of energy and optimization and efficiency of consumption is a necessity.

In line with stricter 2020 requirements for a building's energy frame, many challenges are waiting in relation to design and efficiency.
A significant focus area in relation to consumption and efficiency of a building is its energy consumption in relation to heating, electricity, ventilation, and cooling. This is because these areas constitute the greater part of the total energy and therefore have the most to retrieve precisely in these areas.

An obvious optimization of the areas would be to replace the current main energy sources with a renewable energy source in form of solar, wind and hydro energy, etc. The problem with this change is partly that energy sources are intermittent limited, and partly that the current consumption is constantly fluctuating and last but not least that there is not yet a viable storage solution for the energy produced in order for later use of the resource. Other optimization approaches could be to optimize the building itself in terms of composition and material thereby creating a more optimal product with a better performance. A third approach could be to optimize the consumption in terms of use of resources. The optimization possibilities are numerous and it is quite clear by now that in order to reach the final goal all of the above mentioned optimization possibilities needs to be combined.

Predictive control of installations and electricity-consuming appliances in buildings is expected to reduce energy consumption significantly, if the control is adapted to the current conditions, user behavior and, needs over time [8].
As illustrated in figure 1-2 it is quite important that the operation of a building is done as intelligent and optimal as possible.

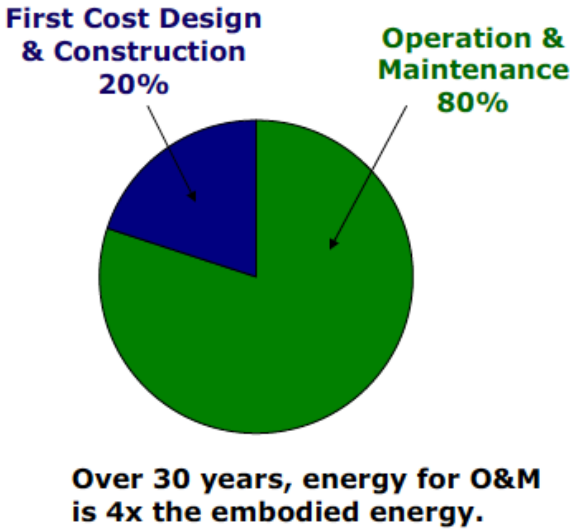

Figure 1-2 - Energy consumption for construction and operation and maintenance (O&M) of a typical Danish house (DTU BYG 2010)

The potential for reduction is found in heating, cooling, ventilation, lighting, standby power consumption etc. The size of the potential can to some extent be identified by the difference between the calculated energy consumption in the ideal scenario and actual energy consumption, which is often significantly higher than the calculated [9] [10] [8]. The majority of this difference is due to factors such as input data, calculation algorithms, user behavior, construction and operation of systems etc.

Besides the potential for reduction in energy consumption, intelligent energy control is also expected to contribute to a better indoor climate in buildings by adapting to the needs of users in form of heating, cooling, ventilation etc.

Associated with the construction of modern energy efficient buildings certain challenges/issues have come to light. Experience of the recent years constructions have revealed issues regarding the indoor environment as well as inconsistencies with the anticipated energy consumptions.

Multiple cases both domestic and foreign have revealed that these improved building designs cause unforeseen issues with overheating during the summer, misjudgment in relations to required heating power, visual discomfort etc. Furthermore investigations have revealed that in many cases the buildings have a higher energy consumption than first predicted [11] [12].

The amount of constructions containing these issues have led to an increasing demand for continuous commissioning of newly constructed buildings in order to ensure that the buildings are functioning as intended, both in terms of thermal indoor environment as well as energy consumption.

1.2 Aim and objective

The overall aim of this thesis is to show the development process and investigations regarding a concept suitable for continuous commissioning based upon model-based predictive control.

The purpose is to use model-based predictive control to document the estimated energy and environment performance of a Danish low-energy single-family house. The intension of the concept is to generate a control strategy for the building control that will ensure the predicted energy consumption while maintaining a required indoor environment. The general purpose of this continuous commissioning through model-based predictive control concept is to create a solution to all the cases of modern low-energy buildings that do not perform as intended in terms of energy consumption and indoor environment.

The developed concept should consist of a simulation model, which is able to generate a control strategy for the heating and cooling of a modern low-energy building. The software should analyze the thermal development of the building and calculate how to regulate this development in the most energy efficient way, in order to ensure that the operative indoor temperature is compliant with the DS/EN 15251.
By means of the predictive control it should be possible to document that the building performs as predicted/intended.

1.2.1 Objectives

The objectives of this project is to:

- Develop a simulation concept based upon the guidelines described in EN13790 – (calculation of the energy consumption for demonstration of the energy frame) that can function with short-term weather data.
    - Analyze and compare weather forecast data from 2011 with measured weather data of the same year.
- Investigate the model in terms of its ability to generate a control strategy for low-energy building services in order to ensure the required indoor environment.
    - The control strategy should have focus on the heating, cooling and ventilation.
    - Investigate the performance of a control strategy based upon the weather forecast vs. an ordinary control in terms of:
        - Energy performance.
        - Indoor environment.
    - Investigate how the inaccuracy of the weather forecast affects the control strategy applied on a building with actual weather measurements.
- Describe a concept where the simulation tool can function as a tool to continuous commissioning for low-energy buildings.
    - Test a concept based upon the guidelines described in EN13790 in order to uncover issues associated with the concept.
    - Describe issues regarding this concepts use for continuous commissioning.

1.2.2 Limitations

When addressing a subject like this, there will be some limitations. The scope of this thesis needs to be limited as a natural consequence of the projects size and advisability resources.

Since there is no clear approach stated in any standard on how to perform continuous commissioning, the limitation of this project is that it will not be possible to determine if the developed concept is operational in relation to current Danish situation. The goal is to develop a generic concept, which can function as a form of basis on how to solve these issues and thereby contribute to the establishment of a valid approach.

The concept of continuous commissioning includes various aspects. In order to achieve a scope in consensus with the expected performance, the following aspects will not be addressed but are relevant in a holistic view of the concept:

- The economical aspect of implementing this concept
    - Economical saving vs. maintaining costs (purchase of weather data).
- Communication between involved elements.
    - Implementation of the generated control strategy in the actual installations in the building.
- Control of installations besides: solar shading, ventilation and heating, in order to achieve a better performance.

1.2.3 Report structure

Part I - Development of a simulation tool:

Part I addresses the development of a simple and transparent simulation tool originated from a model based on DS 13790 method 2: Verification of the energy frame. The calculation method is "simple" and transparent thereby providing insight to all aspects affecting the result.

The simulation tool is capable of generating a control strategy for the different building installations based on model-based predictive control using current weather data. The main objective is to ensure the lowest possible energy consumption, while maintaining the required indoor environment. The control algorithm is based on the requirements for the indoor climate.

Furthermore this part addresses the development of a concept which implements actual weather forecasts for model-based predictive control, as well as a validation of the program in terms of simulation results and limitations. The performance of the simulation tool is investigated and aspects of the process for future improvement of the concept are discussed.

Part II - Continuous Commissioning:

Part II investigates which aspects that affect the concepts ability to be a functioning product. A preliminary study is conducted in order to investigate if the concept is functioning. Furthermore crucial uncertainty aspects are discussed in relation to the concepts ability to function as a continuous commissioning tool. Finally clarification of the target group for this concept at its current state and future development possibilities are debated.

2 Literature study

2.1 Background

Optimization/minimization of a building's energy consumption is a process where there may be numerous areas of focus, the primary focus areas as mentioned earlier are heating, HVAC/electricity.

A building's energy consumption depends on many aspects but the foundation for a low consumption is based on the following aspects:

- Reduction of the total energy requirements, by use of non-energy-using resources.
- Optimization of the building envelope in the form of insulation, windows and minimizing thermal bridges.
- Aspects like the building orientation and geometry must also be optimal in relation to use of daylight and glazing-to-floor ratio.
- Additionally it is important to optimize the building's thermal mass in order to make it able to easily maintain the desired temperature.
- Finally to make the temperature-controlling operations, such as shading etc. If these fundamental aspects are in order it ensures that the heating need is significantly reduced.

Energy-efficient operation depends upon how the various installations are designed and of course how they are managed. One of the most significant energy consuming installations is the HVAC system and for this to be energy efficient, the above mentioned must be in place in order to ensure the most economical operation. Furthermore the system must be designed correctly, in relation to both the unit and the duct system. Finally, and perhaps the most important factor is the operation of the system and the optimization of it.

As mentioned, the last aspect is one of the focus areas of this project. The current research revolves around the concept of "*Model-based predictive control*" (MPC). The basic idea of MPC for installations is to use a virtual model of the building and the weather forecast to predict the future development of the building's indoor environment and amount of energy used. Information from the model is then used to calculate how various installations should be controlled in terms of fulfilling the requirements for the indoor environment using the smallest amount of energy as possible from the various installations to optimize the performance of the building. In short MPC is a control strategy for optimization where PC is a control strategy.

2.2 Model-based Predictive Control

There are many different approaches to the creation of MPC for building services today, but in general they can be divided into three main categories:

The first type is a statistically based model, which means that they have no underlying physical model of the system and how the processes are controlled. These model types are instead statistically derived based on measurements such as exterior temperature, etc., which are used as input to derive outputs like the temperature indoor etc. The process between input and output is unknown. This is called **black-box modeling** and typically this modeling approach does not require the same amount of experience and knowledge regarding the system compared to white-box modeling [13] [14].

The second type, also called **white-box modeling,** is based on modeling physical connections, which means that these types of models represent a virtual model of the building itself containing all the information about the construction and installations, and their control. Typically the user has full access to the model structure as well as full knowledge regarding the algorithms upon which the model is constructed. This approach is often more transparent but also often a lot more complex [15] [16].

The third type is a combination of the two previously explained approaches and it is called **gray-box modeling**. In this modeling approach the user has some insights into the structure and the algorithms used. However, the dynamics of the system is still somewhat unknown, similar to the black-box model. The three different modeling approaches are illustrated in figure 2-1.

Several studies have shown that regardless of the modeling technique for the MPC, it is the correspondence between the system dynamics in the model and the behavior of the actual building that is important. Furthermore the accuracy of the weather forecast is also very important as well as the model of the occupants' behavior. These factors must correspond to the actual situation for the model to be useful. If this is not the case, the models are not able to provide useful results.

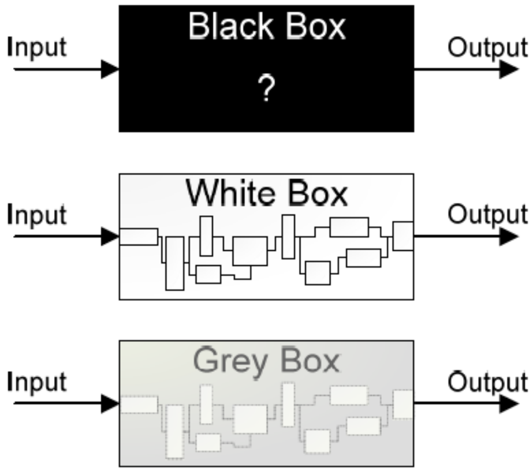

Figure 2-1 - Black, White & Gray-box modeling

The use of MPC is largely dependent on its ability to deliver results that improve operations and thereby reduce energy consumption while maintaining the desired indoor environment. Existing MPC concepts have shown some potential to deliver just that. Several studies comparing MPC concepts with other more conventional system operations have shown some potential.

[17] describe how the use of an MPC concept achieved an energy savings of 7% in relation to ventilation and heating, while the indoor climate is improved from an annual number of overheated hours (indoor operative temperature above 26 degrees) of 62 hours to 15 hours compared to a conventional form of control.
Similarly [18] found a possible saving of 10-12% on the energy consumptions for floor heating through the winter months by using MPC, compared to a conventional heating

strategy. [19] Outlines an energy savings of between 16-41% depending on location, type of building and technical system characteristics.

2.3 Weather forecast

Many different aspects point towards a need for actual weather data forecast in order for the concept MPC to function properly. [20] describes a strategy approach for climate control in the building, taking into account the uncertainty in weather forecast based on a "*Stochastic model predictive control*" (SMPC). The results obtained with this approach suggest that SMPC is able to deliver a lower energy consumption as well as a better indoor air climate compared to current management forms. It should be emphasized that the best results were obtained by means of complex weather models. By using simple weather models, the results were significantly impaired.

Another study that achieved very different results based on simple weather models is [21], however in one case it could be concluded that the uncertainty in the forecast actually directly causes a small increase in the energy consumption.

The complete opposite can be concluded based on [22] studies, conducted in the United States, which show that virtually the full potential of MPC could be achieved in spite of the simple weather models containing variables such as air temperature, humidity and hours of sunshine, all with fluctuating uncertainties and where the models only describe the temporal short intervals. In this context it is important to emphasize that the studies in [20]& [21] do not use the same MPC concept, nor do they examine the same building types, as well as not having the same geographic location.

2.3.1 Indirect caused energy saving

Studies have also been carried out based on factual measurements and where the MPC concepts based on weather forecasts are compared with current management concepts. In these studies, the implementation of the weather forecast is not concluded to be the direct cause of the savings, yet it has a strong influence on the final result. In [23] the potential to reduce the heat load is investigated in three apartment buildings located in Prague using MPC in which the weather forecast is incorporated. These studies show a saving of 15-28%, depending on factors such as the insulation thickness, and the exterior temperature. The savings are compared with a conventional heating strategy where the heating demand is only controlled in relation to the temperature difference between flow and return on the hot water.

2.4 Occupant behavior

A building's energy consumption is also greatly influenced by occupant behavior. A study carried out in [24] very clearly supports this statement. The study examines the energy consumption for a room with one resident, who has the ability to influence six climatic factors, such as to affect the temperature and change clothing etc. The results showed clearly that the residents' behavior largely influenced the energy consumption.

This is also the conclusion in [25] where a study of comparable German houses shows very variable energy consumption. The study also showed that buildings where the heating was controlled manually and not through a thermostat generally had a higher energy consumption.

In a comprehensive study of American homes it was concluded that the occupant behavior had the second largest influence on total energy consumption, surpassed only by the climatic conditions [26].

The influence of a resident's behavior on energy consumption has also been studied in [27]. The study examined 290 identical homes and 35 apartments located in Copenhagen. The conclusion was that the occupant behavior clearly had a huge impact on energy consumption.

Measurements of occupant behavior as well as indoor and outdoor environment was carried out simultaneously in 15 homes in Denmark. Based on these measurements, occupant behavior patterns were defined and implemented in the building simulation program IDA ICE. Comparisons between a building's energy consumption were then made, when the building was exposed to respectively the new occupant behavior in conjunction with the conventional design occupant behavior pattern. Hereby it was found that the heating consumption was three times higher in the building where the occupant behavior pattern was based on the measurements, in relation to the conventional set pattern. Thereby proving that actual consumption often is much higher than the conventional pattern used in simulation tools [28].

2.5 Experiences with Low energy building:

2.5.1 Predicted energy consumption vs. actual energy consumption

Case studies of low energy buildings have shown an increased need for continuous commissioning. In [12] seven different low energy houses built/constructed in six different countries were investigated. All the seven houses were composed in different ways with focus on different aspects, however common elements were high insulation level of the building envelope, improved windows, heat recovery and innovative integrated systems. For all seven cases the measured energy consumption was larger than the predicted. In average the predicted energy consumption was 44kWh/m^2 per year where in reality an average energy consumption of 69kWh/m^2 per year was measured. One of the houses was a town house built in Denmark, where the majority of the windows were facing east and west. The predicted energy consumption was roughly 35kWh/m^2 per year. However, the measured energy consumption was around 65kWh/m^2 and investigations showed that especially the heating demand was underestimated.

Additionally the buildings suffered from overheating during the summer period, which in some cases was minimized by the use of external solar shading as well as pre cooling the construction by means of night ventilation.

Similar results were found in [29] where the estimated and measured energy consumption of different types of low energy single-family houses in Denmark was compared. The investigation revealed that the actual energy consumption was twice as high as estimated. Enlarged energy consumption due to drying of the construction was given as a possible explanation; however this was never confirmed through testing etc.

Recently several research projects have been launched in Denmark in order to investigate different aspects regarding low energy houses. Two of the leading projects are the EnergyFlexHouse in Tåstrup [8] and House for Life in Lystrup [30]. In [30] it could be concluded, based upon the first year of testing/measuring that the actual energy consumption was approximately 20kWh/m^2 per year higher than estimated, however this was mainly due to a higher average indoor temperature than originally assumed during the estimations.

In [30] it was also concluded that an improved indoor environment was achievable by improving the control of sunlight entering the building as well as the ventilation. Moreover it was concluded that the thermal indoor environment would benefit from an optimization of the control of the different installations, and the thermal capacity of the building itself. Finally the results showed that the overall performance of the house would improve if the interaction between the control of the different systems and the occupant behavior were improved.

In [11] the issues regarding indoor environment in Danish low-energy buildings were investigated. Based upon these investigations it could be concluded that Danish modern low-energy buildings contained some of the same problems as regular buildings however in the low energy buildings they were magnified, furthermore they contained some new issues.

2.5.2 Thermal indoor environment [11]

In general overheating is an issue in low-energy buildings, mainly due to window orientation and ineffective solar control. This issue can to great extent be avoided by proper control of exterior shading and “free” cooling by natural ventilation. If the construction has a high thermal mass, it can be used to regulate the thermal indoor environment by correct control of preheating/cooling. However, if the control of the thermal mass of the building is not correctly achieved it can instead aggravate the thermal performance of the building.

Besides overheating, experiences also show that too low temperatures can occur in low-energy buildings in winter due to incorrect dimensioning of the heating system. In some cases the dimensioning of the different heating systems was done without taking into consideration that the predicted maximum heating power was calculated based upon a stationary situation with an exterior temperature of -12°C. As a result, the thermal indoor environment in some buildings deviated from the predictions. Moreover it was concluded that a water-based heating system combined with individual regulation of different thermal zones would deliver the best thermal conditions. In this regard, a dynamic simulation with multiple zones should as a minimum be conducted to reflect the control of temperatures in the different zones.

2.5.3 Demand controlled ventilation [11]

The increased house volume per occupant compared to older buildings has led to a reduced need of fresh air, combined with the fact that different zones have different needs in different periods, and is the primary reason why demand controlled ventilation has proven efficient in the low energy buildings.

In general it was found that demand controlled ventilation could deliver the required atmospheric indoor environment, however the systems must be dimensioned in such a way that they are able to handle small rooms with high intern loads in limited periods.

Furthermore the system must have a satisfying low SEL-value in order for it to be energy efficient. Especially the last part was highly varying from case to case despite all the systems being new. Based upon this fact it is of the utmost importance that ventilation systems performance is verified by demonstration based upon measurement etc.

2.5.4 Occupants [11]

As mentioned previously, several studies found that occupants influence both the energy performance as well as the thermal indoor environment in buildings. Variations in predicted versus measured energy consumption of as much as a factor 3-4 have been recorded.

It was concluded that enlightenment and communication with the occupants could minimize the problem and lead to a needed behavior change. On the other hand, also occupants without the needed knowledge and "energy-efficient" behavior should be able to live in low-energy buildings. In other words, low-energy buildings should be designed in such a way that all occupants should be able to live in the building without feeling limitation on their behavior, as well as they never must feel restricted in their comfort and behavior.

2.6 Experiences regarding continuous commissioning

In [31] a 4 step methodology to organize and standardize ongoing commissioning is developed. The methodology was tested on 17 non-residential buildings where only a minimal dataset was measured on each building. The tests revealed that on the medium to long-term basis even a simple simulation model could be used for MPC and improve the building performance. The investigation suggested that an approach where the building controls are constantly regulated in accordance with weather predictions and anticipated building usage would be successful. It was estimated that the saving potential for the 17 buildings amounted to 4-29%.

[32] discloses a development and investigations of an intelligent resilient control strategy for model based building control. The objective was to improve it, in relation to unanticipated incidents related to weather conditions, component failures, and model mismatch. For building simulation a co-simulation was used to determine the feasibility and effectiveness of the proposed control strategy. The preliminary investigations of the concept showed that it was capable of maintaining an acceptable level of operational normalcy in response to adverse conditions.

A comparison approach between design goal (simulated performance) and actual measurements of building energy performance is described in [33]. The developed tool based upon the comparison approach is able to identify performance problems based upon comparison between simulated and measured data.

A model-based, whole-building energy diagnostics and performance monitoring system, is used in [34] to solve the challenge that a building's energy system often consumes 20% more energy, due to system deviation from the design content.

The model compares continuous acquired measurements in real time, to a reference energy model. A demonstration of the concept revealed numerous important aspects regarding the usability and functionality of the concept. The concept was able to determine multiple operation faults e.g. regarding the artificial light and HVAC control. Based upon the investigation it could also be concluded that real time weather data was essential for building performance monitoring and energy diagnostics.

2.7 Summary

The literature paints an unclear picture of how big an effect, the uncertainty in the weather forecast plays on the final result compared to the potential. The effect seems to depend a lot on the MPC concept and which test cases are being used and where they are geographically and therefore climatically located.

The literature illustrates very clearly that the potential depends a lot on several factors. In particular, the accuracy of the weather forecast, the model's accuracy in relation to the factual thermal indoor environment and energy consumption as well as the correlation between modeled occupant behavior and actual behavior.

Three factors are crucial for the usability of MPC:

1: The weather forecast is consistent with the actual conditions
2: The occupant behavior is correctly modeled
3: The accuracy of the thermal model

Investigations on the overall performance of low-energy buildings have provided great insight into how far the technology has reached, as well as uncovered several aspects for improvement. Based upon these experiences some general statements have been formulated.

The literature could indicate that the future successful low-energy building is capable of providing a satisfying indoor environment at very low energy consumption by means of improved control of the different installations. Furthermore, it is very likely that the control of the building is fully automatic and adjustable to alterations due to several factors.

General experiences regarding low energy buildings:

Higher energy consumption than predicted
Unsatisfying thermal environment during certain periods
Demand controlled ventilation can improve the building performance
Interaction between control and occupant behavior is crucial

The literature study strongly indicates that for the described scenarios to become reality, MPC must be used as a tool to obtain improved building operation control, thereby also ensuring and verifying the building performance.

Furthermore the literature also points to the necessity of a building's design/control of operations, which is capable of performing regardless of the occupants' knowledge and understanding of energy-efficient control. The intelligent control must never pose a limitation to the occupants and the occupants must never feel restricted regarding control of own comfort and behavior. However, involving and informing the occupants about consequences of their choice may lead to a more energy efficient building performance.

Several studies have shown great potential regarding use of MPC as a tool to improve building performance and as a mean for continuous commissioning. Especially concepts, which combine building simulations, measurements, and weather data, have proven to be very promising.

Preliminary experiences regarding use of MPC for CC:

MPC must be able to account for occupant behavior
MPC must be fully automatic
MPC must combine simulation, measurements and weather data

3 Building regulations BR10 & Standards

3.1 Energy frame

The building energy frame in the Danish building regulations includes energy consumption for heating and cooling, ventilation, etc. and hot water consumption.

$$Energy\ consumption = Heating + Ventilation + Cooling + Hot\ water\ demand + Lighting \leq Energy\ frame$$

The legal requirements for a building's energy-frame are described in the Building Regulations 2010 section 7. The section describes both modern requirements and anticipated tightened requirements for buildings in order to live up to the 2015 and 2020 classifications.

Table 1 - Energy frame for Office and Residential buildings.

Class	Energy frame
2010	52.5 + 1650/A [kWh/m²]
2015	30.0 + 1000/A [kWh/m²]
2020	20 [kWh/m²]

The requirements for new buildings today, as well as buildings that meet the 2015 classification, depend on the heated surface area as shown in Table 1. This is not the case for 2020 requirements. Building Class 2020 is expected to be a mandatory requirement for construction of new public buildings by the end of 2018 and the construction of other new buildings by 2020 [35].

According to the Building Regulations different energy sources are weighted in accordance to how environmentally friendly energy is to produce.

Table 2 – Energy factors BR10 (7.2)

Energy source	Energy factor [-]		
	2010	2015	2020
Electricity	2.5	2.5	1.8
District heating	1.0	0.8	0.6

These factors indicate that energy in form of heat for heating and hot water is a cheaper source of energy than electricity for ventilation, pumps, lighting and installations etc. However, it should be emphasized that these factors can change further. With present factors, the rational approach to meet the 2020 energy frame is to optimize the use first of electricity by ensuring a necessary minimum consumption from electric consuming installations. Despite the lower energy factor for heating it is also quite logical to optimize this aspect due to the magnitude of it. In most building heating consumptions is the largest energy aspect.

3.2 Indoor climate demands

A building's indoor climate is the essential aspect of a building. A building's primary function is to create an environment that meet human needs i.e. an indoor environment that is healthy to live in, but also comfortable and at the same time is stimulating and where man can live and be spared from the outside environment.

As mentioned the modern European man stays inside up to 90% of his time, which means that the climate provided by the building has a huge impact on our wellbeing. This fact has led to formulations of various requirements and guidelines for the indoor environment in buildings. The indoor environment is mainly divided into four groups, the thermal indoor environment, the atmospheric indoor climate, the visual indoor climate and, the acoustic indoor climate.

The visual and acoustic indoor climate are not directly in the scope of this investigation, however it is an important aspect for a holistic view additionally the visual indoor climate is to some extend present in this concept development.

3.2.1 Thermal indoor climate

According to BR10 *"Thermal indoor climate is determined by the temperature of the air and surfaces, the air velocity and turbulence intensity and, to a lesser extent, by the humidity of the air; and the level of thermal comfort can be determined in the context of the human activity and clothing"*
The BR10 contains no standard values regarding the design temperature, except restrictions regarding hours above comfort range listed in Table 5. Tables 3 & 4 below describe the recommendations in relation to the thermal indoor environment issued by [5].

Category I:
Category I reflects a thermal indoor environment for an occupant group with special needs, such as elderly, sick and handicapped people, sensitive and fragile people with low metabolic rate and impaired control of body temperature.

Category II:
Category II reflects a thermal indoor environment for an occupant group with a normal level of expectations for the thermal indoor environment. This category is to be used for new buildings and renovations.

Table 3 - Recommended indoor temperature design values category II EN 15251 (Table A.2)

EN 15251: Recommended indoor temperature design values (Category II)		
Type of building:	Min. for heating (~1.0 Clo)	Max. for Cooling (~0.5 Clo)
Residential building (~1.2 met)	20 °C	26 °C
Single Office (~1.2 met)	20 °C	26 °C

Table 4 - Recommended indoor temperature ranges category II EN 15251 (Table A.3)

EN 15251: Recommended indoor temperature ranges (Category II)		
Type of building:	Min. for heating (~1.0 Clo)	Max. for Cooling (~0.5 Clo)
Residential building (~1.2 met)	20-25 °C	23-26 °C
Single Office (~1.2 met)	20-24 °C	23-26 °C

Table 5 - Allowed hours above comfort range (BR10 7.2.1)

Maximum allowed hours above comfort range	
Above 26°C	100 [h]
Above 27°C	25[h]

Specification of the thermal indoor environment is based on the [36] - Specification of thermal indoor climate.

There is a close relation between comfortable operative temperature and an individual's clothing and activity level. It is assumed throughout the investigations in this report that modern individual's will adjust their clothing to a mild extent in relation to the current operative temperature and their activity level.

3.2.2 Atmospheric indoor climate

The primary function of the ventilation system is to ensure a healthy and good indoor atmospheric climate. According to BR10 *"Ventilation systems must be designed, built, operated and maintained such that they achieve no less than the intended performance while they are in use"*

Table 6 - Ventilation requirements (BR10 6.3)

BR10 requirements	
Min. fresh air supply pr. m² heated floor area	0.3 l/s pr m²
Exhaust Kitchen	20 l/s
Exhaust Bath	15 l/s
Exhaust Toilet	10 l/s

According to BR10 the largest value from the table must be chosen. These requirements are consistent with the recommendations for residential buildings listed in EN15251 for Category II during occupied hours except for the ventilation rate pr. m^2, which is recommended to be 0.42 l/s pr. m^2.

