Aalborg University Denmark

Department of Building Energy Design

MSc Thesis

Resilient Cooling-Case Study of a Residential Building in Ry

Supervisors:

Per Kvols Heiselberg

Chen Zhang

External Censor:

Alice Andersen

Authors:

Attila Kopányi

Lajos Ádám Pallagi

Karolina Poczobutt

Aalborg, January 10, 2020

AALBORG UNIVERSITET
STUDENTERRAPPORT

Master Thesis

Thomas Manns Vej 23

DK-9220 Aalborg Øst

Tlf. 99 40 93 09

Title: Resilient Cooling-Case Study of a Residential Building in Ry (Denmark)

Semester: Fourth Semester

Semester Theme: Master Thesis

Project Period: September 2019-January 2020

ECTS: 30

Supervisor: Per Kvols Heiselberg, Chen Zhang **External Examiner:** Alice Andersen

Project Group: 1.307-2

Atilla Kopányi

Lajos Pallagi

Karolina Poczobutt

Pages: 68

Appendix: 30

Summary:

This master thesis is a case study of a newly built single-family house located in Ry (Denmark). The aim is to evaluate technologies' resilience to overheating. The technologies include natural ventilation, phase change materials and shading. The investigation is performed using adaptive comfort model and future weather data up to the year 2100. The following documents were used as the research basis: The Danish Building Regulations 2018 and DS/EN 15251. DesignBuilder was used for building modelling. Meteonorm and CCWorldWeatherGen were used for the assessment of future extreme weather events. The resilience of the technologies was evaluated using POR and hours above 27 °C and 28 °C. Additionally the robustness of technologies against occupancy, climate change and the technology-related uncertainties was investigated. The results of the investigation revealed that all the technologies show very low POR values, below 5%. PCM and natural ventilation were not robust against climate change. When it comes to occupant density, the combination of technologies showed the highest robustness. All the technologies were robust against the technology, weather and occupational time related uncertainties.

By signing this document, each member of the group confirms that everyone has participated in the project work and that everyone is collectively responsible for the content of this report.

Preface

This master thesis was written during the final semester of Building Energy Design education at Aalborg University.

The report is the case study of a residential building located in Ry (Denmark) and the focus is set on resiliency of cooling technologies to overheating and their potential for thermal comfort improvement.

Further areas of investigation include:

- Passive and natural cooling techniques
- Local sensitivity analysis
- Uncertainty analysis
- Future weather data, weather generators and weather data morphing
- Robustness
- Key performance indicators
- Adaptive comfort model

The thesis was written in collaboration with supervisors from Aalborg University, Per Kvols Heiselberg and Chen Zhang, to whom we would like to express our gratitude and thankfulness for their guidance throughout the semester and for constructive criticism.

Furthermore, we would like to thank Anais Machard for providing us with detailed information on future weather data analysis and for introducing us to new tools, such as CCWorldWeatherGen.

We believe that your time and dedication were indispensable for us during the writing process.

Attila Kopányi, Karolina Poczobutt, Lajos Ádám Pallagi

Aalborg, 10.01.2020

List of Contents

List of Figures

List of Tables

1. Introduction

Increased temperatures during cooling season, oversimplified design process and old-fashioned high-performance building standards are the main reasons for the energy performance gap in newly erected buildings, and for their poor thermal comfort (Kolokotroni, Heiselberg 2015). In terms of comfort, overheating is considered to be the greatest issue, especially for residential buildings with 24-hour occupancy. Cooling is an increasing challenge in the building sector and for that reason, alternative solutions should be evaluated. When considering the northern European climate, natural and passive methods present a huge potential for effective cooling with zero or minimal energy consumption (Oropeza-Perez, Østergaard 2018).

In this paper, resilience of different natural and passive cooling technologies will be evaluated, and assessment of their thermal comfort improvement potential will be performed using an adaptive comfort model, according to DS/EN 15251.

1.1 Research questions

Problem formulation:

"How resilient are different cooling technologies and their combinations to increased cooling loads?"

Secondary questions:

"What are the most influential parameters for each of the cooling technology?"

"How will the future climate changes and increased occupant loads affect the performance of cooling technologies and their resilience to overheating?"

1.2 Methodology

The case house and cooling technologies were modelled using DesignBuilder software version 6.1.3. The important and uncertain parameters were evaluated with statistical methods, including local sensitivity analysis (LSA) and uncertainty analysis (UA). The future weather data was obtained and compared using Meteonorm weather generator, CCWorldWeatherGen and the DMI database. The results of the research will be presented quantitatively with key performance indicators, being POR (percentage outside range) and hours above limit temperatures of BR. Additionally, robustness against technology-related uncertainties, climate change and occupant load will be examined and shown on graphs.

1.3 Delimitation

This report is the case study of a single-family house located in Ry (Denmark), so no other buildings were considered in this research. Even though several passive and natural cooling technologies will be mentioned at the beginning of this paper, only the ones applicable in the local climate will be examined further. The aim of the research is to work with the current building design and avoid changing parameters, that are the integral part of the house. Therefore, only natural ventilation, phase change materials and shading were investigated. Each of the technologies and their combinations were examined only in terms of adaptive thermal comfort.

1.4 Executive summary

Chapter 2: Introduces the subject of resilience, its definition and how it applies to cooling of buildings, based on the IEA EBC Annex 80. Moreover, the chapter briefly describes existing natural and passive cooling technologies and their applicability in Danish climate. More detailed description is provided for natural ventilation, shading and phase change materials. In the last part of this chapter, key performance indicators are described, to provide the reader with an overview on how the cooling methods can be evaluated and compared in terms of resilience.

Chapter 3: Provides the description of the examined building case- building construction, location, systems, occupancy profiles, control strategies, existing cooling solutions.

Chapter 4: Describes the DesignBuilder (DB) model and how it was validated based on the monitored data for the summer period and the measured weather data, used for model creation.

Chapter 5: Contains an evaluation of future extreme weather events until year 2100. In this chapter, different weather data sources are compared-Danish Meteorological Institute database, Meteonorm and CCWorldWeatherGen.

Chapter 6: Explains the calculation method behind local sensitivity analysis of three technologies. Each technology is examined separately and as a result, the most influential parameters for each technology are determined and chosen for uncertainty analysis. Theoretical background for sensitivity analysis is also provided in this chapter.

Chapter 7: Introduces the theory behind uncertainty analysis and robustness based on the adaptive comfort model. Additionally, the models used for the examination of the technologies are described in this chapter. Furthermore, detailed description of the design variables is provided.

Chapter 8: Shows the results of uncertainty analysis and robustness for three technologies, separately and combined for three different years-2020, 2060 and 2100. The results of the UA are given in POR (based on DS/EN 15251) and hours above temperature limits stated by BR18. Robustness is evaluated against uncertainties related to technology, future climate change and increased occupant density load.

Chapter 9: Compares the resilience of three technologies and their combination in terms of POR, hours above 27℃ and 28℃ and robustness.

Chapter 10: Summarizes the results of the report and conclusions obtained by the authors. Additionally, ideas for further development of the thesis are proposed.

Chapter 11: Bibliography

Chapter 12 Appendix: Contains additional theoretical information, reference graphs and tables. More detailed calculations are also included in the appendix.

2. Resilient cooling

2.1 Resilience

The concept of resilience is applicable in various areas of building industry. In general, the definition of resilience focuses on the response and recovery of any system after being exposed to a disturbance (Chi-hsiang Wang, Lam Pham).

This paper concentrates on resilience of the cooling systems in a building, therefore a more precise definition had to be used. According to IEA EBC Annex 80, resilient cooling can be characterized as:

- A low energy, affordable solution, which is able to endure changes in the global and local climates, especially those caused by increasing outside temperatures, increasing severity and frequency of extreme events, changing internal loads and changing occupancy profiles (EBC Executive Committee Support Services Unit 2019).

Additionally, resilience can be characterized by four key parameters, also known as 4R-s. According to the National Institute of Building Sciences (National Institute of Building Sciences 2018), those are:

- **Robustness**-the ability to withstand critical events.
- **Resourcefulness**-the ability to foresee, be prepared for and respond to critical future events.
- **Rapid recovery**-the ability to come back to an original state quickly and efficiently after a disruption occurred.
- **Redundancy**-having back-up resources, in case the original solution is not effective/fails to perform.

In this report, three out of the four key parameters will be addressed:

- **Robustness** will be described by examining system behavior in terms of climate change and occupancy.
- **Resourcefulness** will be addressed by inspecting future weather changes, including frequency and duration of extreme climatic events until the year 2100
- **Redundancy** will be evaluated by inspecting the behaviors of cooling systems separately and in combined modes.

Due to the limited timeframe and unavailable resources, rapid recovery will not be addressed in this project report.

2.2 Cooling technologies

In general, cooling technologies can be divided into three main categories being active, passive and natural solutions. Among natural technologies, further division can be performed depending on which natural heat sink is used - outdoor air, ground or sky (for the exact division and heat sink definition, see Appendix 12.1). For the active technologies, the heat sink is created artificially. As part of the limitation and in order to investigate low-energy solutions, only passive and natural strategies will be examined in this report.

2.3 Passive cooling strategies

Passive cooling refers to technologies or integral building features made to prevent heat gain (Liu 2018).

The most common passive cooling strategies are gathered in Table 1.

Passive cooling strategies/technologies	
Shading	Internal
	External
	Advanced
Radiant heat barriers	Green roof
	New roof coating (for example vinyl)
Phase change materials (PCM)	
Advanced glazing	
Thermal mass	

Table 1. Passive cooling technologies/strategies division (Oropeza-Perez, Østergaard 2018).

2.4 Natural cooling strategies

Natural cooling is a method of decreasing cooling loads through removing excessive heat by natural measures. The natural techniques should be applied if there still is a cooling demand after using passive strategies (Liu 2018).

As for the natural cooling strategies, the division is more complex than in the passive methods case. In order to be consistent with Table 34 from Appendix 12.1, the strategies will be divided according to different natural heat sinks, see Table 2. It must be noted that only the most popular natural cooling techniques are included in the table and there are plenty of other methods available on the building market.

Heat sink	Cooling technology
Outdoor air	Controlled natural ventilation during day
	Controlled natural ventilation during night
	Direct evaporative cooling (cooling tower)
Ground	Direct ground cooling
	Indirect ground cooling (air to earth heat ex-changer)
	Water convective panels
	Water radiation panels
Sky	Direct radiant cooling
	Air based flat plate coolers
	Water based flat plate coolers

Table 2. Natural cooling strategies division based on the natural heat sink (Oropeza-Perez, Østergaard 2018).

2.5 Choice of the cooling strategies

The main criteria for choosing applicable cooling strategies for the examined building are the following:

- No change to the core design or structure of the house should be applied by incorporating the cooling technology.
- The technology should be applicable in residential buildings located in Danish climate.
- Abstract solutions, that are not in accordance with the local building practice should not be chosen for this project.

Based on the above-mentioned criteria, the chosen technologies are:

- External shading
- Natural ventilation
- Phase change materials

The analysis of the solution applicability and the definitions of the three chosen solutions can be found in Appendix 12.1 (Givoni 2011).

Note: External shading and natural ventilation were already applied to the case building (see Chapter 3), so they should be seen as the integral parts of the house. Phase change materials are not considered to be a major design variation, as the core structure of the building is not changed.

In the next part of the report, ways of evaluating resilience of cooling technologies will be described.

2.6 Key performance indicators

In order to evaluate and compare the effectiveness of different cooling solutions, key performance indicators (KPI-s) will be used. IEA EBC Annex 62 defines KPI-s as "quantifiable measures used to evaluate design goals and to provide means for the measurement and monitoring of the progress of the design towards those goals" (O'Donnavan, O'Sullivan et al. 2018).

For the project case, the authors of the report decided to work solely with thermal comfort, thus indicators, that would reflect the frequency of overheating and its severity, were selected. Another decisive factor for the selection of KPI-s was to have indicators, that would be applicable to each of the three examined technologies - natural ventilation, shading and phase change materials. The chosen indicators are described in Table 3.

Indicator	Definition	Equation (if any)
Percentage Outside the Range (POR), %	"POR calculates the percentage of occupied hours, when the PMV or the operative temperature is outside a specified range" (O'Donnavan, O'Sullivan et al. 2018)	See equation 1
Number of hours above 27°C and 28°C for a critical room, hrs	"For buildings, where windows can be opened to create ventilation, the provision is usually observed when, by calculation, it can be documented that the indoor temperature exceeds 27 °C for no more than 100 hours per year and for no more than 25 hours per year, the temperature exceeds 28 °C" (Ministry of Transport, Building and Housing 2017)	-
Robustness, %	The probability, based on an uncertainty analysis, that the results of the deterministic analysis are achieved (Parys, Breesch et al. 2012)	See equation 2

Table 3. Key performance indicators for resilience evaluation of cooling technologies

The POR is determined according to eq. 1 (O'Donnavan, O'Sullivan et al. 2018).

$$POR = \frac{\sum_{i=1}^{Oh}(wf_i \cdot h_i)}{\sum_{i=1}^{Oh} h_i} \qquad 1$$

where:

wf: the weighting factor, -

The robustness equals the rank of the deterministic analysis results compared to the uncertainty analysis results. This rank is determined according to eq. 2 (EDUCBA 2019). During the project, the built-in PERCENTILE.RANK excel function was used.

$$rank = \frac{M}{Y} \qquad 2$$

where:

M: number of the uncertainty analysis results at or below the deterministic analysis results

Y: total number of uncertainty analysis results, which equals the number of runs

One of the chosen KPI-s was proposed by standard DS/EN 15251 2007 and can be used for a long-term estimation of buildings' thermal comfort conditions. The indicator is called Percentage Outside the Range, also known as POR. The second KPI was taken from The Danish Building Regulations 2018 and it is the number of hours above limit temperatures for a critical room. The last indicator is the robustness, which in this report will apply to climate changes, occupancy schedules and technologies themselves.

All the KPI-s will be calculated based on the adaptive comfort model and the aimed comfort category will be category II from DS/EN 15251 (see Appendix 12.1).

It must be noted that the final choice of KPI-s was determined by the limited capabilities of the Design-Builder software, since it only provided hours outside the ranges of the adaptive criteria in DS/EN 15251.

3. Bolig 2020

3.1 Building description

The examined building is a single-level family house located in Ry (Denmark), completed in 2017. The house is part of a project, which aims to create a new housing generation, that would fulfill the upcoming 2020 requirements, and at the same time solve problems associated with standard requirements for nearly zero energy buildings (nZEB) (IEN Consultants 2016).

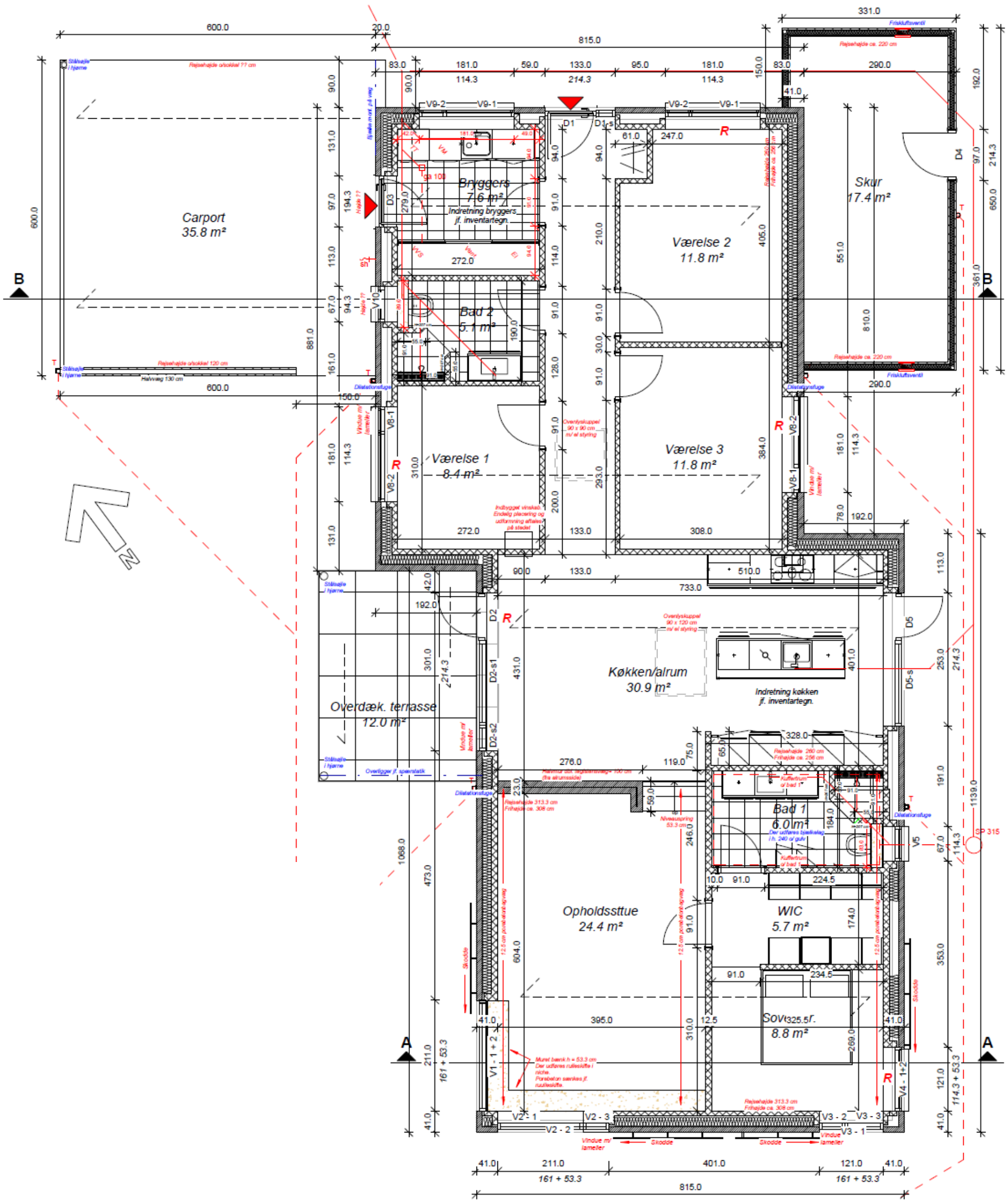


Figure 1. House plan (skur-shed, værelse-bedroom, bryggers-utility room, bad-bathroom, køkken-kitchen, opholdsstue-living room, WIC-walk-in closet) (Lasse Larsen Byggefirma 2017).

