# Stochastic Analysis of Building Energy Modelling Tools

## Simple and advanced tool's abilty to provide useful guidance in the early stages of building design

Master's Thesis

Kasper K. Hansen & Morten H. Silkjær
Indoor Environment and Energy Engineering
Aalborg University

8th of June 2017

AALBORG UNIVERSITY
STUDENT REPORT

AALBORG UNIVERSITY
STUDENT REPORT

**School of Engineering and Science**
**Study Board of Civil Engineering**
**www.civil.aau.dk**

**Title:**

Stochastic Analysis of Building Energy Modelling Tools

**Subtitle:**

Simple and advanced tool's ability to provide useful guidance in the early stages of building design

**Project period:**

September 2016 - June 2017

**Authors:**

Kasper Kingo Hansen
Morten Hjalf Silkjær

**Supervisors:**

Rasmus L. Jensen - Associate Professor
Torben Østergaard - Industrial Ph.d. Student

**Number of copies:** 2
**Number of pages:** 154
**Completed:** 8th of June 2016

**Synopsis**:

This thesis aims to improve the early design phase by guiding the choice of building energy modelling tool, more specifically if a simple or advanced tool should be used and how many zones the building should be divided into. This is done by comparing different models, modelled with simple and advanced tools while using different amounts of zones. The comparison is conducted for a two types of facades, static and dynamic, resulting in a total of 10 different models. The comparisons are done stochastically by conducting 5000 simulations of each model with the use of cloud computing.
The model outputs analysed includes energy consumption for heating, cooling and for some models lighting. The models are compared against three criteria by using sensitivity analysis, Monte Carlo filtering and scatter plots. From this, a guide is obtained showing which tools are suitable as design tools in the early stages of building design moreover the guide also contains information about in which situations they should be used.
The simple tool, Be15, is deemed unsuitable as it does not meet the criteria. The advanced tool, OpenStudio, meet all criteria for models with two and six zones and are deemed suitable for early design phases. The static single zone model is deemed suitable as well while the dynamic model with a single zone struggles with the prediction of lighting consumption, and are not suitable for early design phases. Lastly, the experiences drawn from the use of cloud computer reveal that it is generally useful, but with some inefficiencies.

Abstract

In the early design phase a lot of decisions have to be taken and while most of these decisions revolves around the actual design of the building, another decisions is the choice of building simulation tool. If the design team chooses to use the global design space approach by performing stochastic simulations it requires a simulation tool in which the thousands of simulations can be run. Also it have to considered if simple or advanced tools are necessary and how many zones one should divide the building into. Choosing the right tool for the project is hard if the possibilities are unknown to the design team.

This thesis seeks to elaborate on the different possibilities in order to guide design teams in choosing the design tool that are most suitable for the building project. Knowing the different possibilities and the pros and cons of each choice, makes for an easier decision making process, which again leads to a more effective design process. This is done by comparing different models, modelled with simple and advanced tools while using different amounts of zones.

The comparison is conducted for two types of facades, dynamic which have shading and lighting control and static which have none. The advanced models includes a single zone model, a two zone model, a six zone model and a 15 zone model which have every space as its own zone. This results in a total of 10 different models. The comparisons are done stochastically by conducting 5000 simulations of each model with the use of cloud computing via Amazon Web Services.

The model outputs analysed includes energy consumption for heating, cooling and for the dynamic models, lighting. The models are compared with three criteria, model precision, input tendencies and input rankings, by using Monte Carlo filtering, scatter plots and sensitivity analysis. The 15 zone model is regarded as a baseline model and assumed as the correct result which the other models are compared with. From the comparison, a guide is obtained showing which tools are suitable as design tools in the early stages of building design but the guide also contains pros and cons of the different models and information about in which situations they should be used.

The simple tool, Be15, is deemed unsuitable as a design tool, as it did not meet the precision and input ranking criteria. The advanced tool, OpenStudio, meets all criteria for 1, 2 and 6 zone models, except for the dynamic single zone model, which is deemed unsuitable as design tool. The dynamic model with a single zone does not sufficiently predict the lighting consumption which is the reason for not meeting the criteria.

*Keywords: OpenStudio, Be15, design guide, early design phase, zoning, cloud computing.*

# Preface

This master thesis is created by a group of two students on the Master's programme *Indoor Environmental and Energy Engineering* at Aalborg University. The Thesis is conducted in the period between September 2016 and June 2017. The overall subject of stochastic modelling was chosen because of personal interest in the subject and future development in that field of study. The target group for the project is people with interest in building energy modelling and building design in general.

We would like to thank Brian Ball and Henry "Ry" Horsey from the Commercial Building Research Staff at the National Renewable Energy Laboratory (NREL) for help with the OpenStudio Analysis Spreadsheet. We would also like to thank Jørgen Rose from the Danish Building Research Institute (SBi) for help with converting a weather file for Be15.
A special thanks is also addressed to our two supervisors Rasmus L. Jensen and Torben Østergaard for excellent guidance and support with the project.

**Reading guide**
Throughout the report there will be references to sources which are all listed in the bibliography in the end of the report. The Harvard-method is used for references. The source will be referred to as either "[Surname/Organization, Year]" or "Surname/Organization [Year]" and when relevant also with a specific page or section in the source.

Webpages are listed with author, title, URL and date. Books are listed with author, title, publisher and version, so forth these are available.

The report contains figures and tables which are numbered in relation to the chapter they appear in. Thus, the first figure in chapter 1 will be named figure 1.1, the second figure 1.2 and so on.

In addition to the report there is also an appendix report. Throughout the report there will be references to the appendix, numbered respectively with a letter and a number for parts of the appendix. E.g. appendix A.1, D.4 and so forth. For references to a whole chapter in the appendix only the letter is used. E.g. appendix A, D and so forth.

Aalborg, June 8th 2017

Kasper Kingo Hansen | Morten Hjalf Silkjær

# Table of Content

# Introduction 1

In the later years the increasing awareness regarding the global climate have let to worldwide meetings and agreements, like UN's climate convention, UNFCCC, and the European Unions energy union.
The energy union's goal is to make energy more secure, affordable and sustainable within EU. This is done by following a few objectives, like the new 2030 framework for climate and energy. The overall objective is to reduce the energy consumption of Europe by 27% and to emit 40% less greenhouse gases by 2030. [European Commission, 2017]

In Denmark these agreements are reflected in the national building regulations which have been updated every few years with more strict requirements. The reason why it is important to alter the building requirements is because that households are responsible for 30% of the total national energy consumption and offices are responsible for 12%. [Energistyrelsen, 2017]

These regulations makes building design complicated due to the many conflicting parameters needed to achieve a building that upholds the requirements for energy consumption as well as the indoor environment. Furthermore, decisions have to be taken early in the building design phases in order to obtain efficient buildings with minimum construction and operation costs. But making the right decisions early is often hard and the design of the building can change many times during the process and the later in the process the changes occur the more expensive they will be. This is because changes are easy to implement early before the construction phase while changes during or after the building is constructed is difficult. E.g. if it is discovered that the windows are too large it can easily be changed on the drawing board but changing it on a constructed building is either a costly procedure or impossible. [Löhnert et al., 2003]. This is shown in figure 1.1.

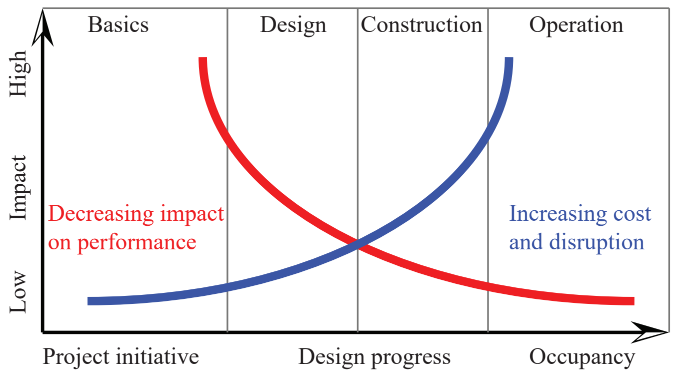



***Figure 1.1.*** Performance impact and cost throughout the design phases. Redrawn from [Löhnert et al., 2003, Figure 6]

The traditional building design process that have been used for many years, have specialists take turns in the design process which leads to a very linear process. This means that first the architects meet up with the building owner and comes up with a design. This design is then handed to the engineers for further inspection and optimization of constructions and systems with the use of simulation tools. [Larsson, 2004]. After the optimization process, the building plans are handed to a contractor that constructs the building. One of the challenges with this method is passing knowledge between these stages, if small bits of information goes missing the final building might not end up as initially imagined by the owner.

Another design process have been developed called the integrated design process. The overall idea behind this design method is putting together a team of specialist to design the building together with the owner from day one. This means that engineers now have a say in what the architects design and vice versa. These teams enables for better choices to be made early, since more parts are involved with each of their area of expertise, [Andresen et al., 2009]. Though this method improve the decision making in early design phases it does not provide a method where decisions can be taken based on performance simulations of the building nor does it remedy the challenges that are present when creating the simulation models, one of these challenges are being able to provide feedback to every design proposal drawn by the architects while having very little info about the building.

A way of providing feedback to the architects design proposals are by exploring a global design space. The global design space is defined as a design space where most if not all design alternatives are included. Figure 1.2 shows three different simulation approaches. Performing a single simulation does not yield much information as shown it can only tell of the criteria are met or not. The one-at-a-time approach is a little better as it explores several design options by varying one input at a time, but it is unknown if better solutions are possible. Finally the global approach explores large amount of design alternatives and the optimal solution can be obtained.

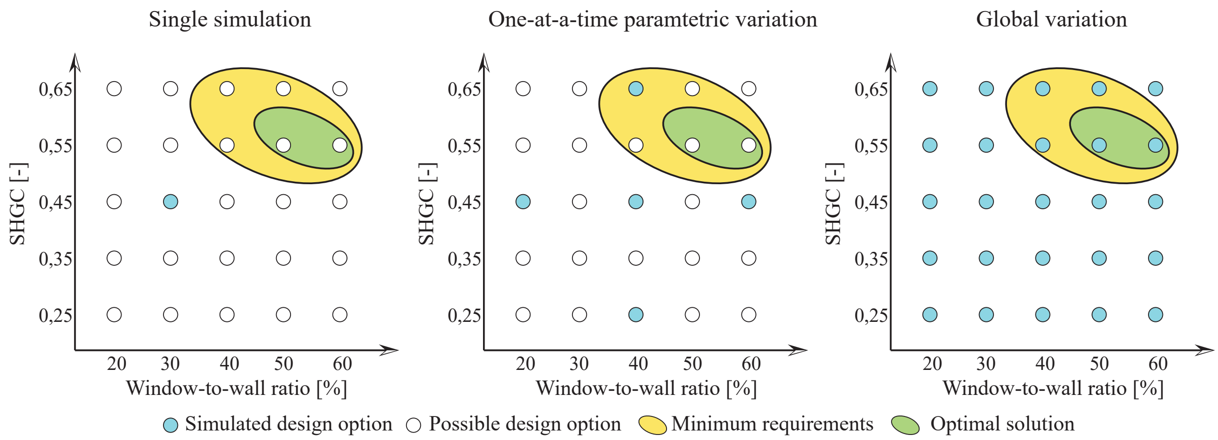



***Figure 1.2.*** Three different simulation approaches. Redrawn from [Østergård et al., 2017, Figure 1]

Østergård et al. [2017] provides an approach to do this where the global design space is explored by using Monte Carlo simulations, which require thousands of simulations to be run. Using the global design space approach with stochastic modelling makes it possible for the engineer to provide guidance for a multidisciplinary design team instantaneously instead of having to wait for new simulations each time something is altered. Furthermore, this approach enables the use of statistical methods, such as sensitivity analysis where the most important parameters and their preferred spans can be identified, to get an efficient building design. The method has been tested with a normative simulation model and as stated by Østergård et al. [2017] it is only hypothesised that the method also works with more advanced calculation tools.

Building simulations are most commonly conducted after architects and owners have decided on the basic design while it might be more efficient to use simulations to guide the basic design. One of the challenges is being able to conduct simulations with very limited information of the building, which is why it is often done later when more information is obtained. Furthermore, the building simulations are mainly used for documentation of whether regulations are met or not. They do not provide any guidance whether to increase or reduce e.g. the window area. In the early design stages such guidance is very important, [Attia et al., 2012a]. Usually deterministic approaches are used to optimize the building performance where only few alterations are tested. This results in a very localized design space where the optimal solution might not have been explored.

When performing advanced dynamic simulations of a buildings indoor environment and energy usage, it is normal practice in Denmark to only simulate parts of the building. This could be critical rooms which are likely to overheat and/or a few representative rooms. The whole building is then designed from those results, [DS 474, 1993]. This is done to reduce the workload and therefore also the money that has to be invested. But the approach makes the design space even more local as it only reflects a part of the building.

One problem that occur when considering the global design exploration which is the time consuming process where thousands of simulations have to be run. To reduce the time consumption one can consider which type of model is used, e.g. steady state versus dynamic. Furthermore the complexity of the model can be of interest, whether to use a single zone or multiple. These considerations are methods where the simulation tools overall complexity is considered, another way to reduce the time consumption is to increase the processing power of the computers that run the simulations. Here a relatively new option has come into practical use which can drastically reduce simulation time. This is the option to use cloud computing where simulations are not run locally on the computer but rather on rented computers through the use of internet. This leaves the option to get huge processing power.

## 1.1 Problem Statement

This thesis focuses on guiding the design team in the early stages of building design. In the early design phase a lot of decisions have to be taken and while most of these decisions revolves around the actual design of the building, another decisions is the choice of building simulation tool. If the design team chooses to use the global design space approach by performing stochastic simulations it requires a simulation tool in which the thousands of simulations can be run. Choosing the right tool for the project is hard if the possibilities are unknown to the design team. Below are listed some of the questions linked to the choice of tool.

- Is it enough to use a simple quasi-steady-state simulation tool or is an advanced dynamic simulation tool required?
- How many zones should be used and how to divide them in the building energy model?
- Is cloud computing a viable option in its current state for global design exploration of buildings?

This thesis seeks to elaborate on the different possibilities in order to guide design teams in choosing the building energy modelling (BEM) tool that is most suitable for the building project.

Moreover to elaborate on the experiences drawn from using cloud computing with no prior knowledge. Knowing the different possibilities and the pros and cons of each choice, makes for an easier decision making process, which again leads to a more effective design process.

To elaborate on the possibilities, this study compares a number of models, modelled in both simple and advanced BEM tools. The analysis is conducted for two types of models, which is referenced to as static facade and dynamic facade in this thesis. The difference between the two, is that the dynamic facade contains automatic controls for artificial lighting and solar shading where the static facade have none.
The dynamic facade is included as most offices are equipped with some sort of shading device either interior or exterior to block/decrease solar radiation and to reduce glare. So tools must be able to guide the design of such buildings.
The static facade is included to investigate if such building types allow for simpler models than that of buildings with the dynamic facade and also to provide the same level of guidance for static facade buildings as for dynamic facade buildings.
An overview of the compared model types are shown in figure 1.3.

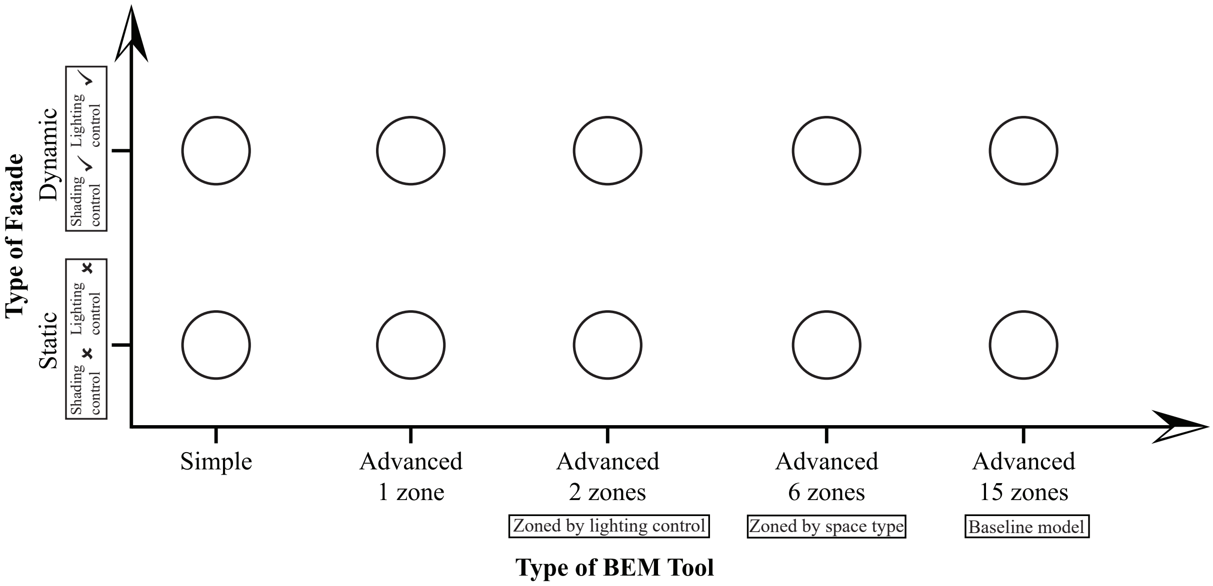



***Figure 1.3.*** Overview of the model types analysed in this thesis. The simple BEM tool uses quasi-steady-state calculations and advanced tools use full dynamic calculations. The baseline model is the one the others are compared with.

The main difference between a simple and an advanced BEM tool is the calculation method. Overall there is two basic methods that tools can utilize, quasi-steady-state and dynamic. [DS/EN ISO 13790, 2008]
Simple tools are modelled with the quasi-steady-state method and advanced tools are modelled with the dynamic method.

The quasi-steady-state method calculates the heat balance over a long time, typically one month. This enables accountability of dynamic effects by using empirically determined utilization factors. The dynamic method calculates the heat balance over short user defined time steps, typically per hour, while accounting for the heat stored and released from the buildings mass.
The difference are further described in detail in appendix B and A for simple and advanced respectively.

## 1.2 Literature Review

Not much literature exists that guides design teams in choosing building energy modelling tools and how to use the tools in the optimal way. However some studies do provide guidance in choosing between some of the many tools currently on the market.

A study by Crawley et al. [2006] compares twenty major building energy modelling tool's features and capabilities. The comparison is divided into categories e.g. general modelling features, daylighting and infiltration and HVAC systems. The information about the specific tools features and capabilities is provided by the tool developers. The result of the study, is a series of tables, one for each category, where the tools features and capabilities are shown. One of the tables are shown in figure 1.4.

| ***Table 1 General Modeling Features*** | BLAST | BSim | DeST | DOE-2.1E | ECOTECT | Ener-Win | Energy Express | Energy-10 | EnergyPlus | eQUEST | ESP-r | HAP | HEED | IDA ICE | IES <VE> | PowerDomus | SUNREL | Tas | TRACE | TRNSYS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ▪ Multi-sided polygons | | X | X | X | X | P | | | X | X | X[21] | | X | X | X | | | X | | |
| Import building geometry from CAD programs | | X[22] | P | | X | | X[22] | | X | X | X | P[23] | | X[24] | X | X[25] | | X | X | X[26] |
| Export building geometry to CAD programs | | | | | X | | | | X[22] | | X[27] | | | | X | | | X | X[28] | |
| Import/export model to other simulation programs | | | | | X | | | | X[29] | | X[30] | | | | | | | | | |
| Number of surfaces, zones, systems, and equipment unlimited | | X[31] | X | | X | | | | X | X[32] | X[33] | X[34] | X[35] | X | X | X | | X | X | X[36] |
| Simple building models for HVAC system simulation | | | | | | | | | | | | | | | | | | | | |
| ▪ Import calculated or measured loads | | | E | | [3] | | | | X | X | X | | | X | | | | | X | X |
| ▪ Simple models (single lumped capacitance per zone) | | | | | | X | | | | | X | | | | | | | | | XO[37] |

***Figure 1.4.*** The table containing the capabilities and features of the twenty tools in regards to the first category, general modelling features. [Crawley et al., 2006, Table 1]

The tables are useful to design teams that knows which features and capabilities that is needed for the project. It is only a matter of going through the tables and finding the tool that is best suited. Furthermore they state that based on their experiences, users generally rely on a single simulation tool where it may be more optimal to use several, that fits the different stages of building design. While this is a good way of guiding the overall choice of tool it does not provide any guidance as to how many zones should be used once a tool is chosen.

A different approach has been used by [Attia et al., 2012b]. They found the five major topics that the simulation community discuss about the tools and conducted a survey among architects and engineers to investigate the differences in tool preference and what features are most important. The five topics are shown below:

- Usability and information management of interface
- Integration of intelligent design knowledge-base
- Accuracy of tool and ability to simulate detailed and complex building components
- Interoperability of building modelling
- Integration with the building design process

The survey included several questions relating to the overall five topics and had 445 participating architects and 453 participating engineers. The study provides some insight about what is important when choosing a design tool to guide both engineers and architects. Figure 1.5 shows the results from one of the questions regarding the first topic.

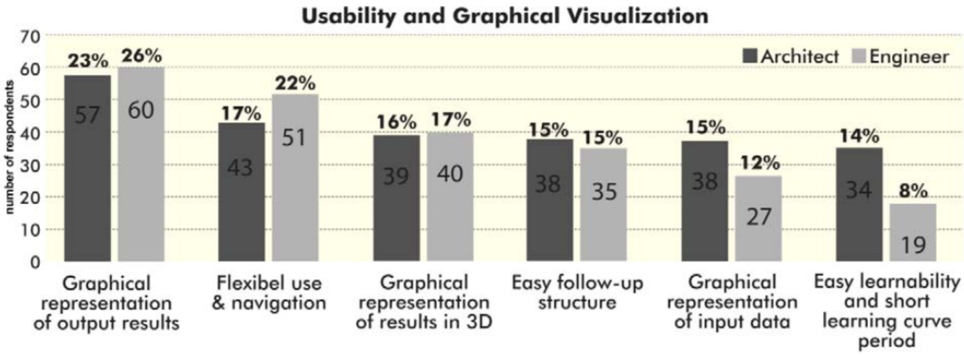



***Figure 1.5.*** Question concerning usability and graphical visualization of building energy modelling tools. [Attia et al., 2012b, Figure 6]

As the figure shows, the graphical representation of output results is important to both engineers and architects. This is important to have in mind when choosing which simulation tool to use. Together with the rest of the answers to the survey, the study provides an inside to what features and preferences are most important to both engineers and architects while also showing the differences between the two. This is important for the early building design phase to improve the collaboration in the design team.

A study by [Rivalin et al., 2014] investigated the influence of building zoning on the annual energy demand. They focused on a 4100 m$^2$ real office building with five floors. The building were modelled using 49 zones, 44 zones, 26 zones, 21 zones, 11 zones and 1 zone. The results are shown in figure 1.6.

| | **Total heating demand (MWh)** | **Total cooling demand (MWh)** |
|---|---|---|
| **49-zone model** | 87.6 | 85.3 |
| **44-zone model** | 86.8 (-1%) | 86.2 (1%) |
| **26-zone model** | 86.6 (-1%) | 86.4 (1%) |
| **21-zone model** | 87.4 (0%) | 85.8 (1%) |
| **11-zone model** | 88.7 (1%) | 84.1 (-1%) |
| **1-zone model** | 93.1 (6%) | 95.9 (11%) |

***Figure 1.6.*** The annual energy demand for heating and cooling for the different models. [Rivalin et al., 2014, Table 2]

They conclude that, except for the single zone model, less zones does not significantly affect the results but does influence the modelling time significantly. The deviation obtained from the single zone model is acceptable in cases where modelling time is lacking and only an approximate result is needed, such as in early design phases. But the deviation is too high for detailed studies of a buildings energy demand. The study provides an easy overview of the deviation from simplifying zones and how those simplifications affect the simulation time which can help choose the amount of zones the building designer should chose. Though this study is conducted on a single building with almost no design alternatives meaning that it does not provide any statistical results. As a result of this, it is unknown if the sensitivity of parameters or parameter tendencies on the outputs change when simplifying from 49 zones to 1.

Several studies exist that evaluate the accuracy of simple building energy modelling tools compared with advanced. [Jokisalo and Kurnistski, 2007], [Corrado and Fabrizio, 2007] and [Kokogiannakis et al., 2010] all asses the accuracy of the simple calculation method based on [EN ISO 13790, 2008]. Young-Jin et al. [2013] compares the heating and cooling consumption calculated with EnergyPlus and a simple monthly calculation using [EN ISO 13790, 2008]. The investigation is conducted on a five storey office building where a set of inputs are varied stochastic. The investigation compares the models by performing a two-sample t-test with a significance level of 5 % on the distribution functions for heating and cooling. The investigation show that the is a significant difference between the distribution between [EN ISO 13790, 2008] and EnergyPlus.

[Christensen et al., 2013] compares a simple BEM tool (Be06), based on DS/EN ISO 13790 [2008], with IES-VE and measured data for a six month period. The study uses a confidence interval based on IES-VE to determine the accuracy of the simple model. The investigation shows that the energy consumption calculated with the simple model for the six month is within the confidence interval, but individually some month are not.

These above mentioned studies focuses on the accuracy of the models and does not investigate the parameters influence on the heating and cooling consumption which is of very high importance in order to guide design teams in early design phases. Building energy modelling tools ability to provide guidance for design teams in the early design phases is more important than accuracy according to a survey among 230 architects by Attia et al. [2012a].

# Method 2

*This chapter contains a description of the method used for analysing simple and advanced building energy modelling tool's ability to provide useful guidance in the early stages of building design.*

As stated in the previous chapter this thesis compares a number of models, modelled in both simple and advanced BEM tools. The methods used in this thesis are described in the following sections and includes the use of the Monte Carlo method, modelling procedure and data analysis.

## 2.1 Monte Carlo Method

The investigation of the models are conducted using the Monte Carlo method where a set of input parameters are used in a model, which in this thesis is the BEM tools. Each set of inputs generate a set of outputs. The input is generated stochastically from a probability density function using Latin Hypercube Sampling (LHS). The principle of the Monte Carlo method is shown in figure 2.1.

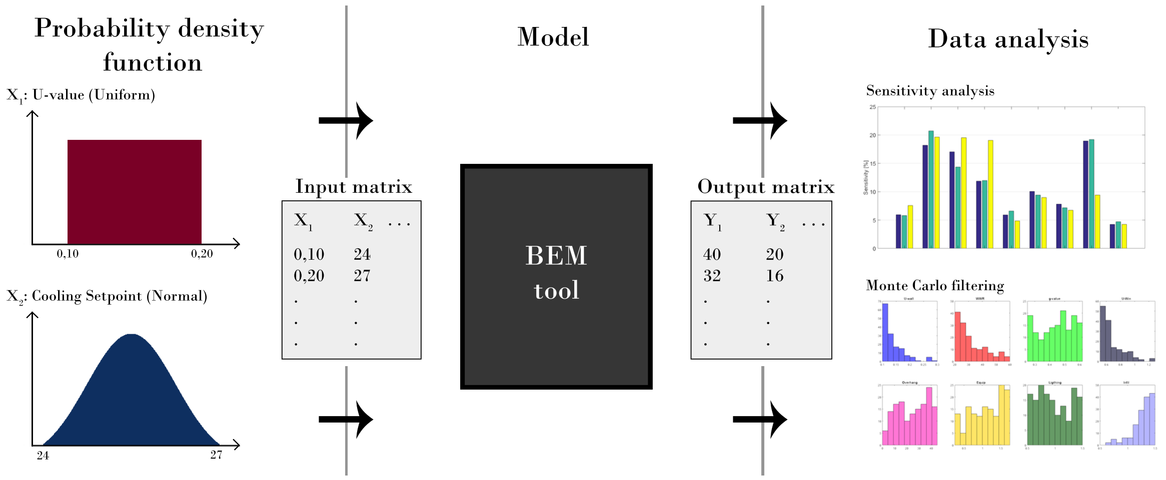



***Figure 2.1.*** The principle of the Monte Carlo method.

LHS is a quasi-random sampling method. When sampling a function of e.g. two variables five times, each variable is divided into 5 equal intervals within their respective ranges. A random value is then generated for each interval. The name comes from a Latin Square which is a square with a grid of sample spaces containing only one sample in each row and each column. LHS uses this concept but with an arbitrary number of dimensions. An example with two variables and two and five samples respectively is shown in figure 2.2.

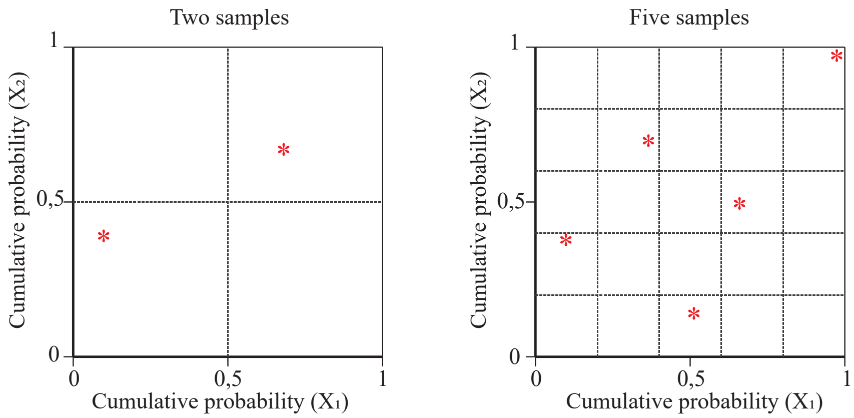



***Figure 2.2.*** The principle of the Latin Hypercube Sampling method.

## 2.2 Modelling Procedure

A flowchart of the modelling procedure is shown in figure 2.3. This provides an overview of what is required to perform stochastic simulations with both the simple and the advanced BEM tool used in this thesis. More about the choice of BEM tool is described in chapter 3.

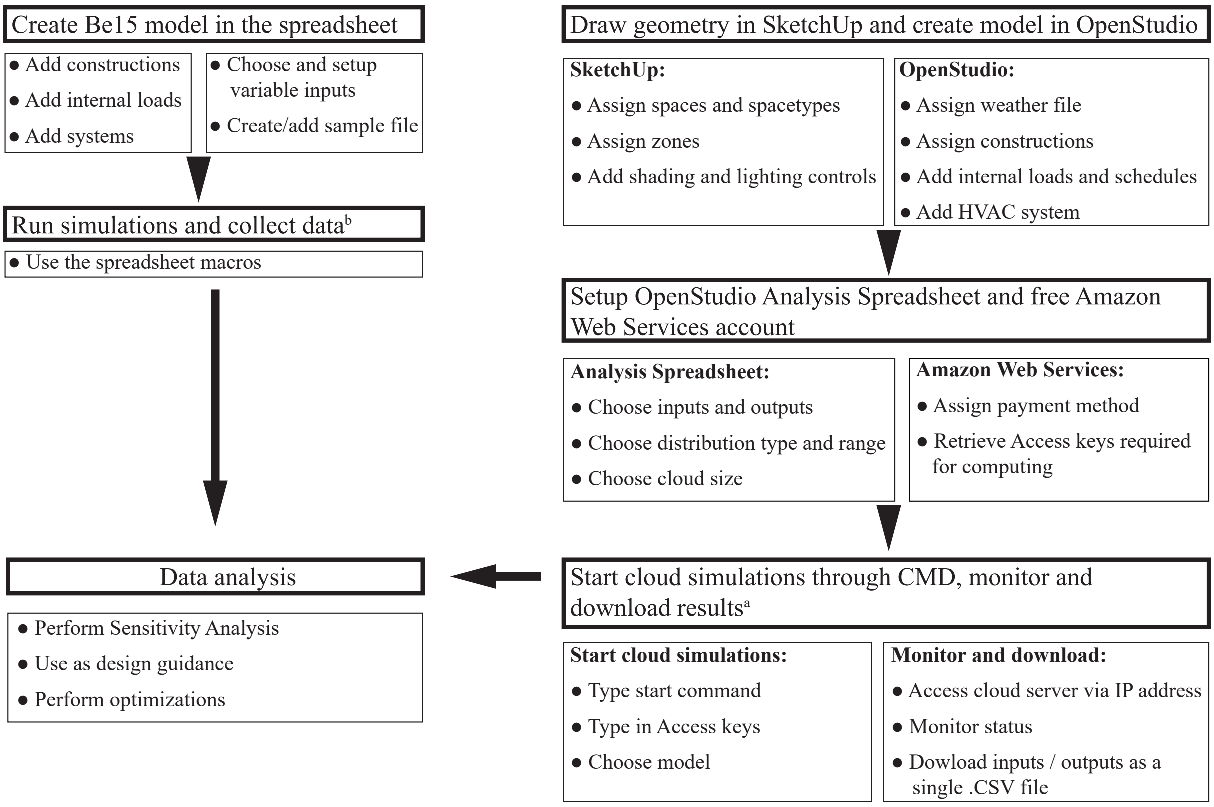



***Figure 2.3.*** Flowchart of the modelling procedure for the advanced (OpenStudio) and the simple (Be15) BEM tool. [a] Further described in appendix A. [b] Further described in appendix B.

This study uses cloud computing for the advanced models, as shown in figure 2.3. Using cloud computing for this study will provide experiences that can be drawn from to guide design teams in what they should know in order to capitalize on cloud computing for global design exploration.

The input structure for simple and advanced BEM tools can differ significantly this means that some inputs are difficult to make completely identical. In situations where this occur, the input is approximated to what is required for the model. An example of this could be the surface coefficient. In advanced BEM tools it is often calculated and different values are used for each time step where in a simple model a constant value is used. The models that are compared are shown in figure 2.4. The shown floor plans are from the case building.

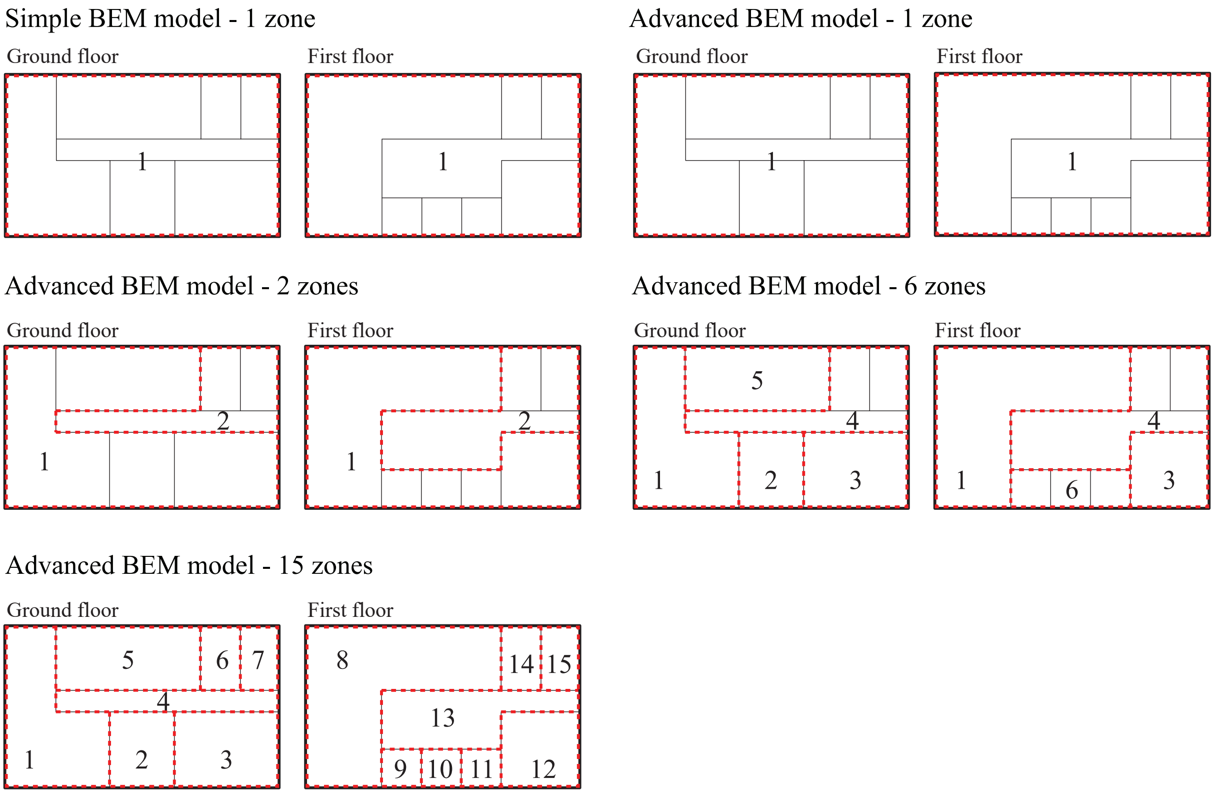



***Figure 2.4.*** Overview of the models that are compared. The numbers and the red dashed lines indicate zones that the building is divided into.

The advanced model with 15 zones is the one used as baseline model and considered as the correct result which the other models are compared against.
To provide guidance connected to how many zones a building should be divided into, the case building is divided into 1, 2 and 6 zones. The model with a single zone is included to investigate the extreme opposite to the model where all spaces are modelled with a zone each. Modelling the entire building as one zone is also where the biggest difference is expected and is of interest when providing guidance.
The two zone model is included for investigating the control of artificial lighting more in depth. The idea is to have one of the zones contain all space with lighting control and the other zone contain all spaces without lighting control.
The six zone model is included as it merges zones of similar space types, e.g. both conference rooms are included in the same zone. This is a simple way of reducing zones which is why it is included in this study.

Seeing as the simple BEM tools have limited capabilities regarding the indoor environment compared to the advanced, it is chosen only to compare the energy consumption. In order to do that, the indoor environment is kept within the same boundaries for all models. The temperature set-point is between 22 °C and 25 °C which ensures high productivity for occupants, [Kasper

Lynge Jensen, 2006]. Moreover this is done to reduce the amount of outputs to consider when comparing the models.

The following outputs are examined on a yearly basis when investigating if the simplified models can be used as guidance in early design phases with both types of facade:

- For the static facade type:
  - Heating consumption [kWh/m$^2$ year]
  - Cooling consumption [kWh/m$^2$ year]
  - Total energy consumption (heating, cooling and lighting) with primary energy factors [kWh/m$^2$ year]
- For the dynamic facade type:
  - Heating consumption [kWh/m$^2$ year]
  - Cooling consumption [kWh/m$^2$ year]
  - Lighting consumption [kWh/m$^2$ year]
  - Total energy consumption (heating, cooling and lighting) with primary energy factors [kWh/m$^2$ year]

The lighting consumption is added for the dynamic facade models to get a clearer understanding on the influence that the different parameters have on the lighting consumption and for validating the placement of the lighting control.

Only these are investigated since the energy consumption for lighting (static), equipment and the fan are kept the same for the each model. All other outputs that does not interact with the cooling and/or the heating consumption are not investigated as for example pumps.

## 2.3 Data Analysis

Directly comparing the raw results from the models alone will not necessarily yield adequate information to determine if the BEM tools can provide reliable guidance in the early design phases. Furthermore guidance from the BEM tools is more important than the accuracy in the early design stages, [Attia et al., 2012a]. Three criteria are set up which must be met for the tools to be deemed suitable. The criteria are as follows:

- The energy consumption for 95 % of the simulations must remain within ± 20 % of the baseline model.
- Changes to the input parameters must yield the same tendencies on the output results as that of the baseline model.
- The influence each input has on the output must be ranked the same as for the baseline model.

Without any limits to the difference between the baseline models and the simplified models, the second and third criteria could be met, but the obtained energy consumption could be completely wrong and lead to wrong decisions. Allowing for 5 % of the simulations to not comply with the criterion makes it so that a few outliers are not enough to deem a BEM tool unsuitable for design. The criterion is set to ± 20 % difference as the accuracy is not the most important factor in early design phases though it is important to some extend, which is why it is not set higher. Kim et al. [2008] show that there is no statistical significant difference in LEED-EAc1

score (building performance ranking) with a simple monthly calculation compared with a detailed dynamic simulation program when the results are within 20 % of each other. This indicates that *pm* 20 % is an acceptable criterion.
The third criteria about rankings is set due to the importance of knowing which parameters are influencing the building the most. If a building is cooling dominated a correct ranking could state that WWR, SHGC and infiltration is the most important, and the design team can adjust these parameters to optimize the design. But if it wrongfully states that U-value for walls and windows is the most important and the design team optimize based on that information, the design might end up worse than to begin with. This is the reason why the ranking of parameters must be correct and is therefore included as the third criteria.
The sensitivity analysis used to examine the third criteria does not provide any information whether the energy consumption is increasing or decreasing when changing an input and thus the second criteria is also necessary.

Scatter plots, Pearson correlation coefficient (PCC) and histograms of the inputs distribution are used to determine if the second criterion is met. The scatter plots is a qualitative method for examining the tendencies while PCC is a quantitative method. Because PCC is a linear correlation method it is only used to get a negative/positive correlation for the sensitivity and not for the sensitivity values themselves. The correlation directly shows if the input parameters yields the same tendencies.
The histograms are used for showing the distribution of the remaining inputs after removing some of the simulations according to filters applied on the outputs.

To analyse the third criterion, a sensitivity analysis (SA) is used to determine the influence that the variable inputs have on the outputs and to determine the ranks of the inputs parameters. The SA used in this paper is a newly developed method called "TOM" created by Østergård [2017]. The method is a regionalized sensitivity analysis where Monte Carlo filters are applied to parameters to split the simulations into behavioural and non behavioural simulations. TOM is based on Kolmogorov-Smirnov two-sample test where the distance between the cumulative distribution function of the filtered behavioural and non behavioural simulations are measured as an indication of the sensitivity of an input. The advantage of TOM is that it does not require specific sampling methods and is capable of calculating sensitivity of inputs according to multiple output parameters. [Østergård, 2017]

# Building Energy Modelling Tools 3

*This chapter describes the pros and cons of one simple BEM tool and two advanced BEM tools. From these it is concluded which tools to use in the thesis.*

As mentioned, this thesis revolves around stochastically comparing a simple BEM tool with an advanced BEM tool. Several tools exist on the market and choosing between them is not an easy task. This chapter aims to describe a few possible BEM tools and list their individual pros and cons, to provide an overview of their possibilities. Based on this, the tools used for this thesis is chosen.

The tools must be able to perform stochastic modelling using the described Monte Carlo method. Furthermore, the advanced models must have multi zone support. Since both models with static and dynamic facade is investigated the BEM tool are required to have lighting and shading control.
The advanced tools under consideration are BSim and OpenStudio and are chosen based on availability. BSim is considered because we have prior experience with it, as it is taught and used at Aalborg University.
At first glance OpenStudio seems like a promising BEM tool in the industry for stochastic modelling with cloud computing, which is the reason for considering it.
For the simple tool only Be15 is considered.

## 3.1 BSim

BSim is the commonly used tool for indoor environment and energy consumption analysis in Denmark. It contains a fairly user friendly interactive view where building geometry, systems, thermal zones, constructions and their properties can be selected. The tool in itself does not support stochastic modelling. A recent study by Bonde et al. [2016] developed an excel document containing the simulation core of BSim that are able to conduct stochastic modelling of a single zone, so additional programming is necessary in order to use BSim for multiple zones.

Pros:

- Cheap
- Input database
- Ideal airloads system
- Simple inputs for systems
- Good presentation of output results

Cons:

- Does not support geometry import
- Can not model real systems
- Poor technical support
- Requires external tools for stochastic modelling
- long simulation time

## 3.2 OpenStudio

OpenStudio (OS) is a collection software tools used for whole building energy modelling. OS is a comprehensive graphical interface for EnergyPlus. The OS collection includes a result viewer tool where the results can be inspected and plotted in graphs. It also includes a tool called Parametric Analysis Tool (PAT) that is meant for stochastic modelling. But, at the time of writing this thesis, it is still in early development and only supports one-at-a-time (OAT) parameter variation which is not useful for the thesis. But the developers have created a spreadsheet that is able to perform global parameter variation via cloud computing the downside being that the spreadsheet is in very early development and can take time to understand. Future plans for the developers of OS are to incorporate the functions of the spreadsheet into the PAT tool, making it much more user friendly.

Pros:

- Free and open source
- Input database
- Great technical support
- Measures
- Good presentation of output results
- Uses SketchUp for geometry
- Supports import of geometry
- Supports stochastic modelling
- Supports cloud computing

Cons:

- No proper ideal airloads system
- $CO_2$-concentration not working
- No interaction between solar shading and lighting control
- Measures might be wrong/make mistakes
- Requires complicated inputs for systems
- Long simulation time
- Difficult to obtain individual models via cloud computing

A more detailed description of OpenStudio is included in appendix A.

## 3.3 Be15

Be15 is a Danish tool created for calculating the energy use of a building and it is mandatory to document the energy use with Be15 in order to obtain a building permit in Denmark. Be15 calculates the energy consumption based on monthly averaged values according to DS/EN ISO 13790 [2008]. Everything is calculated as one zone with no options for multi zone modelling.
Be15 does not support stochastic modelling and must be used in conjunction with an excel spreadsheet.

Pros:

- Very short simulation time
- Simple inputs
- Simple outputs

Cons:

- No proper indoor environment calculations
- Lighting control requires known daylight factors
- Poor technical support
- Requires external tools for stochastic modelling

A more detailed description of Be15 is included in appendix B.

## 3.4 Part Conclusion

It is chosen to move forward with OS as the advanced tool based on the above and a personal curiosity to explore the possibilities that OS offers. The above descriptions shows that OS have a lot to offer but is not that easy to learn and have a semi long learning curve compared to BSim that is already known.
Another reason for choosing OS is to explore its possibilities. OS includes some new features which makes OS stand out, such as incorporating measures into the modelling work flow and also developing a tool which can be used for large scale analysis where BSim have nothing of the sorts. OS also utilizes cloud computing for the large scale analysis which also opens up new possibilities and work flows. Also alot more development is put into OS than BSim which is a sign that it could replace BSim on the Danish market.

There is also the fact that BSim does not provide the ability to run Monte Carlo simulations with multiple zones without creating new automated procedures for it. This is one of the biggest reasons for not choosing BSim.

Be15 is chosen as the simple tool as it is the only simple tool considered in this thesis due to it being mandatory in order to obtain a building permit in Denmark. Since it is a mandatory part of the building process in Denmark the programs potential to be used in early design stages is of interest.

# Case Description 4

*This chapter contains a description of the case building used for the study. Plan drawings, internal loads and systems are described and the inputs chosen as variables are listed.*

The case-building is a fictive two storey office building designed for this study. Seeing that the purpose of this study is to compare the results from the BEM tools, it does not matter if the building is real or not, as long as the model is identical for both tools. The chosen case-building is created to reflect what is considered a "normal" office building. The building is shown in figure 4.1.

The case building is designed as a two storey office building with various space types. A big diversity of the space types is desired while still keeping the building realistic. Various space types means various internal loads and system demands for each space, which is important when comparing models with different amount of zones. If all spaces were the same, it is more likely for a single zone model to do well compared to a multi zone model. Also the building is designed in such a way that the heating and cooling consumption is equal meaning so that when varying parameters, models with varying heating and cooling consumption occurs. E.g. models with high heating and low cooling consumption and vice versa. Having these different combinations of heating and cooling consumption ensures that the results obtained in this thesis can be used for more buildings and therefore also by more design teams.

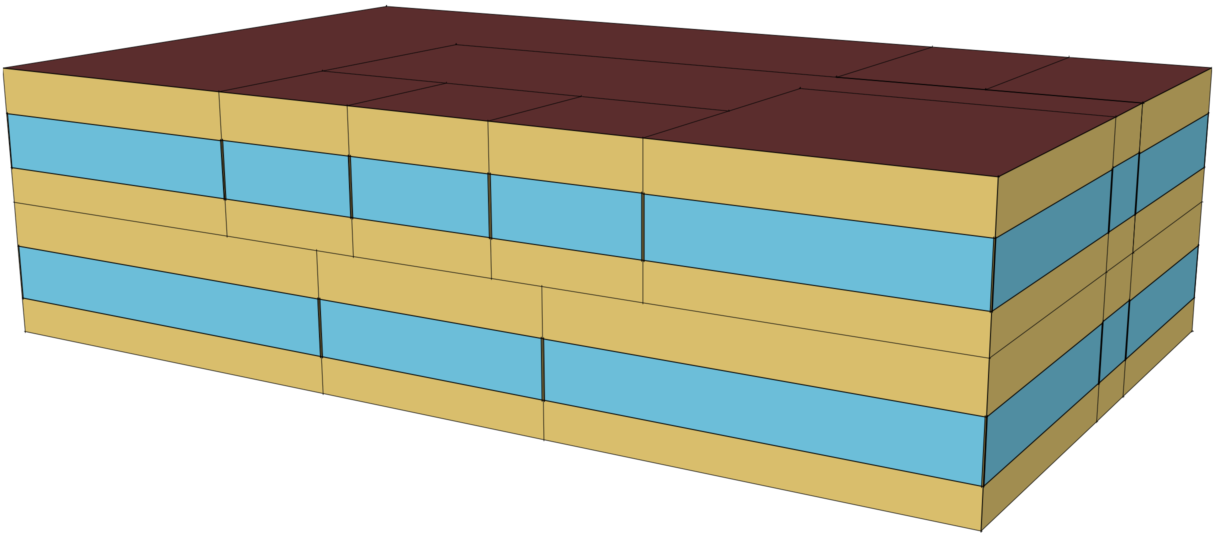


***Figure 4.1.*** SkethUp model of the building used for the study.

The building has a net floor area of $572\,\mathrm{m}^2$, $286\,\mathrm{m}^2$ per storey. It contains spaces normally found in office buildings. The constructions used for the building are shown in table C.1 in appendix C.1 together with detailed compositions of each construction. The windows in OS have no frame due to the way it handles window constructions when using measures to change the size. Because of this, the frame is removed in Be15 as well.

The thermal mass of the building is calculated dynamically in OS and is not available as output, so the thermal mass input in Be15 is assumed to 90 Wh/K $m^2$ which corresponds to a medium heavy building.

Plan drawings for the ground floor and the first floor of the building are shown in figure 4.2.

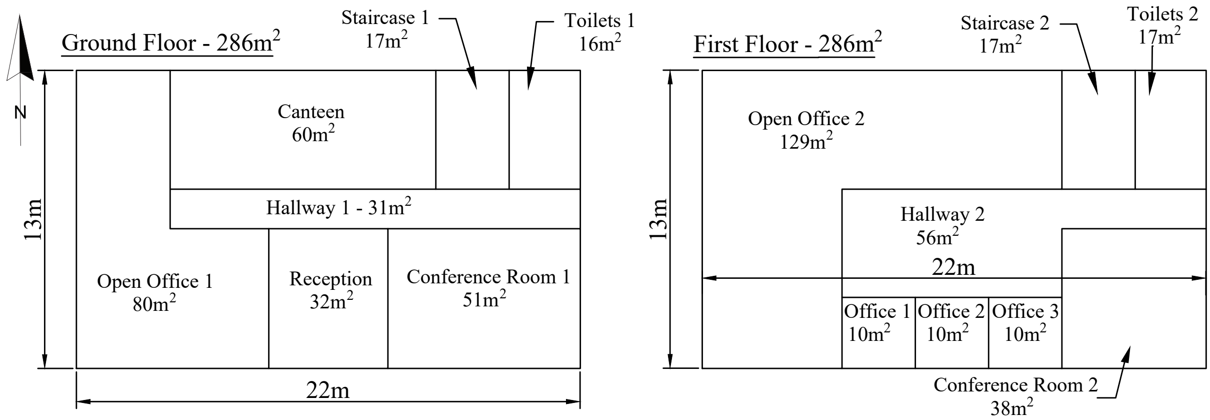



***Figure 4.2.*** Floor plans of the case building.

## 4.1 Internal Loads and Systems

This section contain essential information about the internal loads and the systems used for the models, further information is available in appendix C.2.
The occupied hours for the building is from 8:00 to 17:00, 7 days a week. During this time it is assumed that people are present and equipment and lighting are active. The heating and cooling system is active at all times with a set-point of 22 °C and 25 °C respectively.

The building is equipped with balanced mechanical ventilation with a specific fan power of 1800 j/$m^3$, a heating coil and a direct expansion (DX) cooling system which uses an expansion/compression cycle to directly cool the supply air to the desired temperature. The cooling system is allowed to recirculate indoor air if needed and the fan is modelled to not release any heat to the inlet air. This configuration mimics the use of passive chilled beams. The DX cooling system is active at all times, as mentioned above, while the heating coil is active during occupied hours so heating demands are covered by convective space heaters the rest of the time. An COP factor of 1 is used in all models to obtain the actual cooling demand instead of the electricity demand for the system.

The infiltration is set according to Aggerholm and Grau [2014]. It states that 0,13 l/s $m^2$ must be used during occupancy and 0,09 l/s $m^2$ must be used when unoccupied, unless documented by measurements.

The people load in the building is based on the suggestions in DS/EN 15251 [2007, Table B.2] which also dictates the suggested ventilation flow rates. The people loads are input as a daily averaged value, for each space, based on the schedules shown in appendix C.2.

It is assumed that only workspaces contains equipment and therefore the toilets, hallways and staircases does not have any equipment load. The equipment load is 6 W/$m^2$. The lighting load is assumed higher in workspaces (6 W/$m^2$) to comply with regulations and the rest of the building is bit lower ($5\,\text{W/m}^2$). For the dynamic model types, lighting controls are added. This is further described in the following section.

The base values for ventilation flow rates, infiltration flow rates and all the loads are shown in table C.8 in appendix C.3.

## 4.2 Automatic Controls for Lighting and Solar Shading

### 4.2.1 Lighting Control System

For the dynamic facade models, lighting control is added. Adding lighting control brings a dynamic input to the simulations while adding an interesting discussion of where to place the reference points, as only one point can be placed for each zone. This means that the single zone model can only have one reference point and the placement of it can have significant influence on the results.

The lighting control have a set-point of 300 Lux and are continuously controlled from 0-100% with a standby usage of 10 % of max power. The hallways, toilets and staircases does not have lighting control.

The overall strategy for placing the reference points is to place them at half the width and 4/5 of the room depth into the room, which is assumed to be the edge of the working area where the set-point should be held at all times. The placement of the control points are shown in appendix C.4.

This approach is not possible for the single zone model because only one control point is allowed per zone. For the single zone model the control point is placed in the reception, cf. figure 4.2. The reason for placing it in a south facing room is to maintain the possible correlation between energy consumption for artificial lighting and the overhang.
By only having one zone and one control point, the whole building is controlled equally including the hallways, toilets and staircases. This means that the models are different but that is just one of the challenges with having daylight controls in single zone models.

The approach for Be15 is different as Be15 is unable to calculate daylight factors on its own. Be15 can include a control system if daylight factors are provided for each room where daylight control is wanted. These daylight factors are calculated in an excel spreadsheet based on Johnsen and Christoffersen [2008]. The procedure is described in appendix B.2 on page 61

### 4.2.2 Solar Shading System

The shading system in this study is placed on the outside of the building. Exterior shading systems excels at blocking direct solar radiation from entering the building to contribute to exceeding temperatures unlike interior shading systems. Though the exterior system is exposed to the outdoor climate, such as wind, which can cause problems. These problems are not investigated in this project.

The type of shading used is horizontal blinds. Blinds reflect solar radiation while also providing a view to the outside unlike screen shading which block the view completely. A cross-section of the shading system is shown in figure 4.3.

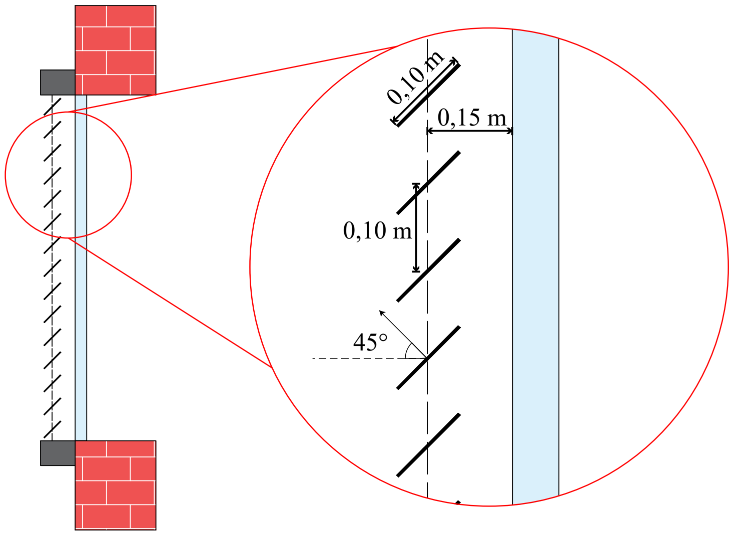



***Figure 4.3.*** Cross-section of the shading system. The shading system does not in any way count as an overhang in the calculations.

The system used in this study is controlled by the sum of direct and diffuse solar radiation on the window surface per square meter. The control set-point for the shading system is 450 W/m$^2$, meaning that whenever the sum of the direct and diffuse solar radiation exceeds this point, the shading system activates. There is no difference in shading for the single and multi zone models as the the shading is controlled by the set-point on each individual window. With a set-point of 450 W/m$^2$ the shading rarely actives when only diffuse solar radiation is present cf. appendix C.5. This correspond with the shading control used in Be15 which is controlled solely by direct solar radiation.

In Be15 a solar shading factor of 0,2 is used. This factor is an estimation as the actual shading value used in OS is calculated and not available as output. The used solar shading factor is estimated based on [Andersen et al., 2002, table 8.6].

## 4.3 Variable Inputs

Parameters with relatively high sensitivity are preferred when investigating the impact of the advanced and simple model. Choosing parameters with small impact on the outputs can create a situation where there is very little variance, which will make it harder to conclude which inputs causes the changes to the output. Furthermore if the parameters have low sensitivity the design space will be small. The selection of variable inputs for this study are based on prior knowledge, literature, small investigations and the availability of OS measures (cf. appendix A).

According to an investigation made by Østergård et al. [2016] the window to wall ratio (WWR), g-value (SHGC) of the window and ventilation flow rate are highly sensitive for the output. The ventilation rate is not varied since this would change the atmospheric indoor climate and this factor is not compared for the models.

An investigation of the window to wall ratio (WWR) and overhang are conducted due to an issue that occurs when sampling a set of four uniformly distributed parameters. The windows in OS is input with a given sill hight of 0,9 m and extends across the full width of the wall, so that increase or decrease in WWR only changes the window hight.

Varying the WWR and overhang of the four facades independently will result in an issue where the average WWR and overhang for the entire building will be almost the same in a large amount of simulation. This is a problem when trying to obtain a distribution covering a large amount of the design space. This means that it is necessary to either vary them all equally or to only vary a few facades while keeping the rest constant.

A sensitivity analysis shows that the sensitivities of WWR for each facade, when varied one at a time, are low and close to each other meaning that they have close to no impact on the building when changed individually. As for the overhangs, the south overhang is slightly more sensitive than north, west and east, which makes sense as the suns angle is much higher towards the south facade and overhangs does not have much impact when used on eastern, western or northern facades.
The investigation is described in further detail in appendix C.6. Based on this, it is decided to have the total WWR towards each facade as a variable instead of the individual facades and to only have overhangs on the south facade.

The variable inputs chosen for the study are shown in table 4.1. The variables are uniformly distributed within the ranges.

| Parameter | Unit | Min | Max | Base value | Unit |
|---|---|---|---|---|---|
| R-value multiplier wall(R wall) | [-] | 0,64 | 0,20 | 4,95 | [m$^2$K/W] |
| WWR[a] | [%] | 20,00 | 60,00 | - | - |
| SHGC | [-] | 0,25 | 0,62 | - | - |
| U-value window (U-win) | [W/m$^2$K] | 0,51 | 1,29 | - | - |
| Overhang projection factor south (OH) | [-] | 0,00 | 0,50 | 0 | [-] |
| Equipment multiplier (Equip) | [-] | 0,25 | 1,75 | 6/0 | [W/m$^2$] |
| Lighting multiplier (Light) | [-] | 0,50 | 1,50 | 6/5 | [W/m$^2$] |
| Infiltration multiplier (Infil) | [-] | 0,50 | 1,50 | 0,13/0,09 | [l/s m$^2$] |

***Table 4.1.*** The variable input parameters used to investigate the simple BEM. The variables are uniformly distributed. [a] WWR is uniform discrete distributed for the dynamic facade models.

The U-value for the wall is input directly in Be15, but for OS it is done differently due to the structure of the tool. It is changed by a multiplier on the total R-value (thermal resistance) of the wall, the range of the multiplier ensures a range on the U-value between 0,1 W/m$^2$K and 0,3 W/m$^2$K.
The U-value is not uniformly distributed across the range due to it being the inverse of the R-value. When calculating the U-value input for Be15 an exterior surface resistance of 0,04 m$^2$K/W and an interior surface resistance of 0,13 m$^2$K/W is used. [DS 418, 2011]

The range of variation for the window U-value is based on a list made by Energivinduer [2017] containing selected approved windows according to Danish regulations for dwellings. The minimum and maximum values from the list was chosen. The SHGC from this list is too high for offices where overheating is a common occurrence. Instead lower values for this is chosen.

The overhang projection factor is a factor that is multiplied with the hight of the window to obtain the length of the overhang. This correspond to a range for the overhang from 0$^\circ$ to 45$^\circ$. The windows are placed inline with the facade, so that the exterior wall does not add to the overhang.

The multiplier for equipment load is higher than the lighting load multiplier. This is based on the assumption that equipment loads vary more in office buildings than lighting loads do.