Regarding offices BR10 states that the ventilation can be determined based on [37] and that it must ensure that the CO_2 concentration does not exceed 900ppm in extended periods of time. This is fairly equivalent to the recommendations in [5] of maximum 500 ppm. above outdoor level (assumed outdoor level 360ppm). The outdoor level does vary depending on location etc.

Table 7 - Recommended CO_2 concentration according to Br10 7.2.5.1 & EN 15251 (Table B.4)

Recommended max. CO_2 concentration	
EN 15251 Category II (above outdoor level)	500 ppm
BR10	900 ppm

3.2.3 Visually indoor climate

Light poses an important factor for the human conception of a pleasant environment. Furthermore it is very important in terms of comfort to have visibility to the outside world in order to maintain a natural circadian rhythm.

BR10 does not impose any real requirements despite statements like *"Workrooms and habitable rooms must have sufficient daylight for the rooms to be well lit"*, which is based on glazed area and daylight factor on work places (Offices). Furthermore these conditions should be provided without causing overheating.

[5] Table D.1 recommends that for office buildings illumination levels of 500 Lux at working areas be maintained. Regulations and conditions for working spaces are further described in [38].

Even though the BR10 and the different standards do not provide many rules and regulations in relations to visually indoor climate, it is of great importance for the overall building performance. Especially windows have a huge impact on other factors like the thermal indoor climate and the building's energy performance. Besides the visually indoor climate, the windows directly affect the heat gains. It needs to be regulated in accordance with minimizing the heat demand and hours of overheating. The most efficient way of regulating the unwanted heat gains of the building is by external blinds. However, this solution is not without disadvantages, such as maintenance etc. Furthermore by regulating the heat gain from the sun you also regulate the amount of natural light entering the building. The regulation therefore needs to take into account both the aspect of heat entering but also the amount of artificial light needed if the external blinds blocks out a percentage of the natural light available. This should be issue of a constant evaluation in order to obtain the optimal control strategy. The more natural sunlight being used for maintaining an optimal visually indoor climate the smaller the energy needed for artificial lighting.

Part I:

4 Model-based Predictive Control

4.1 Model–based predictive control (MPC)

According to [22] the recommended procedure for analysis and development of predictive control based on short-term weather predictions, consists of five steps as illustrated in figure 4-1.

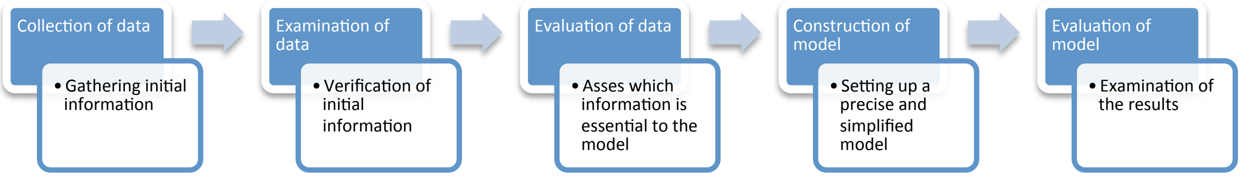

Figure 4-1 - Predictive control procedure

This procedure can be divided into two categories, one concerning gathering necessary initial data for the model, the other creating the model and assessing its results.

The initial data represents amongst others a number of variables that affect the model and its results. The objective is to collect as much relevant data for the model as possible. Primary, data regarding the exterior and interior influences should be gathered. However, the amount of data should be kept to a minimum, only data with direct relevance and reliability should be included.

Weather data
As found from the literature study, one of the most influential aspects in MPC is the weather data. [39] argues that weather data used for predictive control of buildings should be collected from a satellite instead of a ground based weather station due to the fact that satellites provide a larger picture with a worldwide grid compared to a ground station which is dependent on its location.

Furthermore it is very important to analyze and understand the data before applying them on the model. Weather conditions have a huge impact on a building, different conditions impact the building differently and factors like humidity etc. play an important role on how the building works. It is therefore very important which factors the forecast should contain. Factors like exterior temperatures and wind speed are typical measured whereas solar irradiance, for example, is often calculated or estimated based on point measurements.

The model
As described in chapter 2.2 the PC model can be constructed based on three main principles. In [40] it is investigated, which modeling approach is most suitable for which purpose. Based on their findings it can be concluded that the black-box approach has too many limitations and that the white-box method is the best approach for development of predictive control due to the fact that this method has a more insight in the different

aspects, which affect the building´s performance. Furthermore [40] concluded that predictive control through a white box model was able to decrease the energy consumption as well as provide a better indoor environment.

When dealing with MPC, one of the key factors is the ability to construct a model that is as accurate as possible but at the same time is as simple as possible. The simpler the model the easier it is to have complete insight into its dynamics, and the easier it is to identify each individual process and how it affects the final result.

A white-box model improves the insight to what aspects have the highest influence on the results. The more insight one has on the dynamics of the model the easier it is to evaluate the results and identify inconsistencies and sources leading to errors etc. The insight can therefore very well lead to an ability to improve the performance and accuracy of the model compared to the actual performance of the building.
When evaluating the final results of the model one simple theorem should be remembered: incorrect input information, leads to incorrect results.

5 WinDesign

5.1 Theory

WinDesign was original developed as a tool for determination of the optimal window composition in houses. Subsequently it was further developed to a simulation tool, which could be used for optimization of several building components. The method used in the program basically consists of four analyses, which have been divided into four individual steps. By separate analysis in each step, it is possible to analyze and interpret the results individually. Each step has its own graphical user interface (GUI), which improves the usability, and it is possible to analyze and compare multiple scenarios in order to determine the optimal solution in terms of multiple aspects.

Step 1 contains a simple evaluation method of the net energy gain from the windows thereby creating an overview of their general energy performance.

Step 2 is an analysis of a building´s overall energy consumption based on evaluation of heating and cooling demands as well as the energy consumptions of the windows based on the “seasonal method” described in EN ISO 13790 [4].

Step 3 uses the *“Simple hourly method”* ” described in EN ISO 13790 [4] to evaluate the thermal indoor environment and energy consumption of the building in more detail.

Step 4 analyzes the costs and savings for each scenario based on a simple economic evaluation of the *“cost of conserved energy”* (CCE).

Basically it is only Step 3, which is essential for MPC and commissioning. However, step 1 and 2 contribute with input information in step 3 and these steps and their aspects will therefore be briefly addressed in the following.

The weather data used in the simulation tool consists of hourly values for different parameters such as external temperature (°C), direct and diffuse solar radiation (W/m^2) as well as global illuminance (lx), furthermore monthly average values are calculated based upon the hourly values. These values can be found on standard weather data in the IWEC weather data format (International Weather data for Energy and Climate simulations). For Danish cases the calculations are based upon the weather data from *DRY* (Design reference year).
[41].

5.2 The structure of WinDesign.

The following chapter contains brief descriptions of the different analysis steps within the simulation tool. The four steps is illustrated in figure 5-1. The new features that have been implemented during this project will be addressed in a following chapter 6. The original program WinDesign is described in [42].

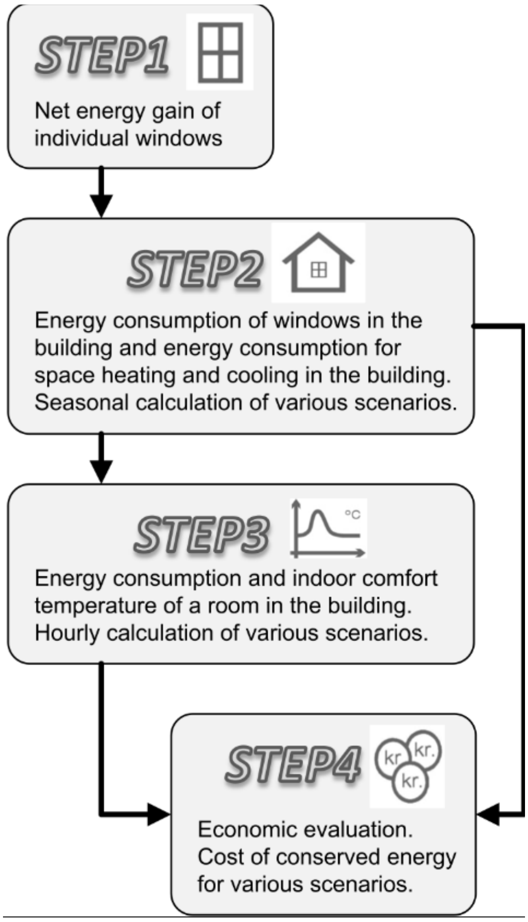

Figure 5-1 - Structure of WinDesign

5.2.1 Step 1: Net Energy Gain of Individual windows

This step analyses the net energy gain, E_{Net}, of the individual windows based on their configurations. E_{Net} (kWh/m²) is calculated based on the definition in [43] for single-family houses.

$$E_{Net} = I \cdot g_w - D \cdot U_w$$

This step creates an opportunity to compare and evaluate each window type, by expressing the energy balance of each window individual, in order to determine the most optimal solution for a given project. The solar radiation I (kWh/m²), and the degree of hour D (kKh) for the given simulation period are automatically calculated based on the weather data. The total solar energy transmittance of the window g_w is determined based on the composition of the window. The composition also influences the thermal transmittance of the window U_w (W/(m²K)).

5.2.2 Step 2: Energy Consumption of the Windows in the building

As mentioned, Step 2 contains an analysis of the energy consumption of the windows in a user-defined building for a given period of one year and also documents the building´s overall energy consumption for heating and cooling. The calculation of the energy consumption is performed for the given period with corresponding weather data and the calculation is based on the seasonal method as described in EN ISO 13790 [4].

The calculation is somewhat simplified due to the fact that the entire dwelling is calculated as one single thermal zone. Moreover, calculations are performed based on the seasonal method.

Demands determined based upon:

- Design of the construction
- Thermal transmittance of the building envelope
- Internal heat gains
- Installations specifications
- Heating and cooling set points

Information about dwelling:

- Window from STEP 1 or definition of U_w, g_w and A_w
- Orientation
- Shadings from horizon, overhangs and side fins
- Solar shading devices Floor area
- Floor to ceiling height
- Total UA-value of the envelope (excluding windows)
- Heat capacity
- Internal gains
- Infiltration rate
- Ventilation rate
- Heat exchanger
- Heating and cooling set point temperatures

In relation to the construction and its performance aspects like infiltration rate and internal heat capacities are likewise taken into account, however this is also somewhat simplified due to the fact that it is calculated as one quantity with a constant value.

The solar heat gain is also determined based on the chosen window components, which could be evaluated in Step 1. Furthermore aspects like orientation, tilt angle, external shade from obstacles, overhang, shading devices etc. are also defined for the different windows in order to calculate an accurate energy consumption.

The total solar irradiation on each window is determined based on a method for calculation of solar irradiation described in [44]. The total radiation is summed into a monthly average value for step 2, but not step 3. The simulated incidence angle is simplified into one angle for the midpoint of the hour using the average incident angle of that hour. Shading factors caused by exterior objects are calculated in accordance with [4].

The total energy consumption of the windows is formulated in two different expressions one for heating and one for cooling season:

$$E_{windows,HS} = \frac{\sum_i (U_{w,i} \cdot A_W \cdot G - \eta_{gn,HS} \cdot F_{sh,ob,i,HS} \cdot A_{sol} \cdot I_{sol})}{A_{floor}} \text{ [kWh/m}^2\text{]}$$

$$E_{windows,CS} = \frac{\sum_i (F_{sh,ob,i,CS} \cdot A_{sol,i,CS} \cdot I_{sol,i,CS} - \eta_{gn,HS} \cdot U_{w,i} \cdot A_{w,i} \cdot G)}{A_{floor}} \text{ [kWh/m}^2\text{]}$$

Where:

$E_{i,HS/CS}$ – Energy consumption of the window during the heating/cooling season
$U_{w,i}$ – Thermal transmittance of the window [W/m²K]
$A_{w,i}$ – Area of the window [m²]
$G_{HS/CS}$ – Number of degree hours during the heating/cooling season [kKh]
$\eta_{HS/CS,gn}$ – Dimensionless utilization factor for the heat gains/losses during the heating/cooling season
$F_{sh,ob,i,HS/CS}$ – Shading factor for external obstacles (horizon, overhangs, side fins)
$A_{sol,i,HS/CS}$ – Window area corrected by the window g-value and movable solar shading devices [m²]
$I_{sol,\,i,\,HS/CS}$ – Total solar radiation on the window over the heating/cooling season [kWh/m²]
A_{floor} – Internal floor area of the dwelling

The energy consumption of the dwelling is calculated in relation to both heating and cooling as follows:

$$Q_{HS/CS,nd} = \frac{Q_{HS/CS,ht} - \eta_{HS/CS,gn} \cdot Q_{HS/CS,gn}}{A_{floor}} \text{ [kWh/m}^2\text{]}$$

Where:

$Q_{HS/CS,gn}$ – Total heat gains (solar + internal) during the heating/cooling season
$\eta_{HS/CS,ls}$ – Loss utilization factor during the heating/cooling season
$Q_{HS/CS,ht}$ – total heat transfer (transmission + ventilation) during the heating/cooling season
A_{floor} – internal floor area of the dwelling

5.2.3 Step 3: Energy consumption and indoor comfort evaluation.

Step 3 is an hourly evaluation of the thermal indoor environment in the different user defined thermal zones. Thermal conditions are being evaluated in terms of thermal development as well as hours above comfort range of each zone. The "simple hourly method" as described in EN ISO 13790 [4] is used for calculation of the energy consumption for space heating and cooling in order to achieve the desired thermal environment in the zone.

Additional information (Step 1+2)

- Floor area
- Total UA-value of the envelope (excluding windows)
- Mechanical cooling
- Venting
- Venting rate
- Venting set point temperature

Output

- Heating/cooling demand
- Hours of overheating
- Hours with need for electrical light
- Electrical light demand

The model is illustrated in figure 5-2 and is based upon a resistance-capacitance model using hourly time steps. The model distinguishes between the mean temperature of the internal surfaces and air temperature. The calculation method is a simplification of the heat transfer between internal and external environment.

The model is a simplification of a dynamic solution. The model is developed in order to obtain transparency and reproducibility. The simple structure and limited equations ensure the traceability of the calculation process. Furthermore the needed input data is reduced as much as possible which combined with unambiguous calculation procedures is done to maintain the simplicity of the model.

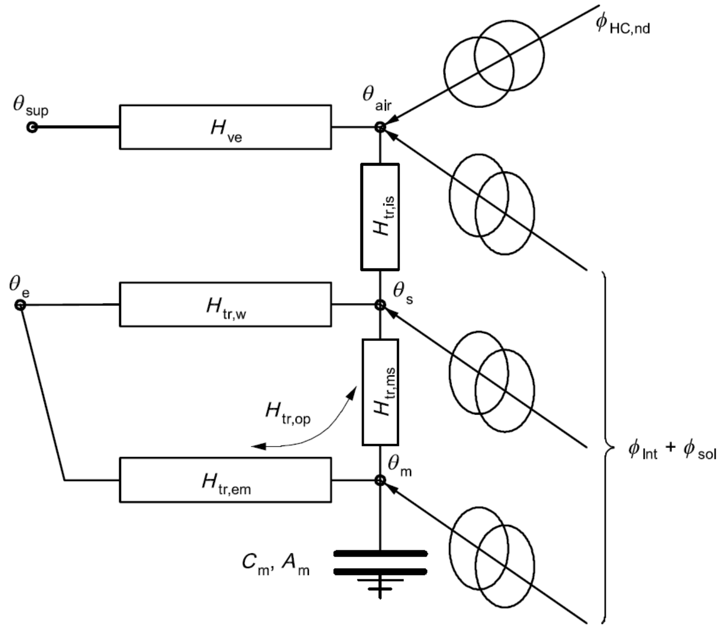

Figure 5-2 - Simply hour calculation method

$\phi_{HC,nd}$ – Needed Heating/cooling for each hour
θ_{air} – Internal air temperature, at measuring point
H_{VE} – Heat transferred by ventilation
θ_{sup} – Supply air temperature
$H_{tr,W}$ – Heat transfer by transmission for windows (zero thermal mass)
$H_{tr,op}$ – Heat transfer by transmission for the rest of the dwelling
$H_{tr,em}$ – Heat transfer between the thermal mass of the building and exterior
$H_{tr,ms}$ – Heat transfer between the thermal mass of the building and interior
$H_{tr,is}$ – Coupling conductance
θ_s – Central operative temperature (mix of θ_{air} and mean radiant temperature $\theta_{r,mn}$)
θ_m – Temperature of the mass of the building
C_m – Thermal capacity of the thermal mass (internal heat capacity)
ϕ_{int} – Heat flow rate due to internal heat sources
ϕ_{sol} – Heat flow rate due to solar heat sources

Installations
This step includes the definition of all the installations in the construction, both in terms of use and settings as well as control strategy.

Solar shade
Movable shadings can be applied to control the amount of solar energy entering the construction. The shadings are defined by their shading coefficient, which is added to the g-value of the window. In WinDesign, the in-use time is standardly simulated by a utilization factor, $F_{sh,with}$ for situation where the radiation is above 300 W/m^2 on the window surface:

$$F_{sh,with} = \frac{\left(\sum_{if\ I>300W/m^2} I\right)}{\sum I}$$

Where:
I – solar irradiation

However, this setting (300W/m^2) can be regulated in order to obtain a different control strategy if needed. This could for instance be the case where a different control strategy regarding solar shading is required in the winter and summer season.

Artificial lighting
The amount of electric lighting is estimated based on a calculated *daylight factor* (DF) inside the room combined with a defined requirement for a minimum light level inside. WinDesign itself is not able to calculate the DF therefore an exterior software has to be used for this purpose. The calculated DF is then used to determine light level for each set-point, which is used to control the electric light in the following manner:

$$P = \begin{cases} \frac{P_{max} \cdot I_{setpoint}}{I_{threshold\ value}} & if\ I_{setpoint} \leq I_{threshold\ value} \\ P_{min} & if\ I_{setpoint} > I_{threshold\ value} \end{cases}$$

Where:
P – Needed amount of artificial light

The limitation of this method is that it does not take visual comfort in terms of glare issues etc. into account. Another simplification is that the method only evaluates the light level in regards to a single point, which could also cause an uncomfortable visual indoor environment. The programs inability to calculate the DF poses an uncertainty resulting in an estimation of the actual electricity consumption for artificial lighting.

Control strategy
The basic control strategy is based on achieving the stated requirements for the indoor thermal environment with the smallest energy consumption as possible. If the operative temperature is outside the optimal range by the end of a time step the proceedings described below will take place.

In this simplified scenario very few parameters are taken into account when evaluating the optimal indoor environment, of which the decisive is the indoor operative temperature. Therefore the overall goal of the control strategy is to keep the indoor operative temperature within the limits described in chapter 3.2 table 3.

Heat capacity of the dwelling is used as storage for the e.g. solar radiation that enters through the windows, in order to achieve/keep the operative temperature within the user defined heating and cooling set point at the end of each hourly time step.

If the internal operative temperature calculated at the end of each time step is higher than the cooling set point, venting will be activated. If it is lower than heating set point temperature + 1°C, the heat exchanger is activated.

If the internal operative temperature at the end of the time step still exceeds the heating or cooling set point, mechanical heating or cooling (optional) is activated.

Hours of overheating are determined in relation to evaluating if the system is able to maintain the indoor temperature in each of the zones, within the mentioned comfort limits at a satisfying level.

Ventilation & Heating/cooling
Heating and cooling demands are based on calculations of internal operative temperature at the end of each time step.

The specific used of the ventilation system is defined in terms of settings and use, including use of heat recovering, bypass-functions, and cooling. The ventilation is calculated for the entire zone. If the building is very complex each room can be simulated individually, however this requires expert knowledge or individual scenarios created.

The heating and cooling requirements are maintained by different systems. The cooling can be regulated, as mentioned, by the ventilation system and "window shading". The cooling can be provided by the ventilation system throughout normal ventilation, mechanical cooling and natural ventilation, the effect of the last possibility is of course highly dependent on the exterior temperature.

Regarding natural ventilation it is possible to obtain different control strategies in relation to heating and cooling season. In the context of the ventilation it should be mentioned that the simulation tool has certain limitations. Regarding the natural ventilation model in the simulation tool, it is assumed that the air change rate is obtained at all times during operation. The natural ventilation model dos not take into account factors like wind speed, direction, buoyancy etc. only temperature and air change rate, which of course is a simplification and a source of error, however still reasonable.

The heating of the building is regulated by the heating system, the ventilation (heat exchanger) and of course by solar gains through the windows and internal gains etc. In the event that the accumulated heat in the construction is not enough to maintain the desired internal operative temperature the heat is supplied by the heating system, if this is not enough the ventilation system can contribute with mechanical heating, however this scenario should be avoided due to the energy consumption.

The simulation tool also contains certain limitations regarding the heating of the building. A certain percentage, most likely the majority, of the heating demand is covered by an ideal system, meaning that it is assumed that the needed effect is always available and can be delivered within an optimal time period. Furthermore the program does not provide options in relation to control the delivered effect, so there is no telling if in fact the system actually is able to deliver the needed amount or if it delivers too much in the actual hour compared to the actual system.
This limitation is due to the fact that the original purpose of the program was to show how much energy is needed in the early design phases and its results are afterwards be used for dimensioning of the system.

5.2.4 Step 4: Simple Economic evaluation

The final step is an economic evaluation based on the criterion of cost of conserved energy (CCE). It is primary used to evaluate different scenarios compared to a reference, in order to determine to optimal economic solution.

$$CCE = \frac{I - I_{ref}}{E_{ref} - E} \cdot \frac{d}{1 - (1 + d)^{-n}}$$

Where:

- I - I_{ref} – Investment cost (monetary unit)
- E_{ref} - E – Annual savings (kWh)
- d – Net discount rate
- n – Econimic evaluation period (years)

This aspect does not pose a focus area in this thesis, but should be considered for a holistic perspective.

5.3 Validation of the program

The simply hourly calculation method contains simplifications and limitations, therefore it is important to check certain aspects if the calculations are to be used in the context of checking for compliance with building regulations. Compliance with the general procedure, boundary conditions and input data is important to be checked in full detail. Irregularities will lead to differences in the results. Relevant aspects to check include:

- Heat transfer via the ground incl. thermal bridges
- Non-adiabatic internal floors and walls
- Linear thermal bridges
- Internal airflow between thermal zones
- External shading and reflection
- Solar properties of windows
- Air infiltration

Various student projects have used the simulation tool to evaluate buildings' energy performance. Furthermore the performance and results delivered by the simulation tool have been compared with results obtained by means of other simulations programs such as, Bsim, Be10 and EnergyPlus. Furthermore, the comparisons of validation results obtained by various test cases, which are all defined in ANSI/ASHREA, EN 15265 [45] and standard 140 [46], clearly illustrate that the simulation tool has the necessary precision in calculating the energy performance and thermal indoor environment in the early design phases, despite the simplified calculation method.

The accuracy of the method was also further investigated in several other studies. [47], [48], [49], [50] all investigated and compared the results obtained by the simplified methods in EN ISO 13790 with results from other dynamic simulation tools. The studies showed that the method was adequate in determining both the heating and cooling demand.

Single room vs. single-family house
[51] performed a set of test defined in [46] for a single-room and the results showed that the heating, illustrated in figure 5-3, and cooling demand determined by WinDesign was comparable with results found by worldwide known energy simulation tools like TRNSYS [52] and ESP-r [53].

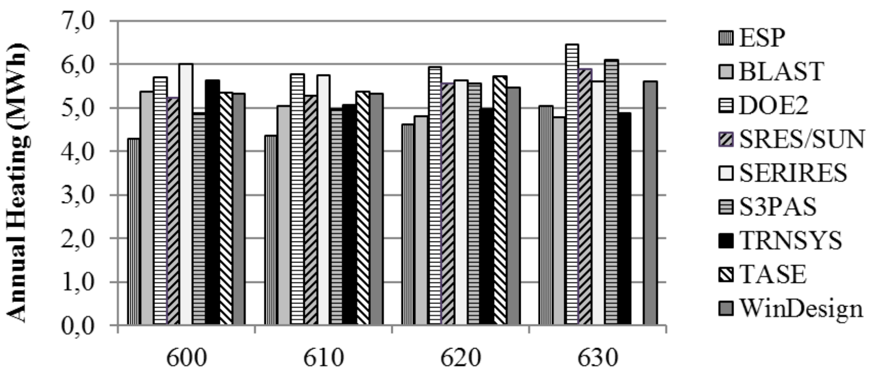

Figure 5-3 - Comparison of annual heating demand for 600-cases simulated with various tools

[51] Describes a more in depth validation of WinDesign where results were compared to results obtained by the dynamic simulation tool Energyplus. Simulations of a single-family house divided into six different thermal zones were made and then compared in order to determine inconsistencies etc. One of the focus areas was the fact that the simple hourly method as implemented in WinDesign does not take interaction between thermal zones into account, and how it affects the final results.

The comparison was made between the WinDesign model and a coupled thermal model with heat transmission and an adiabatic model, both made in EnergyPlus. All models were constructed with ideal conditions in relation to heating/cooling capacities, and were then compared on a variety of parameters like thermal mass, insulation level, window size and type etc.

The comparison revealed a good correspondence between the results for both heating and cooling demand, with maximum deviations around 15%. The study also showed that the largest deviation regarding cooling demand occurred for well-insulated buildings. The largest deviations regarding heating demand occurred for buildings with large glazing-to-floor ratios. It should, however, be noticed that smaller deviations for buildings with large glazing-to-floor ratio were found when comparing with the adiabatic model.

Despite the similarity between the temperature profiles when compared to the adiabatic model, it should be emphasized that the dynamics of the methods are somewhat different. The reason for this variation is properly the simplified way that the simple hourly method treats the thermal mass compared to the dynamic simulation of EnergyPlus. This specific area is worth further investigation in order to determine magnitude of influence on the final results.

WinDesigns ability to calculate the energy performance of a building is consistent with the simple hourly method for the determination of the energy performance of the building [4]. The hourly estimations of the thermal development of energy performance makes it suited for MPC.

Additionally the model is based upon a white-box method where the user has insight in the calculation method and the individual process as well as the different aspects that influences the final results. Furthermore the model is relatively simple in its construction.

The platform upon which the WinDesign is constructed also allows the user to have complete access to the source code and the composition of the program.

6 Predictive control in WinDesign

Development of a method for predictive control of building systems operations can be approached from many different angles.

The MPC method used is based on a concept developed by [17]. This approach to MPC was originally developed for a similar program, and the principles of this approach has been adopted and altered for the purpose of fitting WinDesign and the purpose of this investigation. [17] has developed a method, which is based upon two parameters; temperature and solar irradiation, from actual weather data measurements and forecast.

The method consists of two phases illustrated in figure 6-1. The first phase is a prediction and the second is a test of the conditions. The specifics are that a desired set point for a given period is selected/predicted alongside a strategy for the different operations of installations in order to reach the set point at the end of the given period. Secondly, the strategy and set point is tested (simulated) in order to verify that the set point stays within the boundary conditions, which are determined as the thermal comfort range described in chapter 3.2. The outcome of the test then determines whether or not this strategy should be implemented or updated.

Figure 6-1 - Structure of two phase model

6.1 Time periods

The concept of MPC is based upon prediction of future development, in relation to this prediction it is crucial to define the time periods of the future prediction, as well as to define various periods that can be simulated based upon different initial criteria.
The concept developed by [17] divides a day into three periods of eight hours each. A simulation is run every hour of every day. The period in which the current time step is in is called the *current period* and the following period is called the *following period*. A simulation is run every hour for the remainder of the current period and the entire following period.

Besides the dividing of a day into three periods, the method also differentiates between in-use and out-of-use periods. The main idea is that a building does not need to provide the same indoor environment, if people are not present. This concept is especially useful in relation to offices etc. where people are not present large parts of a day. The in-use/out-of-use periods are essentially different from building type to building type. Given the fact that many different factors influences how periods etc. should be divided, it is difficult to define fixed scenarios which apply for all cases however in general it can be stated that:

- Office buildings typically have an in-use/out-of use period of 8 hours and 16 hours. Where the in-use period typically lies between 9-17 and the remaining hours of the day is the out-of use period for weekdays and 24 hours out-of use periods in the weekend.