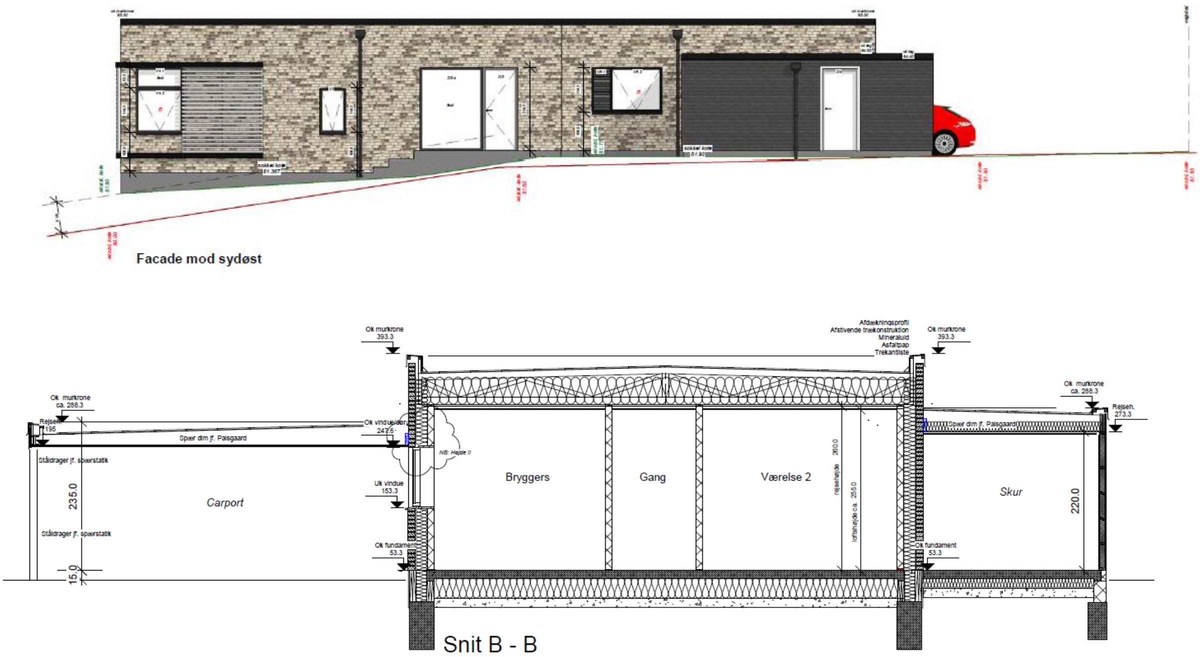


Figure 2. South-east building elevation and section B-B (Lasse Larsen Byggefirma 2017).

The living area adds up to 160 m^2 and consists of 3 bedrooms, 2 bathrooms, a walk-in closet, a utility room, living room, kitchen and a corridor. Additionally, there is a carport and a shed, which together add up to 55.3 m^2 (see Figure 1).

The structure is made of heavyweight construction with 425 mm concrete-brick external walls and concrete partition walls. More detailed description with the element U-values can be found in Appendix 12.2. The building envelope was designed according to the maximum allowed heat requirement stated for building class 2020 (3.7 W/m^2 for one-story building).

The house was also blower-door tested. The results can be found in Appendix 12.2.

3.2 Thermal zone division

In the original model, the living room and the kitchen were merged into one zone. It was decided to keep it that way. All the other rooms were treated as separate thermal zones, apart from the master bedroom, which was merged with the walk-in closet and the utility room merged with the technical room (see Figure 3).

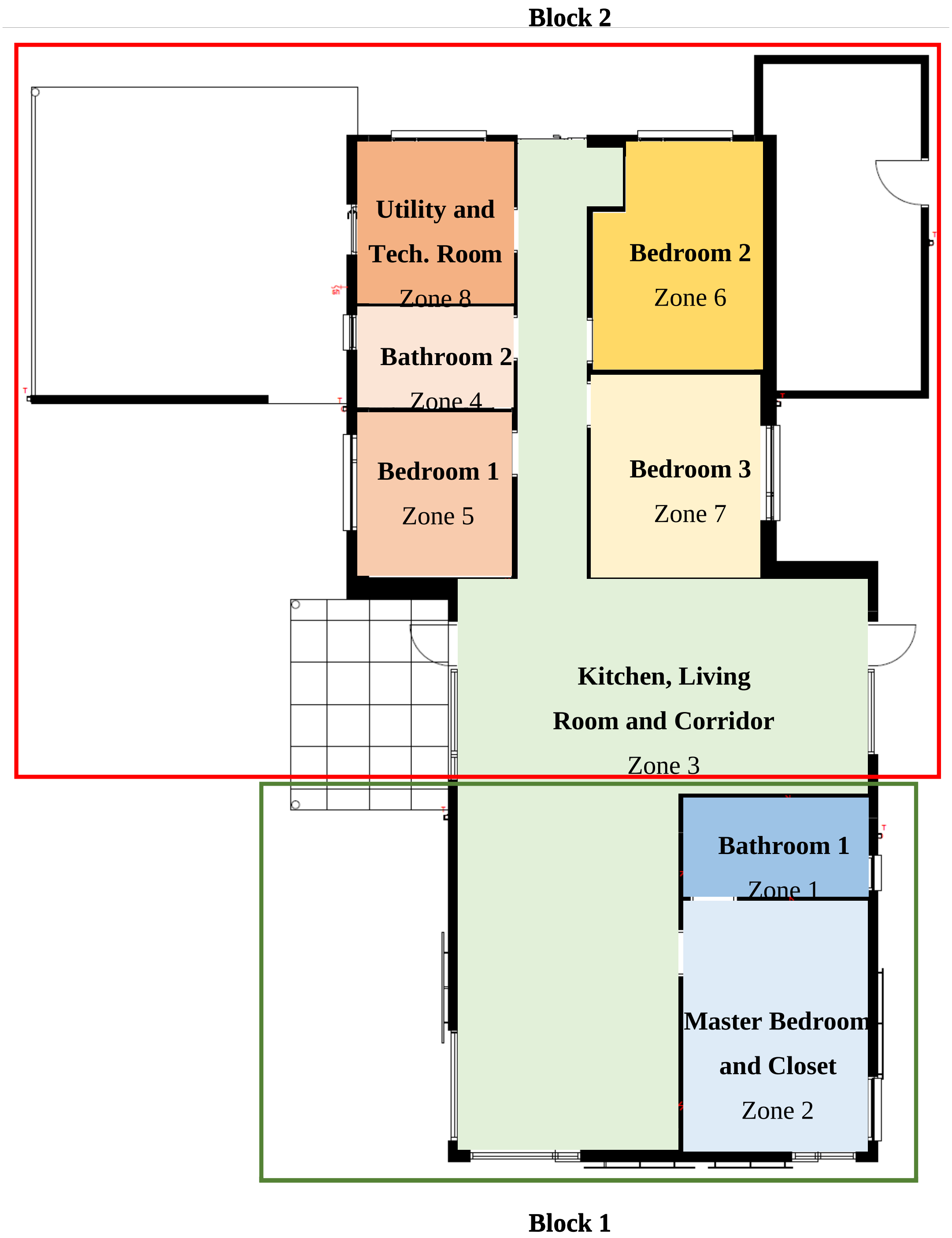


Figure 3. Thermal zone division, modelled building

3.3 Systems, control and load profiles

The systems of the examined house are summarized in Table 4. The list of sensors in each room was added in Appendix 12.2. For load profiles, see Appendix 12.3 (Zhang 2017).

System	Description	Control Strategy	Setpoint (if any)
Mechanical Ventilation	• Fresh air is controlled by the occupancy schedule. • Heat recovery of 85%. • The cooker hood has the minimum extraction of 20 l/s and the efficiency of 150 m^3/h.	• IHC (Intelligent Home Control) system from KL/Schneider. • Reduced to 50% of the min. requirement when the house is not occupied. • Possible holiday mode that switches to the normal vent. performance 24 hours before the users arrive home. • When the house is occupied, the ventilation system is based on user behavior, CO_2 content and relative humidity. • Stops working when the windows and doors are open. • Priority of extraction given in the kitchen. • The inlet fan is pressure controlled (the speed is lowered at lower demand). The outlet fan is controlled based on the moisture content.	• 800 ppm (or open dampers at 900 ppm and closed dampers at 700 ppm) • Open dampers 70% RH and closed dampers 50% RH • Bathroom: 60% open dampers and 50% closed dampers • Temperature setpoint of 20-25 degrees Celsius, when the house is not occupied.
Natural Ventilation	• Activated when there is no need for heat recovery. • Activated only when there is no danger of nuisance. • Windows are equipped with grids. The shutter size is 5% of the space window area, where the area of the shutters is measured as a free-flow area. • 2 skylights placed in the kitchen and the living room. The skylight should have at least a free opening area corresponding to the size of the ventilation shutter, which it serves.	• Controlled based on CO_2, RH, temperature and occupancy.	• Same as for the mechanical ventilation.
Shading	• External solar shading is installed in the living room and bedroom. • Protection of the spaces from solar radiation without outside view reduction. • No external shading where rescue openings are present.	• Temperature and occupancy regulated.	• Temperature setpoint of 20-25 degrees of Celsius

Table 4 .Building systems, Bolig 2020 (Kristensen, 2017)

4. Validation of the DesignBuilder model

The base thermal model of the project building was originally created as part of another project at AAU (Loukou, Heiselberg et al. 2019). This model was validated for electricity and heating use only. However, in order to assess the project building's thermal model performance during summer, it was important to validate the model's thermal performance as well. This was done using measured indoor environment and system data. During the validation we followed the approach of Strachan et. al. (2016) to eliminate the effect of occupants as much as possible, as it is challenging to predict their behavior. Therefore, the focus was on the two weeks long period between 10/07/2018 and 24/07/2018 when the occupants were on holidays.

In order to model the loads during this period precisely, some inputs of the model were adjusted:

- The external solar shading, and the automatic natural ventilation was not modelled, since according to the logged system data, these systems started to work only at the end of October 2018.

The measured and simulated operative temperatures are depicted on Figure 4 and Figure 5 for the selected holiday period. The three important rooms in the building are the bedroom, living room and kitchen. The living room and the kitchen area are connected; therefore, these were modelled as one thermal zone.

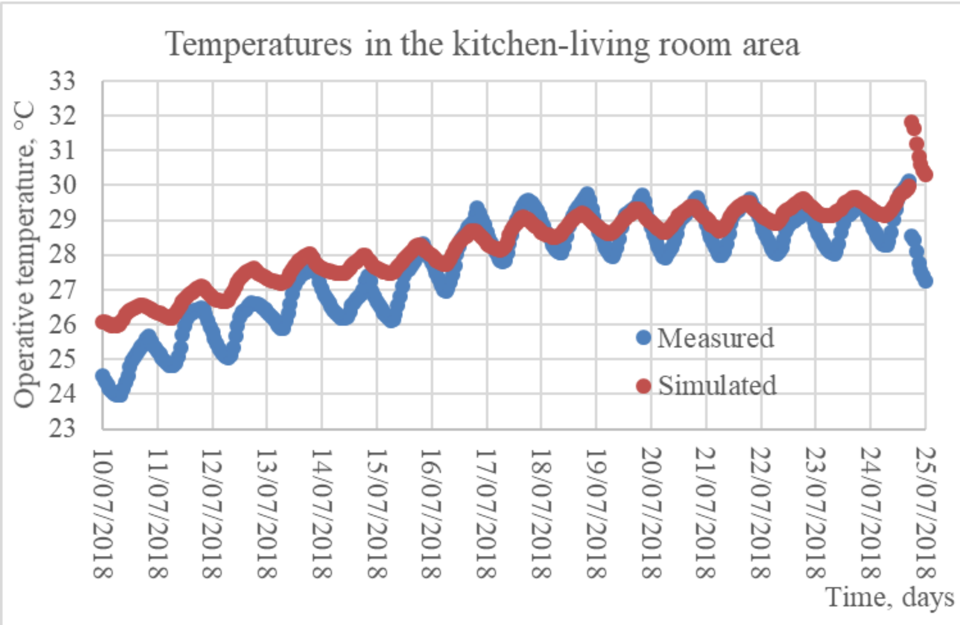


Figure 4. Comparison of temperature values in the living room - kitchen area. In the thermal model, this area was modeled as one thermal zone. Separate measured data was available for kitchen and living room. From this, the average was taken and weighted according to the corresponding zone volumes.

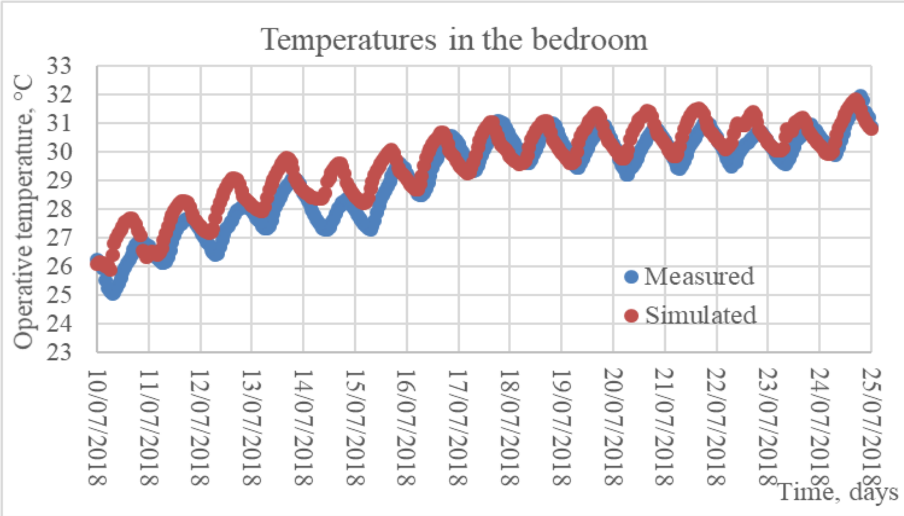


Figure 5. Comparison of the measured and simulated temperatures in the bedroom.

The Spearman's correlation coefficient and the average absolute difference of the measured and simulated operative temperatures for the selected two weeks long period are shown in Table 5 (for the detailed calculation, see Appendix 12.4).

KPI	Bedroom	Merged kitchen and living room
Spearman's correlation coefficient, -	0.89	0.91
Average of the absolute difference, K	0.62	0.68

Table 5. Quantified validation results.

According to the results, the shape of the temperature curves shows an acceptable fit in the bedroom, but the daily amplitude is smaller in the modeled kitchen and living room area, compared to the measured values. This could be caused by the fact that this area was modeled together with the corridor, thus adding additional thermal mass to the zone.

The achieved correlation coefficient and average absolute difference values are appropriate according the literature (STRACHAN, 2016). Therefore, the thermal model of the building was deemed to be suitable for future use in its current stage after validation.