The infiltration is not a direct design parameter that is chosen to be a specific value aside from meeting building regulation requirement. But the infiltration is an uncertain parameter that can vary due to occupant behaviour and weather conditions, which is why it is included in this study with the range displayed in the table.

## 4.4 Weather data

The weather data used for the simulations is the EnergyPlus weather file for Copenhagen, U.S. Department of Energy [2017]. To validate if the weather file contains Danish climate it is compared with the Danish Reference Year (DRY) 2013, which is the mandatory weather data used for simulations in Denmark. The comparison revealed no significant differences and the weather data is concluded to be valid as Danish weather. The comparison results are shown in appendix C.7. The weather is converted from .epw to .xml, which is required for be15, by Jørgen Rose from the Danish Building Research Institute (SBi).

# Results 5

*This chapter contains the results of this thesis, from investigation eight different models ability to provide useful guidance in the early stages of building design.*

As described in chapter 1.1 on page 3, ten models are investigated to elaborate on the different possibilities of simple and advanced BEM tools in order to guide design teams in choosing what is most suitable for the building project. Furthermore, how many zones that are necessary to provide guidance in the early stages of building design are considered. Figure 5.1 shows the outcome of the investigations performed in this thesis.

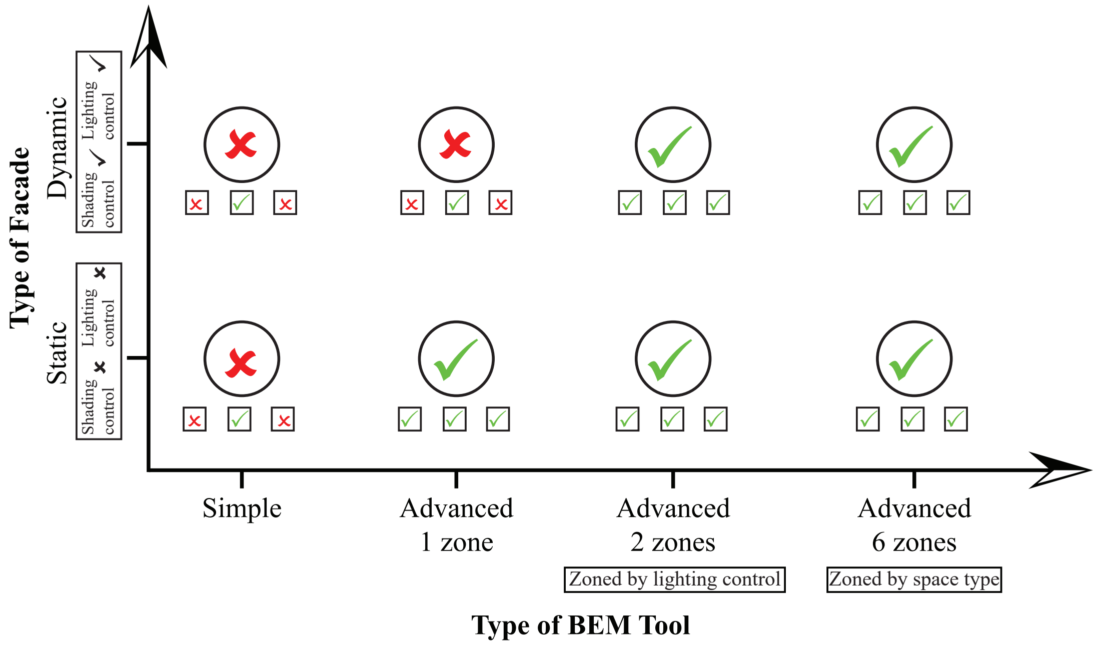



***Figure 5.1.*** Results on the BEM tool's ability to provide useful guidance in the early stages of building design. The results are based on three criteria (small boxes) which have to be met. The simple BEM tool uses quasi-steady-state calculations and advanced tools use full dynamic calculations.

The three small squares, under each model, represents each of the three criteria. This provides inside into which parts the models have problems. The three criteria are shown below, cf. chapter 2 on page 9 for additional information regarding the choice of the three criteria.

- The energy consumption for 95 % of the simulations must remain within ± 20 % of the baseline model.
- Changes to the input parameters must yield the same tendencies on the output results as that of the advanced BEM tool.
- The influence each input has on the output must be ranked the same for both the simple and advanced BEM.

The first criteria is analysed by a direct comparison of the energy consumptions, the second criteria is analysed with scatter plots, Pearson correlation coefficient (PCC) and Monte Carlo filtering while the third criteria is analysed with a sensitivity analysis called TOM. These methods are described in detail in section 2.3 on page 12.

Figure 5.1 shows that seven out of the eight models are suited for early design phases. The simple BEM tools fails both with static and dynamic facade due to it not meeting criteria 1 and 3. The model created in OS with dynamic facade and a single zone fails to provide the sufficient results to meet the first and third criteria.

Throughout this chapter the ten models used in the investigation will be referenced to as stated below. Subscripts s and d denotes static and dynamic models respectively.

- Advanced BEM Tool:
  - OpenStudio with 15 zones: $\text{Baseline}_{\text{s}}$ / $\text{Baseline}_{\text{d}}$
  - OpenStudio with 1 zones: $\text{OS}_{1\text{s}}$ / $\text{OS}_{1\text{d}}$
  - OpenStudio with 2 zones: $\text{OS}_{2\text{s}}$ / $\text{OS}_{2\text{d}}$
  - OpenStudio with 6 zones: $\text{OS}_{6\text{s}}$ / $\text{OS}_{6\text{d}}$
- Simple BEM Tool:
  - Be15: $\text{Be15}_{\text{s}}$ / $\text{Be15}_{\text{d}}$

## 5.1 Heating, Cooling and Lighting Consumption

This section contains the results from the investigations shown in appendix in appendix D and F which contains a step-by-step investigation of the criteria for the 5 static facade and 5 dynamic facade models. A total of 5000 simulations are used for each model for this study, this is proven to be more than enough based on a convergence study shown in appendix E.1. The reason for simulating more than necessary, according to convergence, is to reduce noise when investigating the criteria.

### 5.1.1 Annual Consumption

The annual consumption of heating and cooling for the 8 models are compared with the baseline models and are shown in figure 5.2 and 5.3 respectively. The lighting consumptions of the dynamic models are compared in figure 5.4.

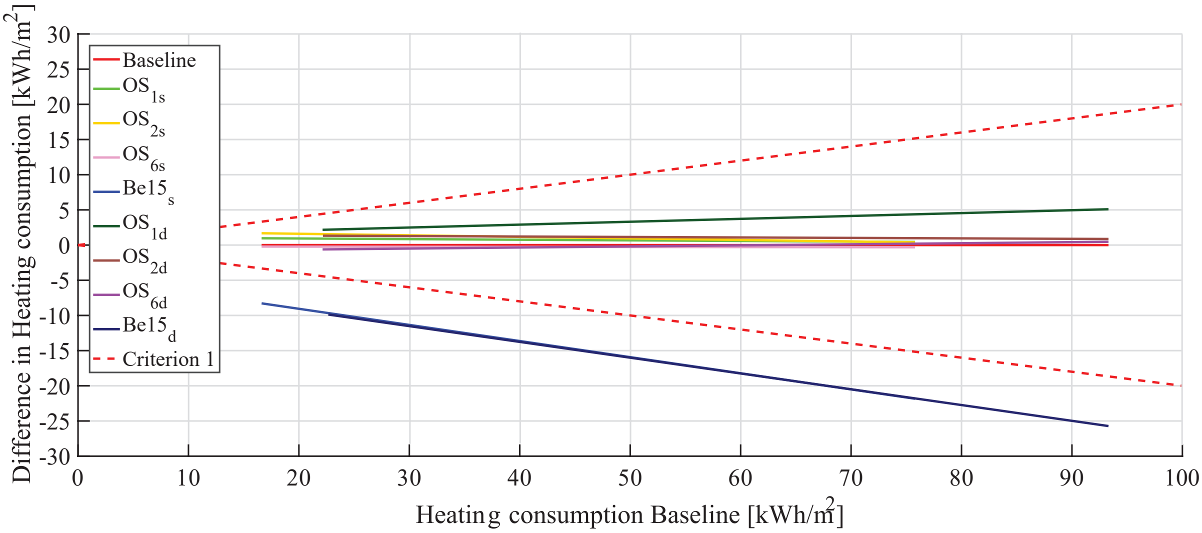



***Figure 5.2.*** Heating consumption from the static and dynamic Baseline models compared with the remaining eight models. Data is represented by linear fits.

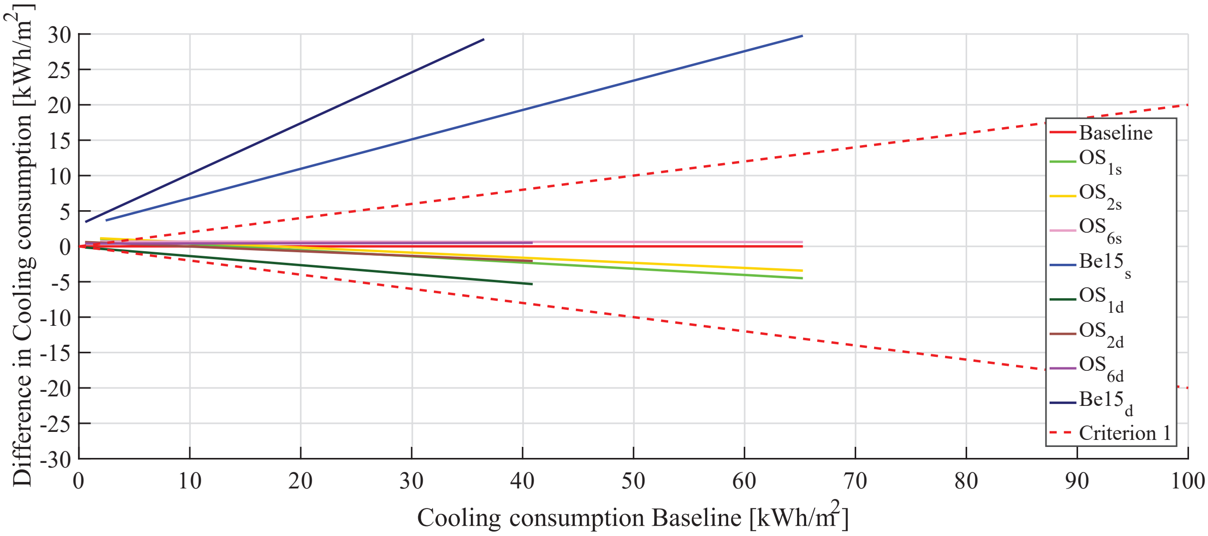



***Figure 5.3.*** Cooling consumption from the static and dynamic Baseline models compared with the remaining eight models. Data is represented by linear fits.

The figures shows that the heating and cooling consumption for the simplified models are very close to the Baseline models with the exception of $Be15_s$, $Be15_d$ and $OS_{1d}$. Be15 underestimates the heating consumption by almost the same amount for both types of facade. The reason why these are so close is because the heating is almost only required outside the occupied hours and the dynamic facade is mostly active during occupied hours. Be15 overestimates the cooling consumption for both static and dynamic facade, but $Be15_{1d}$ more than the other. This could indicate that Be15 overestimate the solar heat gains. The difference between $Be15_s$ and $Be15_d$ is caused by the shading and lighting controls. Lighting has limited influence on the cooling consumption as shown in appendix H.3 which means that it is mostly caused by the shading control.

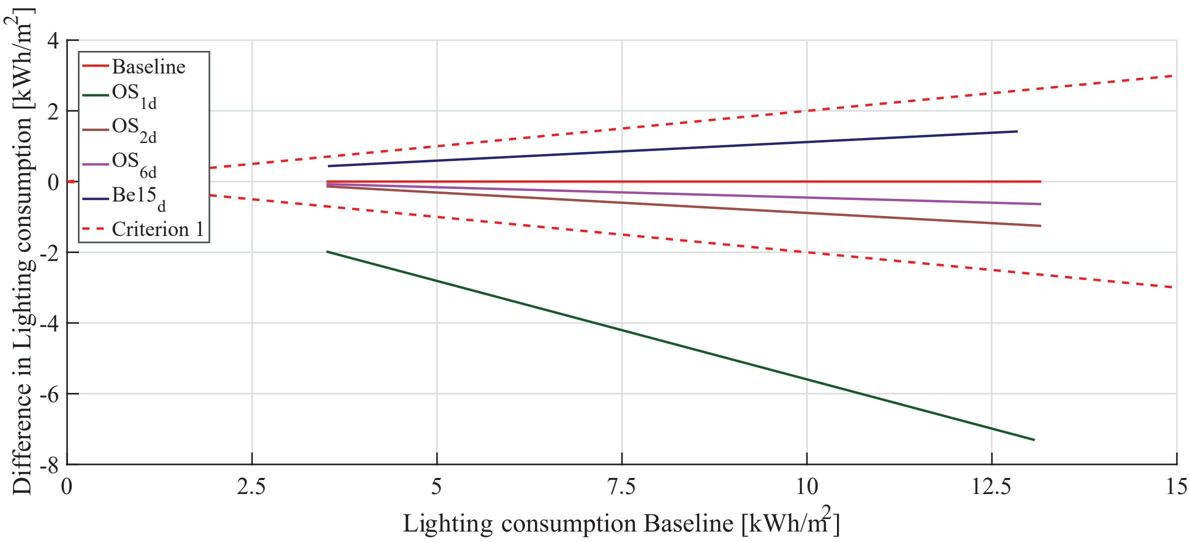



***Figure 5.4.*** Lighting consumption from the dynamic Baseline models compared with the remaining four models. Data is represented by linear fits.

The figure shows that $OS_{1d}$ estimates the lighting consumption a lot lower than the rest. One could consider the fact that $OS_{1d}$ estimates heating and cooling lower/higher due to the underestimation of lighting consumption. This is investigated and it revealed that the lighting alone does not cause the difference, which means it must be the reduced number of zones, cf. appendix H.

$Be15_d$ estimates the lighting consumption better than $OS_{1d}$. This is because the lighting control in $Be15_d$ is modelled with multiple zones. An examination of the difference between $Be15_d$ modelled with a one or multiple lighting control zones is shown in appendix H.3. The examination showed that even with a single zone the simple BEM tool performs better than $OS_{11d}$, but with a larger uncertainty.

In addition the cooling consumption is a lot higher for models with static facade compared to the dynamic, which is excepted since the internal heat gains and solar gains are reduced by the lighting and shading control.

If it is chosen to use Be15 in the early design phase, even though it is advised against, appendix I.5 provides some guidance to correct the heating and cooling consumption. Note that the energy consumption might become more accurate with the corrections, but the sensitivity and input tendencies are not corrected.

### 5.1.2 Model Tendencies

To investigate the second criterion scatter plots together with Pearson correlation coefficient (PCC) is used to identify trends. Furthermore histograms for the different inputs in the models are created with multiple Monte Carlo filters to both heating and cooling consumption. The full investigation is described in appendix D.2 and F.2 for static and dynamic facade models respectively.

The investigations shows no odd tendencies from the scatter plots and the PCC of the inputs shows similar tendencies as well, which is also the case when applying the different Monte Carlo filters. Based on the obtained results it is concluded that criterion two is fulfilled for all the models.

### 5.1.3 Sensitivity Analysis Rankings

To investigate if the third criterion is met for the simplified models, a SA of the parameters is conducted using the method called TOM. The full investigation is described in appendix D.3 and F.3 for static and dynamic facade models respectively.

All of the static facade models fulfils the third criterion with the exception of $Be15_s$. Though $Be15_s$ estimates the top four most important parameters correctly but bot in the same order as $Baseline_s$, leading to the conclusion that $Be15_s$ does not meet the third criterion.

For the dynamic models, all but two models meets the criterion. $Be15_d$ and $OS_{1d}$ estimates different rankings. The difference in ranking obtained by $OS_{1d}$ is caused by the high underestimation of lighting consumption shown in figure 5.4. These differences leads to the conclusion that $Be15_d$ and $OS_{1d}$ does not meet the third criterion.

## 5.2 Total Energy Consumption

When designing buildings the goal is not only to reduce the energy consumption for one output, but rather the total consumption. In this thesis only heating, cooling and lighting consumption are under investigation. These outputs have been weighted with primary energy factors in order to obtain the total energy consumption. The factors used are based on the Danish building regulations 2015 [Energistyrelsen, 2017]:

- Heating 0,8
- Cooling 2,5
- Lighting 2,5

The cooling demand is supplied by a compressor powered by electricity which means it have a primary energy factor of 2.5. The cooling system is assumed to have a COP of 3,5.

### 5.2.1 Annual Consumption

Figure 5.5 shows the consumption for all models represented as linear fits. A figure of the energy consumption is shown in appendix I as a scatter plot.

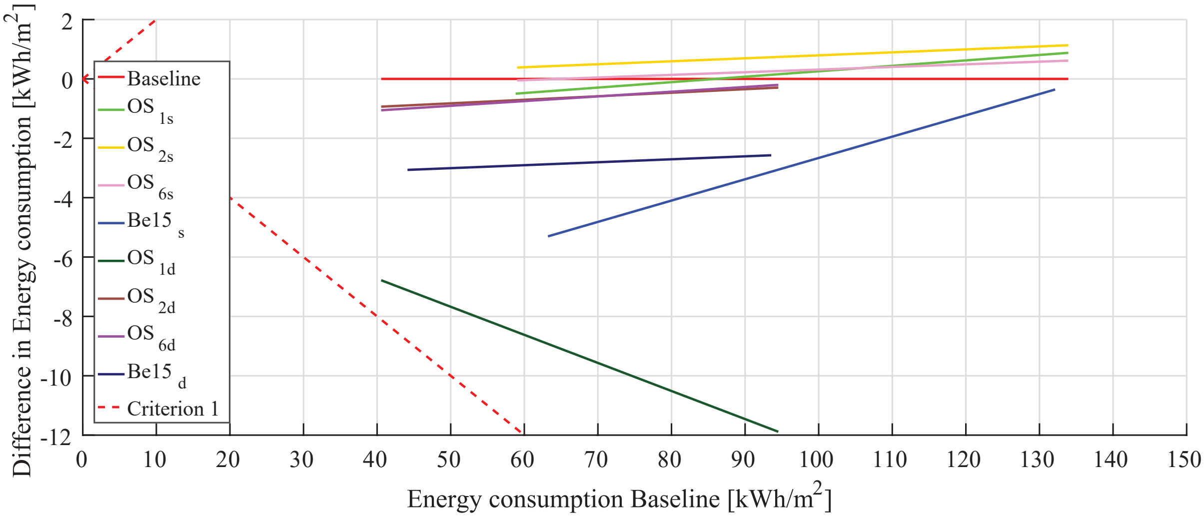



***Figure 5.5.*** Total energy consumption from heating, cooling and lighting for all the models. The consumption has been weighted with primary energy factors.

The figure shows that $OS_{1d}$ performs worse than $Be15_s$ and $Be15_d$. The reason why $OS_{1d}$ performs worse is because of the difference in lighting consumption, as shown in figure 5.4. The reason why $Be15_s$ and $Be15_d$ performs well is because it underestimates cooling and overestimates heating meaning which leads to the total energy consumption to fit well with the baseline models. The remaining models performs close to identical to the baseline models. Table 5.1 shows the amount of simulations that are within the limitations of criterion one.

| | Static facade | | Dynamic facade | |
|---|---|---|---|---|
| | [%] | [qty] | [%] | [qty] |
| $OS_1$ | 100 | 5000 | 92 | 4605 |
| $OS_2$ | 100 | 5000 | 100 | 5000 |
| $OS_6$ | 100 | 5000 | 100 | 5000 |
| Be15 | 100 | 4997 | 98 | 4895 |

***Table 5.1.*** Percentage and quantity of the simulations within the boundaries of criterion 1 for total energy consumption.

From the table it can be seen Be15 for models with both static and dynamic meet criterion one as both have more than 95 % of the simulations with a difference less than 20 % of the baseline. Moreover $OS_{1d}$ does not meet the criterion since only 92 % of the simulations are within the criterion.

It is investigated if the total energy consumption from $Be15_s$ and $Be15_d$ would be different if the heating consumption is much higher than the cooling consumption and vice versa. The investigation is presented in appendix I.2. The investigation shows that having a heating dominated building underestimate the total energy consumption and for a cooling dominated building the models overestimate the total energy consumption. This is excepted since the heating consumption is underestimated and cooling is overestimated.

Distribution characteristics for the difference between the baseline models and the simplified models are shown in table 5.2 when considering total energy consumption.

| | Total energy consumption [kWh/m$^2$] | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $OS_{1s}$ | $OS_{2s}$ | $OS_{6s}$ | $Be15_s$ | $OS_{1d}$ | $OS_{2d}$ | $OS_{6d}$ | $Be15_d$ |
| Mean | 0,2 | 0,7 | 0,3 | -3,1 | -9,1 | -0,6 | -0,7 | -2,9 |
| Standard deviation | 0,6 | 0,6 | 0,3 | 4,8 | 2,9 | 0,9 | 0,6 | 5,3 |
| Min | -2,4 | -1,8 | -1,2 | -16,1 | -16,6 | -3,3 | -2,3 | -16,6 |
| Max | 2,1 | 2,5 | 1,1 | 10,7 | -1,6 | 1,6 | 0,8 | 15,8 |

***Table 5.2.*** Distribution characteristics of the difference between the baseline models and the simplified once for both static and dynamic facade when considering the total energy consumption.

Notice that with increasing number of zones, when modelling in OS, the results obtained with the simplified models improve compared to the baseline. This is the case when looking at both the static and dynamic facade whether it is with heating, cooling and lighting separately or when it is the total energy consumption with primary factors. One exception to this is between $OS_{1s}$ and $OS_{2s}$ for heating consumption which result in the exception for total energy consumption as well.From table 5.2 it can be seen that the difference for the exception is very small and could be considered equally accurate. Moreover table 5.2 indicate that the more complex the building is the more inaccurate the results become. Appendix I.1 contains more information of the differences for total energy consumption. Appendix E.4 and G.1 contains information for static and dynamic facade respectively when examining the differences of heating and cooling consumption.

### 5.2.2 Model Tendencies

The input parameters tendencies on the output results are investigated for total energy consumption. To show the tendencies, a Monte Carlo filter is added to the output. It filters the 33% best performing simulations with regards to total energy consumption and the distribution of the remaining inputs are shown as histograms in table 5.3. To get a better understanding of what these histograms represents, an explanation is in appendix E.6.

| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_s$ | | | | | | | | |
| OS$_{1s}$ | | | | | | | | |
| OS$_{2s}$ | | | | | | | | |
| OS$_{6s}$ | | | | | | | | |
| Be15$_s$ | | | | | | | | |
| Baseline$_d$ | | | | | | | | |
| OS$_{1d}$ | | | | | | | | |
| OS$_{2d}$ | | | | | | | | |
| OS$_{6d}$ | | | | | | | | |
| Be15$_d$ | | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

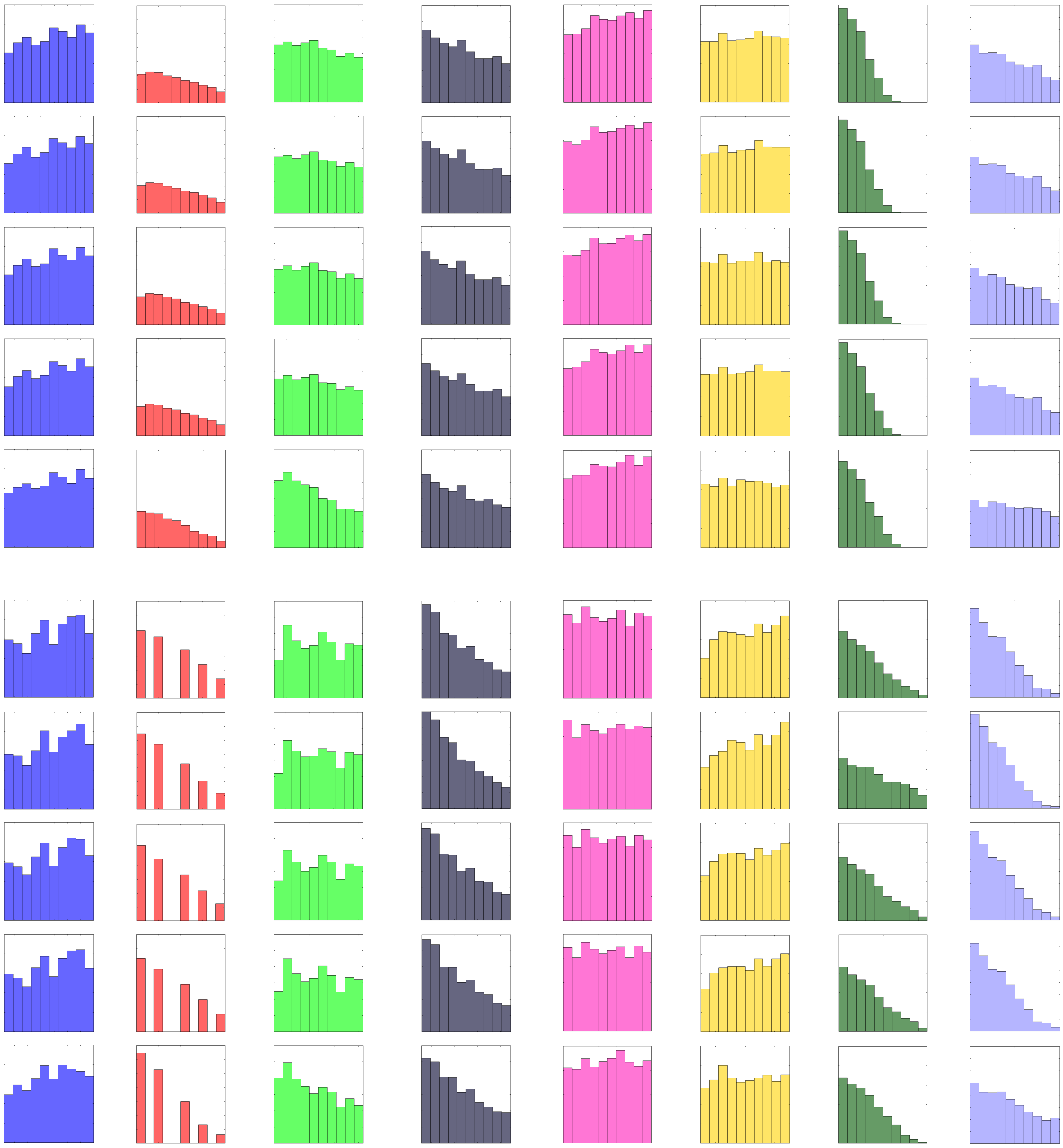


***Table 5.3.*** Histograms of the distribution for the inputs of the 33 % best performing simulations for both static and dynamic facade. The number below the model name indicates the amount of remaining simulations for that specific model.

From the table it is noticed that all models share the same tendencies except for a few. Be15$_s$ and Be15$_d$ struggles with the infiltration, which is almost uniformly distributed while the other models have a significant gradient. Furthermore these two models shows a tendencies that low SHGC is preferred with low energy consumption. Compare this to Baseline$_s$ and Baseline$_d$, these does not shows this.
Lastly, it can be seen that for the models with dynamic facade the resistance of the wall that it is fluctuating within the span. This is also the case for SHGC, especially for the models created with OS. It is unclear what courses this.

In addition to the Monte Carlo filter added to filter the 33 % best performning simulations, scatter

plots and PCC is used to examine the tendencies of the simplified models. The scatter plots contain the relation between the variable inputs and the total energy consumption. Furthermore the scatter plots are also used to inspect the data for any odd trends that might occur. The scatter plots and PCC are shown in appendix I.3.
The scatter plots does not reveal any odd tendencies nor does any inconsistencies of the tendencies occur between the simplified models and their respective baseline mode. The correlation between infiltration and the energy consumption for Be15 for both static and dynamic facade, revealed by the scatter plots and the PCC shows the same as table 5.3 where the correlation is not as big as for the baseline models.

From the Monte Carlo filter, scatter plots and PCC alone none of the simplified models is deemed unsuited for early design phases, but there are some inconstancies. This is taken into consideration in the further examination.

### 5.2.3 Sensitivity Analysis Rankings

The sensitivity analysis is conducted for the correlation between the variable inputs and the total energy consumption. Figure 5.6 and 5.7 shows the SA the models with static and dynamic facade respectively.

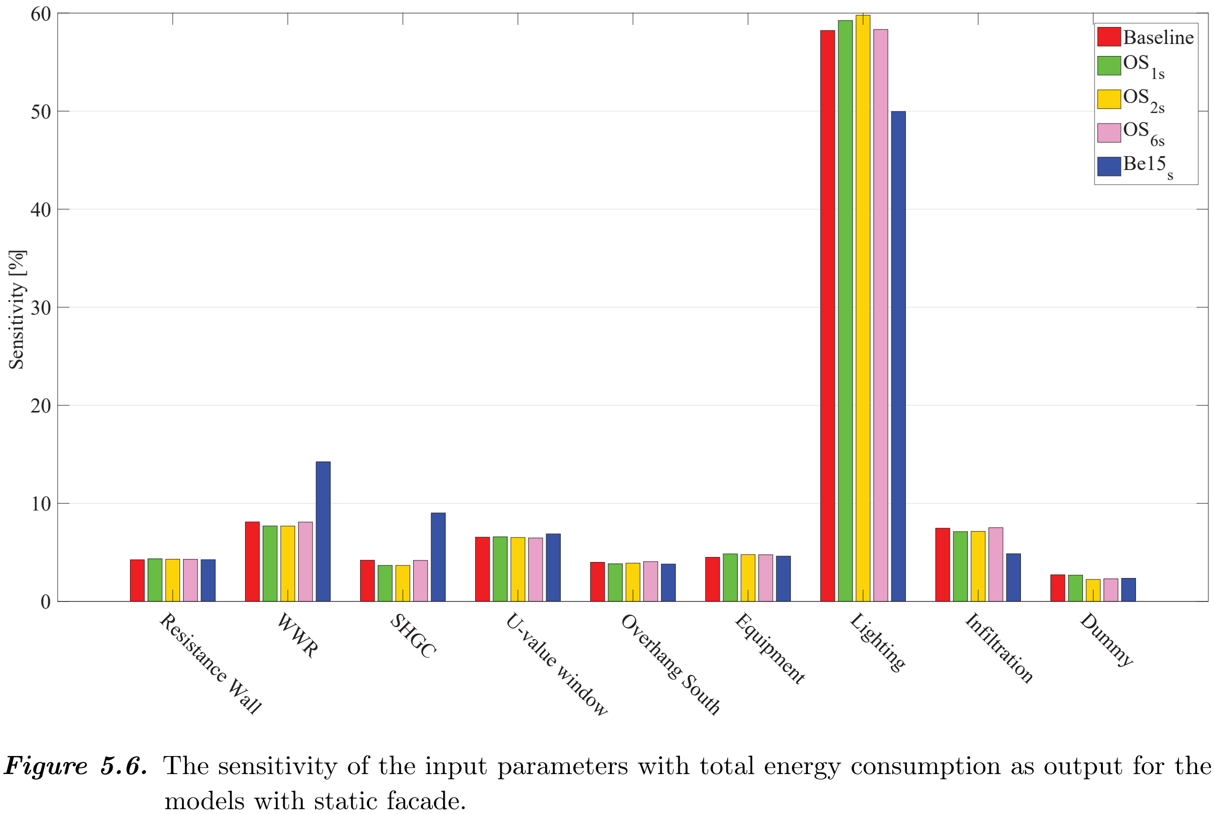



***Figure 5.6.*** The sensitivity of the input parameters with total energy consumption as output for the models with static facade.

As the figure shows, the lighting input is significantly more sensitive than any of the other inputs. This is due to the lighting consumption being a big part of the total energy consumption when using primary energy factors. The advanced models more or less agrees on the ranking of parameters while $Be15_s$ estimates less sensitivity for lighting and infiltration while estimating a higher sensitivity for WWR and SHGC. As for the ranking this means that $Be15_s$ ranks SHGC as the third most important parameter while the advanced modes have infiltration as the third most important. This difference in ranking between $\mathrm{Be15_s}$ and $\mathrm{Baseline_s}$ is likewise discovered when looking at the sensitivity for heating and cooling as output described in appendix D, which ultimately is the reason for rejecting $\mathrm{Be15_s}$ as a design tool as shown in figure 5.1.

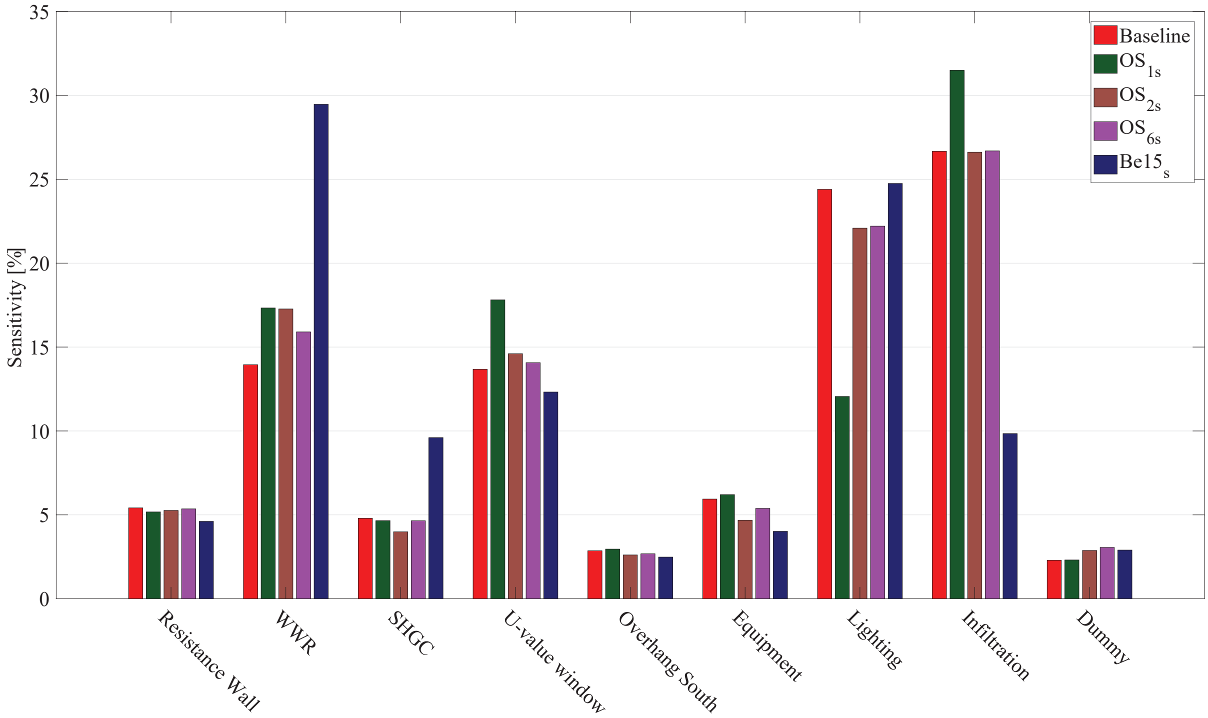



***Figure 5.7.*** The sensitivity of the input parameters with total energy consumption as output for the models with static facade.

The sensitivity analysis for the dynamic facade models, shown in figure 5.7, is not as dominated by the lighting input, since the lighting consumption is lower due to the lighting controls. $\mathrm{OS_{2d}}$, $\mathrm{OS_{6d}}$ and $\mathrm{Baseline_d}$ more or less agrees on the ranking of parameters while $\mathrm{Be15_d}$ and $\mathrm{OS_{1d}}$ estimates the rankings differently.
$\mathrm{Be15_d}$ ranks infiltration as one of the lowest while the advanced models estimates it as the most important parameter. This difference in ranking is likewise discovered when looking at the sensitivity for heating and cooling as output described in appendix F, which ultimately is the reason for rejecting $\mathrm{Be15_d}$ as a design tool as shown in figure 5.1.
$\mathrm{OS_{1d}}$ also struggles with ranking the parameters correctly. Looking at the senstivity analysis with heating, cooling and lighting as outputs, $\mathrm{OS_{1d}}$'s rankings are consistent with the baseline model. This means that the difference is due to the lighting consumption which $\mathrm{OS_{1d}}$ greatly underestimates, cf. figure 5.4. Discovering that $\mathrm{OS_{1d}}$ cannot successfully rank parameters with total energy consumption as output led to rejecting it as a suitable way to model a building.

## 5.3 Experiences Drawn from using Cloud Computing

This sections contains some of the experiences gained from using cloud computing for the OpenStudio simulations in this study. These experiences can help client consultants that have considered using cloud computing but do not know the requirements and the possibilities. It should be noted that these experiences are based on the use of OpenStudio's cloud solution and the OpenStudio Analysis Spreadsheet and thus may not be relevant for other similar services. A detailed description of the whole process is described in appendix A.4.

### 5.3.1 First Time Setup

Setting up a computer for running the cloud simulations the first time is a bit of a difficult process especially when having little tot no knowledge about programming.
The first step is to download the OpenStudio Analysis Spreadsheet directory from National Renewable Energy Laboratory [2017a], which also includes a setup guide. From the directory one have to open up Windows Command Prompt (CMD) and install Ruby, which is a coding language used by OpenStudio. Having installed Ruby one have to install a bunch of gems using a few commands. Installing these are easy enough but getting the different versions and gems to match with the server versions/gems is a bit more difficult and is what took the most time setting up. Though once it works it does not cause any more problems other than needing a update every once in a while. Updating is done using two simple commands.

The second step is to setup a free Amazon Web Services (AWS) account which is very easily done. The account is used to manage billing and connecting to or stopping active servers. Also the account have specific user credentials used to link the simulations to the account.

The third step is to setup the OpenStudio Analysis Spreadsheet which is pretty straight forward. It is divided into tabs with the first one for general info, specifying the server type/size and setting server version. Second tab is where variable inputs are specified and the third tab is for specifying outputs.
The outputs are all annual outputs such as energy consumption and unmet hours. A list of possible outputs is available as a .json file which can be viewed via a web browser.

### 5.3.2 Starting the Cloud Simulations

Once the initial setup is done, starting the actual simulations is easily done by using a single command and then choosing which model to simulate. It takes around ten minutes for the server to boot up. Once booted a IP address is listed in CMD which is used to access the server. Alternatively the server can be accessed via the AWS management console. The AWS management console displays useful information about the status of the servers which can be monitored to ensure everything runs smoothly and it is also where to server is closed once finished with the simulations.

It is important to keep an eye on the simulations as the servers are billed per hour also timing the simulations to finish right before the next billing hour can save some money. Another thing is the CPU utilization, which is most effective when simulating a single batch of thousands of simulations instead of several batches of fewer simulations. This is due to the transfer time between the working servers and the storage server containing the data. After every batch, the results are transferred to the storage server which takes around 10 minutes. In those 10 minutes the working servers are doing nothing while still costing money. Having many batches increase the down time of working computers and thus the money/time efficiency of cloud computing.

### 5.3.3 Retrieving the data from the Cloud

Once the simulations are finished or any time during, it is possible to download a .CSV file containing the specified annual output and the variable inputs of each simulation. It is very convenient being able to download everything to one single file and to be able to asses the results any time throughout and having a single file makes for easy data treatment.
Though if the hourly outputs for every model is wanted it is a bigger problem as this requires one to click download on every single model. This is a very tedious task that takes way too long especially if thousands of simulations are used. This is annoying if one want to analyse the indoor environment seeing that the temperatures and $CO_2$-concentration etc. cannot be imported. Though this was not too big of problem for this thesis as only the annual energy consumption were considered.

# Conclusion 6

This study shows that a simple Quasi-steady-state model based on DS/EN ISO 13790 [2008] should not be used for guidance in the early design stages for an office building. The model does not provide adequate ranking of the sensitivity for parameters nor does it provide accurate estimations of heating and cooling consumption. One big reason for this is the models inability to accurately determine the relation between infiltration and heating consumption, cf. figure E.26 and G.27.
This thesis points out that Be15 does not calculate heating and cooling consumption correctly when looked at individually. The difference between Be15 and the baseline model differ with an average of $-14{,}0\,\mathrm{kWh/m^2}$ and $28{,}6\,\mathrm{kWh/m^2}$ for heating and cooling respectively for models with static facade. For Be15 with dynamic facade the consumption differ with an average of $-15{,}6\,\mathrm{kWh/m^2}$ and $10{,}5\,\mathrm{kWh/m^2}$ for heating and cooling respectively.
In Denmark Be15 is used to calculate the total energy consumption with primary energy factors, where a certain limit has to be met to get a building permit. As shown in figure 5.5 on page 30, Be15 estimates the total energy consumption quite well. This indicate that the program fulfils its purpose well. The fairly accurate total energy consumption occur because of the under- and overestimation of heating and cooling consumptions, which cancels each other out. However when having simulations with high heating and low cool or vice versa it is clear that the simple tool becomes more inaccurate.
Christensen et al. [2013] found comparable results regarding the accuracy of Be06 (previous version of Be15) when examining the total energy consumption with primary energy factors. They found, based on a deterministic approach, a deviation between Be06 and a baseline model of 13 %. In their case it was not because of heating and cooling, but rather an underestimation of some outputs and overestimation of domestic hot water.

Considering an office building with lighting and shading control, using the advanced BEM tool with a single zone can not provide sufficient guidance in early design stages. This is caused because of inaccurate estimation of lighting consumption and inaccurate ranking of parameters according to the sensitivity analysis. The underestimation of the lighting occur because all lighting in the entire building is controlled by one reference point, even rooms like hallways which have no control.
If an office building does not have any solar shading or lighting controls it is sufficient to use an advanced single zone model. The estimated heating and cooling consumption is within ± 20 % of the baseline model. In addition to this the yielded ranking and tendencies of the parameters are sufficient.

When comparing the advanced BEM tool containing one zone with the simple BEM tool, more accurate estimation of the lighting consumption can be obtained with the simple BEM tool when the office building contains solar shading and lighting control. Even though the advanced single zone model does not estimate accurate lighting consumption, it still provides a more accurate heating and cooling consumption than the simple model, but rankings of the input parameters are faulty because of the lighting consumption. The inconsistency in lighting consumption becomes more apparent when investigating the total energy consumption of the case office building with added primary energy factors for heating, cooling and lighting consumption. This results in the advanced single zone model becoming more inaccurate than the simple model.

Dividing the building into two zones, according to rooms with and without lighting control, reveals to be sufficient enough for the accuracy, input tendencies and sensitivity rankings for an office when modelled in an advanced BEM tool. Furthermore dividing the building according to space types is sufficient.
The findings also show that increasing the amount of zones used in the advanced BEM tool offer more accurate energy consumption for heating, cooling and lighting compared with the baseline models. Even though this is the case, increasing the number of zones does not change the ranking nor the tendencies which are key features when working in early design stages.

The experiences drawn from using cloud computing reveal that it is generally useful in its current state, however some things are still missing. The initial setup of the cloud service is no easy task, especially if having no prior programming knowledge. There are several programs and versions of these that have to match the server which run the simulations. Furthermore to efficiently use the cloud, one batch of many simulations has to be run rather than a lot of small because of ineffective coding of the server. Lastly, retrieving the individual hourly data from the simulations is very inconvenient and the start-up of the server is slow.

The focus of the thesis is to provide guidance for design teams dealing with early design stages, but the findings could be useful for teams in later stages when having to choose how to divide their building into zones when modelling a building project.

# Discussion 7

*In this chapter the applied method and the obtained results are discussed in regards of applicability and what parts that could have been done differently.*

This thesis compares a number of models, modelled in both simple and advanced BEM tools. The method used for the comparison is to use the Monte-Carlo method on the different models in order to obtain the data. This data is then compared with a baseline model with three criteria. The criteria serves as a central part of this thesis as the final conclusions are based solely on the tool's ability to follow those three criteria making the definition of these criteria very important. The criteria needs to be broad in order to be applicable to all kinds of buildings while being specific about the important parts in the early design phases. According to Attia et al. [2012a], guidance is more important than accuracy in the early design phases. Guidance is obtained from the tendencies and sensitivity rankings of input parameters and to some extend the accuracy of the results. On these deductions the three criteria were defined. If other criteria were defined the conclusions drawn in this thesis might change. E.g. if the if the allowed difference of ± 20 % of the baseline model were set to ± 5 % or if the ranking criteria were comparing the magnitude of the sensitivities directly instead of the ranking.

Another study has also compared a simple and an advanced BEM tool but with a different method.
Young-Jin et al. [2013] compare EnergyPlus and the simplified calculation, DS/EN ISO 13790 [2008], using a stochastic approach as well. The study shows that the simple calculation is significantly different from EnergyPlus using two-sample t-test with a significance level of 5 % when comparing the distribution of heating and cooling consumption. Their result correspond well with the results in this thesis where criterion 1, stating that the results must remain within ± 20 % of the baseline model, is not met. The method used in this thesis is considered better for this case as it compares the individual model results instead of the distribution as a whole while criterion one is not as strict as the two-sample t-test with a significance level of 5 %. In early design the accuracy of the results is not the most important and a difference of ± 20 % of the baseline model is deemed sufficient enough while also making sure the tendencies and the sensitivity rankings of input parameters are acceptable.

A thing that could have been done differently is the choice of case building. The building used in the study is very simple and does not have spaces of the same type facing opposite directions. E.g. All single offices face south and both conference rooms are facing south-east. Reducing the zones by space type leads to similar results as the baseline model but that might be caused by the orientation of the space. Different results might have been obtained of an office facing south were added together with an office facing north. Aside from the orientation of spaces, the size of the building could also be changed to something larger than 572 $m^2$. Having a larger building would allow for more variance in space type distribution and space type orientation, improving the zoning part of the study. Having more zoning divisions than 1, 2 and 6 could have given more

insight of accuracy when reducing the number of zones.
Rivalin et al. [2014] conducted an investigation on a building, approximately seven times bigger, than the case used for this study, with a maximum of 49 zones, but not conducted exploring the global design space. They found that increasing the number of zones provide more accurate energy consumption. The results from both investigations shows the same tendency when reducing the amount of zones, which indicate that the results from this thesis can be applied to bigger office buildings.

# Further Studies 8

Writing this thesis revealed some ideas for studies which is interesting but were not investigated due to time frame and relevance. Some of the suggested studies relate to developing OpenStudio databases and measures that fits Danish regulations and standards. while other relate to some of the problems discovered, e.g. placement of lighting control in single zone models.

OpenStudios inclusion of measures in the work flow facilitates the development of a measure that automates the energy frame calculation which is usually calculated with Be15. The measure could be coded in such a way that it extracts all the needed information from the model, calculates the energy frame and then presents the results in the output tab. It could even validate other regulations such as hours above 27 °C and 28 °C.
An issue is connecting the simple input structure from a normative BEM tool with limited modelling bias to be compatible with OS.

Another idea relating to OpenStudio came to mind when drawing the model in SketchUp. In SketchUp it is possible to assign space types and constructions from a database. When assigning a space type from the database, e.g. medium sized open office or meeting room, it assigns internal loads and schedules as well. The problem is that all these space types are based on U.S. regulations and design standards, making it ineffective to use in Denmark.
Developing constructions and space types that fit Danish regulations and building types/design could improve the modelling procedure by a lot. Being able to assign a space types including internal loads, schedules and set-points with one mouse click will reduce the modelling time significantly and eliminate mistakes that can occur when typing the data manually. Though for this to be relevant it requires for companies to start using OpenStudio as their preferred building energy modelling tool. It also requires investigating which space types that are relevant and how to model the internal loads for each given space type.

In this thesis the indoor environment were held constant due to the poor capabilities of calculating this in Be15. Though if the indoor environment is included, it is necessary to develop a method to handle all the extra output parameters, e.g temperatures and $CO_2$-concentration. In this thesis annual outputs were used which greatly reduce the amount of data but analysing the $CO_2$-concentration or temperatures with one annual value is complicated and even more so if the model have more than one zone. Also the results needs to be presentable to the design team in an easy to understand way, maybe in a parallel coordinate plot or similar.

It is concluded in the thesis that the dynamic single zone model is unsuitable as design tool due to a underestimating the lighting consumption. It would be interesting to investigate if there is any way of placing the reference point in single zone models to obtain more reliable results and to develop some sort of guideline on how to model lighting controls in a way that makes single zone models usable as design tools, seeing that they estimate the consumption of heating and cooling quite well.

# Bibliography

**Aggerholm and Grau, 2014**. Søren Aggerholm and Karl Grau. *Bygningers Energybehov*. ISBN: 978-87-563-1642-2. Statens byggeforskningsinstitut, 2014.

**Andersen et al., 2002**. Karl Terpager Andersen, Per Heiselberg and Søren Aggerholm. *Naturlig ventilation i erhvervsbygninger - By og Byg Anvisning 202*. ISBN: 87-563-1128-1. Statens byggeforskningsinstitut, 2002.

**Andresen et al., 2009**. Inger Andresen, Anne Grete Hestnes, Simon Kamper, Per F. Jørgensen, Katharina Bramslec, Erik Hammer, Arne Førland-Larsen, Hanne Lehrskov, Dagny Rynska, Nicole Holanek Afroditi Synnefa, Michael Wilson and Kristien Sander. *Integrated Energy Design*. 2009.

**Attia et al., 2012a**. Shady Attia, Elisabeth Gratia, André De Herde and Jan L.M. Hensen. *Simulation-based decision support tool for early stages of zero-energy building design*. Energy and Buildings, 2012. ISSN 03787788. URL `http://dx.doi.org/10.1016/j.enbuild.2012.01.028`.

**Attia et al., 2012b**. Shady Attia, Jan L.M. Hensen, Liliana Beltrán and André De Herde. *Selection criteria for building performance simulation tools: contrasting architects' and engineers' needs*. Journal of Building Performance Simulation, 2012. URL `http://www.tandfonline.com/doi/abs/10.1080/19401493.2010.549573`.

**Bonde et al., 2016**. Emil Greve Bonde, Frederik Søndergaard Mikkelsen and Mia Buhrkal Donau. *Automatisering af stokastisk modellering i BSim*. 2016. URL `https://goo.gl/2x7dvm`.

**Christensen et al., 2013**. Jørgen Erik Christensen, Peder Schiønning and Espen Dethlefsen. *Comparison of simplified and advanced building simulation tool with measured data*. Proceedings of BS2013, 2013.

**Corrado and Fabrizio, 2007**. Vincenzo Corrado and Enrico Fabrizio. *Assessment of building cooling energy need through a quasi-steady state model: Simplified correlation for gain-loss mismatch*. Energy and Buildings, 2007. ISSN 03787788. URL `http://www.sciencedirect.com/science/article/pii/S0378778806002325`.

**Crawley et al., 2006**. Drury B Crawley, Jon W Hand, Michael Kummert and Brent T Griffith. *Contrasting the capabilities of building energy performance simulation programs*. Building and Environment, 2006. URL `http://dx.doi.org/10.1016/j.buildenv.2006.10.027`.

**DS 418, 2011**. DS 418. *Beregning af bygningers varmetab, 7. udgave*. ICS: 91.120.10. Dansk standard, 2011.

**DS 474, 1993**. DS 474. *Norm for specifikation af termisk indeklima, 1. udgave*. UDK: 628.8 697. Dansk standard, 1993.

**DS/EN 15251, 2007**. DS/EN 15251. *Input parametre til indklimaet, 1. udgave*. ICS: 91.040.01. Dansk standard, 2007.

**DS/EN ISO 13790, 2008**. DS/EN ISO 13790. *Energy performance of buildings - Calculation of energy use for space heating and cooling*. ICS: 91.120.10. Dansk standard, 2008.

**EN ISO 13790, 2008**. EN ISO 13790. *Bygningers energieffektivitet - Beregning af energiforbrug til rumopvarmning og -køling*. ICS: 91.120.10. International Organization for Standardization, 2008.

**Energistyrelsen, 2017**. Energistyrelsen. *Bygningsreglement 2015*. `http://bygningsreglementet.dk/`, 2017. Last visited: 27-05-2017.

**Energistyrelsen, 2017**. Energistyrelsen. *Basisfremskriving 2017*. ISBN: 978-87-93180-28-4. 2017.

**Energivinduer, 2017**. Energivinduer. *Energivinduer*. `http://energivinduer.dk/`, 2017. Last visited: 13-02-2017.

**European Commission, 2017**. European Commission. *Energy union and climate*. `https://ec.europa.eu/commission/priorities/energy-union-and-climate_en`, 2017. Last visited: 04-06-2017.

**Johnsen and Christoffersen, 2008**. Kjeld Johnsen and Jens Christoffersen. *Dagslys i rum og bygninger 1. udgave, 2008*. ISBN: 978-87-563-1240-7. Statens Byggeforskningsinstitut, 2008.

**Jokisalo and Kurnistski, 2007**. Juha Jokisalo and Jarek Kurnistski. *Performance of EN ISO 13790 utilisation factor heat demand calculation method in a cold climate*. Energy and Buildings, 2007. ISSN 03787788. URL https://goo.gl/BoMjaO.

**Kasper Lynge Jensen, 2006**. Kasper Lynge Jensen. *Indeklima og produktivitet*. http://ipaper.ipapercms.dk/TechMedia/HVACMagasinet/2006/8/, 2006.

**Kim et al., 2008**. Ji-Hyun Kim, Godfried Augenbroe and Hye-Soo Suh. *COMPARATIVE STUDY OF THE LEED AND ISO-CEN BUILDING ENERGY PERFORMANCE RATING METHODS*. 2008. URL https://goo.gl/1K6mfI.

**Kokogiannakis et al., 2010**. Georgios Kokogiannakis, Paul Strachan and Joe Clarke. *Comparison of the simplified methods of the ISO 13790 standard and detailed modelling programs in a regulatory context*. Tandfonline, 2010. ISSN 1940-1507. URL http://dx.doi.org/10.1080/19401490802509388.

**Larsson, 2004**. N Larsson. *The integrated design process*. 2004. URL https://goo.gl/rdXkyO.

**Laursen and Bøgh, 2015**. Mathilde Brandsen Laursen and Nicolaj Ladefoged Bøgh. *Designværktøj til dagslysberegning*. 2015.

**Löhnert et al., 2003**. Günter Löhnert, Andreas Dalkowski and Werner Sutter. *Integrated Design Process: A Guideline for Sustainable and Solar-Optimised Building Design*. Berlin: IEA International Energy Agency, 2003.

**National Renewable Energy Laboratory, 2017a**. National Renewable Energy Laboratory. *OpenStudio Analysis Spreadsheet repository*. https://github.com/NREL/OpenStudio-analysis-spreadsheet, 2017. Last visited: 19-05-2017.

**National Renewable Energy Laboratory, 2017b**. National Renewable Energy Laboratory. *Testing and Validation*. https://energyplus.net/testing, 2017. Last visited: 11-04-2017.

**Rivalin et al., 2014**. Lisa Rivalin, Dominique Marchio, Mines Paristech, Pascal Stabat, Marcello Caciolo, Cofely Axima and Benoit Cogné. *Influence Of Building Zoning On Annual Energy Demand*, 2014.

**Østergård, 2017**. Torben Østergård. *Interactive Building Design Space Exploration Using Regionalized Sensitivity Analysis Nomenclature*. 2017.

**Østergård et al., 2016**. Torben Østergård, Steffen E. Maagaard and Rasmus L. Jensen. *Thermal Comfort in Residential Buildings by the Millions - Early Design Support from Stochastic Simulations*. CLIMA 2016 - proceedings of the 12th REHVA World Congress, 6, 2016.

**Østergård et al., 2017**. Torben Østergård, Rasmus L. Jensen and Steffen E. Maagaard. *Early Building Design - Informed decision-making by exploring multidimensional design space using sensitivity analysis*. Energy and Buildings, 2017.

**U.S. Department of Energy, 2017**. U.S. Department of Energy. *Weather Data By Location*. https://www.energyplus.net/weather-location/europe_wmo_region_6/DNK/DNK_Copenhagen.061800_IWEC, 2017. Last visited: 13-1-2017.

**U.S. Department of Energy, 2016**. U.S. Department of Energy. *Engineering Reference*, 2016.

**Young-Jin et al., 2013**. Kim Young-Jin, Yoon Seong-Hwan and Park Cheol-Soo. *Stochastic comparison between simplified energy calculation and dynamic simulation*. Energy and Buildings, 2013. ISSN 03787788. URL http://www.sciencedirect.com/science/article/pii/S0378778813003022.

# OpenStudio A

*This chapter contains a description of OpenStudio, EnergyPlus calculation procedure, the use of measures, stochastic modelling and cloud computing.*

OpenStudio is a collection of building energy simulation tools which was first released in 2008. It includes the OpenStudio application (OS), Parametric analysis tool (PAT) and ResultsViewer. It is developed by the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy (DOE). The tool collection is free and available to the public and is a open source project.

OS is a graphical user-interface created for the EnergyPlus core. It handles the building geometry and envelope along with many other inputs which is then loaded into EnergyPlus.
PAT is used for creating design variations but as of now it does not support large scale variations preferred in stochastic modelling so this tool is not used in the study.

The building geometry is modelled using a plug-in for SketchUp. The plug-in makes it possible to quickly create building geometries which can be loaded directly into OS from within SketchUp. When creating the geometry it is possible to assign space types and zones, when assigning space types one can chose from a list of predefined space types or create custom ones. When choosing from the predefined list, it also creates constructions, schedules, internal loads etc. that fits the given space type. This feature is not used in this project though as the list of space types are mostly fit for U.S. standards, regulations and climate.

After creating and loading the geometry the rest of the inputs are added in the OS interface, such as constructions, loads, schedules and HVAC systems. The SketchUp plug-in and the OS interface is shown in figure A.1 and figure A.2 respectively.

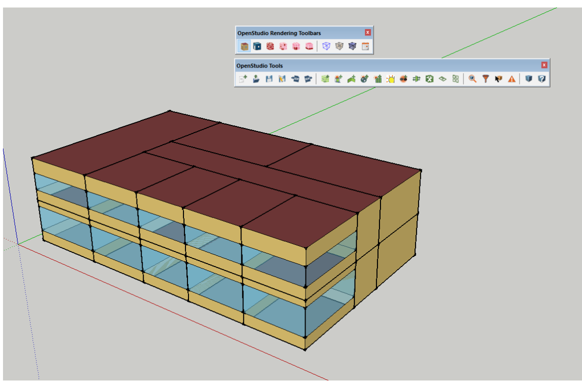


***Figure A.1.*** The SketchUp interface and the plug-in tools.

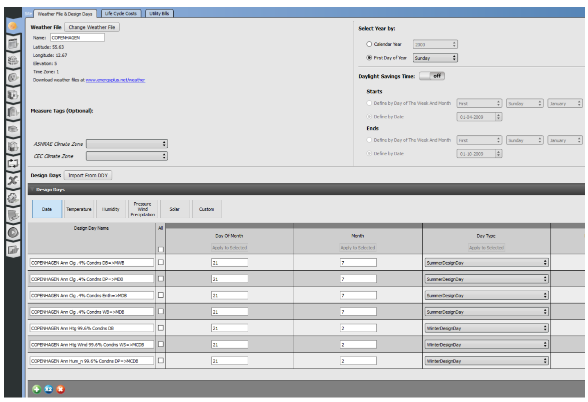


***Figure A.2.*** The OS interface with the different input tabs on the left side.

After learning the work flow for OS, it becomes easy to create and run basic building simulations. The great thing about using SketchUp for geometry is that it can be used by architects in the early design stages. Architects can easily draw the basic form of a building. This basic form can then be used directly in OS. This is extra useful for stochastic modelling as the basic geometry is the only thing needed to perform thousands of possible solutions. This skips the need for having detailed CAD models before simulations can be made. Thus making it possible to implement stochastic modelling earlier in the design process.

## A.1 Energy Plus Calculation Procedure

The calculation procedure for EnergyPlus is described by U.S. Department of Energy [2016] which is the basis for the following description.

EnergyPlus consists of many program modules used for calculating the energy required for cooling and heating for the building and much more. The simulation core is a building model based on fundamental heat balance principles. All the modules are managed by a simulation manager. The EnergyPlus program schematic is shown in figure A.3.

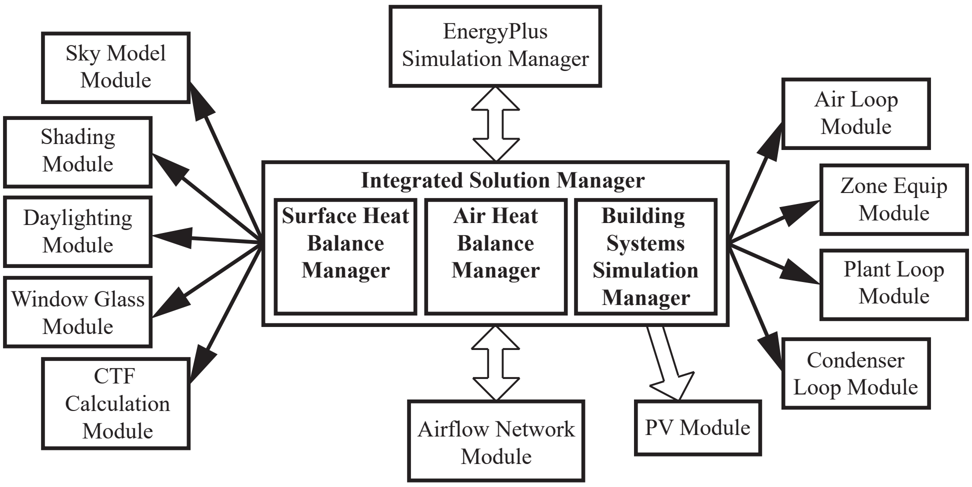



***Figure A.3.*** EnergyPlus program schematic. Redrawn from [U.S. Department of Energy, 2016, Figure 1.1]

The central part of the schematic is the Integrated Solution Manager. EnergyPlus utilizes integrated simulations which means that the three mayor parts; building zones, HVAC systems and plant equipment are solved simultaneously. For tools using sequential simulations, these parts are simulated one by on having no feedback between them. To obtain physically realistic simulations the three parts are linked by fluid loops, which is shown in figure A.4.