- Residential buildings have a more fluctuating user pattern etc. resulting in difficulty to divide a day into in-use- and out-of use periods. However the majority of residential buildings are non-occupied during a period from the morning to the afternoon.

The procedure is illustrated in figure 6-2, with an in-use/out-of-use division for a typical house. The method operates with two different time steps, a time step for each hour of every year *n*, where a simulation is done, and a second time step for the current simulation *i*.

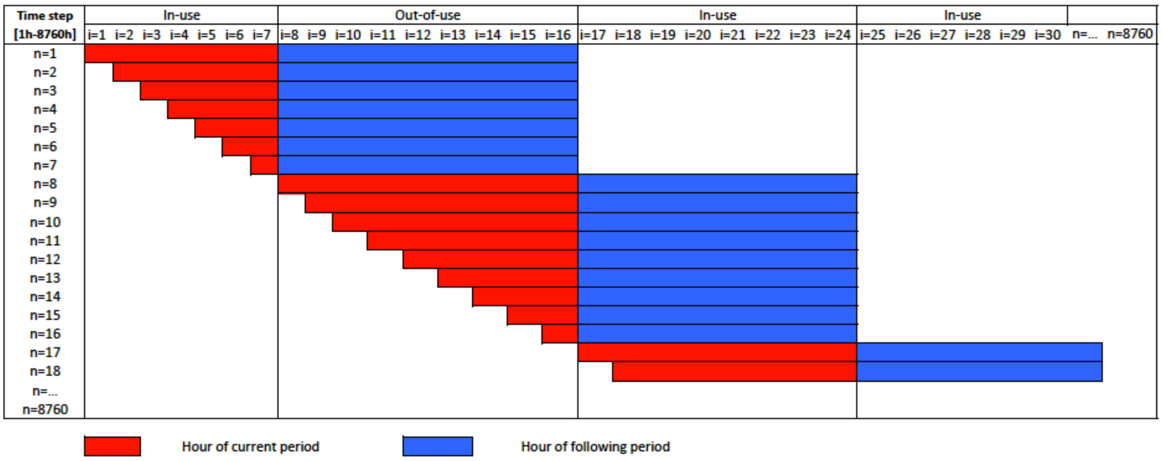

Figure 6-2 - MPC method with current/following period and in-use/out-of-use periods for a typically house

As previously described a simulation is done for the remainder of the current period and the following period. The main focus for this method is to keep the operative temperature within the thermal comfort range, which is described in chapter 3.2. In order to simplify the simulation it is assumed that occupants will dress in accordance with the current operative temperature thereby simulations do not have to take into account heating/cooling season and only operate in relation to the temperature range in chapter 3.2 table 3. These values can of course be adapted in accordance with the different individual needs and requirements, in case their requirements do not correspond with the standards.

6.2 Control strategy

The control strategy of the building is defined from a focus on energy efficiency. Therefore the least energy consuming installations is activated first in order to ensure the lowest possible energy consumption need in relation to keeping the operative temperature inside comfort range.

6.2.1 Cooling strategy:

If a simulation predicts that the operative temperature inside the building will rise above the comfort range, the following procedure will take place in the listed order:

I. Solar shading will be activated providing a reduction of heat entering the room. Given that the sun is present.
II. Natural ventilation will be activated, providing an air temperature approximately similar to the external air temperature to enter the building. (Night ventilation)
III. Mechanical ventilation will be activated, ensuring a higher air change rate in the building.
IV. Mechanical cooling will be activated, ensuring a higher cooling capacity.

The solar shading provides a reduction in the amount of energy/heat entering the building. This reduction is determined in relation to its shading factor. In the simulation, the shading factor is a constant percentage reduction of the average irradiation of the current hour.

Solar shading is the obvious first choice for a cooling strategy, due to the fact that it can lower the energy entering the building, which otherwise most likely will cause a further increase in temperature.

Furthermore, shading can be lowered with a minimum energy use. The only energy consumption is that of energy needed to operate the system. The disadvantage of this solution is that by lowering the shading the sunlight entering the building is reduced and the potential need for artificial light might increase.

Natural ventilation is in reality wind speed depending however in these simulations it is a constant air change rate. Natural ventilation also includes night ventilation, which is used to lower the thermal storage in the building mass given that the temperature in the following period is estimated to increase unwantedly. The disadvantages of natural ventilation are that the effect depends on the outside temperature and wind speed. However, this ventilation form can provide results with a minimum of energy use.

Mechanical ventilation is set to provide an air change rate of $2h^{-1}$ with an air temperature corresponding to the external air temperature. This solution has some of the same disadvantages as natural ventilation (inlet air temperature) however, the air change rate is much higher which is at the expenses of a higher energy consumption. Furthermore there aspects like draught, due to high air change rate, temperature difference between the indoor and supplied air etc. to consider, which all can cause local discomfort.

Mechanical cooling is able to cool the inlet air to a lower temperature. In this scenario it is important to not create a too large temperature difference in order to avoid draught etc. This solution is a last resort due to the corresponding high-energy consumption compared to the previous three possibilities. This option should therefore be avoided.

6.2.2 Heating strategy:

The necessary heating is provided on an hourly basis in order to ensure that the operative temperature never goes below the thermal comfort range.
A certain percentage of the heating demand is covered by the heat exchanger in the ventilation prevented that it is being used. The use of the heat exchanger is energy efficient, however it has a limited capacity and the heat exchanger causes a higher pressure loss in the system, resulting in larger energy consumption for the fans. When the heat exchanger is not active, the entire heat demand is covered by the heating system.

The program is simplified in the heating and mechanical cooling aspect in terms of only being able to calculate a needed energy demand on an hourly basis, and not taken into account the source in its abilities/constrains. The energy amount is simply being delivered the instant it is need in the simulation. In real life this process would be more time consuming and consequently affect the thermal development differently.

6.3 Simulation strategy

The method of the simulation strategy is based on the concept described in [17]. The simulation strategy is knowingly kept at a relatively simple level in order to fully investigate and understand every aspect of the process and how each individual process affects the final result, by using this approach it is possible to obtain more insight to the overall process and thereby create a basis for further investigations and improvements.

6.3.1 General strategy:

The general strategy for the algorithm is to determine the thermal development of the building and establish a control strategy in accordance. The basic principles and method for such is listed below:

- **A.** The temperature development without any form of control.
- **B.** Determination of required set points in order to ensure thermal comfort.
- **C.** Determination of heating/cooling strategy in order to keep the operative temperature within the thermal comfort range.
- **D.** Calculation of new temperature development and energy consumption if the control strategy is implemented. If the strategy is not implemented, the operative temperature is determined by A.

6.3.2 Algorithm implemented:

The algorithm implemented in WinDesign is divided into 6 stages, which are described in figure 6-3 and are based on the general strategy for MPC in building system control developed by [17]. The aim of the developed algorithm is to keep the structure as simple as possible while simultaneously delivering the desired performance/result.

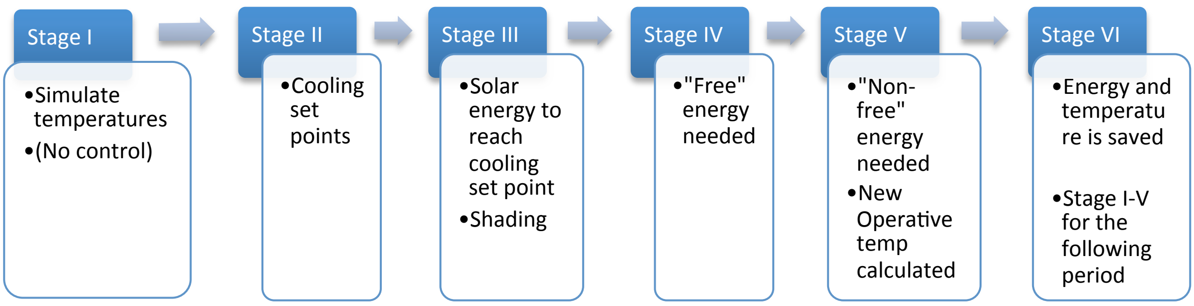

Figure 6-3 - Structure of simulation algorithm

Stage I:
The first stage is an estimation of the temperature of the thermal mass of the building, for the remainder of the current period.

The period is simulated without any form of influences from systems. The operative temperature is simulated for each hour of the given period.

If the simulated operative temperature goes outside the thermal comfort range, the following correlations are assumed:

$$\theta^*_{m,t} = \theta_{comfort,u} \quad IF \quad \theta^*_{op} > \theta_{comfort,u}$$
$$\theta^*_{m,t} = \theta_{comfort,l} \quad IF \quad \theta^*_{op} < \theta_{comfort,u}$$
$$\theta^*_{m,t} = \theta^*_{m,t} \quad IF \quad \theta_{comfort,u} < \theta^*_{op} < \theta_{comfort,l}$$

Where:

$\theta^*_{m,t}$ – Temperature of thermal mass
θ^*_{op} – Operative temperature
$\theta_{comfort,u,l}$ – Temperature for upper/lower limit of comfort range

The temperature of the thermal mass is assumed equal to the heating/cooling set points if the operative temperature goes outside the thermal comfort range. This is of course also a simplification.

The simulated end temperature is used as a start temperature for the simulation of the following period.

Stage II:
The second stage is determination of the cooling set point for the current period. This set point is determined on the estimation of the end operative temperature of the current period. The simulation for the end temperature is run with the same assumptions etc. as stage I.

$$\theta^*_{set,cool} = \theta_{comfort,u} \quad IF \quad \theta^*_{op} \leq \theta_{comfort,l}$$
$$\theta^*_{set,cool} = \theta_{comfort,u} \quad IF \quad \theta^*_{op} \leq \theta_{comfort,av}$$
$$\theta^*_{set,cool} = \theta_{comfort,av} \quad IF \quad \theta^*_{op} \leq \theta_{comfort,u}$$
$$\theta^*_{set,cool} = \theta_{comfort,l} \quad IF \quad \theta^*_{op} > \theta_{comfort,u}$$

Where:

$\theta^*_{set,cool}$ – Cooling set point
$\theta_{comfort,av}$ – Average temperature for upper & lower comfort temperature

Stage III:
In stage III the needed solar energy ϕ^*_{sol} needed to reach the cooling set point is calculated. If the amount is reached or exceeded, the boundaries conditions (solar shading) are activated and they overrule the calculated value.
If the solar energy needed to reach the cooling set point is not available, there is no further action. In case of the opposite scenario the controlling strategy is activated.
The calculation of ϕ^*_{sol} is illustrated in appendix I

Stage IV:
In stage IV it is investigated if the operative temperature is inside the required interval. If this is not the case “free” heating/cooling is provided by the ventilation system. The possible amount of “free” heating/cooling that the ventilation system can provide is $H_{VE,corr}$ and is of course restricted by the physical ability of the given system.
The calculation of $H_{VE,corr}$ is illustrated in appendix I

Stage V:
Stage V calculates if the previous steps were not sufficient to keep the operative temperature inside the required interval. If this is the case a simulation is made to determine the amount of "non-free" energy necessary to get the operative temperature inside the required interval. The amount of "non-free" energy is applied and a new real start temperature is determined.

Stage VI:
The control procedure is done for the current period. Amount of energy used and corresponding temperature is saved and the same procedure (stage I-V) is complete for the following period.

The flowchart of the control algorithm is illustrated in appendix II

7 Weather

7.1 Weather forecast

A modern weather forecast is a computer-simulated model based on fluid dynamics and thermodynamics. The model is generated upon initial weather information from e.g. weather stations, satellites, water buoys, aircrafts, and ships etc. The accuracy of the weather information is highly dependent upon the sources, local weather stations etc. has a higher accuracy compared to a satellite, a satellite however is capable of covering a greater area.

The forecast model uses the information to estimate the current state of the atmosphere and the changes in the immediate future. These estimations are then constantly upgraded based upon the previous estimations in order to obtain a new forecast. Every update is called a time step and it can vary depending on the needed accuracy and range of the model.

The leading meteorological institute in Denmark DMI uses a forecast regional model HIRLAM (High Resolution Limited Area System) with adjustable resolution [54]. This model is based upon boundary conditions provided by global models. DMI uses the best global model available which is ECMWF (European Centre for Medium-Range Weather Forecasts). This model has a resolution of 16km horizontally [55]. This model is based upon global observations, which is used to generate the boundary conditions used for the regional models like illustrated in figure 7-1.

Figure 7-1 - Global to regional climate model

ECMWF is the best global model due to the fact of its enormous amount of observation and its very powerful simulation abilities. The model includes multiple parameters like movements of ocean waves and their roughness thereby estimating the wind stress and speed at ocean and land level etc.

As mentioned earlier, the ECMWF model is based upon numerous observations from multiple sources. The forecast is typical generated every 12th hour at 12 and 00 UTC (Coordinated universal time). Simulation time etc. makes the global model information available for the regional models some time subsequent. This means that the 12 UTC HIRLAM model (regional) is based on the 12 hour older 00 UTC ECMWF (global) information's etc. [55].

DMI used a model in 2011, which had a time step of 1 min and a forecast period of 72 hours [56].

7.1.1 Accuracy of the model

In general the uncertainty of a weather forecast is caused by one or more of the following five aspects [57]:

- Errors in observation/measurements of the initial conditions
- Chaotic nature of the atmosphere
- Failure in ability to understand the dynamic process of the atmosphere
- Inadequate simulation possibilities and power
- Accumulating errors from previous predictions

The global model ECMWF quantifies the uncertainty of the forecast models with EPS (Ensemble Predictions System). EPS uses the fact that every forecast contains uncertainties and even small imperfections can potentially have a huge impact on the final result, by creating a variety of 50 different forecast, all based upon slightly different initial conditions. These 50 different simulations are then compared to the original simulation based upon the initial conditions thereby estimating the uncertainty of the forecast [57].

DMI verifies their forecast by illustrating the difference between predicted and measured temperature of the highest temperature on a day in September, with an acceptable difference of 2°C. The highest temperature is a good indicator of the accuracy due to the fact that the temperature is dependent on many other factors such as type of weather, cloud cover and wind speed [58]. The accuracy is specified for three different intervals. Table 8 shows that the highest accuracy is reached for the shortest prediction interval period. It should be noticed that this illustration of accuracy is only based on highest temperature, however many other factors than the highest temperature of the day has an impact on the building performance and the indoor environment of the building. Furthermore an acceptable difference of 2°C is quite a low success criteria thereby making the likelihood of succeeding (100% accuracy) larger.
The percentage displayed in the parentheses is the accuracy for the previous 12 months.

Table 8 - Estimation of the accuracy of DMI weather forecast for September 2013

Accuracy	September 2013	Previous 12 months
Day 1	100%	96%
Day 3	90%	88%
Day 5	87%	75%

DMI has no calculations of the accuracy of the estimated solar irradiance compared to the actual irradiance. This parameter must be assumed to have a lower accuracy due to multiple influential parameters like cloud cover etc.

These assumptions regarding accuracy are identified and investigated in the following chapter 7.3. Where comparisons between forecast and actual observations are evaluated in order to determine the accuracy etc.

7.2 Weather data

The weather data used for this project is provided by DMI and constitute prognoses and observations for the entire year 2011.

7.2.1 Provided data & locations

The provided weather and forecast data from DMI is for slightly different locations. The following three datasets were provided:

- Forecast dataset. Prognoses [P]
- Observation dataset from Sjælsmark. Actual weather measurements [O]
- Gridded observation point. Interpolated values [G]

Forecast dataset contains data for one year, with four daily runs/updates (a new each 6 hour) up to +54 hours in 1-hour intervals, for the parameters solar radiation (global radiation) [W/m²] and temperature [°C].

Regarding the solar irradiation in the forecast dataset, it can be noticed that at 12 run (applies also for 06 and 18 in summer) the irradiance is very low at +00 timestep. This is because the value at e.g. +01 meaning 13.00, is the cumulative irradiance between 12 and 13. The projection at 12 does not have an accumulation from 11-12 hours, it has only a sampling period of a few minutes and therefore the value will be very small +00.

Observation dataset is hourly values measured at Sjælsmark, for the parameters solar radiation [W/m²] and temperature [°C].

In the dataset 286 hours of solar irradiance and 218 hours of temperature was not registered. The majority of hours were isolated cases where the missing values could be interpolated. However an entire period from 16/7 at 18:00 – 18/7 at 13:00 as well as 22/7 at 08:00 – 25/7 at 08:00 is missing, thereby making interpolation impossible. The missing values were therefore replaced by the gridded values, which means that the values at most vary on the decimal from the original observation value. For solar radiation measurements 3.3% of data was missing and for temperature it was 2.5%.
The most maximum values from 2011 is listed in table 9.
The Structure of the dataset is listed in appendix IV

Table 9 - Extreme measured values of 2011

Max. solar irradiation 16/6	**kl:12:00**	**898 [W/m²]**
Max. temperature 6/6	**kl:17:00**	**26.3 [°C]**
Min. temperature 27/1	**kl:07:00**	**-11.3 [°C]**

The gridded observation dataset contains interpolated observations data to a point close to forecast point. The values are interpolated from the original observation dataset. Due to the relatively small distance between the weather station and the gridded point, values vary at most on the decimal making the gridded dataset and the observation dataset almost identical. Luckily they did not contain any errors within the same hour therefore by combining the two sets, a full dataset of observations from 2011 could be achieved. For solar radiation measurements 0.4% of data was missing and for temperature it was 0.4%.

Figure 7-2 illustrates by means of Google Earth the different locations of the three different points. Furthermore table 10 lists the distances between the three points in order to give an impression of the layout.

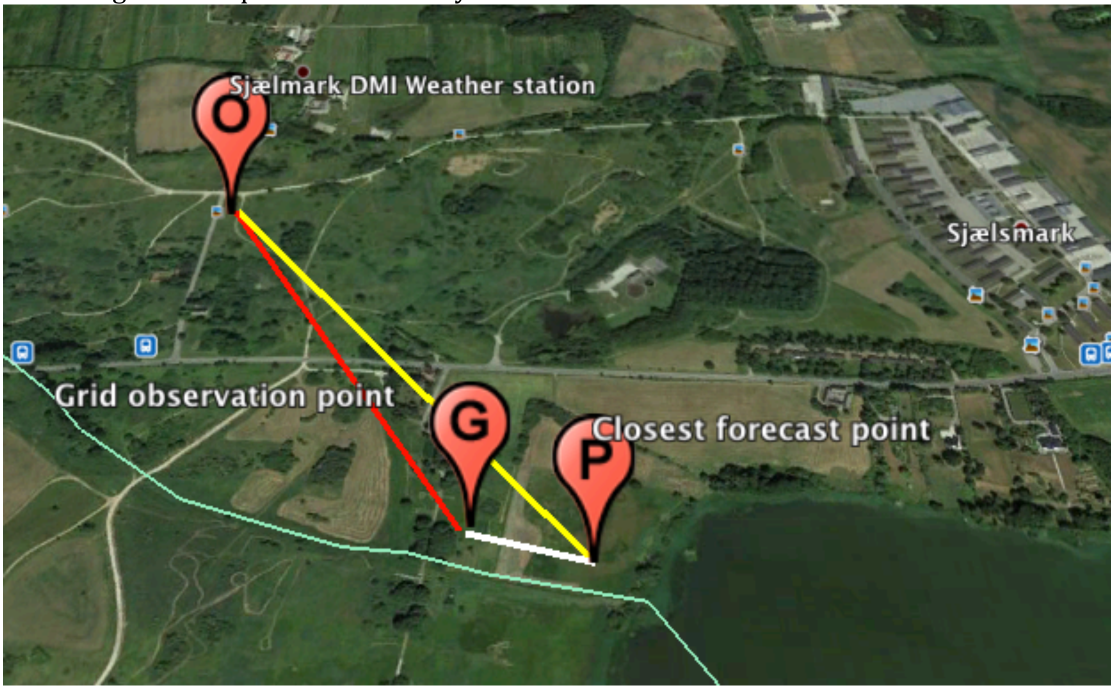

Figure 7-2 - Locations of weather stations etc.

Table 10 - Distances between stations

	Distance [m]
O-G	675
O-P	801
G-P	160

The distance between the three point causes an uncertainty however the distances are all below 1 km and all points are at the same level above the sea-level, thereby making the uncertainty associated with the distance minimal almost negligible. However an ideal situation would be that all three points were located at exactly the same location. The uncertainty is of course closely related to the distance between the forecast point and the placement of the house. The further the distance the greater the uncertainty, especially regarding micro-climate changes like a local temperature difference due to a placement at a lower level than the surrounding grounds or a large difference in solar irradiance due to cloud formation etc.

7.3 Accuracy of the forecast

This section addresses the accuracy of the weather forecast in relation to the measured weather conditions. The parameters: external temperature and global solar radiation are examined individually and the forecast data is compared with the measured data in order to determine possible differences and uncertainties.

7.3.1 External temperature analysis

In order to obtain the most precise forecast values as possible, only the first six hours of each forecast is used in the comparison with the measured values.

The difference is defined as:

$$Difference = T_{Forecast} - T_{Measured}$$

Resulting in a positive outcome equaling an overestimation and the opposite an underestimation.

Figure 7-3 illustrates the temperature difference for the entire 2011:

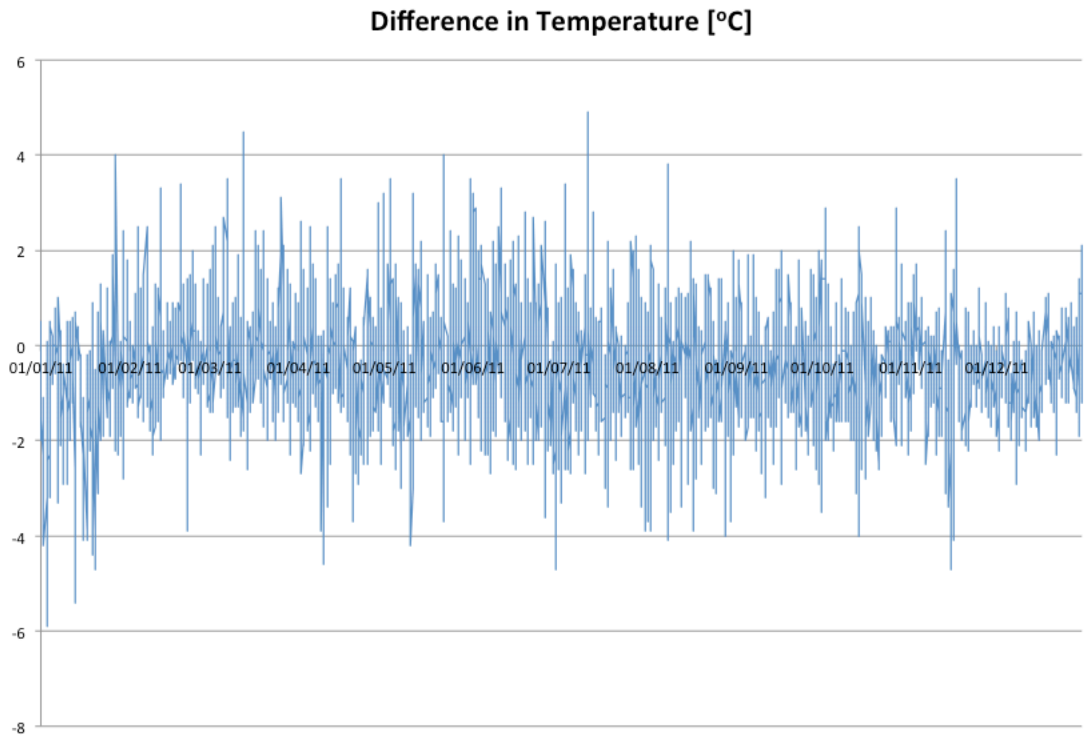

Figure 7-3 - Temperature difference for 2011

Figure 7-3 clearly indicates that the majority of difference is between ±2˚C, it also shows that January contains the biggest underestimation of nearly 6˚C and July the biggest overestimation of approximately 5˚C.

To obtain a better statistical understanding of the comparison, a Gaussian distribution of number of occurrences was constructed.

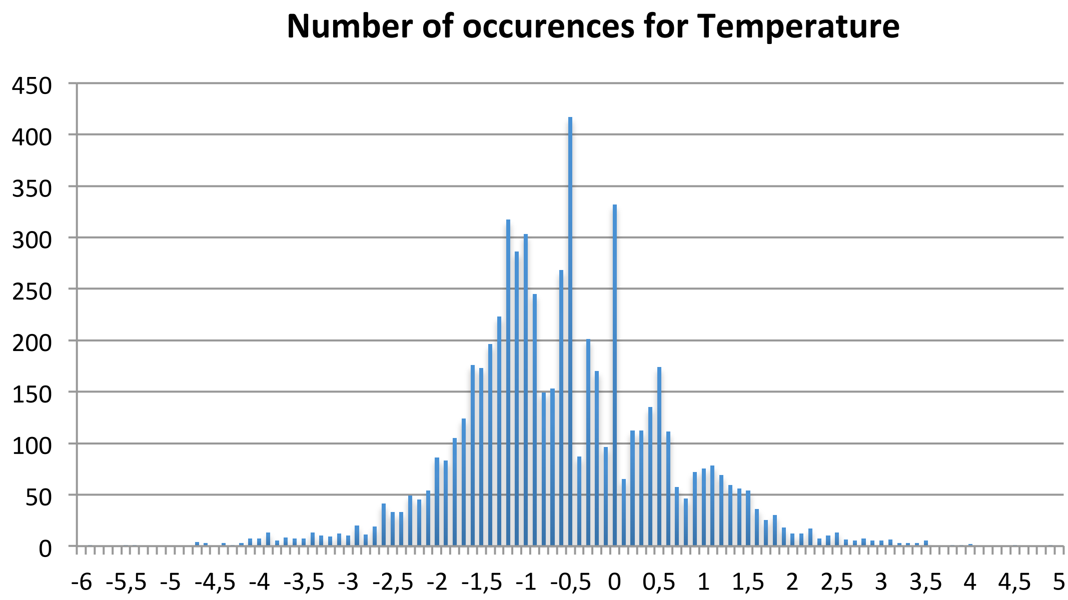

Figure 7-4 - Normal distribution of temperature occurrences

Figure 7-4 clearly illustrates tendencies to a normal distribution, even though the distribution is not perfectly normally distributed.

The occurrences has a mean value μ = -0.5˚C and standard deviation σ = 1˚C meaning that 95% of all occurrences is within -0.5˚C ± 2*1˚C. In short this means that 95% of all the forecast prediction is at most [-2.5 – 1.5˚C] divergent from the actual measured temperature.

Furthermore it should be noticed that the mean value is -0.5˚C meaning that the forecast in general is underestimating the temperature, ideally the mean value should be 0˚C. In the relation to collection of weather data it has previously been discussed whether these were influenced by, for example, heat from the surrounding buildings, cities etc. However, this is not the case here as the measuring station in Sjælsmark is not located near anything that could affect temperature measurements.

A monthly overview of accuracy is illustrated in table 11. It can be seen that all months in general are slightly underestimated which also was the case for the entire year. Furthermore it can be seen that Feb, Mar, May and Jun have an average difference close to zero. In this context it should be emphasized that it is the large deviation that has a crucial effect. A summation of monthly weather forecast with an average deviation close to 0 could still be very imprecise. The success criteria for the accuracy are dependent on the amount of deviation as well as the magnitude of the deviations.

Table 11 - Monthly Max, Min, Avg. for the temperature

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	4	3,4	4,5	3,5	4	3,3	4,9	3,8	2	2,9	3,5	2,1
Min	-5,9	-3,9	-2,6	-4,6	-4,2	-4,7	-3,9	-4,1	-3,2	-4	-4,7	-2,9
Avg	-0,9	-0,2	-0,1	-0,6	-0,2	-0,2	-0,5	-0,6	-0,6	-0,5	-0,6	-0,5

It was not possible to find any similar research results regarding the accuracy of forecast models for the last couple of years and with similar location (Denmark), and a comparison to older studies would not be usable due to the progression within this area.