5. Future weather data used in the project

In this project, future weather data was used to determine the robustness of the examined cooling technologies against changes in climate and to examine whether these technologies can provide comfort in the future as well.

The studies of the Intergovernmental Panel for Climate Change (IPCC) provide the basis to produce future weather datasets in most of the applications. The 3rd, 4th and 5th IPCC Assessment Report is relevant in this context – these were released in 2001, 2007 and 2014, respectively (Core Writing Team, Pachauri et al. 2007, Core Writing Team, Pachauri et al. 2014, Core Writing Team, Watson 2001). The IPCC reports provide optimistic, middle and pessimistic predictions for changes in the weather, based on different socio-economic scenarios. The following scenarios are usually used by applications and researchers:

- The optimistic scenario is called B2 in the 4th and RCP2.6 in the 5th IPCC report.
- The middle scenario is denoted as A1B in the 4th and as RCP4.5 in the 5th report.
- The pessimistic scenario is called A2 in the 3rd and 4th report and RCP8.5 in the 5th report.

These scenarios form the basis for global and regional climate models (Herrera, Natarajan et al. 2017). According to Herrera et al. (2017) there are two methods to produce future weather datasets used in building simulations:

- A weather generator tool will produce synthetic series of weather data based on the global and regional climate models (i.e. the Meteonorm software)
- Future weather data can be produced by morphing as well: this is a mathematical transformation of present-day weather data considering the changes in the climate models (Herrera, Natarajan et al. 2017). This method is used by the CCWorldWeatherGen tool.

For the different analyses in this project, the future weather datasets produced by the Meteonorm (version 7) software were used, that were made based on the A1B (middle) scenario. In Chapter 5.1, this data is compared to future climate predictions from the Danish Meteorological Institute. Significant differences were found especially in the number of predicted warm summer nights.

In order to check the quality of the weather data generated by Meteonorm, it was also compared to weather data produced by another tool, called CCWorldWeatherGen. It was found that both tools generate similar data when considering warm summer nights, which makes the Meteonorm data used in this project more credible.

5.1 Comparison of future weather data produced by DMI, Meteonorm and CCWorldWeatherGen

In The future climate changes in Denmark (Fremtidige klimaforandringer i Danmark) report, the DMI gives estimations for several KPI-s describing the weather in the future. Five of these KPI-s are connected to buildings' thermal performance. They are defined the following way by DMI (Olesen, Skovgaard Madsen et al. 2014):

- **Warm summer nights -** the number of summer nights in a year, where the temperature during night is over 20 degrees Celsius (days/year).
- **Heat wave days -** the number of annual nationwide heat wave days. A heat wave is defined by the mean of the highest recorded temperatures measured over three consecutive days exceeding 28 degrees Celsius. At a nationwide heat wave, at least half of the country has a heat wave (days/year).
- **Longest heat wave days -** the length of the longest heat wave averaged over a 30-year period (days).
- **Hot wave days -** the number of annual nationwide hot wave days. A hot wave is defined by the mean of the highest recorded temperatures measured over three consecutive days exceeding 25 degrees Celsius. At a nationwide hot wave, at least half of the country has a hot wave (days/year).
- **Longest hot wave days -** the length of the longest hot wave period averaged over a 30-year period (days).

The data coming from the three sources (DMI, Meteonorm, CCWorldWeatherGen) that are compared in this chapter (see Table 6) is based on different scenarios:

- DMI used the A1B scenario from the 4th IPCC report. The DMI data is given as average values for the periods of 2021-2050 and 2071-2100 (Olesen, Skovgaard Madsen et al. 2014).
- The Meteonorm 7.1 software is able to consider different scenarios from the 4th report and also to generate extremely warm years – these are defined as years that occur every ten years only. Meteonorm is able to provide predictions with a 10-year timestep, therefore the given data for the period of 2020-2050 is the average of the years of 2020, 2030, 2040 and 2050. The data given for the period of 2070-2100 is the average of 2070, 2080, 2090 and 2100.
- CCWorldWeatherGen can generate data based on the A2 (pessimistic) scenario of the 3rd IPCC report for the years of 2020, 2050 and 2080 only. Therefore, the average of 2020 and 2050 was

compared to the 2020-2050 period of the first two sources and the data for 2080 was compared to the 2070-2100 period.

There are differences in the calculation methods of Meteonorm and CCWorldWeatherGen as well:

- Meteonorm is a weather generator tool, that uses extrapolation of statistical data (see Appendix 12.5).
- CCWorldWeatherGen uses morphing of present-day weather data (see also Appendix 12.5). When producing the predicted weather data, the DRY-v2 (Danish Reference Year) weather file was used as a base.

The KPI-s defined by DMI were calculated for predicted weather data from DMI, Meteonorm and CCWorldWeatherGen and are given in Table 6. The number of warm summer nights for the different sources is compared in Figure 6, the number of hot wave days is compared in Figure 7, and the longest hot wave periods are compared in Figure 8.

KPI	DMI, A1B scenario			DRY-v2	Meteonorm, A1B scenario				Meteonorm, A2 scenario				CCWeatherGen, A2 scenario	
					Typical year		P10 warm year		Typical year		P10 warm year			
	1960-1990	2021-2050	2071-2100		2020-2050	2070-2100	2020-2050	2070-2100	2020-2050	2070-2100	2020-2050	2070-2100	2020-2050	2080
Warm summer nights	8.0	13.0	44.0	0.0	0.3	1.3	2.0	3.8	0.0	2.3	0.8	5.0	0.0	1.0
Heat wave days (days/year)	1.5	2.8	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
The longest heat wave (days)	3.2	4.2	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
Hot wave days (days/year)	5.8	8.7	13.9	0.0	1.8	4.0	1.5	6.5	3.3	8.3	3.5	9.8	12.0	25.0
The longest hot wave (days)	6.9	8.2	10.1	0.0	1.8	2.5	0.8	4.0	2.5	3.8	1.4	4.0	4.5	7.0

Table 6. Comparison of the future weather data produced by Meteonorm, CCWorldWeatherGen and DMI. Meteonorm can consider different scenarios and generate extremely warm (P10) years. The DMI data is given as average values for the periods of 2021-2050 and 2071-2100. Meteonorm is able to provide predictions with a 10-year timestep, therefore the given data is the average of the years of 2020, 2030, 2040 2050 and 2070, 2080, 2090,2100, correspondingly. CCWorldWeatherGen can generate data for 2020, 2050 and 2080 only, thus here the average of 2020 and 2050 was given for the period of 2020-2050 and the data for 2080 was given for the period of 2070-2100.

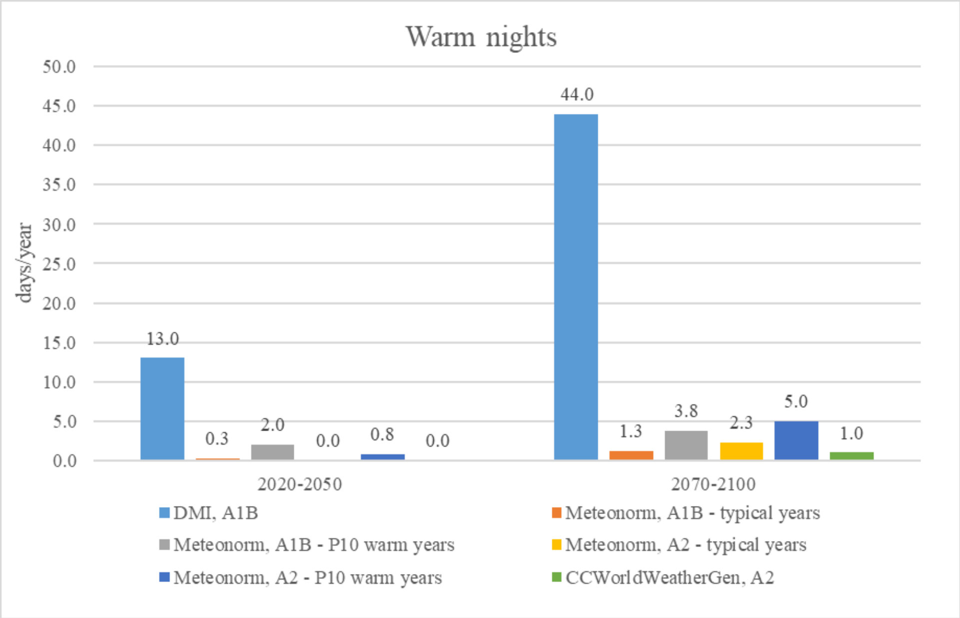


Figure 6 Average number of warm nights in the periods of 2020-2050 and 2070-2100. The Meteonorm data is given as the average of the years of 2020, 2030, 2040 2050 and 2070, 2080, 2090,2100, correspondingly. CCWorldWeatherGen can generate data for 2020, 2050 and 2080 only, thus here the average of 2020 and 2050 was given for the period of 2020-2050 and the data for 2080 was given for the period of 2070-2100.

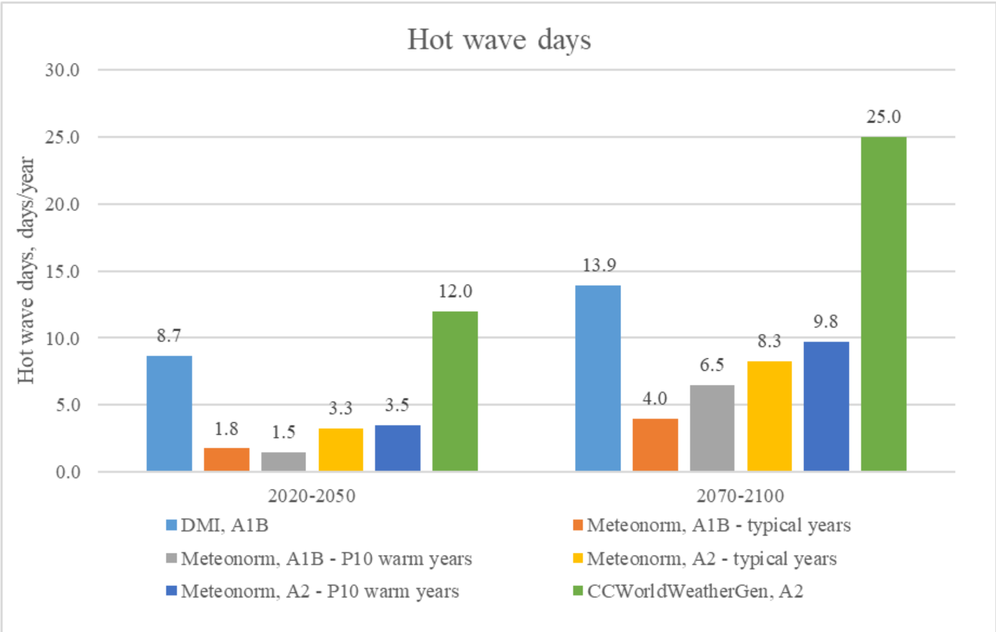


Figure 7. Average number of hot wave days for the periods of 2020-2050 and 2070-2100. The Meteonorm data is given as the average of the years of 2020, 2030, 2040 2050 and 2070, 2080, 2090,2100, correspondingly. CCWorldWeatherGen can generate data for 2020, 2050 and 2080 only, thus here the average of 2020 and 2050 was given for the period of 2020-2050 and the data for 2080 was given for the period of 2070-2100.

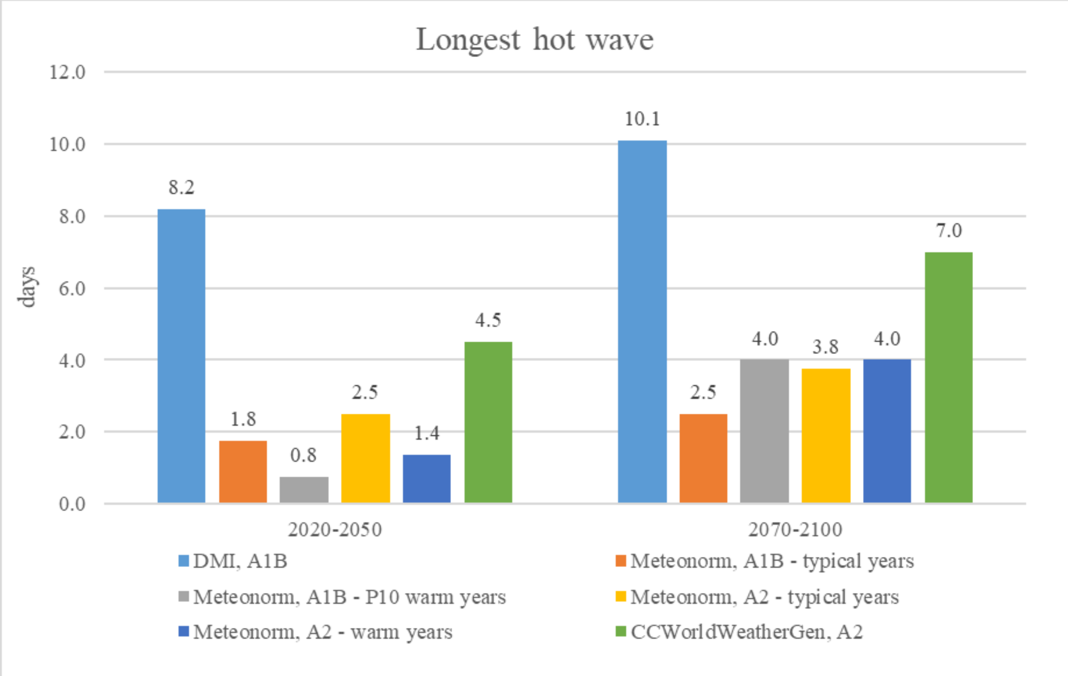


Figure 8. The length of the longest hot wave period for the years of 2020-2050 and 2070-2100. The Meteonorm data is given as the average of the years of 2020, 2030, 2040 2050 and 2070, 2080, 2090,2100, correspondingly. CCWorldWeatherGen can generate data for 2020, 2050 and 2080 only, thus here the average of 2020 and 2050 was given for the period of 2020-2050 and the data for 2080 was given for the period of 2070-2100.

Significant differences can be observed in several KPI-s when comparing the predicted weather data produced by the different sources:

- The number of warm nights is predicted to be significantly higher according to DMI when compared to the other two sources (see Figure 6). Meteonorm and CCWorldWeatherGen produces similar values for this KPI.
- According to Meteonorm, there is no heat wave period in the future weather data. CCWorldWeatherGen produces similar results, as there is only one heat wave period in 2020 and 2050, and only one heat wave period in 2080. DMI predicts more frequent heat wave periods.
- The number of hot wave days and the longest hot wave is predicted to be 2-3 times higher according to DMI when compared to Meteonorm. CCWorldWeatherGen also gives higher estimates for this KPI, and for the number of hot wave days it predicts even higher values than DMI. The CCWorldWeatherGen prediction for the longest hot wave period is between the estimates of Meteonorm and DMI.

To summarize the differences: the DMI generally predicts warmer future weather than Meteonorm and CCWorldWeatherGen. No clear reason for this was found, as DMI used the A1B (middle) scenario when making the estimates. Nevertheless, the data given by Meteonorm was deemed credible, since it was similar to values produced by CCWorldWeatherGen in 3 out of 5 KPI-s. Therefore, Meteonorm was chosen to be the source of the future weather data for this investigation.

6. Sensitivity Analysis

Sensitivity Analysis (SA) determines how the output parameter of a model (e.g.: operative temperature) can be affected by various input parameters (e.g.: U-value of the construction) which flow into the model (Saltelli, Ratto et al. 2008). According to Liu (2015), SA should answer the following questions:

- Which parameters can be filtered out because of their lack of importance?
- What will be the consequence of changing the input parameters?
- Which parameters require more attention because of their greater level of effect on the output?
- What will be the ranking and level of importance between the influential parameters?

The classical sensitivity analysis is mostly conducted before the building is completed. In this case, the researchers were working with an existing house, and cooling technologies that have already been implemented (apart from PCM). Only parameters that significantly affect the model output, and which behavior cannot be predicted, will be investigated. Those will be the important parameters for further uncertainty analysis.

There are three different classes of SA:

- Screening methods (SM),
- Local sensitivity analysis (LSA),
- Global sensitivity analysis (GSA)

The following chapter describes the fundamentals and the differences between them.

SM and LSA are commonly used when complex situations occur in the model and the there is too much computing effort to solve the situation. These methods might be called OAT-methods (one parameter at a time), which means that the change of output is based on the diversion of one input, while the rest does not shift. The difference between the two methods is the sampling method of the inputs. In SM a reference value changes based on predefined steps (e.g.: changing with +/- extreme value), in LSA there is a predicted range which fits the reference point (e.g.: U-value from 0.3 to 0.6).