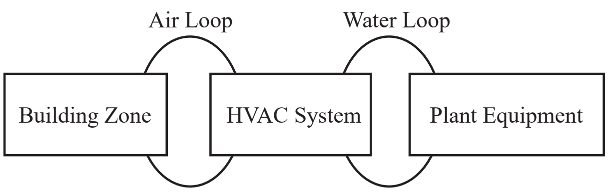



***Figure A.4.*** Schematic of the simultaneous solution scheme. Redrawn from [U.S. Department of Energy, 2016, Figure 2.2]

The zone and system integration is based on energy and moisture balance equations for the zone which result in ordinary differential equations which are solved using a predictor-corrector approach. The actual solution algorithm used for solving the energy and moisture balance equations is a 3rd order finite difference method named 3rd Order Backward Difference. As the name suggests it requires the zone air temperatures for the three previous time steps and it uses constant temperature coefficients.

Conduction through walls are handled by conduction transfer functions. A single, simple, linear equation is enough to calculate the conductive heat transfer through an element. The equation have constant coefficients that are determined for each element once throughout the whole simulation period while temperature and flux terms are calculated for each time step.

The daylighting calculation in EnergyPlus utilizes daylight factors, which is the ratio between interior illuminance and exterior illuminance. The daylight factors are calculated at user specified reference points, one for each zone where daylight control is wanted. The daylight factor is calculated for every hourly sun position, for representative days, while taking into account direct light from the windows and the reflected light from ceilings, floors and walls.
Daylighting calculations are performed for each time step. The illuminance at the reference points are obtained by interpolating between the daylight factors using the current sky condition and the sun position of the time step, and then multiplying this factor with the exterior horizontal illuminance.
Lastly the lighting energy needed for reaching the illuminance set-point is calculated and a electric reduction factor is calculated which is used for reducing the heat gain from lights.

Time steps refer to the amount of time between each calculation and is specified as a number of time steps per hour. In EnergyPlus the choice must be evenly divisible into 60. So 2 time steps per hours means that a calculation is conducted every 30 minutes while a value of 60 means that a calculation is performed every 1 minute. The value is important regarding the modelling accuracy and the overall simulation time, so the choice is usually a compromise between time and accuracy.
In this thesis a value of 10 time steps per hours is chosen. This ensures relatively low simulation times without compromising the results.

### A.1.1 Performance Test of EnergyPlus

BEM tools have to be performance tested regularly to ensure that the results obtained are correct. Furthermore the tests are used to develop and improve the tools. EnergyPlus is tested by the developers each time a mayor version is completed and released to the public. The tests follows industry standards and includes both analytical and comparative tests. [National Renewable Energy Laboratory, 2017b]

## A.2 Measures

A major thing in the OS work flow, is the use of measures. A measure is a piece of code that makes changes to the OS model thus reducing modelling time and cost while maintaining quality and consistency. Measures can be created and then shared via the Building Component Library (BCL) which is an online library hosted by NREL, which is accessed through a browser or directly from within OS. For example, if you want to add windows to a model giving a specific window-to-wall ratio. This would normally be done by manually drawing the windows in SketchUp or similar but with OS and measures, all you have to do is write in the ratio and everything else is automatic (given that the measure already exists).

The following measures are used in this project:

- Window-to-Wall Ratio (WWR)
- Window overhangs
- External wall U-value
- Window properties
- Equipment load
- Lighting load
- Infiltration

The fact that OS is open source means that a lot of measures already exists on BCL and most receive updates every now and then. A downside of this system is if people lose interest and stop creating/updating measures. This would mean that the amount of compatible measure are reduced.
Another downside is that, since every person can upload measures to BCL, faults might occur if a measure is coded wrong. This can lead to calculation mistakes, that if not discovered, can lead to fault in the building design.

A fault in the WWR measure were discovered in this thesis where when it updates the WWR, it actually removes the windows and adds new ones with the given size. But in removing the old window it also removes "attachments" from the windows such as solar shading and window frames. This was a problem for the dynamic facade simulations and were fixed by using a uniform discrete distribution of WWR and then not use the measure, but perform five sets of 1000 simulations with a WWR of 20%, 30%, 40%, 50% and 60%. This had a negative impact on the cost efficiency of using cloud computing. This is shown in section A.4.1.

Creating measures can be a comprehensive task depending on what the measure should do. To provide a better understanding of the measures size and time having to be invested, the WWR measure is shown in the following section.

## A.3 Window-to-Wall Ratio Measure

```
class SetWindowToWallRatioByFacade < OpenStudio::Ruleset::ModelUserScript

  # override name to return the name of your script
  def name
    return "Set Window to Wall Ratio by Facade"
  end

  # return a vector of arguments
  def arguments(model)
    args = OpenStudio::Ruleset::OSArgumentVector.new

    #make double argument for wwr
    wwr = OpenStudio::Ruleset::OSArgument::makeDoubleArgument("wwr",true)
    wwr.setDisplayName("Window to Wall Ratio (fraction).")
    wwr.setDefaultValue(0.4)
    args << wwr

    #make double argument for sillHeight
    sillHeight = OpenStudio::Ruleset::OSArgument::makeDoubleArgument("sillHeight",true)
    sillHeight.setDisplayName("Sill Height (in).")
    sillHeight.setDefaultValue(30.0)
    args << sillHeight

    #make choice argument for facade
    choices = OpenStudio::StringVector.new
    choices << "North"
    choices << "East"
    choices << "South"
    choices << "West"
    facade = OpenStudio::Ruleset::OSArgument::makeChoiceArgument("facade", choices,true)
    facade.setDisplayName("Cardinal Direction.")
    facade.setDefaultValue("South")
    args << facade

    return args
  end  #end the arguments method

  #define what happens when the measure is run
  def run(model, runner, user_arguments)
    super(model, runner, user_arguments)

    #use the built-in error checking
    if not runner.validateUserArguments(arguments(model),user_arguments)
      return false
    end

    #assign the user inputs to variables
    wwr = runner.getDoubleArgumentValue("wwr",user_arguments)
    sillHeight = runner.getDoubleArgumentValue("sillHeight",user_arguments)
    facade = runner.getStringArgumentValue("facade",user_arguments)

    #check reasonableness of fraction
    if wwr <= 0 or wwr >= 1
      runner.registerError("Window to Wall Ratio must be greater than 0 and less than 1.")
      return false
    end

    #check reasonableness of fraction
    if sillHeight <= 0
      runner.registerError("Sill height must be > 0.")
      return false
    elsif sillHeight > 360
      runner.registerWarning("#{sillHeight} inches seems like an unusually high sill height.")
    elsif sillHeight > 9999
      runner.registerError("#{sillHeight} inches is above the measure limit for sill height.")
      return false
    end
```

```
    #setup OpenStudio units that we will need
    unit_sillHeight_ip = OpenStudio::createUnit("ft").get
    unit_sillHeight_si = OpenStudio::createUnit("m").get
    unit_area_ip = OpenStudio::createUnit("ft^2").get
    unit_area_si = OpenStudio::createUnit("m^2").get
    unit_cost_per_area_ip = OpenStudio::createUnit("1/ft^2").get #$/ft^2 does not work
    unit_cost_per_area_si = OpenStudio::createUnit("1/m^2").get

    #define starting units
    sillHeight_ip = OpenStudio::Quantity.new(sillHeight/12, unit_sillHeight_ip)

    #unit conversion
    sillHeight_si = OpenStudio::convert(sillHeight_ip, unit_sillHeight_si).get

    #hold data for initial condition
    starting_gross_ext_wall_area = 0.0 # includes windows and doors
    starting_ext_window_area = 0.0

    #hold data for final condition
    final_gross_ext_wall_area = 0.0 # includes windows and doors
    final_ext_window_area = 0.0

    #flag for not applicable
    exterior_walls = false
    windows_added = false

    #flag to track notifications of zone multipliers
    space_warning_issued = []

    #flag to track warning for new windows without construction
    empty_const_warning = false

    #calculate initial envelope cost as negative value
    envelope_cost = 0
    constructions = model.getConstructions
    constructions.each do |construction|
      const_llcs = construction.lifeCycleCosts
      const_llcs.each do |const_llc|
        if const_llc.category == "Construction"
          envelope_cost += const_llc.totalCost*-1
        end
      end
    end #end of constructions.each do

    #loop through surfaces finding exterior walls with proper orientation
    surfaces = model.getSurfaces
    surfaces.each do |s|

      next if not s.surfaceType == "Wall"
      next if not s.outsideBoundaryCondition == "Outdoors"
      if s.space.empty?
        runner.registerWarning("#{s.name} doesn't have a parent space and won't be included in the
measure reporting or modifications.")
        next
      end

      # get the absoluteAzimuth for the surface so we can categorize it
      absoluteAzimuth =  OpenStudio::convert(s.azimuth,"rad","deg").get +
s.space.get.directionofRelativeNorth + model.getBuilding.northAxis
      until absoluteAzimuth < 360.0
        absoluteAzimuth = absoluteAzimuth - 360.0
      end

      if facade == "North"
        next if not (absoluteAzimuth >= 315.0 or absoluteAzimuth < 45.0)
      elsif facade == "East"
        next if not (absoluteAzimuth >= 45.0 and absoluteAzimuth < 135.0)
      elsif facade == "South"
        next if not (absoluteAzimuth >= 135.0 and absoluteAzimuth < 225.0)
```

```
      elsif facade == "West"
        next if not (absoluteAzimuth >= 225.0 and absoluteAzimuth < 315.0)
      else
        runner.registerError("Unexpected value of facade: " + facade + ".")
        return false
      end
      exterior_walls = true

      #get surface area adjusting for zone multiplier
      space = s.space
      if not space.empty?
        zone = space.get.thermalZone
      end
      if not zone.empty?
        zone_multiplier = zone.get.multiplier
        if zone_multiplier > 1 and not space_warning_issued.include?(space.get.name.to_s)
          runner.registerInfo("Space #{space.get.name.to_s} in thermal zone #{zone.get.name.to_s}
has a zone multiplier of #{zone_multiplier}. Adjusting area calculations.")
          space_warning_issued << space.get.name.to_s
        end
      else
        zone_multiplier = 1 #space is not in a thermal zone
        runner.registerWarning("Space #{space.get.name.to_s} is not in a thermal zone and won't be
included in in the simulation. Windows will still be altered with an assumed zone multiplier of
1")
      end
      surface_gross_area = s.grossArea * zone_multiplier

      #loop through sub surfaces and add area including multiplier
      ext_window_area = 0
      s.subSurfaces.each do |subSurface|
        ext_window_area = ext_window_area + subSurface.grossArea * subSurface.multiplier *
zone_multiplier
        if subSurface.multiplier > 1
          runner.registerInfo("Sub-surface #{subSurface.name.to_s} in space #{space.get.name.to_s}
has a sub-surface multiplier of #{subSurface.multiplier}. Adjusting area calculations.")
        end
      end

      starting_gross_ext_wall_area += surface_gross_area
      starting_ext_window_area += ext_window_area

      new_window = s.setWindowToWallRatio(wwr, sillHeight_si.value, true)
      if new_window.empty?
        runner.registerWarning("The requested window to wall ratio for surface '#{s.name}' was too
large. Fenestration was not altered for this surface.")
      else
        windows_added = true
        #warn user if resulting window doesn't have a construction, as it will result in failed
simulation. In the future may use logic from starting windows to apply construction to new window.
        if new_window.get.construction.empty? and empty_const_warning == false
          runner.registerWarning("one or more resulting windows do not have constructions. This
script is intended to be used with models using construction sets versus hard assigned
constructions.")
          empty_const_warning = true
        end
      end

    end #end of surfaces.each do

    #report initial condition wwr
    #the initial and final ratios does not currently account for either sub-surface or zone
multipliers.
    starting_wwr = sprintf("%.02f",(starting_ext_window_area/starting_gross_ext_wall_area))
    runner.registerInitialCondition("The model's initial window to wall ratio for #{facade} facing
exterior walls was #{starting_wwr}.")

    if not exterior_walls
      runner.registerAsNotApplicable("The model has no exterior #{facade.downcase} walls and was
```

```
not altered")
      return true
    elsif not windows_added
      runner.registerAsNotApplicable("The model has exterior #{facade.downcase} walls, but no
windows could be added with the requested window to wall ratio")
      return true
    end

    #data for final condition wwr
    surfaces = model.getSurfaces
    surfaces.each do |s|
      next if not s.surfaceType == "Wall"
      next if not s.outsideBoundaryCondition == "Outdoors"
      if s.space.empty?
        runner.registerWarning("#{s.name} doesn't have a parent space and won't be included in the
measure reporting or modifications.")
        next
      end

      # get the absoluteAzimuth for the surface so we can categorize it
      absoluteAzimuth =  OpenStudio::convert(s.azimuth,"rad","deg").get +
s.space.get.directionofRelativeNorth + model.getBuilding.northAxis
      until absoluteAzimuth < 360.0
        absoluteAzimuth = absoluteAzimuth - 360.0
      end

      if facade == "North"
        next if not (absoluteAzimuth >= 315.0 or absoluteAzimuth < 45.0)
      elsif facade == "East"
        next if not (absoluteAzimuth >= 45.0 and absoluteAzimuth < 135.0)
      elsif facade == "South"
        next if not (absoluteAzimuth >= 135.0 and absoluteAzimuth < 225.0)
      elsif facade == "West"
        next if not (absoluteAzimuth >= 225.0 and absoluteAzimuth < 315.0)
      else
        runner.registerError("Unexpected value of facade: " + facade + ".")
        return false
      end

      #get surface area adjusting for zone multiplier
      space = s.space
      if not space.empty?
        zone = space.get.thermalZone
      end
      if not zone.empty?
        zone_multiplier = zone.get.multiplier
        if zone_multiplier > 1
        end
      else
        zone_multiplier = 1 #space is not in a thermal zone
      end
      surface_gross_area = s.grossArea * zone_multiplier

      #loop through sub surfaces and add area including multiplier
      ext_window_area = 0
      s.subSurfaces.each do |subSurface| #onlky one and should have multiplier of 1
        ext_window_area = ext_window_area + subSurface.grossArea * subSurface.multiplier *
zone_multiplier
      end

      final_gross_ext_wall_area += surface_gross_area
      final_ext_window_area += ext_window_area
    end #end of surfaces.each do

    #short def to make numbers pretty (converts 4125001.25641 to 4,125,001.26 or 4,125,001). The
definition be called through this measure
    def neat_numbers(number, roundto = 2) #round to 0 or 2)
      # round to zero or two decimals
      if roundto == 2
```

```
        number = sprintf "%.2f", number
      else
        number = number.round
      end
      #regex to add commas
      number.to_s.reverse.gsub(%r{([0-9]{3}(?=([0-9])))}, "\\1,").reverse
    end #end def pretty_numbers

    #get delta in ft^2 for final - starting window area
    increase_window_area_si = OpenStudio::Quantity.new(final_ext_window_area -
starting_ext_window_area, unit_area_si)
    increase_window_area_ip = OpenStudio::convert(increase_window_area_si, unit_area_ip).get

    #calculate final envelope cost as positive value
    constructions = model.getConstructions
    constructions.each do |construction|
      const_llcs = construction.lifeCycleCosts
      const_llcs.each do |const_llc|
        if const_llc.category == "Construction"
          envelope_cost += const_llc.totalCost
        end
      end
    end #end of constructions.each do

    #report final condition
    final_wwr = sprintf("%.02f",(final_ext_window_area/final_gross_ext_wall_area))
    runner.registerFinalCondition("The model's final window to wall ratio for #{facade} facing
exterior walls is #{final_wwr}. Window area increased by #
{neat_numbers(increase_window_area_ip.value,0)} (ft^2). The material and construction costs
increased by $#{neat_numbers(envelope_cost,0)}.")

    return true

  end #end the run method

end #end the measure

#this allows the measure to be used by the application
SetWindowToWallRatioByFacade.new.registerWithApplication
```

### A.3.1 Radiance

A measure is developed to use Radiance for daylighting calculation instead of the EnergyPlus calculation. Radiance is one of the leading daylighting calculation tools on the market and having the possibility to use it in the simulations is a great feature.

The radiance measures extracts the geometry and needed data from OS and does the daylight simulations and then it adds the results back into the OS model, which uses it for control of electric lighting. It further outputs daylight metric results and illuminance maps for the simulated zones.

As of now, it only supports one daylight reference point per zone, so when having one zone with many spaces one have to chose which space to simulate. Also errors occur if a 2 or more plan building with one zone does not contain a reference point on the ground floor. Another downside of Radiance is that it does not do well with solar shading systems meaning that one have to chose between having lighting controls or solar shading controls. For this very reason, Radiance is not used in this thesis, as both lighting control and shading control is required.

The daylight metrics output from Radiance includes Daylight Autonomy (DA), Continues Daylight Autonomy (cDA) and Useful Daylight Illuminance (UDI).

## A.4 Stochastic Modelling and Cloud Computing

Stochastic modelling with OpenStudio is run with cloud computing. Using cloud computing for building energy simulations is a new approach that has a great potential when combined with stochastic modelling where thousands of simulations have to be run.

As mentioned, OS have a dedicated tool to run the cloud simulations called PAT but, at the time of writing this thesis, it is still not fully developed. Though OpenStudio 2.0 were released in spring 2017 and is briefly described in section A.5. Instead the OpenStudio Analysis Spreadsheet is used. The analysis spreadsheet is an excel spreadsheet with a format that can be interpreted by the OpenStudio cloud server, allowing users to conduct large-scale analyses without the use of PAT.

The spreadsheet utilizes measures, which are described in appendix A. The measure data are added to the spreadsheet where it is decided which entries should be treated as variables and which should be treated as arguments. For each variable, a range and distribution type is chosen. The variable tab of the spreadsheet is shown in figure A.5.

| | | | Inputs | | | | | | | Continuous Variable Description | | | | | Discrete Variable Description | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # Measure En | Measure Display Name | Measure Directory Name | Measure Class Name | | | | | | | | | | | | | | |
| # Variable | type | Measure Directory | Parameter Display Name (will make machine name) | Parameter Name in Measure | Parameter Short Display Name | Variable Type | Units | Static/Default Value | Enumerations | Min | Max | Mean | Std Dev | Delta X | Discrete Values | Discrete Weights | Distribution |
| TRUE | B_Window to Wall Ratio South | SetWindowToWallRatioByFacade | SetWindowToWallRatioByFacade | RubyMeasure | | | | | | | | | | | | | |
| | variable | | South WWR | wwr | | Double | | 0.4 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Sill Height (in). | sillHeight | | Double | | 35 | | | | | | | | | |
| | argument | | Cardinal Direction. | facade | | Choice | | South | \|North,East,South,West\| | | | | | | | | |
| TRUE | D_Window to Wall Ratio East | SetWindowToWallRatioByFacade | SetWindowToWallRatioByFacade | RubyMeasure | | | | | | | | | | | | | |
| | variable | | East WWR | wwr | | Double | | 0.4 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Sill Height (in). | sillHeight | | Double | | 35 | | | | | | | | | |
| | argument | | Cardinal Direction. | facade | | Choice | | East | \|North,East,South,West\| | | | | | | | | |
| TRUE | C_Window to Wall Ratio North | SetWindowToWallRatioByFacade | SetWindowToWallRatioByFacade | RubyMeasure | | | | | | | | | | | | | |
| | variable | | North WWR | wwr | | Double | | 0.4 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Sill Height (in). | sillHeight | | Double | | 35 | | | | | | | | | |
| | argument | | Cardinal Direction. | facade | | Choice | | North | \|North,East,South,West\| | | | | | | | | |
| TRUE | E_Window to Wall Ratio West | SetWindowToWallRatioByFacade | SetWindowToWallRatioByFacade | RubyMeasure | | | | | | | | | | | | | |
| | variable | | West WWR | wwr | | Double | | 0.4 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Sill Height (in). | sillHeight | | Double | | 35 | | | | | | | | | |
| | argument | | Cardinal Direction. | facade | | Choice | | West | \|North,East,South,West\| | | | | | | | | |
| TRUE | H_Add Overhang South | AddOverhangsByProjectionFactor | AddOverhangsByProjectionFactor | RubyMeasure | | | | | | | | | | | | | |
| | variable | | Projection Factor South | projection_factor | static | Double | | 0.5 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Cardinal Direction | facade | static | Choice | | South | \|North,East,South,West\| | | | | | | | | |
| | argument | | Remove Existing Space Shading Surfaces From the Model? | remove_ext_space_shading | static | Bool | | FALSE | | | | | | | | | |
| | argument | | Optionally Choose a Construction for the Overhangs. | construction | static | Choice | | | | | | | | | | | |
| TRUE | J_Add Overhang East | AddOverhangsByProjectionFactor | AddOverhangsByProjectionFactor | RubyMeasure | | | | | | | | | | | | | |
| | variable | | Projection Factor East | projection_factor | static | Double | | 0.5 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Cardinal Direction | facade | static | Choice | | East | \|North,East,South,West\| | | | | | | | | |
| | argument | | Remove Existing Space Shading Surfaces From the Model? | remove_ext_space_shading | static | Bool | | FALSE | | | | | | | | | |
| | argument | | Optionally Choose a Construction for the Overhangs. | construction | static | Choice | | | | | | | | | | | |
| TRUE | I_Add Overhang North | AddOverhangsByProjectionFactor | AddOverhangsByProjectionFactor | RubyMeasure | | | | | | | | | | | | | |
| | variable | | Projection Factor North | projection_factor | static | Double | | 0.5 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Cardinal Direction | facade | static | Choice | | North | \|North,East,South,West\| | | | | | | | | |
| | argument | | Remove Existing Space Shading Surfaces From the Model? | remove_ext_space_shading | static | Bool | | FALSE | | | | | | | | | |
| | argument | | Optionally Choose a Construction for the Overhangs. | construction | static | Choice | | | | | | | | | | | |
| TRUE | K_Add Overhang West | AddOverhangsByProjectionFactor | AddOverhangsByProjectionFactor | RubyMeasure | | | | | | | | | | | | | |
| | variable | | Projection Factor West | projection_factor | static | Double | | 0.5 | | 0.05 | 0.95 | 0.4 | 0.15 | | | | uniform |
| | argument | | Cardinal Direction | facade | static | Choice | | West | \|North,East,South,West\| | | | | | | | | |
| | argument | | Remove Existing Space Shading Surfaces From the Model? | remove_ext_space_shading | static | Bool | | FALSE | | | | | | | | | |
| | argument | | Optionally Choose a Construction for the Overhangs. | construction | static | Choice | | | | | | | | | | | |
| TRUE | A_Change Exterior Wall Thermal Properti | ChangeExteriorWallThermalPropertie: | ChangeExteriorWallThermalProperties | RubyMeasure | | | | | | | | | | | | | |
| | variable | | Wall total R-value multiplier | r_value_mult | | Double | | 1 | | 0.5 | 3 | 1.75 | 0.25 | | | | uniform |
| | argument | | Exterior wall solar absorptance multiplier | solar_abs_mult | | Double | | 1 | | | | | | | | | |
| | variable | | Exterior wall thermal mass multiplier | thermal_mass_mult | | Double | | 1 | | 0.5 | 3 | 1.75 | 0.25 | | | | uniform |

***Figure A.5.*** The tab in the OpenStudio Analysis Spreadsheet where the variable input parameters can be determined.

In the spreadsheet it is also specified which size/type of server to use and how many CPUs to use. It might not be unusual for a company to have a powerful designated simulation computer, but even that cannot support hundreds of CPUs. With cloud computing one can choose to use 500 CPUs, as the price of using the clouds scale linear with the amount of CPUs. This means that the only thing one have to consider is the amount of time available for conducting the simulations and then choosing a fitting number of CPUs.

The spreadsheet is uploaded to the cloud server through a few commands in Windows Command Prompt (CMD). But for this to work one need to install Ruby together with a bundler gem, these are needed in order to execute the run commands. A detailed setup guide is provided by National Renewable Energy Laboratory [2017a]. When this is all done and setup, the simulations can be started from CMD. This is shown in figure A.6. The commands must be run from the spreadsheet directory.

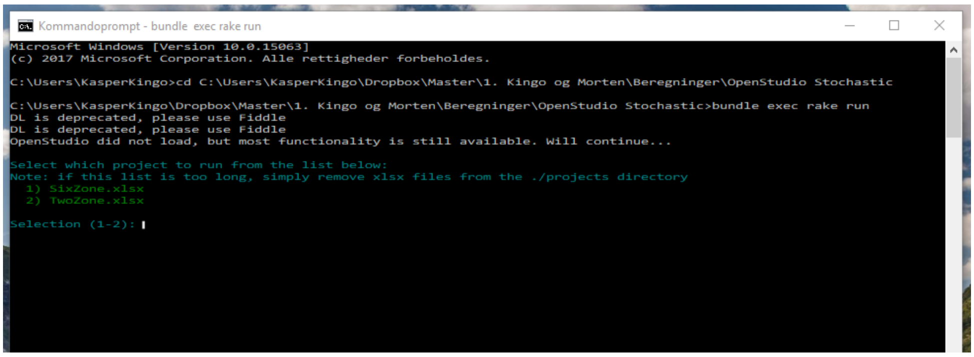



***Figure A.6.*** Windows Command Prompt with the run commands typed in.

The cloud servers are run via Amazon Web Services (AWS) and the user is billed per hour of usage. It is possible to connect to the cloud server via browser. The interface of the server includes an overview of the number of queued, started and finished simulations. It also gives access to a few relevant plots, like a parallel coordinate plot. When finished, the annual results and inputs for each models is added to a single file, which can be downloaded for further data treatment and analysis. The interface of the cloud server is shown in figure A.7.

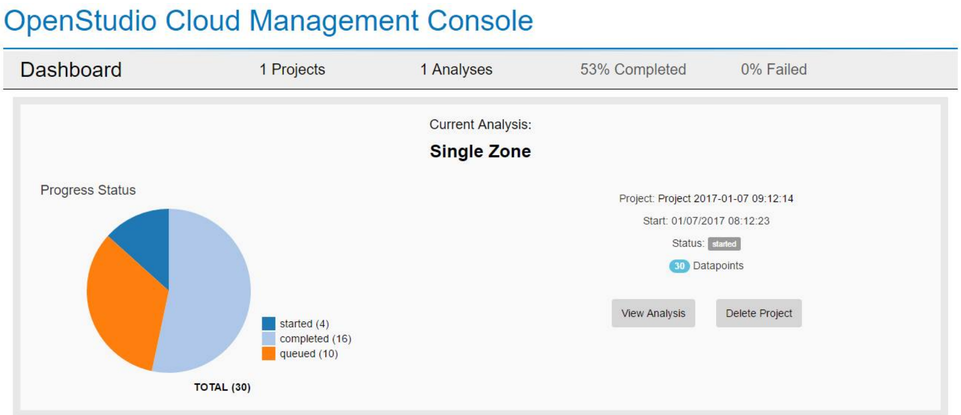



***Figure A.7.*** The interface of the OpenStudio cloud server.

### A.4.1 Cloud Server CPU Utilization

In general the cloud server is made up of two parts, a server to store all the data and a number of “workers” to do the actual simulations. When simulating the dynamic facade models, which are divided into five sets of 1000 simulations, it was discovered that the transferring time from the “workers” to the server is significant and the CPU utilization is close to zero every time this happens. This is illustrated on figure A.8 and A.9.

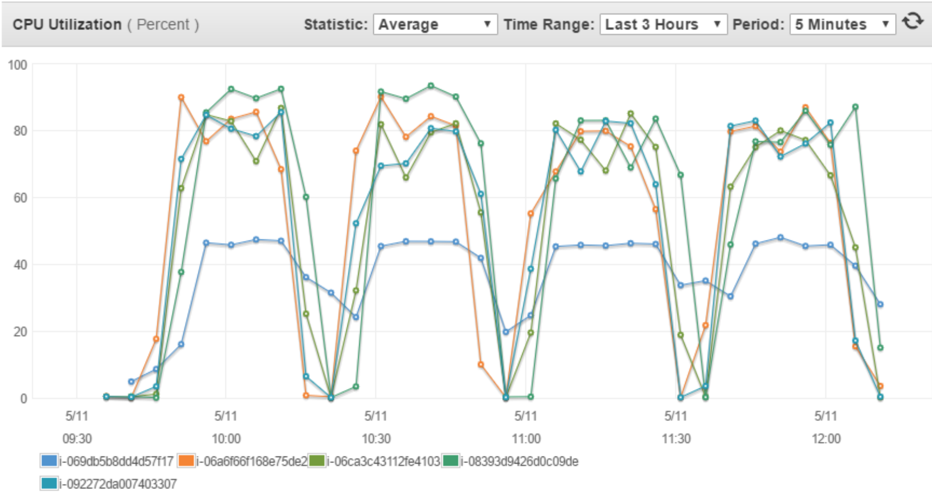



***Figure A.8.*** The CPU utilization of 4 workers when performing five sets of 1000 simulations.

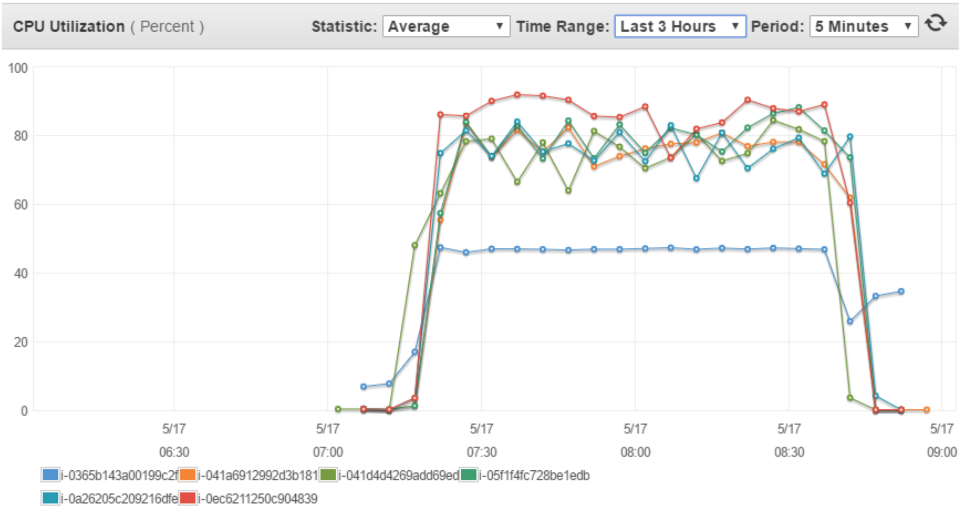



***Figure A.9.*** The CPU utilization of 5 workers when performing 5000 continuous simulations.

As shown in the figures, it is much more cost effective to perform many continuous simulations than to perform sets of simulations. When performing sets, it might be more cost effective to run them locally instead of on a cloud. This is something that a design team needs to have in mind and make a decision based on the situation at hand.

### A.4.2 Performance Test of the OpenStudio Analysis Spreadsheet

It is investigated if the OpenStudio Analysis Spreadsheet, used to run stochastic simulations on the cloud, compiles the models correctly and that sampling of the parameters are working as intended.
The reason for investigating this is due to the spreadsheet being in very early development. Seeing as the spreadsheet is a mayor part of this project it is important to verify that the results gained are reliable compared to what the local desktop version of OS calculates.

One of the many cloud simulations were chosen and compared to an identical model simulated locally. The results of the comparison is shown in table A.1.

| | Cooling [MJ/m²] | Heating [Mbtu] | Fan power [MJ/m²] | Equipment [MJ/m²] | Lighting [MJ/m²] | Total energy [MJ/m²] |
|---|---|---|---|---|---|---|
| Cloud | 33,497 | 7,542 | 97,379 | 80,701 | 87,064 | 331,890 |
| Local | 33,497 | 7,545 | 97,378 | 80,699 | 87,063 | 331,890 |
| Difference | 0,001 | 0,002 | 0,002 | 0,001 | 0,002 | 0,000 |

***Table A.1.*** The differences between a cloud computed model and a local computed model.

As shown in the table it can be concluded that the spreadsheet and cloud computing is working as intended. The small differences are assumed to be due to round-off.

## A.5 OpenStudio 2.0

In the early spring of 2017, OpenStudio 2.0 was released. The update did not change OpenStudio much but brought along an updated version of the Parametric Analysis Tool (PAT) which now enables one to perform stochastic modelling and cloud simulations instead of having to use the analysis spreadsheet. Due to the late release of 2.0, it was not used for this thesis, but instead were briefly examined to discover its potential for future design projects.

The first tab in the PAT tool is shown in figure A.10. This tab is used for setting up the model. First step is to choose analysis type from the two available options, manual and algorithmic. Manual is for choosing a few design alternatives by hand and uses the one at a time approach and algorithmic is for large scale analyses using a stochastic approach. The next steps are to choose sampling method, seed model and weather file. After that one have to fill in the algorithm settings associated with the sampling method.

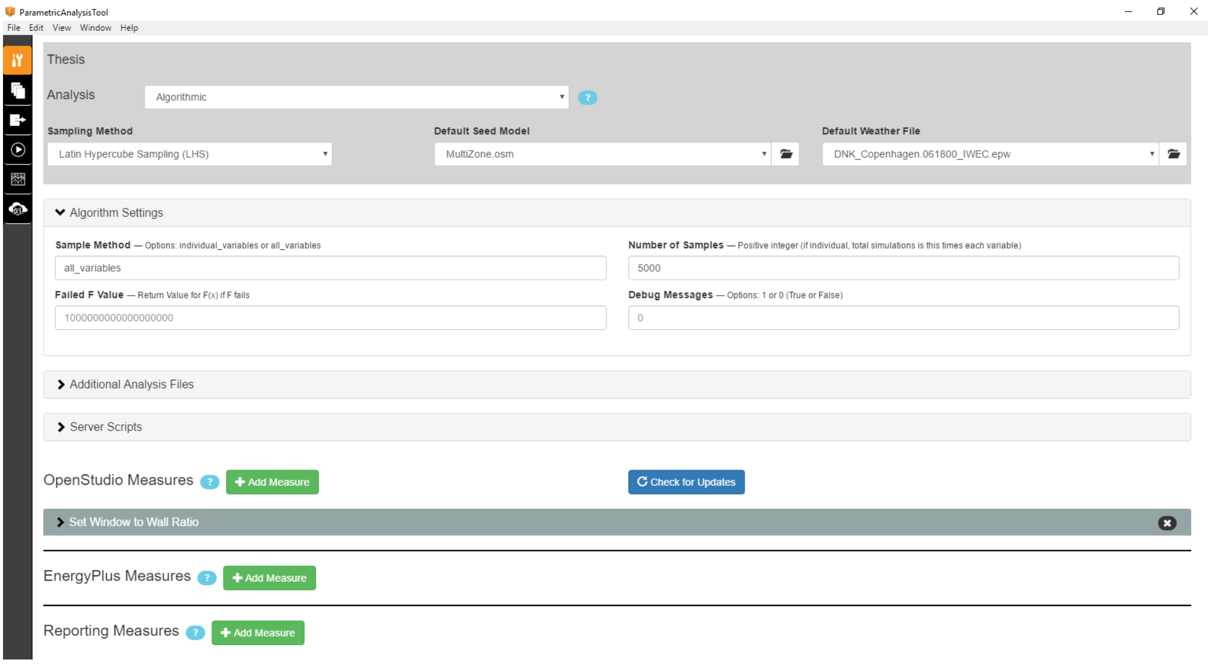



***Figure A.10.*** Interface of PAT used for setting up the baseline model, weather data, sampling method and algorithm settings for OpenStudio 2.0.

At the bottom of the tab, measures are added. The measures serves as variables and distribution and range are decided for each of the variables. This is shown in figure A.11

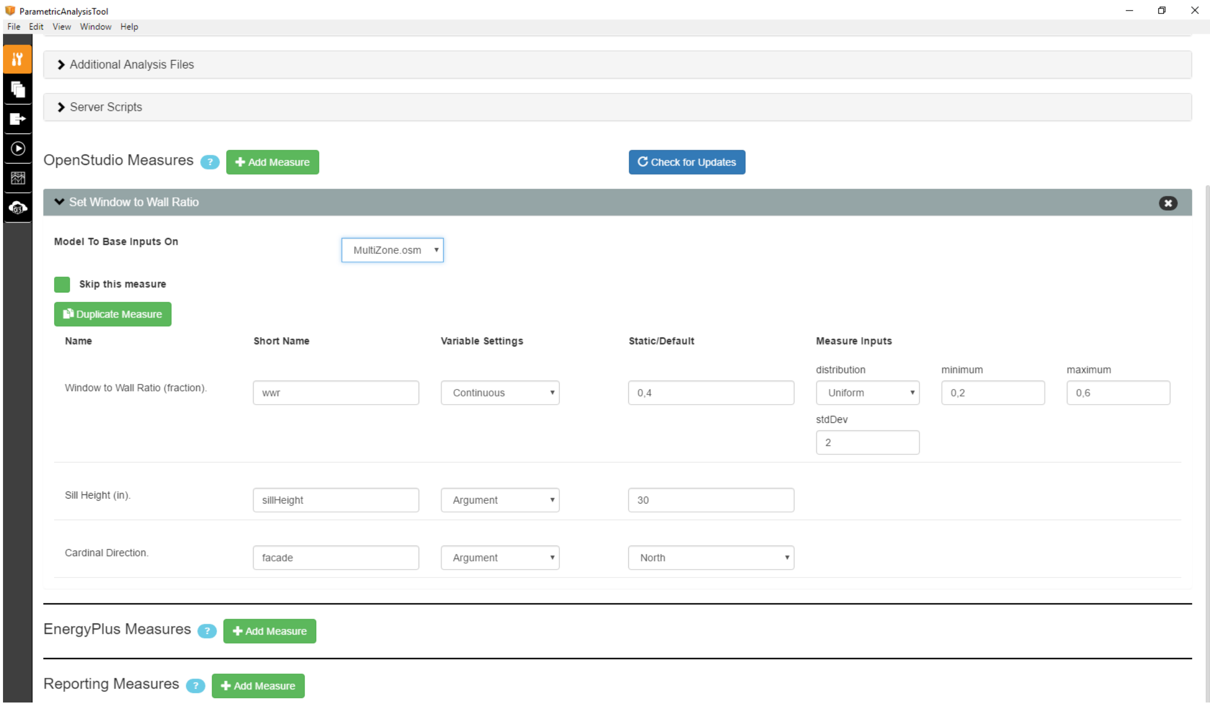



***Figure A.11.*** Interface of PAT used for setting up measures, distributions and ranges for OpenStudio 2.0.

When finished setting everything up, the next step is to configure the cloud server. This is done from the run tab in PAT as shown in figure A.12. Here the server and worker size together with the Amazon Web Services (AWS) credentials and user ID is specified. After this the simulations are started by clicking the start button. The cloud server itself works as with the analysis spreadsheet. It gives access to live graphs of the simulations and the data can be downloaded.

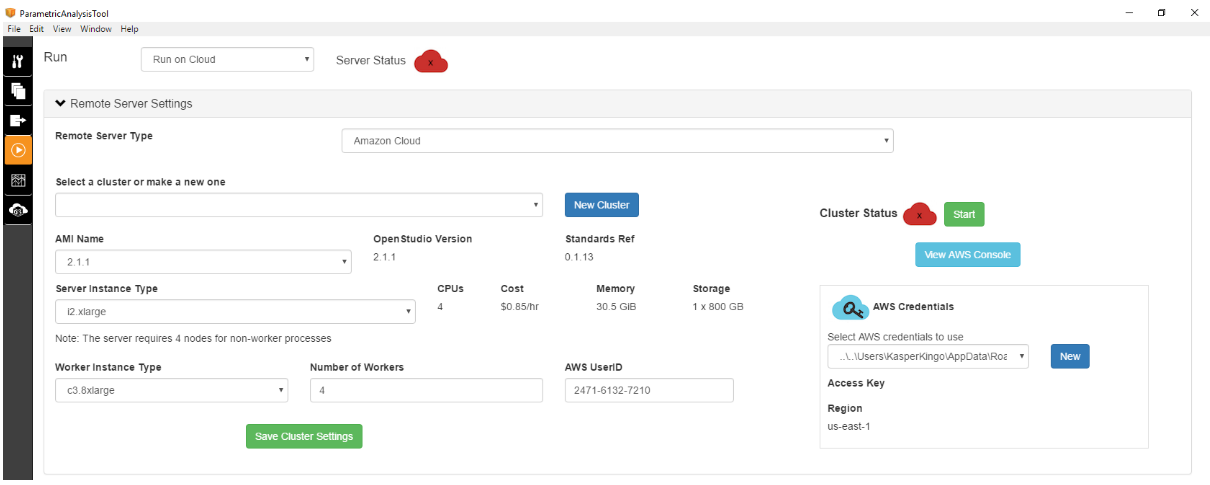



***Figure A.12.*** Interface PAT used for setting up the cloud server for OpenStudio 2.0.

This update is a great step towards developing a software tool that is easy to use and understand, which can be used for conducting large scale stochastic building simulations.

# Be15 B

*This chapter contains a description of Be15 hereunder the use of the excel spreadsheet needed for performing the stochastic simulations.*

Be15 is developed by the Danish building research institute (SBi) in order to document that the energy requirements listed in the building regulations and other legislations are followed. Aside from that it can also be used for calculating the energy demand and usage through the stages of building design to ensure energy efficient buildings.

The calculation method in Be15 for heating and cooling needs are based on DS/EN ISO 13790 [2008] and the rest of the calculations are based on various European and international standards. The calculations are performed on a monthly basis with steady state conditions. The tool is simple to use and because of the simple calculation method, there is no simulation time. This makes Be15 a fast way of obtaining results regarding energy demand and consumption which is useful during the early and late design phases.

Be15 uses a Quasi-steady-state method to calculate the total energy consumption on a monthly bases. To include dynamic effects utilization factors for loss and/or gain are used, which are determined empirically, [DS/EN ISO 13790, 2008, p. 15]. The calculation method only includes sensible heat for the heat balance, [DS/EN ISO 13790, 2008, p. 11].
The utilization factor for heating takes into account that only some of the internal and solar gains are utilized for estimating the heating consumption. For cooling two factors are used. One that takes into account that only some of the transmission and ventilation losses are used to decrease the cooling demand. The other factor accounts for the heat gain that leads to a temperature increase above the set-point for cooling, [DS/EN ISO 13790, 2008, Annex I]. Be15 has to option to model the lighting control as a multi zone model, e.g. different daylight and schedules for each room.

In figure B.1 the Be15 user interface is shown. When designing a building one have to fill out data by going through the different tabs shown in the left side. When finished or at any time during the modelling it is possible to click on the results tab. This contains key numbers of the buildings total energy usage and the energy contribution from heating, cooling and selected electricity sources.

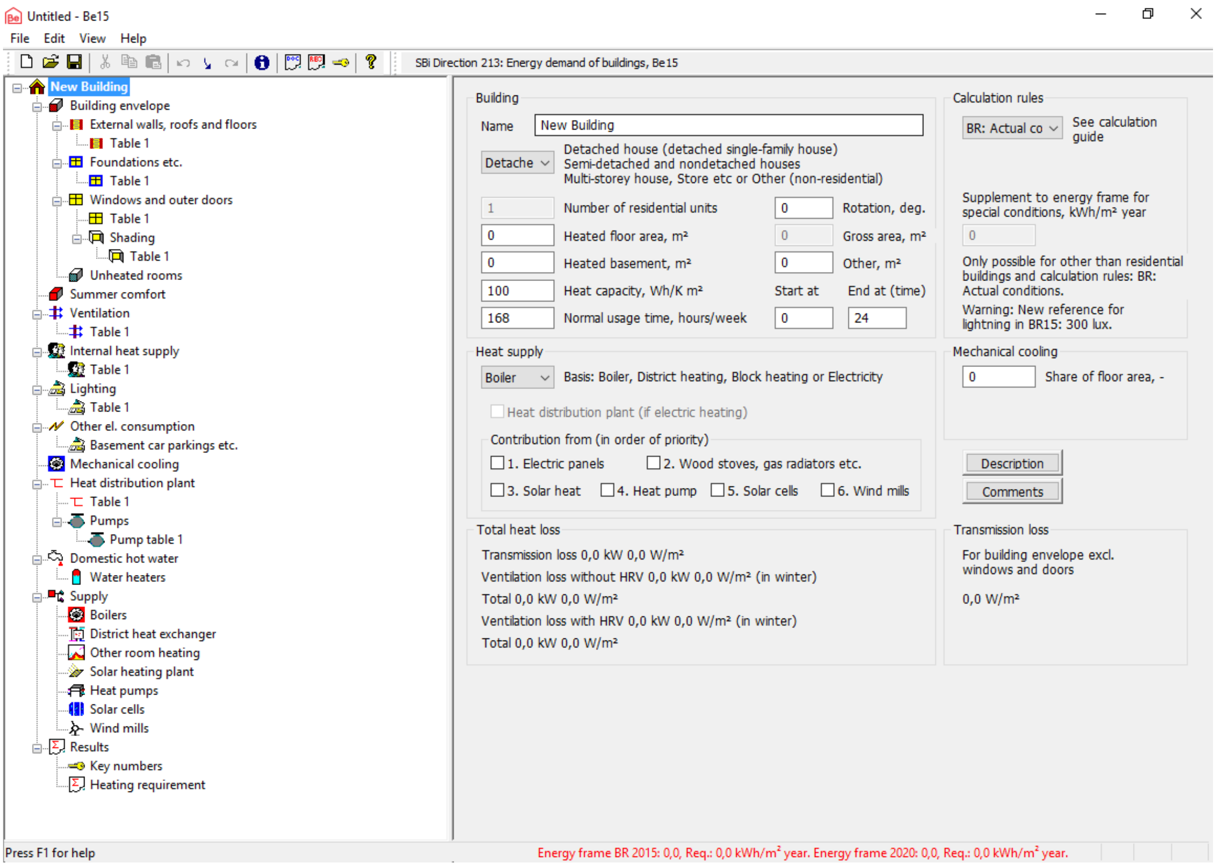



***Figure B.1.*** The Be15 user interface.

Be15 does not support stochastic modelling in itself so an alternative method is used. This method is described in section B.1. Be15 also does not support calculation of daylight factors, though it does support daylight control if daylight factors are input. So to utilize this in the thesis, the daylight factors are calculated by a stand alone tool and input in Be15. This method is described in section B.2.

## B.1 Stochastic Modelling

As mentioned an alternative method is used for stochastic modelling of Be15. Instead of using the Be15 tool, a excel spreadsheet is used instead, which is created by Kim Trangbæk Jønsson from Aalborg University. The interface of the spreadsheet is shown in figure B.2.

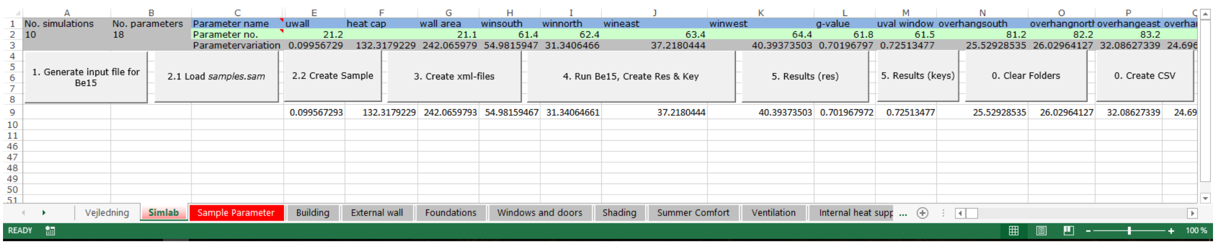



***Figure B.2.*** The Be15 spreadsheet user interface used for stochastic modelling.

The excel tabs are like the tabs in Be15 and are used to type in the building information. When everything is typed in, it is chosen which parameters to stochastic vary, this is typed into row

1 and 2 shown in the figure. Row 1 is manually input where a user chosen name can be given. Row 2 is the one that determines which input is varied. This number refers to a certain row and column marked with red numbers in a specific tab, e.g. "External wall". This tab is shown in figure B.3

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | External walls | | | | | | | | |
| 2 | | Table 1 | | | | | | | | |
| 3 | | External walls, roofs and floors | Area (m²) | U (W/m²K) | b | Ht (W/K) | Dim.Inside (C) | Dim.Outside (C) | Loss (W) | |
| 4 | No. | | 907 | | CtrlClick | 181.40 | | | 0.00 | |
| 5 | | | 1 | 2 | 3 | | 4 | 5 | | |
| 6 | 21 | External wall | 314 | 0.2 | 1 | 62.80 | | | 0.00 | |
| 7 | 22 | Ground deck | 286 | 0.2 | 1 | 57.20 | | | 0.00 | |
| 8 | 23 | Roof | 307 | 0.2 | 1 | 61.40 | | | 0.00 | |
| 9 | 24 | | | | | 0.00 | | | 0.00 | |
| 10 | 25 | | | | | 0.00 | | | 0.00 | |
| 26 | | | | | | | | | | |

Simlab | Sample Parameter | Building | External wall | Foundations | Windows and doors | Shading | Summer Comfort | Ventilation | Internal heat supply | Lighting | Other

***Figure B.3.*** The spreadsheet tab "External Wall" where inputs can be varied by using the red numbers.

To begin the simulations, a sample file needs to be loaded. The file used is created from the OS sample to ensure that the simulations are based on equal samples. When the sample is loaded, the next step is to create the xml-files, which is the Be15 models. The amount of created models are equal to the specified number of simulations. The last step is to run the actual models to generate the results and key numbers. The last process which is executed is to gather all the results into a text file which can then be analysed.

## B.2 Calculation of Daylight Factors

Be15 cannot calculate daylight factors but is able to use daylight control if daylight factors are input. These factors must be calculated using another tool. For this thesis, the factors are calculated using a spreadsheet developed for calculating daylight factors in office spaces. The spreadsheet was developed by two students at Aarhus University supervised by MOE, [Laursen and Bøgh, 2015].

The tool builds upon regressions created from curves shown in Johnsen and Christoffersen [2008]. Results and corrections in relation to Johnsen and Christoffersen [2008] are conducted using the VELUX Visualizer tool as reference. The corrections included are corrections for visual transmittance, wall thickness, room width and hight and mean reflectance. The calculations are based on the following assumptions:

- Sky conditions are CIE Overcast Sky
- There is a free horizon
- The reflectance of the surroundings are equal to 0,1
- A sill hight of 0,85 m

The input structure of the spreadsheet is simple, as shown in figure B.4. It requires room and window dimensions, window properties, reflectance of surfaces and overhang properties.

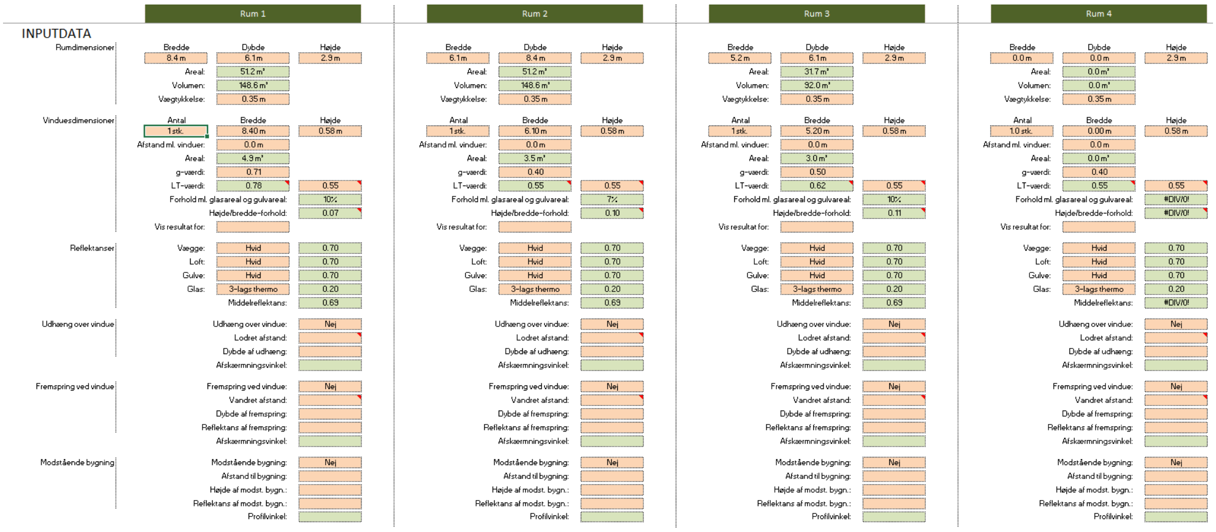


***Figure B.4.*** Input structure of the daylight calculation spreadsheet.

The output of the spreadsheet is a graph with the daylight factor as a function of the room depth with the option to choose a specific reference point with a given distance from the window. The reference point in this thesis is the same as used for the OpenStudio models, shown in figure C.4 on page 68

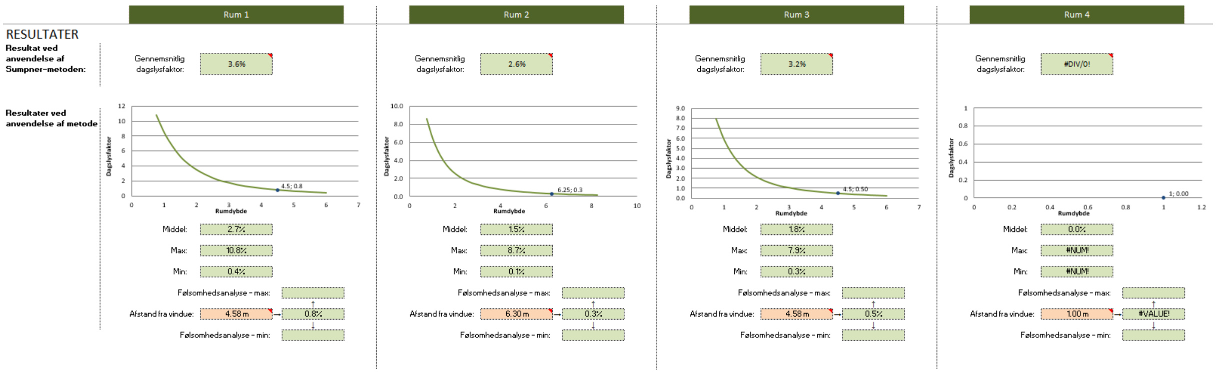


***Figure B.5.*** Outputs of the daylight calculation spreadsheet.

The case building have nine spaces that requires daylighting control, the open offices, the conference rooms, the canteen, the reception and the three offices. For the spaces that does not have an overhang the daylight factor is calculated for each discrete window to wall ratio (WWR) and used in the simulations. For the spaces that have an overhang, three daylight factors are calculated for each discrete value of WWR. A second order regression curve is added to each set of three to obtain an equation from which the daylight factor can be calculated as a function of the overhang. These curves and equations are shown in figure B.6 - B.9. The rooms and dimensions are shown in figure B.10. Rooms that have windows towards two distinct facades are calculated as the sum of daylighting through both windows.

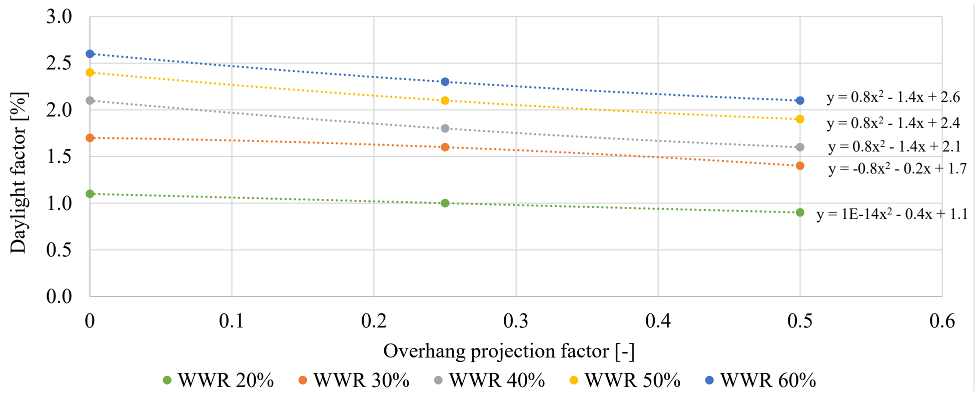



***Figure B.6.*** Equations for daylight factors used for open office 1 and conference room 1.

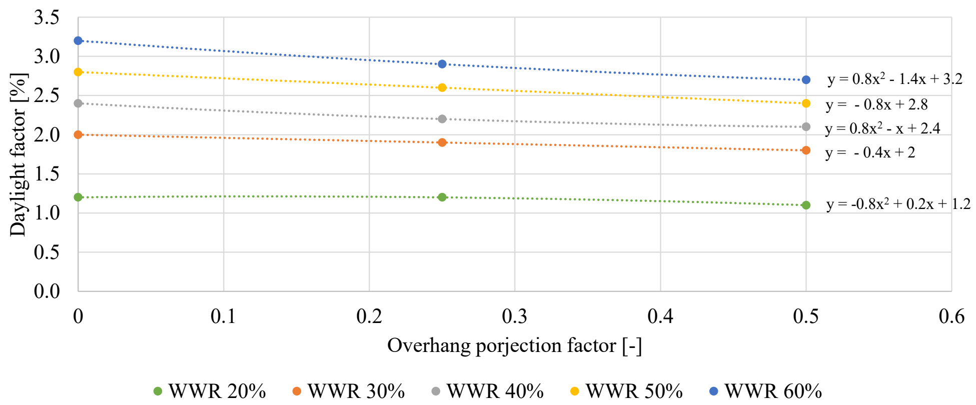



***Figure B.7.*** Equations for daylight factors used for conference room 2.

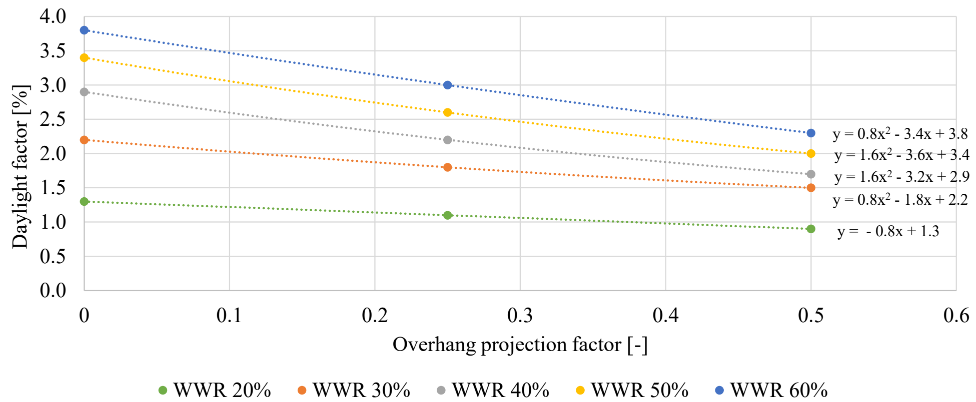



***Figure B.8.*** Equations for daylight factors used for office 1-3.

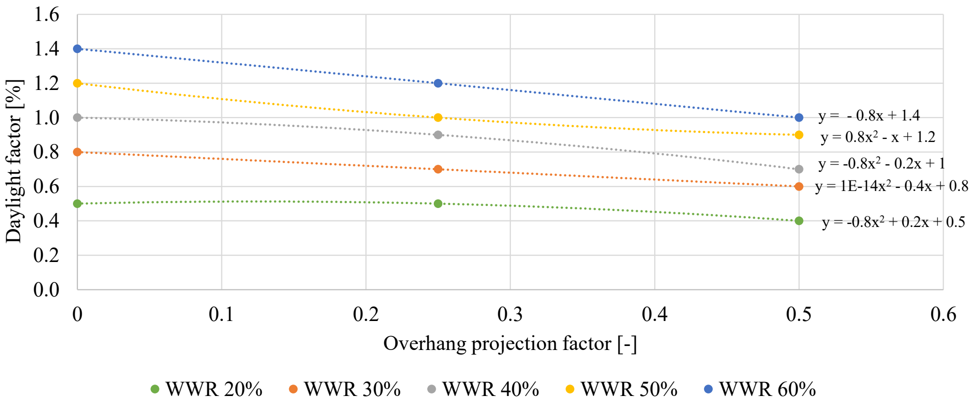



***Figure B.9.*** Equations for daylight factors used for the reception.

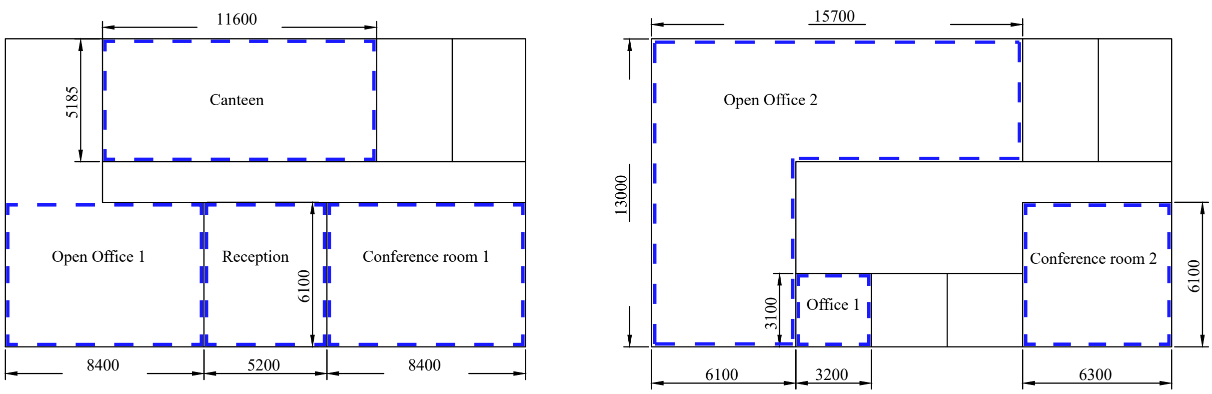



***Figure B.10.*** Spaces where the daylight is calculated using the spreadsheet. Dimensions in mm.

# Case Building Data C

## C.1 Constructions

| Construction | Thickness [m] | U-value [W/m²K] | SHGC [–] | $V_t$ [–] |
|---|---|---|---|---|
| Exterior wall | 0,35 | 0,20 | - | - |
| Roof | 0,27 | 0,19 | - | - |
| Ground deck | 0,29 | 0,19 | - | - |
| Interior wall | 0,14 | - | - | - |
| Floor | 0,12 | - | - | - |
| ceiling | 0,12 | - | - | - |
| Window | - | 0,80 | 0,29 | 0,55 |

***Table C.1.*** Overview of the constructions used for the case-building.

### C.1.1 Exterior Constructions

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m²K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| $R_{se}$ | - | - | 0,04 | - | - |
| Brick | 0,102 | 0,780 | 0,13 | 0,70 | 0,70 |
| Insulation | 0,150 | 0,032 | 4,69 | 0,50 | 0,50 |
| Brick | 0,102 | 0,780 | 0,13 | 0,70 | 0,70 |
| $R_{si}$ | - | - | 0,13 | - | - |
| U-value | 0,20 W/m²K | | | | |

***Table C.2.*** Exterior wall construction.

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m²K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| $R_{se}$ | - | - | 0,04 | - | - |
| Concrete | 0,120 | 1,800 | 0,07 | 0,65 | 0,65 |
| Insulation | 0,150 | 0,032 | 4,69 | 0,50 | 0,50 |
| Acoustic tile | 0,019 | 0,060 | 0,32 | 0,30 | 0,30 |
| $R_{si}$ | - | - | 0,10 | - | - |
| U-value | 0,19 W/m²K | | | | |

***Table C.3.*** Roof construction.

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m$^2$K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| $R_{se}$ | - | - | 0,04 | - | - |
| Insulation | 0,150 | 0,032 | 4,69 | 0,50 | 0,50 |
| Concrete | 0,120 | 1,800 | 0,07 | 0,65 | 0,65 |
| Acoustic tile | 0,019 | 0,060 | 0,32 | 0,30 | 0,30 |
| $R_{si}$ | - | - | 0,17 | - | - |
| U-value | | | 0,19 W/m$^2$K | | |

***Table C.4.*** Ground deck construction.

### C.1.2 Interior Constructions

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m$^2$K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| Gypsum | 0,019 | 0,160 | 0,12 | 0,40 | 0,30 |
| Concrete | 0,100 | 1,800 | 0,06 | 0,65 | 0,65 |
| Gypsum | 0,019 | 0,160 | 0,12 | 0,40 | 0,30 |
| U-value | | | 3,41 W/m$^2$K | | |

***Table C.5.*** Interior wall construction.

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m$^2$K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| Acoustic tile | 0,019 | 0,060 | 0,32 | 0,30 | 0,30 |
| Air | - | - | 0,18 | - | - |
| Light concrete | 0,1 | 0,530 | 0,19 | 0,50 | 0,50 |
| U-value | | | 1,46 W/m$^2$K | | |

***Table C.6.*** Floor construction.

| Layer | Thickness [m] | Conductivity [W/mK] | Resistance [m$^2$K/W] | Solar absorp. [-] | Visible absorp. [-] |
|---|---|---|---|---|---|
| Acoustic tile | 0,019 | 0,060 | 0,32 | 0,30 | 0,30 |
| Air | - | - | 0,18 | - | - |
| Light concrete | 0,1 | 0,530 | 0,19 | 0,50 | 0,50 |
| U-value | | | 1,46 W/m$^2$K | | |

***Table C.7.*** Ceiling construction.

## C.2 People Load Distribution

The people are distributed as shown below in order to obtain varying distributions throughout a day. Some spaces have high peak loads a few hours a day, like the conference rooms and the canteen while others are constant throughout the day. The distributions are designed to mimic some of the situations that normally occur in office buildings.