A comparison between the obtained results and the verification which DMI has done regarding the accuracy of their own model reveals that DMI claimed to have a 100% accuracy within 12 hour predictions, with an acceptable difference of ± 2˚C [58]. These investigations showed a 95% accuracy within the interval of [-2.5 to 1.5˚C], which is slightly more inaccurate compared to what DMI predicts. It should however be mentioned that DMI's verification is done for specific days, whereas the comparison in this investigation is done for the entire year. Finally it should be noticed that DMI is biased regarding verification of their own model therefore the verification should be assessed with some reservation.

7.3.2 Global solar radiation analysis

The comparison between the forecast and measured solar radiation is like the comparison between the external temperatures done for values of the first six hours of every forecast and the difference is likewise calculated as the forecast value minus the measured value.

Figure 7-5 illustrates the difference for the entirety of 2011. It is evident that the amount of overestimations is fare greater compared to underestimations. Basically only underestimations appear during the summer months whereas the overestimations are present at all months.

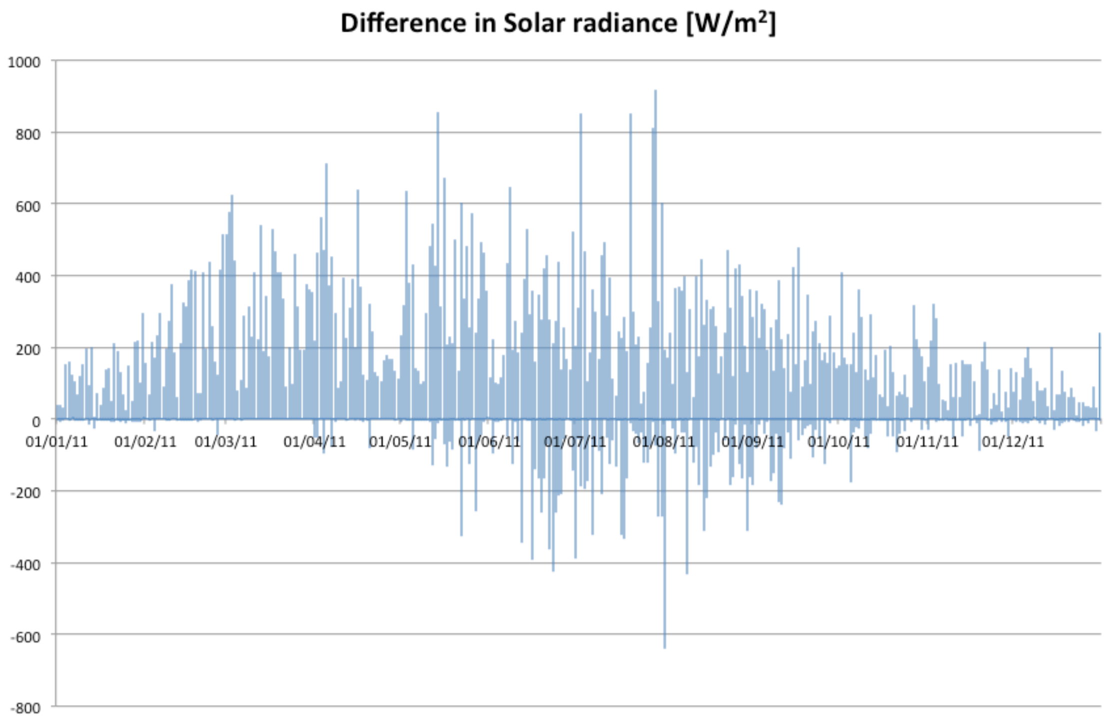

Figure 7-5 – Solar irradiance difference for 2011

Figure 7-6 illustrates tendencies to a normal distribution, even though the distribution skewed towards overestimation.

The occurrences have a mean value μ = 39 W/m² and standard deviation σ = 95 W/m² meaning that 95% of all occurrences are within -39 ± 95 W/m². However this representation is highly influenced by the periods without sun (night time), where accuracy off course is 100% during several hours each day. The picture is somewhat different if only hours with actual solar radiation are examined which figure 7-5 also indicates.

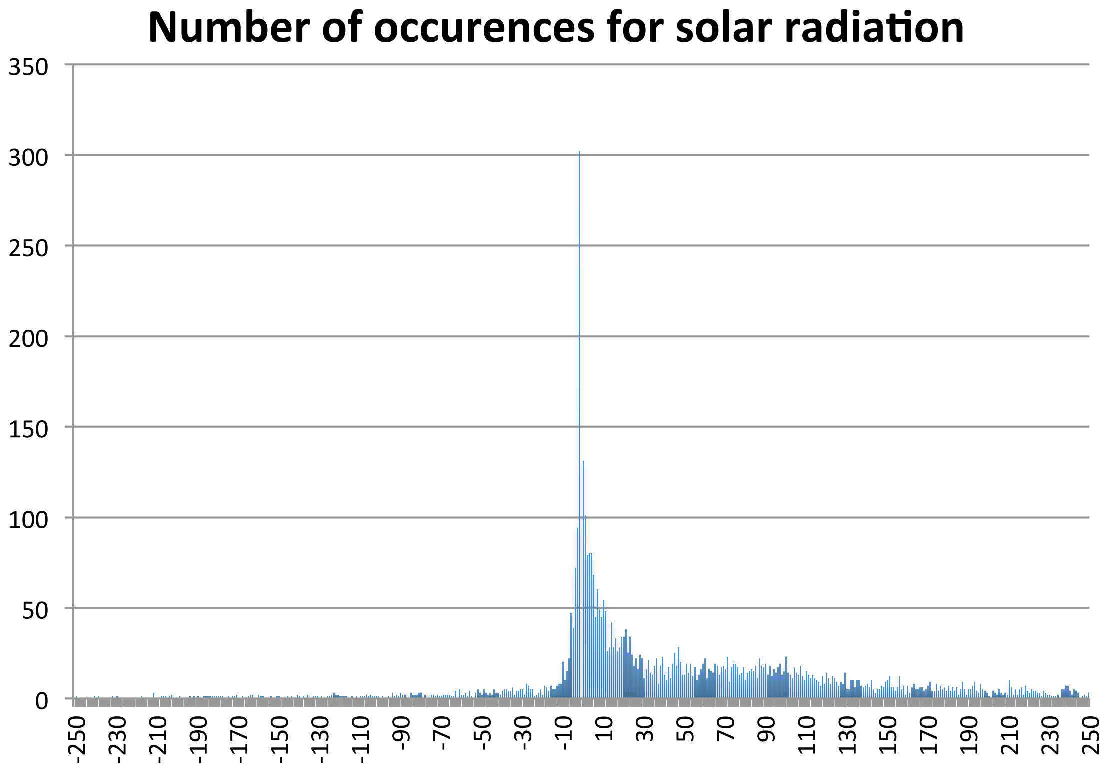

Figure 7-6 - Normal distribution of solar irradiance occurrences

A monthly overview of accuracy is illustrated in table 12. It can be seen that all months in general are slightly overestimated, and especially the period from April to September show large max/min deviations.

Table 12 - Monthly Max, Min, Avg for the solar radiation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	295	515	622	712	855	646	917	468	478	406	318	238
Min	-26	-43	-1	-95	-325	-425	-386	-637	-238	-174	-87	-31
Avg	16	38	64	60	71	47	50	37	32	23	14	8

DMI has no validation for the accuracy of their forecast regarding solar radiation. Furthermore it was not possible to find any Danish studies from this decade regarding accuracy of solar radiation in weather forecasts.

7.3.3 Inaccuracy of the forecast

The inaccuracy of a forecast could be caused by a number of sources, as explained in section 7.1.1.

The days with the largest deviations will be investigated in order to illustrate some of the sources that lead to inaccurate forecasts.

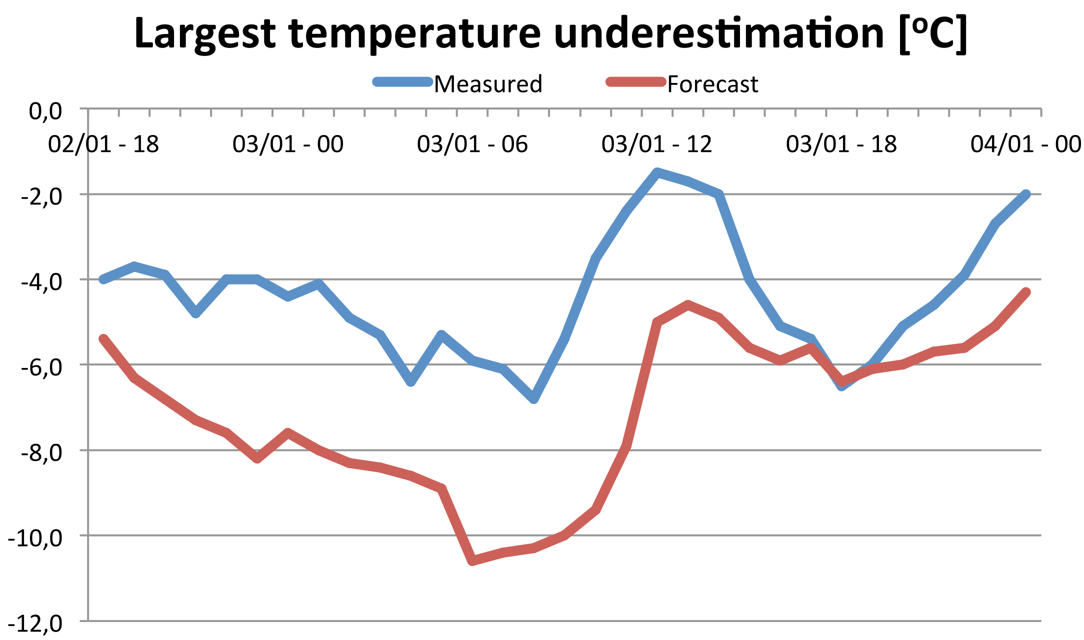

Figure 7-7 - Largest temperature underestimations

Figure 7-7 shows the largest temperature underestimation. It shows that the forecast prediction is based on underestimated values. It is also clear that both the measured and the predicted temperature profile follow the same development however the forecast prediction is constantly a couple degrees below the measured values. It is also interesting that measurements and predicted values are equal at 18:00 03/01 where the forecast is updated, however the forecast continues to underestimate the following development. This could indicate deficiencies in the model or analysis errors.

Figure 7-8 reveals a different and more precise picture, here it is quite clear that the forecast model is fairly accurate however the forecast model is not able to predict, what must be assumed is a local temperature drop of almost six degrees. This drop leads to the largest temperature overestimation of the entire year.

It must however be assumed that a temperature drop of this magnitude could very well indicate a measurement error or an external influence like a thunderstorm or similar, due to the development of a drop and following spike of around 6 degrees within a couple of hours.

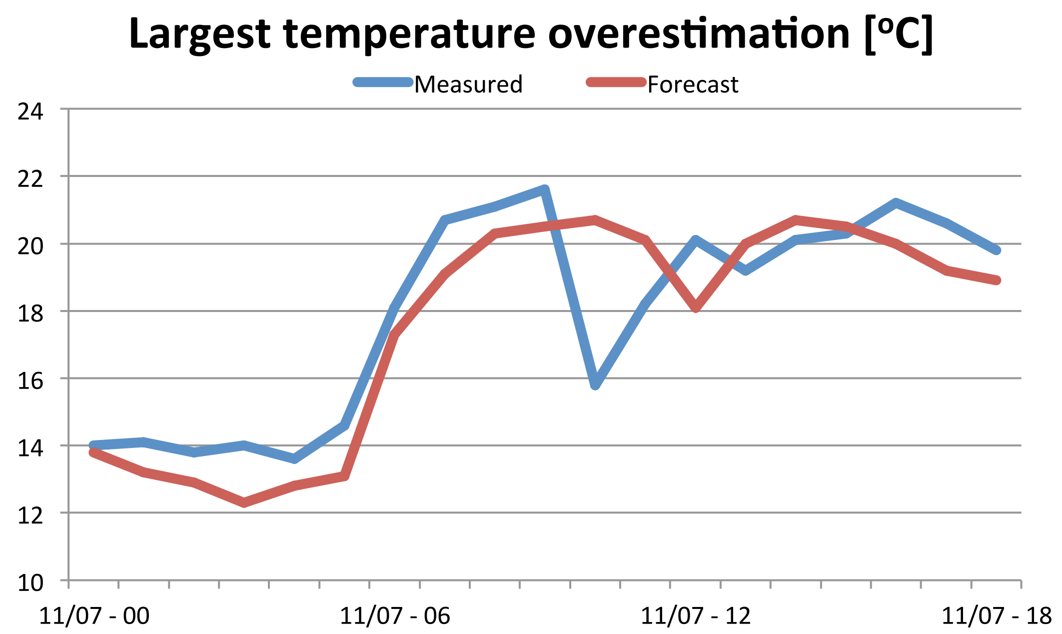

Figure 7-8 - Largest temperature overestimations

Figure 7-9 illustrates a forecast model, which due to the fact that it is primarily based upon its previous calculated value, accumulates an error of some kind and predicts a wrong development. The accumulated error is then corrected with the next forecast simulation (12:00) however the model itself must contain some kind of analysis error of the given data or deficiencies in its formulation, because the overestimated development continues. It could also indicate that the initial information upon which the model predictions are based are inaccurate e.g. the model predicts clear sky the entire day except around noon, but in reality it is cloudy most of the day at that exact spot etc.

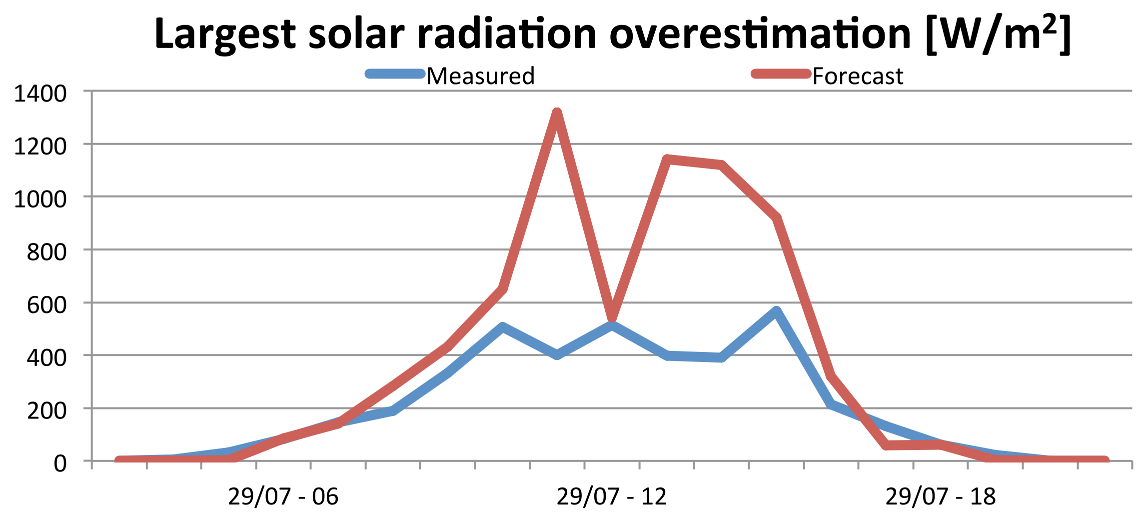

Figure 7-9 – Largest solar radiation overestimation

Figure 7-10 shows the largest underestimation of the year, the most obvious reason for this underestimation must be that the forecast model predicts a cloudy period right after noon on the 1. October, however the sky stays clear.

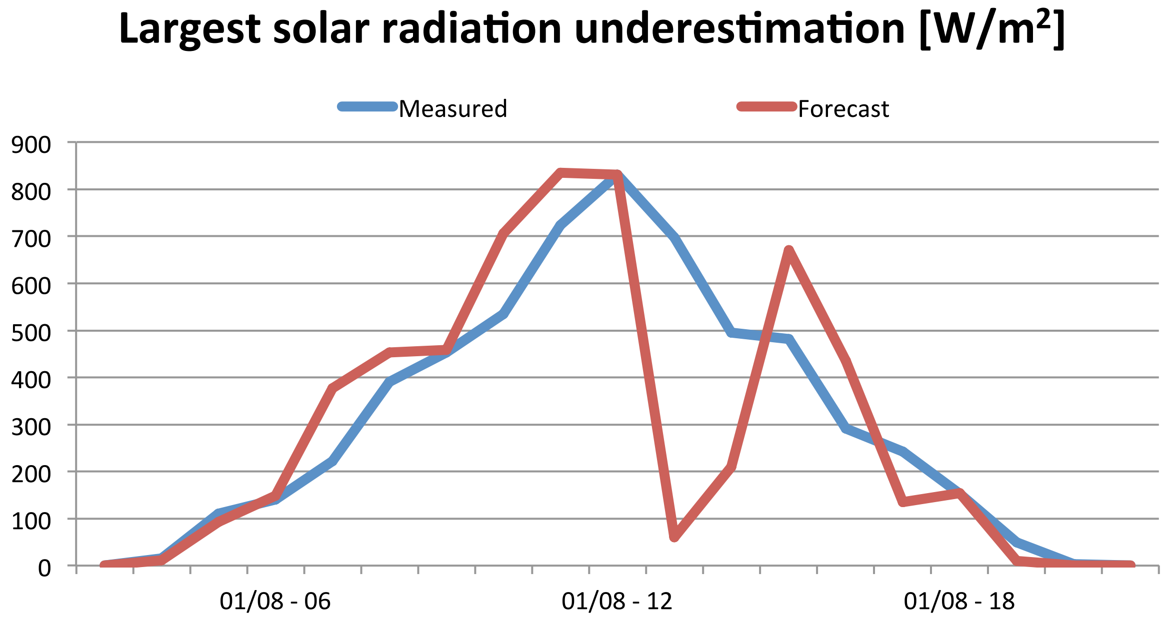

Figure 7-10 - Largest solar radiation underestimation

All forecast today contains uncertainties, which also will be the case for the near future. Nevertheless some of the uncertainties might be minimized if certain aspects are improved.

The prior sections have illustrated certain uncertainties and the reasons for these. The most dominant fact discovered is that some of the inaccuracies might be eliminated if the forecast is simulated/updated more frequently, thereby ensuring that accumulated errors are minimized.

Another aspect could be to intensify the measure points delivering the initial data which the forecast model is based upon, this could, most likely improve the models ability to predict local weather changes.

7.5 Implementing of weather data into WinDesign

As described in chapter 5 the present method in WinDesign is a weather data set divided into monthly and hourly values of exterior temperature and solar radiation. The weather data contains hourly values of the following parameters; external temperature (°C), direct, diffuse and global solar radiation (W/m^2) as well as global illuminance (lx). Furthermore monthly average values are calculated based upon the hourly values.

The file is constructed with no leap resulting in 8760 hours a year etc. The setup is illustrated in table 13.

Besides the weather data the simulation tool also needs geographical information of the building in order to calculate the solar radiation on the windows:

- Latitude [Φ]
- Longitude [lon]
- Local time standard meridian [lsm]
- Albedo number [ρ]

Table 13 - Weather data file (Hourly values)

Time	Month	Day	Hour	External air temperature	Solar Radiation			Solar illuminance		
					Global	Diffuse	Direct	Global	Diffuse	Direct
[1h-8760h]	[1-12]	[1-31]	[1-24]	[°C]	W/m²	W/m²	W/m²	lx	lx	lx
1	1	1	1	2,8	0	0	0	0	0	0
2	1	1	2	2,6	0	0	0	0	0	0
3	1	1	3	2,6	0	0	0	0	0	0
4	1	1	4	2,8	0	0	0	0	0	0
5	1	1	5	2,9	0	0	0	0	0	0
6	1	1	6	3,2	0	0	0	0	0	0
7	1	1	7	2,9	0	0	0	0	0	0
8	1	1	8	2,3	0	0	0	0	0	0
9	1	1	9	2,2	2	2	0	251	0	0
10	1	1	10	3,2	43	29	190	4441	0	400
11	1	1	11	3,5	57	50	48	6269	6300	3400
12	1	1	12	4,0	21	20	5	2346	7000	5800
13	1	1	13	4,9	34	34	0	3995	18500	5300
14	1	1	14	6,0	22	21	6	2455	9200	4600
15	1	1	15	6,4	22	19	28	2524	0	2400
16	1	1	16	7,1	8	7	27	905	0	100

7.5.1 The setup of the predicted weather file

All weather data received from DMI are in *Universal time, Coordinated* (UTC) as all other meteorological data. However when weather data is used in building simulation tools the time needs to be local, without accounting for summer time etc.

The received data is therefore converted into danish time, the conversion results in the values of all the parameters for the first hour are missing. In order to compensate for this, the values for the next hour was used, which is at 01:00 on 1st of January.

As described in chapter 7.2.1 the forecast file received from DMI contained exterior temperature and global solar irradiation. The additional solar parameters are estimated based on the global irradiation by means of the method described in [59]. The calculation procedure is illustrated in appendix V and follows the approach described in [60].

There can be a lot of different ways to approach the construction of the predictive weather file. In relation to WinDesign an obvious solution is to create a setup as follows:

The forecast is calculated four times a day at 00:00, 06:00, 12:00, and 18:00. The prognosis is for the following 54 hours, equaling 55 data sets in each prediction from hour 0 to hour 54. For an entire year that equals 80300 data sets.

The most simple way is to create a new sheet with the data and let the simulation tool read the newest sheet every 6 hour. Another way for the simulation tool to easily be able to process this data is to organize it in a 8760x1460 matrix (hours per year) x (4 prognoses per day each day of the year), and then update the sheet every 6 hour. The setup is illustrated in figure 7-11.

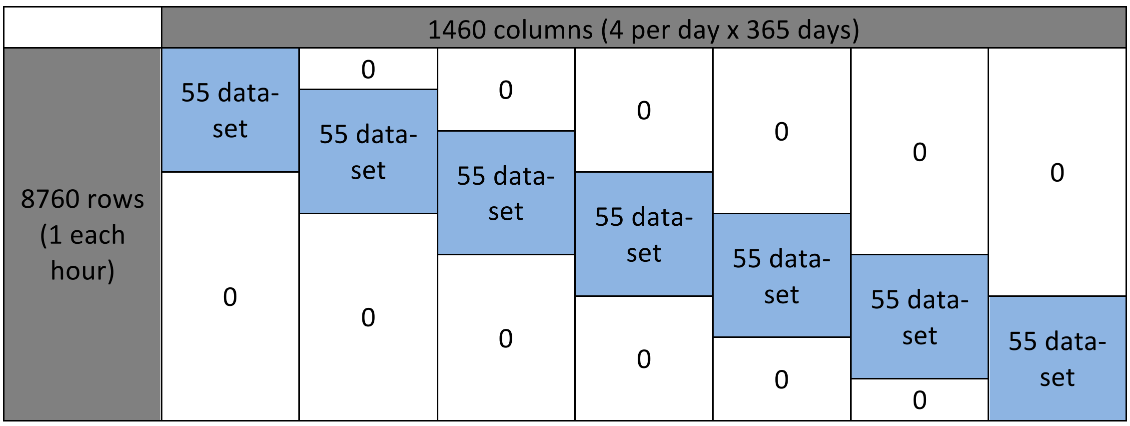

Figure 7-11 - Possible setup of prognoses file

The forecast data delivered:

- Exterior temperature
- Global radiation

Data automatic calculated based upon values above:

- Direct radiation
- Diffuse radiation
- Illuminance levels

- Based upon the hourly values the monthly average values are determined.

7.5.2 MPC in relation to the weather forecast

The simulation tool is developed to handle the scenario of MPC based on a weather forecast of the following 54 hours and is updated ever sixth hour.

The process for the MPC is as following:

i. The weather data is updated every six hours, based on the data received from DMI the remaining weather data is calculated and implemented in the weather data sheet.
ii. A simulation is run and a control strategy is determined for the remainder of the current period and the following period.
iii. This process is repeated every time the weather data is updated.

This setup is kept at a very simple level, which has its advantages however it also includes obvious disadvantages. These disadvantages and improvement possibilities are subject for further development and will be discussed in chapter 9.

At this point the process of implementing the weather data into the program weather file is not fully automated. A few manual steps are necessary in order for the weather file to be updated. The simulation tool is simply not able to automatically open and extract and paste the data from a potential DMI weather data file into its own excel weather data file.

7.6 Simulation tool summary

A summary of the simulation process is illustrated in figure 7-12.

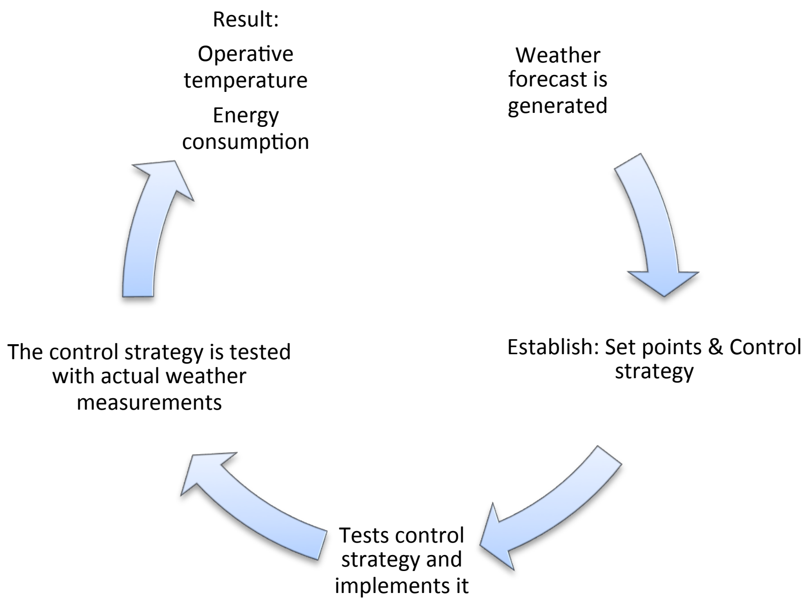

Figure 7-12 – The simulation process

8 Results

In order to evaluate the performance of the new predictive control algorithm a comparison between the original control strategy and the new PC is made.

Both simulations are done for the same low-energy building with the same conditions except weather.

The original control is a regular control strategy similar to the one the original version of WD uses. It represents how an ordinary control strategy for a house is. It is based on the weather file with actual measurements. The original control only “reacts” to present situations, it does not account for future development nor does it calculate any predictive control.

The new PC is the previous explained control strategy, where the forecast is used to predict a control strategy. This strategy is then implemented on the house and thereby tested in relation to the actual weather measurements.

Since the concept is being tested on a house the same initial settings are used for the in/out of use period for the building.

The primary focus of this concept is its ability to document and register deviations, secondly, if possible, to provide a more energy efficient control of a building while maintaining or improving the indoor environment.

This section will mainly focus on the energy and environmental part, whereas part II will address the primary focus point of the concept.

The results of the comparison are illustrated in table 14 below:

Table 14 - Comparison between original control & new PC

	Original Control	New predictive control
Room heating demand [kWh/m² year]	10.1	10.9
Room cooling demand [kWh/m² year]	1.2	0
Ventilation demand [kWh/m² year]	19	18.2
Hours of overheating (above 26°C) [hours/year]	58	31
Operative temperature within class II	100%	100%
Electrical light demand [kWh/m² year]	7.9	7.9
Daylight factor in point [%]	5	5

The calculation results are listed in appendix VII.

8.1 Energy consumption

The predictive control only delivered an energy saving of 4% in kwh/m^2 year. This energy saving is primarily achieved through preventive control strategy. The original control only “reacts” to present situations, it does not account for future development nor does it calculate any predictive control etc.

8.1.1 Heating

It can be seen from table 14 that the MPC strategy has a higher heating demand compared to the original control strategy. This is due to the fact that WD is designed for hourly calculations.

A typical scenario causing a large heating demand would be that the MPC determines that the operative temperature exceeds the required thermal comfort range, resulting in a cooling strategy of shading and venting. In the case where the solar shading and natural ventilation is not enough to prevent overheating, mechanical ventilation will be activated for an entire hour, due to the hourly calculations. This will in some rare cases result in the operative temperature going below the required thermal comfort range thereby creating a heating demand.

8.1.2 Cooling

The original control strategy has a cooling demand due to scenarios where the mechanical ventilation is not sufficient to keep the operative temperature within the required thermal range for a longer period or not sufficient to prevent severe overheating (>27°C).