GSA is the opposite of the above-mentioned two classes. Although this method investigates the changes of the output, it works with all the relevant inputs at the same time with respect of one another. This means that instead of changing only one parameter and calculating the results, it changes all relevant parameters and shows how they work with each other. (Heiselberg, Brohus et al. 2007).

For this project, the LSA method described by Spitz was chosen as the preferred analysis approach (Spitz, Mora et al. 2012). According to this method, the distance of the sensitivity index should be the main judge of the different inputs. This method does not only show the ranking, but the changes in the actual values as well (e.g. if the chosen output parameter is operative temperature, then the calculation shows how high the temperature change is, by the different parameters in Celsius). With this method the Sensitivity Index (SI) is first calculated - see eq. 3 (Spitz, Mora et al. 2012).

$$S_i(t) = X_i \cdot \frac{\partial y_k(t)}{\partial X_i} \quad (3)$$

where:

S_i : sensitivity index, -

X_i : nominal value of input 'i'

∂X_i : a small perturbation of the input 'i', +10% in this project

∂y_k : change in the output as a result of the change in input (compared to the baseline output)

Afterwards, the distance of the sensitivity index is determined, see eq. 4 (Spitz, Mora et al. 2012).

$$S_{i,d} = \sqrt{{S_{i,m}}^2 + {S_{i,std}}^2} \quad (4)$$

where:

$S_{i,m}$: mean of the sensitivity index

$S_{i,std}$: standard deviation of the sensitivity index

Another way of calculating can be the Morris method**,** where instead of SI, the Elementary Effect (EE) is calculated. In the end of the method the relation between standard deviation and mean of the EE determines the importance of the different input parameters (Heiselberg, Brohus et al. 2007). To use Morris method, more precise range and more samples would be necessary, which does not change the result of the rankings but makes them more precise. That is why, for this project the Spitz method is presented instead.

In the following chapter, the analyses of 3 different technologies are presented. These are: phase change materials (PCM), solar shading and natural ventilation. Two out of these three had already been placed in the building. Therefore, some of the inputs are the same as mentioned before. At the end of the analyses the reader can get a clearer picture of which technology-related parameters are the most important to conduct the UA. It was assumed from the beginning that the occupant load and climate influence would be important parameters. Therefore, they are not investigated in the three upcoming chapters.

6.1 Local sensitivity analysis of using phase-change materials

Phase-change materials (PCM) can help utilize the solar gains and improve thermal comfort, by increasing the heat capacity of the building constructions. This extra heat capacity is used when the internal temperatures are close to the melting point of the PCM material (Aschehoug, Andresen et al. 2008). That is why, in this project, a PCM material with a melting point close to 23 °C was chosen. This temperature would allow the PCM to be used both during heating season, to utilize solar and internal gains, and to reduce the internal temperatures during summer. In Table 7 the effect of PCM materials on the summer comfort with different melting points is compared.

Melting point, °C	No PCM	21	23	25
Bedroom	492	540	11	0
Living room	227	157	0	0

Table 7. Number of hours with operative temperatures higher than 25 °C, applying different PCM materials

In his report, Johra applied PCM wall-mounted panels to the internal surfaces of the building constructions. After performing sizing calculations, he found that the thickness of 15 mm was optimal (Johra, Heiselberg 2016). Therefore, in this project, a PCM with similar thermal properties was chosen (BioPCM® M182/Q23, from Phase Change Energy Solutions – the density was changed to correspond to the material used by Johra) and applied, using the same thickness.

Table 8 summarizes the inputs that were considered when conducting local sensitivity analysis for the PCM technology.

- The specific heat capacity refers to the value of the solid form of PCM.
- To determine the effect of different melting points, the applied PCM's temperature-enthalpy curve was shifted by 2.3 K, which corresponds to 10% of the original melting point.
- A similar approach was used when assessing the influence of the materials enthalpy: in this case, the temperature-enthalpy curve was shifted upwards by 20188 J/kg, which corresponds to 10% of the enthalpy at the melting point.
- The influence of the occupant density and the weather was not investigated in the local sensitivity analysis, because these inputs, regardless of their importance, were planned to be incorporated in the uncertainty analysis, as they appear in the definition of resiliency (see Chapter 2.1)

The results of the sensitivity analysis are shown in Figure 9. Since the goal was to analyze the effect of changing inputs during the summer season only, the distance of the sensitivity index was calculated considering only operative temperatures higher than 25 °C. The operative temperatures were compared to the adaptive comfort criteria of category II in DS/EN 15251. However, no overheating was detected in any case. Therefore, it was not possible to use the limit temperatures of DS/EN 15251 to filter the results for the sensitivity analysis.

Changed input	Original value		Changed value	Reason for analyzing the input
Conductivity of PCM, W/mK	0.2		0.22	Uncertainty from the manufacturing process
Thickness of PCM, m	0.015		0.0165	Uncertainty from the manufacturing process
Specific heat capacity, J/kg/K	1970		2167	Uncertainty from the manufacturing process
Density of PCM, kg/m^3	1000		1100	Uncertainty from the manufacturing process
Melting point (shift in temperature-enthalpy curve)	23 °C		The temperature-enthalpy curve was shifted by 2,3 K	Uncertainty from the manufacturing process
Mechanical ventilation, l/s/m^2	0,3		0,33	Uncertainty in the air-flow rate provided by the mechanical ventilation
Enthalpy, J/kg (shift upwards in temperature-enthaply curve)	201,9 kJ/kg at 23 °C		The temperature-enthalpy curve was shifted by 20,19 kJ/kg	Uncertainty from the manufacturing process
Equipment load, W/m^2	computers	0.92	1.01	Uncertainty in equipment load in buildings
	Dishwasher	3.82	4.20	
	cooking plate	0.95	1.05	
	Cooker	7.49	8.24	
	other equipment	0.05	0.06	
	Washing machine	67.32	74.05	
	Dryer	65.16	71.68	
Lighting load, W/m^2	0.264		0.290	Uncertainty in lighting load in buildings

Table 8. Inputs of the local sensitivity analysis for PCM.

Unlike in the case of natural ventilation and shading, it was not possible to use 26 °C as a threshold value either, since in the majority of the cases the operative temperature never reached 26 °C.

The most influential inputs are:

- Melting point of the PCM
- Mechanical ventilation rate

The outcome is similar to the one in the studies conducted by Zsembinszki et. al. and Mazo et. al. It was found that from the properties of PCM, the melting point has the biggest influence (Zsembinszki, Moreno et al. 2014, Mazo, El Badry et al. 2015). The equipment loads and the density of the PCM have a slight effect as well. The other variables showed to have negligible influence on the operative temperature of the model.

During the uncertainty analysis of the PCM technology, these two most influential inputs were considered, along with the occupant load and the weather.

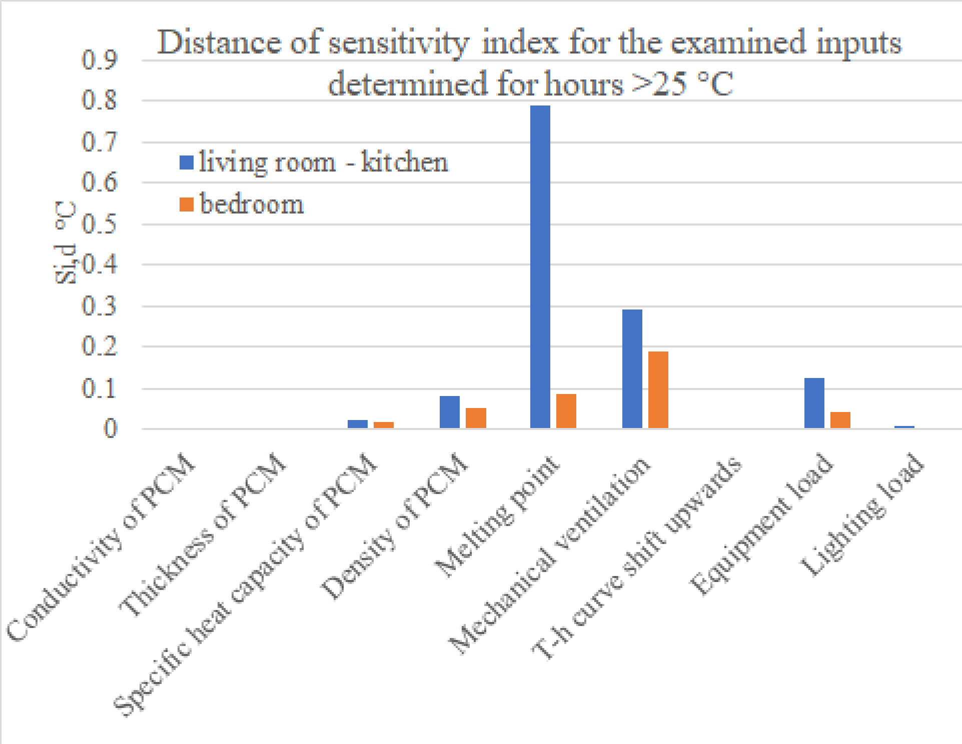


Figure 9. Distance of the sensitivity index for the examined inputs for PCM.

6.2 Local sensitivity analysis of the shading technology

The purpose of shading (or solar radiation control) is to prevent/control the heat gain from solar radiation. There are different ways through which the solar radiation can be limited (for example the right building orientation or overhangs). Basically, all the different solutions take into consideration that the sun heats up a space with different intensity. Full or semi-mobile shading devices are the most commonly used solutions. However, a lowered quality of visual comfort is a significant disadvantage of those devices.

As it was stated earlier, the shading system has already been placed in the living room and master bedroom. As Figure 10 shows, both corner windows are covered by shading devices if the control system requires it.

Figure 10. The existing building shading system

According to Carpino report (2018) and Figure 10, the shading system is made of a horizontal wooden lamella, that works against the direct solar radiation. The system takes into consideration the visual comfort, therefore, there are some spaces between the lamellas to provide view to the outside and introduce daylight in the occupied space. This type of system is called slat shading. The system is motor driven. If it is necessary to protect the building's thermal comfort, the shading can be moved from its original place to the front of the different windows of the same room. It is controlled by sensors located inside of the rooms. Based on Kristensen report (2017), the following setpoints can be differentiated (Table 9):

Set point	
If the occupants are in the dwellings:	
25 ⁰C or the tenants' preference (tenants have the individual right to overwrite the system's set ups, after 1 day, or if they leave the building it goes back to automatic control mode)	
If the occupants are outside from the dwellings:	
25 ⁰C	The order is the same as in the occupied times. The only difference is that the control goes into automatic mode with one set point.

Table 9. Shading system control set ups

The shading system control is based on the indoor temperature setpoint and not on the intensity of the solar radiation. Therefore, if the outdoor temperature increases, the system cannot resist against this change.

Table 10 represents the hours above 26°C with or without shading for the living room and master bedroom.

Shading type	No shading	Slat shading
Bedroom	492	47
Living room	227	58

Table 10. Number of hours when the operative temperature is above 26°C with or without shading device

As the table shows, significant changes can be achieved just with a simple slat shader. In the examined case, the temperature was minimum 4 times lower, which is also above the threshold. According to Oropeza-Perez study (2018), on average the temperature can be dropped with 3°C through an appropriately designed sheading device.

To define the different inputs, which affect the model output, the already placed slat shading was investigated. The aim of the analysis was to find those parameters which are uncertain. Table 11 collects all the shading-related parameters which can be found in the DesignBuilder, together with the predicted changed input values.

Changed input	Original value		Changed value	Reason for analyzing the input
Type [-]	-		-	Not important (already placed the shading device)
Position [-]	-		-	Not important (already placed the shading device)
Control type [-]	-		-	Not important (already placed the shading device)
Inside air temperature [°C]	25		27.5	Uncertainty can come from the measure device
Slat angle control [-]	-		-	Not important (already placed the shading device)
Operational schedule [day]	It will part of UA		It will part of UA	Uncertainty from occupation
Equipment load [W/m^2]	It will part of UA		It will part of UA	Uncertainty from occupation
Occupant load [people/m^2]	bedroom	0.138	0.1518	Uncertainty from occupation
	living room	0.03	0.033	Uncertainty from occupation
Local shading [-]	-		-	Not important (already placed the shading device)
Shading from other objectives [-]	Cannot be implement in DB		Cannot be implement in DB	Uncertainty from occupation
Weather data (Radiation) [Wh/m^2]	DRY 2013 file		add 10% to the radiations	Uncertainty fromweather changes
Slat:reflectance [-]	0.15		0.165	Uncertainty from manufacuring process
Slat: with [m]	0.045		0.0495	Uncertainty from manufacuring process
Slat: separation [m]	0.03959		0.043549	Uncertainty from manufacuring process
Slat: thickness [m]	0.004		0.0044	Uncertainty from manufacuring process
Slat: distance from glass [m]	0.1		0.11	Uncertainty from manufacuring process
Mech. Ventilation ACH [l/s/m^2]	0.3		0.33	Uncertainty can come from the measure device

Table 11. Shading-related parameters

The table clearly defines that 12 out of 17 input parameters can disclose important results for this research and only 9 out of those 12 are analyzed. The reason is that modelling shading from another object might be too complicated to simulate. In addition, the equipment load is associated with the changed occupant schedule. Therefore, both situations had to be investigated and evaluated independently from the viewpoint of the local sensitivity analysis.

Figure 11 shows the result of the sensitivity analysis. This diagram explains that only those parameters, which were found as important considering the UA, were analyzed. The graph is based on a calculation describing the distance of the sensitivity index. It proves that the two most influential input parameters are:

- Set point
- Mechanical ventilation air change rate

In Figure 11, it can be observed that 2 slat properties (slat separation and slat width) contribute to the output change. Nevertheless, according to Lee research (1998), the 10% increase would be too great and unrealistic in real life, as the accuracy of slat producing machines is very high. Therefore, those two inputs will not be examined further in the uncertainty analysis.

The equipment load also appears to be important, but as it was stated before it will be the part of the occupant load. The reason behind it is the design of the simulation software.

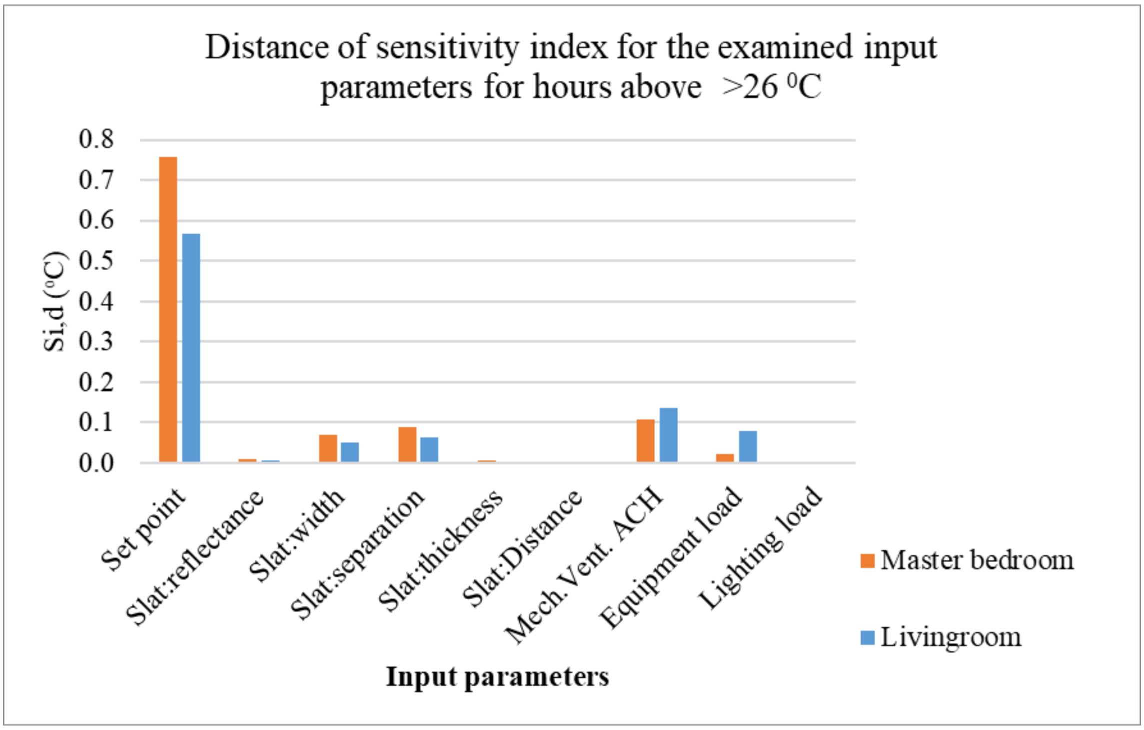


Figure 11. Distance of the sensitivity index for the examined inputs for shading

6.3 Local sensitivity analysis of natural ventilation

The American Society of Heating, Refrigerating and Air Conditioning Engineers describes natural ventilation as "introduction of outdoor air into the building space, caused by natural driving forces: wind pressure and buoyancy" (Oropeza-Perez, Østergaard 2018). In the investigated project, natural ventilation was introduced to the house through automatically controlled openings (skylights and window vents with 25℃ setpoint) and through the occupants' manual operation. The control mode is different for each of the window parts, as seen in example in Figure 12. It must be noted that not all the windows are openable. To see the exact drawings with highlighted window operation, see Appendix 12.6.