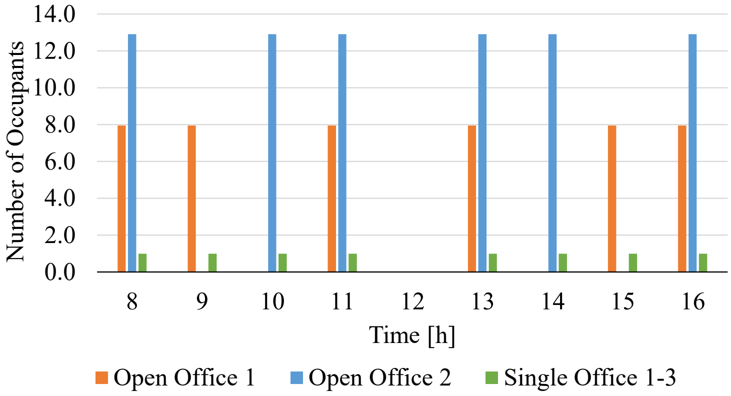



***Figure C.1.*** Number of occupants in the offices during the day.

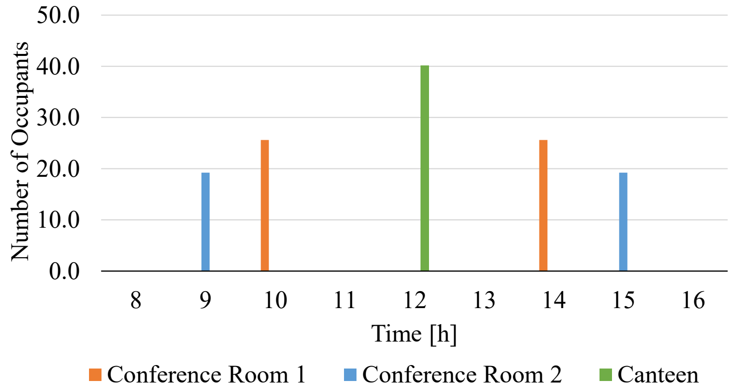



***Figure C.2.*** Number of occupants in the Conference rooms and the canteen during the day.

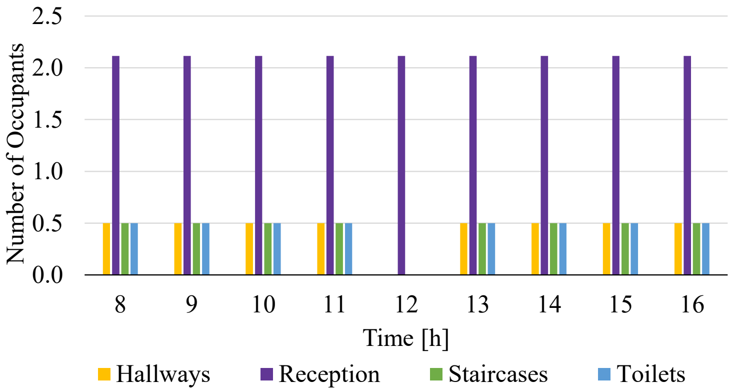



***Figure C.3.*** Number of occupants in the reception, hallways, staircases and toilets during the day.

## C.3 Internal Loads and Systems

| Space | Ventilation [m$^3$/s] | Infiltration [m$^3$/s] | People load [W/m$^2$] | Equip. load [W/m$^2$] | Light. load [W/m$^2$] |
|---|---|---|---|---|---|
| Open Office 1 | 0,064 | 0,010 | 5,60 | 6,0 | 6,0 |
| Open Office 2 | 0,103 | 0,017 | 5,60 | 6,0 | 6,0 |
| Conference room 1 | 0,048 | 0,007 | 14,00 | 6,0 | 6,0 |
| Conference room 2 | 0,036 | 0,005 | 14,00 | 6,0 | 6,0 |
| Office 1-3 | 0,012 | 0,001 | 11,20 | 6,0 | 6,0 |
| Canteen | 0,037 | 0,008 | 9,33 | 6,0 | 6,0 |
| Reception | 0,038 | 0,004 | 8,40 | 6,0 | 6,0 |
| Toilet 1-2 | 0,010 | 0,002 | 3,48 | 0,0 | 5,0 |
| Staircase 1-2 | 0,010 | 0,002 | 3,38 | 0,0 | 5,0 |
| Hallway 1 | 0,019 | 0,004 | 1,82 | 0,0 | 5,0 |
| Hallway 2 | 0,035 | 0,007 | 1,00 | 0,0 | 5,0 |

***Table C.8.*** Ventilation and infiltration flow rates and internal loads in the case building.

## C.4 Lighting Control

In figure C.4 are the placements of lighting controls shown for the Baseline and the simplified models with one, two and six zones are shown in C.5 and C.7.

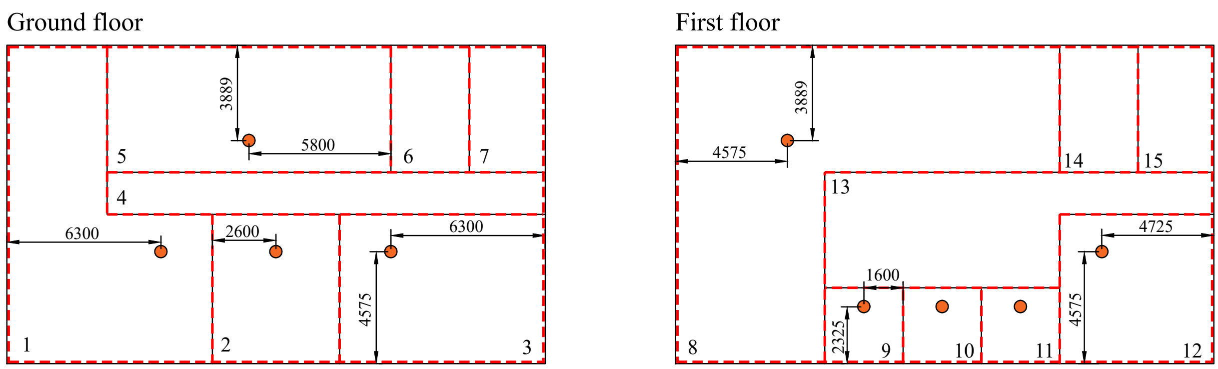



***Figure C.4.*** The placement of the lighting controls for the baseline model with dynamic facade. Dimensions are in mm.The numbers and the red dashed lines indicate zones

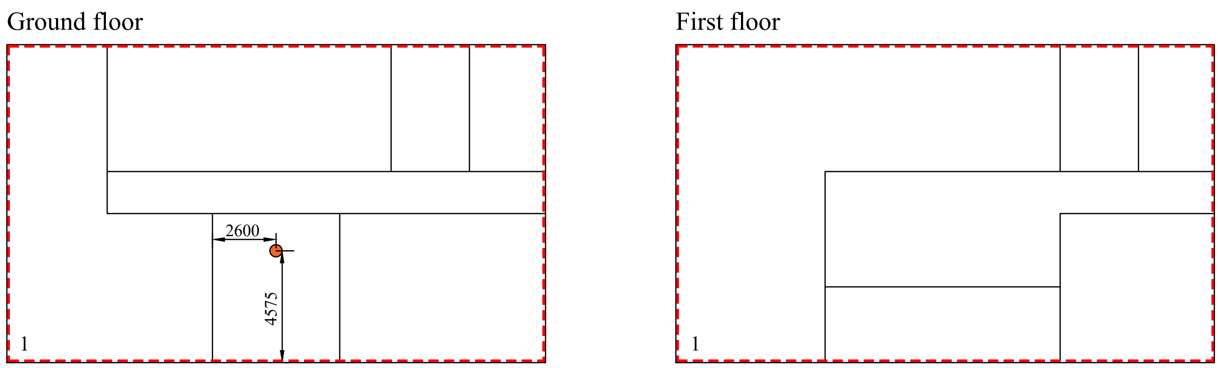



***Figure C.5.*** The placement of the lighting controls for the model with one zones. Dimensions are in mm.The numbers and the red dashed lines indicate zones.

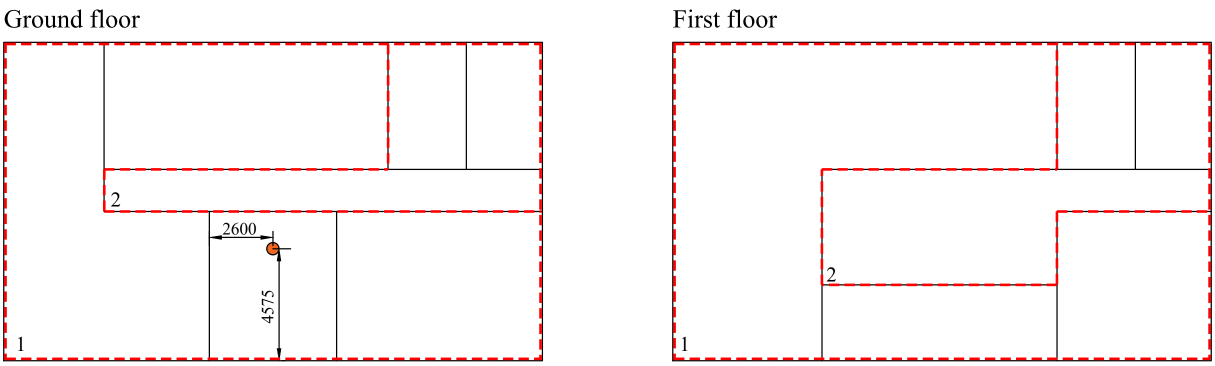



***Figure C.6.*** The placement of the lighting controls for the model with two zones. Dimensions are in mm.The numbers and the red dashed lines indicate zones.

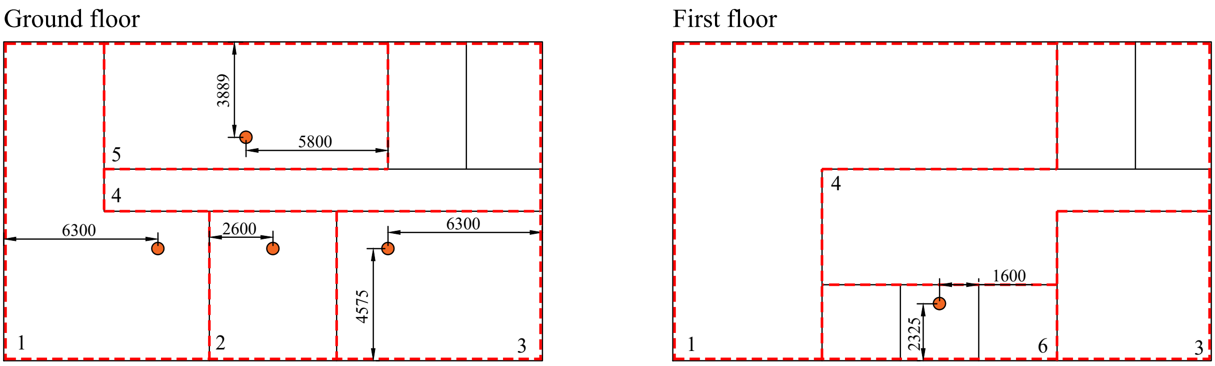



***Figure C.7.*** The placement of the lighting controls for the model with six zones. Dimensions are in mm.The numbers and the red dashed lines indicate zones.

## C.5 Shading Control

Figure C.8 contains information about the direct and diffuse solar radition during the year for the weather data used in this thesis.

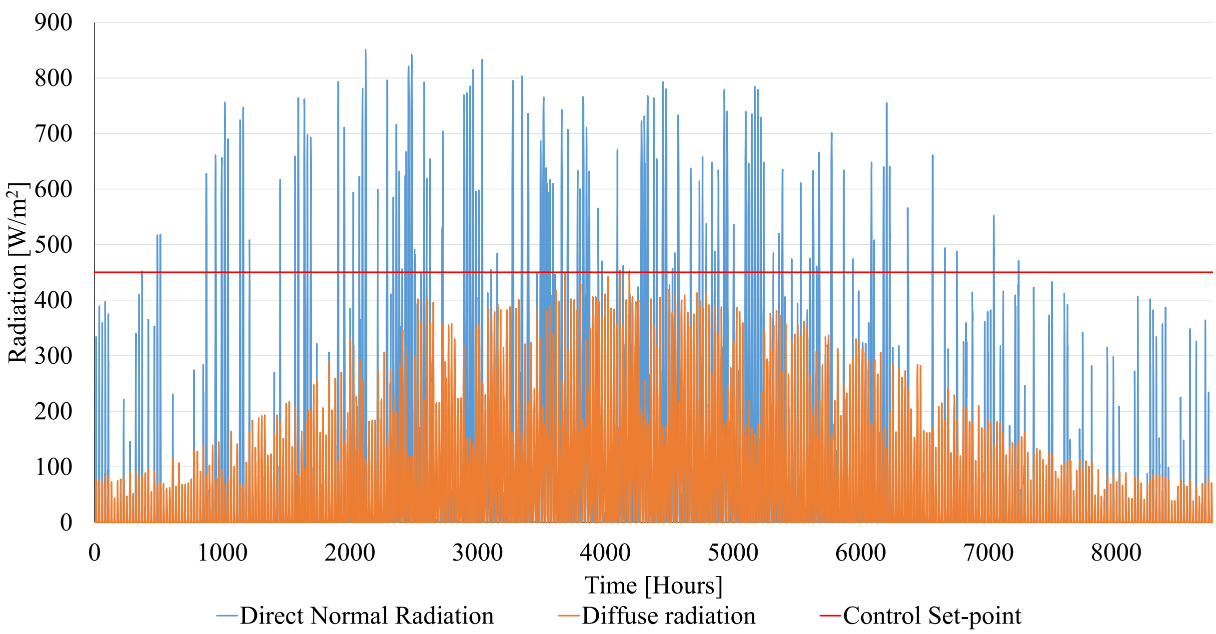



***Figure C.8.*** Diffuse and direct solar radiation during the year with the weather data used in this thesis.

The figure shows that the diffuse radiation rarely exceed 450 W/m$^2$ alone, which indicate that the shading will not be activated without direct radiation.

## C.6 Sampling of two or more Uniformly Distributed Parameters

Varying the WWR and overhang of the four facades independently will result in the issue shown in figure C.9 where the average WWR and overhang for the entire building will be almost the same in every simulation. This is a problem when trying to obtain a uniform distribution across the whole design space because some of the values close to the boundaries might be excluded.

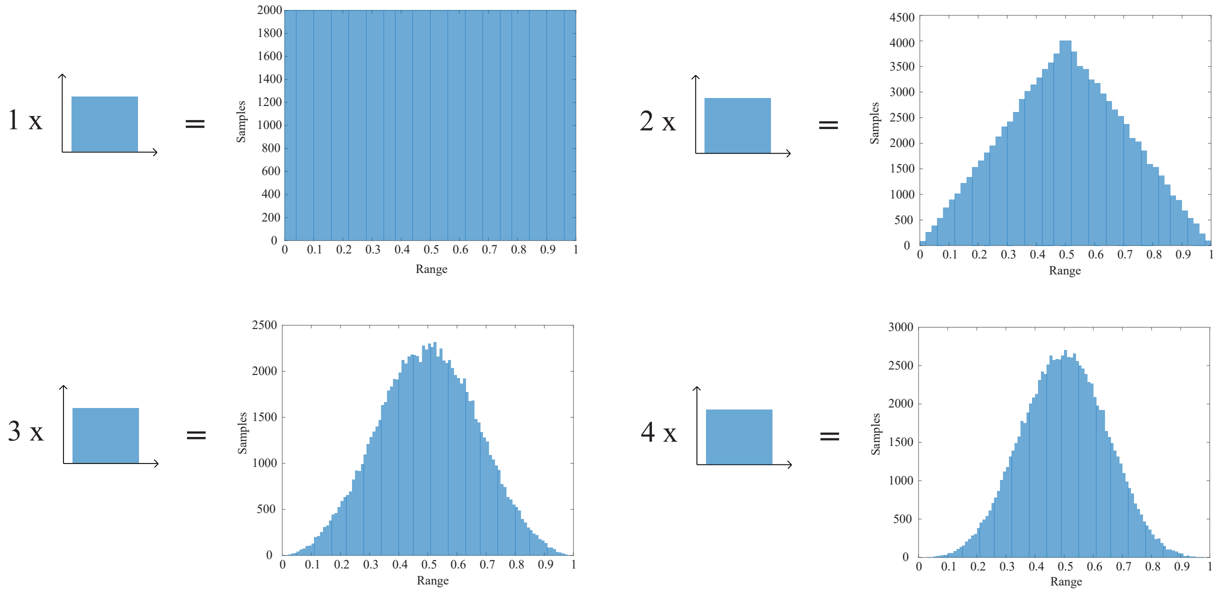



***Figure C.9.*** The principle of the issue that occurs when sampling a set of uniformly distributed parameters.

As the figure shows, the combined distribution is no longer uniform and it gets worse for each uniform parameter added. This means that it is necessary to either vary them all equally or to only vary a few facades while keeping the rest constant.

If only a few facades are to be varied it is necessary to investigate which ones have the most impact on the buildings energy consumption. For this a series of simulations are run. One model are simulated for each pair of WWR and overhang. So for instance, one model is run with varying WWR South and overhang south, while keeping the other WWR's and overhang constant. The WWR's are constant at 40% and the overhangs are at 0 degrees. This results in four different models. This investigation is conducted on the static facade. A sensitivity analysis is then run on each using TOM to determine which have the most influence on the buildings cooling and heating consumption.
Before the sensitivity analysis can be used the number of simulations have to be determined in order to obtain converged results. The amount of simulations necessary to achieve convergence with TOM is shown in figure C.10.

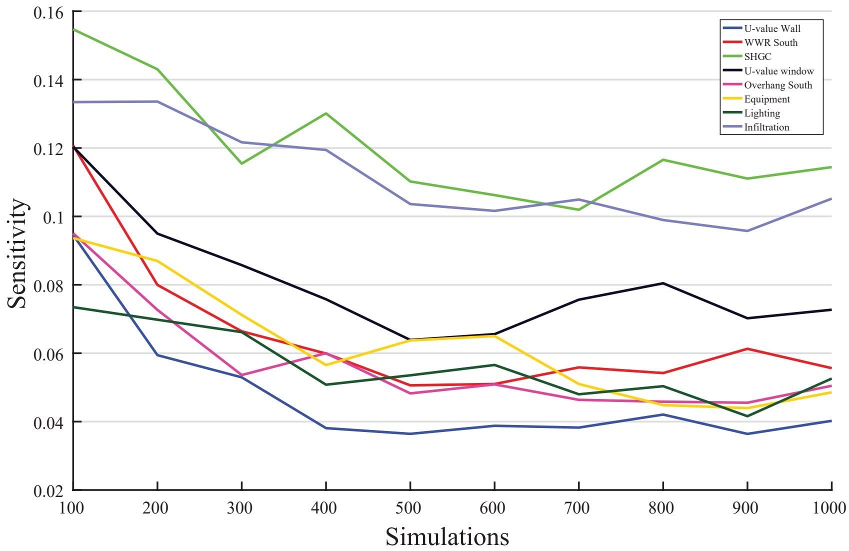



***Figure C.10.*** Convergence of the sensitivity of the input parameters.

From the figure it is shown that with 1000 simulations it is not 100% converged but seeing as this is a quick preliminary investigation, 1000 simulations is assumed enough to obtain useful information. The sensitivity of the WWR and overhang for each cardinal direction is shown in table C.9.

| | South [-] | East [-] | North [-] | West [-] |
|---|---|---|---|---|
| WWR | 0,032 | 0,028 | 0,028 | 0,028 |
| Overhang | 0,031 | 0,027 | 0,027 | 0,028 |

***Table C.9.*** The sensitivity of the eight parameters in question.

As the table shows, the sensitivities are low and close to each other meaning that they have close to no impact on the building. For the WWR this might be caused by the small impact that one facade have compared to the three constant ones. The overall average WWR is barely changed when only changing one side leading to the small sensitivities showed in the table. As for the overhangs, the south overhang is slightly more sensitive which makes sense as the suns angle is much higher towards the south facade and overhangs does not have much impact when used on eastern, western or northern facades.

## C.7 Weather Data

The weather data used in the report is developed for EnergyPlus for the location of Copenhagen in Denmark [U.S. Department of Energy, 2017]. The wind speed, external temperature and normal radiation for the weather data are compared with the DRY weather file and shown as box plots in figure C.11.

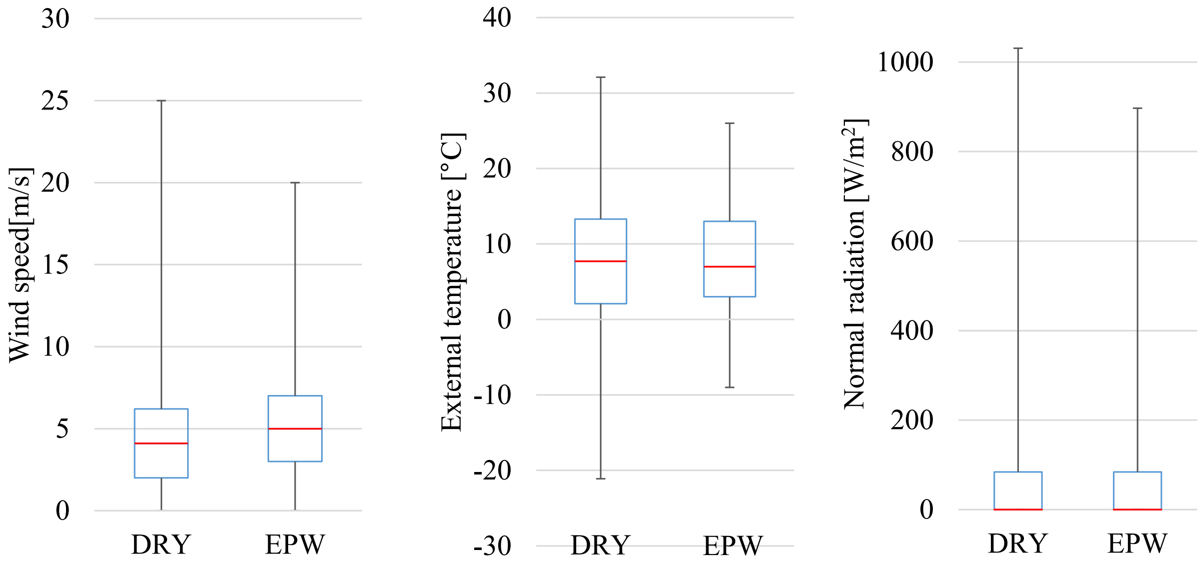



***Figure C.11.*** Box plot of the wind speed, external temperature and normal radiation showing whisker for minimum and maximum and the box showing 25, 50 and 75 % quartile.

# Data Analysis and Results - Static Facade D

*This chapter contains the data analysis and results of the static facade models. The analysis includes a comparison of annual heating and cooling consumption, investigation of model tendencies and a sensitivity analysis.*

On the basis of the described method in chapter 2 and the case description in chapter 4 the models are simulated. A total of 5000 simulations are used for each model for this study, this is proven to be more than enough based on a convergence study shown in appendix E.1. The reason for simulating more than what is necessary, according to convergence, is to reduce noise when investigating the criteria.

This data is analysed and compared with the three criteria described in chapter 2 which is shown below as well. Any simplified model must meet these criteria before it is deemed suitable for guidance in the early design phases.

- The energy consumption for 95 % of the simulations must remain within ± 20 % of the baseline model.
- Changes to the input parameters must yield the same tendencies on the output results as that of the baseline model.
- The influence each input has on the output must be ranked the same as that of the baseline model.

The first criterion is analysed by a direct comparison of the energy consumptions, the second criterion is analysed with scatter plots, Pearson correlation coefficient (PCC) and Monte Carlo filtering while the third criterion is analysed with a sensitivity analysis called TOM. These methods are described in detail in section 2.3 on page 12.

Throughout the chapter the models under investigation will be refereed to as follows:

- Advanced BEM Tool:
  - OpenStudio with 15 zones: $\text{Baseline}_\text{s}$
  - OpenStudio with 1 zone: $\text{OS}_\text{1s}$
  - OpenStudio with 2 zones: $\text{OS}_\text{2s}$
  - OpenStudio with 6 zones: $\text{OS}_\text{6s}$
- Simple BEM Tool:
  - Be15: $\text{Be15}_\text{s}$

## D.1 Annual Consumption

The comparison of the annual consumption is divided into two, one for heating consumption and one for cooling. As the five models are simulated using the same inputs it is possible to compare the outputs from $OS_{1s}$, $OS_{2s}$, $OS_{6s}$ and $Be15_s$ with the outputs from the baseline model. This is shown in figure D.1 as a scatter plot, where the x-axis represents the annual consumption of $Baseline_s$ and the y-axis represents the annual consumption of $Be15_s$ and $OS_{1s}$.

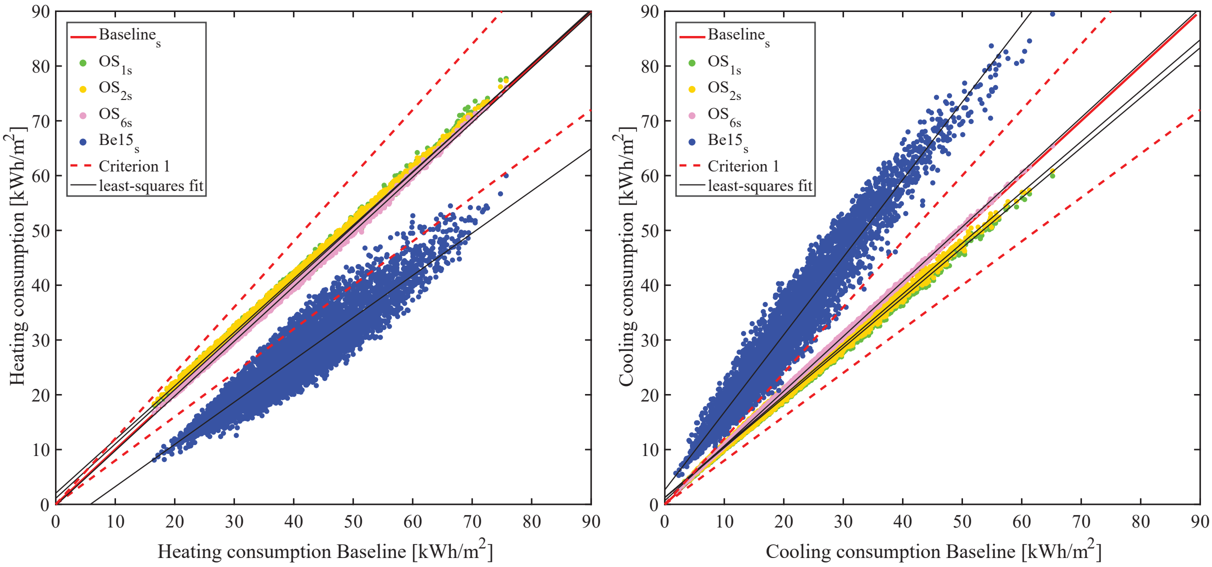



***Figure D.1.*** Heating and cooling consumption from $Baseline_s$ compared with $OS_{1s}$, $OS_{2s}$, $OS_{6s}$ and Be15 for all 5000 simulations with static facade. $R^2$-value of the fits are above 0,99 for all OS models and for $Be15_s$ it is 0,86 heating and 0,96 for cooling.

From the figure it is shown that the results from $OS_{1s}$ and $OS_{2s}$ are very similar to $Baseline_s$ and $OS_{6s}$ is almost identical with $Baseline_s$ while $Be15_s$ differ a great deal more. $OS_{1s}$, $OS_{2s}$ and $OS_{6s}$ fulfils the first criterion while $Be15_s$ does not. Table D.1 shows the percentage of simulations that fulfils the criterion for each model.

| | Heating | | Cooling | |
|---|---|---|---|---|
| | [%] | [qty] | [%] | [qty] |
| $OS_{1s}$ | 100 | 5000 | 100 | 4999 |
| $OS_{2s}$ | 100 | 5000 | 100 | 5000 |
| $OS_{6s}$ | 100 | 5000 | 100 | 5000 |
| $Be15_s$ | 4 | 201 | 1 | 41 |

***Table D.1.*** Percentage and quantity of the static model simulations within the boundaries of criterion 1.

Discovering how close the model with a single zone is to the multi zone model leads to another investigation in order to provide further insight. One of the reason for splitting the model into more zones is to cope with the difference in energy demand and indoor environment that occurs at the different orientations because of the solar heat gains. So it is investigated if the expected difference between north and south actually occurs in the multi zone model. Figure E.4 - E.6 shows the cooling consumption and the indoor air temperature for two rooms facing north and south respectively. From the figures it is concluded that the models behave as expected and that the single zone results are reliable.

The results are shown in figure D.2 as box plots. The box plots provide a way of checking the distribution of the heating and cooling outputs of the models. Further details of the distributions of the heating and cooling consumption for all models are shown in appendix E.3. The distribution of the difference between the simplified models and $\text{Baseline}_s$ are also shown in appendix E.3.

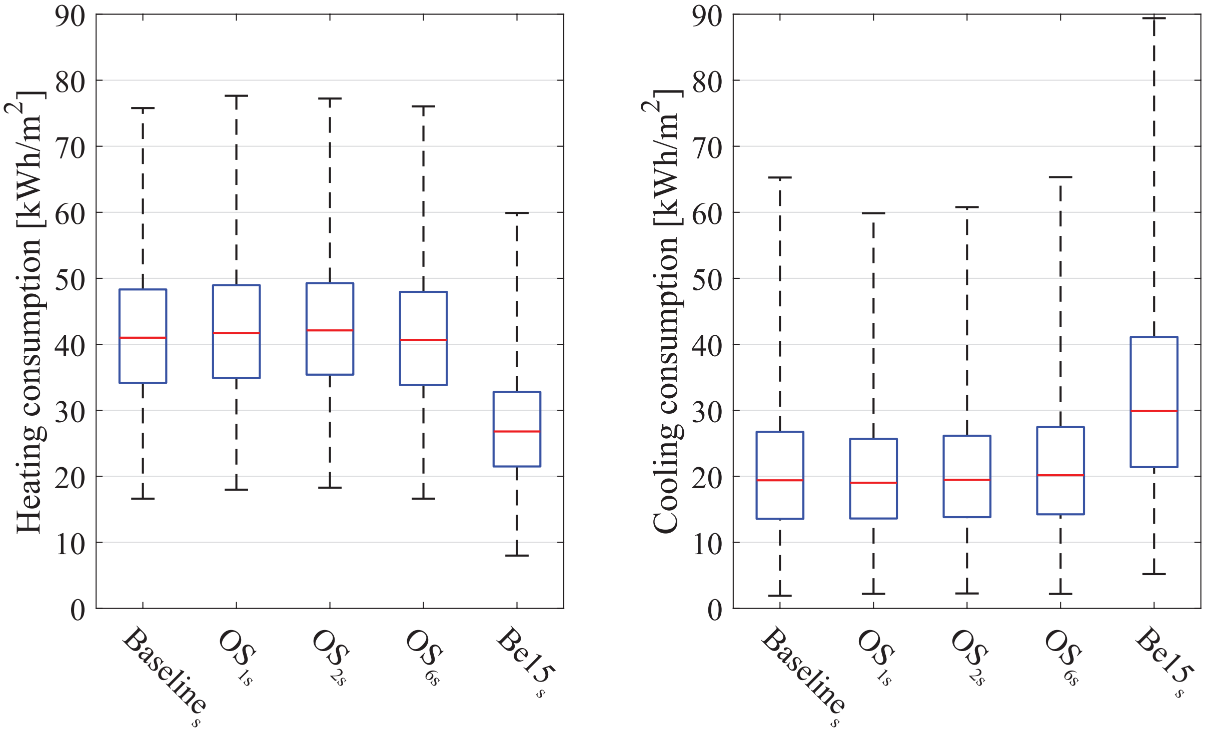



***Figure D.2.*** Heating and cooling consumption for 5000 simulations with static facade presented as box plots.

Figure D.1 and D.2 reveal that the two simpler models, $\text{OS}_{1s}$ and $\text{OS}_{2s}$, estimates consumption in different directions, e.g. $\text{OS}_{1s}$ uses more heating than $\text{Baseline}_s$, but $\text{Be15}_s$ uses less. $\text{OS}_{6s}$ estimates the consumption close to the $\text{Baseline}_s$ though a small deviance is seen in the same direction as $\text{Be15}_s$ and not opposite like $\text{OS}_{1s}$ and $\text{OS}_{2s}$. This could indicate that the deviation occurring is non-linear when moving closer to the y-axis on figure 1.3 on page 4. For example $\text{OS}_{1s}$ could have a consumption $2\,\text{kWh/m}^2$ higher than $\text{Baseline}_s$. This does not necessarily mean than $\text{Be15}_s$ would have a consumption which is even higher, but it could actually be $-3\,\text{kWh/m}^2$ lower than the $\text{Baseline}_s$. Looking only at the magnitude of the error the results shows an increase, with increasing simplicity of the models.

## D.2 Model Tendencies

To investigate the second criterion scatter plots together with Pearson correlation coefficient (PCC) is used to identify trends. Furthermore histograms for the different inputs in the models are created with multiple Monte Carlo filters to both heating and cooling consumption.

16 figures with five scatter plots each representing one of the five models, have been examined for the tendencies of the relation between inputs and outputs and one is presented in this chapter while the rest are in appendix E.5. The figures are also used to inspect the data for any odd trends that might occur. Five scatter plots are shown in figure D.3 for the relation between the heating consumption and artificial lighting for the five models. Note that the magnitude of the correlation is not of interest for criterion two, but rather if changes to an input yield same

tendencies on the output as that of $\text{Baseline}_s$. The scatter plots are manually examined as a qualitative validation approach. To further validate the results PCC is used as a quantitative approach.

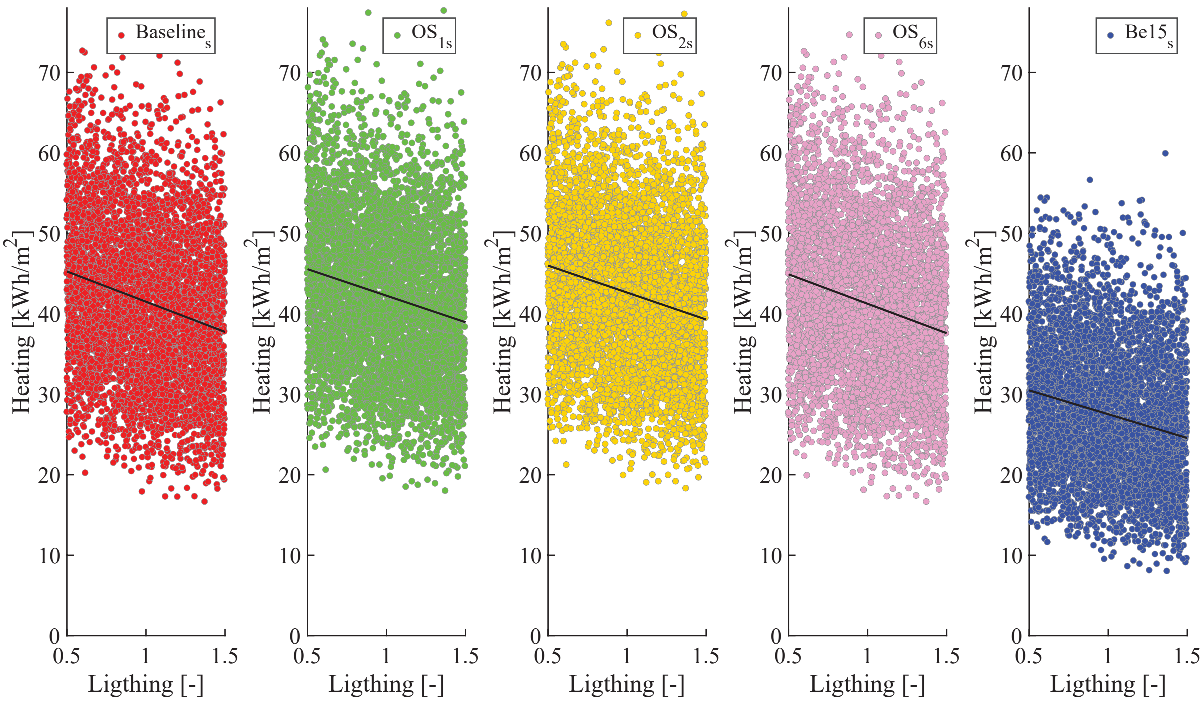



***Figure D.3.*** Relation between lighting and heating consumption for all 5000 simulations with static facade.

From the figure it can be seen that increasing the lighting consumption reduces the need for heating, which is expected as the internal heat gain increases.

From the scatter plots in figure D.3 and the ones in appendix E.5 it is concluded that $\text{OS}_{1s}$, $\text{OS}_{2s}$, $\text{OS}_{6s}$ and $\text{Be15}_s$ comply with the second criterion so far. Furthermore the figures shows that there are no odd tendencies.

In combination with the scatter plots, the PCC is used to determine if the tendencies are the same for the five models. The correlation presented in table D.2 is between one input and one output for all the simulations. A positive value means that increasing the input will increase the consumption, while a negative value means that increasing the input reduces the energy consumption.

| | | R wall | WWR | SHGC | U-win | OH | Equip | Light | Infil |
|---|---|---|---|---|---|---|---|---|---|
| Heating | Baseline$_s$ | -0,13 | 0,14 | -0,33 | 0,49 | 0,06 | -0,23 | -0,22 | 0,67 |
| | OS$_{1s}$ | -0,13 | 0,18 | -0,31 | 0,50 | 0,06 | -0,24 | -0,19 | 0,67 |
| | OS$_{2s}$ | -0,13 | 0,17 | 0,33 | 0,50 | 0,06 | -0,21 | 0,20 | 0,67 |
| | OS$_{6s}$ | -0,13 | 0,16 | -0,33 | 0,49 | 0,06 | -0,22 | -0,21 | 0,67 |
| | Be15$_s$ | -0,19 | 0,25 | -0,35 | 0,67 | 0,06 | -0,27 | -0,21 | 0,36 |
| Cooling | Baseline$_s$ | 0,05 | 0,56 | 0,53 | -0,17 | -0,17 | 0,36 | 0,23 | 0,23 |
| | OS$_{1s}$ | 0,05 | 0,56 | 0,56 | -0,17 | -0,17 | 0,37 | 0,28 | -0,24 |
| | OS$_{2s}$ | 0,05 | 0,55 | 0,53 | -0,17 | -0,16 | 0,40 | 0,26 | -0,24 |
| | OS$_{6s}$ | 0,05 | 0,56 | 0,55 | -0,17 | -0,17 | 0,37 | 0,24 | -0,24 |
| | Be15$_s$ | 0,06 | 0,60 | 0,64 | -0,16 | -0,13 | 0,26 | 0,18 | -0,10 |

***Table D.2.*** PCC for each input for all models with static facade for heating and cooling consumption.

From the table D.2 it is concluded that the tendencies of changing an input result in a change in consumption in the same direction. Note that the magnitude of the values should not be compared with other inputs. It is only used to determine a tendency between inputs and outputs for the three models. The magnitude of the correlation is further investigated in section D.3.

To further investigate the tendencies of the simplified models, histograms of the inputs with Monte Carlo filters on the outputs are used. Four different filters are added to the outputs with different combinations of heating and cooling consumption. The four together contain the entire data-set of 5000 simulations. The different filter combinations are shown in table D.3. The filters are based on the median of the data set, e.g. filter one includes all simulations that are below the median of both heating and cooling. Appendix E.6 contains a detailed explanation of what these histograms represents.

| | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|
| | Low/Low | Low/High | High/Low | High/High |

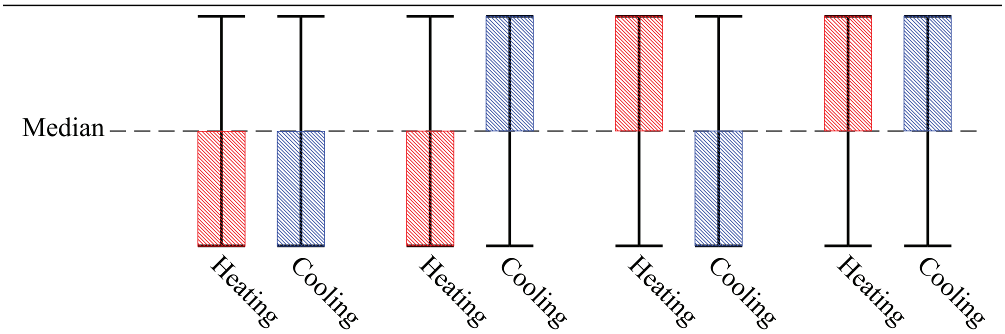



***Table D.3.*** Four different filters used to split the 5000 simulations for investigation of the tendencies.

The remaining inputs after adding filter 1 are shown in table D.4, recall that without any filters added the distribution for all the inputs are uniform. The rest of the histograms are shown in figure E.2 - E.4.

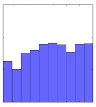
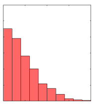
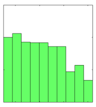
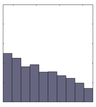
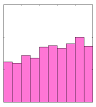
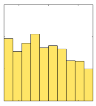
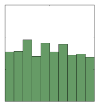
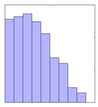
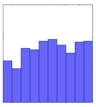
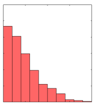
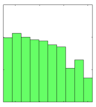
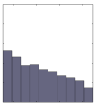
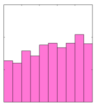
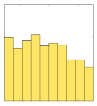
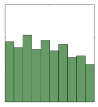
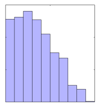
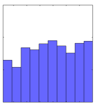
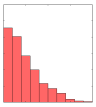
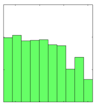
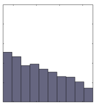
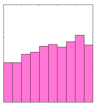
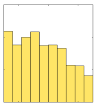
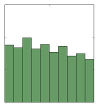
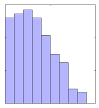
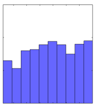
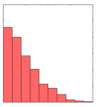
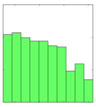
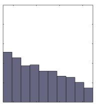
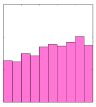
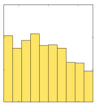
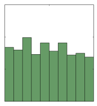
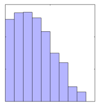
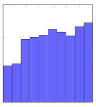
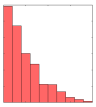
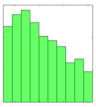
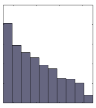
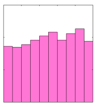
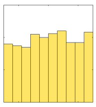
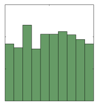
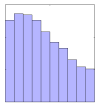
| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_s$ #793 |  |  |  |  |  |  |  |  |
| OS$_{1s}$ #822 |  |  |  |  |  |  |  |  |
| OS$_{2s}$ #817 |  |  |  |  |  |  |  |  |
| OS$_{6s}$ #812 |  |  |  |  |  |  |  |  |
| Be15$_s$ #975 |  |  |  |  |  |  |  |  |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table D.4.*** Histograms of the distribution for the remaining inputs when filter 1 is applied. The number below the model name indicates the amount of remaining simulations. These are the tendencies for the models with static facade.

The figure shows OS$_{1s}$, OS$_{2s}$, OS$_{6s}$ and Be15$_s$ have the same tendencies as Baseline$_s$. This is also the case when adding the other three filters. The distribution of the individual inputs behave as expected based on the filters. E.g. a model with a low cooling consumption and a low heating consumption, as shown in figure D.4, is expected to have a low U-Win and a low WWR. The tendency of WWR and U-Win has to be low to avoid overheating because of solar heat gains and to avoid heat loss respectively.

Based on the results presented in this section it is concluded that criterion two is fulfilled for all the models, both simple and advanced.

## D.3 Sensitivity Analysis Rankings

To investigate if the third criterion is met for the simplified models, a sensitivity analysis (SA) of the parameters is conducted using the method called TOM, which is described in detail in chapter 2. The sensitivity for the parameters are shown in figure D.4. Note that the SA uses both heating and cooling as outputs. In addition to this the results of the SA is shown as a table in appendix E.8. The SA for the inputs with heating or cooling as a single output are shown in appendix E.8.

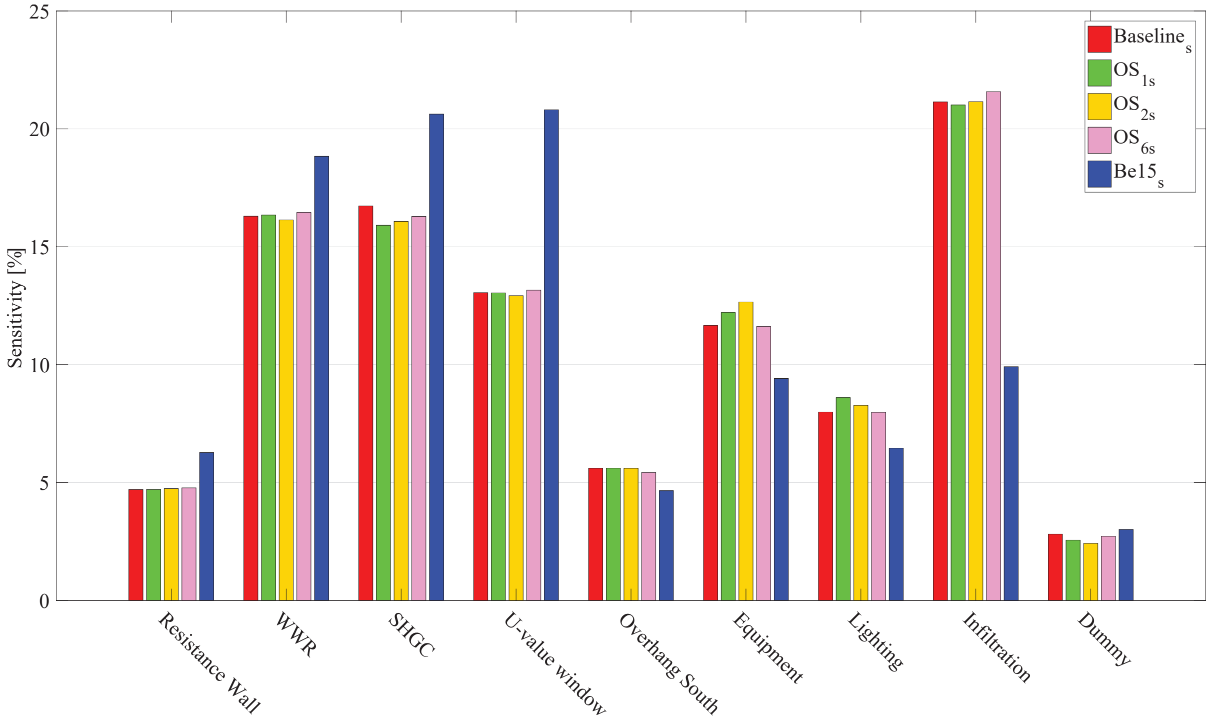



***Figure D.4.*** The sensitivity on the input parameters with heating and cooling consumption as output for the models with static facade.

The dummy variable is an additional input which is added in the method which has zero influence on the result since it is not included in the model. It is used to determine if some inputs are irrelevant. With the dummy variable added it is clear that the resistance of the wall and the overhang towards south have very limited influence on the energy consumption. From the figure it can be seen that the sensitivity of each parameter changes from model to model some more than other. One that stick out is the infiltration where $\text{Be15}_s$'s sensitivity to infiltration is half of that of $\text{Baseline}_s$. Furthermore the sensitivity of WWR and U-value Window is higher than for $\text{Baseline}_s$. From the figure it is clear that the U-value for the window and the infiltration have considerably different influence on the consumptions.

For $\text{OS}_{1s}$ and $\text{Baseline}_s$, the ranking of WWR and SHGC are switched. But seeing that the difference is relatively small it is not a problem and the two parameters are regarded as having the same rank.

All the different models agree on which inputs are the top four parameters and from the 5th to the 8th parameter as well. Looking at these four means that $\text{Be15}_s$ actually meets the second criterion. Though if having a heating dominated building and wanting to know which parameter to optimize between the U-value of the window and the infiltration, $\text{Be15}_s$ would guide towards increasing the u-value of the windows while in reality it would be more efficient to lower the infiltration. In cases like this, it is insufficient to use $\text{Be15}_s$ as it provides falsified guidance.

Based on these results it is concluded that $\text{Be15}_s$ does not meet the third criterion due to the inconsistencies in the ranking of parameters compared to $\text{Baseline}_s$. Also it is concluded that $\text{OS}_{1s}$, $\text{OS}_{2s}$ and $\text{OS}_{6s}$ fulfil the second criterion.

## D.4 Partial Conclusion

Based on the investigations described in this chapter it is concluded that $Be15_s$ is unsuitable as a design tool in the early stages of building design. This is concluded even though Be15 did pass the tendency criteria. The ranking of parameters from conducting SA is important in the early design phase which ultimately is the reason for deeming Be15 unsuitable.

$OS_{1s}$ on the other hand did well in both criteria and as a result of that, it is concluded to be suitable as a design tool in the early stages of building design. The interesting thing about $OS_{1s}$ is how close it performs to the baseline model and that not much is gained from the extra time spend on a multi zone model compared to that of a single zone model. The same goes for $OS_{2s}$ and $OS_{6s}$, which performs even better than the single zone model and is deemed suitable as well.

The conclusions in this chapter is based on models with no solar shading or automatic lighting controls. This is analysed in chapter F.

# Additional Results - Static Facade E

## E.1 Convergence of Baseline

To determine the amount of simulations needed to reach a converged result for the sensitivity analysis, TOM, a series of simulations have been run. This investigation starts with 1000 simulations since the examination of the WWR descriped in chapter 4 revealed that at least this was needed. 1000 to 1500 simulations have been run with a step of 100. the results are shown in figure E.1. The convergence test has only been done on the baseline model.

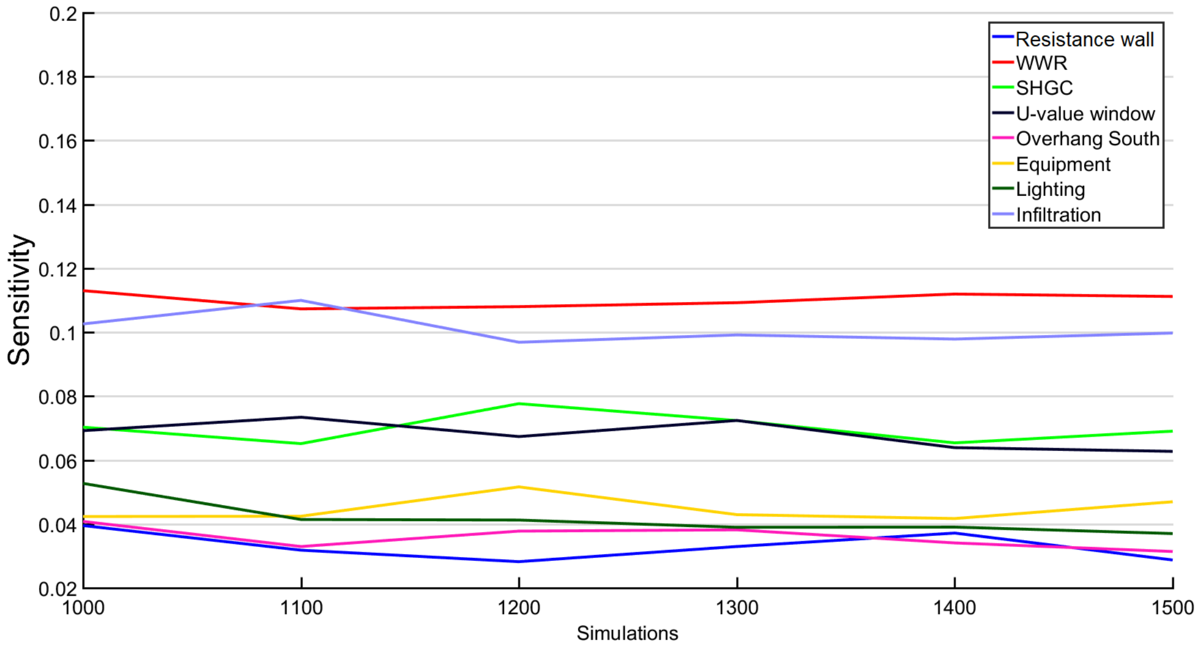



***Figure E.1.*** Convergence of the results gained with the SA SAtom.

Figure E.1 shows that SA calculated with SAtom has converged. The rank of the parameters does not change much, The only once that does are those whom have a low sensitivity or where the sensitivity are very close. Furthermore a box plot have been shown in figure E.2 and E.3, the whiskers show the interquartile and the pluses indicate values outside the interquartile range.

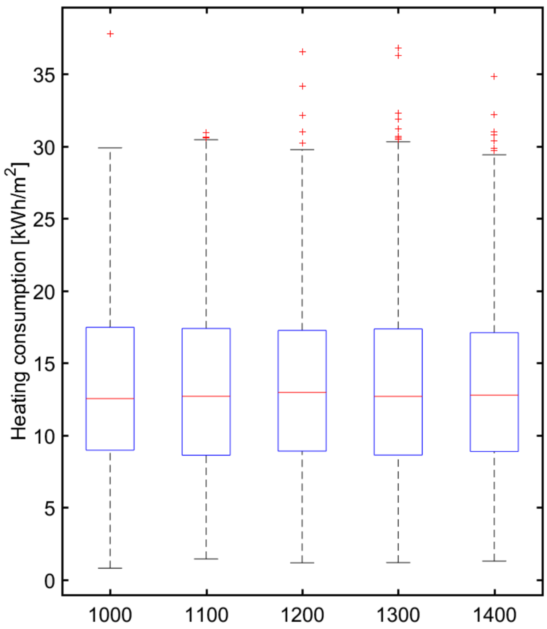



***Figure E.2.*** Boxplot showing the heating consumption for the convergence investigation with static facade.

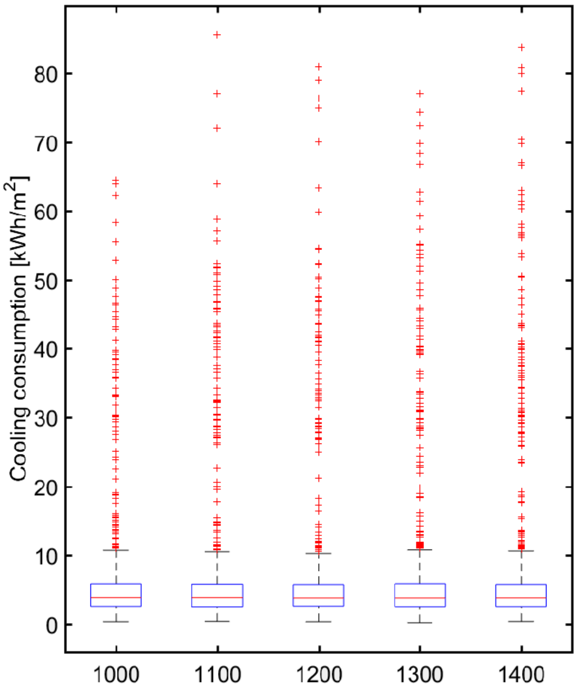



***Figure E.3.*** Boxplot showing the cooling consumption for the convergence investigation with static facade.

The figures show that the data in the box plot is kept almost identical for all the simulations, which indicate that data is well represented. Comparing the energy consumption for heating and cooling it can be seen that there is a lot results above the interquartile range for cooling than heating, but the max values are not changing much.

## E.2 OpenStudio Model Behaviour

The models are examined for differences between north and south facing facades. This is due to the single zone model obtaining such accurate results but that can be due to a fault in the model where there is no difference between north and south, so nothing is gained from having the extra zones. The two rooms used for this investigation is staircase 2 facing north and Office 1 facing south, they both have a window area of 3,7 $m^2$.

The investigation shows that there is a clear difference between north and south, as shown in figure E.4 - E.6. The investigation is conducted for winter, summer and spring and it shows that the south room generally is warmer and has a higher cooling demand, specially in the week in April shown in the figure.