Overheating hours could be completely prevented by mechanical cooling, however this would lead to a higher energy consumption, which is not preferable since the amount of overheating hours do not exceed the required limit.

Table 14 also shows that the mechanical cooling demand is eliminated for the MPC case due to preventive controlling of solar shading and natural ventilation.

8.1.3 Ventilation

Table 14 shows that the MPC has a lower energy consumption regarding ventilation. This is due to preventive control and additional utilization of natural ventilation compared to the original control strategy. The amount of ventilation hours is higher for the MPC case however a large amount of those hours are natural ventilation providing preventive cooling etc. at a much lower energy consumption.

8.1.4 Artificial lighting

The artificial lighting demand is the same for the two cases, which is mainly due to the simplified calculation of the demand.

It can be assumed that if the occupant behavior was modeled more comprehensive in the simulations an increased artificial lighting demand would be revealed due to use of solar shading during occupied hours.

8.2 Indoor environment

8.2.1 Operative temperature

The average operative temperature for the original control is 21.8 C while for the new PC it is 21.9°C throughout the year.

In general the MPC provides a better indoor environment regarding operative temperature. This should probably be seen as a result of preventive control, which anticipates the course of events thereby in many cases is able to smoothen out the development.

Overheating
Common for both control principles is that the operative temperature only exceeds the upper thermal comfort limit in a part per thousand and only during the summer months. For the year 2011 only 2 hours with exterior temperature just above 26 degrees was registered.

The MPC strategy has a lower amount of overheating hours during the summer due to preventive control strategy ensuring a lower starting point whenever high temperature periods occur. Preventive solar shading and natural ventilation are capable of ensuring a sufficient low operative temperature before a "hot " period occurs. Thereby ensuring that overheating does not occur in the majority of the cases, whereas when the original control is used it is simply not possible to prevent overheating due to a to high temperature starting point at the beginning of a "hot" period.

Reason for overheating hours with MPC:

In general the forecast predicts a lower exterior temperature than measured and a higher solar irradiance than measured.

This results in the MPC underestimates the predicted max operative temperature for the period, which affects the cooling set point. E.g. if the max predicted operative temperature for the period is >26°C, the cooling set point will be 20°C. However if the max predicted operative temperature is just below 26°C, e.g. 25.8°C, the cooling set point will be 23°C instead.

This leads to the following scenario: weather forecast predicts too low exterior temperature and solar irradiation for the period. This leads to a low predicted operative temperature, which results in a too high set point for the period. The building is then not prepared for the exterior temperature and solar irradiation leading to hours above comfort temperature.

Temperature below comfort limit:
Temperature below the comfort range does almost not occur due to the ideal heating system, which always provides the needed heating, combined with the constant regulated heating set point.

8.3 Weather predictions vs. actual conditions

In the following section the four examples where the forecast deviated the most from the actual weather measurements will be analyzed in order to determine the impact the inaccuracy had on the operative temperature. The values are listed in appendix VIII.

8.3.1 Exterior temperature

Forecast < Actual:
Temperature difference: -5.9°C on 3. January 10am. The difference of solar irradiance is 30W/m².

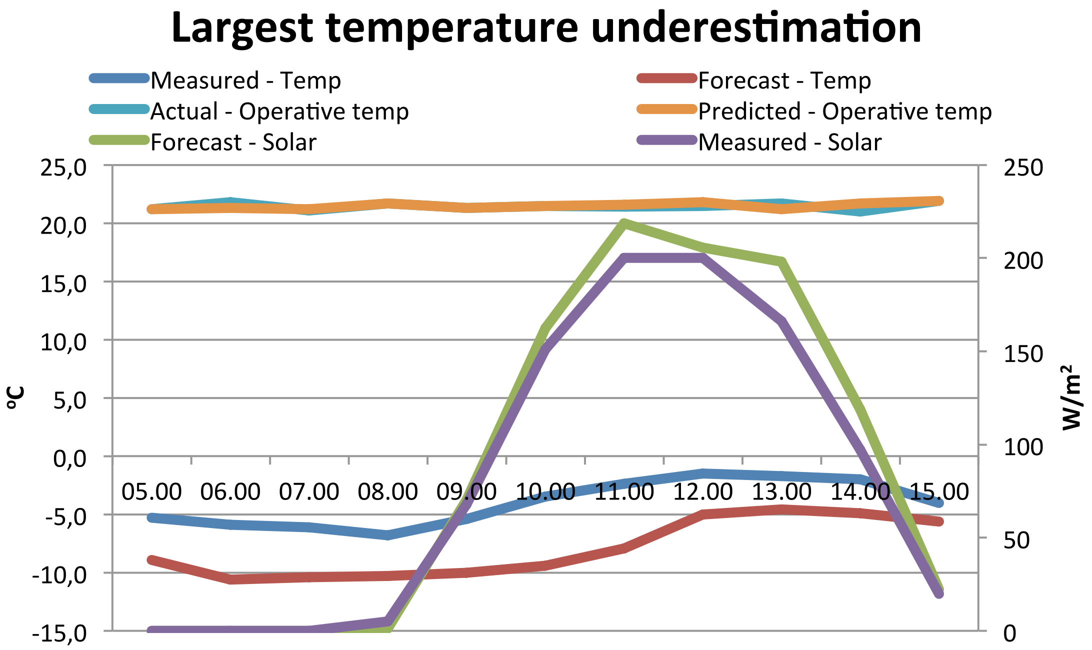

Figure 8-1 - Largest exterior temperature underestimation

Figure 8-1 clearly illustrates that a too low predicted exterior temperature during the winter does not affect the operative temperature nor the energy consumption due to a cooling set point of 26°C. The estimated operative temperature was less than 23°C for the entire period.

Figure 8-1 also shows that a deviation between the predicted and actual exterior temperature does not necessary mean that it affects the operative temperature.

Forecast > Actual:
Temperature difference: 4.9°C on 11. July 10am. The difference of solar irradiance is 300 W/m²

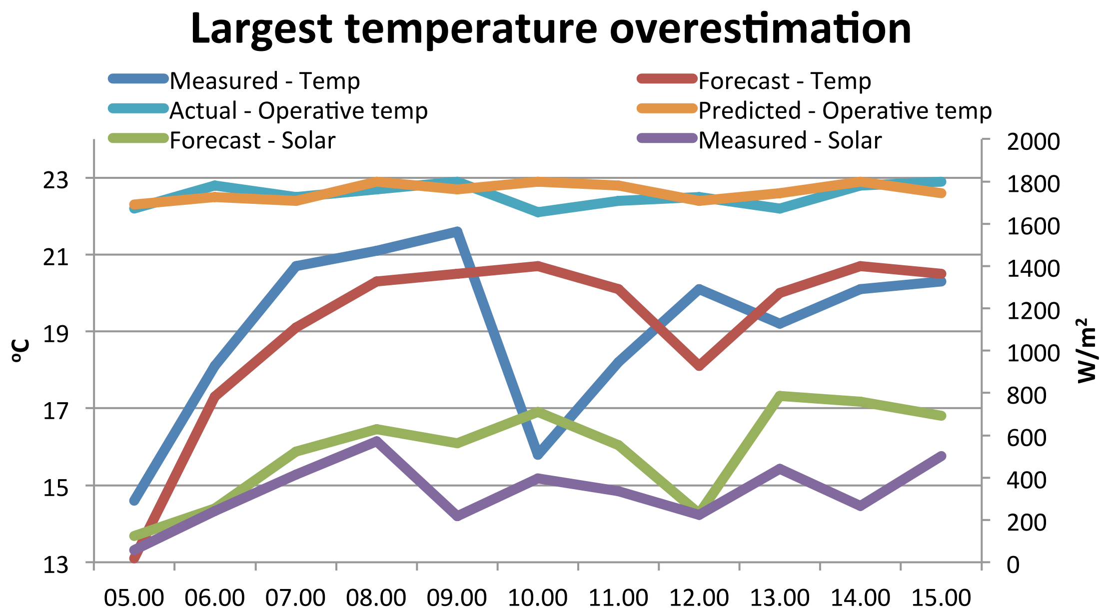

Figure 8-2 - Largest exterior temperature overestimation

Figure 8-2 also shows that a large difference between predicted and actual exterior temperature does not have a large effect on the operative temperature during the summer, due to a cooling set-point of 26°C. Had the estimated operative temperature been above 23°C, the cooling set point would have been 23°C which would have changed the scenario and thereby the control strategy.

8.3.2 Solar irradiation

Forecast < Actual:
Solar irradiance difference: -637 W/m² on 1. August 13pm. The temperature difference of is 3.1°C.

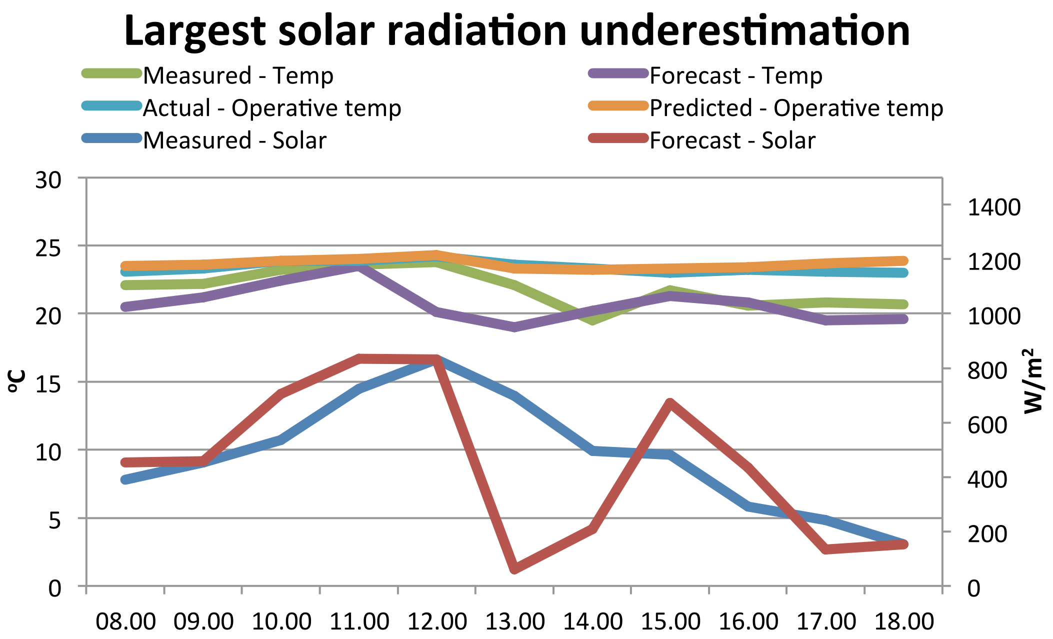

Figure 8-3 - Largest solar irradiance underestimation

Figure 8-3 illustrates solar irradiance and temperature. In both of the simulations the predicted maximum operative temperature is above 26°C, equaling a cooling set point of 20°C. This results in the fact that the difference of the solar gains and temperature does not affect the operative temperature because the set points and strategy were the same.

Despite a large difference between both predicted solar gains and exterior temperature both simulations scenarios are capable of maintaining an acceptable operative temperature without mechanical cooling.

Forecast > Actual:
Solar irradiance difference: 917 W/m² on 29. July 11am. The temperature difference is 2.5°C.

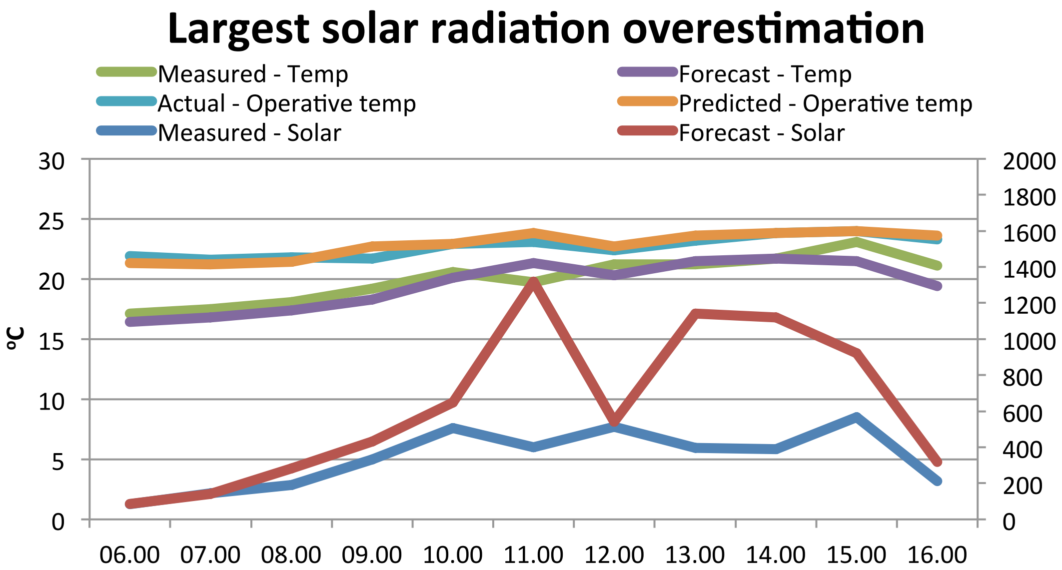

Figure 8-4 - Largest solar irradiance overestimation

Figure 8-4 shows the similar results as the previous scenarios. Despite a deviation in both temperature and solar irradiation both simulated operative temperatures are within the interval 23-26°C equaling the same control strategy. This means that the control strategy predicted based on the forecast are also correct for the actual conditions.

8.3.3 Conclusion on temperature and solar difference

The largest deviations between predicted and actual values typically occur around noon etc. when the forecast is updated and therefore the predicted values are furthest away from the initial start prediction.

From the investigation it can be concluded that it is not necessarily extreme deviations between predicted and actual weather conditions that have the largest impact on the indoor environment and energy consumption. It seems like major differences over short periods do not have a large effect on the overall performance.

The investigation also showed indications of a modern low-energy building is somewhat "self-regulating" due to the buffer of the thermal mass of the building and the internal loads etc. E.g. if the temperature in the building is somewhat higher than predicted it also has a higher thermal loss on the other hand if the temperature in the building is lower than predicted it results in a better exploitation of the internal loads etc. than predicted.

However scenarios where the predicted operative temperature was within the one cooling set point interval but the actual operative temperature was outside that interval it would result in a wrong control strategy due to a wrong cooling set point.

An example of the above stated, is if the predicted control strategy is based on a simulation where the operative temperature is between 23-26°C equaling a cooling set point of 23°C. However the actual operative temperature went above 26°C, resulting in a needed cooling set point of 20°C. This results in hours of overheating due to a strategy that did not account for the temperature rise.

9 Discussion

As previously mentioned this stage of the MPC concept is not fully automated, in order to make it work certain aspects need to be completed manually. At this point the simulation is running automatically however loading of weather data and extraction of some of the output data needs to be done manually which requires insight into the process. This situation is of course not optimal however this part of the process was not the primary focus area because of the time consuming factor and the fact that results can be obtained without it.

The simulation results showed the MPC strategy had a higher energy consumption for heating but a lower for ventilation and cooling as well as a slightly better indoor environment. These findings are highly comparable with the findings of [17] where an energy saving of 7% was achieved by a MPC strategy compared to an original control strategy. In this study it was also found that the MPC had an increased energy consumption for heating but a decreased consumption for ventilation as well as less overheating hours.

9.1 Future development & optimization possibilities

This section will clarify some of the limitations of the current simulation model and highlight further possible improvements in order to develop a more functional and accurate model.

9.1.1 Simulation setup/structure

The results revealed some issues regarding the setup/structure of the simulation. A critical error detected was due to the fact that the simulation is hourly based. It would in some cases cause an increased heating demand as a result of a full hour ventilation the previous hour. The obvious solution to this error would be to alternate the algorithm to calculate exactly how much ventilation is needed in order to bring the operative temperature down to a desired value and then only embed that exact amount instead of a full hour.

9.1.2 Simulations time

The complexity of the algorithm and structure of Excel leads to a prolonged simulation time. Depending on the CPU *(central processing unit)* the simulation time takes from 10 minutes to several hours (for a year of simulation results). The simulation time can be improved a bit by splitting the program into smaller bits and calculate step 1-3 and the intelligent control separately, however it would seem like the boundaries of what Excel is capable of is reached and it should probably be investigated which platform would be best suited for further development of the concept.

9.1.3 Simulation platform

The platform of the simulation tool needs to be able to execute simulations continuously in order to update datasets and values ongoing in relation to the development.
In relation to the current state of the simulation tool, aspects like better clarity and illustration of results as well as ease of use could be much improved, especially the usability.

A platform with a different structure might also provide possibilities of calculating multiple scenarios simultaneously and thereby be able to predict the most likely scenarios as well as the uncertainty factor of each scenario.

9.1.4 Ongoing process

In order for the simulation tool to be more functional it needs to be developed into a tool that can administrate the ongoing process that CC is. The simulation tool needs to be able to automatically update dataset and values and simulate continuously. At this stage some of these processes need to be done manually, which requires personnel with the necessary knowledge to operate the model. This aspect needs to be automated in order for the simulation tool to be functional for CC.

At this current state if the concept was to be applied to an actual building it would require personnel to implement and extract information as well as start/stop the process, several times daily.

An associated aspect is the issue of communication between the model and installations in relation to implementing the simulated strategy in the actual building as well as registration of the performed control and the resulting indoor environment for documentation etc.

These aspects will not be investigated in this project however they are very important in order to obtain holistic view and thereby develop a fully functioning concept.

9.1.5 Minimizing the source of error from the weather data (short-term optimization):

Chapter 7 clearly illustrates that despite the very advanced weather simulation models available today, weather forecasts contain uncertainties and errors. These uncertainties can potentially lead to increased energy consumption due to a control strategy based on an imprecise forecast.

A solution to this problem could be to measure the weather data locally at the building. By measuring exterior and solar radiation locally it is possible to feed the simulation tool with accurate data.

The concept could then be, given the scenario e.g. that the forecast predicts something and the local measurements states that the forecast is wrong, that a new simulation is done for the close forthcoming period.

Concept:

- The simulation tool determined the control strategy based on the delivered forecast but adjust relative to local measurements.

The GPS:

- The control strategy is determined based on the delivered forecast for a foreseeable future e.g. the following 48 hours (the final destination).

The Road:

- The overall control strategy is adjusted based on local measurements for the following 6-12 hours (keeping the car on the road).

This improvement of the concept could potentially improve the overall performance of the simulation tool and thereby the building, by ensuring that the control strategy delivers the required indoor thermal environment at any given time. But that it is also able to account for the current and further development and determine the optimal strategy accordingly.

9.1.6 The division of length of simulation period:

In order for the simulation tool to be most effective and exact, the simulation period and division of in/out-of use periods needs to be flexible depending on building type and use.

If the long-term weather data became accurate enough it would open up possibilities by using MPC to predictions storage of heat/cold for future need, and thereby lowering the overall energy use. For this to be possible the simulation period needs to have certain length of days instead of hours. Thereby the concept could be able to predict e.g. if heat is needed the next day and that cooling strategy should be postponed/changed. Of course the main focus should still be to preserve the thermal indoor environment.

A scenario could be that e.g. the simulation predicts that the internal operative temperature of a house will rise above a certain level during non-occupied hours. The system then lowers the temperature to an acceptable level through a cooling strategy. Subsequently the simulation shows that for the following period the exterior temperature drops resulting in a heating demand. If the simulation period were longer, the system would be able to establish a different control strategy, where the overheating was allowed during non-occupied hours and the "extra" heat was used to cover the following heating demand caused by the external changes.

The downside of this approach is the increased uncertainty associated with long-term prediction periods. This uncertainty is of course influenced by many different factors. For instance highly insulated buildings are not as easily affected by external temperature changes therefore modern low-energy buildings could advantageously have longer simulation periods compared to older buildings. However if the simulations are incorrect due to various reasons and the control strategy causes an increased energy consumption this would affect the overall performance of a low-energy build more greatly due to the already low level of energy consumption.

9.1.7 Ensuring a precise starting point

MPC is as a concept very depending on the initial information supplied to the model. If the supplied data is inaccurate or wrong, it will affect the given outcome to some extent. A control strategy based on inaccurate output could very well lead to increased energy consumption and an aggravation of the indoor thermal environment. It is therefore of the utmost importance that the input data is as accurate as possible. Given the different aspects having influence on the final outcome, some kind of deviation between input data and the actual situation is to be expected, however keeping that difference as small as possible must be strived towards.

In order to achieve as correct output as possible different procedures can be implemented into the simulation process.

To eliminate errors from previous estimations the temperature of the thermal mass and the air can be reset every 24 hours. The simulation tool is given a precise measured temperature of the internal air, measured over night at 4 am. At this hour it is most likely that the temperature equilibrium is achieved, given that no night ventilation etc. has been used. If this is not the case it can, in the absence of a better solution, be assumed that the temperature of the building mass is closest to the indoor air temperature and thereby the operative temperature. This will ensure that the initial information for the point of origin for the simulation of the following day is as correct as possible.

By implementing this approach it is possible to eliminate a potential accumulation of errors related to the simulation process.

A further development of this mindset could be to make hourly measurements of temperature in order to regulate the control strategy ongoing. A scenario could be to measure the following parameters on an hourly basis and feed that information to the model:

- Internal temperature, CO_2-level, humidity
- Exterior temperature
- Solar irradiance

All measurements should be able to be performed with relatively simple and inexpensive equipment. By performing these measurements it is possible to create a fairly precise microclimate representive of the local conditions affecting the specific building. This could provide the necessary information to ensure that the simulated control strategy if based upon wrong information is corrected in accordance with actual conditions. The scenarios would then be that the control strategy for the coming period every hour is adapted to current conditions as illustrated in figure 9-1.

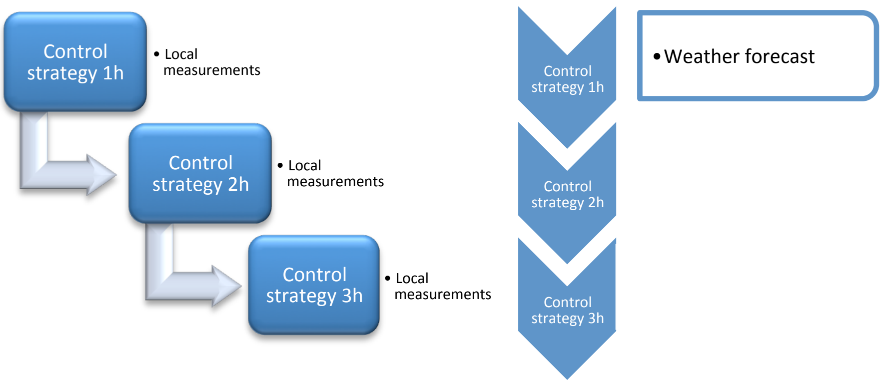

Figure 9-1 - Adaption of simulated control strategy based on local measurements

A solution to hourly indoor measurements could be the IC-Meter, which is a new climate-logging product on the market at a low price around 2000 DDK. The simple plug & play dongle can fit in any room without causing any distraction and it can log the following parameters: Temperature [°C], Humidity [%]. CO_2-level [ppm]. The device is pictured in figure 9-2. [61]

Figure 9-2 - IC-meter - professional measuring equipment

The exterior measurements could be done by a simple thermometer and solar irradiation sensor.

9.2 Future control strategy

This section describes some of the future control aspects, which could be implemented in the control strategy in order to improve the building performance.

9.2.1 Solar shading:

In order to obtain an even better indoor thermal environment and lower energy consumption, a focus area could be to improve the strategy of solar shading from the current situation, where solar shading is used as a preventive measure for avoiding overheating.

If a simulation predicts that the temperature will rise above the cooling set point, solar shading is activated during morning/noon to keep the temperature low. However, this can lead to an increased electrical consumption from artificial lighting.

This scenario could theoretically be improved by having a system that is aware of the occupant's presence. With the knowledge of occupant behavior, the system could be able to optimize the use of solar shading by e.g. completely lowering/closing the blinds to the room during non-occupied hours etc. This would regulate the thermal indoor environment with minimum effect on the energy consumption for electrical lighting.

For the opposite scenario it would be beneficial if the system was aware of the occupant's presence in relation a possible future heating demand. This concept could then be used for scenarios where the room is not occupied, in terms of using the shading as an extra insolation in form of vacuum shutters etc. to lower the heat loss through the windows and thereby lowering the buildings heat demand.

9.2.2 Ventilation:

A future aspect of the possibilities and control of the ventilation system could be to further develop it to contain possibilities of being controlling in relation to other parameters like CO_2 concentration or moisture. Further development within demand-controlled ventilation in order to e.g. ventilate the bathroom during the morning when the moisture level can be high, for only the needed time to bring down the a certain acceptable level. Several other scenarios where certain zones need to be ventilated for a small time period and not necessarily for an hour could also be mentioned.

Furthermore, the system could be further improved to take into account a concept like a system that can redistribute air to other zones in the building in order to save energy for heating and cooling etc.

9.2.3 Heating:

The current model does not provide any form of control etc. regarding the heating system. It only calculates the needed effect of the given hour and assumes that this effect can be delivered that instant. In reality the process would be much slower.

In relation to MPC, it could be more energy efficient to have a system that could determine the future needed heat amount for the entire day and transfer it to the thermal mass of the construction, thereby ensuring that the thermal mass has enough heat stored to maintain a steady temperature throughout the entire period. This process is of course only possible if the building has a large thermal mass and is well insulated.

Part II

10 Continuous Commissioning

In 2013 a public hearing was conducted of [62]. The standard was adopted in 2013 and it states the conditions for commissioning of installations in Danish buildings. Section 10 addresses the operational phase of the commissioning, where the procedure for both the testing of the building operation and one year review of the construction is described.

It is stated that the functional building operation, must be tested in a period of in use and fully loaded, in order to verify that the building installation has a performance as required by the commissioning requirements.

This section will address aspects of using MPC implemented on a building and the opportunities this may bring regarding continuous commissioning (CC).

First and foremost for this scenario to be operational there needs to be compliance between the PC model and the actual building etc.

A concept where the MPC is used to form a control strategy, which is then implemented as the actual control strategy for the building, would make it possible as a minimum, to detect large deviations from the anticipated performance already calculated in the model.

Taken this scenario it would be possible to immediately correct the error causing the deviations and thereby improving or at least insuring the correct control of the building installations. Such a concept could be a solution to the problems of the 2020 low-energy buildings not performing as predicted. By using this technology it would be possible to illustrate/prove that the buildings energy and indoor environment performance is as estimated or at least documenting why its performance is as it is, thereby creating a basis for improvement.

The main aspect of CC is documentation and therefore clarity. In order for the MPC concept to be relative to CC, insights to the dynamics of the model might very well be an essential aspect. The model therefore needs to have a white box structure necessary in relation to having the vital insight to the dynamics and all of the aspects in the process etc.

11 Requirements analysis

11.1 Preliminary study of weather data & occupant behavior influence on real life PC:

In order to test if the basic MPC-concept, based on the simple hourly method, is suitable for further development in relation to creating a concept of MPC for CC, a preliminary study was conducted.

Additionally the literature has shown that one of the key aspects for the accuracy of MPC in relation to predicting the building energy consumption and indoor environment is a correct modeling of the occupant behavior. This setup also provided an opportunity to investigate some of the aspects affecting the use of PC on real life buildings. The preliminary study was made at the facility of the Danish Technological Institute (TI) in Tåstrup.

11.1.1 Simulation tool

As a part of a larger project at TI a simple simulation model was developed for PC. The model was based on the simulation tool described in part I.

The two concepts were differentiated by the fact that the entire control strategy in the model used in this preliminary project, was a model in accordance with the actual operation/control strategy of the different building installations such as: heating pump, exterior solar shades and ventilation units.

This created a model, which was compliant with the actual building and its advanced control strategy for its installations and not a model that simulated the control strategy for the building to implement.

The primary function of this model was to predict the future energy consumption based on a future control strategy determined by slightly different control algorithm/operation strategy compared to the one explained in part I. The occupants of the building could at any time overrule the control strategy for the building installation.

This setup is perfect to test the following two aspects:

1. Is a daily weather forecast accurate enough for the concept to be able to predict a fairly precise estimate of the actual conditions, or is a 24-hour prediction too imprecise causing too great an uncertainty.
2. How occupant behavior can affect the predetermined control strategies and thereby the development of the indoor environment and energy consumption of a building.