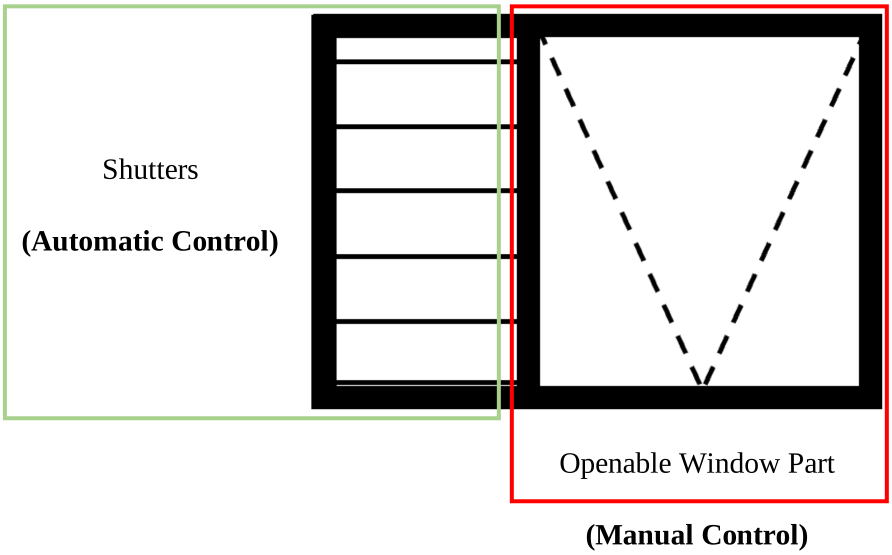


Figure 12. An example of operation of different window parts in the examined house

The list of different opening types is provided in Table 12.

Room type	Number of windows	Total number of windows' subdivisions	Control mode of the openings
Living room	2	5	1 opening automatically controlled 4 non-openable parts
Master bedroom	2	5	1 opening automatically controlled 1 opening manually controlled 3 non-openable parts
Room 1	1	2	1 opening automatically controlled 1 opening manually controlled
Room 2	1	2	1 opening automatically controlled 1 non-openable part
Room 3	1	2	1 opening automatically controlled 1 opening manually controlled

Table 12. List of window openings for different rooms

The exact information about the modelling of natural ventilation in DesignBuilder for Bolig 2020 can be found in Appendix 12.6.

In Table 13, the number of hours per year above 26 degrees Celsius is shown for 4 different scenarios - without any natural ventilation, ventilation with automatic vents only, manually controlled ventilation and combined solution.

Ventilation type	Room type	Number of hours above 26°C
Automatic venting	Master bedroom	28
	Living room	21
Occupant manual operation	Master bedroom	25
	Living room	23
Combined solution	Master bedroom	23
	Living room	21
No natural ventilation	Master bedroom	492
	Living room	227

Table 13. Number of hours above 26 degrees Celsius for the living room and master bedroom in 3 different scenarios

Table 14 summarizes the inputs that were considered when conducting local sensitivity analysis for the natural ventilation. It needs to be noted, that a) only uncertain, not constant parameters are included in the tables, b) only parameters, that were possible to manipulate in the DesignBuilder are included in the tables c) the simulations were performed based on the set temperature control mode, not the adaptive comfort d) it was not possible to implement mixed mode in the model (to turn off mechanical ventilation when the natural one starts to work), therefore mechanical ventilation is constantly active.

Natural Ventilation			
Changed input	**Original value**	**Changed value (+10%)**	**Reason for analyzing the input**
Indoor temperature setpoint, °C	25	27.5	Uncertainty from the inside temp. control setpoint
Mechanical ventilation ACH, l/s/m^2	0.3	0.33	Uncertainty from the mechanical ventilation
Time the external doors are open, %	5	5.5	Uncertainty from how long the external door is open
Time the internal doors are open, %	10	11	Uncertainty from how long the internal door is open
Outdoor max. temperature control, °C	28	30.8	Uncertainty from the outside temp. control setpoint
Window discharge coefficient	0.51	0.561	Uncertainty from the width the windows are open
Equipment load, W/m^2	0.92 3.82 0.95 7.49 0.05	1.01 4.202 1.045 8.239 0.055	Uncertainty from the equipment load
Lighting load, W/m^2	2.64	2.904	Uncertainty from the artificial light load

Table 14. Inputs considered while conducting local sensitivity analysis natural ventilation

It was discovered, that even though it was possible to insert the outdoor temperature control, the software did not take this parameter into account when performing the simulations.

The results of the sensitivity analysis are shown in Figure 13. Based on the calculated distance of the sensitivity index values, the most influential input for the natural ventilation is the indoor temperature setpoint.

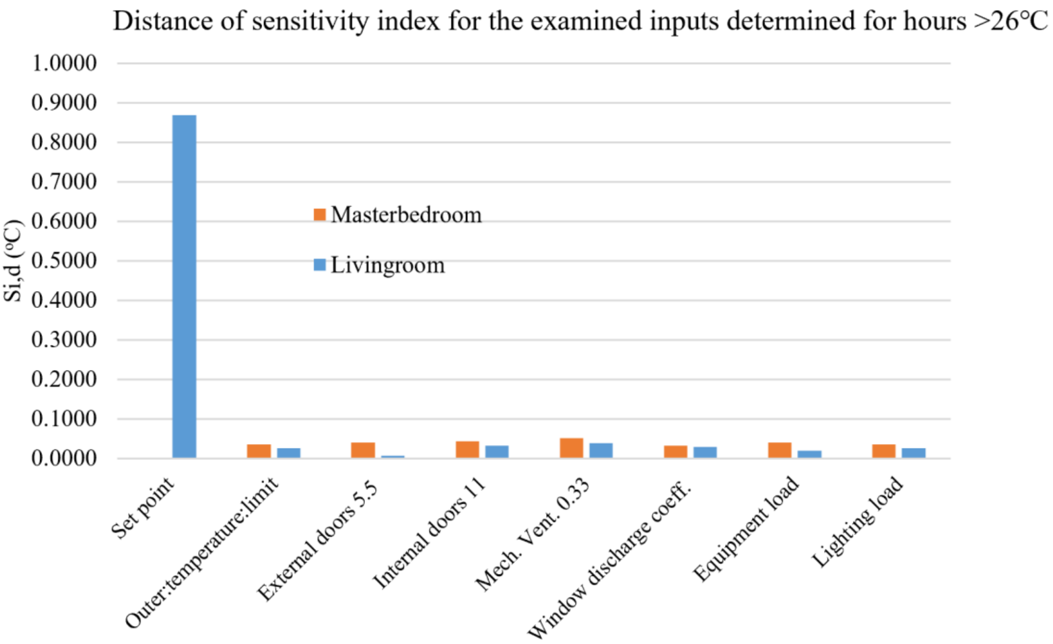


Figure 13. Distance of the sensitivity index for the examined inputs for natural ventilation

6.4 Summary of the LSA for all the technologies

As it was mentioned at the beginning of this chapter, local sensitivity analysis is the OAT method, which helps to define the distance of sensitivity index of various input parameters. By doing so, the most important parameters for the cooling technologies are determined. For the examined cases, each input parameter was increased with 10% of its original value. Additionally, there were two parameters, which per default were assumed to have a significant influence on each of the cooling technologies - climate change and occupant schedule. These two parameters will be examined in Chapter 7**.** All the important parameters for the investigated scenarios are summarized in Table 15.

Important parameters	**Cooling technologies**		
	PCM	**Shading**	**Natural Ventilation**
Climate change			
Occupant schedule			
Mechanical ventilation			
PCM melting point			
Shading setpoint			
Nat. vent. setpoint			

Table 15. Summary of LSA for PCM, shading and natural ventilation. Red color implies the important parameter for a particular technology.

7. Uncertainty Analysis

The aim of the uncertainty analysis (UA) is to appraise the different technologies and to determine their level of resilience. The following chapter describes the procedure of performing UA in this project for each of the examined technologies and their combination.

There are numerous input parameters which cannot be estimated to an exact degree. In this project, those parameters are for instance the occupant behavior and the future weather data. Therefore, it is necessary to take those random factors into account through the UA. Through the uncertainty analysis, one can determine the distribution of the model output data based on the input parameters' probability distribution (Belleri, Lollini et al. 2014). In other words, it considers the possible range of changes of the input parameters and after a given number of simulations, gives a distribution of the desired results.

This tool relies on important statistical theories. It is essential because all input parameters are presented in a range with different occurrences. There are two types of occurrences:

- **Population** - if the full range is well-known
- **Samples** - if these criteria are only valid for a part of the range

In both cases, the input parameters can be defined with a good probability distribution. One of the criteria can be the number of people in the building. For instance, it can be two adults or a family with 4 members. In this case the number of people can be from 1 until a reasonable number. It can be determined from the statistical data of a country (in Denmark: Statistics Denmark). This shows that there are different possibilities of how many people can live in an average-sized apartment. In the examined case, the range of possibilities was provided from the statistical data which presented the frequency of 2, 5 or 8 people living in an apartment (Kim B. Wittchen 2004). As the example shows, it is not enough to know the range of an input, but it is also necessary to understand how often the different events in the range occur. Therefore, probability density functions (PDF) are used to describe the input parameters properly. There are two main groups of PDF-s (Yıldız, Arsan 2011):

- **Discrete** - each possible variable has its own independent probability
- **Continuous** - the probability can be assigned only to a part of the function, not to specific numbers in it

All the input parameters presented in this thesis are based on different researches or statistical data to ensure the accuracy of the UA. As Mathematics recommends input and output parameters PDF form will be presented (Mathematics).

The input parameters are based on two different things. The first explains how sensitive the model is depending on the input parameter. The SA highlighted those important parameters which are placed in the different simulations. The second one determines the right PDF-s. In this way, the level of precision can be increased. There are some input parameters which are the same and occur in at least two of the examined technologies. These are:

- Occupant loads (number and schedule of the occupants)
- Future weather data
- Mechanical ventilation ($l/s/m^2$)

In chapters 7.3, 7.4, 7.5 and 7.6 the PDFs of each input parameter are described in greater detail.

The outputs of the UA are given by the DesignBuilder (DB) software, which used the adaptive comfort DS/EN 15251 cat II in hours (DesignBuilder 2020). The reason for selecting this method was due to the limited software capabilities.

The last part of the procedure is to find the correct sampling method, to avoid excessive simulation time. In this project, it was necessary to change every input one by one. Based on other studies, it was discovered that the level of accuracy does not change dramatically after a certain number of simulations, such as 60-80-100 or even more per variable (Parys, Breesch et al. 2012). This great number of simulations per variable might cause a substantial computing effort and is therefore unnecessary. The name of this approach is Random Sampling Method (Parys, Breesch et al. 2012).

According to the DB help file (2020) and Parys study (2012), Latin Hypercube Sampling (LHS) is a more sophisticated sampling method. It divides the range equally based on the number of simulations in the DB. For example, if a uniform distribution PDF was used (where every possibility in the range is equal) with a range from 1 to 4, and 4 simulations were set up, then, all 4 numbers are represented. Meanwhile, in the random sampling, one or two numbers might be reoccurring. In DesignBuilder (2020) 10 simulations per variable are sufficient to reach an accurate range of results.

7.1 Robustness

As it was stated in Chapter 2, robustness is one of the key parameters of resiliency. One of the aims of this thesis is to discover how robust the investigated technologies are. Therefore, it is important to determine how robustness should be evaluated.

Parys (2012)defines the robustness as the probability that the results of a deterministic analysis are achieved by the results of the uncertainty analysis (2012). For the deterministic analysis, a mean case should be set up. In this case all input parameters should represent an average or mean incident from the UA design variables range being:

- Typical annual weather data
- 16.3 average hours regarding the number of hours the occupants stay at home
- 0.3 l/s/m^2 ventilation air flow
- Shading and natural ventilation system activated at the temperature point of 25 ^{o}C

Deterministic analyses were conducted using the mean inputs. The uncertainty analyses were performed using the PDF-s described in Chapter 7.3-7.6. Then, based on the uncertainty analysis, the probability that the deterministic analysis results would be achieved was determined. The closer this probability is to 100%, the more robust the technology is. For this study to be more precise, three distinct robustness analyses will be presented:

- First, the robustness against the technology, weather and occupant schedule related uncertainties is calculated. Since these uncertainties are incorporated in the UA by defined PDF-s, the deterministic analyses results are compared to the corresponding uncertainty analyses results.
- The second analysis will be the resistance against climate change, so the 2020's 2 and 5 people baseline model cases will be compared to the corresponding 2060's and 2100's UA result cases.
- The third analysis will introduce the resistance against the occupant load, which is the probability that the deterministic results of the two-person model are achieved based on the uncertainty analysis of the five-person models.

7.2 Model description

The original model was based on the Carpino report (2018) "the actual profile". This model was changed to fit the examined case. The reason for that was, that when the research model was created, it was validated based on the building's energy consumption. It means that the internal gains as well as the schedule were the same, except for the occupant load. A baseline model was established to compare the results of the UA to an original model, so the robustness of technologies could be investigated. To do that, six baseline models were required. The models were created based on the number of people and different weather files, as shown in Table 16:

Nr. of people/Weather	2020 Typical	2060 Typical	2100 Typical
2 people	1st model	2nd model	3rd model
5 people	4th model	5th model.	6th model

Table 16. Difference between the 6 shading baseline models

In each of the cases, mean values were chosen for the baseline models. The properties of those baseline models are listed below:

- The occupants stay at home exactly 16.3 hours (mean value from the statistical data).
- The heating set point was increased up to 22 ^{0}C to avoid underheating problems over the winter period.
- When 5 people occupy the building, 3 extra rooms are modelled.
- The corresponding typical weather data was uploaded to every model.

The diversions from the original model, for each of the technologies, are listed below:

- **PCM:** The base thermal model was supplemented with the PCM layers on the constructions (see Chapter 6.1).
- **Shading:** A shading device was added to the model to represent the reality (see Chapter 6.2). Five glazing templates were made to cover the changes to the set point.
- **Natural ventilation:** The same uncertainty was applied to each sensor in every thermal zone, which means that every thermal zone had the same setpoint for a certain simulation. This simplification was done in order to avoid excessive computation time. In reality, the sensors would measure different temperatures, thus the effects of the uncertainty would even out.
  The setpoint for natural ventilation was increased from 25 °C to 26 °C in order to avoid uncontrollable air change rates in the living room.

In Chapter 7.3 to 7.5, the 4 common input parameters are presented.

7.3 Number of occupants

When considering occupant load, there is uncertainty in the number of people living in the building and in the number of hours they spend indoors. The statistical data for both aspects is provided in Table 17 and Figure 14.

No. of occupants	Households	Probability, %
2	400.237	39.83
4	189.545	18.86
1	177.802	17.69
3	158.875	15.81
5	61.406	6.11
6	12.48	1.24
7	2.742	0.27
8	1.774	0.18

Table 17. Probability distribution of the different number of people living in a detached house

Due to the limitations of the DB software, it was not possible to incorporate the uncertainty in the number of people, since different numbers of occupants would require different schedules for the thermal zones. Therefore, the following method was used:

- To account for the uncertainty in the number of occupants, separate analyses were made for 2 scenarios: with 2 occupants and with 5 occupants. Greater numbers of occupants occur very rarely in this building type (below 1,7%, see Table 17).
- The uncertainty of the time the occupants spend indoors will be analyzed in the uncertainty analysis. To do so, different schedules were created.

7.4 Occupancy schedule

Another important part of the occupant load is the schedule of tenants. Due to the software limitation, the schedule and number of people are separated from each other. The different scenarios of how much time could be spent at home, according to Keiding (2003), are summarized in Figure 14.