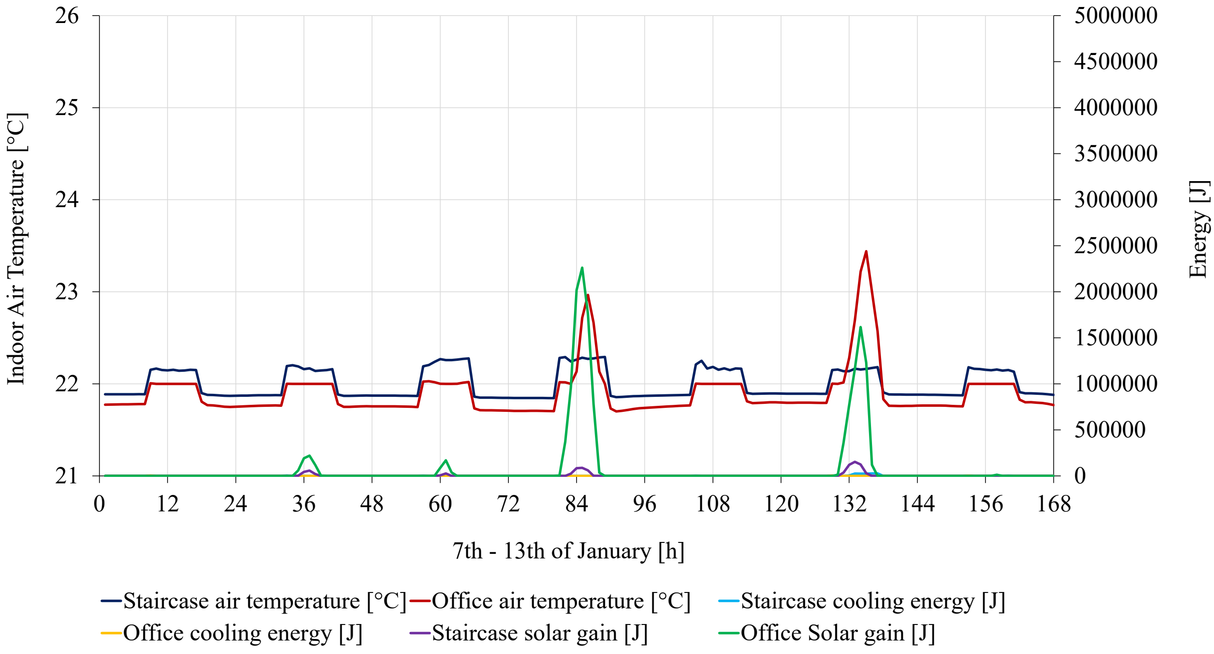



***Figure E.4.*** Temperature,cooling consumption and solar gain for a south and north facing room.

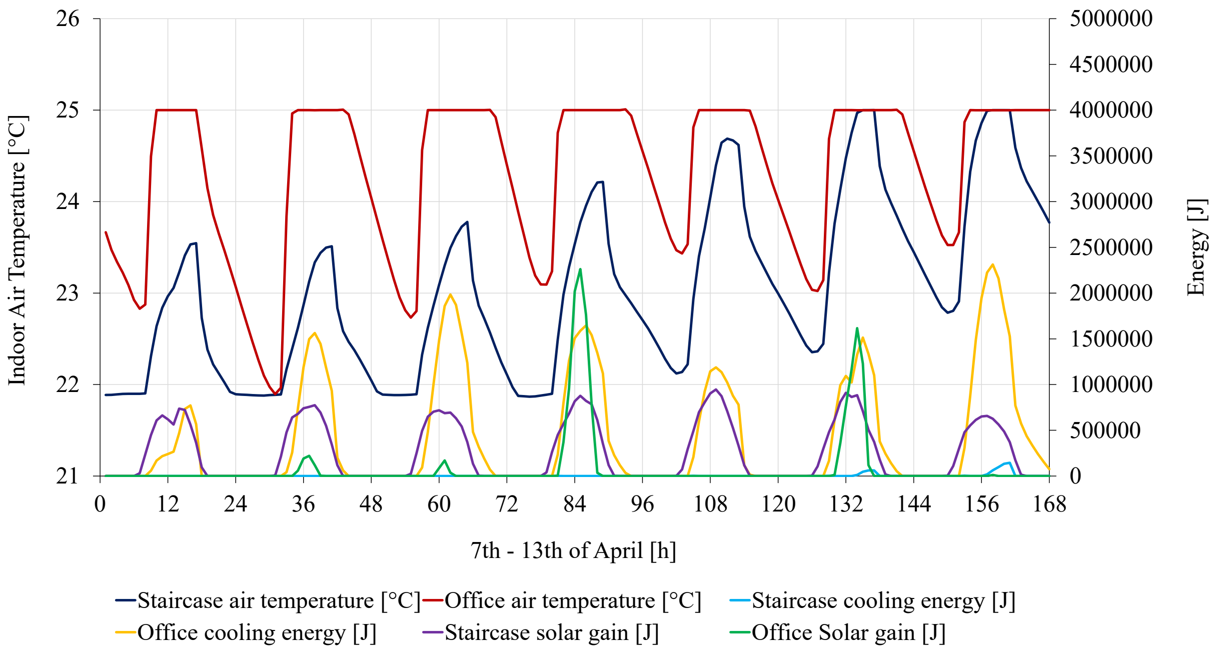



***Figure E.5.*** Temperature,cooling consumption and solar gain for a south and north facing room.

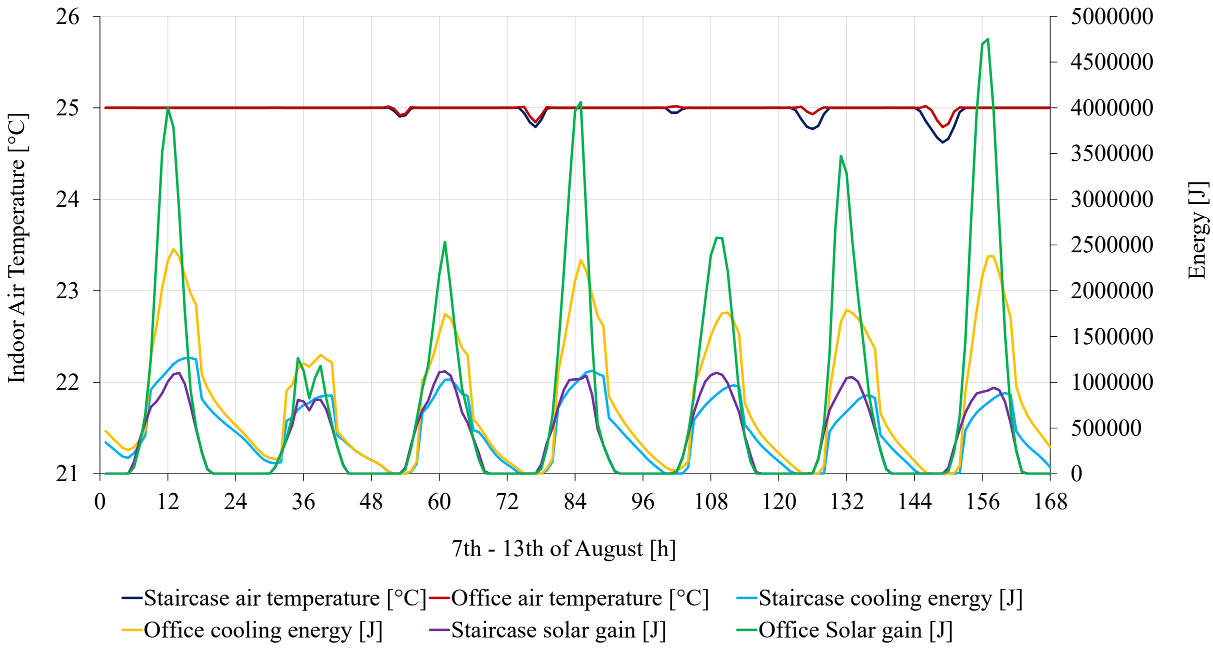



***Figure E.6.*** Temperature,cooling consumption and solar gain for a south and north facing room.

## E.3 Distribution of Results

## E.4 Distribution of Heating, Cooling and Lighting Consumption

Figure E.7 shows the distribution of the results for all models for both heating and cooling consumption. The difference between the Baseline model and the simplified models are shown in figure E.8

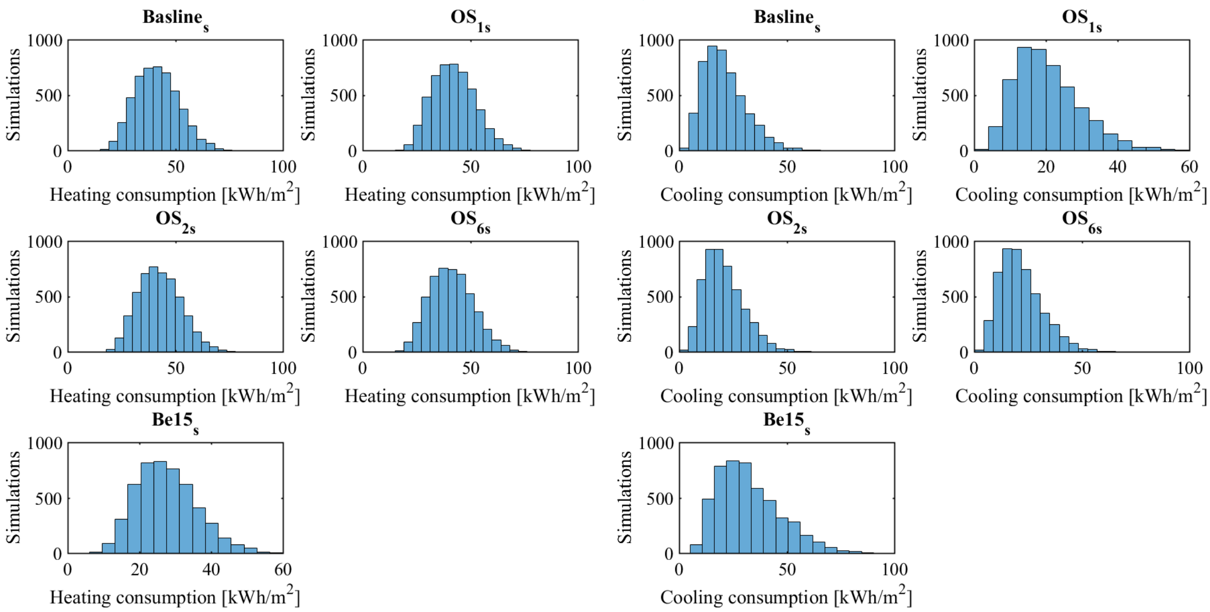



***Figure E.7.*** Distribution of the results for heating and cooling consumptio for static facaden.

From figure D.2 on page 75 and E.7 it is clear that the majority of the data is centred around the mean value of the data-sets for each model.

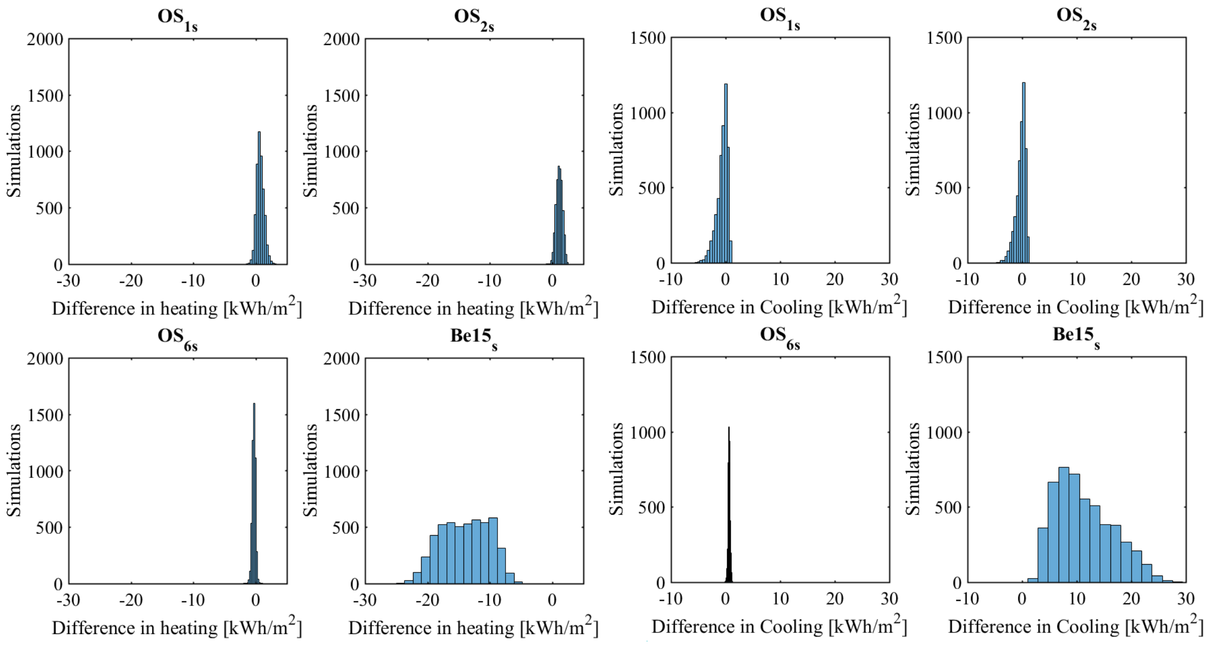



***Figure E.8.*** The distribution of the difference between the baseline model and the simplified models for the static facade.

In table E.1 is shown more distribution characteristics for these differences. The standard deviation of the $Be15_s$ results are higher than the others for both heating and cooling which means that inconsistencies occurs between inputs and outputs for $Be15_s$.

| | Heating [kWh/m$^2$] | | | | Cooling [kWh/m$^2$] | | | |
|---|---|---|---|---|---|---|---|---|
| | $OS_{1s}$ | $OS_{2s}$ | $OS_{6s}$ | $Be15_s$ | $OS_{1s}$ | $OS_{2s}$ | $OS_{6s}$ | $Be15_s$ |
| Mean | 0,7 | 1,1 | -0,2 | -14,0 | -0,6 | -0,2 | 0,7 | 11,0 |
| Standard deviation | 0,6 | 0,5 | 0,3 | 3,8 | 1,0 | 0,9 | 0,2 | 5,2 |
| Min | -0,0 | -0,0 | -0,0 | -4,8 | -0,0 | -0,0 | 0,0 | 1,5 |
| Max | 3,3 | 2,6 | -1,9 | -24,2 | -5,4 | -4,5 | 1,2 | 28,6 |

***Table E.1.*** Statistical properties of the difference between $Baseline_s$, $OS_{1s}$ and $Be15_s$ for models with static facade.

From figure E.8 and table E.1 that the more zones that are included in the advanced BEM tool the more simulations are closer to 0 kWh/m$^2$ in difference.

## E.5 Scatter Plots

The scatter plots for the relation between the inputs and the outputs for the three models are shown in the following figures from E.9 to E.23.

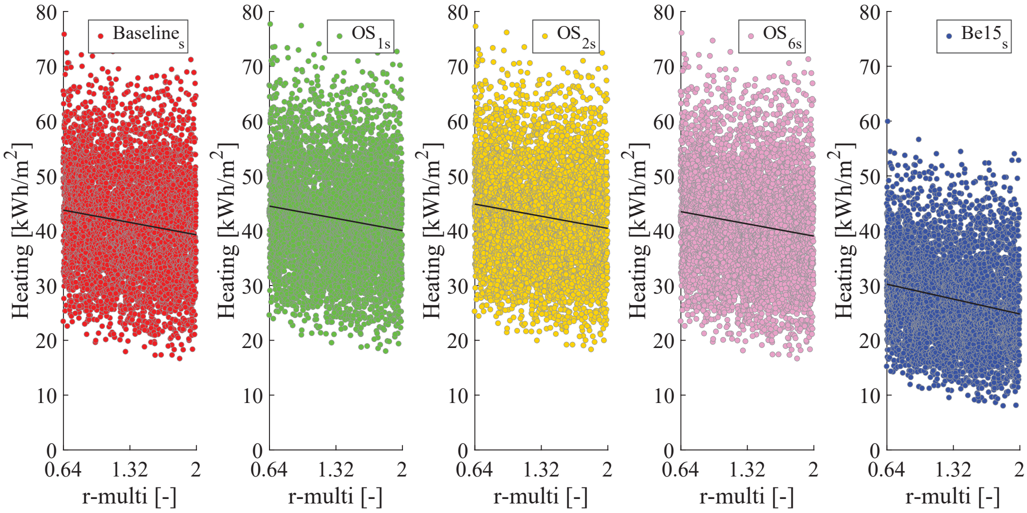



***Figure E.9.*** Relation between U-value for the wall and the heating consumption for all 5000 simulations.

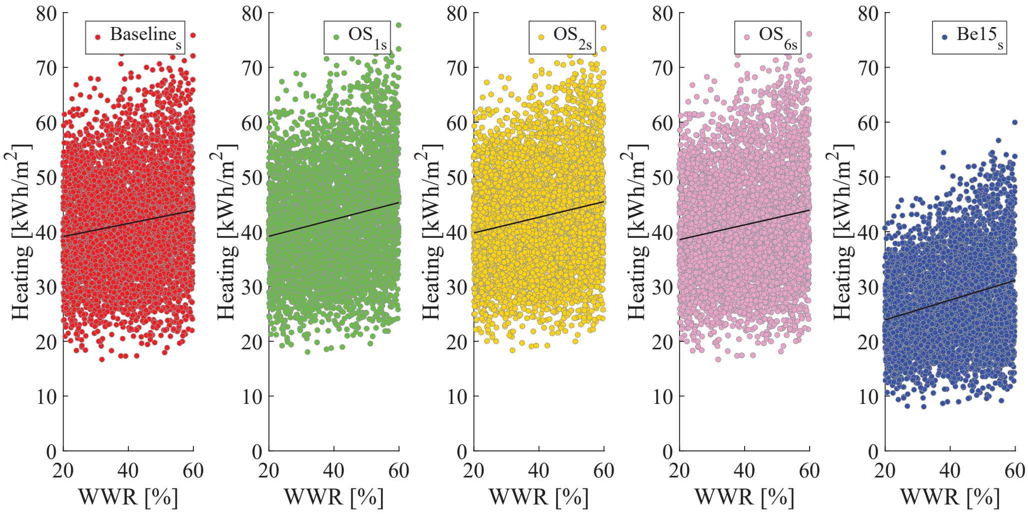



***Figure E.10.*** Relation between window to wall ratio and the heating consumption for all 5000 simulations.

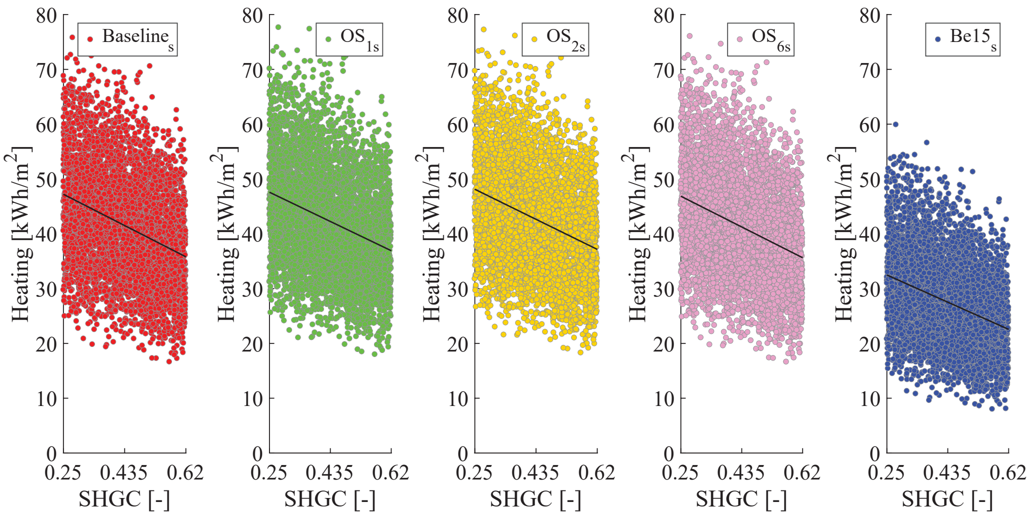



***Figure E.11.*** Relation between SHGC and the heating consumption for all 5000 simulations.

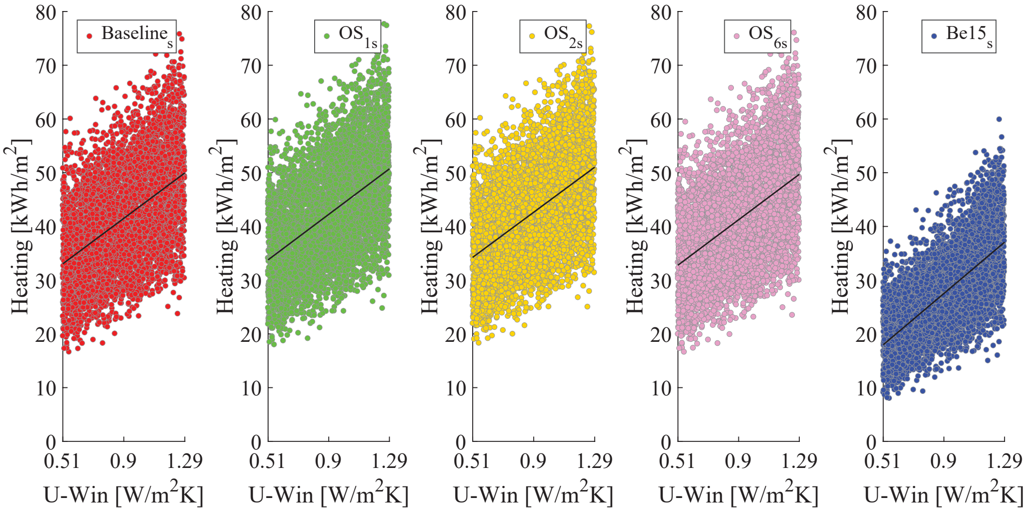



***Figure E.12.*** Relation between u-value for the window and the heating consumption for all 5000 simulations.

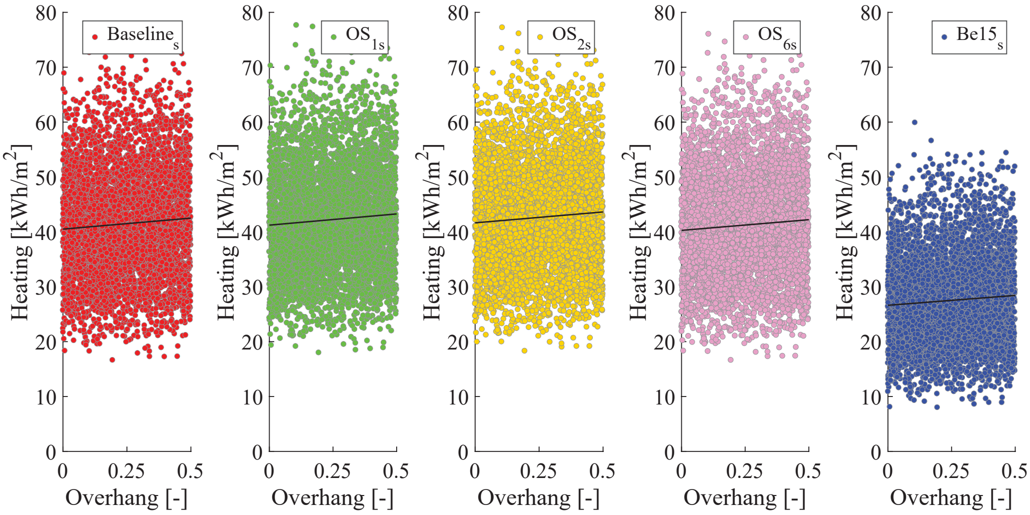



***Figure E.13.*** Relation between overhang south and the heating consumption for all 5000 simulations.

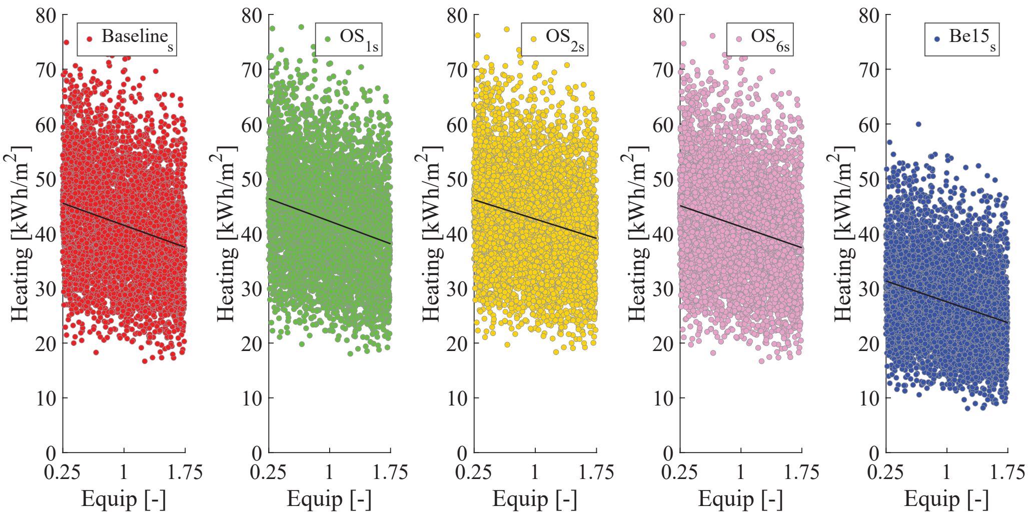



***Figure E.14.*** Relation between equipment and the heating consumption for all 5000 simulations.

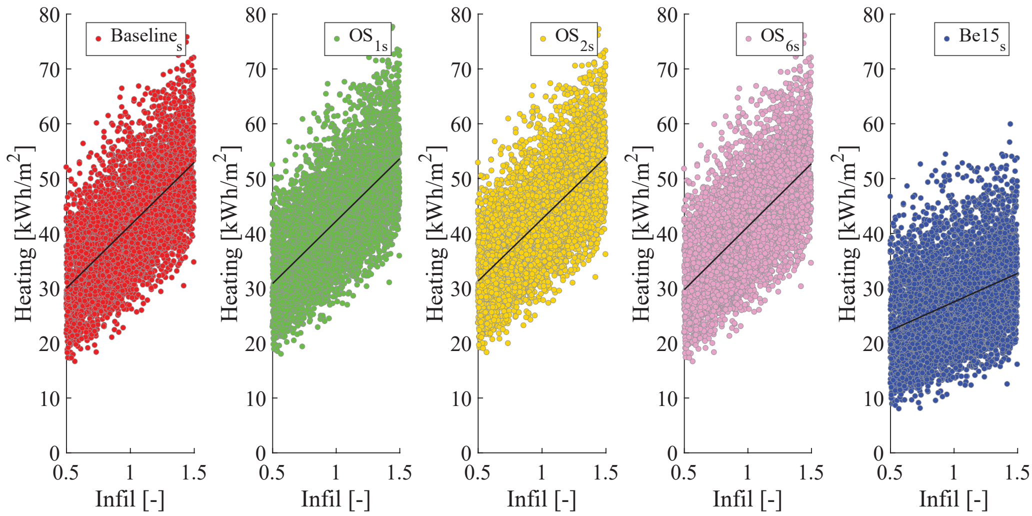



***Figure E.15.*** Relation between infiltration and the heating consumption for all 5000 simulations.

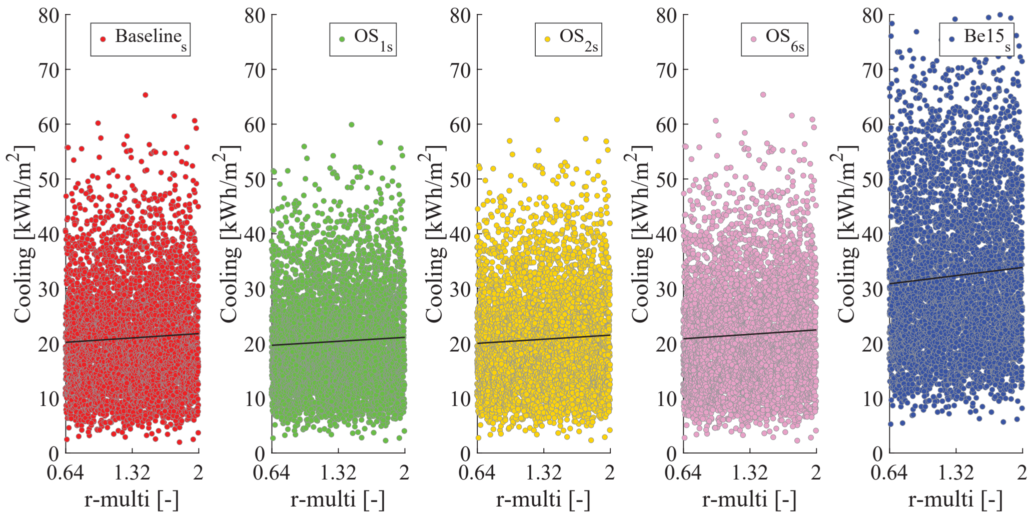



***Figure E.16.*** Relation between thermal resistance of the wall and the cooling consumption for all 5000 simulations.

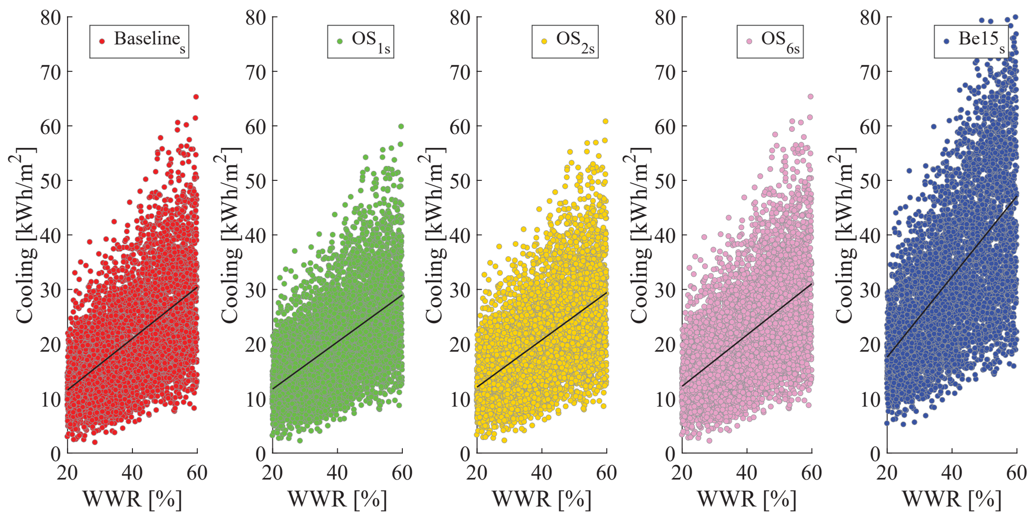



***Figure E.17.*** Relation between window to wall ratio and the cooling consumption for all 5000 simulations.

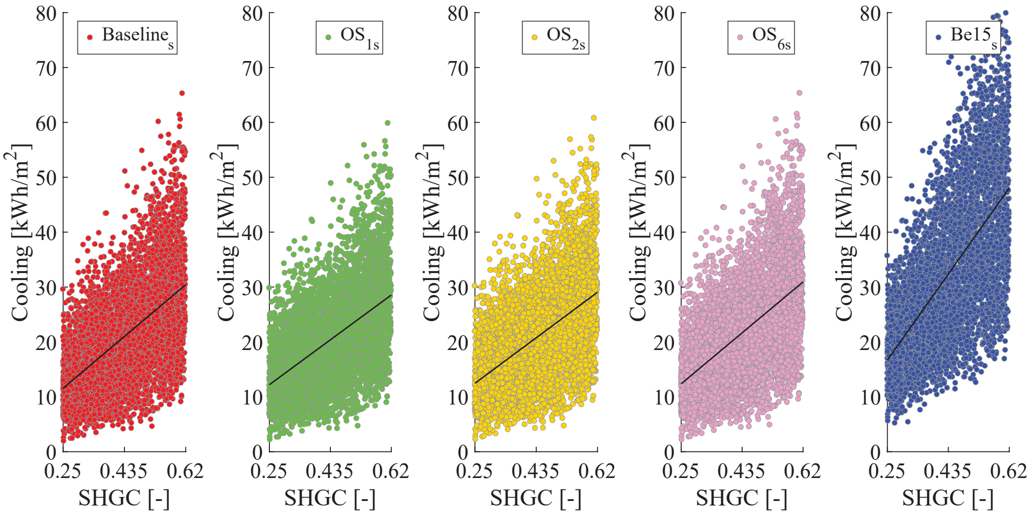



***Figure E.18.*** Relation between SHGC and the cooling consumption for all 5000 simulations.

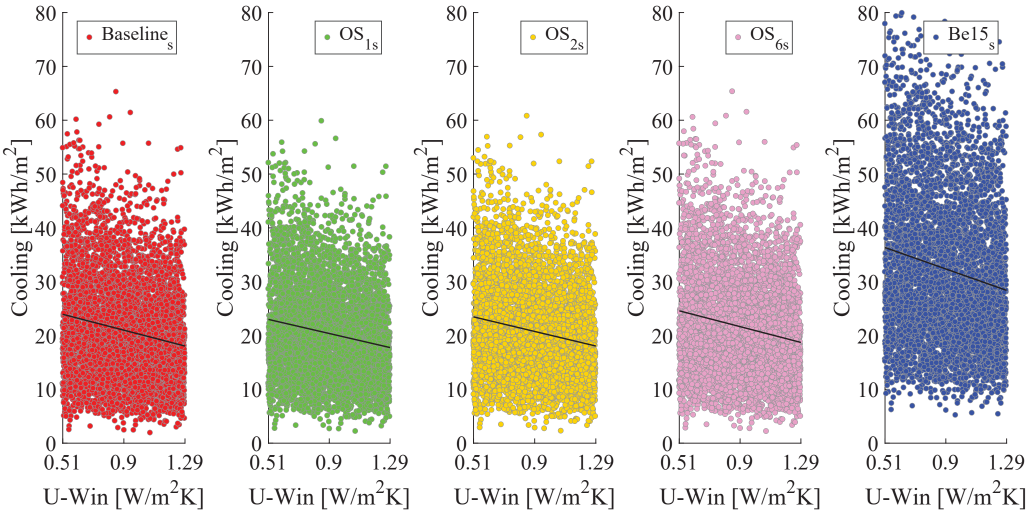



***Figure E.19.*** Relation between u-value for the window and the cooling consumption for all 5000 simulations.

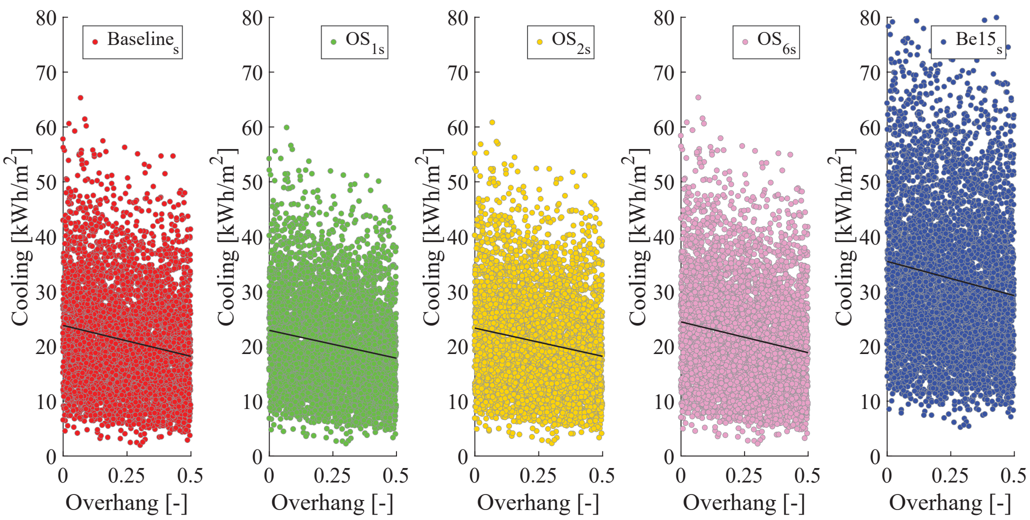



***Figure E.20.*** Relation between overhang south and the cooling consumption for all 5000 simulations.

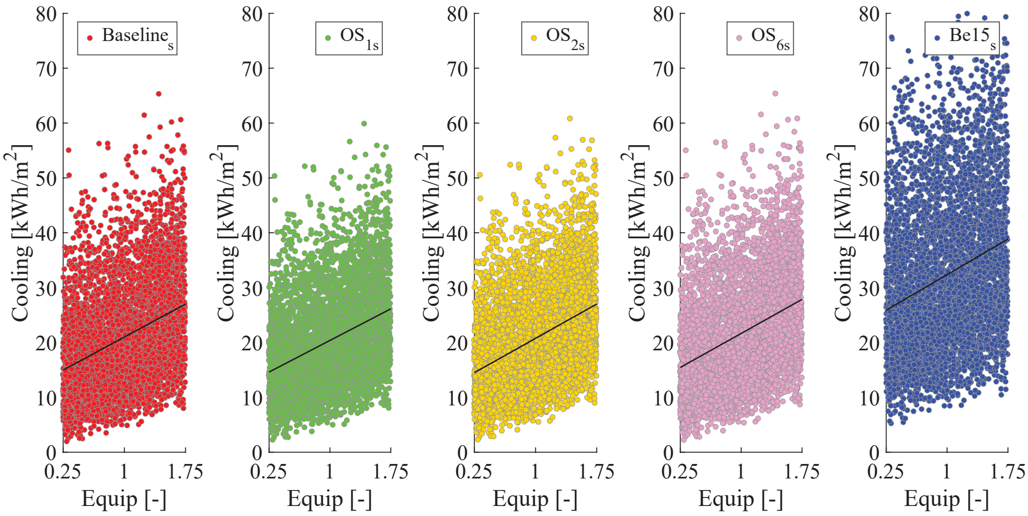



***Figure E.21.*** Relation between equipment and the cooling consumption for all 5000 simulations.

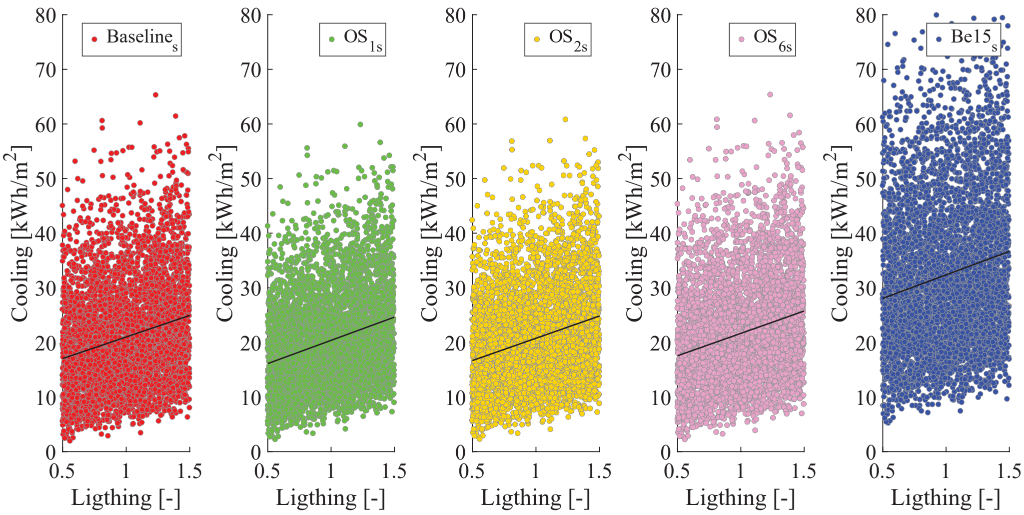



***Figure E.22.*** Relation between lighting and the cooling consumption for all 5000 simulations.

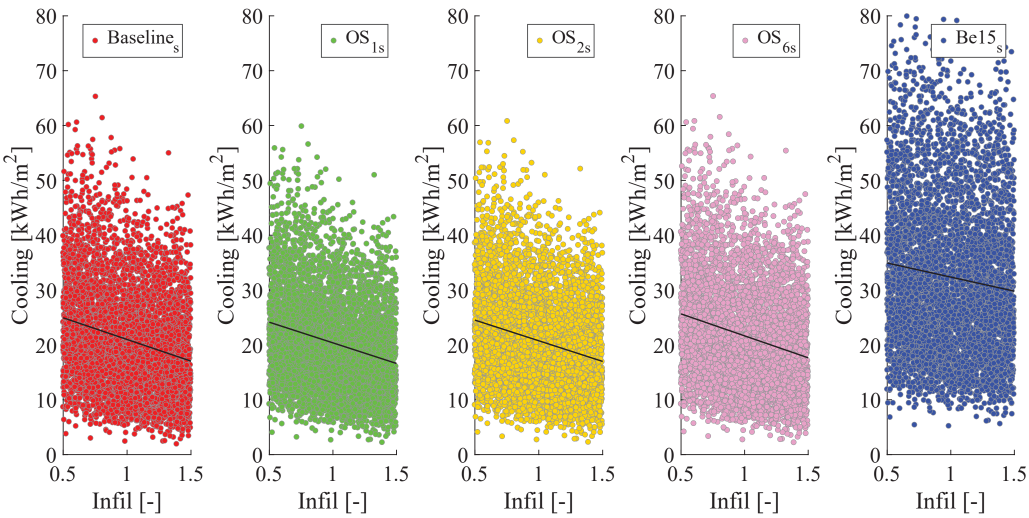



***Figure E.23.*** Relation between infiltration and the cooling consumption for all 5000 simulations.

## E.6 Monte Carlo Filtering

A short description is explained here to further clarify what is shown in the histogram tables when performing Monte Carlo filtering. Figure E.24 shows an example of a parallel coordinate plot which contains 8 inputs and 2 outputs. Each line represents one simulation with its input value and corresponding outputs. The horizontal histograms on the inputs shows the distribution.

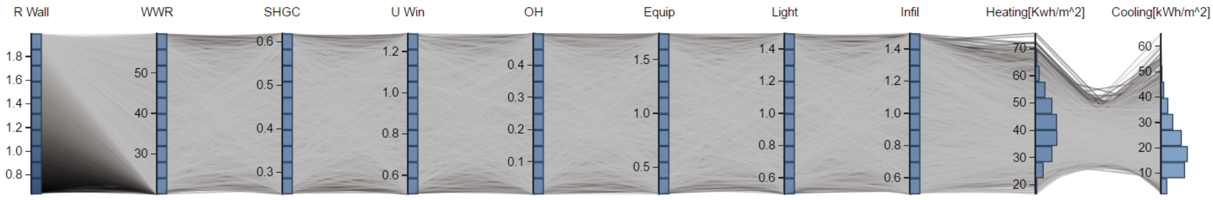



***Figure E.24.*** An example of a parallel coordinate plot with eight inputs and their corresponding distributions indicated as histograms marked with blue and two outputs.

On figure E.25 2 Monte Carlo filters are added which are highlighted with the grey rectangular shapes on the outputs. What can be seen when comparing figure E.24 and E.25 is that the distribution changes when adding filters to the outputs. What is shown in table D.4 is the histograms belonging to each input.

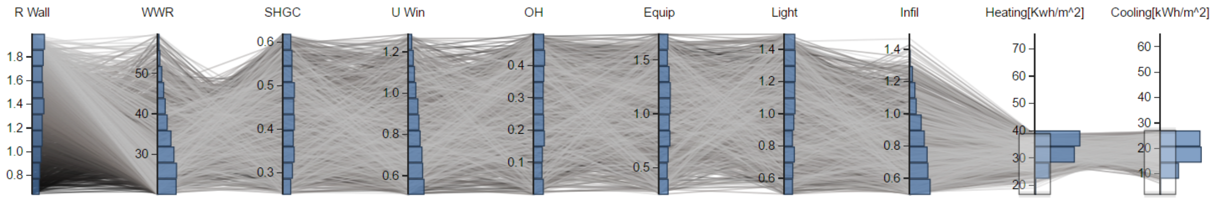



***Figure E.25.*** Parallel coordinate plot with eight inputs and two outputs and 2 filters added. The distribution of the inputs are indicated with histograms marked with blue.

## E.7 Histograms

The histogram for the inputs when applying the Monte Carlo filters shown in table D.3 are shown in figure E.2 to E.4.

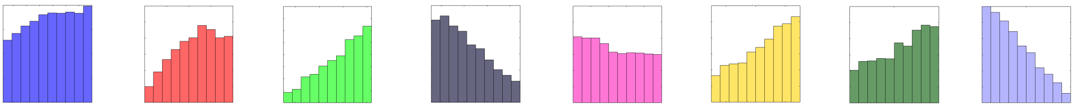
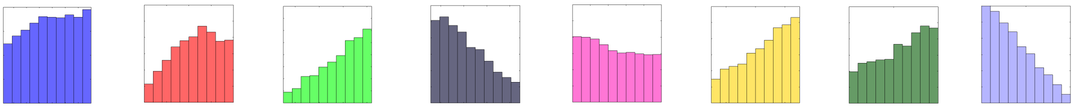
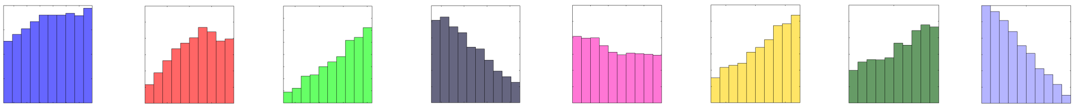
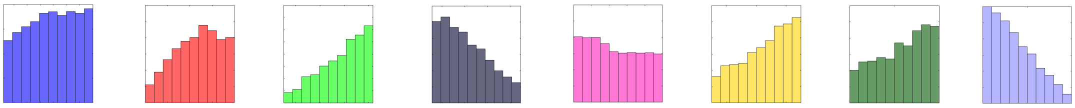
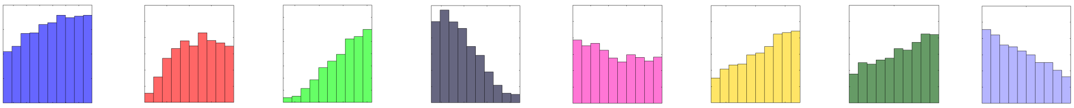
| Model | R wall [m²K/W] | WWR [%] | SHGC [–] | U-win [W/m²K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_s$ #1708 |  | | | | | | | |
| OS$_{1s}$ #1678 |  | | | | | | | |
| OS$_{2s}$ #1684 |  | | | | | | | |
| OS$_{6s}$ #1694 |  | | | | | | | |
| Be15$_s$ #1539 |  | | | | | | | |
| | 0,64-2 | 20-60 | 0,25-0,62 | 0,51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table E.2.*** Histograms of the distribution for the remaining inputs when filter 2 is applied for the models with static facade. The number below the model name indicates the amount of remaining simulations.

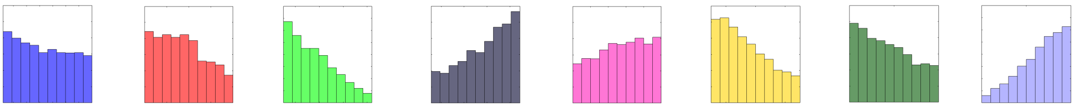
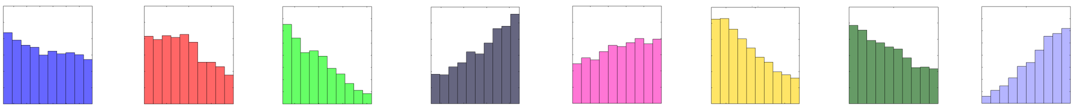
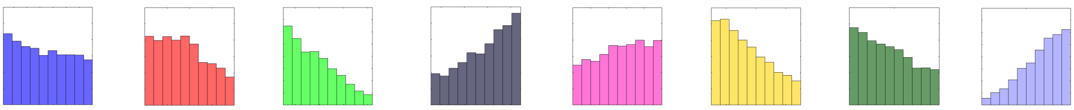
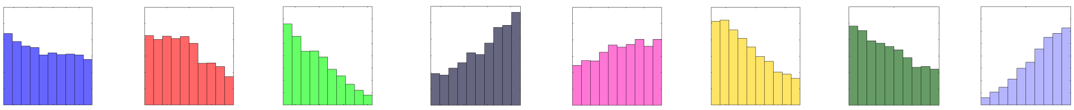
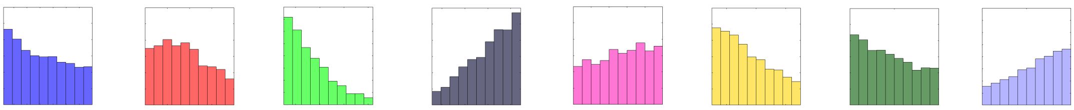
| Model | R wall [m²K/W] | WWR [%] | SHGC [–] | U-win [W/m²K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_s$ #1709 |  | | | | | | | |
| OS$_{1s}$ #1678 |  | | | | | | | |
| OS$_{2s}$ #1684 |  | | | | | | | |
| OS$_{6s}$ #1690 |  | | | | | | | |
| Be15$_s$ #1537 |  | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0,51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table E.3.*** Histograms of the distribution for the remaining inputs when filter 3 is applied for the models with static facade. The number below the model name indicates the amount of remaining simulations.

| Model | R wall [m$^2$K/W] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_s$ #790 | | | | | | | | |
| OS$_{1s}$ #822 | | | | | | | | |
| OS$_{2s}$ #815 | | | | | | | | |
| OS$_{6s}$ #804 | | | | | | | | |
| Be15$_s$ #572 | | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0.62 | 0,51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table E.4.*** Histograms of the distribution for the remaining inputs when filter 4 is applied for the models with static facade. The number below the model name indicates the amount of remaining simulations.

## E.8 Sensitivity Analysis

The ranking of the SA presented in table E.5 with both heating and cooling as output is shown in table G.7 as a table.

| | Baseline$_s$ | | OS$_{1s}$ | | OS$_{2s}$ | | OS$_{6s}$ | | Be15$_s$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] |
| Infiltration | 1 | 21 | 1 | 21 | 1 | 22 | 1 | 22 | 4 | 10 |
| SHGC | 2 | 17 | 3 | 17 | 3 | 16 | 3 | 17 | 2 | 21 |
| WWR | 3 | 17 | 2 | 16 | 2 | 15 | 2 | 17 | 3 | 18 |
| U-value window | 4 | 13 | 4 | 13 | 4 | 13 | 4 | 13 | 1 | 21 |
| Equipment | 5 | 11 | 5 | 12 | 5 | 12 | 5 | 12 | 5 | 10 |
| Lighting | 6 | 8 | 6 | 8 | 6 | 8 | 6 | 8 | 6 | 7 |
| Overhang south | 7 | 6 | 7 | 5 | 7 | 5 | 7 | 6 | 8 | 6 |
| Resistance wall | 8 | 5 | 8 | 5 | 8 | 5 | 8 | 5 | 7 | 5 |
| Dummy | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 3 |

***Table E.5.*** Sensitivity analysis of the inputs with heating and cooling as outputs for the models with static facade.

On figure E.26 and E.27 are shown the sensitivity for the variable inputs with only heating or cooling as output for models with static facade.

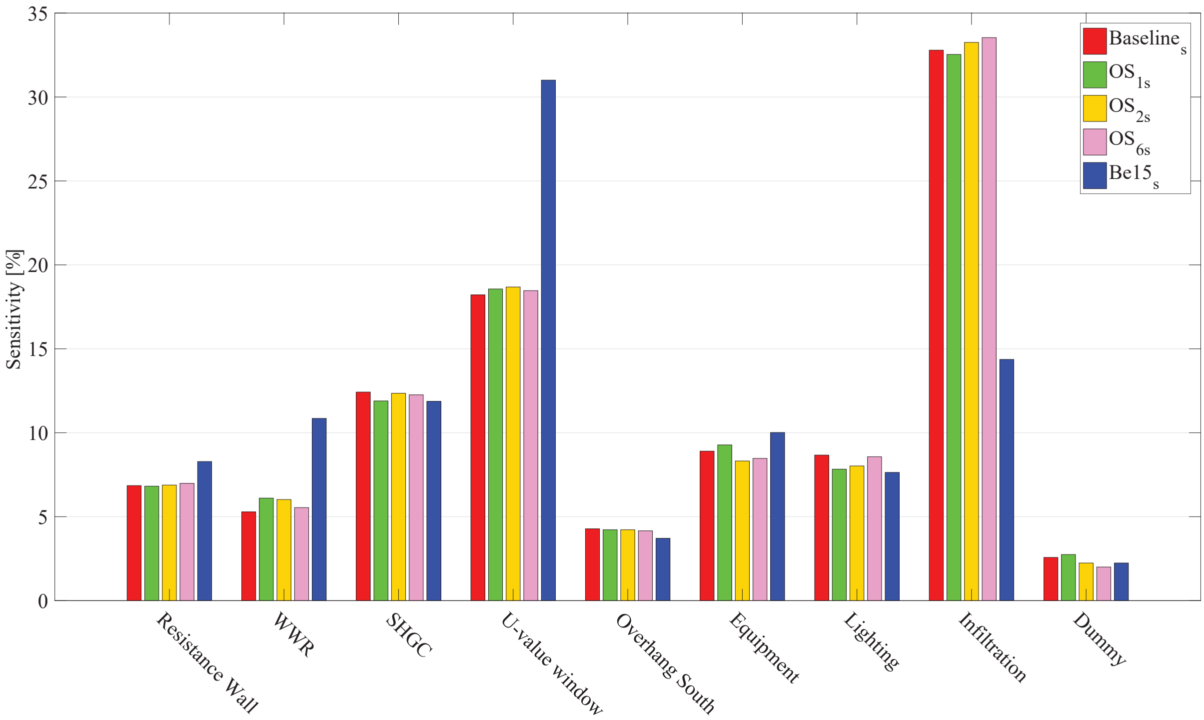



***Figure E.26.*** Sensitivity of the variable inputs with only heating as an output based on all 5000 simulations with static facade.

From figure E.26 it can be seen that the sensitivity of the u-value for the window for Be15$_s$ is approximately 15 % higher than Baseline$_s$, while the infiltration is off by almost 20 %. In addition to this the sensitivity of WWR is off by a large margin. This leads to inconsistent ranking of the input parameters when investigation the heating consumption.
The simplified models simulated with OS show very consistent ranking of sensitivity of the parameters.

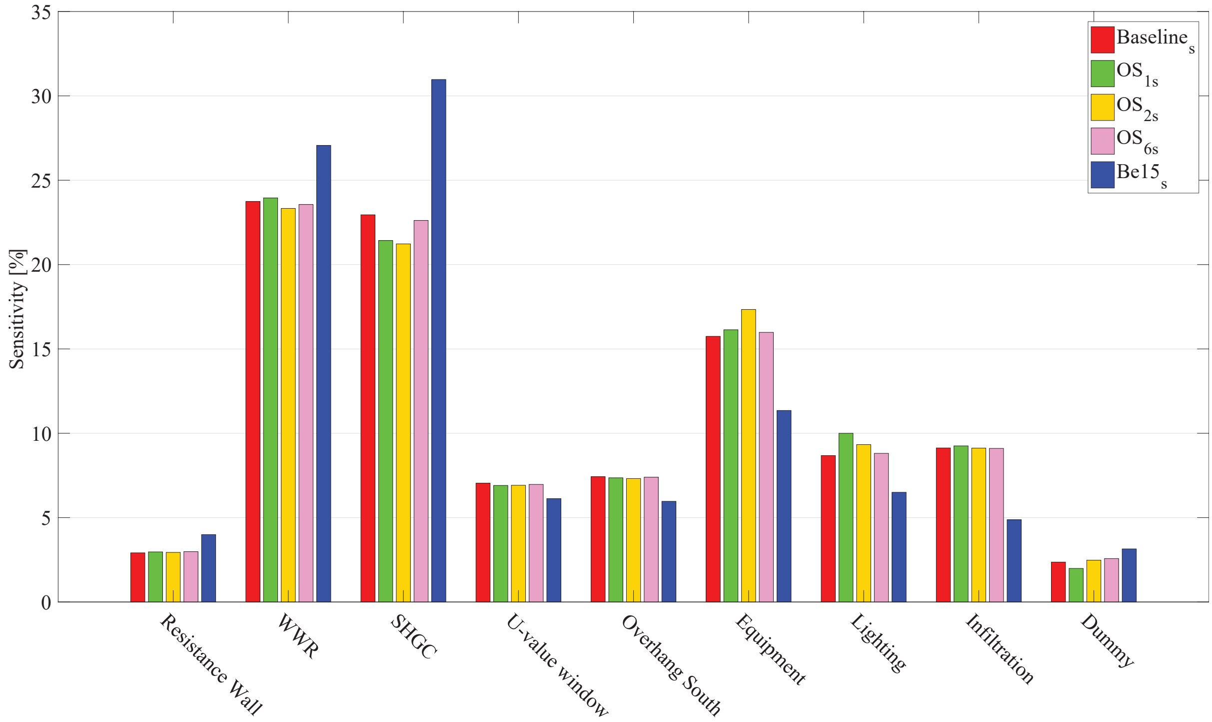



***Figure E.27.*** Sensitivity of the variable inputs with only cooling as an output based on all 5000 simulations with static facade.

Having the cooling consumption as output when ranking sensitivity of the input parameters show that $Be15_s$ struggles. The sensitivity of most of the parameters are not accurate and leads to a faulty ranking.

# Data Analysis and Results - Dynamic Facade F

*This chapter contains the data analysis and results of the dynamic facade models. The analysis includes a comparison of annual heating, cooling consumption and electricity for lighting. Furthermore it includes investigation of model tendencies and a sensitivity analysis.*

As with the results from the static facade models, the data for dynamic facade includes 5000 simulations for each model. This data is analysed and compared with the three criteria described in chapter 2 which is shown below as well. The models must meet these criteria to be deemed suitable for guidance in the early design phases.

- The energy consumption for 95 % of the simulations must remain within ± 20 % of the baseline model.
- Changes to the input parameters must yield the same tendencies on the output results as that of the baseline model.
- The influence each input has on the output must be ranked the same as for the baseline model.

The first criterion is analysed by a direct comparison of the energy consumptions, the second criterion is analysed with scatter plots, Pearson correlation coefficient (PCC) and Monte Carlo filtering while the third criterion is analysed with a sensitivity analysis called TOM. These methods are described in detail in section 2.3 on page 12.

Throughout the chapter the models under investigation will be referenced to as stated below.

- Advanced BEM Tool:
  - OpenStudio with 15 zones: $\text{Baseline}_{\text{d}}$
  - OpenStudio with 1 zone: $\text{OS}_{\text{1d}}$
  - OpenStudio with 2 zones: $\text{OS}_{\text{2d}}$
  - OpenStudio with 6 zones: $\text{OS}_{\text{6d}}$
- Simple BEM Tool:
  - Be15: $\text{Be15}_{\text{d}}$

## F.1 Annual Consumption

The models, $\text{OS}_{\text{1d}}$, $\text{OS}_{\text{2d}}$, $\text{OS}_{\text{6d}}$ and $\text{Be15}_{\text{d}}$, consumption of heating, cooling and electricity for lighting are compared with $\text{Baseline}_{\text{d}}$ and are shown in figure F.1.

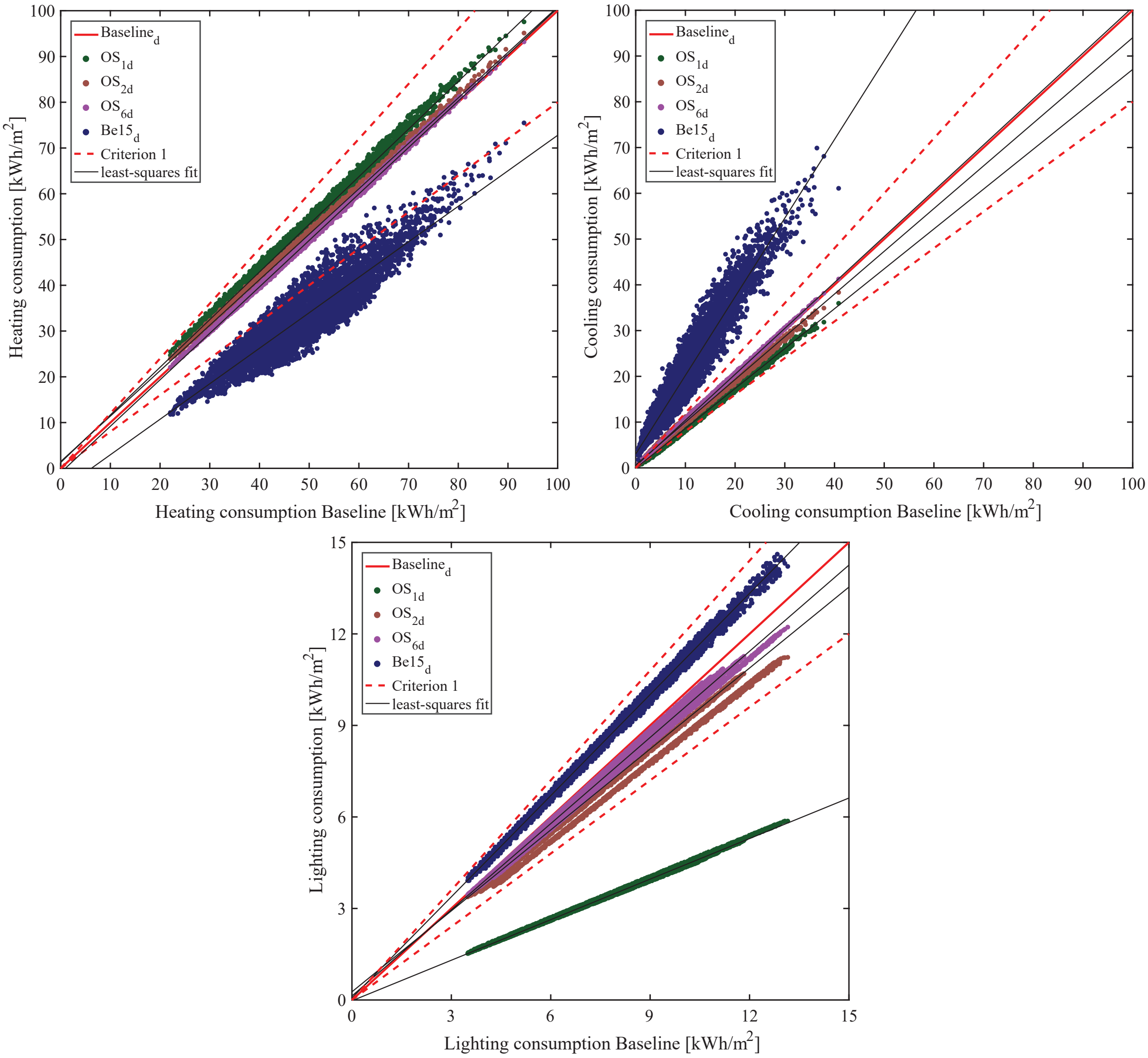



***Figure F.1.*** Every simulations heating, cooling and electricity for lighting for $OS_{1d}$, $OS_{2d}$ and $OS_{6d}$ compared with the Baseline. The $R^2$-value for the fits for all OS models are above 0,99 except for $OS_{2d}$ with 0,98. The $R^2$-values for $Be15_d$ are 0,93 and 0,86 for heating and cooling respectively, and 0,99 for lighting.