11.1.2 Test setup (EnergyFlexHouse)

Facility

The preliminary study was conducted on the EnergyFlexHouse (EFH) shown in figure 11-1. EFH consists of two highly energy efficient identical buildings designed as single-family houses. Each building is 216 m^2 and has two floors. EFH is a residential "living lab" for the interaction between user and technology. All energy services including heating, ventilation, hot water, household lighting, etc. can be registered individually. EFH is equipped with extensive instrumentation that ensures intensive monitoring and makes it possible to analyze energy consumption, energy services, operational conditions and functions. The measuring platform in EFH currently comprises more than 700 control points and is developed so energy consumption and efficiency can be separated from each other on all of the individual energy services.

Figure 11-1 - EnergyFlexHouse

A detailed description of the facilities is provided at [63].

Test period:

The measurements were made throughout the period from 1. October to 15. November 2012.

Weather data:

The weather data used for the preliminary investigation was obtained twice a day for the following 12 hours.

The collected dataset contained exterior temperature and a simplified estimation of the solar irradiance. It was not possible to obtain precise forecast values for the solar irradiation therefore a simplification was made regarding solar irradiation.
The solar irradiation was divided into different scenarios, with according standard values for each scenario.

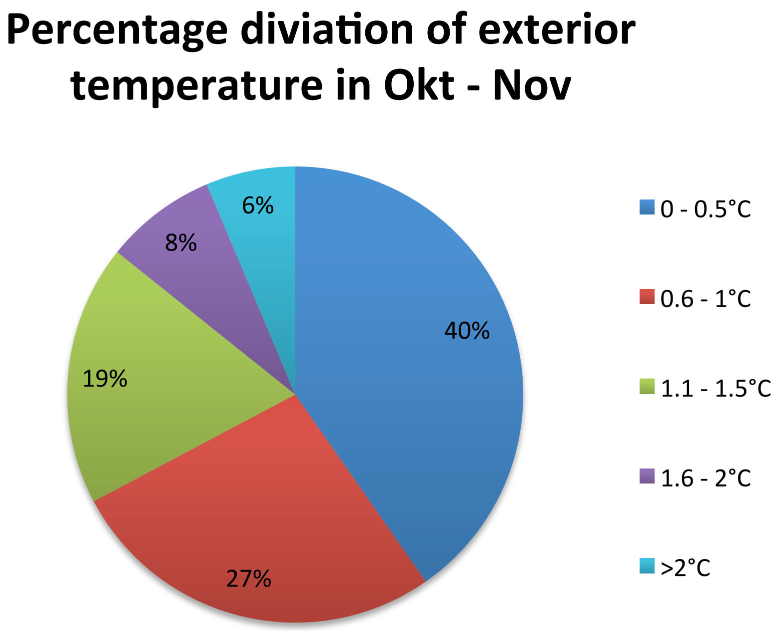

Figure 11-2 - Percentage deviation of exterior temperature for test period

Figure 11-2 shows that 67% of the time the forecast is precise with an accuracy of 0-1°C. The largest deviation registered in the period was 4.5°C. Furthermore no long periods with large deviations were registered.
A statically illustration of the weather data is illustrated in appendix IX

Occupants:
During the test period a family of four, a father, mother and two teenagers occupied the house. The family lived in the house for a period of three months. Throughout the occupied period the family had full ability to override the control strategy, by changing the settings for heating and cooling of the different zones as well as settings for the solar shades and ventilation.

11.1.3 Control period:

In order to validate the created PC-model a control period was created.
The control period consisted of a one-month simulation and monitoring of the thermal development and energy consumption during September. In order to limit the amount of uncertainty aspects as much as possible, the control period was conducted with as little external interference as possible and without any form of occupant behavior etc. Thereby it could be ensured that the only major uncertainty aspect was the accuracy of the forecast.

Weather conditions for control period:

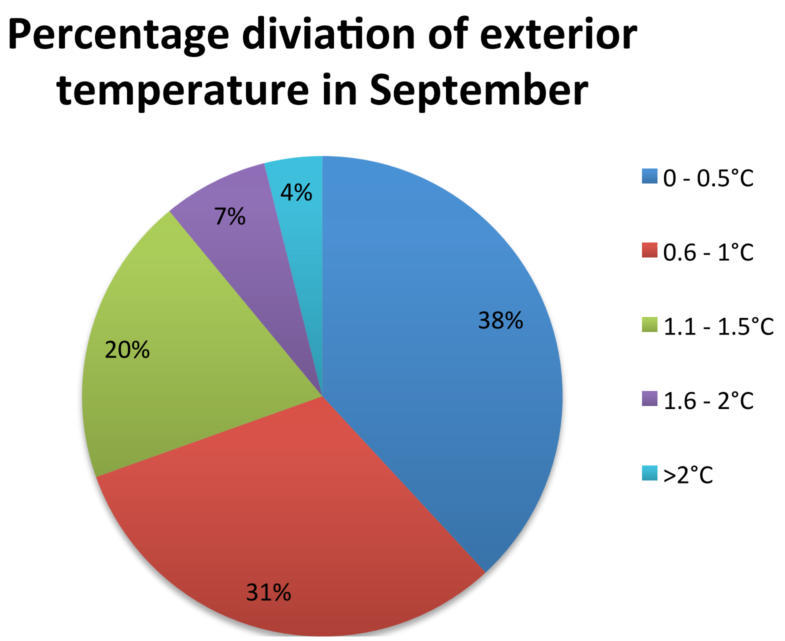

Figure 11-3 - Percentage deviation of exterior temperature for control period

Figure 11-3 shows that 69% of the time the forecast is precise with an accuracy of 0-1°C

All systems were fully functioning during the entire control period and the required thermal indoor environment was maintained throughout the entire process.

A statically illustration of the weather data is illustrated in appendix IX

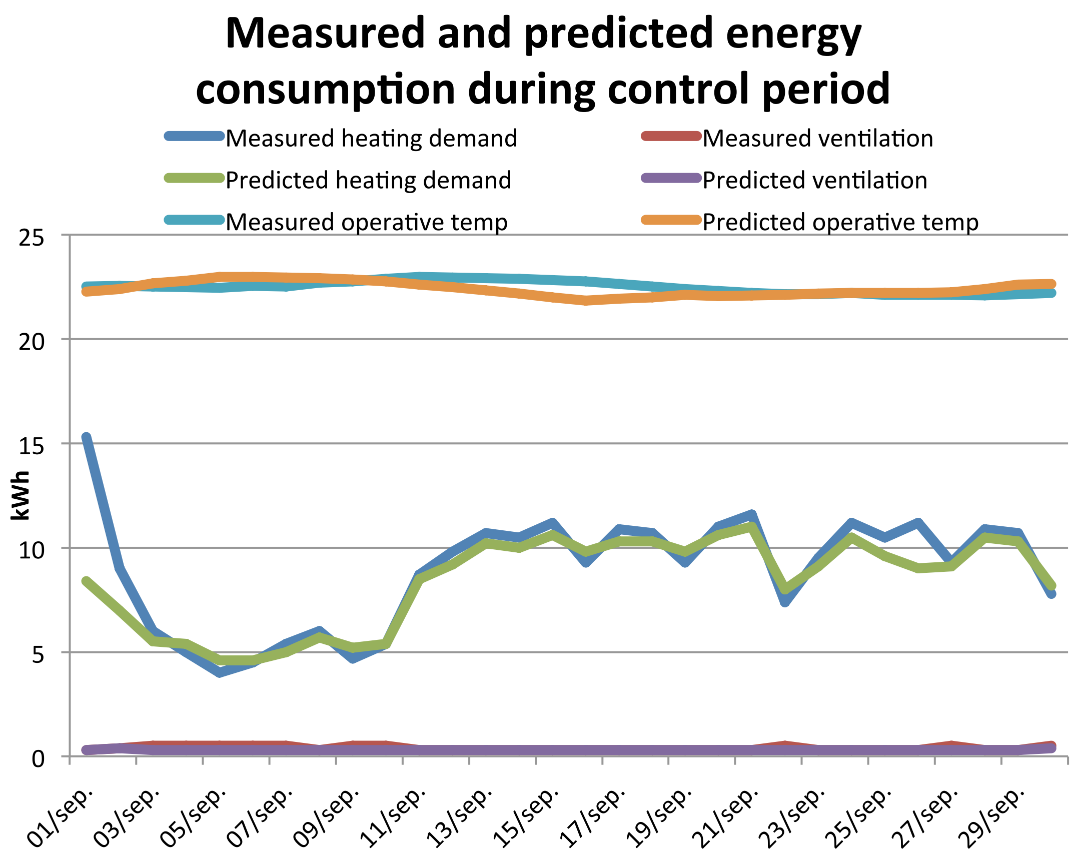

Figure 11-4 - Measured and predicted energy consumption during the control period

Figure 11-4 shows the measured energy consumption during the control period. The results are illustrated as an average per day thereby creating a somewhat smoothed out image, however it still provides a rather good insight into how well the PC model functions.

It can be seen that the predicted energy consumption was smaller during the first couple of days of the period, this was due to the fact that the model had an initial operative temperature of the building around 23 degrees however the actual initial operative temperature was around 18 degrees.

84 % of the time the deviation between predicted and actual consumption for heating was < 10%. The largest deviation of 45% was on the first day of testing.
The deviation of the energy consumption for ventilation was almost negligible due to its relatively small size. The deviation between the predicted and actual energy consumption is likely due to the inaccuracy of the weather forecast and the imperfections of the model.

The results of the control period, revealed clear correlation between the predicted and actual energy consumption. Only minor deviations were detected whenever the forecast was consistent with the actual weather conditions. Based on these results the simplified model showed great potential in relation to predicting the actual consumption.

The data for the control period is shown in appendix X.

11.1.4 Results from test period

Figure 11-5 shows the measured and predicted consumptions as a daily amount.

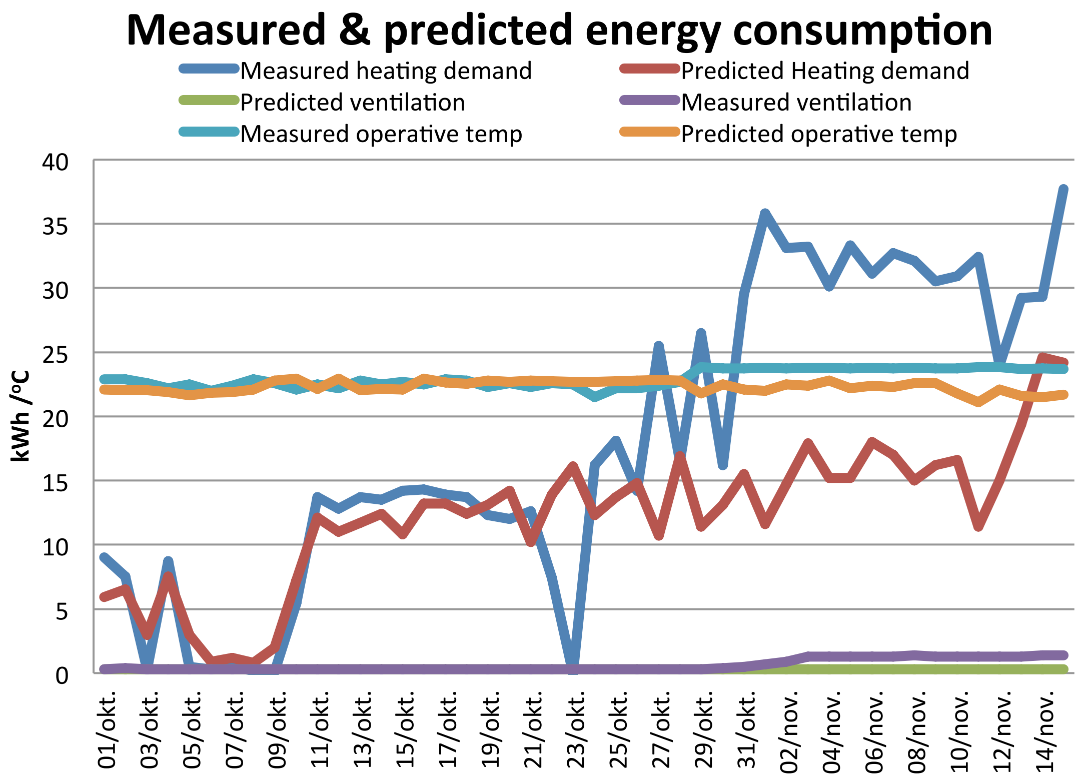

Figure 11-5 - Measured and predicted energy consumption

When comparing the accuracy of the weather forecast for the test period with accuracy of the forecast of the control period it can be seen that the forecast for the test period in average was slightly more accurate however it is only by a few percentages, therefore this should not be a factor that would influence the results in any major way. The only major differences between the control and test period was occupant behavior.

The comparison between the weather forecast and the measured weather conditions for the test period showed, that the inaccuracy of the weather forecast was fairly small and this should not cause any major incorrect simulation results. Minor inaccurate results were obtained however it was mere bagatelle.

It should be mentioned that this statement is primarily valid for the exterior temperature and that the forecast values for the solar irradiation was not compared to any measured values. However the control period revealed close consistency between the simulated and measured result.

The results show that the measured energy consumption is somewhat similar to the predicted one for the first section of the test period. The first large deviation is the 23 of October. Closer investigations revealed that the family had left the house and completely turned off the heating resulting in no heating demand on this particular day and increased demand on the following days.

During the last week of October measurements showed that increased manual natural ventilation caused a larger heating demand than the one the model had predicted.

The period from the 30 of October and the remainder of the period has large deviations between both the heating demand and ventilation energy consumption. Investigations showed that this was caused by a manual override of the control function. The occupants had increased the set temperature by 2 degrees resulting in a large increase of the energy consumption for the heating pump. Furthermore the alteration of the heating system was not implemented into the controlling strategy of the ventilation system, which still had the original set point. This resulted in a situation where two different installations acted against one another. On one hand the heating system was trying to maintain an internal operative temperature of 24°C and on the other hand the ventilation system was trying to ensure that the internal operative temperature did not exceed 23°C.

This development is clearly illustrated in figure 11-5 where the predicted heating demand is roughly half of the measured furthermore it can be seen that the ventilation goes from ordinary operation to having maximum flow rate throughout the remaining part of the period.

One could argue that the fact that this scenario could happen is a result of bad engineering. It should simply not be possible for an occupant to alter the settings for one installation without it affecting the settings for the different installations.
If the simulation results had been compared to the actual measurements on a daily basis it would have been possible to detect the deviation within 24 hours and correct the occurred error thereby preventing the exceeded energy consumption.

The data for the test period and an output file for occupants is shown in appendix XI.

11.1.5 Conclusion

This preliminary study was conducted to uncover if PC could be implemented on a real life low-energy building and as well to investigate some of the challenges regarding MPC especially the uncertainty associated with the use of weather forecasts and occupant behavior.

The study illustrated some of the challenges and the magnitude and extent of which the different aspects influence the process and final results regarding the models ability to predict the future development.

The control period revealed that if the only large uncertainty factor was the uncertainty of the weather prediction, it was possible by means of simplified PC-concept to predict the energy consumption of a modern low energy house.

The study showed that:

- The PC-concept could predict the future energy consumption of the building
    - It was possible to predict the actual energy consumption in periods where the occupant behavior was modeled correct.
- A very energy efficient house as EFH is very sensitive to alterations due to occupant behavior.
    - The large thermal mass and very low heating demand causes the house to be sensitive to heat loss due to increased ventilation from open windows etc.
- The complexity of the model is indifferent if the occupant behavior is not modeled accurately.
- The occupant behavior is one of the key factors regarding prediction of the energy consumption.
- It was possible to detect large deviation and determine the source of the deviation by means of the model and measurements. This made it possible to correct either the control strategy or the occupant behavior.
- The control of the different installations needs to be integrated in order to ensure that different installations do not work against one another.
- Inaccuracy of the weather forecast would have a limited influence on the results for the given period.

The results found in this preliminary study were consistent with results found in other studies carried out on occupants' abilities to influence energy performance and MPC of a building (See Section 2.4). The study clearly showed that if the simulated control strategy is alternated the results will be significant different.

Furthermore the results showed that the MPC concept has potential for correct prediction of the energy consumption and therefor suitable for further development in order to create a concept where MPC is used for CC of low energy buildings.

It also revealed the importance of integrated design in order to ensure that different installations are controlled by the same settings.

11.2 Crucial uncertainty aspects

Previously the uncertainty aspects of the model, the weather forecast and occupant behavior have been discussed, however these are not the only uncertainty aspects of this concept.

Another crucial uncertainty aspect of using a simulation model for continuous commissioning is the uncertainty of the input data. All the physical data of the actual building and system operations modeled contains a certain uncertainty in form of the difference between the stated data and the actual data for each component etc.

This section will briefly address the uncertainties associated with actual uncertainties of the material and functional properties of the different elements included in a construction, installations etc. and the modeling of those.

11.2.1 Physical input-data of the different building components:

In general every component in a building is defined by certain physical data described in the product standards. However not every product is 100% compliant with the described specifications. Most product standards state that a certain percentage of the components will comply with the declared values, whereas a small percentage will differ within a certain interval.

In the following section the more influential components uncertainties of the simulation tool model will be examined briefly.

Windows:
The essential data properties of a window are listed below as well as the related uncertainty.

- Thermal transmittance, U_w [W/m^{2}K]
- Light transmittance, τ [%]
- Total solar energy transmittance, g [%]

According to [64] the thermal transmittance is allowed to differ with ±5%.
The light and solar transmittance is maximum allowed to differ with ±5% according to [65]

Building envelope - U-values:
The essential data properties for the building envelope are the UA-values leading to thermal transmission through the envelope and infiltration. The heat capacity is equally important due to its effect on the thermal performance.

According to [66] the different CE-marked components need to comply with a 90% tolerance interval with a 90% confidence level meaning that for 90% of the test 90% of the test objects needs to have the declared value.

TI tests e.g. the different insolating materials. They determine the design values and their corrections in relation to moisture, air pockets etc.

Installations:
Every ventilation unit has a datasheet documenting its performance abilities etc. The standard procedure of confirming its performance is by test, thereby also determining the exact performance and uncertainty.

In general [67] and [68] state that the uncertainty of the measured air flow rate of a ventilation unit needs to be within ±10%. The uncertainty of the measured supply temperature needs to be within ±2°C (±1.5°C in occupied zone). The uncertainty of the measured air velocity needs to be within ±0.05m/s. According to [69] the HVAC unit needs to have an accuracy of ±5% for the terminal performance such as heat recovery/exchange.

The heating system in the building must be tested and controlled in order to ensure that it does not contain any errors [70], however it is not stated how large a deviation is considered an error.

Shading:
The uncertainty of the properties of solar shading depends on the individual model and type of shading, furthermore there are no standards regarding the maximum allowed uncertainty, which means that nothing general can be stated regarding the uncertainty. The performance of a shading device is highly dependent on being mounted correctly etc.

It was not possible to uncover any information regarding the uncertainty of Danish external solar shades performance properties at this point.

Internal heat loads/gains:
The uncertainty of the internal loads is impossible to precisely predict based on a standard. The internal heat loads such as heat produced by appliances, occupants, and electrical lighting are typical set in accordance to standard values which all are determined based upon testing etc.

These values can vary a lot from product to product, activity level etc.
For product used in Denmark [71] contain standard values for most products.
In relation to heat gains from occupants is determined in accordance with size and activity level [72].

11.2.2 Construction and execution errors

A crucial aspect affecting the building and its performance is how accurate the building has been constructed. Experiences show that a large amount of buildings have been constructed with faults. [73] Investigated by means of case studies the magnitude of construction errors in the Danish buildings. In 07/08 it was estimated that the amount of construction faults of newly constructed buildings was 9 billion DKK.
It goes without saying that if the building is not constructed correctly it will affect the overall building performance.
When a new 2020 building is constructed it must be recommended to review the construction in accordance with [62] and furthermore conduct a series of test in order to ensure that the building is constructed properly without any faults.
It is recommended as a minimum to conduct:

- A thermographic investigation of the building envelope
- A blower-door test
- Test of the building operations

By conducting these investigations most construction and product fault can be detected and a complete delivery report can be crafted, thereby ensuring the best possible basis for the simulation tool.

The primary function of the simulation tool is to ensure an "optimal" control strategy and detect deviations, thereby ensuring the intended indoor environment and the estimated energy performance.
If the building contains any construction errors it will most likely affect the energy performance and thereby the control strategy. The simulation tool could possible detect the deviation given the correct circumstances e.g. an increased heating demand in a room due to a thermal bridge as a consequence of a construction fault, however the simulation tool is not developed to determine a the exact cause of the deviation, only that a deviation has occurred.
Based upon the output data of the program and the measured input parameters such as temperature and weather conditions, the cause of the deviations can probably be determined, or at least narrowed down to a few possibilities.
However if a construction error is present from before the building is being used, the deviation it causes could very well be assigned to the uncertainty of the different components or similar and therefore never be detected by the simulation tool.

Furthermore certain faults could very well hide behind other aspects affecting the scenario e.g. if a construction fault caused a increased heat demand in a room but most of the loss would be covered by better exploitation of the solar and internal gain etc.

11.3 Error threshold

This section will address the total uncertainty aspects regarding the concept of using MPC as a simulation tool for CC. In chapters 11.1 & 11.2 the different sources of error are discussed as well as their effect of the final result and therefore the ability for MPC to be used as a simulation tool for CC.

In order for this concept to be functional, it must first be determined which sources of errors that are present in the model and the margin of error they entail.

Bases on this knowledge, the magnitude of the sources of error can be converted into an acceptable deviation in the model, which must be accredited uncertainties of the different aspects.

This acceptable deviation or error threshold must be defined in order to differentiate a true system fault from a fault caused by imperfect simulation.

Experiences from studies and literature have provided several scenarios, whereas the calibration is the only scenario that ensures a needed security. The estimation should be seen more as a secondary solution if the first one is not an option due to various reasons.

11.3.1 1. Scenario – A calibration of the model:

The preferable solution would be to calibrate the model in order to determine the size of the deviation caused by the uncertainties. This calibration should be conducted in a scenario that is as controlled as possible. Aspects such as: occupant behavior, internal heat gains etc. should be eliminated during the calibration period in order to ensure a controlled environment with as few uncertainties as possible.

Furthermore it would be preferable to test the model and the different installations individually thereby containing exact information on the performance. A scenario could be to test the model with only the heating operational and thereby determine the error threshold of this aspect and so forth.

By doing this it is possible to test if the different systems installed in the house perform as expected and if the total performance of the house is as expected, and if it is not, which factors that differentiate and by how much, thus leading to the determination of the error threshold.

Another aspect that can be verified by this approach is the fact that the data specifications, performance and uncertainties of all products are verified by tests, however are these tests realistic in relation to the actual usage situations?

There are a few downsides to this approach. The calibration is during certain weather conditions. A house located in Denmark undergoes a whole variety of weather conditions, which might affect the performance of the different installations in the house as well as the overall performance of the house therefore the error threshold might change as the weather conditions change. This aspect cannot be fully taken into account unless the calibration is performed during a longer period of time, which is not a viable solution for obvious reasons.

Furthermore a calibration period like e.g. the control period in the preliminary project, where the uncertainty aspects are limited and the house is fully functioning without it being occupied, is rarely possible due to economic aspects.

11.3.2 2. Scenario – Estimation of error threshold:

If a calibration of the model is not possible, an estimated initial guess of the error threshold is a solution. The estimated error threshold should be based on the uncertainty of each product of the house combined. In order to ensure that errors due to uncertainties are not perceived as an actual fault the estimated error threshold should be a summation of all the uncertainties combined. A form of worst case scenario where all the uncertainties of all products are taken into account and statistical summed into a probabilistic error threshold.

However this approach of determining the error threshold is not preferable, due to the large uncertainties associated with the estimation (see chapter 11.2). A scenario could very well be that the error threshold is determined so large that it could conceal actual faults in the performance, control strategy etc.

A scenario could be to estimate the error threshold based on the first months simulation results compared to the measured, however as former discussed this has multiple disadvantages.

11.4 Clarification of the target group

When a concept is developed it is important to clarify the primary target group of the concept. This concept is basically a total solution to a current Danish situation divided into sub-concepts, one being model predictive control and the other being continuous commissioning.

11.4.1 MPC

The sub-concept of MPC based on a developed WinDesign concept has a primary target group of modern low-energy 2020 buildings, primarily single-family houses.

The current state of this concept is only suitable for a certain type of building, which is consistent with the preferences of which the concept is developed and where all the aspects of the control concept can be exploited. The building needs to be equipped with the different installations and control possibilities for this concept to reach its full potential.

Studies have shown that there is a need for improving the control of Danish low-energy buildings. The control strategy has a large impact on the overall performance because of the very low heating demand and overall energy consumption compared with a regular building.

Another aspect is the concepts ability to estimate the need for preventive cooling through "low energy consuming" functions, which can only be used if the systems in the building contain these possibilities etc.

However with that being said it is of course also possible to use the concept on buildings of a different standard, in order to obtain a better performance. This could be done by simply alternate the model in accordance with the intended building. A scenario could be to use the model only to determine the needed heating demand for a building etc. that could be possible with a few alterations in the model, but the current state of the simulation tool is intended for a low-energy building.

11.4.2 MPC for CC

The second sub-concept is to develop MPC for CC of modern low-energy buildings. In this case the target group is fairly obvious. However in this case the concept could also be modified into CC of other types of buildings nevertheless the concept of CC is primary suited for newly constructed buildings in order to make sure that they perform as intended and if not located the source of error leading to a correction of it.

Related to the last aspect, CC also holds certain possibilities to appoint a responsibility for errors and thereby clean up an industry, which contains too many faults and imperfections.

By using MPC as a simulation tool for CC it is possible to detect adverse deviations and correct the source with a short time frame, thereby ensuring an appropriate and more optimal control of the different systems in the building, which would possibly lead to a better and more energy efficient result, for the entire period of use. This approach also makes it possible to document the operation of the building and ensure a deeper level of insight and understanding of the process.

12 Discussion & Perspective

The main objective of this investigation was to develop a simple simulation program suitable for continuous commissioning by being able to document the estimated energy and environment performance of a low-energy one family house through a simple simulated control strategy.

12.1 The concept

Given the correct scenario the simulation tool is capable of calculating a control strategy in order for a low-energy building to meet the estimated energy consumption and indoor environment. If the building did not meet the estimated performance the simulation tool would provide documentation of which parameters caused the deviation.

12.1.1 The simulation tool & continuous commissioning

In theory this concept is suitable for CC however in order to confirm this, additional full-scale real life testing of the newly developed concept on an actual building needs to be completed.

As described in Part I the platform on which this concept is constructed is not suitable for further development. The limitations of excel is simply too great in order for this concept to be further developed. The simulations tool and its structure needs to be converted into another platform more suitable for these types of simulations.

The simple structure and very specified/limited control options of the simulation tool makes it suitable for CC of a very specific building segment compliant with exactly these specifications, thereby also limiting the use of this concept to exactly those and excluding al other building types.

For the CC concept to be useable the building needs to contain the same possibilities as the simulation tool contains. However if the building contained more complex control possibilities e.g. control setting relative to seasons, occupants behavior scenarios etc., it could be possible to achieve an even lower energy consumption. Unfortunately the simulation tool is not capable of handling these aspects at this stage.

The current control possibilities of the simulation tool is somewhat similar to the one of a typical Danish low-energy building, however for the concept to be fully functional the settings needs to be adjusted in accordance with each case.

The program WinDesign on which the simulation tool is developed is validated in relation to the early design phase of a construction. Investigations have shown that WinDesign obtains similar results as other simulations programs however experiences have shown that in many cases there is a gap between simulation and reality. Therefore additional testing of the concept on a real building is necessary in order to proper validate the concept. This validation is to some extent made by the preliminary study at TI at least in relation to energy consumption.

Among aspects where the simulation tool and reality is different is the delivered heating and cooling effect. The ideal heating and cooling in the simulation tool will in many situations not be possible. Thus leading to a slightly different thermal development than predicted by the program. However the preliminary study showed that this did not affect the final outcome. The study showed great resemblance between predicted and actual operative temperature.