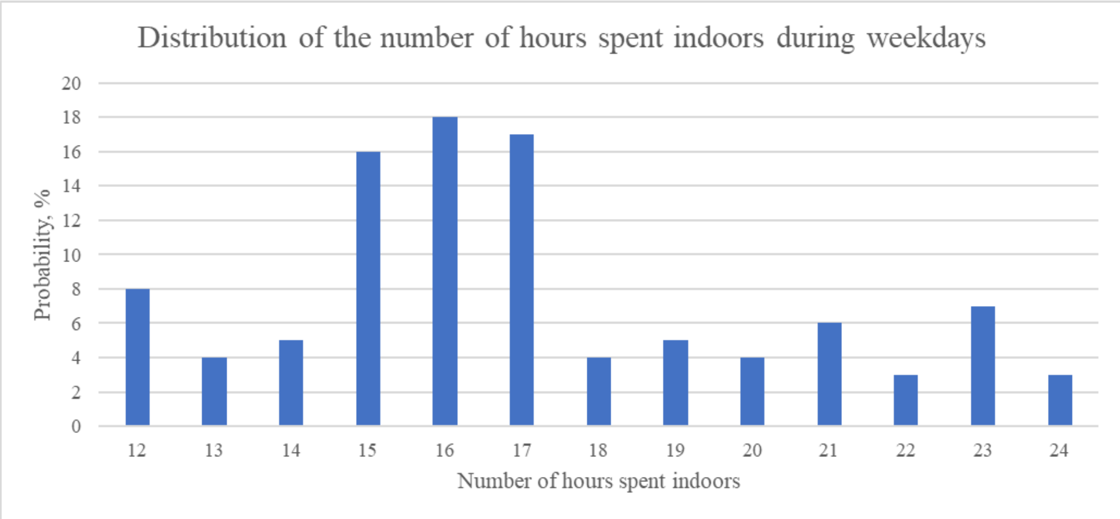


Figure 14. Probabilities of the different time-length when an average Danish citizen is at home.

To perform uncertainty analysis for this case, different schedules were created. First, several possibilities presented in Figure 14 were grouped, so the number of necessary schedules could be reduced. After grouping these possibilities, it was found that the probability distribution could be well approximated with a uniform distribution (with a probability-weighted average difference of 1.38%), see Figure 15.

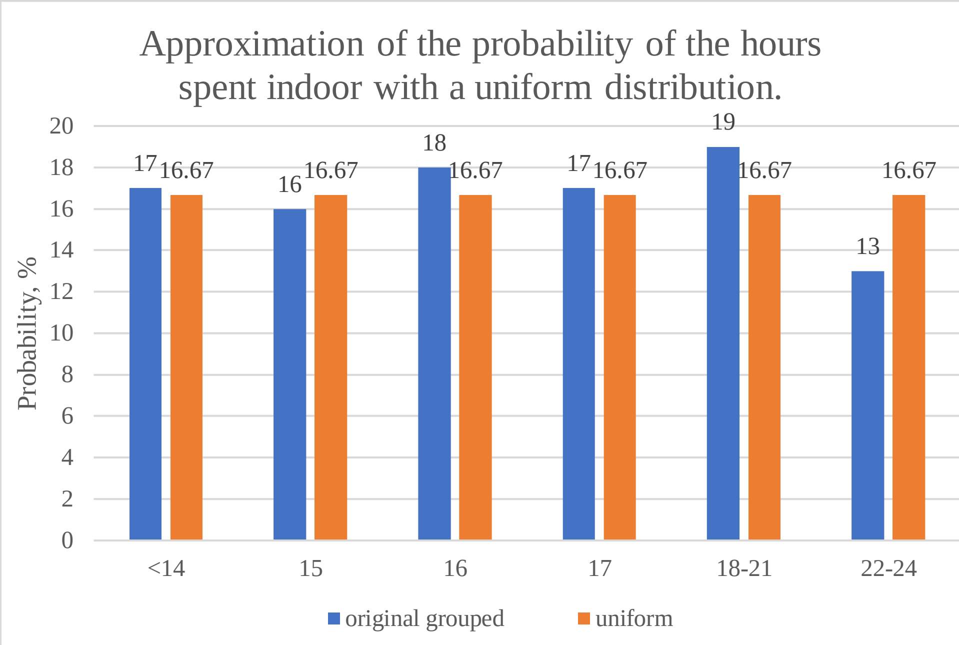


Figure 15. The probability density function of the hours spend indoors by the occupants was approximated with a uniform distribution. This figure represents values only for weekdays.

It must be noted that the data in Figure 15 represents only weekdays. The number of hours spent indoors by the occupants during weekends was studied by Knudsen et al. (2010), who found that the mean duration is 19,9 hours. This study examined 40 households only, therefore it was decided to use the original distribution of the number of hours for weekdays from Keiding (see Figure 15) for the weekend occupancy as well. However, for the duration of weekend occupancy, the results of Knudsen were used.

It is necessary to note that the hours spent indoor represent the whole building, however, in the DB model, schedules need to be assigned to each thermal zone. Therefore, the schedules representing the different number of hours spent inside were created in the following way: the variation in the occupation was considered only for the living room-kitchen area, and the time spent in the bedrooms, bathroom and utility room remained constant through the different scenarios. This was done in order to obtain the same distribution that exists for the whole building.

Another important simplification was that no occupancy was assigned to the bathrooms and utility room. This is because the uncertainty analysis tool in the DesignBuilder determines overheating hours for the thermal zones where there is occupancy and provides only the sum of the overheating hours for the whole building. However, as the utility room and bathroom are not considered to be rooms of occupancy, the overheating hours were not assessed in there.

7.5 Considering the uncertainties in the weather

To assess whether a technology is resilient towards changes in the weather, these changes must be incorporated in the uncertainty analysis. The changes in the weather are twofold:

- There are long-term, trend-like changes in weather. This is depicted in Figure 17. Here, the cooling degree hours above 25 °C and the global horizontal radiation data in the period of 2020-2100 (as determined by the Meteonorm software considering the middle A1B IPCC scenario) are given. The long-term trends in the weather are considered in this study by conducting uncertainty analysis for three selected years: 2020, 2060 and 2100. These are years with low, middle and high cooling degree hours and radiation.

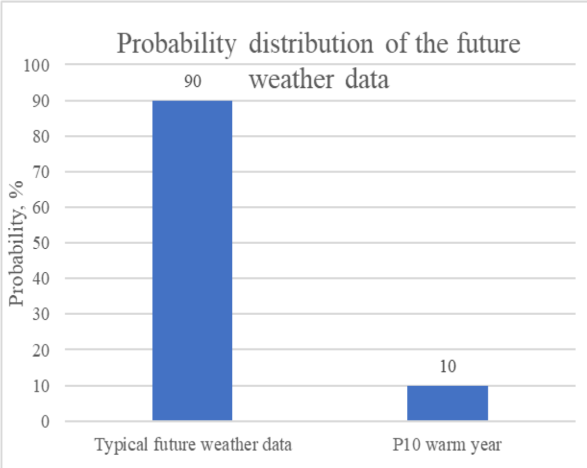


Figure 16. The probability distribution function of the weather data.

	CdH>25°C	ISGH, kWh/m²/year
2020	4.7	927.0
2030	33.2	926.9
2040	67.4	928.6
2050	81.2	928.3
2060	112.2	930.1
2070	120	930.9
2080	129	933.2
2090	174.1	933.6
2100	178.9	933.4

Figure 17. Future weather data as determined by the Meteonorm software. The red and green values show the data above and below the 75th and 25th percentile.

- There are also year-to year variations: one year can be warmer than the previous one. To consider these variations, extremely warm P10 (10% probability) weather data sets were determined using Meteonorm for 2020, 2060 and 2100. Then the following discrete probability distribution Bernoulli function was used: 90% probability of typical future weather dataset and 10% probability of the extremely warm dataset (see Figure 16).

7.6 The uncertainty of the mechanical ventilation rate

In the DesignBuilder thermal model, the airflow rate of the ventilation system is constant - 0.3 l/s/m^2. According to Parys (2012) and Breech (2010), ±10% uniform uncertainty can be attributed to the mechanical ventilation rate (see Figure 18).

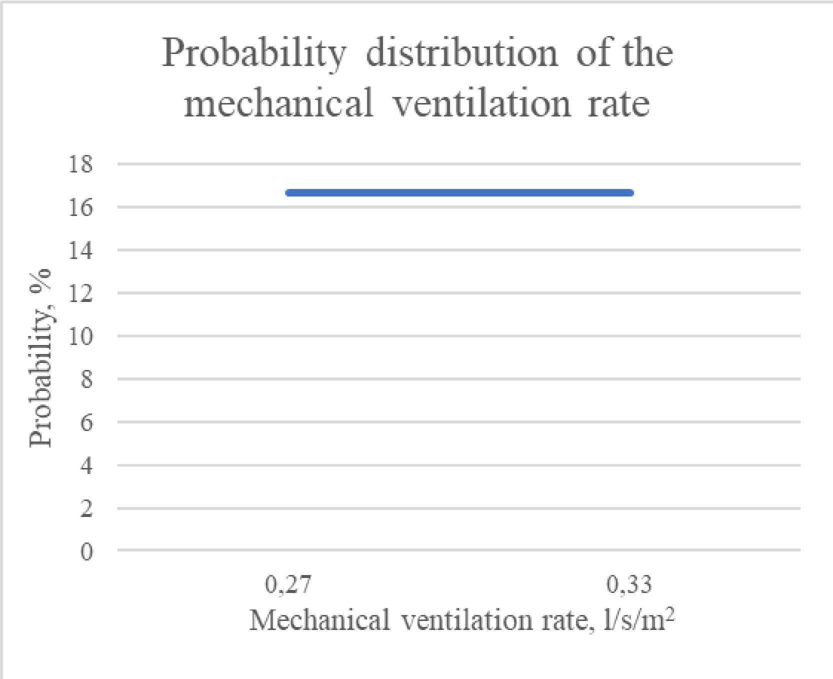


Figure 18. Uniform continuous PDF of the mechanical ventilation rate.

In the next chapters, the uncertainty analyses of the three examined technologies and their combination are presented in detail. Three different results are given:

- The maximum POR per technology on building level to fulfill requirements of the DS/EN 15251 (yearly no more than 5% occupied time outside of the category)
- The number of hours above 27 and 28 °C for the critical room, as required by Danish Building Regulation
- The robustness of technologies

Using these KPI-s, the technologies can be compared in terms of comfort and resiliency level in order to fulfill the aim of the thesis.

8. The UA results and unique input parameters of the technologies

8.1 Uncertainty analyses of the PCM technology

In order to run UA of the PCM technology, the base thermal model had to be supplemented with the PCM layers. Additionally, since the melting point turned out to be the most influential input (see Chapter 6.1), the uncertainty of the melting point had to be incorporated in the uncertainty analysis. This was accomplished by defining different PCM materials. These had different enthalpy-temperature curves, to obtain materials with different melting points. Then, probabilities were assigned to these materials. To determine the probability-density function of the melting point, the research by Johra was used (2016).

- Johra measured the melting point of the PCM used in his study (Johra, Heiselberg 2016) and found a deviation of 1.7 K from the melting point stated by the producer and 2 K from the melting point measured by Kuznik et al. (Kuznik, Virgone et al. 2008). Johra states that the differences in the thermo-physical properties can be caused by the manufacturing process.
- Assuming that a similar uncertainty applies to the PCM used in this study, a normal distribution with a standard deviation of 1 K and a mean of 23 °C was chosen for the melting point of the PCM.
- However, as stated above, it was not possible to consider the melting point of the PCM as a continuous variable, but only possible to use different PCM-s with varying probabilities, as shown in Figure 19. Therefore, the normal distribution was approximated with a binomial distribution. This caused a probability-weighted average difference of 1.4%, which was found acceptable. (see Figure 19).

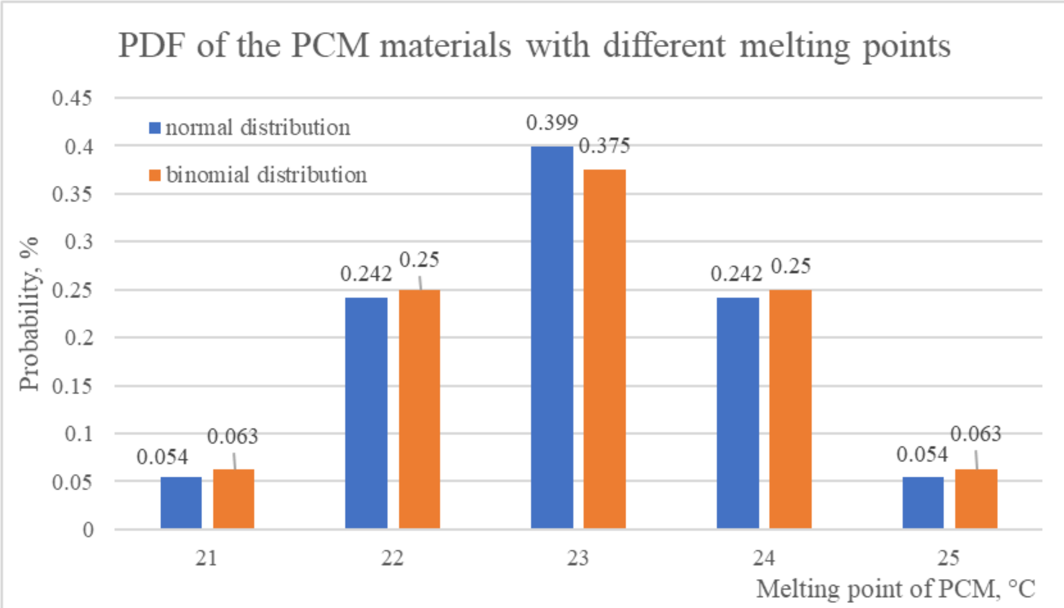


Figure 19. PDF of the PCM materials with varying melting points. The normal distribution was approximated with a binomial distribution, since it was possible to consider the materials as discrete variables only.

8.1.1 Results of the uncertainty and deterministic analyses for the PCM technology

The results of the uncertainty and deterministic analyses of the six analyzed cases for the PCM technology are summarized in Table 18, Table 19 and Table 20. In Table 18, the distribution of the POR for the six examined cases is characterized by its highest value and its median. The results of the corresponding deterministic analyses are also given, stating the POR outside the DS/EN 15251 adaptive limits, and the POR excluding undercooling (considering only the cases where the operative temperatures were higher than upper adaptive limits).

Case	Analysis type	Distribution	POR, %		
			2020	2060	2100
2 persons	Uncertainty analysis	Median	0.00	0.15	0.29
		Maximum	0.11	1.34	3.42
	Deterministic analysis	Outside adaptive limits	0.02	0.42	0.86
		Over adaptive limits	0.00	0.30	0.85
5 persons	Uncertainty analysis	Median	0.03	0.50	1.78
		Maximum	0.87	4.06	6.15
	Deterministic analysis	Outside adaptive limits	0.22	1.12	3.53
		Over adaptive limits	0.22	1.12	3.48

Table 18. Results of the uncertainty and deterministic analyses for the PCM technology. Values exceeding the 5% limit are highlighted.

DS/EN 15251 suggests that 5% POR can be acceptable – values higher than 5% are highlighted in Table 18. According to the deterministic analyses, this limit was never exceeded. The uncertainty analyses show similar results, here only the highest result for the 5 persons 2100 case surpassed the 5% limit.

The distributions of the different cases show clear trends: the higher number of occupants and warmer weather always resulted in a higher value of POR.

The performance of the PCM technology was also assessed taking the Danish Building Regulations into account. These state that the number of hours above 27 and 28 °C should not exceed 100 and 25, correspondingly. This KPI could be assessed only for the results of the deterministic analyses, since the DesignBuilder software provided hourly results only for this type of analysis.

Case	No. of hours	2020	2060	2100
2 persons	>27	0.00	32.00	314.80
	>28	0.00	0.00	40.45
5 persons	>27	10.60	254.50	857.25
	>28	0.00	40.75	207.15

Table 19. Performance of the PCM technology considering the Danish Building Regulations. The values exceeding the limits were highlighted.

According to the results shown in Table 19, the PCM technology in itself cannot provide satisfactory comfort in three out of six cases: for the 2 persons case with 2100 weather data, for the 5 persons case with 2060, and for the 5 persons case with 2100 weather data.

Finally, the outcomes of the robustness calculation are summarized in Table 20. The robustness calculation is described in detail in Chapter 2.6 and 7.1. The robustness of the examined technologies is compared in Chapter 9.

Robustness type	No. of occupants	Probability, %		
		2020	2060	2100
Robustness for technology, weather and occupational time related uncertainties	2	84.3	97.5	92.9
	5	73.2	79.6	76.2
Robustness for climate change	2	-	0.0	0.0
	5	-	13.8	0.0
Robustness for number of occupants	5	42.1	39.6	23.4

Table 20. The results of the robustness calculation of the PCM technology.

Based on the robustness calculation results, the PCM technology proved to be robust against the technology (melting point of PCM), weather (extremely warm years) and occupational-time related uncertainties, when considering the POR criteria. Significantly lower robustness was determined against the increasing number of occupants: on average, only 35%.