From the figure it is shown that the heating and cooling consumption of $OS_{1d}$ and $OS_{2d}$ are very similar to $Baseline_d$ and $OS_{6d}$ is almost identical with $Baseline_d$ while $Be15_d$ differ a great deal more. For lighting consumption it is noticed that $OS_{1d}$ have a lower estimation that the rest. Overall only $OS_{2d}$ and $OS_{6d}$ fulfils the first criterion while $OS_{1d}$ and $Be15_d$ does not. Table F.1 shows the percentage of simulations that fulfils the criterion for each model.

| | Heating [%] | Heating [qty] | Cooling [%] | Cooling [qty] | Lighting [%] | Lighting [qty] |
|---|---|---|---|---|---|---|
| $OS_{1d}$ | 100 | 5000 | 85 | 4252 | 0 | 0 |
| $OS_{2d}$ | 100 | 5000 | 99 | 4969 | 100 | 5000 |
| $OS_{6d}$ | 100 | 5000 | 100 | 4991 | 100 | 5000 |
| $Be15_d$ | 5 | 243 | 0 | 0 | 100 | 5000 |

***Table F.1.*** Percentage and quantity of the dynamic model simulations within the boundaries of criterion 1.

From figure F.1 it is seen that the energy consumption for artificial lighting is a lot lower than the baseline model when using a single zone. It is therefore investigated if the difference in lighting consumption leads to the difference in heating and cooling consumption alone. This is not the case, more information on this in appendix H.

The heating, cooling and lighting consumptions are shown in figure F.2 as box plots. The box plots provide a way of checking the distribution of the heating and cooling outputs of the models. Further details of the distributions for heating, cooling and lighting consumption are shown in appendix G.1. The appendix also include distributions of the differences between $Baseline_d$ and the simplified models.

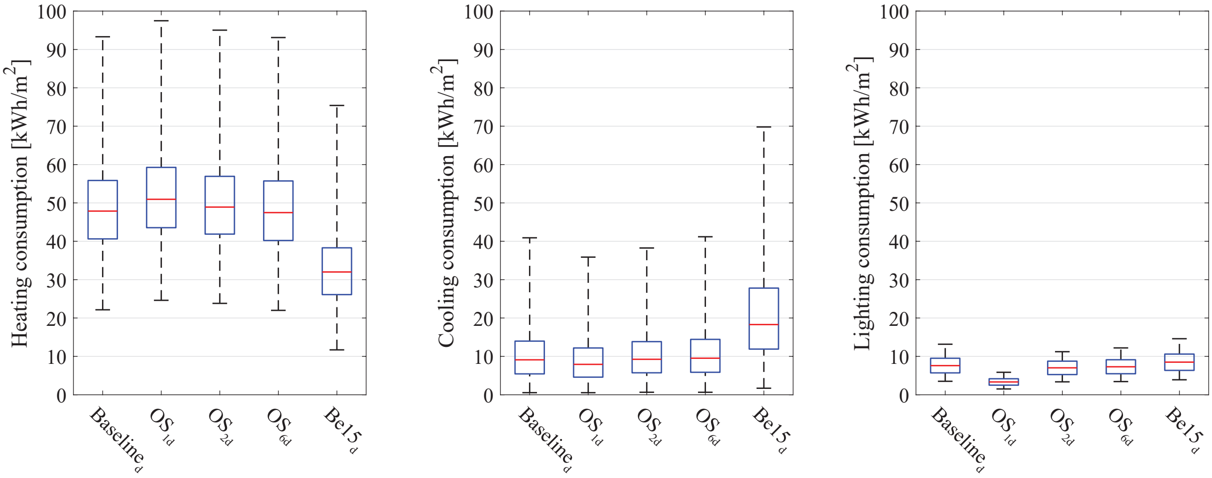



***Figure F.2.*** Heating and cooling consumption for 5000 simulations with dynamic facade presented as box plots.

## F.2 Model Tendencies

To investigate the first criterion scatter plots together with Pearson correlation coefficient (PCC) is used to identify trends. Furthermore histograms for the different inputs in the models are created with multiple Monte Carlo filters to both heating and cooling consumption.

A total of 24 figures, with five scatter plots each representing the five models, is examined for the tendencies of the relation between inputs and outputs and one will be presented in this chapter while the rest are in appendix G. The figures are also used to inspect the data for any odd trends that might occur. Five scatter plots are shown in figure D.3 for the relation between the heating consumption and the infiltration.

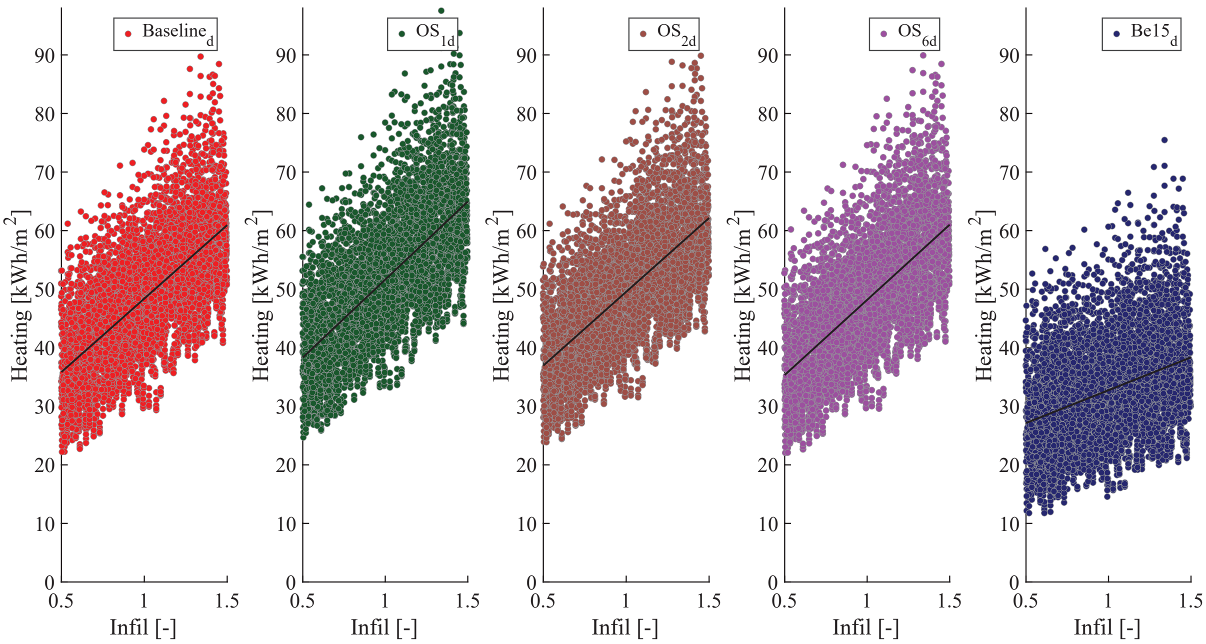



***Figure F.3.*** Relation between infiltration and heating consumption for all 5000 simulations.

From the figure it can be seen that there is a correlation between heating consumption and infiltration. Increasing the infiltration increase the heating consumption, which is as expected since it is an increase in heat losses.

From the scatter plots in figure F.3 and the ones in appendix E.5 it is concluded that all four simplifications comply with the first criterion so far. Furthermore the figures shows that there is no odd tendencies.

To further validate the findings from the inspection of the scatter plots the PCC between inputs and the three outputs are shown in table. Note that the magnitude of the correlation is not of interest for criterion one, but rather if changes to an input yield same tendencies on the output as that of the Baseline. F.2.

| | | R wall | WWR | SHGC | U-Win | OH | Equip | Light | Infil |
|---|---|---|---|---|---|---|---|---|---|
| Heating | $\text{Baseline}_\text{d}$ | -0,16 | 0,20 | -0,26 | 0,50 | 0,04 | -0,33 | -0,09 | 0,66 |
| | $\text{OS}_\text{1d}$ | -0,15 | 0,20 | -0,24 | 0,50 | 0,04 | -0,35 | -0,02 | 0,67 |
| | $\text{OS}_\text{2d}$ | -0,16 | 0,20 | -0,25 | 0,51 | 0,04 | -0,32 | -0,07 | 0,67 |
| | $\text{OS}_\text{6d}$ | -0,16 | 0,20 | -0,25 | 0,50 | 0,04 | -0,33 | -0,09 | 0,66 |
| | $\text{Be15}_\text{d}$ | -0,22 | 0,33 | -0,32 | 0,65 | 0,8 | -0,30 | -0,11 | 0,35 |
| Cooling | $\text{Baseline}_\text{d}$ | 0,06 | 0,63 | 0,53 | -0,19 | -0,05 | 0,40 | 0,05 | -0,19 |
| | $\text{OS}_\text{1d}$ | 0,06 | 0,65 | 0,51 | -0,17 | -0,05 | 0,40 | -0,00 | -0,19 |
| | $\text{OS}_\text{2d}$ | 0,06 | 0,63 | 0,51 | -0,18 | -0,05 | 0,44 | 0,04 | -0,20 |
| | $\text{OS}_\text{6d}$ | 0,06 | 0,63 | 0,52 | -0,19 | -0,05 | 0,41 | 0,05 | -0,20 |
| | $\text{Be15}_\text{d}$ | 0,08 | 0,67 | 0,60 | -0,16 | -0,12 | 0,28 | 0,06 | -0,20 |
| Lighting | $\text{Baseline}_\text{d}$ | 0,02 | -0,24 | -0,04 | -0,01 | -0,01 | -0,02 | 0,97 | 0,06 |
| | $\text{OS}_\text{1d}$ | 0,02 | -0,27 | -0,05 | -0,01 | 0,01 | -0,02 | 0,97 | 0,06 |
| | $\text{OS}_\text{2d}$ | 0,02 | -0,11 | -0,03 | -0,01 | -0,01 | -0,02 | 0,99 | 0,06 |
| | $\text{OS}_\text{6d}$ | 0,02 | -0,18 | -0,04 | -0,01 | -0,01 | -0,02 | 0,98 | 0,06 |
| | $\text{Be15}_\text{d}$ | 0,02 | -0,22 | -0,02 | -0,01 | 0,02 | -0,15 | 0,97 | 0,06 |

***Table F.2.*** PCC for each input for all 5 models for heating, cooling and lighting consumption with dynamic facade.

The table shows mostly expected tendencies, e.g increasing the insulation of the wall reduces the heating consumption, increasing internal loads reduces heating consumption but increase the cooling consumption. Increasing the WWR increases the heating consumption which indicate that the heat gain from solar radiation is less than the transmission loss through the window. There are some inputs which appear to have an influence on the lighting consumption even though this should not be the case. This includes the resistance of the wall, SHGC, U-value of the window, equipment and infiltration. These correlations are very low and caused by the fact that input variables are all varied at the same time.

Table F.2 shows that even though the correlation is very small, e.g. overhang and lighting, the tendency still remain the same when reducing the zones in the models except for one input. The one input where a mismatch occur is between cooling and lighting. Though the correlation is almost zero there is still a difference where the model with a single zone has a negative correlation where $\text{Baseline}_\text{d}$ is positive. The magnitude of the correlation between lighting and cooling is further elaborated on in appendix G.4.

To further investigate the tendencies of the simplified models, histograms of the inputs with Monte Carlo filters on the outputs are used. Four different filters are added to the outputs with different combinations of heating and cooling consumption. The four together contain the entire data-set of the 5000 simulations. The different filter combinations are the same as used in the investigation for the simplified models for the static facade and are shown in table D.3 on page 77. To get a better understanding of what these histograms represents an explanation is in appendix E.6.
Table F.3 contains the input ditributions for the best performing simulations which correspond to filter 1. recall that without any filters added the distribution for all the inputs are uniform. The histograms with the filters 2-4 are shown in figure G.2 - G.4 in appendix G.3.

| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m²K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_d$ #932 | | | | | | | | |
| OS$_{1d}$ #966 | | | | | | | | |
| OS$_{2d}$ #940 | | | | | | | | |
| OS$_{6d}$ #939 | | | | | | | | |
| Be15$_d$ #1126 | | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table F.3.*** Histograms of the distribution for the remaining inputs when filter 1 is applied. The number below the model name indicates the amount of remaining simulations.

The figure shows OS$_{1d}$, OS$_{2d}$, OS$_{6d}$ and Be15$_d$ have the same tendencies as Baseline$_d$. This is also the case when adding the other three filters. The distribution of the individual inputs behave as expected based on the filters. E.g. a model with a low cooling consumption and a low heating consumption, as shown in figure F.3, is expected to have a low U-Win and a low WWR. The tendency of WWR and U-value for the window has to be low to avoid overheating because of solar heat gains and to avoid heat loss respectively.

Based on the results presented in this section it is concluded that criterion two is fulfilled for all the models, both simple and advanced.

## F.3 Sensitivity analysis Ranking

To investigate if the second criterion is met for the simplified models, a SA of the parameters is conducted using the method called TOM, which is described in detail in chapter 2. The sensitivity of the variable inputs are shown in figure F.4 where heating, cooling and lighting consumption are used as outputs. The sensitivity of the inputs with only heating, cooling or lighting as outputs are shown in appendix G.4. Furthermore the results are also presented as a table in appendix G.4.

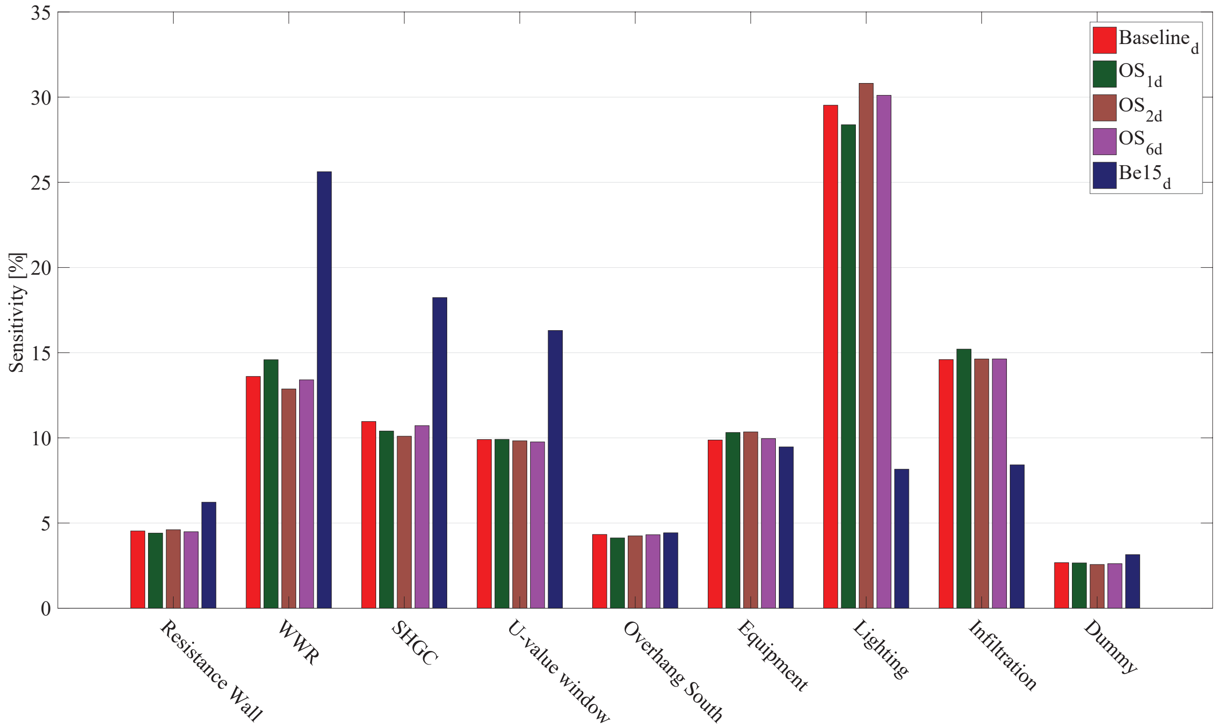



***Figure F.4.*** The sensitivity of the input parameters with heating, cooling and lighting consumption as output for the models with dynamic facade.

The dummy variable is an additional input which is added in the method which has zero influence on the result since it is not included in the model. It is used to determine if some inputs are irrelevant. With the dummy variable added it is clear that the thermal resistance of the wall and the overhang towards south have very limited influence on the energy consumption.

The figure shows that the rankings are very similar for all the simplifications, except for Be15$_d$. In few cases the ranking of the advanced model inputs change, but only due to a very small change in the sensitivity. The difference in the sensitivity which result in ranking change is no more than 1 %, cf. G.7. For this reason it is deemed sufficient to use any of the advanced model simplification when exploring the global design space in the early design phases.

Be15$_d$ struggles to determine both the ranking and magnitude of the sensitivity compared with Baseline$_d$. It is clear from the figure that WWR, SHGC and U-value for the window are a lot more sensitive for Be15$_d$ than for the baseline model. Though some of the inputs sensitivity differ a lot from Baseline$_d$, resistance for the wall, overhang towards south, and equipment are very close. Furthermore Be15$_d$ is only able to rank the two least sensitive inputs, resistance for the wall and overhang south, correctly. The sensitivity of parameters is a very important factor for early phase building design and Be15$_d$ does not sufficiently obtain the same rankings as the other models. Because of this it is concluded that Be15$_d$ does not meet the second criterion.

## F.4 Part Conclusion

Based on the investigations described in this chapter it is concluded that Be15$_d$ is insufficient as a design tool in the initial phases of building design. Be15$_d$ meets the tendency criterion quite well but struggles with correct ranking of input parameters as shown in figure F.4 which is the reason for drawing the conclusion of deeming $Be15_d$ unsuitable for early stage design purposes. It is worth noticing that $Be15_d$ calculates the lighting consumption more precise than $OS_{1d}$, but this is to be expected as $Be15_d$ have multi zone lighting control. An investigation where $Be15_d$ only have one lighting zone is shown in appendix H.3. This investigation shows that $Be15_d$ with one zone still performs better than $OS_{1d}$ with regards to lighting consumption while $OS_{1d}$ performs better for heating and cooling consumption.

$OS_{1d}$, $OS_{2d}$ and $OS_{6d}$ performs well compared to Baseline with $OS_{6d}$ performing best of the three. As a result of this, all three simplifications are deemed suitable as design tools in the early stages of building design. Again it is an interesting find, that the simple models perform so well while also saving time on modelling and simulations compared to the baseline model.

# Additional Results - Dynamic Facade G

## G.1 Distribution of Heating, Cooling and Lighting Consumption

The distributions of the heating and cooling for all the models with dynamic facade are shown in figure G.1. The distribution of the differences are shown in figure G.2. The distrbution of the lighting consumption and the difference between Baseline$_{\mathrm{d}}$ and the simplified models are shown in figure G.3.

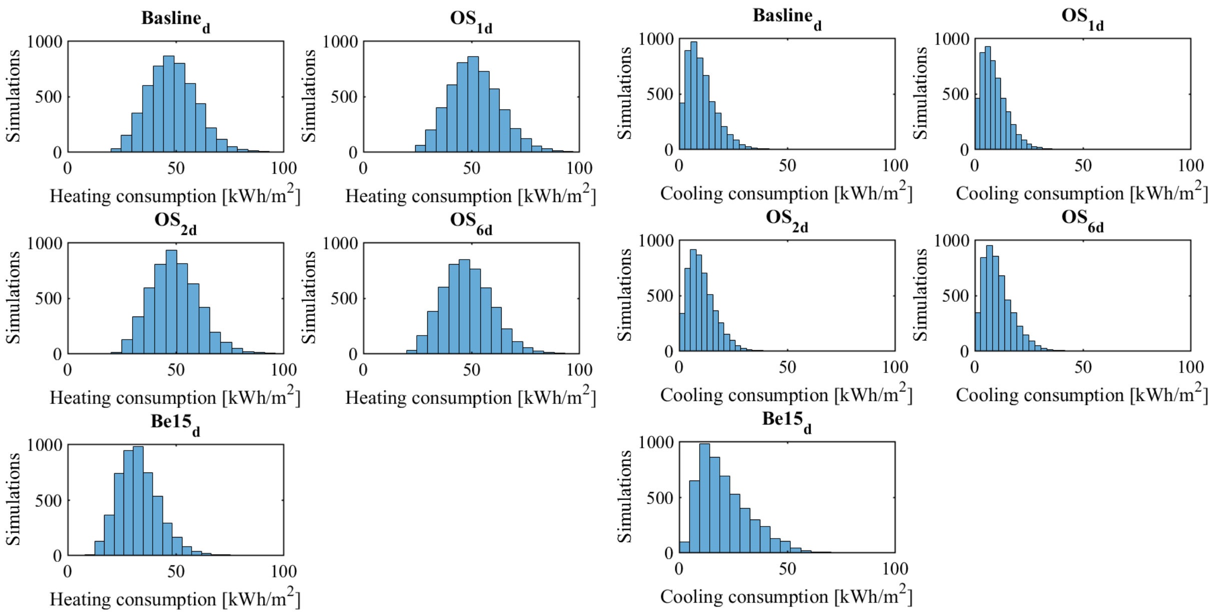



***Figure G.1.*** Distribution of the heating and cooling consumption for all models with dynamic facade.

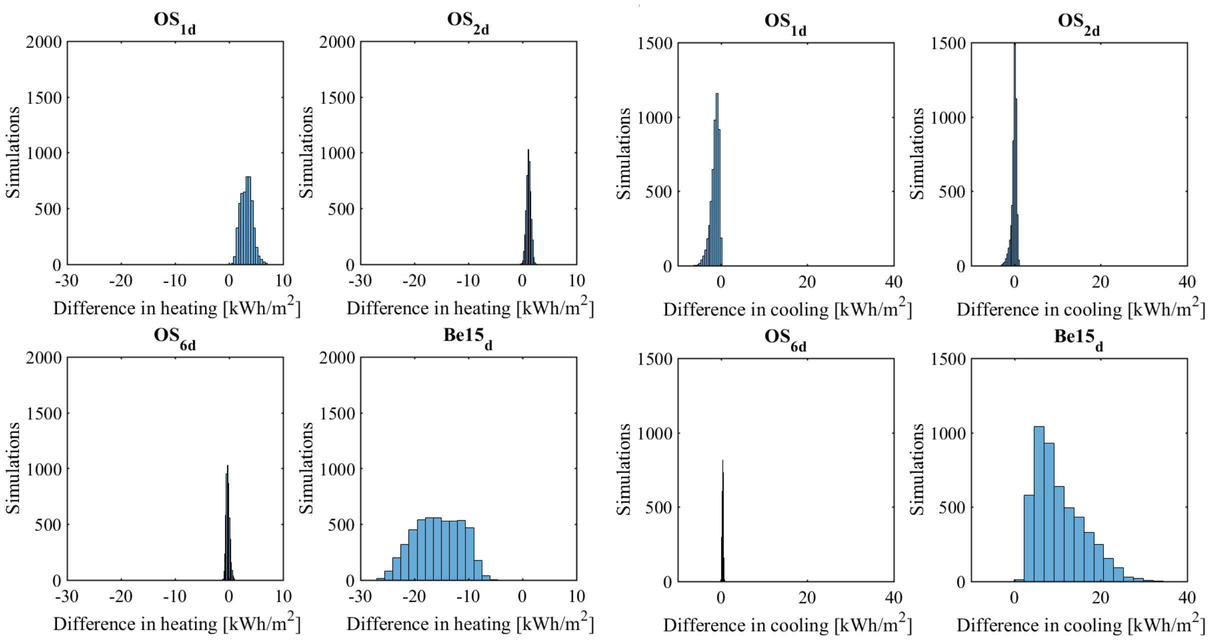



***Figure G.2.*** Distribution of the difference in heating and cooling compared with $\text{Baseline}_\text{d}$ for all models with dynamic facade.

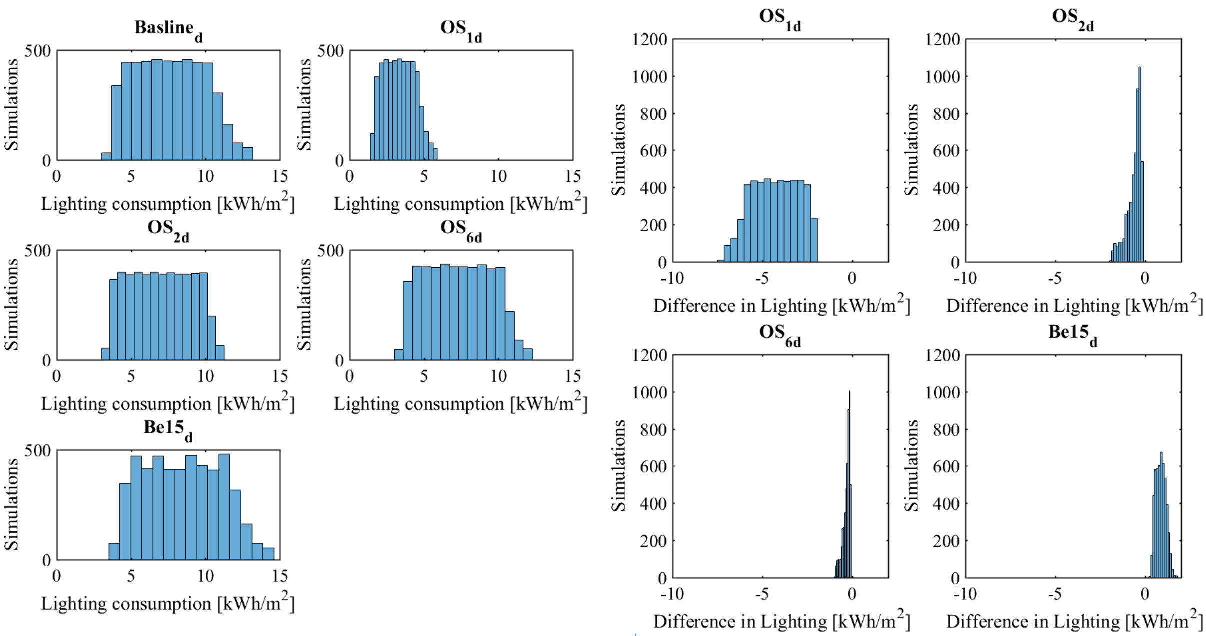



***Figure G.3.*** The distribution of the lighting consumption and the difference between $\text{Baseline}_\text{d}$ and the simplified models are shown in figure G.3.

In table G.1 is shown distribution characteristics on these differences. The mean and max of $\text{Be15}_\text{d}$ are lower/higher than the others for both heating and cooling which means that inconsistencies occurs between inputs and outputs for $\text{Be15}_\text{d}$. The mean and max of $\text{OS}_\text{1d}$ differs from the rest as well.

| | Heating [kWh/m$^2$] | | | | Cooling [kWh/m$^2$] | | | | Lighting [kWh/m$^2$] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $OS_{1d}$ | $OS_{2d}$ | $OS_{6d}$ | $Be15_d$ | $OS_{1d}$ | $OS_{2d}$ | $OS_{6d}$ | $Be15_d$ | $OS_{1d}$ | $OS_{2d}$ | $OS_{6d}$ | $Be15_d$ |
| Mean | 3,2 | 1,1 | -0,2 | -15,6 | -1,4 | -0,0 | 0,4 | 10,5 | -4,3 | -0,6 | -0,3 | 0,9 |
| st.d. | 1,1 | 0,4 | 0,3 | 4,3 | 0,9 | 0,6 | 0,1 | 5,6 | 1,3 | 0,4 | 0,2 | 0,3 |
| Min | 0,7 | 0,0 | 0,0 | -5,5 | 0,0 | 0,0 | 0,0 | 1,1 | -2,0 | -0,1 | -0,1 | 0,3 |
| Max | 7,1 | 2,6 | -1,2 | -26,3 | -6,2 | -3,1 | 0,8 | 33,3 | -7,3 | -1,9 | -1,0 | 1,8 |

***Table G.1.*** Statistical properties for the difference between the $Baseline_d$ and the simplified models for dynamic facade.

## G.2 Scatter Plots

Scatter plots for the relation between the variable inputs and the heating, cooling and lighting consumption are shown in figure G.4 to G.26.

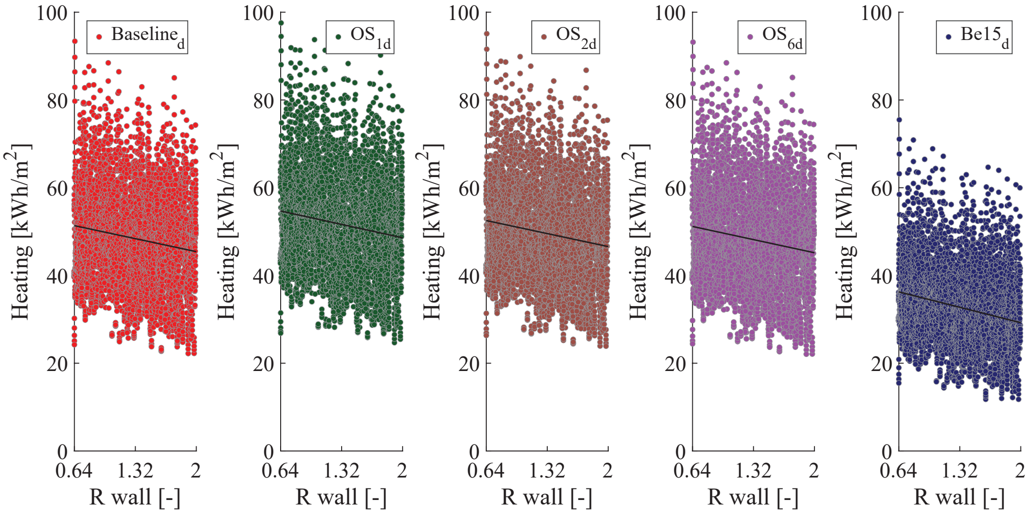



***Figure G.4.*** Relation between Resistance of the wall and the heating consumption for all 5000 simulations for models with dynamic facade.

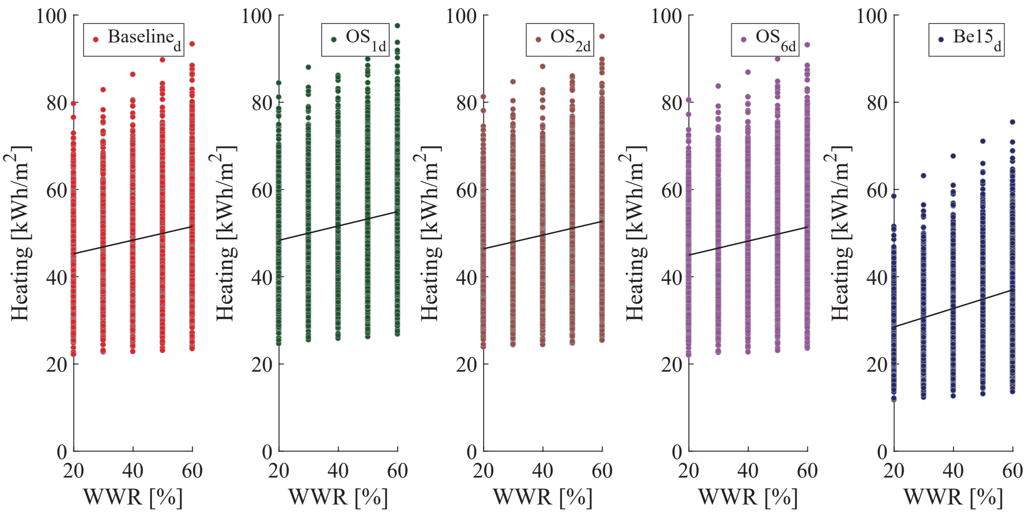



***Figure G.5.*** Relation between WWR and the heating consumption for all 5000 simulations for models with dynamic facade.

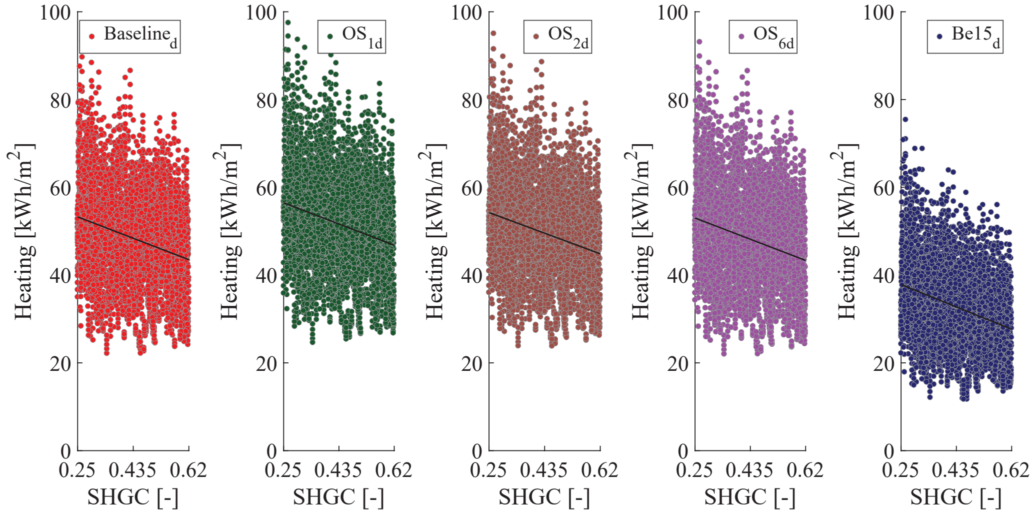



***Figure G.6.*** Relation between SHGC and the heating consumption for all 5000 simulations for models with dynamic facade.

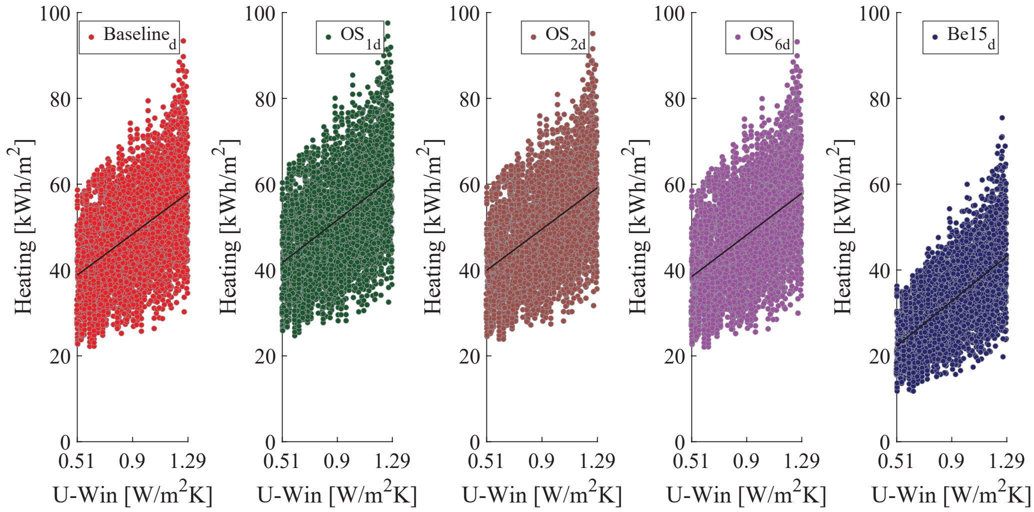



***Figure G.7.*** Relation between U-value for the window and the heating consumption for all 5000 simulations for models with dynamic facade.

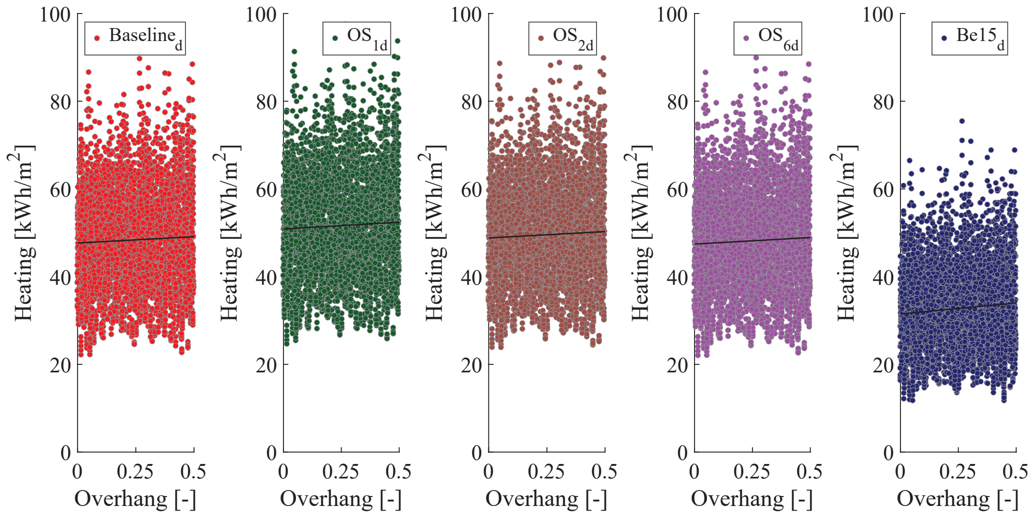



***Figure G.8.*** Relation between overhang and the heating consumption for all 5000 simulations for models with dynamic facade.

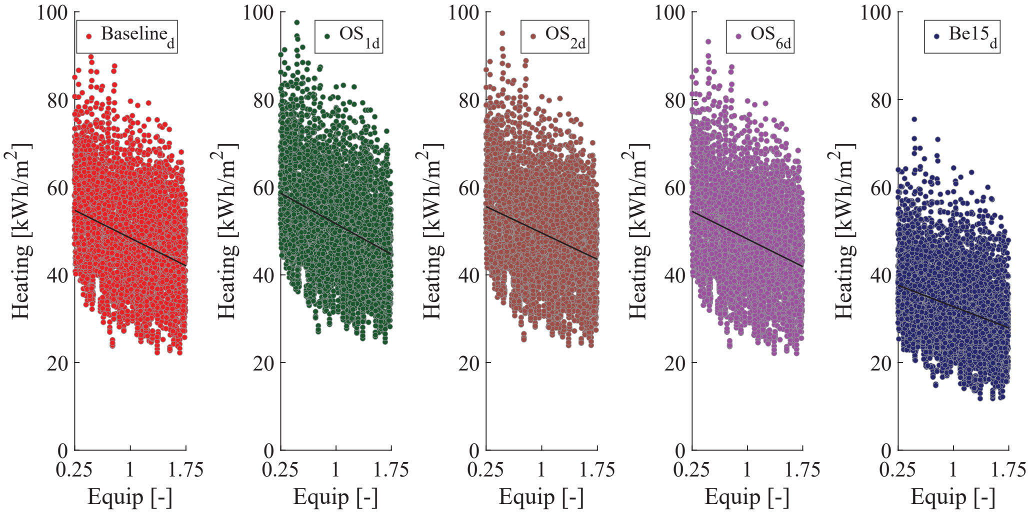



***Figure G.9.*** Relation between equipment and the heating consumption for all 5000 simulations for models with dynamic facade.

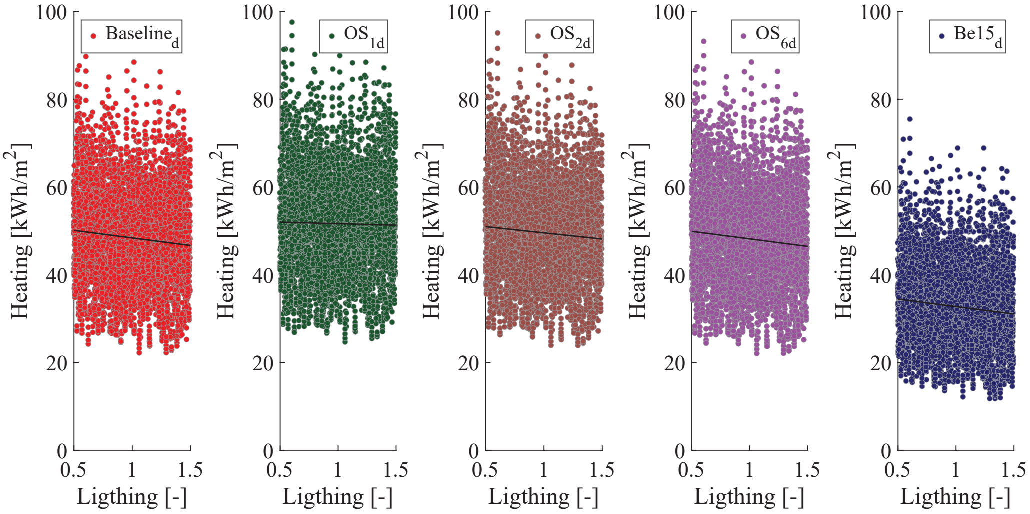



***Figure G.10.*** Relation between lighting and the heating consumption for all 5000 simulations for models with dynamic facade.

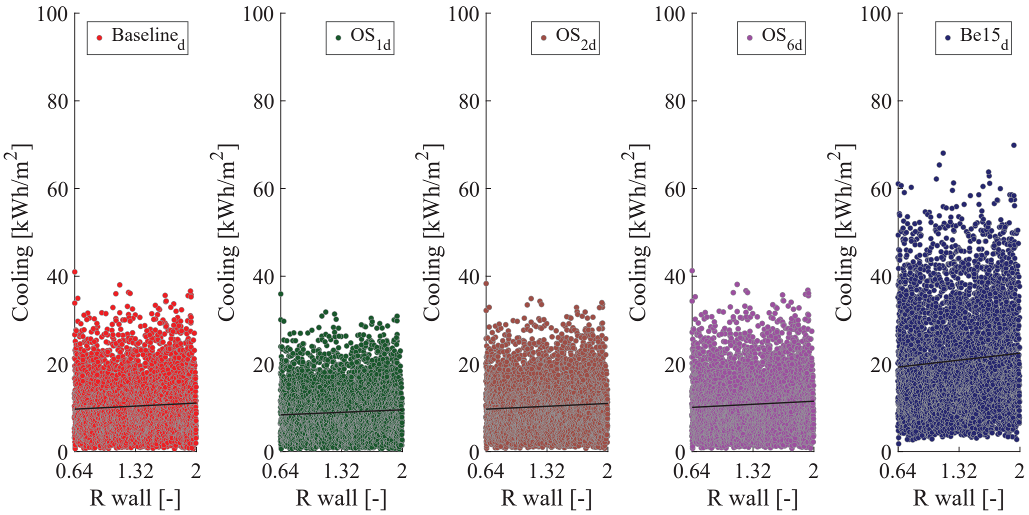



***Figure G.11.*** Relation between Resistance of the wall and the cooling consumption for all 5000 simulations for models with dynamic facade.

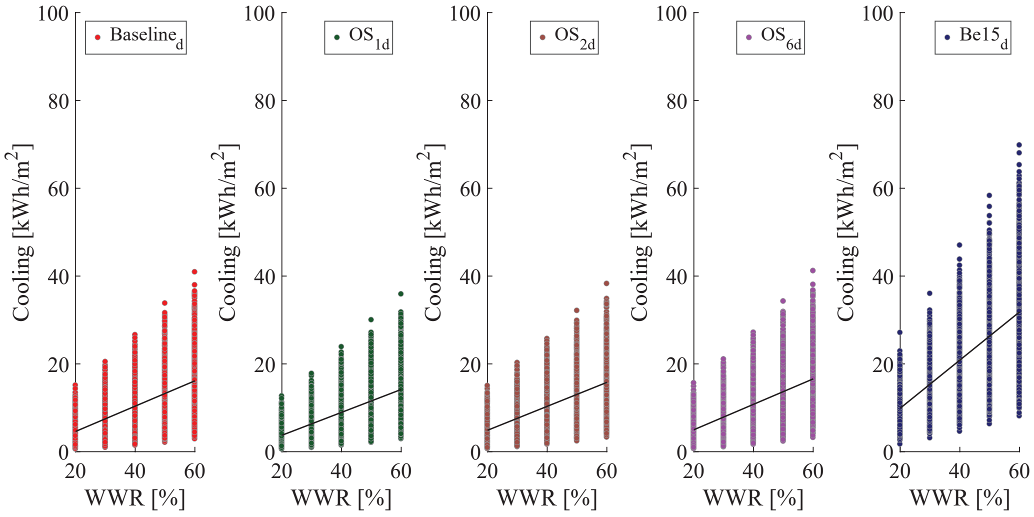



***Figure G.12.*** Relation between WWR and the cooling consumption for all 5000 simulations for models with dynamic facade.

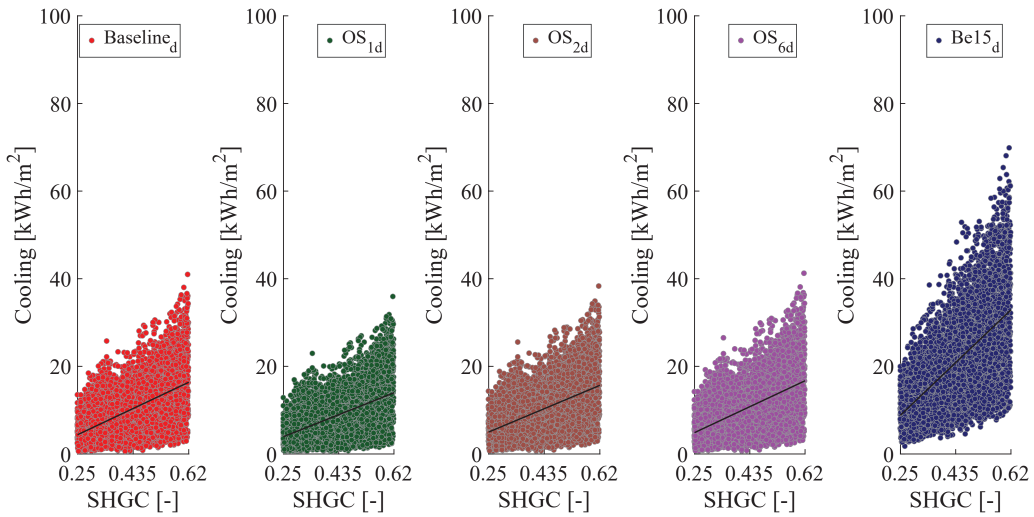



***Figure G.13.*** Relation between SHGC and the cooling consumption for all 5000 simulations for models with dynamic facade.

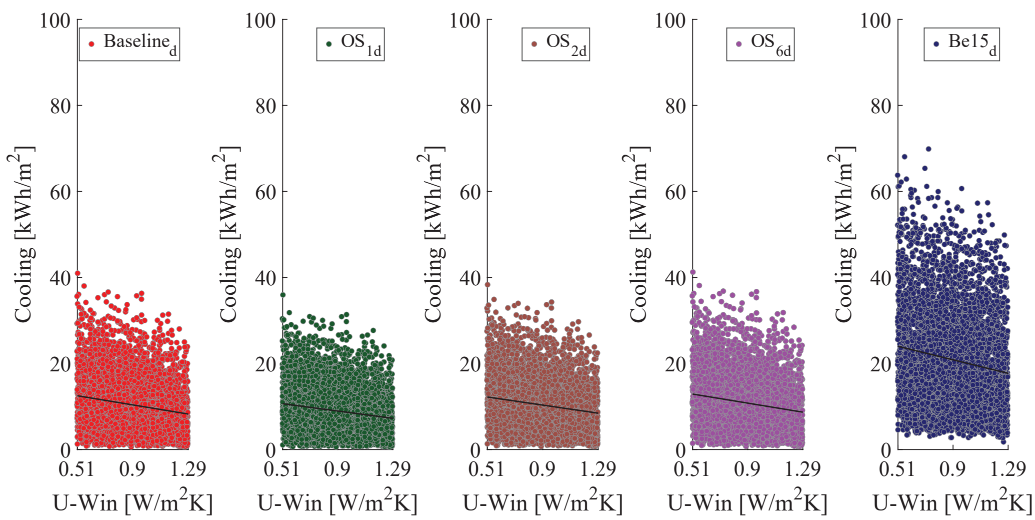



***Figure G.14.*** Relation between U-value for the window and the cooling consumption for all 5000 simulations for models with dynamic facade.

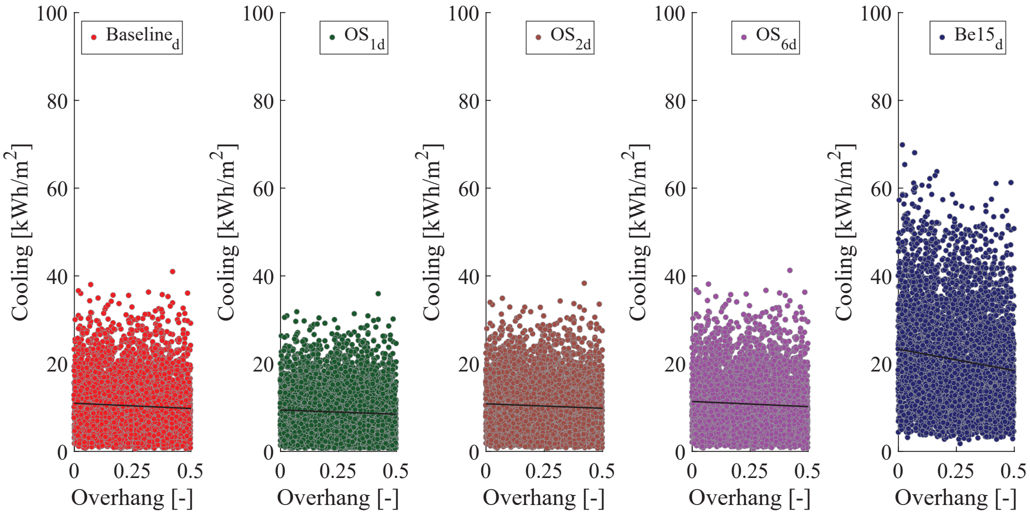



***Figure G.15.*** Relation between overhang and the cooling consumption for all 5000 simulations for models with dynamic facade.

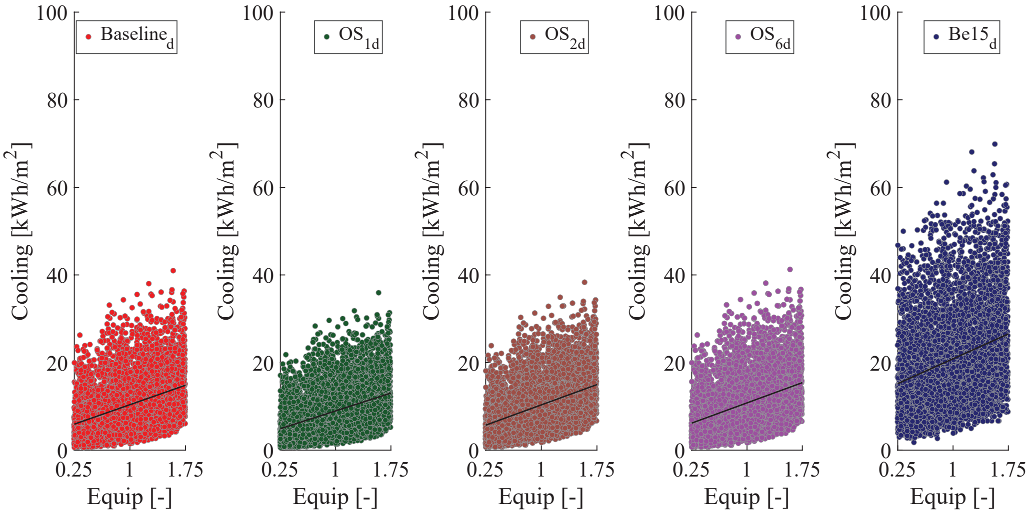



***Figure G.16.*** Relation between equipment and the cooling consumption for all 5000 simulations for models with dynamic facade.

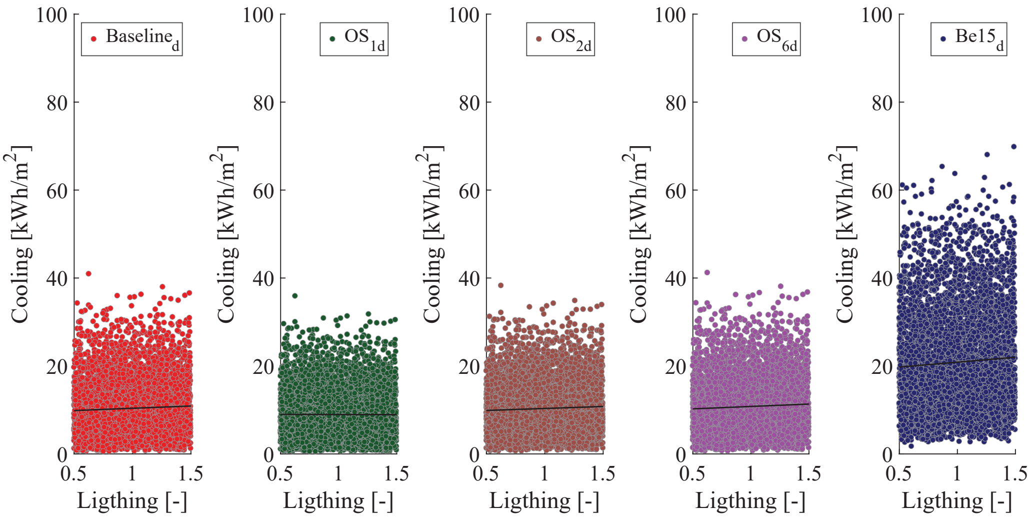



***Figure G.17.*** Relation between lighting and the cooling consumption for all 5000 simulations for models with dynamic facade.

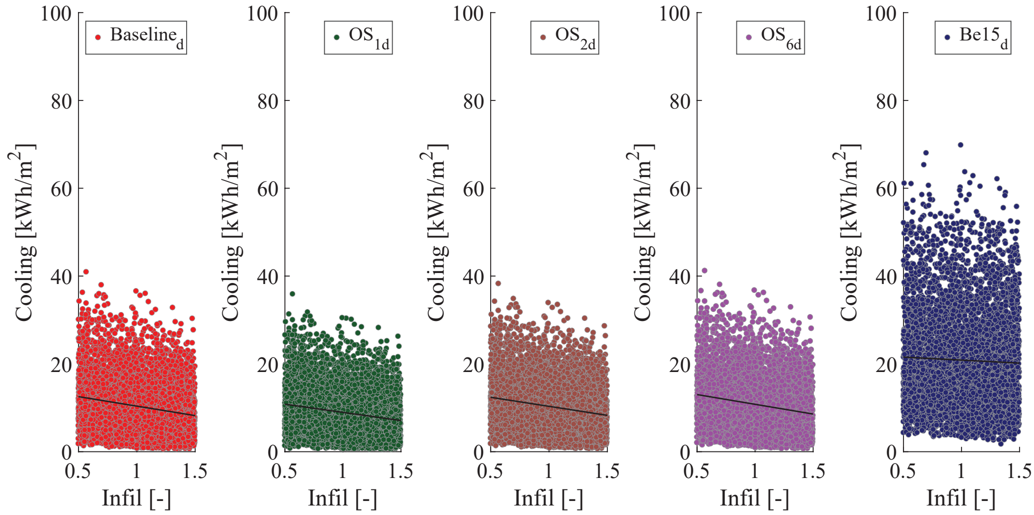



***Figure G.18.*** Relation between infiltration and the cooling consumption for all 5000 simulations for models with dynamic facade.

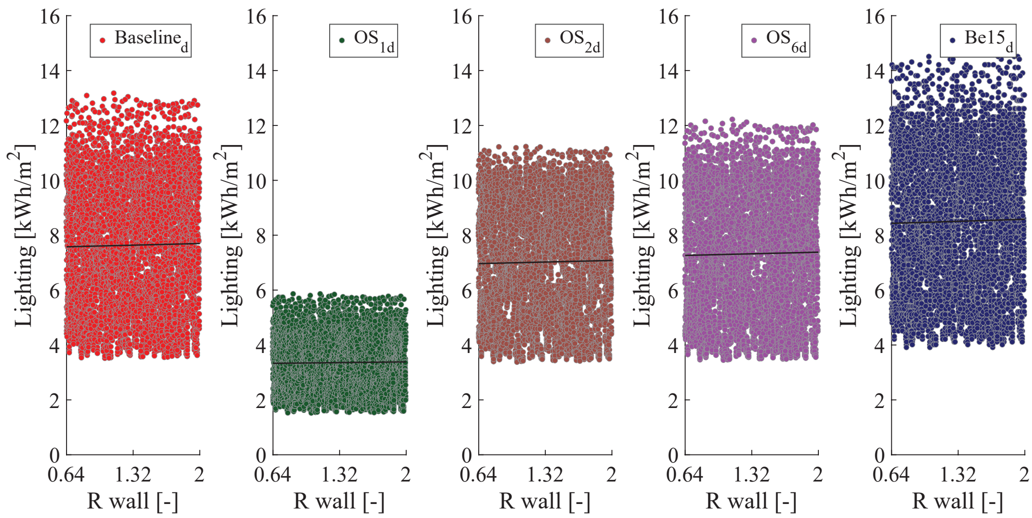



***Figure G.19.*** Relation between Resistance of the wall and the electricity for lighting for all 5000 simulations for models with dynamic facade.

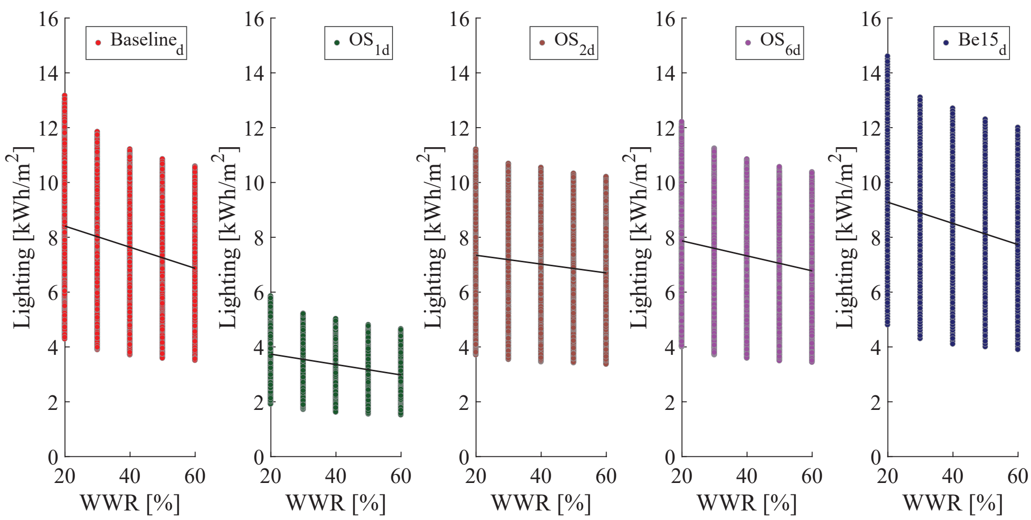



***Figure G.20.*** Relation between WWR and the electricity for lighting for all 5000 simulations for models with dynamic facade.

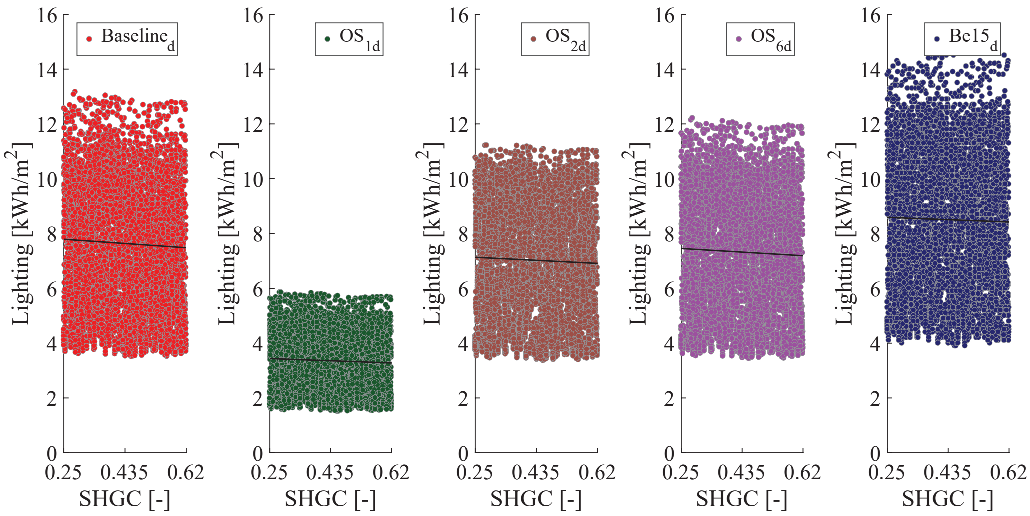



***Figure G.21.*** Relation between SHGC and the electricity for lighting for all 5000 simulations for models with dynamic facade.