In order for the concept to be fully useful for CC it is also essential that it is further developed into being fully automatically. The simulation tool needs to be able to insert/extract information during the simulation process.

Simulations needs to be conducted as an ongoing process and new input information and outputs needs to be updated/extracted continuously. At this stage the concept is not able to do that automatically which means that it needs to be done manually.
During the investigation it was not possible to develop the concept to this level. The experience with this development has indicated that the concept needs to be converted into another platform with fewer limitations.

In relation to CC and detection of errors the investigation showed that if the actual measured performance deviated more than the threshold allows there is a need for some kind of alarm to inform about the deviation.
A situation could be based on the allowed error threshold that the program sets an acceptable deviation interval, and if the measured performance goes outside this interval, an alarm will go off thereby informing the involved parties.
Another aspect of this mindset could be that by having this it is also possible to detect if e.g. some of the measuring equipment malfunctions.

Similar constrains could also be constructed for the input data in order to detect e.g. errors in the forecast. A scenario could be that the predicted temperatures for the following 6 hours is 22°C, 22°C, 22°C, 0°C, 0°C, 0°C, which clearly is a malfunction. If this occurred the program automatically sets off an alarm instead of making a simulation based on clearly false input data.

12.1.2 Occupant behavior

Occupant behavior is an important aspect to take into account. The preliminary investigation revealed that in order for the concept to be viable some parts of the occupant behavior needs to be implemented in the control strategy and commissioning part otherwise the results will not be useable. These findings are consistent with multiple other investigations (See chapter 2).

The user pattern of the occupants needs to be integrated in the control strategy to some extent, in order to ensure that the building performs as predicted based on the given assumptions. The current version of the simulation tool does not take into account any form of alternations due to deviant occupant behavior. It assumes that the thermal conditions are not altered as a consequence of occupant behavior, such as opening of windows, regulations of thermostats etc.

A solution to this problem could be to create a schematic of the occupant behavior based on some kind of start-up period where their behavior is recorded and thus forms the basis of a general scheduling, however occupants behavior is among other things seasonal etc. thereby creating new challenges regarding a correct modeling of the occupant behavior.

Another option regarding implementing the user behavior in the simulation could be to create some kind of interaction between the program and the occupants, where the occupants could feed information into the simulation in relation to their future behavior. This could then be developed as a two-way communication, where the simulation program was able to inform the occupants about the consequences of their future planned behavior, a concept that TI currently is investigating.

As a part of an ongoing project at the Danish Technological Institute elements of user involvement and visualization of the consequences of their choices is investigated. The project investigates the effects of PC with predefined user patterns where the occupants have the possibility to influence the setup user pattern for the following period. Furthermore, they have the ability to override the preset control of the different installations. However, if they do so the consequences will be illustrated to them in terms of the impact on the indoor thermal environment and energy use [74].
It has not been possible to develop a viable solution for implementing the occupant behavior in this concept at this stage.

The stage of the simulation tool does not take occupant behavior into account. Furthermore aspects like internal heat gains from occupants, appliances etc. is considered constant, which is a simplification.

Of course many of these suggestions will complicate the simulation tool and thereby eliminate its simplicity. Therefore, these suggestions are merely observations intended for further investigation in order to determine if their level of improvement can justify the increased complexity.

12.1.3 Weather

Investigations have shown that the accuracy of the weather data has a significant influence on the accuracy of the results. However it is also revealed that small deviations only sometimes had a crucial impact on the outcome. Investigations also showed that the accuracy of forecast was very dependent on how far into the future the predicted period was.

Investigations of how far a weather prediction is reliable indicates that the uncertainty associated with the weather forecast combined with other aspects like user behavior is too large in order for the concept to use long-term weather predictions which could very well result in wrongful control strategies thereby resulting in a higher energy consumption etc.

The opportunity of using long-term prediction for calculating the buildings energy needs for a long forthcoming period, with all the advantages associated with this, is somewhat limited due to the high uncertainty of the forecast.

However the results on a short-term weather prediction looks very promising despite the associated uncertainties, which indicates that the concept is functional in theory if aspects like user behavior etc. is modeled correctly. Additional testing is however essential in order to fully determine if the concept is functional.

12.1.4 Future smart-grid aspects (long-term optimization possibility)

The use of MPC also enables smart-grid solution possibilities. If MPC is used for controlled strategies for low energy buildings and the simulated strategy is complied, it enables an aspect of a known future energy consumption, which could be exploited throughout smart-grid solutions.

If the producers of energy know the future necessary power that should be available it would be possible to optimize. The amount of power available on the electricity grid is maintained on the basis of a frequency. If consumption increases the frequency decreases and producers increase production in order to maintain an adequate amount of electricity available in the power network. This unpredictability is the main reason for the unstable and relatively high energy prices.

If the electricity and heat consumption was known to the producers it would result in greater security in relation to the current demand leading to a reduction in uncertainty among manufacturers which in turn will result in a lower final price to the consumer. The accuracy in terms of both length and time is essential compared to cost of delivery and the product itself.

Furthermore if the exact amount of needed energy was known it would create possibilities of using surplus energy from different plants to heat or power buildings in low consuming periods. A scenario could be to use surplus heat to heat a low energy house for the following days, the surplus heat could be distributed to the thermal mass of the house during the low consuming period 00-06 and be stored in the construction, which then would have the enough energy stored to ensure the required operative temperature in the building for the following period and therefore not require heat at e.g. 18:00 when everyone else also needs heat.

This aspect however demands a higher security in relation to that the predicted control strategy is accurate. A smart grid solution like this would only be functioning if the actual control strategy does not differ from the simulated control strategy, which is not always the case at this stage of the concept.

13 Conclusion

It was possible to develop a generic simulation concept based on the guidelines described in EN 13790 that could function with short-term weather data.

13.1Weather

A comparison and analyze of the weather data for 2011 revealed that in general the weather forecast underestimates the temperature with 0.5°C and overestimates the solar irradiance with 39W/m^2. This inaccuracy resulted in the fact that the PC simulation did not always estimate correct cooling strategies and set points, which resulted in a number of overheating hours despite a control algorithm which should prevent operative temperatures outside the thermal comfort range by a preventive control strategy.

13.2 Investigation of the simulation tool

The investigation revealed that the simulation tool could generate a control strategy for the heating, cooling and ventilation of a low-energy building that could ensure the required indoor environment.

Based on the simulation results it can be concluded that MPC does not provide large direct energy savings (4%) compared to the original control. Furthermore it was revealed that the MPC strategy could provide a slightly better indoor environment with less overheating hours compared to the original control strategy.

Simulation revealed that inaccurate forecasts did not always have a huge impact on the indoor thermal environment and energy consumption because the set points did not change as a result of the error.

The inaccuracy only had a huge impact on the cases where it caused the simulation to calculate an operative temperature within the comfort range and in reality went outside the comfort range thereby creating a scenario of e.g. overheating that the control strategy based upon the forecast has not accounted for.

Despite the fact that the uncertainties of the weather forecast did not have a huge impact on the overall performance of the MPC strategy it should still be taken into account when the simulation results should be implemented on a real building.

13.3 Concept for continuous commissioning

Based on Part I it was possible to describe a concept that could be used as a tool to continuous commissioning for a low-energy building. Throughout the tests in a preliminary study, several issues regarding the usability of the concept was uncovered.

It can be concluded that in order for model-based predictive control to be used for continuous commissioning it is essential to implement user behavior otherwise this will affect the results too much. Furthermore the importance of integrated control that ensures that all involved systems are controlled in accordance similar set points was uncovered.

Finally it was uncovered that the concept most likely would not provide large direct energy savings however the concept can provide huge savings in form of detection of control errors.

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15 Appendix

I. **Simulation strategy**

II. **Control Algorithm**

III. **Correspondence with DMI**

IV. **Forecast file structure**

V. **Calculation of Direct and diffuse solar radiation**

VI. **WinDesign weather file**

VII. **WinDesign results**

VIII. **Predicted and actual operative temperature**

IX. **Preliminary study weather data**

X. **Control period results**

XI. **Test period results**

I. Simulation strategy

Stage III:

The solar energy needed to reach the cooling set point is determined by:

$\phi_{sol}^{*} = 2 \cdot A_{tot} \cdot \frac{N}{O}$

The characters are described in chapter 5.2.1 – simply hour calculation model, and in more detail in EN ISO 13790.

Where:

$$N = \left(\theta_{set,cool} \cdot [H_{tr,ms} + H_{tr,w} + H_{tr,1}] - Var2\right) \cdot \left(C_{m,corr} + \frac{1}{2} \cdot H_{tr,3} + \frac{1}{2} \cdot H_{tr,em}\right) \cdot H_{tr,2} - \frac{1}{4} \cdot Var1 \cdot H_{tr,2} \cdot \phi_{int} \cdot \left(2 \cdot C_{m,corr} + H_{tr,3} + H_{tr,em}\right) - \frac{1}{4} \cdot H_{tr,ms} \cdot \left[H_{tr,2} \cdot \left(4 \cdot \theta_{m,t-1} \cdot C_{m,corr} + \frac{A_m}{A_{tot}} \cdot \phi_{int} + 2 \cdot H_{tr,em} \cdot \theta_e\right) + H_{tr,3} \cdot (Var1 \cdot \phi_{int} + 2 \cdot Var2)\right]$$

$$O = H_{tr,ms} \cdot A_m \cdot H_{tr,2} + A_{tot} \cdot Var1 \cdot \left[H_{tr,ms} + H_{tr,3} + H_{tr,2} \cdot \left(2 \cdot C_{m,corr} + H_{tr,3} + H_{tr,em}\right)\right]$$

$$Var1 = 1 - \frac{A_m}{A_{tot}} - \frac{H_{tr,w}}{Var3 \cdot A_{tot}}, \qquad Var3 = 9.1$$

$$Var2 = H_{tr,w} \cdot \theta_e + H_{tr,1} \cdot \left(\theta_{sup} + \frac{\phi_{ia} + \phi_{HC,nd}}{H_{ve}}\right)$$

Stage IV:

$H_{VE,corr} = H_{tr,is} \cdot \frac{L}{M}$

The characters are described in chapter 5.2.1 – simply hour calculation model, and in more detail in EN ISO 13790.

$$L = -2 \cdot \theta_{m,t-1} \cdot C_{m,corr} \cdot H_{tr,em} - \phi_{ia} \cdot \left(H_{tr,ms} + 2 \cdot C_{m,corr} + H_{tr,em}\right) - \theta_e \cdot \left[H_{tr,em} \cdot H_{tr,ms} + H_{tr,w} \cdot \left(H_{tr,em} \cdot H_{tr,ms} + 2 \cdot C_{m,corr}\right)\right] + \theta_{set,cool} \cdot \left[H_{tr,ms} \cdot \left(2 \cdot C_{m,corr} + H_{tr,w} + H_{tr,em}\right) + H_{tr,w} \cdot \left(2 \cdot C_{m,corr} + H_{tr,em}\right)\right] - \theta_{st} \cdot \left(H_{tr,ms} \cdot H_{tr,em} + 2 \cdot C_{m,corr}\right) - \phi_{HC,nd} \cdot \left(H_{tr,ms} + 2 \cdot C_{m,corr} + H_{tr,em}\right) - \phi_m \cdot H_{tr,ms}$$

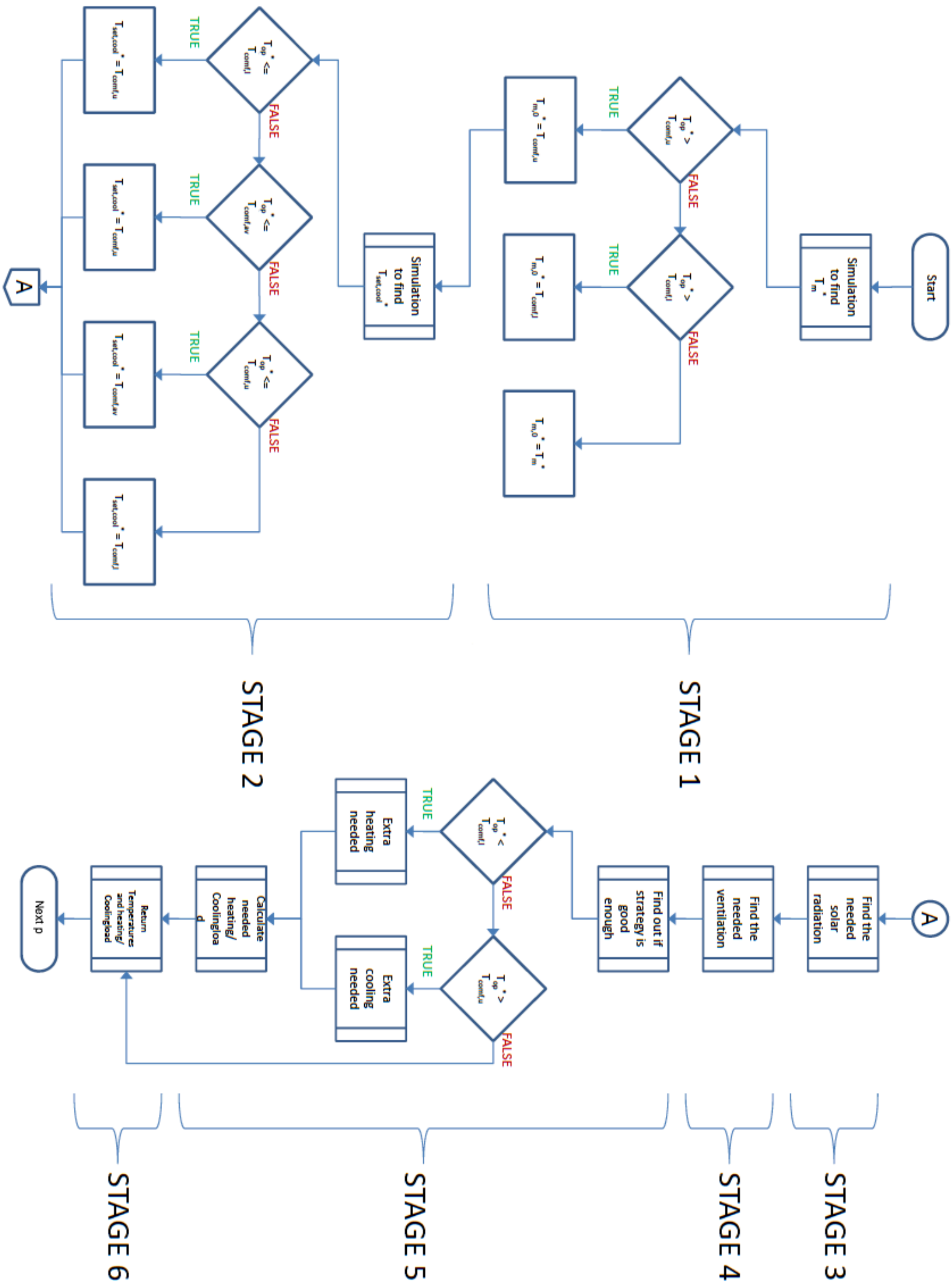
$$M = -2 \cdot \theta_{m,t-1} \cdot C_{m,corr} \cdot H_{tr,ms} - \phi_{st} \cdot \left(H_{tr,ms} + 2 \cdot C_{m,corr} + H_{tr,em}\right)$$

$$-\theta_e \cdot \left(H_{tr,em} \cdot H_{tr,ms} + H_{tr,em} \cdot H_{tr,w} + H_{tr,ms} \cdot H_{tr,w} + 2 \cdot C_{m,corr} \cdot H_{tr,w}\right)$$
$$-\theta_{sup} \cdot \left(H_{tr,ms} \cdot H_{tr,is} + H_{tr,is} \cdot H_{tr,em} + 2 \cdot H_{tr,is} \cdot C_{m,corr}\right) - \phi_m \cdot H_{tr,ms}$$
$$+\theta_{set,cool}$$
$$\cdot \left[H_{tr,ms} \cdot \left(2 \cdot C_{m,corr} + H_{tr,is} + H_{tr,w} + H_{tr,em}\right) + H_{tr,em} \cdot \left(H_{tr,is} + H_{tr,w}\right) \cdot 2 \cdot C_{m,corr}\right.$$
$$\left. \cdot \left(H_{tr,is} + H_{tr,w}\right)\right]$$

Where:

$$C_{m,corr} = \frac{C_m}{3600}$$
$$H_{tr,1} = \frac{1}{\frac{1}{H_{ve}} + \frac{1}{H_{tr,is}}}$$
$$H_{tr,2} = H_{tr,1} + H_{tr,w}$$
$$H_{tr,3} = \frac{1}{\frac{1}{H_{tr,2}} + \frac{1}{H_{tr,ms}}}$$

II. Control Algorithm



III. Correspondence with DMI

salg-adm <salg-adm@dmi.dk> 31/10/2013

to me

Danish > English Translate message Turn off for: Danish

Hej Thomas

Så lykkedes det at finde filerne - de var heldigvis gemt :)

Der er 4 stks i alt
1 prognosefil -Prognose_07908.txt
1 observations fil fra Sjælsmark - OBS_618800.txt
1 gridded observation - GODB_07908.txt
1 kml fil der viserp laceringen af punkterne i google earth - GoogleEarthFile.kml

Prognose filen indeholder data for et år, med 4 daglige kørsler/opdateringer ud til +54 timer i 1times intervaller
for parametrene solindstråling (kaldet globalstråling i DMi termer, og temepraturen i celsius)
Observationsfilen er timeværdier for Sjælsmark, dato tidsstempel, indstråling W/m2, temepratur i Celsius.
Den griddede observationsfil indeholder interpoleret observation til et punkt tæt på pronosepunktet

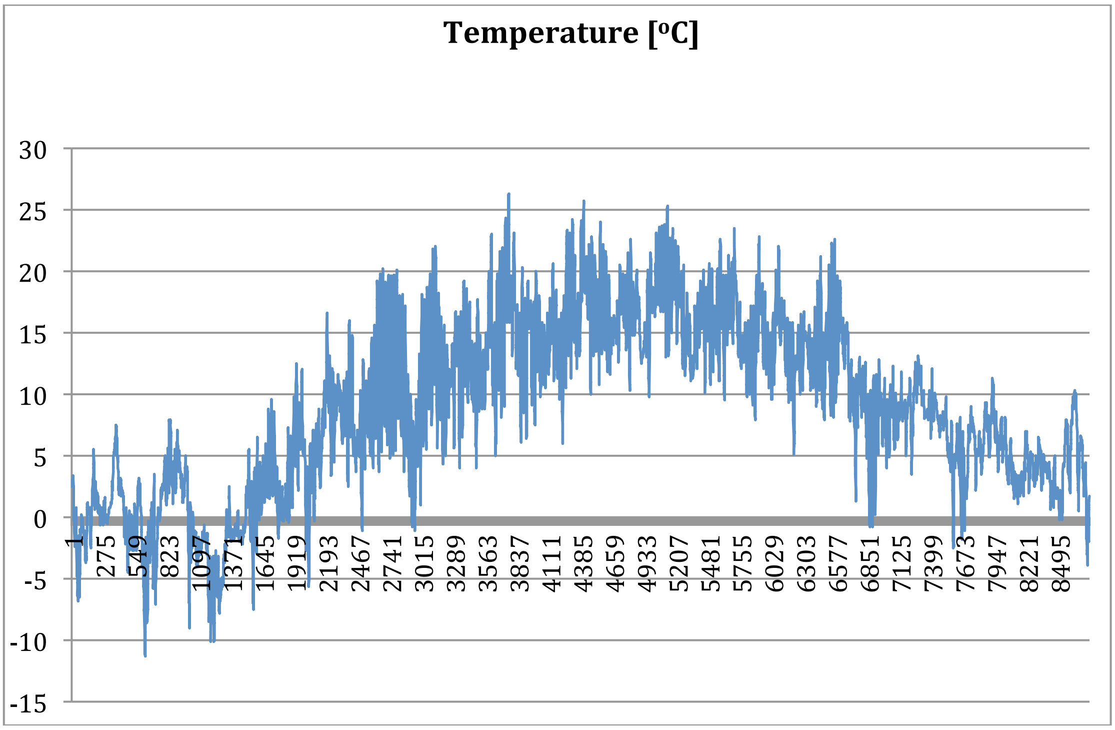
Mht pronosefilens solindstråling på kl 12 kørslen (gælder og for kl 06 og 18 om sommeren) vil du se at indstrålingen er meget lav på +00 tidsskridtet. Det skyldes at værdien kl f.eks. +01 dvs kl 13 er den akkumulerede indstråling mellem kl 12 og 13 og prognosen kl 12 har ikke en akkumulering fra kl 11-12, den har kun en samplingsperiode på nogle få minutter og derfor bliver værdien +00 meget lille.

Håber du får gode resultater ud af dit projekt

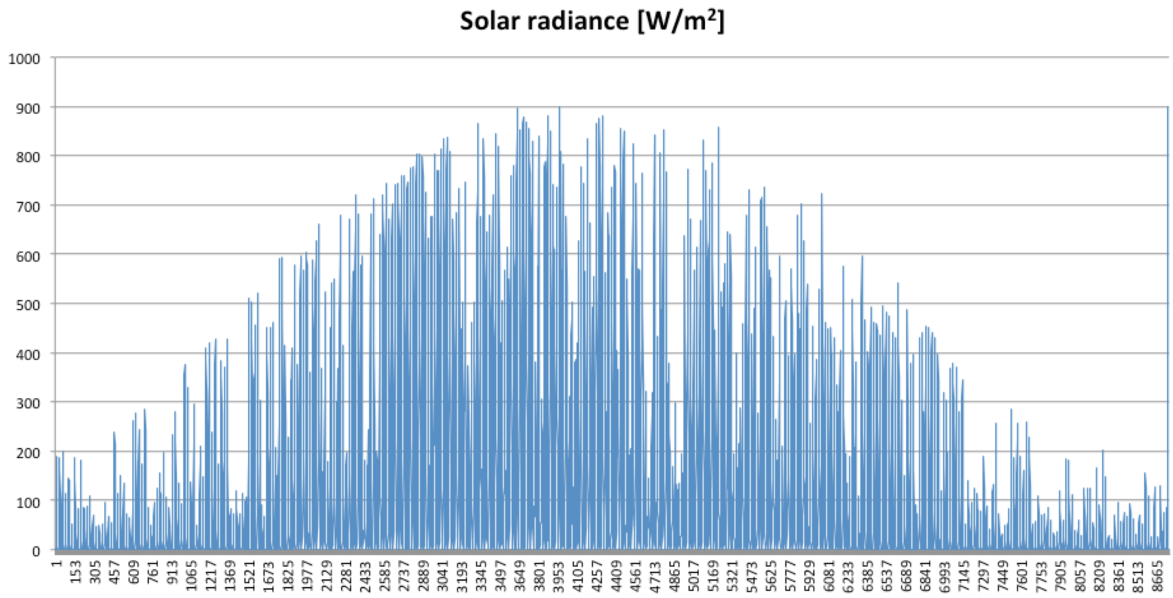
mvh
Ulrik

IV. Forecast file structure

```
#
#Parameter	Analysis time	+000	+001	+002	+003	+004	+005	+006
	+007	+008	+009	+010	+011	+012	+013	+014	+015	+016
	+017	+018	+019	+020	+021	+022	+023	+024	+025	+026
	+027	+028	+029	+030	+031	+032	+033	+034	+035	+036
	+037	+038	+039	+040	+041	+042	+043	+044	+045	+046
	+047	+048	+049	+050	+051	+052	+053	+054
#
Temperatur[C]	2011010100	1,9	2,4	2,5	2,4	2,4	2,2	2,0	1,9
	1,8	2,1	2,3	2,2	2,1	2,0	1,7	1,3	0,8	0,5	0,7
	0,4	0,0	-0,4	-0,6	-0,5	-0,2	-0,2	-0,5	-1,4	-2,1	-2,5
	-3,9	-4,6	-5,1	-5,6	-4,7	-4,0	-3,3	-2,5	-2,6	-3,0	-2,9
	-3,8	-3,7	-4,6	-5,8	-6,4	-6,9	-7,7	-8,1	-8,4	-8,0	-7,8
	-7,1	-7,7	-7,7
Solstråling[W/m2]	2011010100	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	1,0	59,9	128,1	192,0	205,9	186,0	102,9	17,6	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	1,1	68,8	161,5	216,1	227,5	191,1	113,7
	19,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0

Temperatur[C]	2011010106	2,4	2,4	2,3	2,4	2,7	2,8	1,9	1,9
	1,8	1,3	1,3	1,2	0,8	0,2	-0,4	-0,5	-0,2	-0,3	-0,2
	-0,5	-0,4	-0,7	-1,9	-2,6	-2,9	-3,4	-3,7	-4,4	-3,9	-2,6
	-1,2	-0,9	-1,0	-1,9	-2,9	-3,9	-4,3	-4,9	-5,9	-6,7	-7,6
	-8,4	-8,8	-8,8	-9,0	-9,0	-9,2	-8,6	-9,0	-9,4	-9,5	-9,1
	-8,3	-7,0	-5,6
Solstråling[W/m2]	2011010106	0,0	0,0	1,0	63,9	147,4	213,6
	195,6	164,9	91,0	15,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,1
	65,9	158,7	218,4	228,6	192,2	114,9	19,3	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	1,1	76,2	185,4	275,3	236,6

Temperatur[C]	2011010112	2,5	2,4	2,1	1,6	1,5	1,3	1,0	0,0
	-1,0	-2,0	-2,2	-3,1	-3,7	-3,9	-4,0	-3,0	-3,9	-4,8	-5,5
	-6,2	-6,2	-5,3	-4,2	-3,1	-2,4	-2,3	-2,4	-3,4	-4,7	-5,9
	-6,9	-7,5	-7,8	-8,3	-8,8	-9,0	-9,4	-9,4	-9,5	-9,7	-9,5
	-10,0	-10,2	-10,4	-10,7	-10,3	-9,4	-8,3	-7,2	-6,6	-6,7	-7,5
	-8,1	-8,7	-9,1
Solstråling[W/m2]	2011010112	5,2	184,5	112,2	18,2	0,0	0,2	0,0
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,9	66,9	159,2	215,6	226,9	191,1	112,6	19,3	0,0
	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
	0,0	0,0	0,0	0,0	1,7	81,3	196,8	228,1	232,1	226,4
	161,5	26,1	0,0	0,0	0,0

Temperatur[C]	2011010118	0,2	-0,8	-2,4	-2,8	-2,8	-2,7	-2,8	-3,3
	-3,2	-3,5	-3,5	-4,8	-5,2	-4,6	-4,7	-4,3	-3,2	-1,6	-0,6
```



Temperature [°C]
30
25
20
15
10
5
0
-5
-10
-15



Solar radiance [W/m²]
1000
900
800
700
600
500
400
300
200
100
0

V. Calculation of Direct and diffuse solar radiation

For the given hour the sun-earth distance factor, DA, is calculated:

$$DA = 1 + 0.0334 \cdot \sin\left(\frac{\pi \cdot DN}{182.5}\right)$$

DN = Number of the day

The extraterrestrial irradiation on horizontal, I_e, is calculated:

$$I_e = 1353 \cdot DA \cdot \sin(h_s)$$

h_s = solar altitude angle

A relation to the absolute humidity expressed by the morning minimum temperature, RMIN, is calculated:

$$RMIN = 0.165 + 0.004 \cdot t_{min}$$

$$NB: if\ RMIN < 0.140\ then\ RMIN = 0.140$$

t_{min} = minimum temperature

The relation between global and cosmic irradiation, K_t, is calculated:

$$K_t = \frac{G_h}{I_e}$$

G_h = Global irradiation

The relation to the absolute humidity, RELD, is calculated:

$$RELD = 0.913 - \frac{(0.913 - RMIN) \cdot (K_t - 0.36)}{0.4}$$

$$if\, K_t > 0.75\ then\ RELD = RMIN$$

Direct radiation:

$$I_0 = \frac{G_h \cdot (1 - RELD)}{\sin(h_s)}$$

Diffuse radiation:

$$D_h = G_h - I_0 \cdot \sin(h_s)$$

Conversion of W/m^2 to Lux: Assumes cloudy during the entire year in order to prevent overestimation.