Additionally, the PCM technology was found to have almost no robustness against climate change. There is zero probability that the deterministic analysis result of the 2020 is achieved in the uncertainty analysis for the 2060 and 2100 case with two occupants. This happens when the baseline result of the 2020 case is lower than the lowest result of the uncertainty analysis for the 2060 and 2100 case. The same is true for the case with five occupants, except the 2060 case.

8.2 Uncertainty Analysis of Shading

In the LSA Chapter 6 shading system was described. This section presents the results of the UA and the special input parameter which was used in the analyses. Furthermore, not only is the result shown, but also the performance indicators are illustrated.

8.2.1 Input parameter in UA

In the DB the input parameters are called design variables. As stated in Chapter 6.2, the model is sensitive to the changes in the set point. Since none of the sensors can measure with 100% accuracy, it would be important to take this diversion into consideration. According to DesignBuilder 2020 there is currently no possibility to change the set point for the shading device exclusively. The only solution is to create different glazing templates, where every setup can be the same, while the indoor temperature's set point changes. The issue with this solution is that only a few PDF can be incorporated in the template design variables. Due to this limitation of the DB, discrete binominal PDF was chosen. As reported by Parys (2012), the typical sensor measuring inaccuracy is described by a normal distribution with a standard deviation of 0.25 °C (see Figure 20).

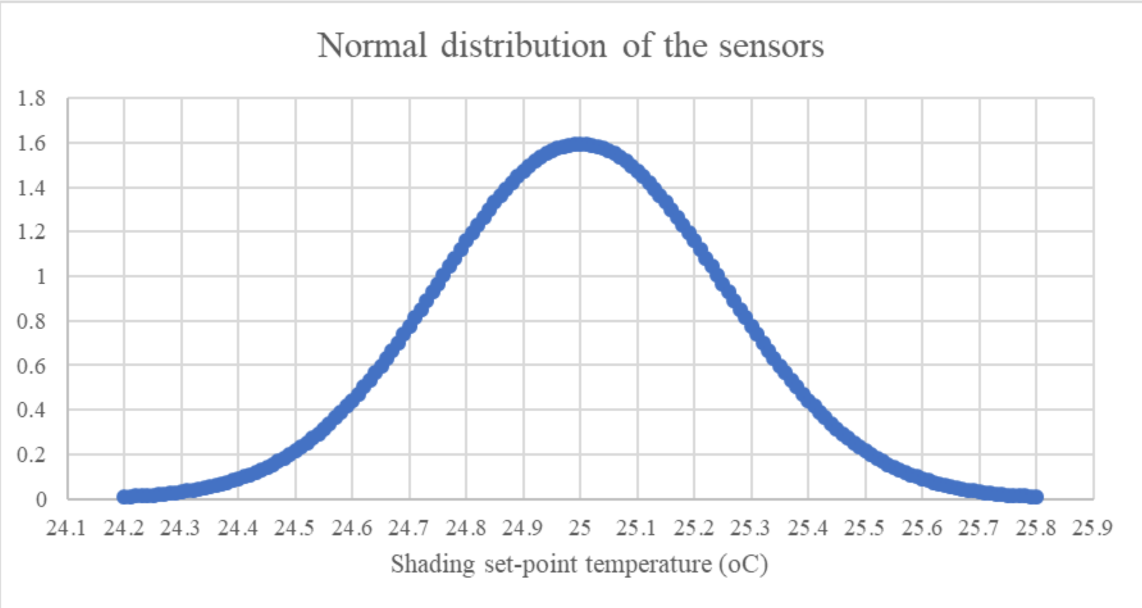


Figure 20. Normal distribution of the indoor comfort sensors' possible errors

As it was mentioned earlier, the program is not able to handle normal distribution for templates. Therefore, the closest distribution is the binominal method, which was also used through the simulations. It means that this graph should be changed to the corresponding binominal graph with the adequate values. The first step is to change the normal distribution graph to a cumulative graph (see Figure 21).

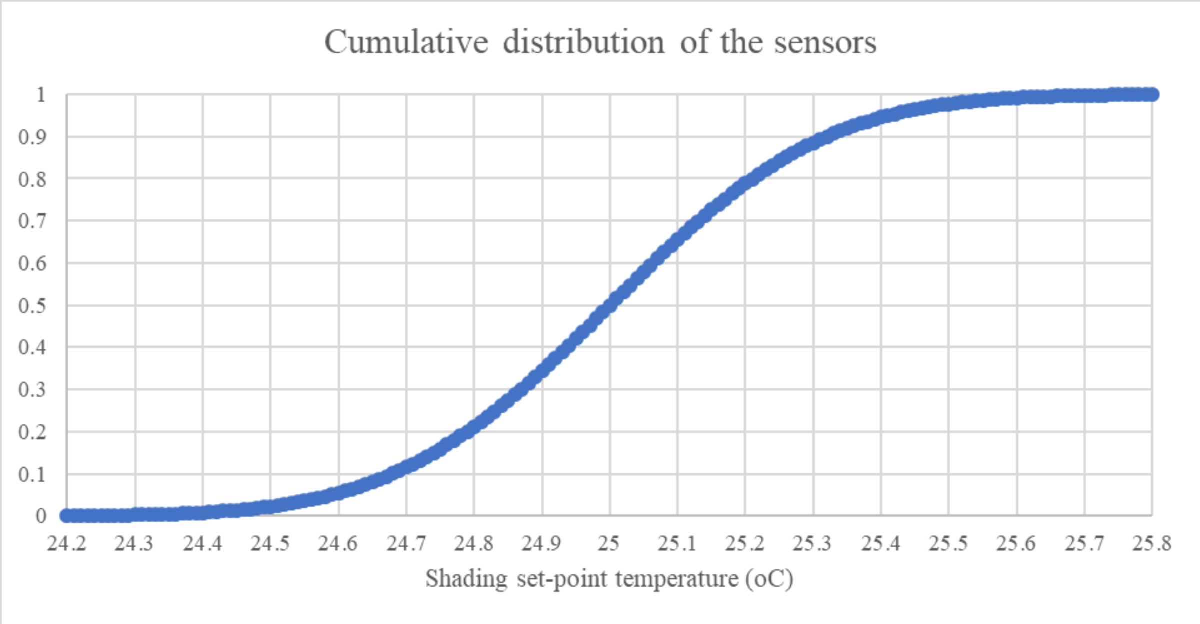


Figure 21. Cumulative curve of the indoor comfort sensors' possible errors

This change is important because the cumulative curve shows that the value of a variable is assigned to a percentage, which is associated with exactly that value or less. This way ranges can be connected to the exact percentages, for instance, there is a possibility of 13% that the set point temperature is between 24.9 and 25 ^{0}C. Following this approach, the right percentage can be connected to the corresponding temperature range. The second step was to determine the binominal parameters. Due to the limitation, 5 cases were added, meaning that the number of trials was 4 (5-1=4). The probability of success was 0.5 because this way the function was symmetrical, similar to the normal distribution, as illustrated in Figure 22.

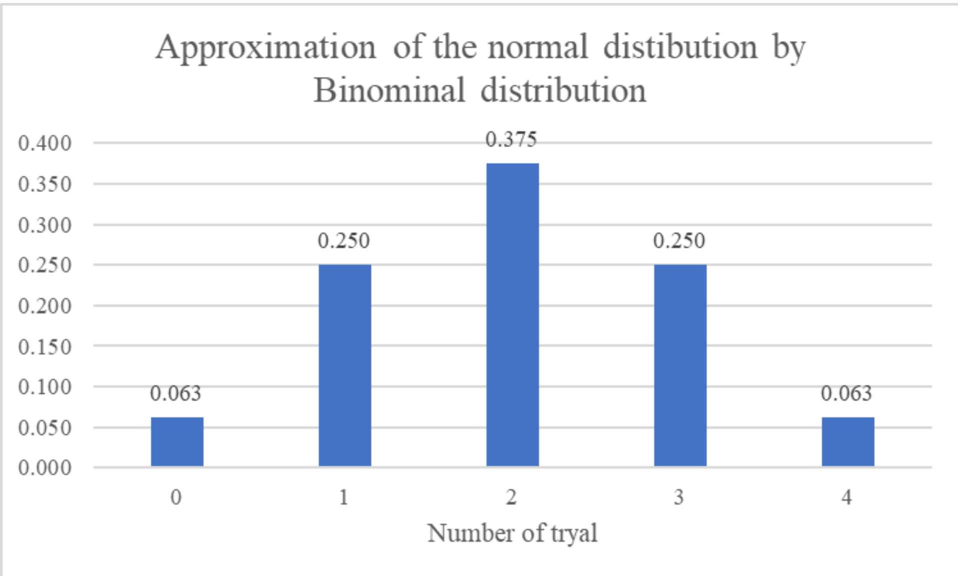


Figure 22. Approximation of the normal distribution by the binomial distribution

In the next step, the normal distribution (with a mean of 25 °C and a standard deviation of 0,25 °C) was divided into five areas, where each area has the probability described by the binomial distribution. The ranges started with 24.2 – 24.618 ^{0}C; 24.618 – 24.878 ^{0}C; 24.878 – 25.121 ^{0}C; 25.121 – 25.381 ^{0}C; and 25.381 – 25.8 ^{0}C (see Figure 23).

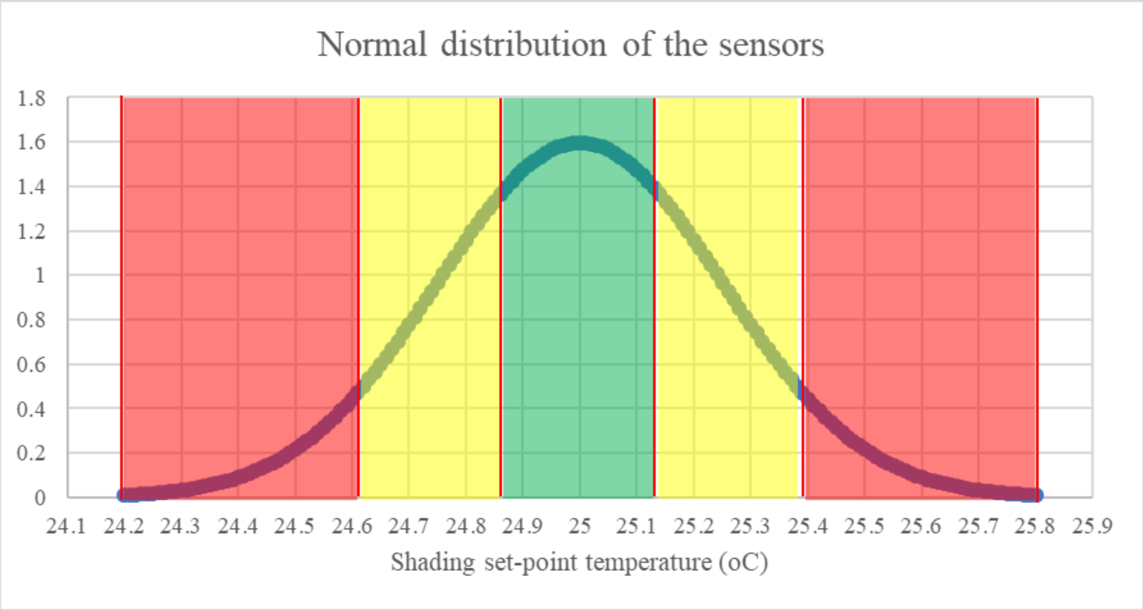


Figure 23. Five threshold ranges for the 5-binominal column

The last step was to assign one value to the five areas defined earlier. Each value represents the middle probability of the corresponding area (see Figure 24).

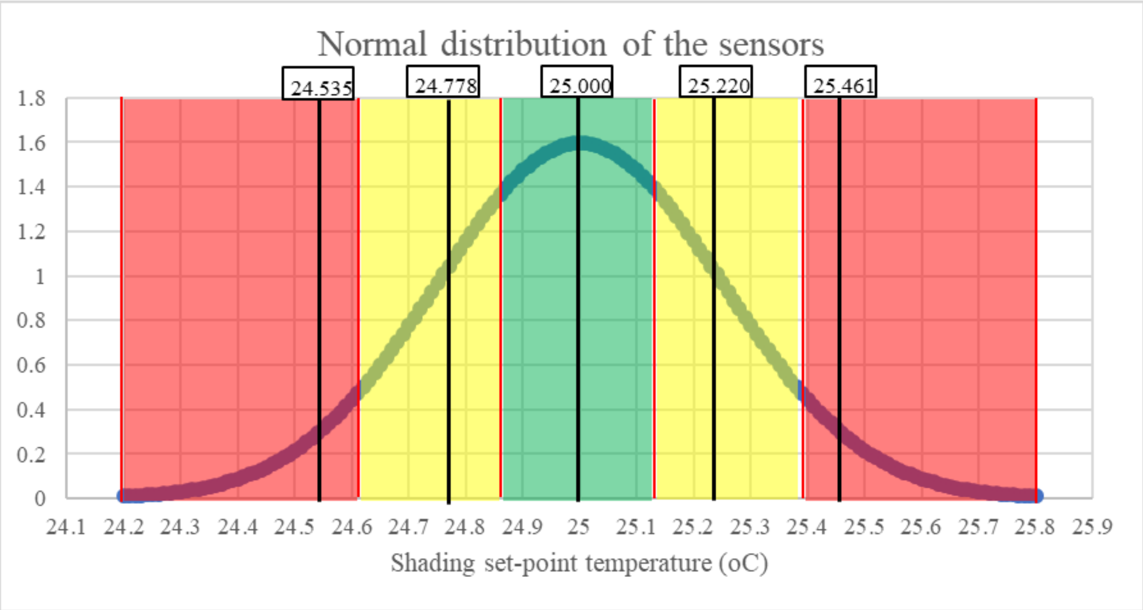


Figure 24. Five representative number from the thresholds to the binominal distribution

These 5 numbers with 0.5 probability of success and 4 numbers of trials acted the same way as the normal distribution with 25 ^{0}C of the mean value and the standard deviation of 0.25 °C. Therefore, 5 templates were created for the project and each template had its unique calculated number from Figure 24.

8.2.2 Results of the UA

Three different types of results are presented in this chapter. The first result introduces POR according to DS/EN 15251. Then the hours outside of the range according to Danish Building Regulation are presented. The final outcome is the robustness of the shading technology against climate change, changes in occupancy, and against uncertainties in the technology, the occupant schedules and extreme weather events.

According to DS/EN 15251, the comfort cannot be outside of the range for more than 5% of the year. Table 21 shows the results of POR calculations.

Case	Distribution	POR [%]		
		2020	2060	2100
2 persons	50th percentile	0.00	0.00	0.00
	Maximum	0.10	0.14	0.26
5 persons	50th percentile	0.01	0.03	0.00
	Maximum	0.16	0.32	0.55

Table 21. Percentage outside the Range of the shading system

As the table displays, the maximum percentage outside of the range is less than 1%. It means, that in the worst-case scenario, 48 hours occur through the whole year when the temperature might be worse than the adaptive comfort temperature requires. Sometimes the discomfort happens because of over-cooling, but for shading, the discomfort is caused by overheating. From the viewpoint of POR, these technologies are sufficient to keep a pleasant thermal comfort in the summer period.

The subsequent result introduces those times when the temperature exceeds 27 and 28 ^{0}C in the critical room. This thesis investigates 2 rooms: a living room and a master bedroom if two occupants live in the house. Then 5 rooms are investigated: 1-3 room(s), a living room and a master bedroom, if 5 people occupy the house. Table 22 shows the worst-case scenario for number of hours above the maximum required temperature in the critical room.

Case	No. of hours	2020	2060	2100
2 persons	>27	0.00	50.67	67.00
	>28	0.00	2.83	4.33
5 persons	>27	8.67	135.33	235.33
	>28	0.00	32.17	30.67

Table 22. Hours above 27 and 28℃ using the shading device

The regulation states that 27 ^{0}C can be exceeded for no more than 100 hours and 28 ^{0}C for no more than 25 hours. The number of hours above the limit is acceptable in more than half of the cases, but for 5 people in 2060 and in 2100 the temperature exceeds the allowed range. It is because the technology only prevents the overheating from the solar radiation. Therefore, if the weather conditions are too extreme with the internal gain, the shading itself will not be enough to cool down the building.

The last three results are based on Parys study (2012). The outcome of the technology's robustness is divided into 3 different cases, as Chapter 7.1 describes. The first one is the robustness against climate change; the second describes the robustness against changes in occupancy; and the final one illustrates the robustness against uncertainties in the technology, the occupant schedules and extreme weather events. For the 2020 case, the 2-5 people baseline model was compared with itself, 2060, and 2100 UA results. In the 2020, 2060 and 2100 two occupants baseline models were compared to the corresponding five occupants UA results. In the third robustness calculation, every deterministic analysis result was compared to the corresponding UA results.