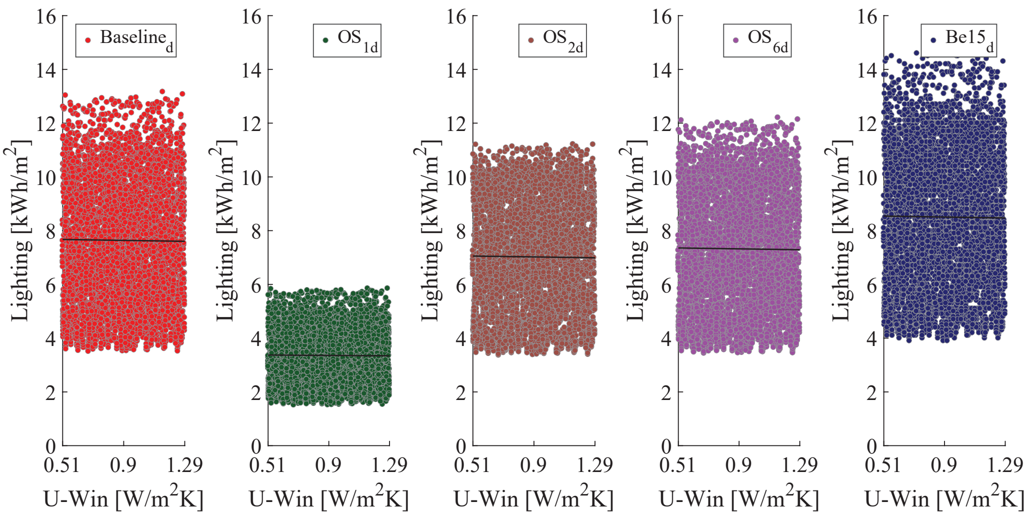



***Figure G.22.*** Relation between U-value for the window and the electricity for lighting for all 5000 simulations for models with dynamic facade.

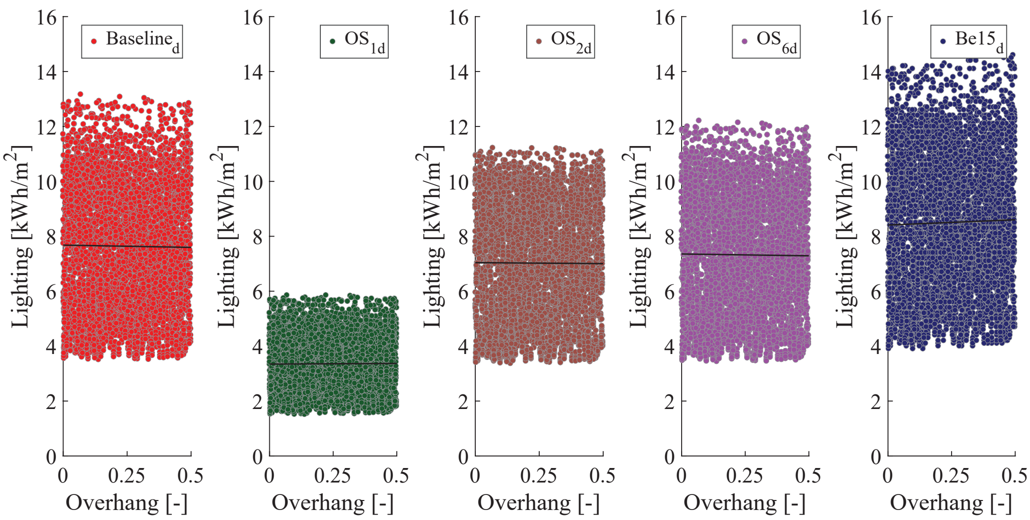



***Figure G.23.*** Relation between overhang and the electricity for lighting for all 5000 simulations for models with dynamic facade.

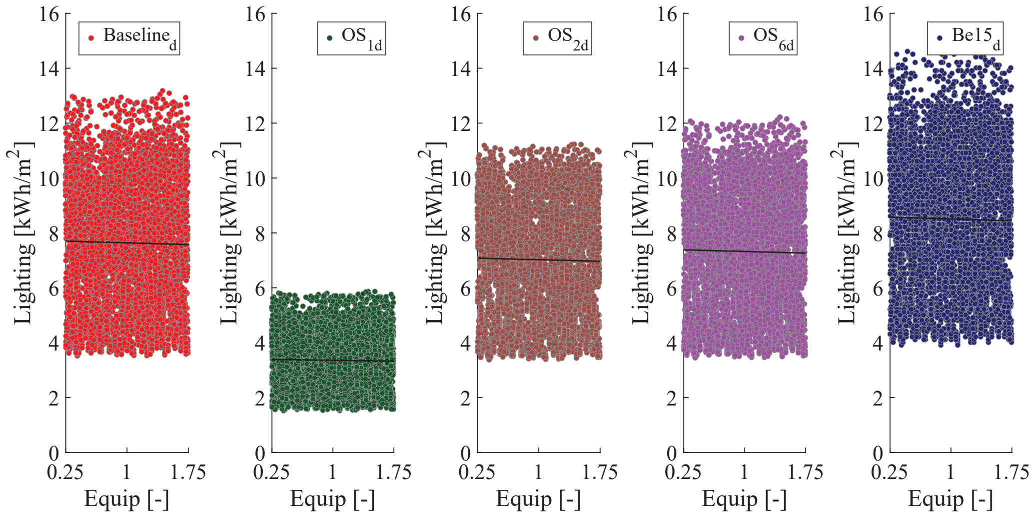



***Figure G.24.*** Relation between equipment and the electricity for lighting for all 5000 simulations for models with dynamic facade.

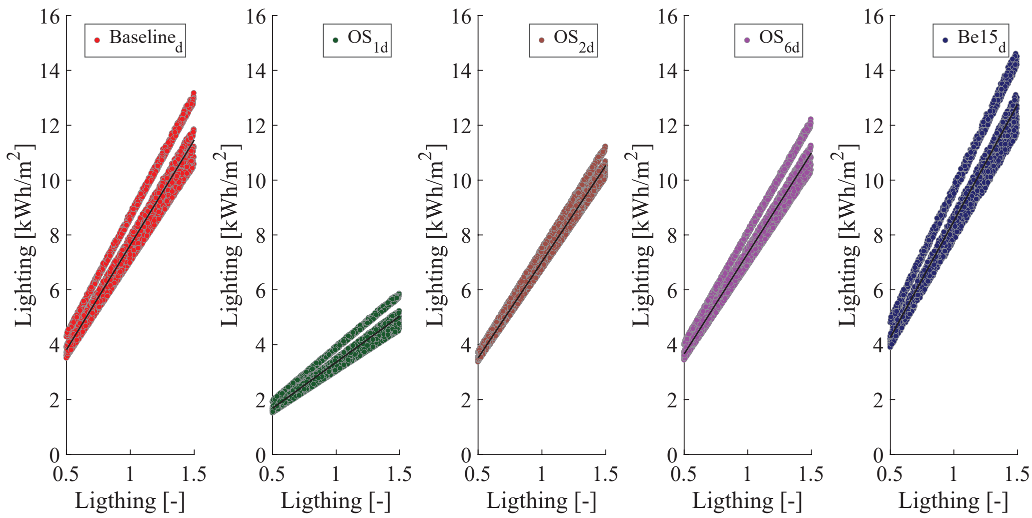



***Figure G.25.*** Relation between lighting and the electricity for lighting for all 5000 simulations for models with dynamic facade.

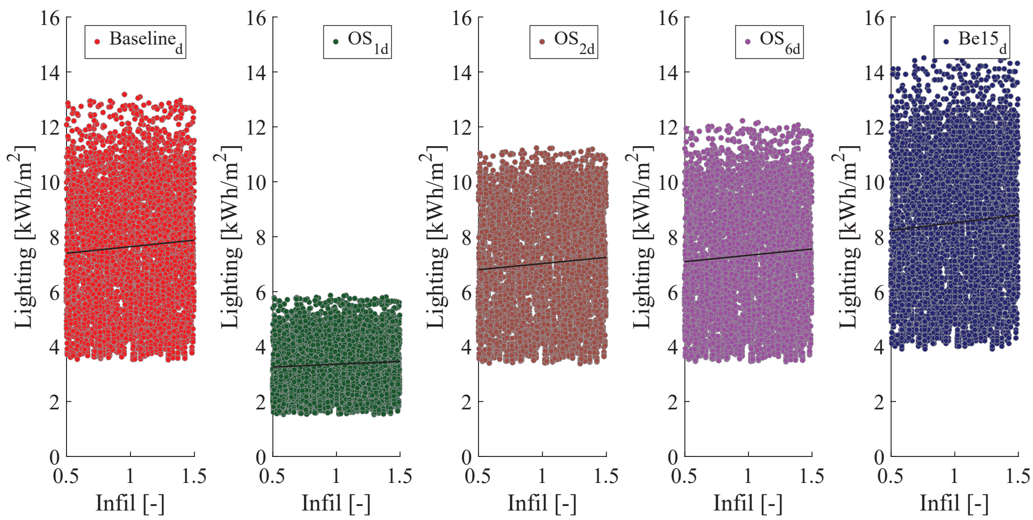



***Figure G.26.*** Relation between infiltration and the electricity for lighting for all 5000 simulations for models with dynamic facade.

## G.3 Monte Carlo filters

The input distribution for the 8 variable inputs with the Monte Carlo filters 2,3,4 for $\text{Baseline}_d$, $OS_{1d}$, $OS_{2d}$, $OS_{6d}$ and $Be15_d$ are shown in table G.2, G.3 and G.4.

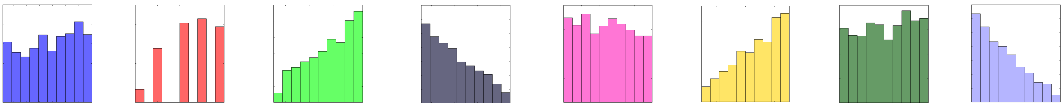
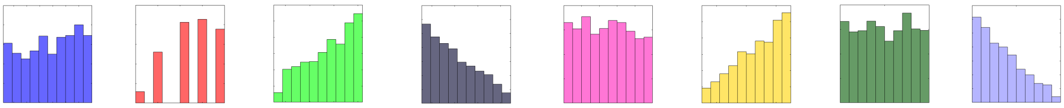
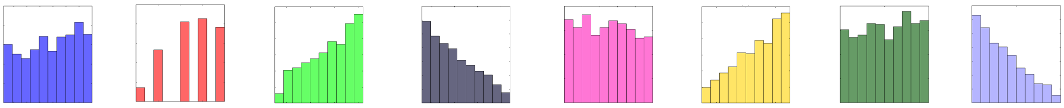
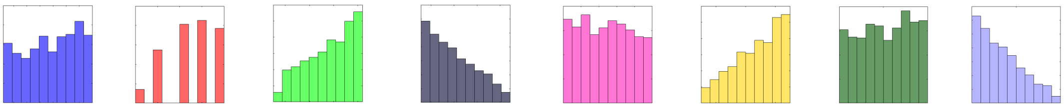
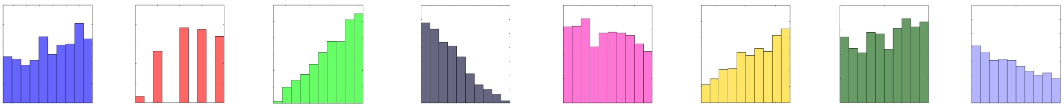
| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| $\text{Baseline}_d$ #1569 |  | | | | | | | |
| $OS_{1d}$ #1536 |  | | | | | | | |
| $OS_{2d}$ #1562 |  | | | | | | | |
| $OS_{6d}$ #1564 |  | | | | | | | |
| $Be15_d$ #1395 |  | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table G.2.*** Histograms of the distribution for the remaining inputs when filter 2 is applied. The number below the model name indicates the amount of remaining simulations.

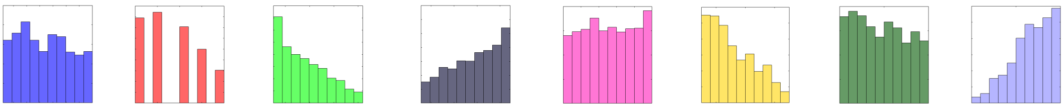
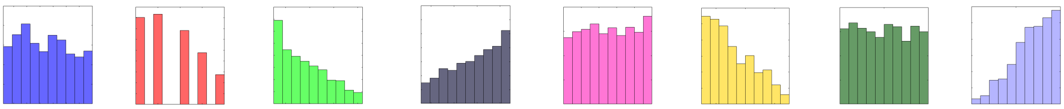
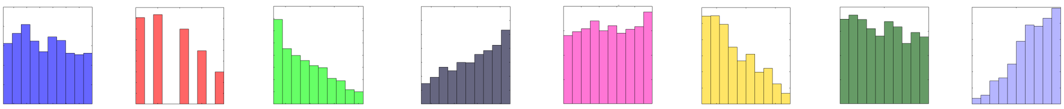
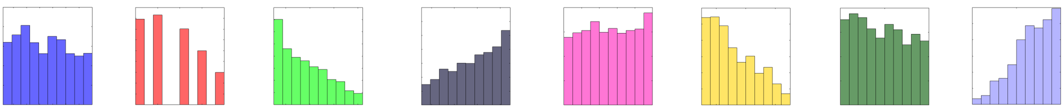
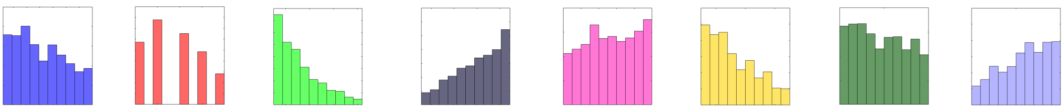
| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| $\text{Baseline}_d$ #1571 |  | | | | | | | |
| $OS_{1d}$ #1535 |  | | | | | | | |
| $OS_{2d}$ #1566 |  | | | | | | | |
| $OS_{6d}$ #1562 |  | | | | | | | |
| $Be15_d$ #1386 |  | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table G.3.*** Histograms of the distribution for the remaining inputs when filter 3 is applied. The number below the model name indicates the amount of remaining simulations.

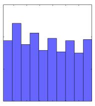
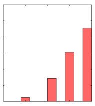
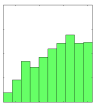
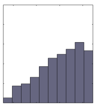
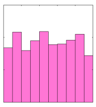
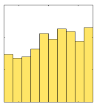
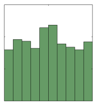
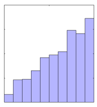
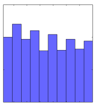
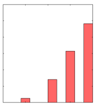
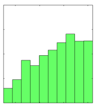
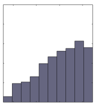
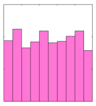
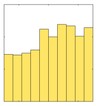
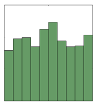
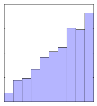
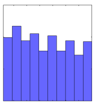
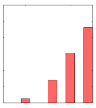
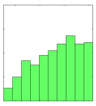
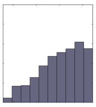
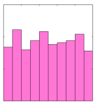
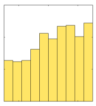
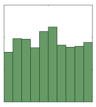
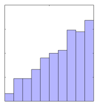
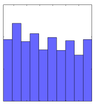
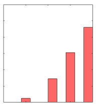
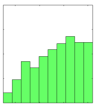
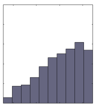
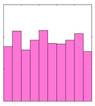
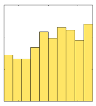
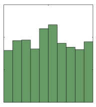
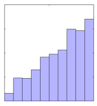
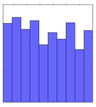
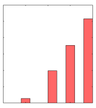
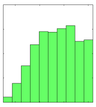
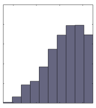
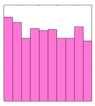
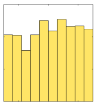
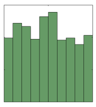
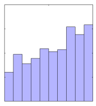
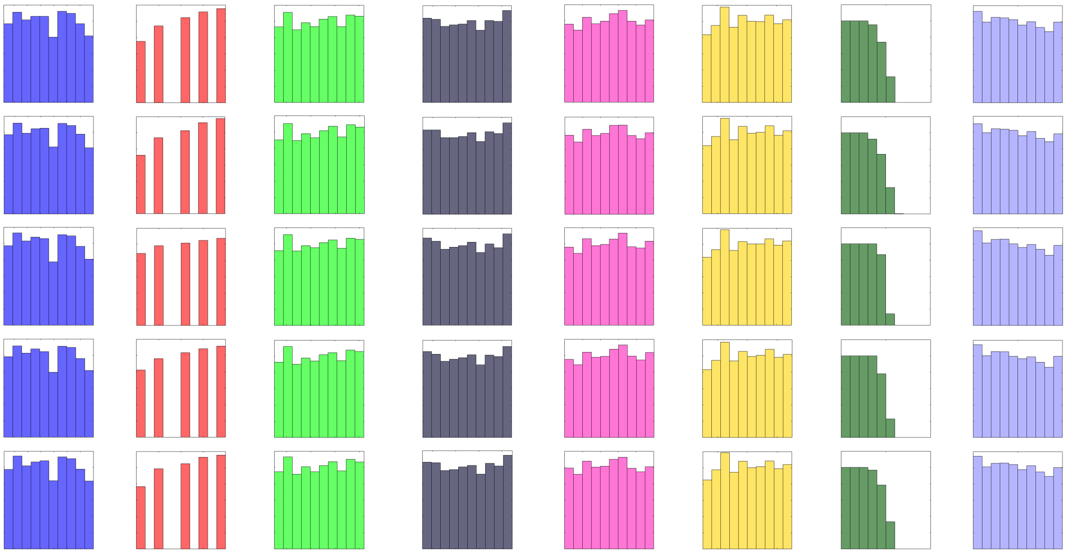
| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_d$ #928 |  |  |  |  |  |  |  |  |
| OS$_{1d}$ #963 |  |  |  |  |  |  |  |  |
| OS$_{2d}$ #932 |  |  |  |  |  |  |  |  |
| OS$_{6d}$ #935 |  |  |  |  |  |  |  |  |
| Be15$_d$ #1093 |  |  |  |  |  |  |  |  |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

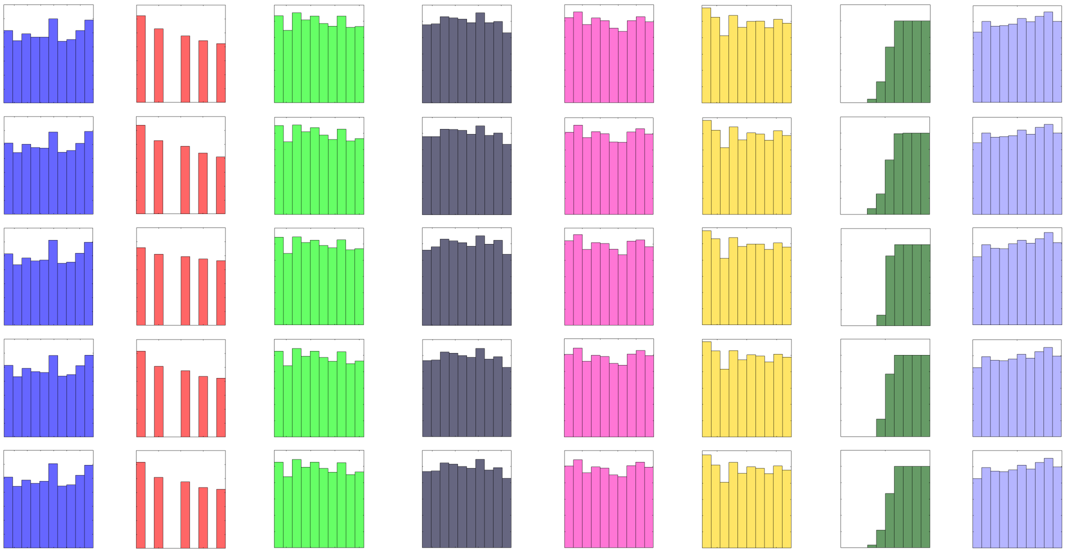
***Table G.4.*** Histograms of the distribution for the remaining inputs when filter 4 is applied. The number below the model name indicates the amount of remaining simulations.

Lastly, similar to the filters used for heating and lighting (cf. table D.3) Monte Carlo filters has been added to the lighting consumption. Two filters are used, one with all the simulations with a lighting consumption lower than the median, and the other containing only the simulations with a lighting consumption higher than the median. These are shown in table G.5 and G.6 for low and high lighting consumption respectively.



| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_d$ #1571 | | | | | | | | |
| OS$_{1d}$ #1535 | | | | | | | | |
| OS$_{2d}$ #1566 | | | | | | | | |
| OS$_{6d}$ #1562 | | | | | | | | |
| Be15$_d$ #1386 | | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table G.5.*** Histograms of the distribution for the remaining inputs when only simulations with a lighting consumption lower than the median remain. The number below the model name indicates the amount of remaining simulations.



| Model | R wall [–] | WWR [%] | SHGC [–] | U-win [W/m$^2$K] | OH [–] | Equip [–] | Light [–] | Infil [–] |
|---|---|---|---|---|---|---|---|---|
| Baseline$_d$ #932 | | | | | | | | |
| OS$_{1d}$ #966 | | | | | | | | |
| OS$_{2d}$ #940 | | | | | | | | |
| OS$_{6d}$ #939 | | | | | | | | |
| Be15$_d$ #1126 | | | | | | | | |
| | 0,64-2 | 20-60 | 0,49-0,62 | 0.51-1,29 | 0-45 | 0,25-1,75 | 0,5-1,5 | 0,5-1,5 |

***Table G.6.*** Histograms of the distribution for the remaining inputs when only simulations with a lighting consumption higher than the median remain. The number below the model name indicates the amount of remaining simulations.

## G.4 Sensitivity analysis

On figure G.27 and G.28 are shown the sensitivity for the variable inputs with only heating,cooling or lighting as output for models with dynamic facade.

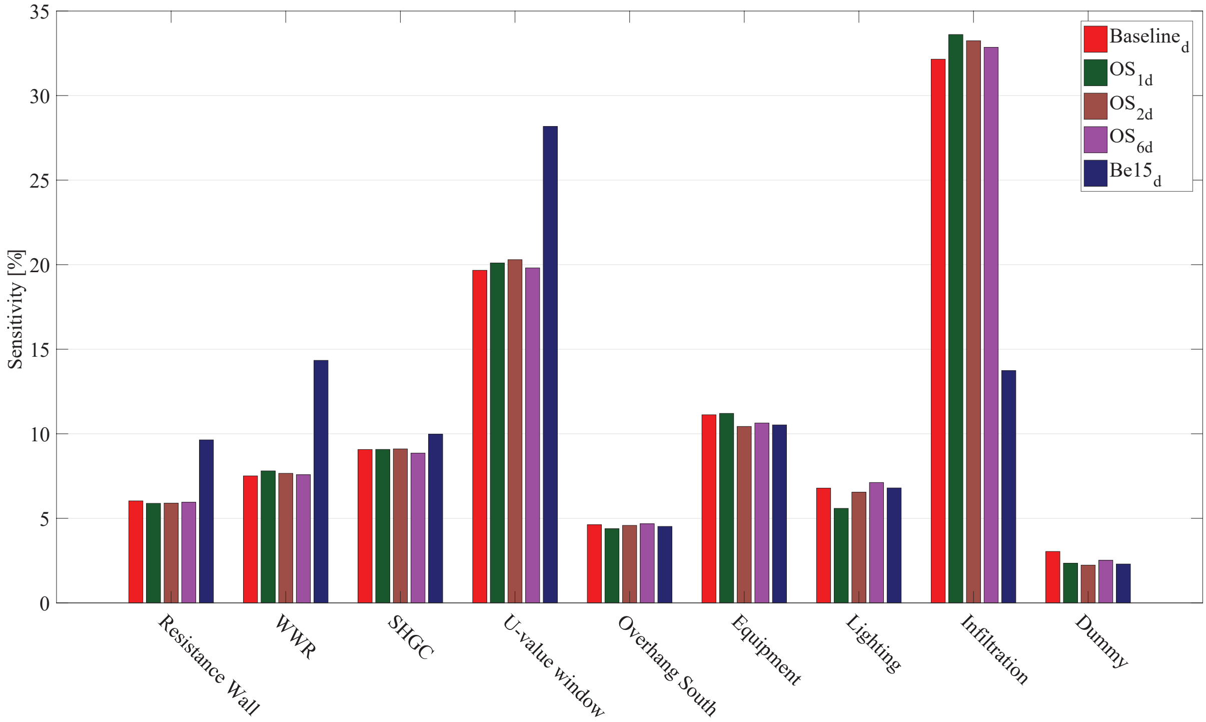



***Figure G.27.*** Sensitivity of the variable inputs with only heating as an output based on all 5000 simulations with dynamic facade.

The figure shows that infiltration and U-value window is generally regarded as the most important parameters regarding heating consumption. It is expected that parameters contributing to heat loss is important. $Be15_d$ estimated a different ranking with U-value window and WWR as the most important with infiltration as the third most important.

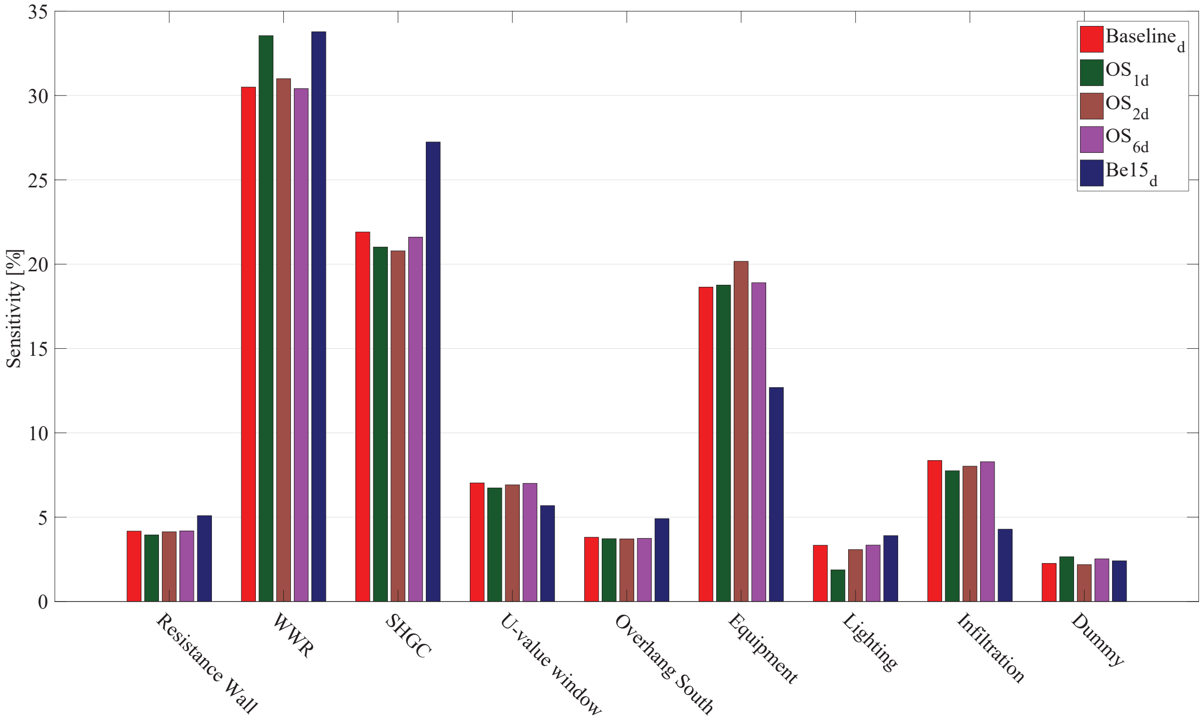



***Figure G.28.*** Sensitivity of the variable inputs with only cooling as an output based on all 5000 simulations with dynamic facade.

The reason the sensitivity of the lighting on the cooling consumption is as low as shown in figure G.28 is because when cooling is needed the lighting is on standby. An examination of the lighting use is shown in appendix H.

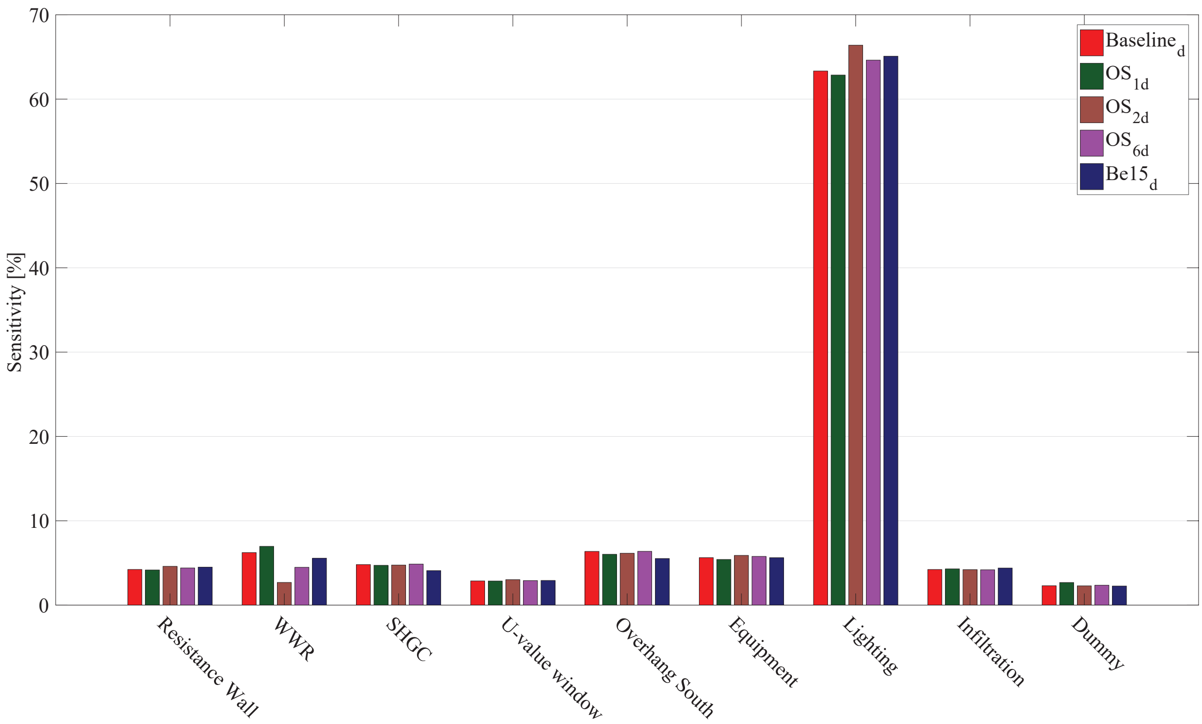



***Figure G.29.*** Sensitivity of the variable inputs with only lighting as an output based on all 5000 simulations with dynamic facade.

Figure G.29 shows that the lighting input i most influential on the annual lighting consumption, which is expected. The reason the overhang and the WWR has a low sensitivity is because the point where the lighting is controlled after is 80 % into the room from the facade. This means that changing the WWR does not change the daylight much. Some example can be seen in appendix B. Also daylight is controlled by daylight factors meaning that only diffuse light is included which overhangs does not effect much compared with direct daylight.

The ranking of the SA presented in table G.7 with both heating, cooling and lighting as output.

| | $\text{Baseline}_\text{d}$ | | $\text{OS}_\text{1d}$ | | $\text{OS}_\text{2d}$ | | $\text{OS}_\text{6d}$ | | $\text{Be15}_\text{d}$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] |
| Lighting | 1 | 29 | 1 | 29 | 1 | 31 | 1 | 30 | 6 | 8 |
| Infiltration | 2 | 15 | 2 | 15 | 2 | 15 | 2 | 15 | 5 | 8 |
| WWR | 3 | 14 | 3 | 15 | 3 | 13 | 3 | 13 | 1 | 26 |
| SHGC | 4 | 11 | 4 | 11 | 4 | 11 | 4 | 11 | 2 | 19 |
| U-value window | 5 | 10 | 6 | 10 | 6 | 10 | 6 | 10 | 3 | 16 |
| Equipment | 6 | 10 | 5 | 10 | 5 | 10 | 5 | 10 | 4 | 10 |
| Resistance wall | 7 | 5 | 7 | 4 | 7 | 4 | 7 | 4 | 7 | 6 |
| Overhang south | 8 | 4 | 8 | 4 | 8 | 4 | 8 | 4 | 8 | 4 |
| Dummy | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 3 |

***Table G.7.*** SA rankings of the inputs with heating, cooling and lighting as output for the models with dynamic facade.

From the table it can be seen that there are a few occurrences where the ranking of the inputs are changing, but the actual sensitivity which result in the change is very small. This indicate that the reduction in the amount of zones has no significant influence on the rankings, which means that criterion three is fulfilled for all simplified models for the advanced model. This differs a lot from $\text{Be15}_\text{d}$ which fail to rank anything else than the last two inputs and the dummy.

# Lighting Consumption for the Dynamic Facade H

## H.1 Examination of Standby for Lighting

Two cases are examined for the standby electricity consumption for lighting, these two cases are shown in table H.1. These are a best and a worst case scenario.

| | WWR [%] | Overhang projection [−] | Standby El consumption [%] |
|---|---|---|---|
| Case 1 | 60 | 0 | 67 |
| Case 2 | 20 | 0.5 | 30 |

***Table H.1.*** Two cases which are examined for standby lighting consumption.

These two cases revealed that that 67% and 30% of the the electricity for lighting is consumed while the control system is on standby, for case 1 and 2 respectively.

Figure H.1 and H.2 shows the energy consumption for lighting within occupied hours for case 1 and 2 respectively.

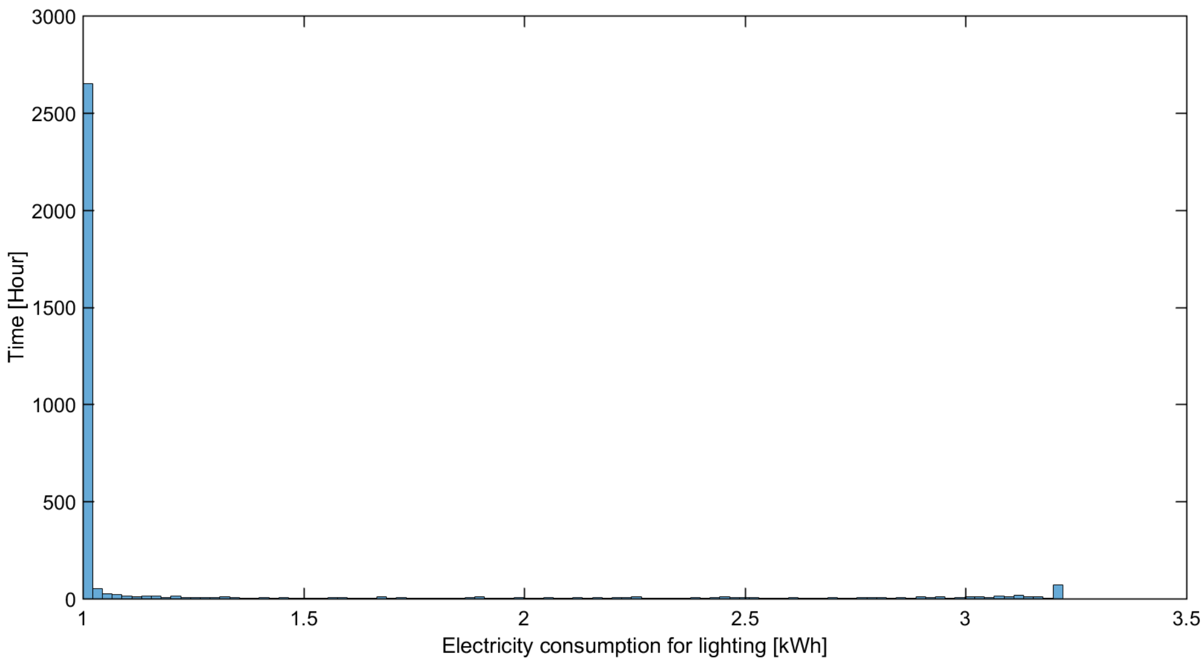



***Figure H.1.*** Histogram of the amount of hours with different electricity consumption for lighting. A case with 60 % WWR and 45 % overhang calculated with the baseline model. Only the occupied hours are included (3285 hours).

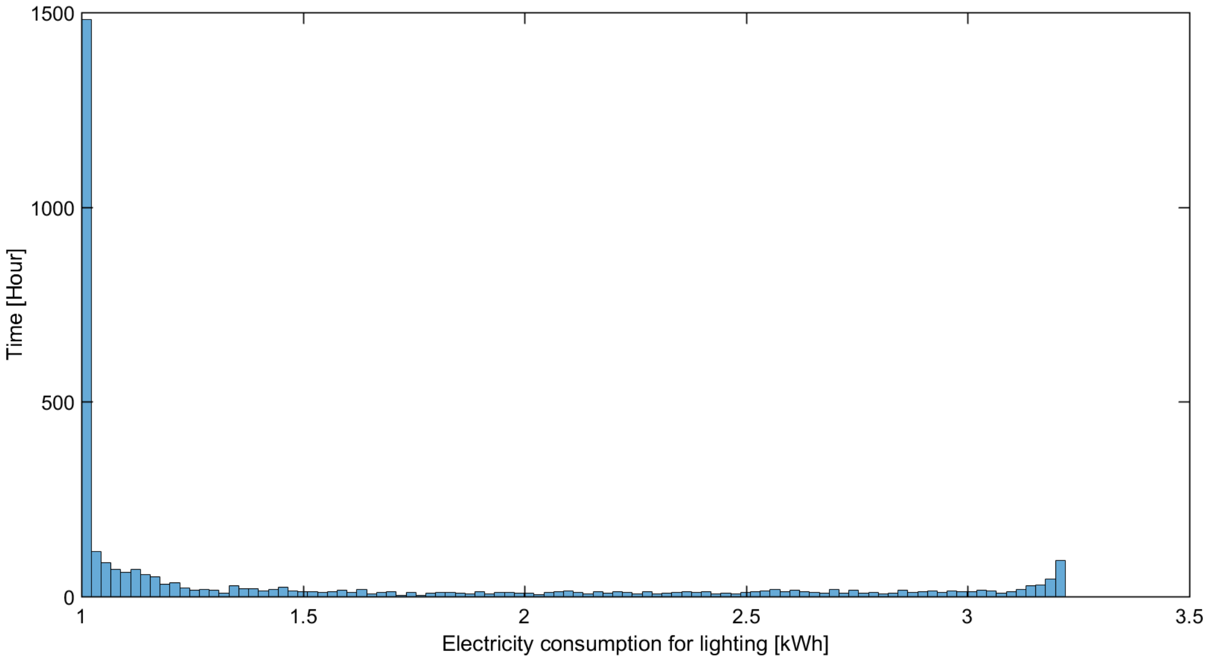



***Figure H.2.*** Histogram of the amount of hours with different electricity consumption for lighting. A case with 20 % WWR and 45 % overhang calculated with the baseline model. Only the occupied hours are included (3285 hours).

Both figure H.1 and H.2 shows that there is a large portion of the time where the consumption for lighting is low. This is when the lighting is on standby which correspond to 10 % of when the lighting is fully turned on.

Figure H.3 shows when the artificial lighting is in use for case 1 and figure H.4 (cf. H.1 on the previous page).

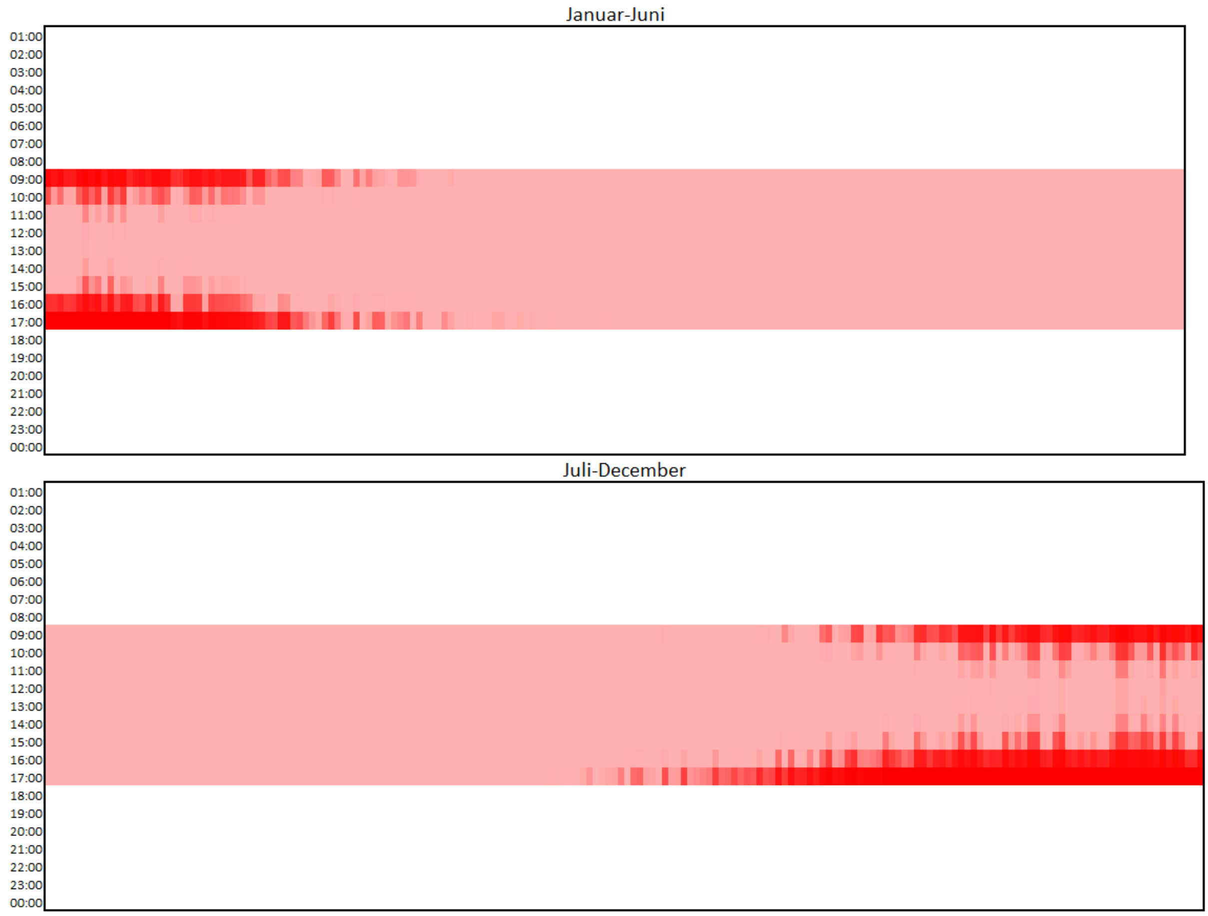



***Figure H.3.*** A whole years energy consumption both inside and outside occupied hours for case 1 (cf. H.1 on page 121). The level of lighting used is scaled with a red color, where the darker red represent fully turned on lights and white is turned off.

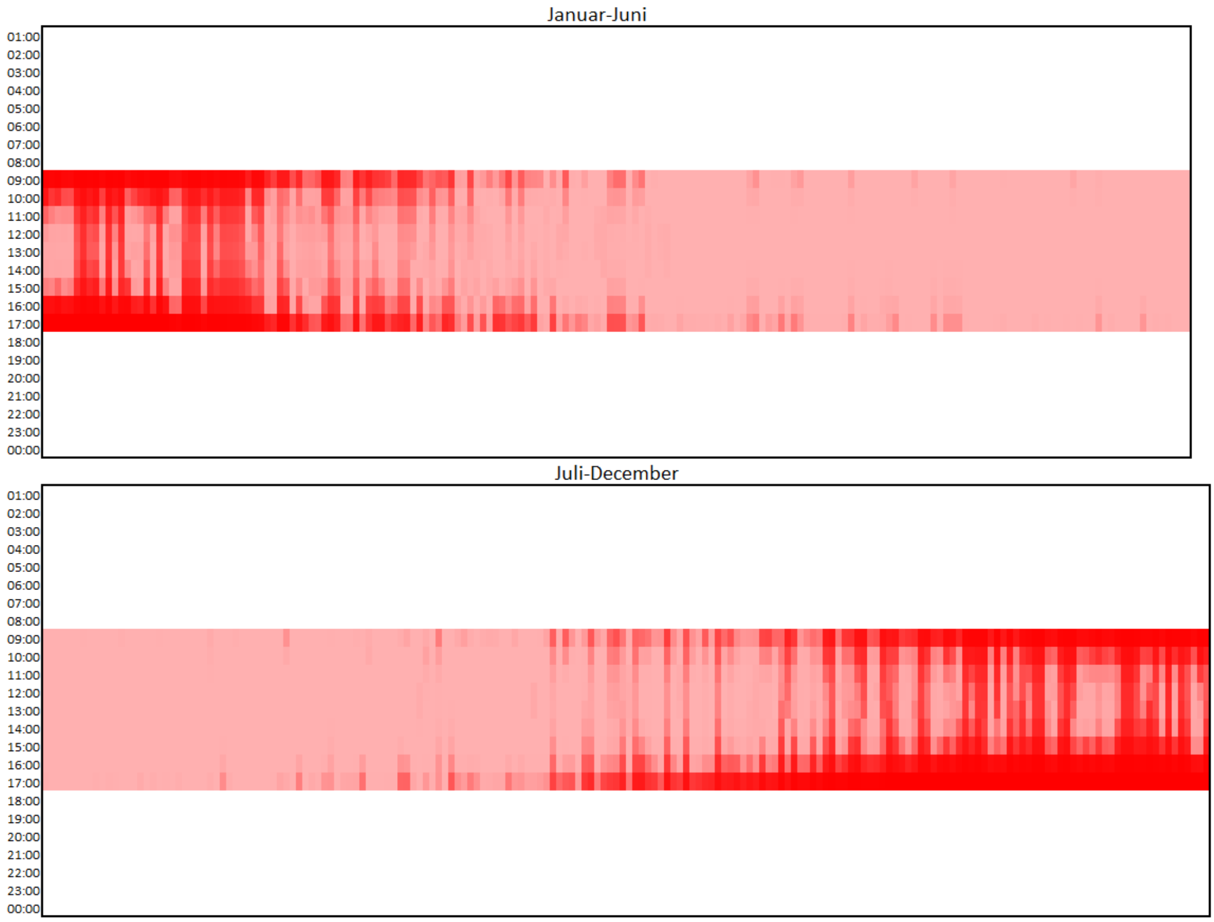



***Figure H.4.*** A whole years energy consumption both inside and outside occupied hours for case 2 (cf. H.1 on page 121). The level of lighting used is scaled with a red color, where the darker red represent fully turned on lights and white is turned off.

Figure H.3 shows that it is almost only in the early morning or in the late afternoon where the light is fully turned on, and there is very limited need for artificial lighting during the middle of the day. Furthermore it can be seen that during the occupied hours that it is largely dominated by standby consumption. Figure H.4 shows that slightly more lighting is needed for case 2 compared to case 1 which is excepted since the WWR is lower and overhang larger for case 2.

## H.2 Model with no Lighting

From figure F.1 on page 98 it can be seen that the lighting consumption for $OS_{1d}$ is lower than the baseline. In this section it is investigated if the deviation in lighting consumption is the sole reason for the deviation in heating and cooling consumption. To examine this both $Baseline_d$ and $OS_{1d}$ are simulated without any lighting. The heating and cooling consumption is shown in figure H.5

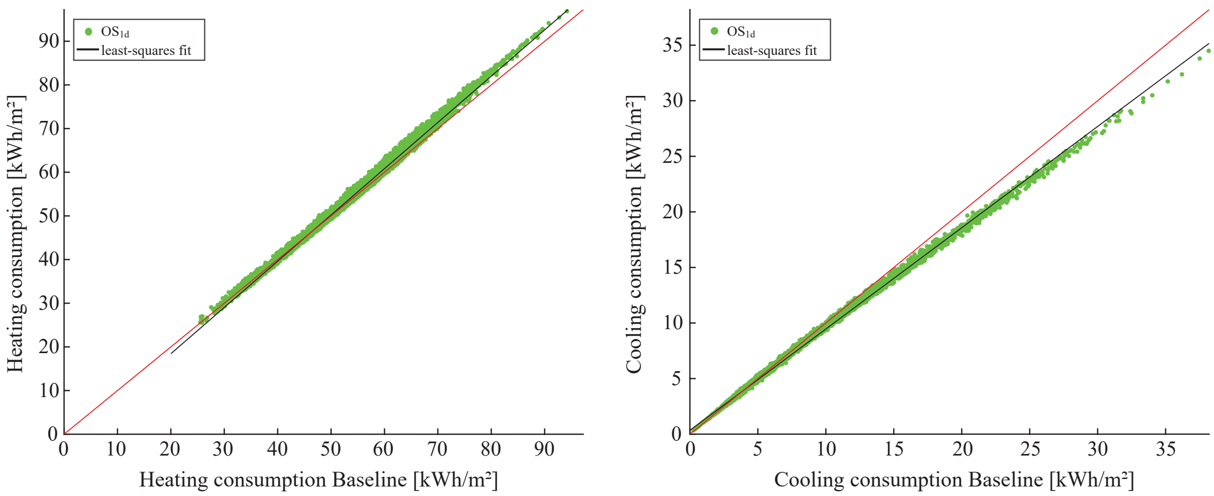



***Figure H.5.*** Heating and cooling consumption for $OS_{1d}$ without lighting compared to $Baseline_d$ without lighting.

From the figure it is seen that there is a difference in the consumption, which means that the lighting alone is not the reason for the differences that occur for heating and cooling consumption.

## H.3 Single v.s. Multi Zone Be15 Lighting

Be15 comes with the option to divide the lighting control into multiple zones, whereas the thermal calculation is done as a single zone model. The difference between modelling the Be15 model with multi zone lighting control compared with only using one zone is shown in figure H.6. The model with multi zone lighting control is modelled the same way as $Baseline_d$ and the single zone model is controlled as $OS_{1d}$. This means that the multi zone models has lighting control in all rooms except hallways, toilets and staircases and all the lighting is controlled with the reference point in the reception for the single zone model. Further details on the control systems in chapter 4 and appendix C.4.

The four models used in the investigation of the Be15 multi and single zone lighting control models will be referred to as follows:

- Advanced BEM Tool:
  - OpenStudio with 15 zones: $Baseline_d$
  - OpenStudio with 1 zone: $OS_{1d}$
- Simple BEM Tool:
  - Be15 with single zone lighting control: $Be15_{1d}$
  - Be15 with multi zone lighting control: $Be15_d$

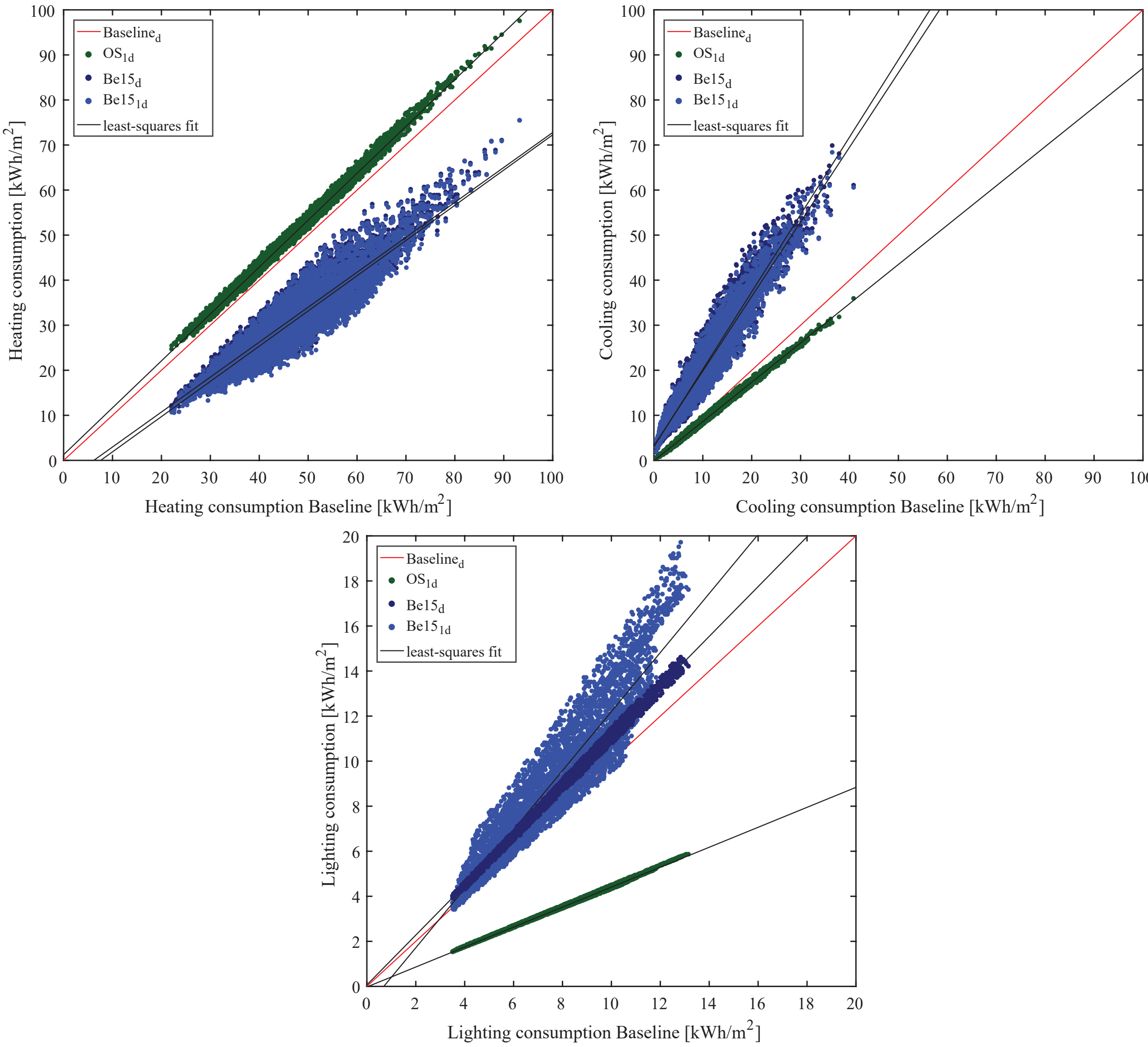



***Figure H.6.*** Heating, cooling and lighting consumption for Baseline$_{d}$, Be15$_{1d}$ and Be15$_{d}$ and OS$_{1d}$. All the models are with dynamic facade.

From the figure it is seen that the heating and cooling consumption for the two Be15 models does not differ much, but the lighting consumption does. The results obtain from Be15$_{d}$ are more consistent than Be15$_{1d}$. The difference between Baseline$_{d}$ and Be15$_{1d}$ has a larger standard deviation than Be15$_{d}$ and some of the simulations even obtain a lighting consumption which is almost the same as Baseline$_{d}$. The 25 % smallest difference between Baseline$_{d}$ and Be15$_{1d}$ is $\pm$ 0,5 kWh/m$^2$. This is highly correlated with the WWR which can be seen on figure H.7.

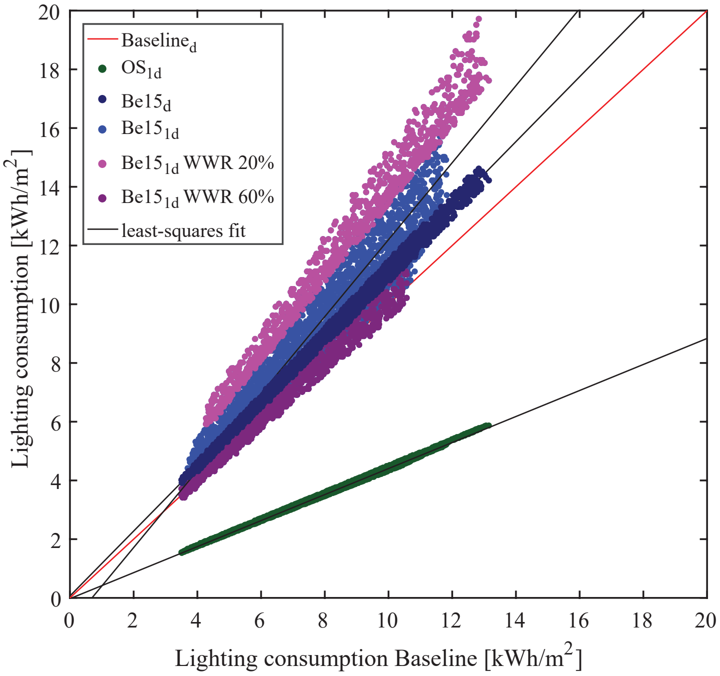



***Figure H.7.*** Lighting consumption for Baseline$_d$, OS$_{1d}$, Be15$_{1d}$ and Be15$_d$. All models with dynamic facade.

The figure shows that when having 60 % WWR, the lighting consumption calculated with Be15$_{1d}$ and Baseline$_d$ are very similar. A large part of the consumption for lighting is because of the standby consumption which is shown in H.1. When the WWR increase so does the standby consumption which means that more and more of the consumption is standby. Since there is no control when it is only the standby power, the estimated consumption is less reliant on the type of model or amount of zones used to describe the simulations, but rather if the values put into the models are consistent. The reason why there is still a difference in the model is because not 100 % of the lighting consumption is caused by standby.

The distribution of the difference between Baseline$_d$ and the simplified models is shown in figure H.8.

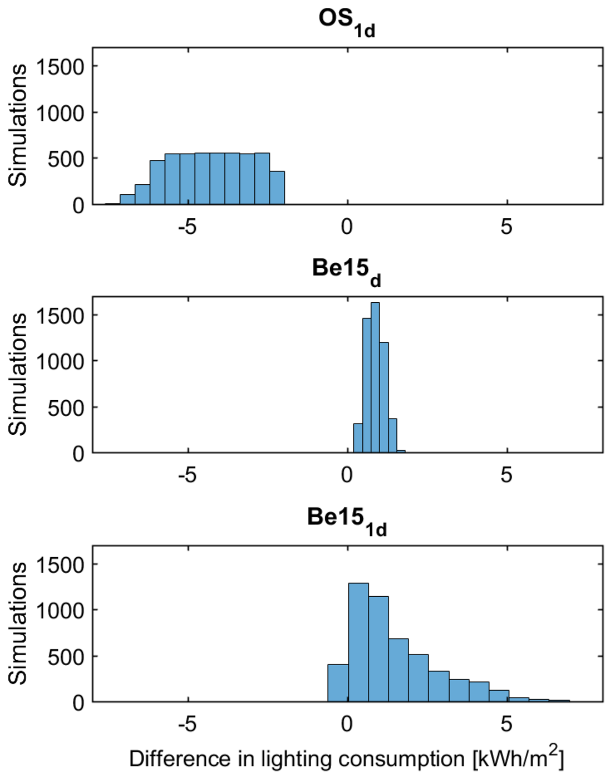



***Figure H.8.*** The distribution of the difference between $\text{Baseline}_\text{d}$ and the simplified once.

Figure H.8 shows that the simple model provide better results than the advanced model does when modelled as one zone. Furthermore 70 % of all the simulations has a difference of $\pm$ 1,5 kWh/m$^2$ for $\text{Be15}_\text{1d}$ where all the simulations for $\text{OS}_\text{1d}$ has a difference bigger that $-2$ kWh/m$^2$.
From figure H.6 and H.8 it can be concluded that the simple Be15 model can provide a more accurate estimation of the lighting consumption than the advanced model can if the advanced models with a single zone. But most importantly from the investigation it can be seen that when modelling the case building's lighting as a single zone the simple model provide more accurate lighting consumption than the advanced. It still has to be noted that the simple model might provide better results for lighting, but it does not provide as accurate results for heating and cooling consumption as the advanced model.

# Total Energy Consumption with Primary Energy Factors I

Total energy consumption with primary energy factors for the simplified models compared with their respective baseline model is shown in figure I.1.

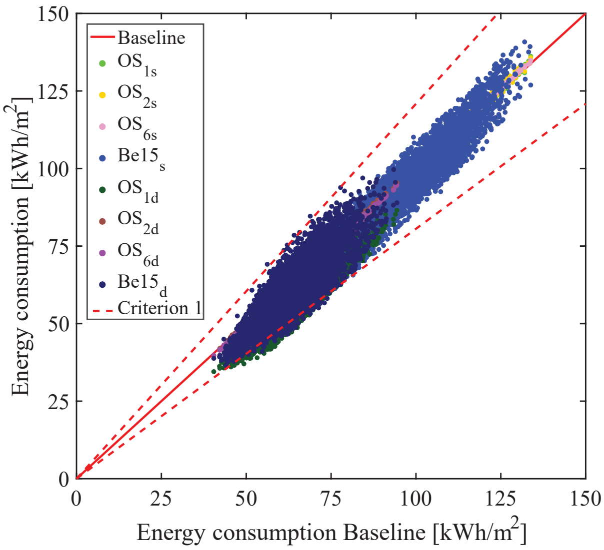



***Figure I.1.*** Total energy consumption with primary energy factors for the simplified models compared with their respective baseline model. The $R^2$-value is higher than 0,99 for all models except $\text{Be15}_\text{s}$, $\text{OS}_\text{1d}$ and $\text{Be15}_\text{d}$. These are 0,92, 0,89 and 0,55 respectively.