Sources:

- DRY report. www.byg.dtu.dk
- www.lysviden.dk
- EU sun radiation atlas

Clip of the calculation file:

1		External air													
2					BSIM			RMIN >= 0.140			K_t > 0.75 RELD=RMIN				
3		tempera	Global	DA	h_s	I_e	RMIN	RMIN	K_t	RELD	RELD	Diffuse	Diffuse	Direct	Direct
4	DN	[°C]	W/m²		Deg	W/m2	-	-	-	-	-	W/m²	W/m²	W/m²	W/m²
203	9	0	0	1,00009	-18,042	-419,1	0,165	0,165	0	1,5862	1,5862	0	0	0	0
204	9	-0,6	0	1,00009	-10,3742	-243,7	0,1626	0,1626	0	1,58836	1,58836	0	0	0	0
205	9	-1,2	3	1,00009	-3,42739	-80,9	0,1602	0,1602	-0,03709	1,660315	1,660314615	4,980944	4,980944	33,13525	33,13525
206	9	-1,4	88,6	1,00009	2,462675	58,1	0,1594	0,1594	1,523863	-1,27972	0,1594	-113,383	0	4700,716	4700,716
207	9	-0,7	185,8	1,00009	6,96005	164,0	0,1622	0,1622	1,133151	-0,5382	0,1622	-99,9982	0	2358,514	2358,514
208	9	0,1	250	1,00009	9,759486	229,4	0,1654	0,1654	1,089936	-0,45125	0,1654	-112,812	0	2140,326	2140,326
209	9	0,6	185,9	1,00009	10,64253	249,9	0,1674	0,1674	0,74391	0,197392	0,197391631	36,6951	36,6951	807,9066	807,9066
210	9	0,8	222,3	1,00009	9,53489	224,1	0,1682	0,1682	0,991781	-0,26338	0,1682	-58,5486	0	1695,452	1695,452
211	9	1	109,5	1,00009	6,529316	153,9	0,169	0,169	0,71166	0,258913	0,258912811	28,35095	28,35095	713,6393	713,6393
212	9	1,2	18,3	1,00009	1,857311	43,9	0,1698	0,1698	0,417281	0,806573	0,806572648	14,76028	14,76028	109,2152	109,2152
213	9	1,3	0	1,00009	-4,00674	-94,5	0,1702	0,1702	0	1,58152	1,58152	0	0	0	0
214	9	1	0	1,00009	-11,0514	-259,4	0,169	0,169	0	1,5826	1,5826	0	0	0	0
215	9	1,5	0	1,00009	-18,7798	-435,6	0,171	0,171	0	1,5808	1,5808	0	0	0	0
216	9	1,6	0	1,00009	-26,8544	-611,2	0,1714	0,1714	0	1,58044	1,58044	0	0	0	0
217	9	1,5	0	1,00009	-34,9056	-774,3	0,171	0,171	0	1,5808	1,5808	0	0	0	0
218	9	1,5	0	1,00009	-42,4712	-913,7	0,171	0,171	0	1,5808	1,5808	0	0	0	0
219	9	1,4	0	1,00009	-48,911	-1019,8	0,1706	0,1706	0	1,58116	1,58116	0	0	0	0
220	9	1,1	0	1,00009	-53,3491	-1085,6	0,1694	0,1694	0	1,58224	1,58224	0	0	0	0
221	10	0,3	0	1,0001	-54,8553	-1106,5	0,1662	0,1662	0	1,58512	1,58512	0	0	0	0
222	10	-0,1	0	1,0001	-53,0233	-1081,0	0,1646	0,1646	0	1,58656	1,58656	0	0	0	0
223	10	-0,8	0	1,0001	-48,3405	-1010,9	0,1618	0,1618	0	1,58908	1,58908	0	0	0	0
224	10	-0,9	0	1,0001	-41,7523	-901,1	0,1614	0,1614	0	1,58944	1,58944	0	0	0	0
225	10	-0,7	0	1,0001	-34,1129	-758,9	0,1622	0,1622	0	1,58872	1,58872	0	0	0	0
226	10	-0,6	0	1,0001	-26,0408	-594,0	0,1626	0,1626	0	1,58836	1,58836	0	0	0	0
227	10	-0,1	0	1,0001	-17,985	-417,8	0,1646	0,1646	0	1,58656	1,58656	0	0	0	0
228	10	-0,6	0	1,0001	-10,31	-242,2	0,1626	0,1626	0	1,58836	1,58836	0	0	0	0
229	10	-1,2	2,7	1,0001	-3,35223	-79,1	0,1602	0,1602	-0,03412	1,654741	1,654741202	4,467801	4,467801	30,23221	30,23221
230	10	-1,4	71,6	1,0001	2,551671	60,2	0,1594	0,1594	1,188538	-0,64797	0,1594	-46,3944	0	2650,347	2650,347
231	10	-0,8	149,7	1,0001	7,064709	166,4	0,1618	0,1618	0,899518	-0,10021	0,1618	-15,0021	0	1339,148	1339,148
232	10	0	210,4	1,0001	9,880161	232,2	0,165	0,165	0,906186	-0,10837	0,165	-22,8007	0	1359,073	1359,073
233	10	0,2	88,2	1,0001	10,77786	253,0	0,1658	0,1658	0,348563	0,934364	0,934363912	82,4109	82,4109	30,95748	30,95748
234	10	0,6	215,8	1,0001	9,68208	227,6	0,1674	0,1674	0,948272	-0,18354	0,1674	-39,6077	0	1518,647	1518,647

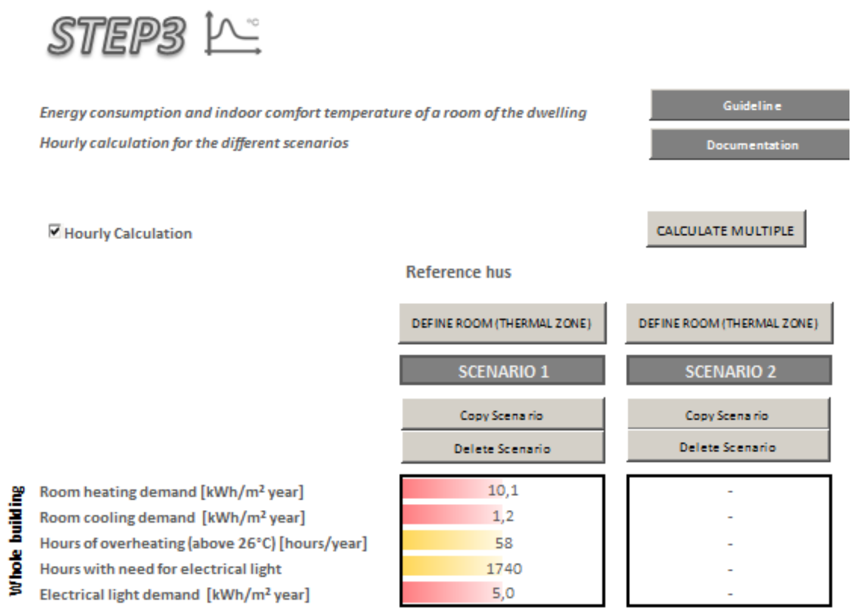
VI. WinDesign weather file

Clip of the WinDesign weather file:

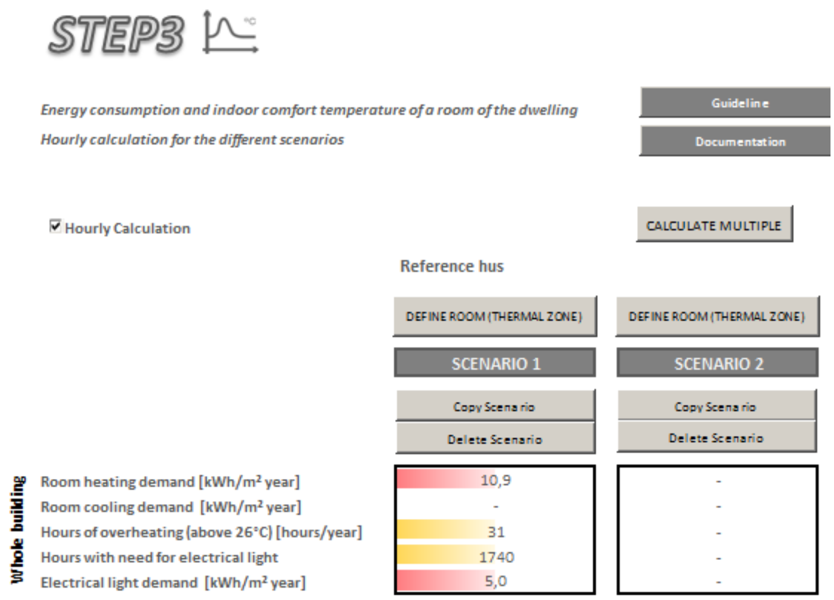
				External air temperature	Solar Radiation			Solar illuminance		
Time	Month	Day	Hour		Global	Diffuse	Direct	Global	Diffuse	Direct
[1h-8760h]	[1-12]	[1-31]	[1-24]	[°C]	W/m²	W/m²	W/m²	lx	lx	lx
1	1	1	1	2,8	0	0	0	0	0	0
2	1	1	2	2,6	0	0	0	0	0	0
3	1	1	3	2,6	0	0	0	0	0	0
4	1	1	4	2,8	0	0	0	0	0	0
5	1	1	5	2,9	0	0	0	0	0	0
6	1	1	6	3,2	0	0	0	0	0	0
7	1	1	7	2,9	0	0	0	0	0	0
8	1	1	8	2,3	0	0	0	0	0	0
9	1	1	9	2,2	2	2	0	251	0	0
10	1	1	10	3,2	43	29	190	4441	0	400
11	1	1	11	3,5	57	50	48	6269	6300	3400
12	1	1	12	4,0	21	20	5	2346	7000	5800
13	1	1	13	4,9	34	34	0	3995	18500	5300
14	1	1	14	6,0	22	21	6	2455	9200	4600
15	1	1	15	6,4	22	19	28	2524	0	2400
16	1	1	16	7,1	8	7	27	905	0	100

VII. WinDesign results

Original Control:



New predictive control



VIII. Predicted and actual operative temperature

Largest temperature under/over-estimation

		Observation		Operative		Forecast		Difference	
Date	Time	Solar radianc	Temp [C]	Predicted	Actual	Solar radianc	Temp [C]	Solar radianc	Temp [C]
03/01 - 06	06:00:00	0	-5,9	21,3	21,8	0	-10,6	0	-4,7
	07:00:00	0	-6,1	21,2	21,1	0	-10,4	0	-4,3
	08:00:00	5	-6,8	21,7	21,7	1,2	-10,3	-3,8	-3,5
	09:00:00	68	-5,4	21,3	21,3	70,2	-10	2,2	-4,6
	10:00:00	151	-3,5	21,5	21,5	162,5	-9,4	11,5	-5,9
	11:00:00	200	-2,4	21,6	21,4	218,7	-7,9	18,7	-5,5
03/01 - 12	12:00:00	200	-1,5	21,8	21,5	205,6	-5	5,6	-3,5
	13:00:00	166	-1,7	21,2	21,7	198,1	-4,6	32,1	-2,9
	14:00:00	97	-2,0	21,7	21	118,8	-4,9	21,8	-2,9
	15:00:00	20	-4,0	21,9	21,9	22,3	-5,6	2,3	-1,6

	04:00:00	25	13,6			39,5	12,8	14,5	-0,8
	05:00:00	57	14,6	22,3	22,2	122,8	13,1	65,8	-1,5
11/07 - 06	06:00:00	242	18,1	22,5	22,8	253,1	17,3	11,1	-0,8
	07:00:00	415	20,7	22,4	22,5	522,4	19,1	107,4	-1,6
	08:00:00	571	21,1	22,9	22,7	630,4	20,3	59,4	-0,8
	09:00:00	218	21,6	22,7	22,9	563,7	20,5	345,4	-1,1
	10:00:00	396	15,8	22,9	22,1	712	20,7	315,9	4,9
	11:00:00	335	18,2	22,8	22,4	552,2	20,1	216,8	1,9
11/07 - 12	12:00:00	224	20,1	22,4	22,5	230,5	18,1	6,2	-2
	13:00:00	442	19,2	22,6	22,2	785,8	20	343,8	0,8
	14:00:00	267	20,1	22,9	22,8	759,5	20,7	492,5	0,6
	15:00:00	502	20,3	22,6	22,9	691,7	20,5	189,7	0,2

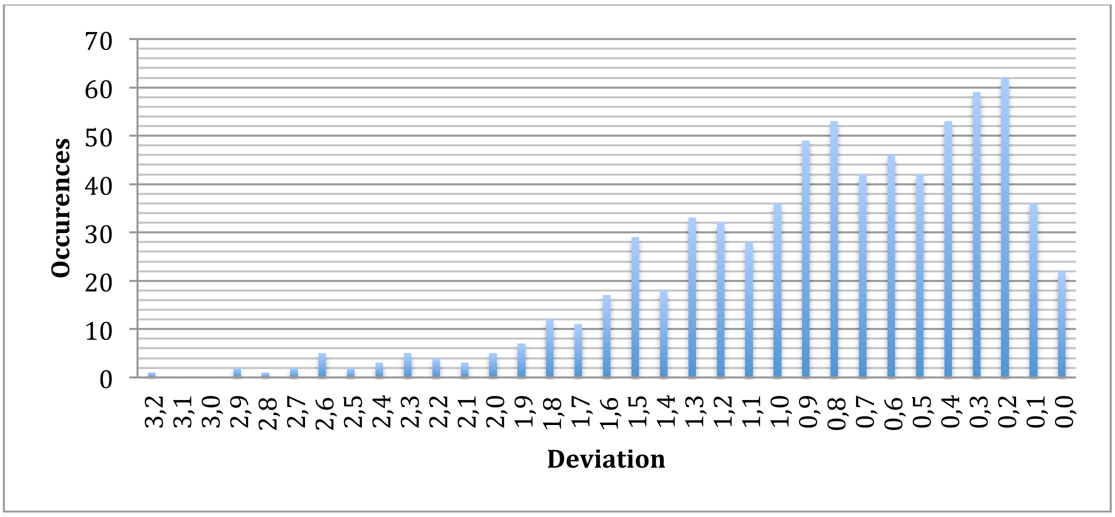
Largest irradiance under/over-estimation

		Measured		Operative		Forecast		Difference	
Date	Time	Solar radianc	Temp [C]	Predicted	Actual	Solar radianc	Temp [C]	Solar radianc	Temp [C]
29/07 - 06	06:00:00	83	17,1	21,3	21,9	85,7	16,4	2,6	
	07:00:00	146	17,5	21,2	21,6	141	16,8	-5	
	08:00:00	189	18,1	21,4	21,8	284,7	17,4	95,7	
	09:00:00	332	19,2	22,7	21,7	431,2	18,3	99,2	
	10:00:00	508	20,6	22,9	22,9	649,1	20,1	141,1	
	11:00:00	401	19,7	23,8	23,1	1318	21,3	917	
29/07 - 12	12:00:00	514	21,2	22,7	22,4	542,5	20,3	28,5	
	13:00:00	397	21,2	23,6	23,2	1141,6	21,5	744,6	
	14:00:00	390	21,7	23,8	23,8	1120,3	21,7	730,3	
	15:00:00	567	23,1	24	24	921	21,5	354	
	16:00:00	213	21,1	23,6	23,3	319,9	19,4	106,9	

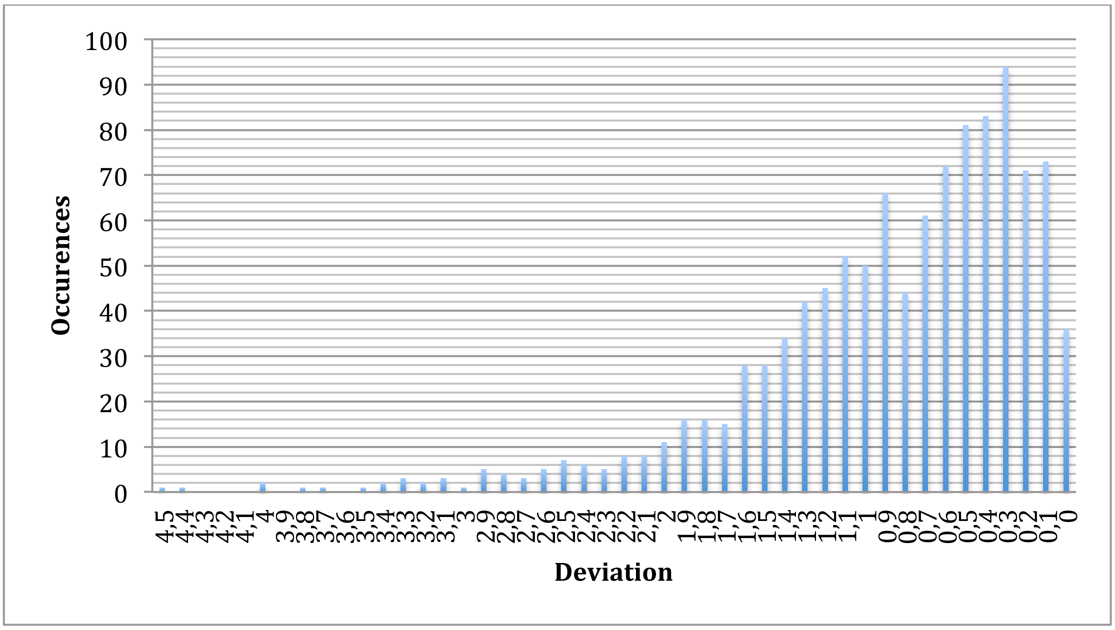
	08:00:00	390	22,1	23,5	23,1	453	20,5	63	
	09:00:00	453	22,2	23,6	23,3	458,9	21,2	5,9	
	10:00:00	535	23,2	23,9	23,9	705,7	22,4	170,7	
	11:00:00	723	23,6	24	23,9	834,6	23,5	111,6	
01/08 - 12	12:00:00	831	23,8	24,3	24,2	831,7	20,1	0,7	
	13:00:00	697	22,1	23,3	23,6	60	19	-637,4	
	14:00:00	495	19,5	23,2	23,3	209,4	20,2	-285,3	
	15:00:00	481	21,7	23,3	23	671,2	21,3	190,2	
	16:00:00	291	20,6	23,4	23,2	435,1	20,8	144,1	
	17:00:00	242	20,8	23,7	23,1	134,7	19,5	-107,3	
01/08 - 18	18:00:00	153	20,7	23,9	23	153,6	19,6	0,6	

IX. Preliminary study weather data

Control period - Temperature deviation between predicted and measured.



Test period - Temperature deviation between predicted and measured.



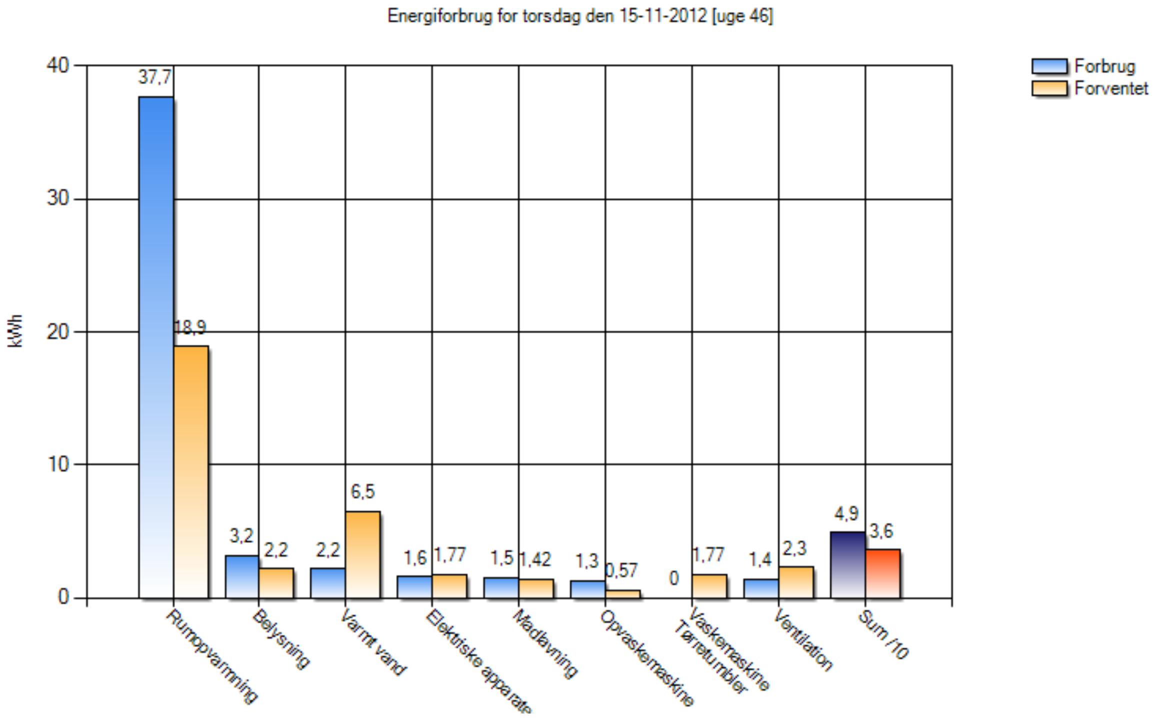
X. Control period results

3			Measured heati	Measured ventila	Measured operati	Predicted heatir	Predicted vent	Predicted oper	Deviation - Heating [
4	lørdag	01-sep	15,3	0,3	22,5	8,4	0,3	22,3	45%
5	søndag	02-sep	9	0,4	22,6	7	0,4	22,4	22%
6	mandag	03-sep	6	0,5	22,5	5,5	0,3	22,7	8%
7	tirsdag	04-sep	5	0,5	22,5	5,4	0,3	22,8	8%
8	onsdag	05-sep	4	0,5	22,5	4,6	0,3	23,0	15%
9	torsdag	06-sep	4,5	0,5	22,6	4,6	0,3	23,0	2%
10	fredag	07-sep	5,4	0,5	22,5	5	0,3	23,0	7%
11	lørdag	08-sep	6	0,3	22,7	5,7	0,3	22,9	5%
12	søndag	09-sep	4,7	0,5	22,8	5,2	0,3	22,9	11%
13	mandag	10-sep	5,4	0,5	22,9	5,4	0,3	22,8	0%
14	tirsdag	11-sep	8,7	0,3	23,0	8,5	0,3	22,6	2%
15	onsdag	12-sep	9,8	0,3	23,0	9,2	0,3	22,5	6%
16	torsdag	13-sep	10,7	0,3	22,9	10,2	0,3	22,3	5%
17	fredag	14-sep	10,5	0,3	22,9	10	0,3	22,2	5%
18	lørdag	15-sep	11,2	0,3	22,8	10,6	0,3	22,0	5%
19	søndag	16-sep	9,3	0,3	22,8	9,8	0,3	21,8	5%
20	mandag	17-sep	10,9	0,3	22,6	10,3	0,3	21,9	6%
21	tirsdag	18-sep	10,7	0,3	22,5	10,3	0,3	22,0	4%
22	onsdag	19-sep	9,3	0,3	22,4	9,8	0,3	22,1	5%
23	torsdag	20-sep	11	0,3	22,3	10,6	0,3	22,1	4%
24	fredag	21-sep	11,6	0,3	22,2	11	0,3	22,1	5%
25	lørdag	22-sep	7,4	0,5	22,1	8	0,3	22,1	8%
26	søndag	23-sep	9,5	0,3	22,2	9,1	0,3	22,2	4%
27	mandag	24-sep	11,2	0,3	22,2	10,5	0,3	22,2	6%
28	tirsdag	25-sep	10,5	0,3	22,1	9,6	0,3	22,2	9%
29	onsdag	26-sep	11,2	0,3	22,1	9	0,3	22,2	20%
30	torsdag	27-sep	9,3	0,5	22,1	9,1	0,3	22,3	2%
31	fredag	28-sep	10,9	0,3	22,1	10,5	0,3	22,4	4%
32	lørdag	29-sep	10,7	0,3	22,1	10,3	0,3	22,6	4%
33	søndag	30-sep	7,8	0,5	22,2	8,2	0,4	22,6	5%

XI. Test period results

		Measured heating d	Measured ventilati	Measured operative temp	Predicted he	Predicted ventilat	Predicted operative temp
mandag	01/okt	9	0,3	22,9	5,9	0,3	22,11
tirsdag	02/okt	7,5	0,4	22,9	6,5	0,3	22,0
onsdag	03/okt	0,3	0,3	22,6	3	0,3	22,1
torsdag	04/okt	8,7	0,3	22,2	7,5	0,3	21,9
fredag	05/okt	0,5	0,3	22,5	3	0,3	21,7
lørdag	06/okt	0,3	0,3	22	0,9	0,3	21,8
søndag	07/okt	0,5	0,3	22,4	1,2	0,3	21,9
mandag	08/okt	0,2	0,3	22,9	0,8	0,3	22,1
tirsdag	09/okt	0,1	0,3	22,6	2	0,3	22,8
onsdag	10/okt	5,4	0,3	22,1	7,2	0,3	22,9
torsdag	11/okt	13,7	0,3	22,5	12,1	0,3	22,1
fredag	12/okt	12,8	0,3	22,2	11	0,3	23,0
lørdag	13/okt	13,7	0,3	22,8	11,7	0,3	22,0
søndag	14/okt	13,5	0,3	22,5	12,4	0,3	22,1
mandag	15/okt	14,2	0,3	22,7	10,8	0,3	22,1
tirsdag	16/okt	14,3	0,3	22,5	13,2	0,3	22,9
onsdag	17/okt	13,9	0,3	22,9	13,2	0,3	22,7
torsdag	18/okt	13,7	0,3	22,8	12,4	0,3	22,6
fredag	19/okt	12,3	0,3	22,3	13,1	0,3	22,8
lørdag	20/okt	12	0,3	22,6	14,2	0,3	22,7
søndag	21/okt	12,6	0,3	22,3	10,2	0,3	22,8
mandag	22/okt	7,4	0,3	22,6	13,9	0,3	22,8
tirsdag	23/okt	0	0,3	22,5	16,1	0,3	22,7
onsdag	24/okt	16,2	0,3	21,5	12,3	0,3	22,7
torsdag	25/okt	18,1	0,3	22,2	13,7	0,3	22,8
fredag	26/okt	14,2	0,3	22,2	14,8	0,3	22,8
lørdag	27/okt	25,5	0,3	22,4	10,7	0,3	22,8
søndag	28/okt	16,5	0,3	22,7	16,9	0,3	22,8
mandag	29/okt	26,5	0,3	23,8	11,4	0,3	21,8
tirsdag	30/okt	16,2	0,4	23,7	13,1	0,3	22,5
onsdag	31/okt	29,5	0,5	23,8	15,5	0,3	22,1
torsdag	01/nov	35,8	0,7	23,8	11,6	0,3	22,0
fredag	02/nov	33,1	0,9	23,7	14,7	0,3	22,5
lørdag	03/nov	33,2	1,3	23,8	17,9	0,3	22,4
søndag	04/nov	30,1	1,3	23,8	15,2	0,3	22,8
mandag	05/nov	33,3	1,3	23,7	15,2	0,3	22,2
tirsdag	06/nov	31,1	1,3	23,8	18	0,3	22,4
onsdag	07/nov	32,7	1,3	23,8	17	0,3	22,3
torsdag	08/nov	32,1	1,4	23,8	15	0,3	22,6
fredag	09/nov	30,5	1,3	23,7	16,2	0,3	22,6
lørdag	10/nov	30,9	1,3	23,7	16,6	0,3	21,8
søndag	11/nov	32,4	1,3	23,8	11,4	0,3	21,1
mandag	12/nov	24	1,3	23,8	15	0,3	22,1
tirsdag	13/nov	29,2	1,3	23,7	19,4	0,3	21,6
onsdag	14/nov	29,3	1,4	23,7	24,6	0,3	21,5
torsdag	15/nov	37,7	1,4	23,7	24,2	0,3	21,7

Output file for occupants:



The anticipated energy consumption illustrated above is based upon a previous calculation method used by TI. At the point this output file was generated the model described in the project was not yet implemented in the project.