## I.1 Distribution of Total Energy Consumption

The distribution of the total energy consumption is shown in figure I.2 for all models. Furthermore the distribution of the difference between the baseline models and the simplified are shown in figure I.3.

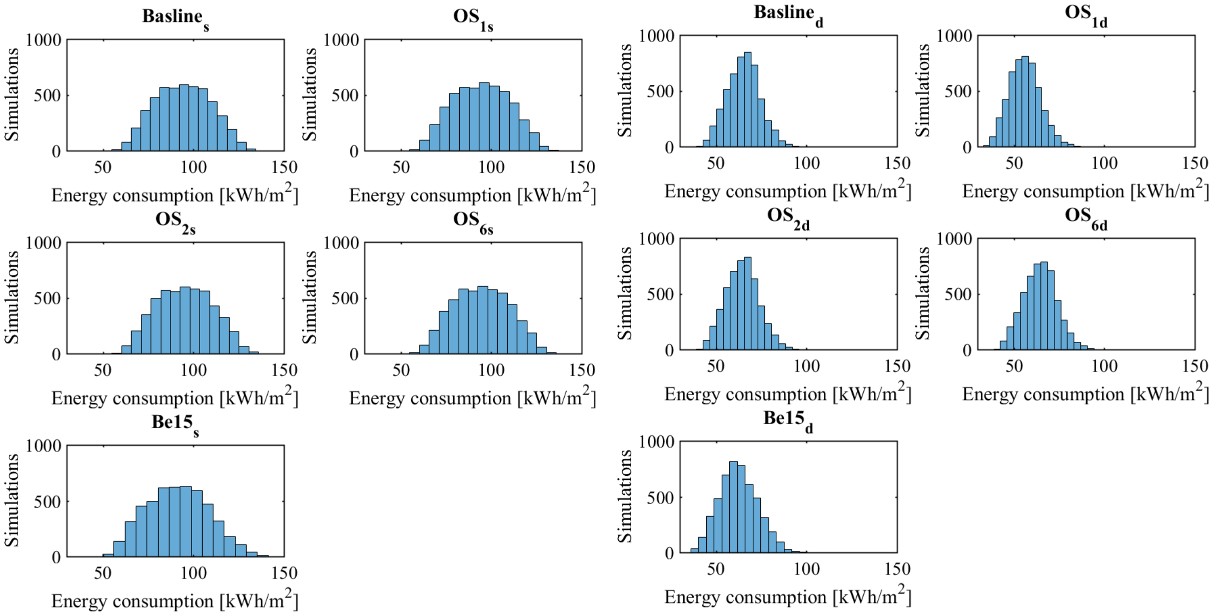



***Figure I.2.*** Distribution of the total energy consumption for models with both static and dynamic facade.

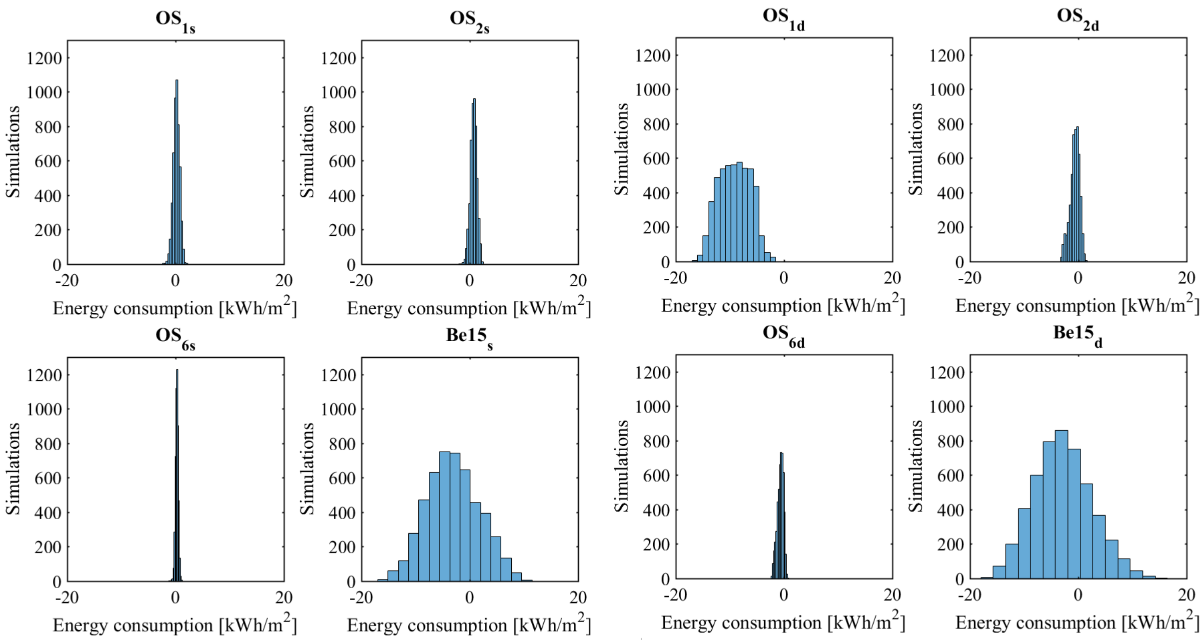



***Figure I.3.*** Distribution of the difference for total energy consumption between the baseline models and the simplified once.

It is clear from figure I.3 that increasing the number of zones increases the accuracy of the energy consumption, as more simulations are closer to having 0 kWh/m$^2$ difference from the baseline. One exception to this is between $OS_{1s}$ and $OS_{2s}$ where $OS_{1s}$ is lightly better than $OS_{2s}$. Furthermore It can be seen that the difference between the baseline models and the simplified is bigger for models with dynamic facade than static facade. This indicate, when looking at total energy consumption, that the more complex the building becomes the bigger difference can be expected.

## I.2 Be15 Total Energy Consumption with Monte Carlo filters

As shown in figure 5.5 on page 30, $Be15_s$ and $Be15_d$ predicts the total energy demand close to what is predicted by $Baseline_s$ and $Baseline_d$ receptively. It is investigated if the results would be different if the heating consumption were much higher than the cooling consumption and vice versa. The investigation is described in this section.

$Be15_s$ and $Be15_d$ total energy consumption is investigated by added filters to the heating and cooling output. The filters are shown in figure I.1.

| | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|
| | Low/Low | Low/High | High/Low | High/High |

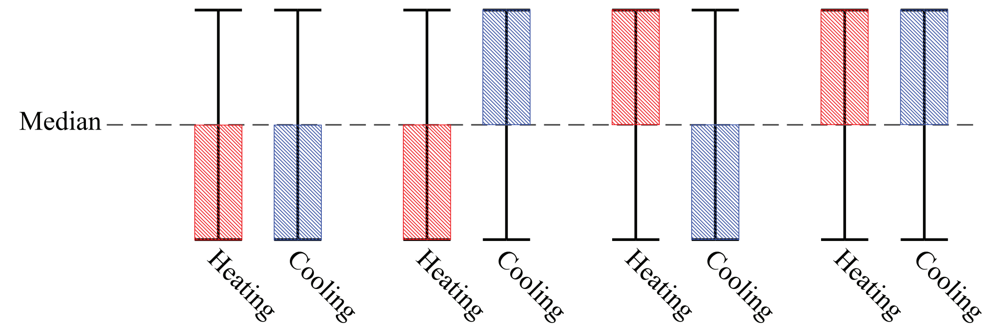



***Table I.1.*** Four different filters used to split the 5000 simulations for the investigation of $Be15_s$ and $Be15_d$ total energy demand.

The total energy consumption of $Be15_s$ and $Be15_d$, when filter 1 is added, is shown in figure I.4.

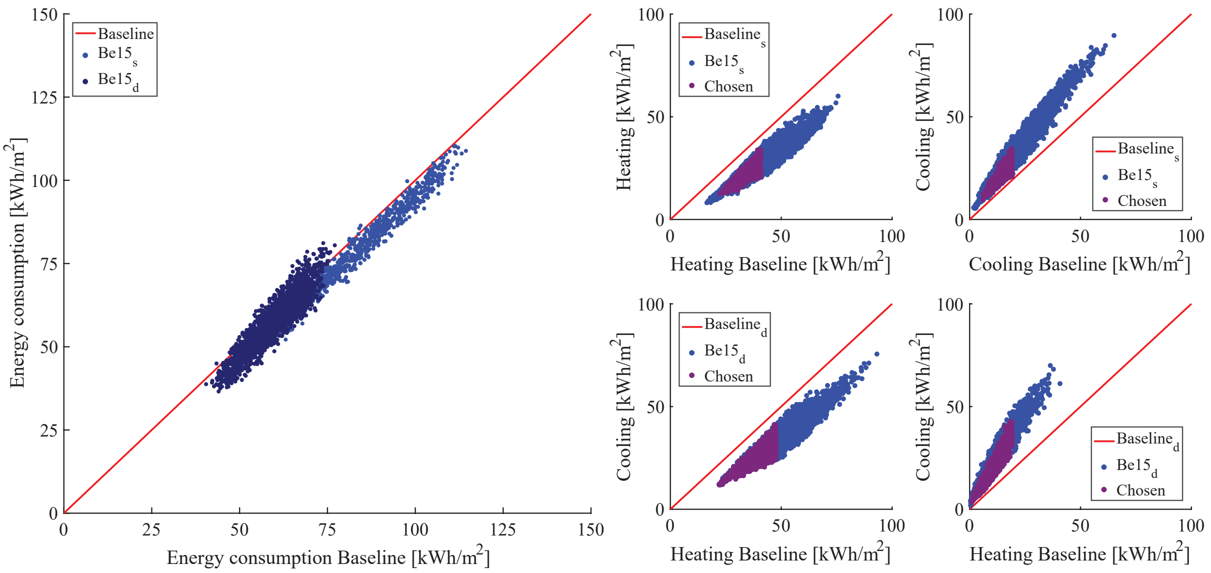



***Figure I.4.*** Total energy consumption of $Be15_s$ and $Be15_d$ with low heating and low cooling consumption. The four plots on the right indicates the included simulations with purple.

The figure shows that $Be15_s$ underestimate the energy consumption. This is due to the low heating simulations having a bigger offset than the low cooling simulations, meaning that the total energy consumption underestimates.

Be15$_d$ predicts the energy consumption well though a small underestimation is noticed which is assumed to be caused by the same reason as for Be15$_s$.

The total energy consumption of Be15$_s$ and Be15$_d$, when filter 2 is added, is shown in figure I.4.

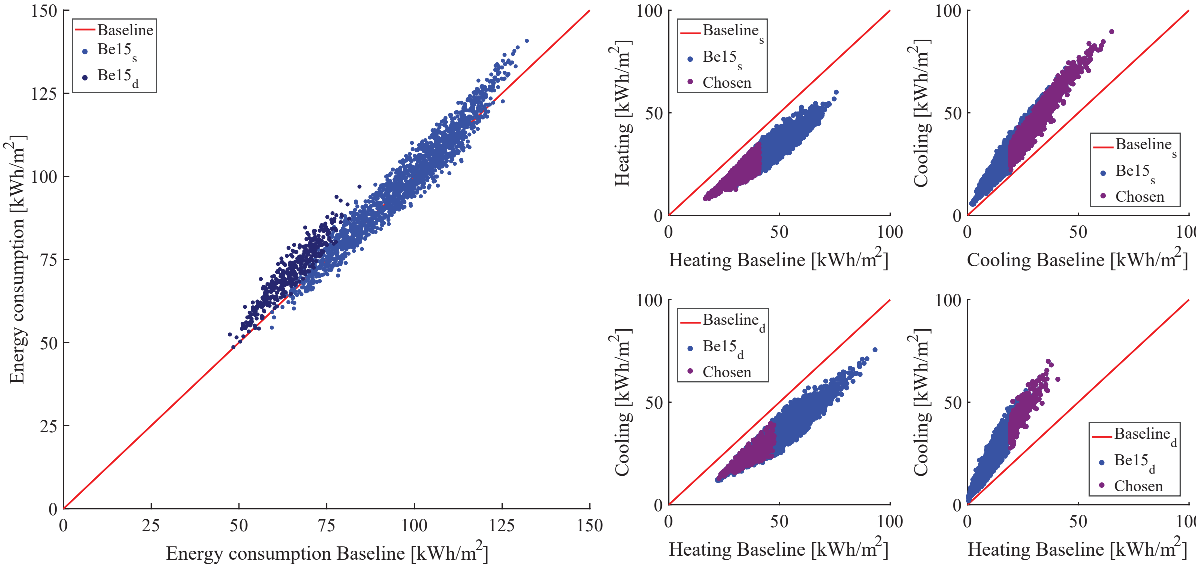



***Figure I.5.*** Total energy consumption of Be15$_s$ and Be15$_d$ with low heating and high cooling consumption. The four plots on the right indicates the included simulations with purple.

It is expected that Be15$_s$ and Be15$_d$ with high cooling and low heating consumption will over estimate the total energy consumption, though figure I.5 only shows a small tendency towards this. The reason for the overestimation not being higher could be due to the high density of simulation in the low end of cooling consumption while the simulations with a high cooling consumption is spread across a larger range, minimizing the effect.

The total energy consumption of Be15$_s$ and Be15$_d$, when filter 3 is added, is shown in figure I.6.

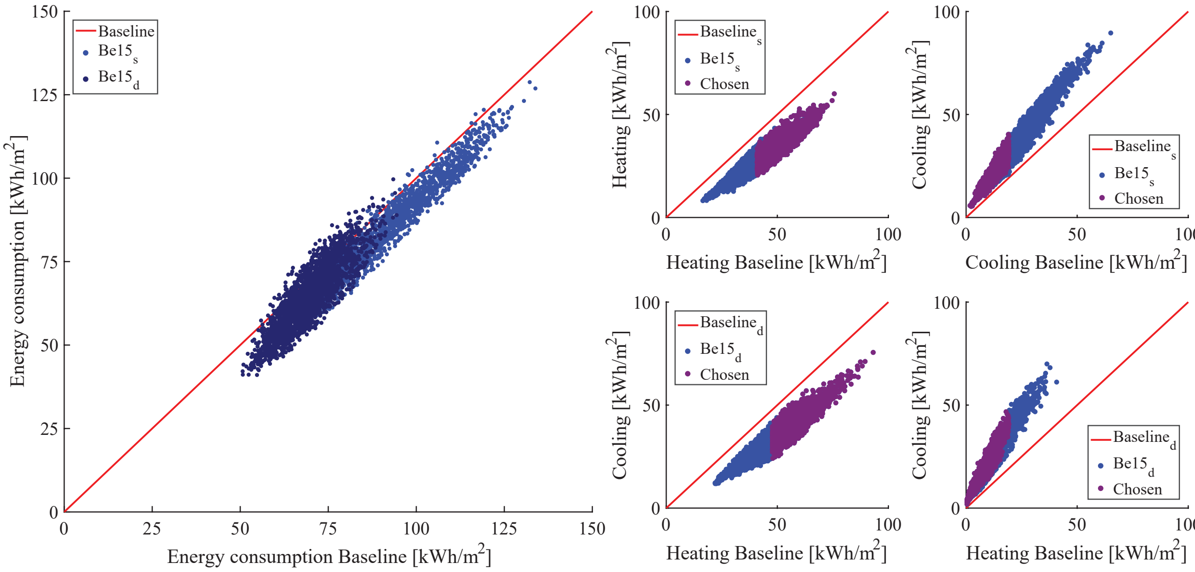



***Figure I.6.*** Total energy consumption of Be15$_s$ and Be15$_d$ with high heating and low cooling consumption. The four plots on the right indicates the included simulations with purple.

The figure shows an expected underestimation of the energy consumption for both $\text{Be15}_\text{s}$ and $\text{Be15}_\text{d}$. This is due to the heating consumption being the dominating factor.

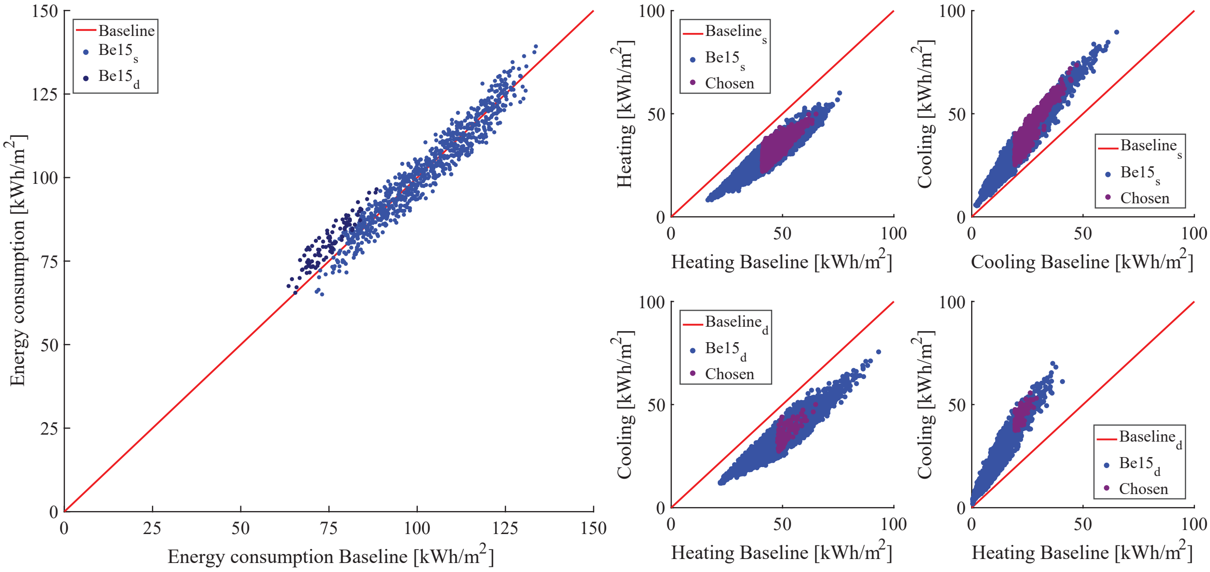



***Figure I.7.*** Total energy consumption of $\text{Be15}_\text{s}$ and $\text{Be15}_\text{d}$ with high heating and high cooling consumption. The four plots on the right indicates the included simulations with purple.

The figure shows that for high heating and cooling consumption, $\text{Be15}_\text{s}$ and $\text{Be15}_\text{d}$ estimates the total energy consumption well with no unexpected tendencies.

Overall the investigations shows tendencies to what would be expected but nothing of significance. Though this is concluded on the background of a single case building and investigating a building which is more dominated by heating or cooling than the this case building might result in stronger tendencies towards over-/undershooting.

## I.3 Model Tendencies

In addition to the Monte Carlo filter added containing the 33 % best performing simulations, scatter plots and PCC is use to examine the model tendencies.

16 figures with five scatter plots each representing the five models, have been examined for the tendencies of the relation between inputs and outputs. Note that the magnitude of the correlation is not of interest for criterion two, but rather if changes to an input yield same tendencies on the output as that of the baseline models. The scatter plots are manually examined as a qualitative validation approach. To further validate the results PCC is used as a quantitative approach. The figures I.8-I.23 contains the scatter plots for all ten models with the relation between the inputs and total energy consumption. The PCC are shown in table I.2.

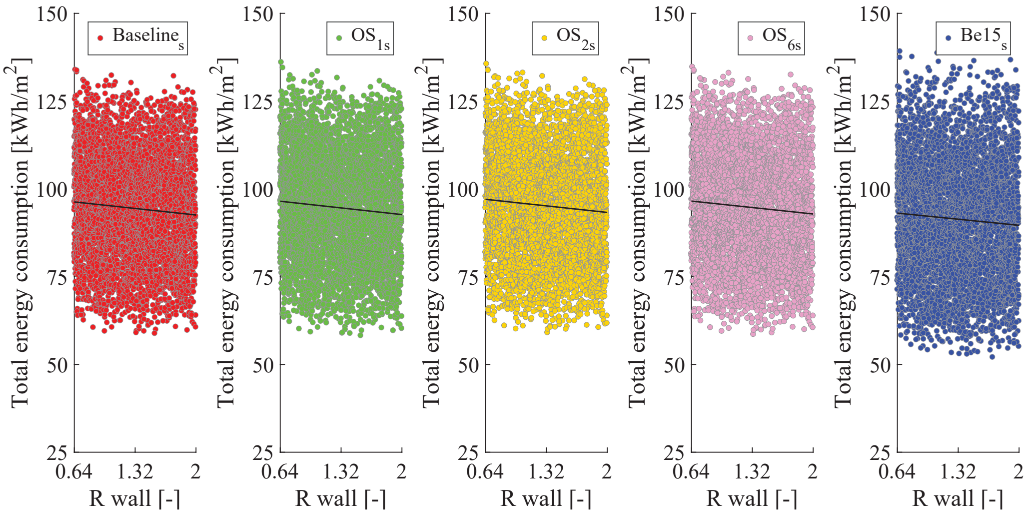



***Figure I.8.*** Relation between resistance of the wall and the Total energy consumption for 5000 simulation with static facade.

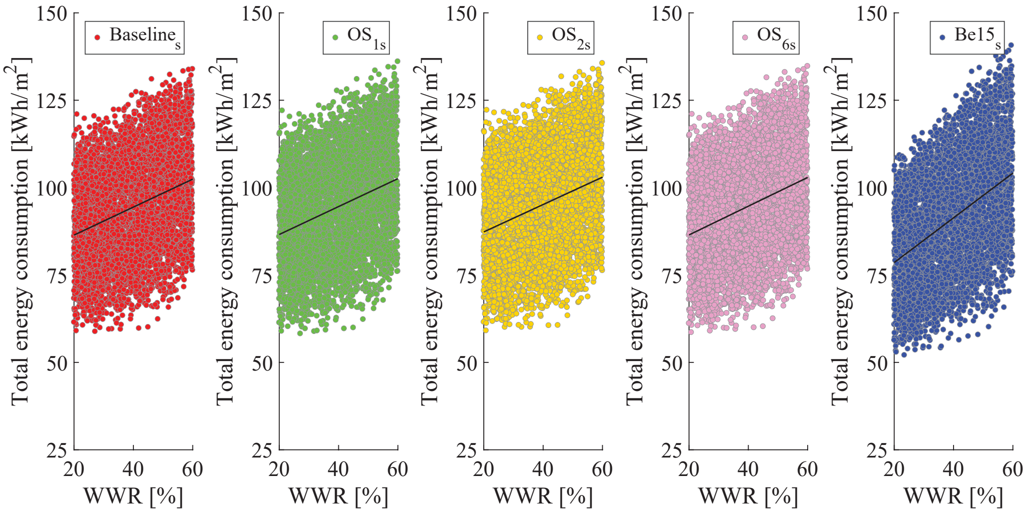



***Figure I.9.*** Relation between WWR and the Total energy consumption for 5000 simulation with static facade.

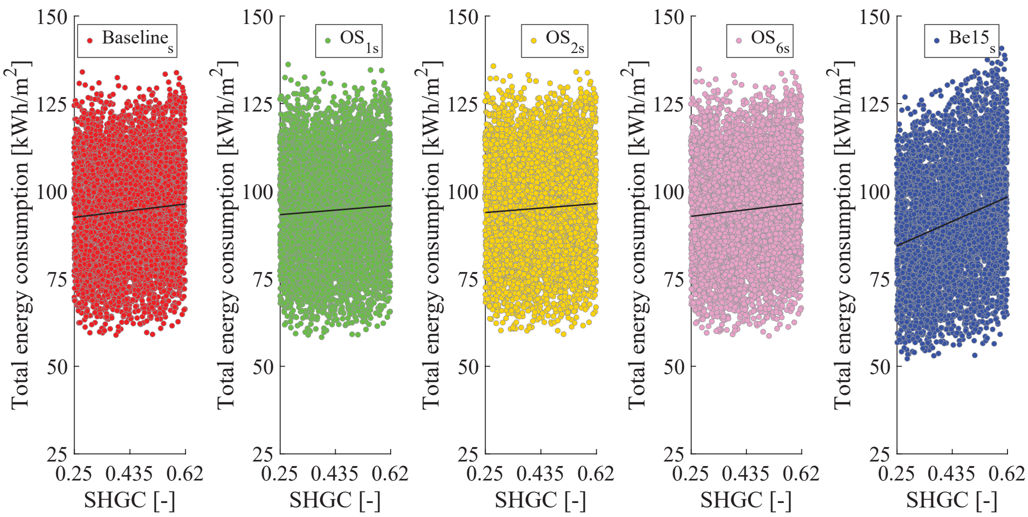



***Figure I.10.*** Relation between SHGC and the Total energy consumption for 5000 simulation with static facade.

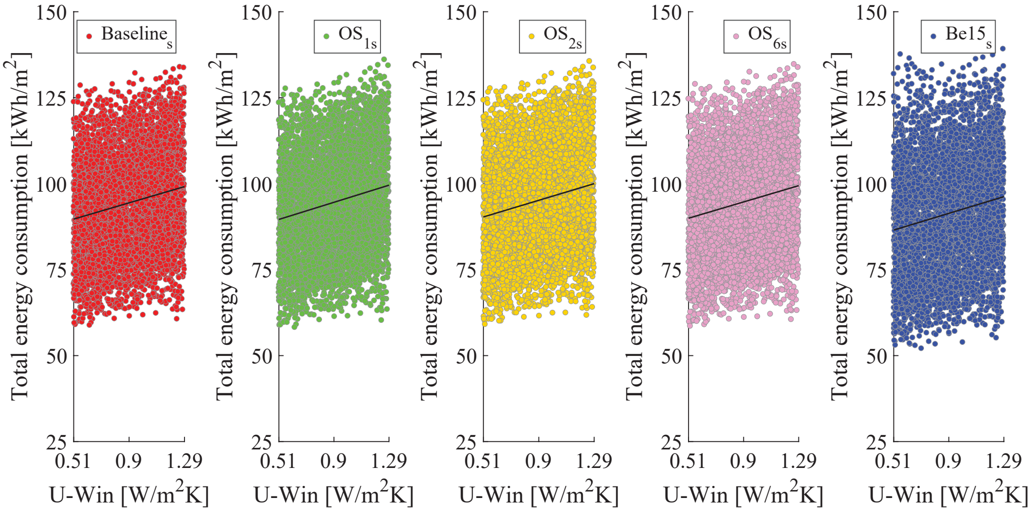



***Figure I.11.*** Relation between U-value of the window and the Total energy consumption for 5000 simulation with static facade.

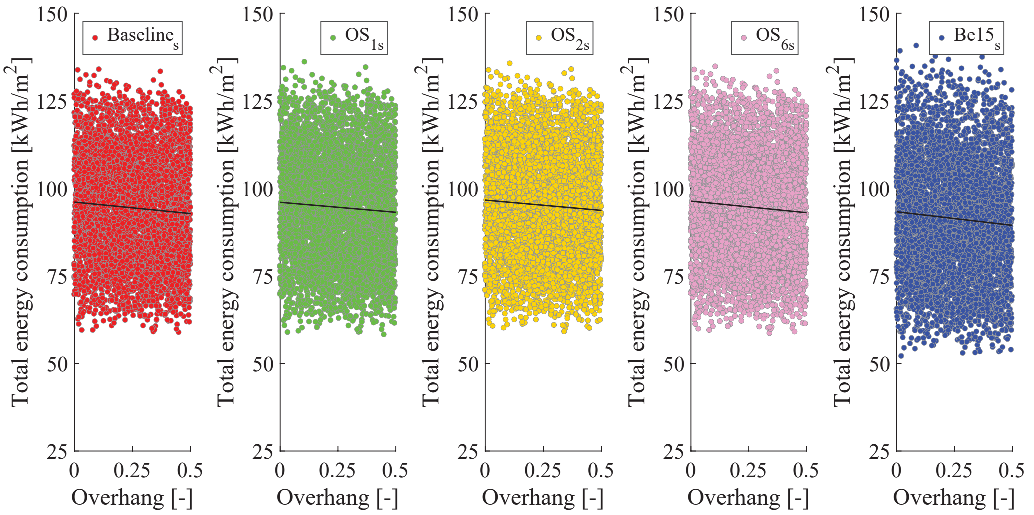



***Figure I.12.*** Relation between Overhang towards south and the Total energy consumption for 5000 simulation with static facade.

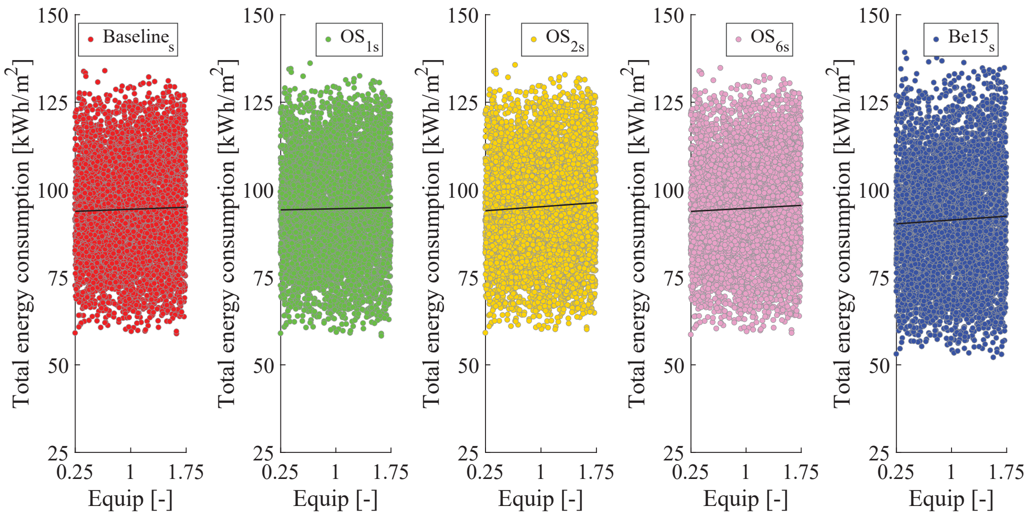



***Figure I.13.*** Relation between equipment and the Total energy consumption for 5000 simulation with static facade.

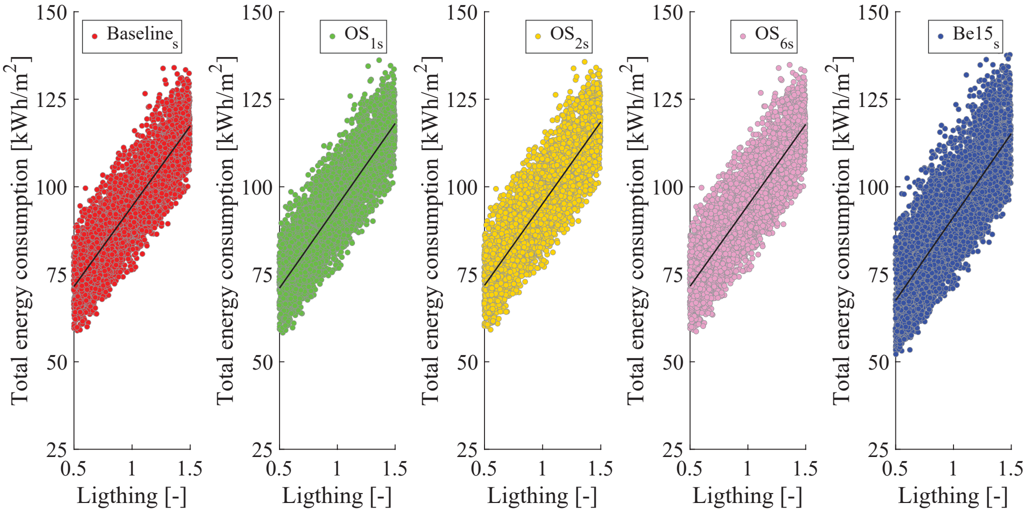



***Figure I.14.*** Relation between lighting and the Total energy consumption for 5000 simulation with static facade.

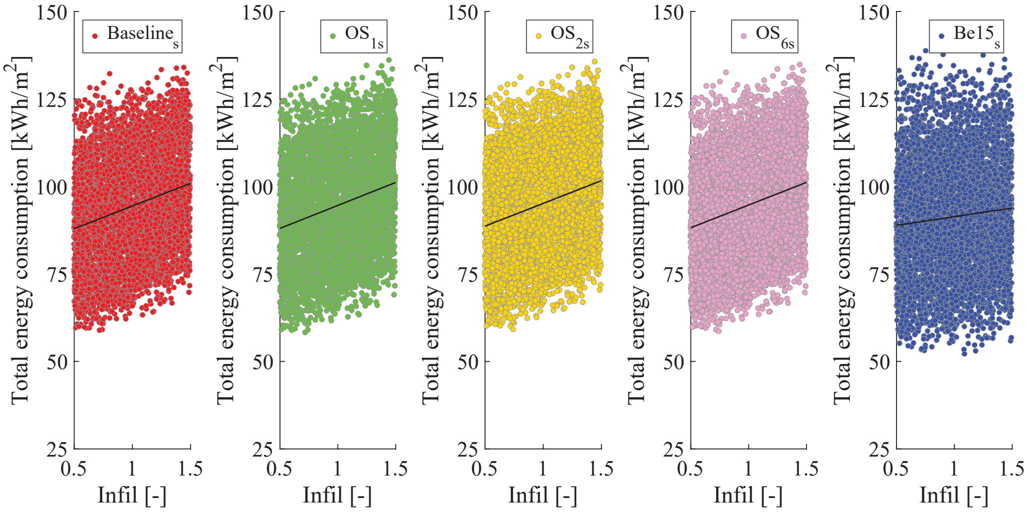



***Figure I.15.*** Relation between infiltration and the Total energy consumption for 5000 simulation with static facade.

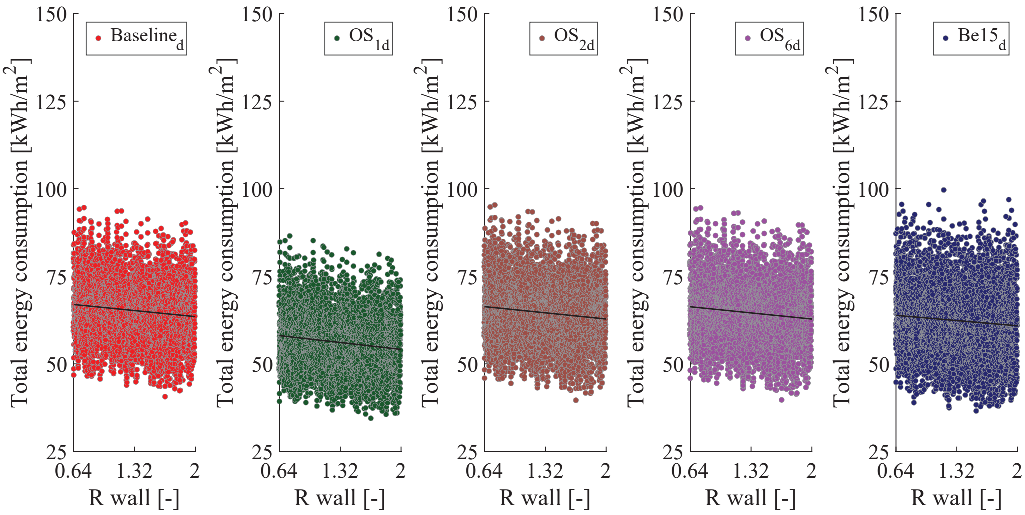



***Figure I.16.*** Relation between resistance of the wall and the Total energy consumption for 5000 simulation with dynamic facade.

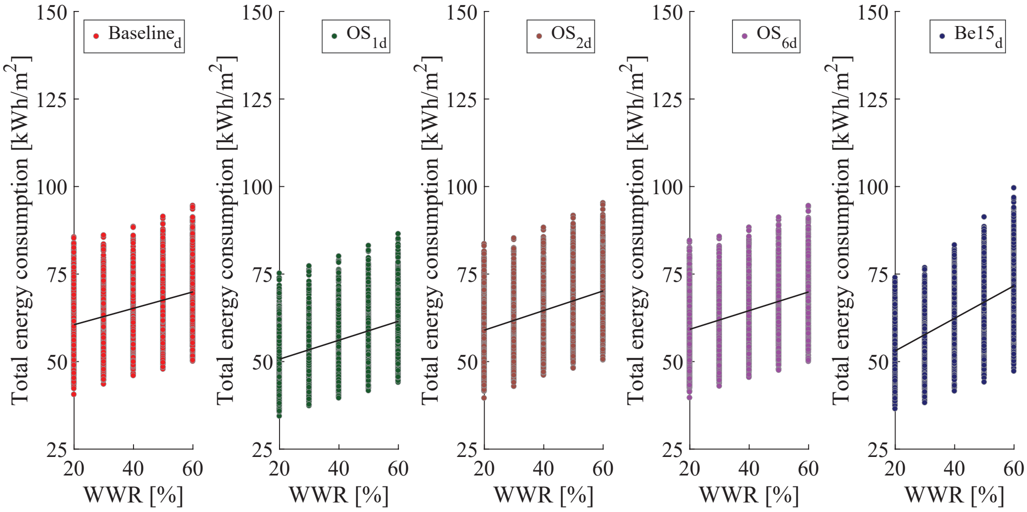



***Figure I.17.*** Relation between WWR and the Total energy consumption for 5000 simulation with dynamic facade.

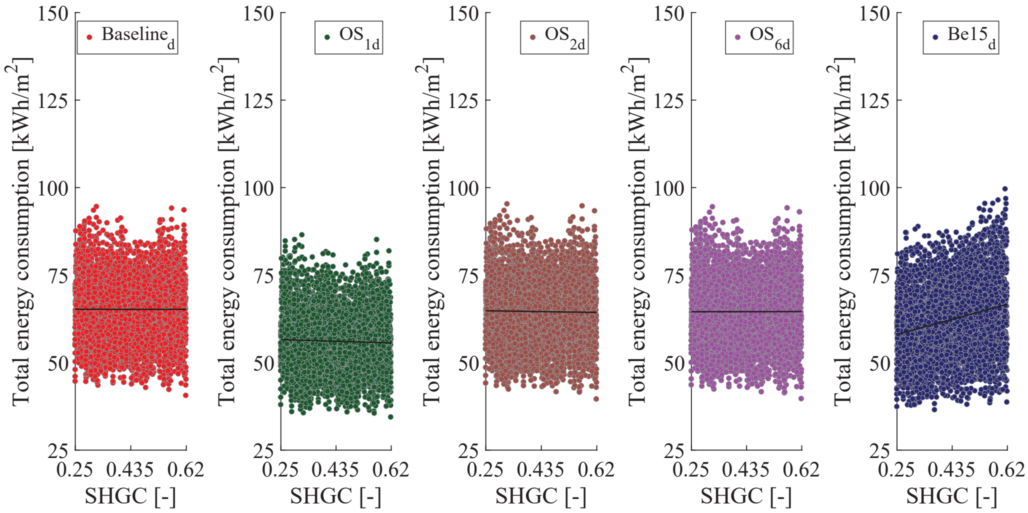



***Figure I.18.*** Relation between SHGC and the Total energy consumption for 5000 simulation with dynamic facade.

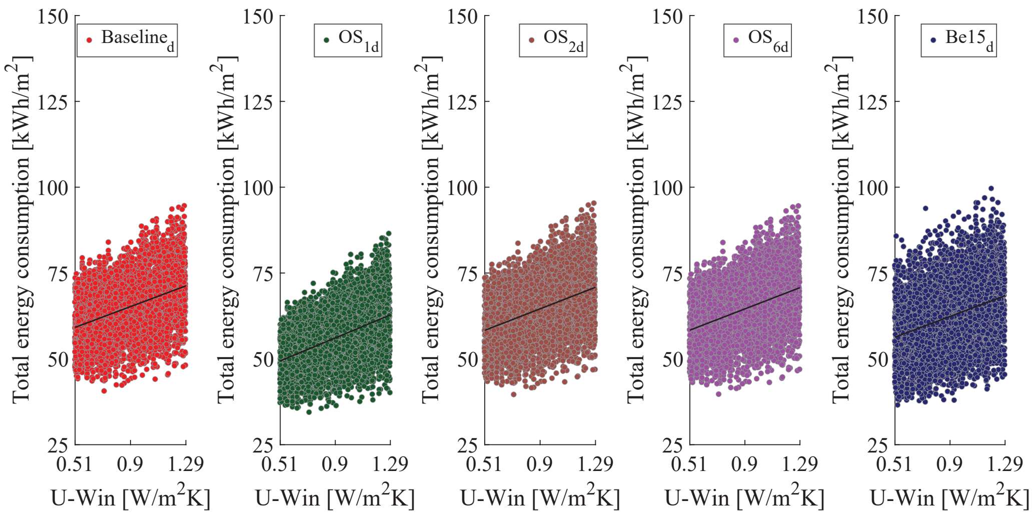



***Figure I.19.*** Relation between U-value of the window and the Total energy consumption for 5000 simulation with dynamic facade.

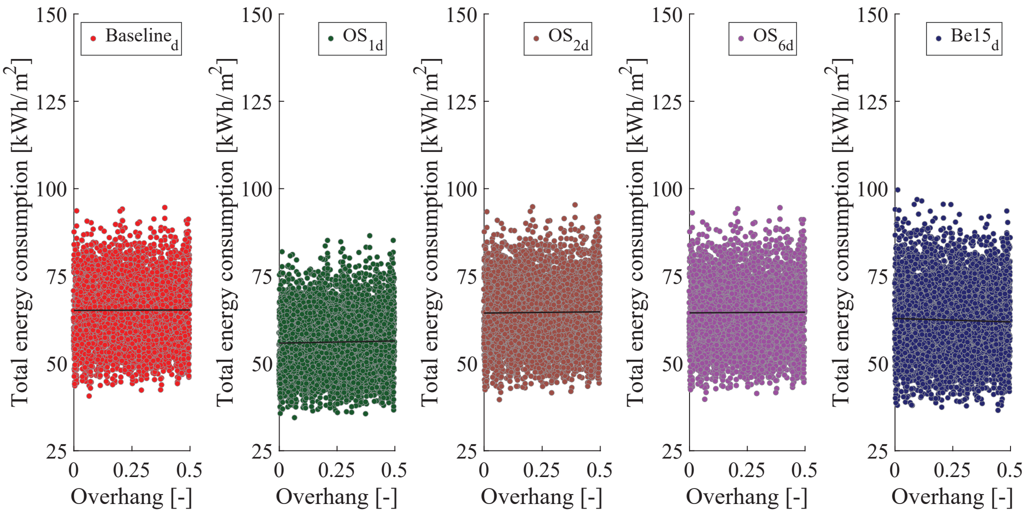



***Figure I.20.*** Relation between Overhang towards south and the Total energy consumption for 5000 simulation with dynamic facade.

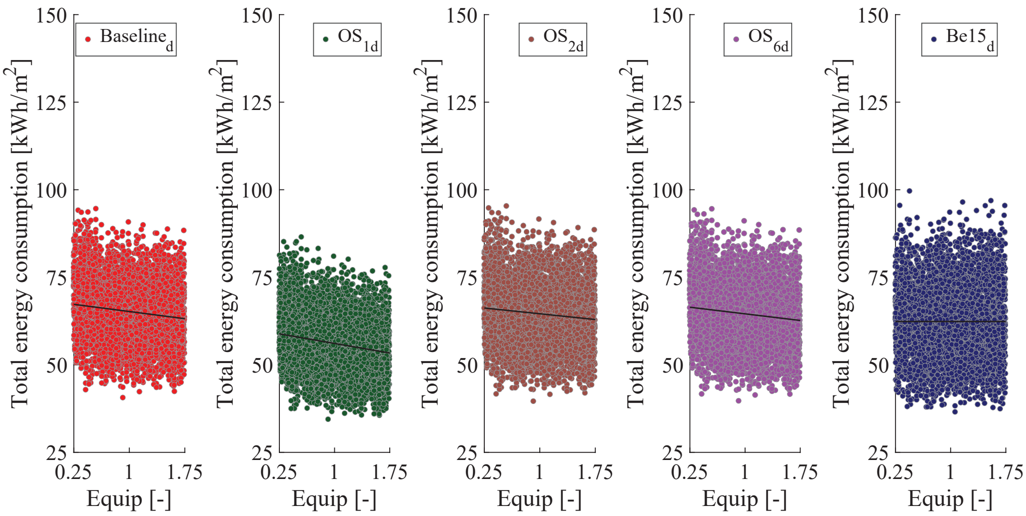



***Figure I.21.*** Relation between equipment and the Total energy consumption for 5000 simulation with dynamic facade.

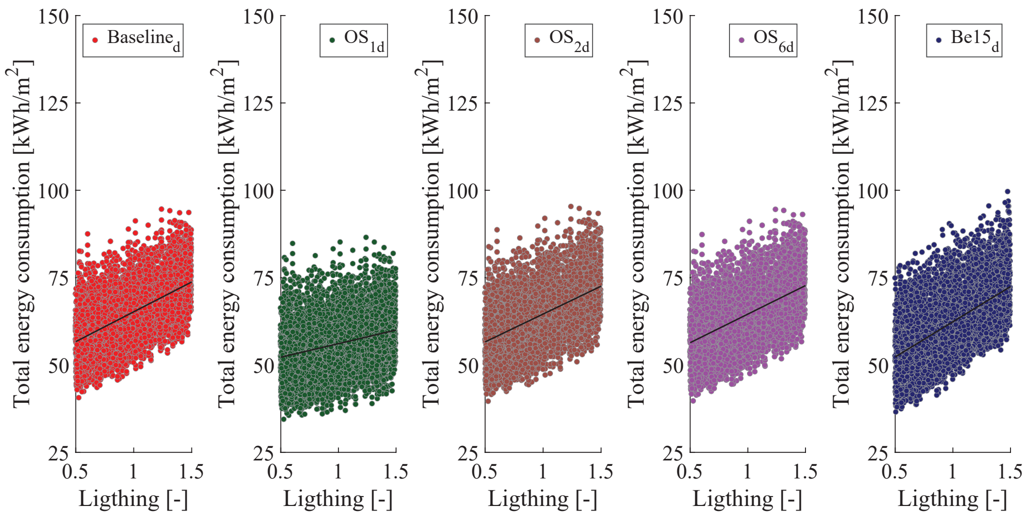



***Figure I.22.*** Relation between lighting and the Total energy consumption for 5000 simulation with dynamic facade.

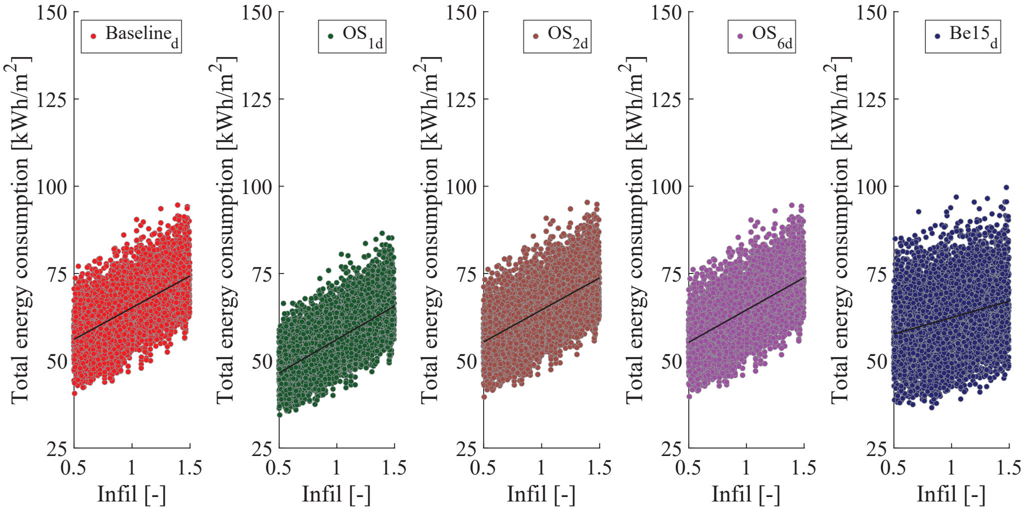



***Figure I.23.*** Relation between infiltration and the Total energy consumption for 5000 simulation with dynamic facade.

| | | R wall | WWR | SHGC | U-Win | OH | Equip | Light | Infil |
|---|---|---|---|---|---|---|---|---|---|
| Total energy consumption | Baseline$_s$ | -0,07 | 0,31 | 0,07 | 0,18 | -0,06 | 0,02 | 0,88 | 0,25 |
| | OS$_{1s}$ | -0,07 | 0,30 | 0,05 | 0,19 | -0,05 | 0,01 | 0,88 | 0,25 |
| | OS$_{2s}$ | -0,07 | 0,30 | 0,05 | 0,18 | -0,06 | 0,04 | 0,88 | 0,25 |
| | OS$_{6s}$ | -0,07 | 0,31 | 0,07 | 0,18 | -0,06 | 0,03 | 0,88 | 0,25 |
| | Be15$_s$ | -0,06 | 0,44 | 0,24 | 0,17 | -0,07 | 0,04 | 0,82 | 0,09 |
| | Baseline$_d$ | -0,11 | 0,38 | -0,00 | 0,40 | 0,00 | -0,13 | 0,56 | 0,59 |
| | OS$_{1d}$ | -0,13 | 0,45 | -0,03 | 0,46 | 0,02 | -0,19 | 0,27 | 0,65 |
| | OS$_{2d}$ | -0,11 | 0,44 | -0,02 | 0,40 | 0,01 | -0,11 | 0,51 | 0,59 |
| | OS$_{6d}$ | -0,11 | 0,42 | 0,00 | 0,40 | 0,01 | -0,12 | 0,53 | 0,60 |
| | Be15$_d$ | -0,08 | 0,63 | 0,24 | 0,34 | -0,03 | 0,00 | 0,56 | 0,26 |

***Table I.2.*** PCC for each input for all models with static facade for heating and cooling consumption.

## I.4 Sensitivity Analysis of Total Energy Consumption

Table I.3 and I.4 contains the sensitivity analysis of the variable input parameters for the total energy consumption for both static and dynamic facade.

| | $Baseline_s$ | | $OS_{1s}$ | | $OS_{2s}$ | | $OS_{6s}$ | | $Be15_s$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] |
| Lighting | 1 | 59 | 1 | 59 | 1 | 59 | 1 | 58 | 1 | 50 |
| WWR | 2 | 8 | 2 | 8 | 2 | 8 | 2 | 8 | 2 | 14 |
| Infiltration | 3 | 7 | 3 | 7 | 3 | 7 | 3 | 8 | 5 | 5 |
| U-value window | 4 | 6 | 4 | 7 | 4 | 6 | 4 | 7 | 4 | 7 |
| Equipment | 5 | 5 | 6 | 5 | 6 | 5 | 6 | 5 | 6 | 5 |
| Resistance wall | 6 | 4 | 5 | 4 | 5 | 4 | 5 | 4 | 7 | 4 |
| SHGC | 7 | 4 | 8 | 4 | 8 | 4 | 7 | 4 | 3 | 9 |
| Overhang south | 8 | 4 | 7 | 4 | 7 | 4 | 8 | 4 | 8 | 4 |
| Dummy | 9 | 2 | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 3 |

***Table I.3.*** Sensitivity analysis for the total energy consumption for models with static facade.

| | $Baseline_d$ | | $OS_{1d}$ | | $OS_{2d}$ | | $OS_{6d}$ | | $Be15_d$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] | [Rank] | [%] |
| Infiltration | 1 | 26 | 1 | 31 | 1 | 27 | 1 | 27 | 4 | 10 |
| Lighting | 2 | 24 | 4 | 12 | 2 | 22 | 2 | 22 | 2 | 25 |
| WWR | 3 | 14 | 3 | 17 | 3 | 17 | 3 | 16 | 1 | 30 |
| U-value window | 4 | 14 | 2 | 18 | 4 | 15 | 4 | 14 | 3 | 12 |
| Equipment | 5 | 6 | 6 | 5 | 6 | 5 | 5 | 5 | 7 | 4 |
| Resistance wall | 6 | 5 | 5 | 6 | 5 | 5 | 6 | 5 | 6 | 5 |
| SHGC | 7 | 5 | 7 | 5 | 7 | 4 | 7 | 5 | 5 | 10 |
| Overhang south | 8 | 3 | 8 | 3 | 8 | 3 | 8 | 3 | 9 | 2 |
| Dummy | 9 | 3 | 9 | 3 | 9 | 3 | 9 | 2 | 8 | 3 |

***Table I.4.*** Sensitivity analysis for the total energy consumption for models with dynamic facade.

The two tables I.3 and I.4 reveal that only minor changes to the ranking of the inputs occur with the advanced BEM tool. When it occurs the difference is very small, often lower than 1 %. They also reveal that the ranking of inputs for Be15, either for static or dynamic facade, is insufficient compared to the baseline models. Also the only occurrence of the dummy variable being ranked higher than an input parameter takes place for $Be15_d$ and shown in table I.4.

## I.5 Be15 Guide

If it is chosen to use Be15 in the early design phase, even though it is advised against, this sections provides some guidance to correct the calculations. The energy demand for both heating and cooling, calculated by Be15, can be corrected based on the values shown in figure I.24 for static facade buildings and in figure I.25 for dynamic facade buildings. This must be used with caution as these corrections are obtained base on a single case building. Furthermore the corrections does not change the tendencies nor the sensitivity of the inputs.
Different amount of data has been used to create the boxplots in figure I.24 and figure I.25. The amount of data used is shown in appendix I.5. The outer edges of the bins have low amounts of data points compared to the middle and should be used with more caution than the rest.

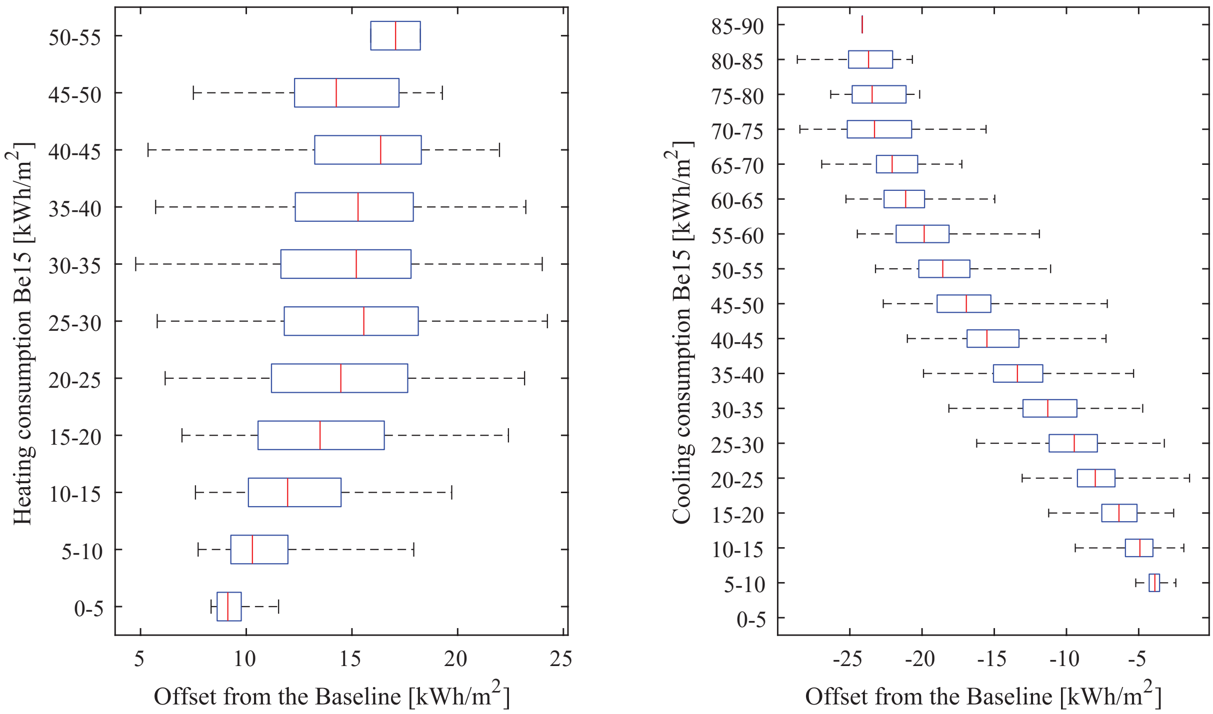



***Figure I.24.*** Be15 offset compared to the Baseline model, for the static facade models.

If Be15, with static facade, is used to obtain a result of e.g 22 kWh/m$^2$ heating consumption and 44 kWh/m$^2$ cooling consumption, the figure can be used to correct it to approximately 36 kWh/m$^2$ heating and 29 kWh/m$^2$ cooling.

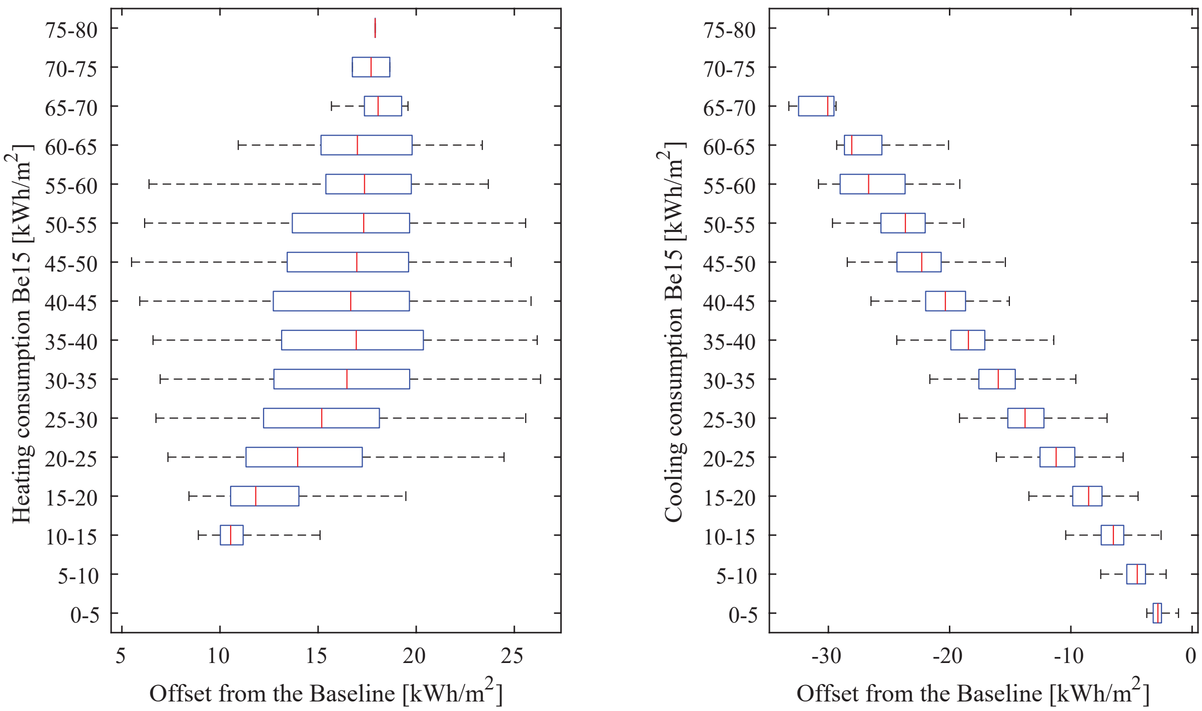



***Figure I.25.*** Be15 offset compared to the Baseline model, for the dynamic facade models.

The amount of data points used to create the box plots in figure I.24 are shown in table I.5.

| Spans [kWh/m$^2$] | Heating [qty.] | Cooling [qty.] |
|---|---|---|
| 0-5 | 0 | 0 |
| 5-10 | 14 | 55 |
| 10-15 | 197 | 339 |
| 15-20 | 732 | 634 |
| 20-25 | 1132 | 722 |
| 25-30 | 1114 | 762 |
| 30-35 | 902 | 630 |
| 35-40 | 508 | 509 |
| 40-45 | 254 | 404 |
| 45-50 | 106 | 286 |
| 50-55 | 39 | 257 |
| 55-60 | 2 | 171 |
| 60-65 | 0 | 106 |
| 65-70 | 0 | 69 |
| 70-75 | 0 | 30 |
| 75-80 | 0 | 15 |
| 80-85 | 0 | 10 |
| 85-90 | 0 | 1 |

***Table I.5.*** The amount of data points used to create the box plots in figure I.24 for Be15 with static facade.

The amount of data points used to create the box plots in figure I.25 are shown in table I.6.

| Spans [kWh/m$^2$] | Heating [qty.] | Cooling [qty.] |
|---|---|---|
| 0-5 | 0 | 114 |
| 5-10 | 0 | 729 |
| 10-15 | 37 | 1033 |
| 15-20 | 288 | 893 |
| 20-25 | 725 | 677 |
| 25-30 | 1001 | 508 |
| 30-35 | 1100 | 388 |
| 35-40 | 824 | 254 |
| 40-45 | 517 | 199 |
| 45-50 | 285 | 103 |
| 50-55 | 134 | 70 |
| 55-60 | 55 | 20 |
| 60-65 | 25 | 9 |
| 65-70 | 6 | 3 |
| 70-75 | 2 | 0 |
| 75-80 | 1 | 0 |

***Table I.6.*** The amount of data points used to create the box plots in figure I.25 for Be15 with dynamic facade.