Weather			
Case	2020	2060	2100
2 persons	-	89.7	74.3
5 persons	79.9	56.9	46.4

Table 23. Result of the robustness analyses with weather changes

As Table 23 presents, the shading was quite robust for 2 people because in the worst-case scenario the percentage almost reached 75%. It can be acceptable as stated by Parys (2012), although in that study a greater number of simulations was used. However, the shading proved to be less robust against an increasing number of occupants. The cause behind this can be the lack of shading system in the three extra rooms, even though those rooms were facing North-West and North-East. As it was described earlier, none of the constructional parts of the original building were changed, which is why no additional shading device was placed in the model. Even though the shading is active, the energy introduced to the house from solar activity cannot be avoided.

Occupant load			
Case	2020	2060	2100
2 persons	-	-	-
5 persons	25.6	32.2	40.3

Table 24. Results of the robustness analysis with the occupant load

Table 24 shows the results of the robustness analysis. For every case where 2 people baseline model was compared to its UA results, the robustness was proper. With 5 people UA results, the level of robustness was significantly lower, especially in 2020. The reason behind it can be the changed number of people and rooms. With more people, the gains in the living room change significantly, as those people use more devices, which emit heat to the living room. In those zones, the temperature can be higher.

All design variables			
Case	2020	2060	2100
2 persons	92.1	90.6	87
5 persons	79.9	78.2	83.8

Table 25. Results of the robustness analysis with all design variables

Table 25 demonstrates the comparison of the corresponding baseline and UA result model. The worst result is above 75%.

Among the three analyses, the technology was least sensitive to the combined analysis and the climate change. The shading is less robust against the increased number of people. The POR of the technology was outstanding, below 1%. In 2 out of 6 cases the hours exceeded the required number of hours below 27 and 28 degrees Celsius. To sum up, the technology is effective in terms of preventing and reducing gain from solar radiation, but it was not enough to reduce all the cooling loads in the building.

8.3 Uncertainty Analysis of Natural Ventilation

8.3.1 Probability density functions

According to the results of local sensitivity analysis presented in Chapter 6.3, the important parameters influencing natural ventilation are:

- Natural ventilation cooling setpoint
- Weather data and occupant schedule (those were not calculated in the LSA but determined uncertain by default)

These parameters are also referred to as design variables and were previously described in Chapter 7. Table 26 shows the design variable specific for the natural ventilation, together with all the data required for the DesignBuilder.

Design variable	Distribution parameters	Distribution curve/category	Variable values	Target
Natural ventilation setpoint	Mean 26°C Standard deviation 0.25	Normal/Continuous	-	Building

Table 26. Design variables in the DesignBuilder for natural ventilation UA

8.3.2 Results of the UA, natural ventilation

In this part of the report, the results of uncertainty analysis for natural ventilation are presented, based on KPI-s introduced in Chapter 2.6. The results include:

- Percentage outside range (POR), based on DS/EN 15251
- Hours outside of the range, based on The Danish Building Regulations 2018
- Robustness, based on weather, occupancy and technology-related uncertainties

According to DS/EN 1525, the indoor environmental parameters meet the demands of a particular category, when no more than 3% or 5% of occupied hours per year are outside of the limits of that category (European Comittee for Standardization 2007).

The results of POR for natural ventilation are gathered in Table 27.

Case	Distribution	POR [%]		
		2020	2060	2100
2 persons	50th percentile	0.00	0.05	0.01
	Maximum	0.24	0.16	0.26
5 persons	50th percentile	0.00	0.07	0.05
	Maximum	0.10	0.22	0.12

Table 27. Percentage outside the range of the natural ventilation

As it can be observed in Table 27, there is no POR greater than 1%. The highest POR is 0.26% for 2 people in 2100. This means 23 hours in the entire year, when the temperatures are outside of the adaptive comfort cat. II required range. Therefore, natural ventilation itself is sufficient to maintain satisfactory thermal comfort of the occupants throughout all the examined years.

The Danish Building Regulation 2018 states that the maximum number of hours exceeding 27°C throughout a year should be 100 and the maximum number of hours exceeding 28°C should be 25 for a critical room (Ministry of Transport, Building and Housing 2017).

The number of hours outside the specific BR ranges are for natural ventilation are shown in Table 28.

Case	No of hours	2020	2060	2100
2 persons	>27	0	91	111
	>28	0	0	0
5 persons	>27	0	149	151
	>28	0	33	6

Table 28. Hours above 27 and 28 degrees Celsius for the critical rooms, natural ventilation

As it can be seen in Table 28, there are no hours above 27°C or 28°C in the year 2020. In 2060, 27 degrees of Celsius is exceeded in both the 2 and 5-person cases. For the 5-person scenario, there is also a number of hours above 28°C. This can be caused by the fact that there are higher internal loads when the house is occupied by 5 people (both from the occupants and from the devices). In 2100, the temperatures exceed the required limits for 27°C but not for 28°C, which cannot be explained considering that 2100 is warmer according to the previously analyzed weather data.

The results of robustness are divided into three categories: robustness against weather (climate change), against occupancy, and robustness against climate change and occupancy together with technology-related uncertainties.

As for the robustness against climate change, the goal was to examine the probability that the 2020 deterministic analyses results were achieved by the uncertainty analyses of 2060 and 2100 weather data.

For both cases (and correspondingly for 2 and 5 people), the calculated robustness of natural ventilation was 0, meaning that the technology is not robust against climate change, and that the baseline results of the 2020 case are lower than the lowest result of the uncertainty analysis for the 2060 and 2100 case.

As for the robustness against occupant density, the probability of the deterministic analyses results for 2 people being reached by the UA for 5 person-case in three separate years was estimated. The results of the calculations are shown in Table 29.

Occupant load			
Case	2020	2060	2100
5 persons	76.7	42.3	11

Table 29. Robustness against the occupant load for natural ventilation, given in %

As it can be observed, the robustness against occupancy-related uncertainties is the highest for 2020 and the lowest for 2100.

For the robustness against technology, weather and occupational time related uncertainties, the results are gathered in Table 30.

Technology, climate and occupational time			
Case	2020	2060	2100
2 persons	93.3	82.7	87.2
5 persons	76.7	92.1	93.4

Table 30. Robustness of the natural ventilation against the technology-related uncertainties, weather changes and occupational time for 3 different years, given in %.

As before, the results were obtained by calculating the probability of uncertainty analysis achieving the results of the deterministic analysis. As it can be seen, the probability does not go below 76%, which means that robustness of the natural ventilation is high in all the cases.

8.4 Results of the uncertainty and deterministic analyses for the combined technologies

The results of the uncertainty and deterministic analyses for the case when all the three analyzed technologies were applied are summarized in Table 31, Table 32 and Table 33. In Table 31, the distribution of the POR for the six examined cases is characterized by its highest value and its median. The results of the corresponding deterministic analyses are also given, stating the POR outside the DS/EN 15251 adaptive limits, and the POR excluding undercooling (considering only the cases when the operative temperatures were higher than upper adaptive limits).

Case	Analysis type	Distribution	POR, %		
			2020	2060	2100
2 persons	Uncertainty analysis	Median	0.00	0.04	0.00
		Maximum	0.34	0.33	0.32
	Deterministic analysis	Outside adaptive limits	0.06	0.16	0.15
		Over adaptive limits	0.00	0.00	0.00
5 persons	Uncertainty analysis	Median	0.00	0.00	0.00
		Maximum	0.52	0.32	0.43
	Deterministic analysis	Outside adaptive limits	0.00	0.17	0.15
		Over adaptive limits	0.00	0.00	0.00

Table 31. Results of the uncertainty and deterministic analyses for the combined technology case. Values exceeding the 5% limit were highlighted.

According to both the uncertainty and deterministic analyses, the 5% limit suggested by DS/EN 15251 was never exceeded. In contrast to the cases where only one technology was applied, the results do not show clear trends: the warmer weather does not always result in a higher value of POR. Based on the deterministic analysis results, this is probably caused by the fact that the warmer weather results in less undercooling, since there was no overheating in any of the deterministic results.

The combined technologies show very good results considering the Danish Building Regulations as well. This could be assessed only for the results of the deterministic analyses, since the DesignBuilder software provided hourly results only for this type of analysis. According to the results shown in Table 32, the combined technologies almost never resulted in temperatures exceeding the temperature limits set by the Danish Building Regulations.

Case	No. of hours	2020	2060	2100
2 persons	>27	0.00	0.00	0.00
	>28	0.00	0.00	0.00
5 persons	>27	0.00	4.75	0.70
	>28	0.00	0.00	0.00

Table 32. Performance of the combined technologies considering the Danish Building Regulations.

The outcomes of the robustness calculation are summarized in Table 33. The robustness calculation is described in detail in Chapter 7.1. The robustness of the examined technologies is compared in Chapter 9.

Robustness type	No. of occupants	Probability, %		
		2020	2060	2100
Robustness for technology, weather and occupational time related uncertainties	2	89.9	86.1	65.4
	5	85.0	96.4	92.0
Robustness for climate change	2	-	55.9	61.9
	5	-	43.3	65.0
Robustness for number of occupants	5	94.8	86.2	95.3

Table 33. The results of the robustness-calculation of the combined technology case.

Based on the robustness calculation results, the combination of technologies proved to be robust against the technology, weather and occupational-time related uncertainties, when considering the POR criteria. The combined technologies were found to be similarly robust against the increasing number of occupants as well.

Lower robustness was found against climate change, but the values are still comparatively high (see Chapter 9), with an average of 56.5%.

9. Comparison of the uncertainty analysis and robustness calculation results of the examined technologies

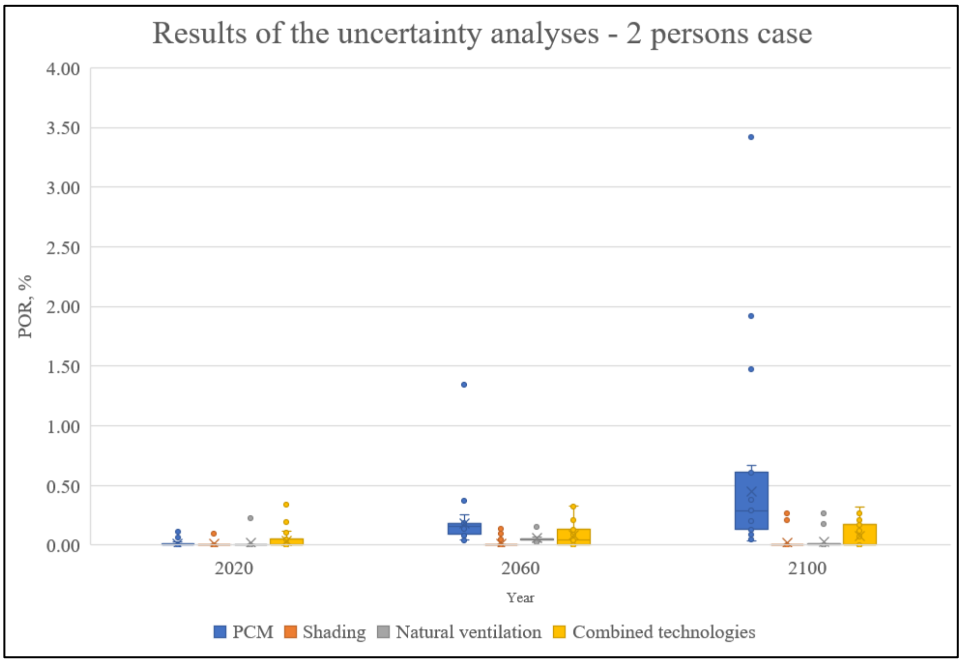


Figure 25. Results of the uncertainty analyses for the examined technologies in the cases with 2 persons. The lower end of the boxes depicts the lower 25th percentile, and the upper end of the boxes depicts the 75th percentile of the distributions. The lines in the boxes show the median and the 'x' marks the mean.

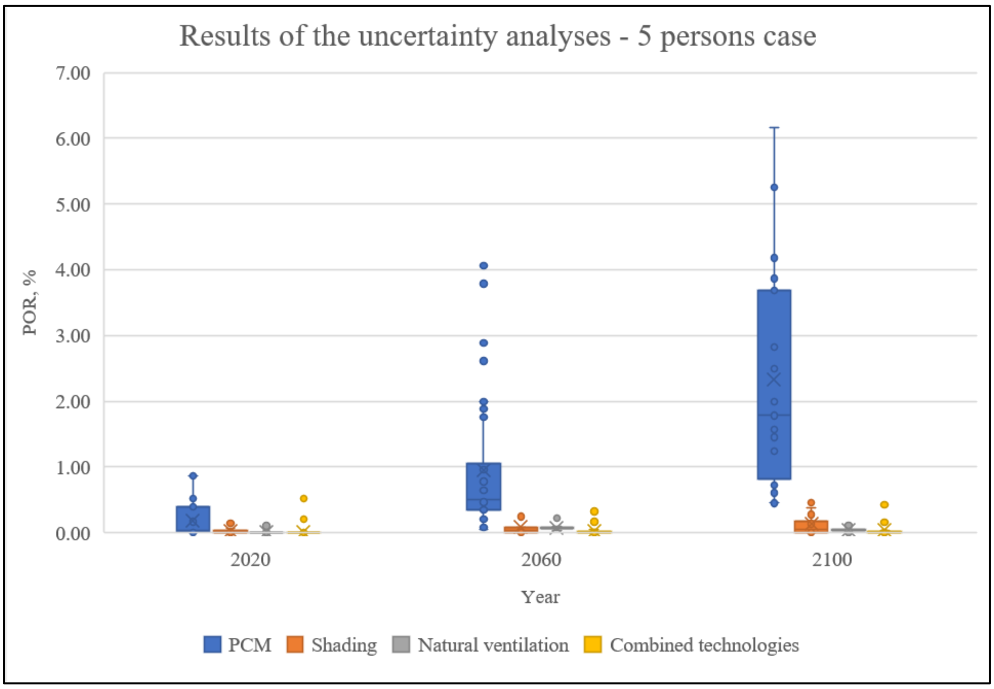


Figure 26. Results of the uncertainty analyses for the examined technologies in the cases with 5 persons. The lower end of the boxes depicts the lower 25th percentile, the upper end of the boxes the 75th percentile of the distributions. The lines in the boxes show the median and the `x` marks the mean.

The results of the uncertainty analyses for the analyzed technologies are compared in Figure 25 and Figure 26. The external shading, the natural ventilation and the combination of the three technologies show similar and very low POR values for the adaptive criteria of DS/EN 15251. The application of PCM technology resulted in significantly higher POR values, however, for the majority of the cases, it was still below the 5% limit suggested by the standard.

9.1 Robustness against the technology, weather and occupational time related uncertainties

The robustness against the technology, weather and occupational time related uncertainties of the examined technologies is compared in Figure 27 and Figure 28.

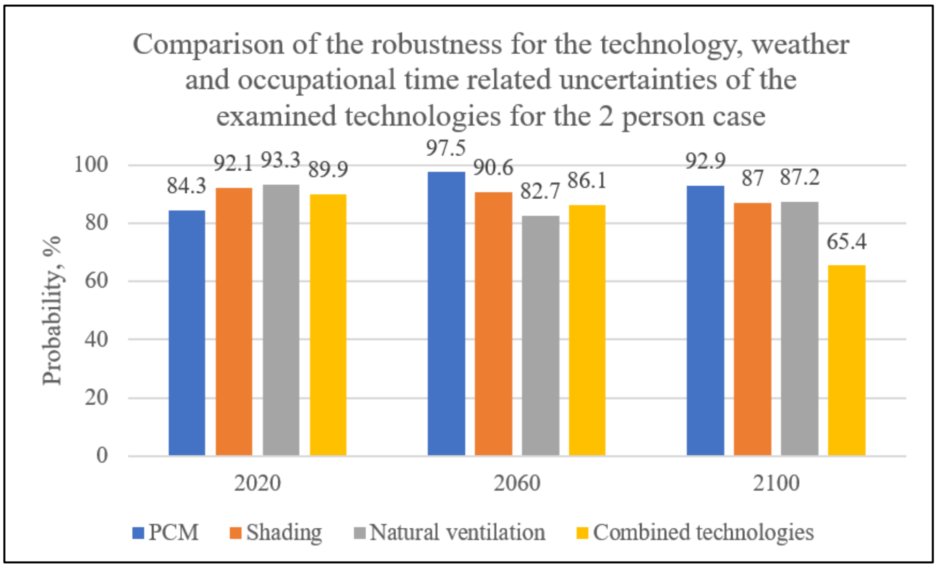


Figure 27. The robustness of the examined technologies against the technology, weather and occupational time related uncertainties for the 2-person cases.

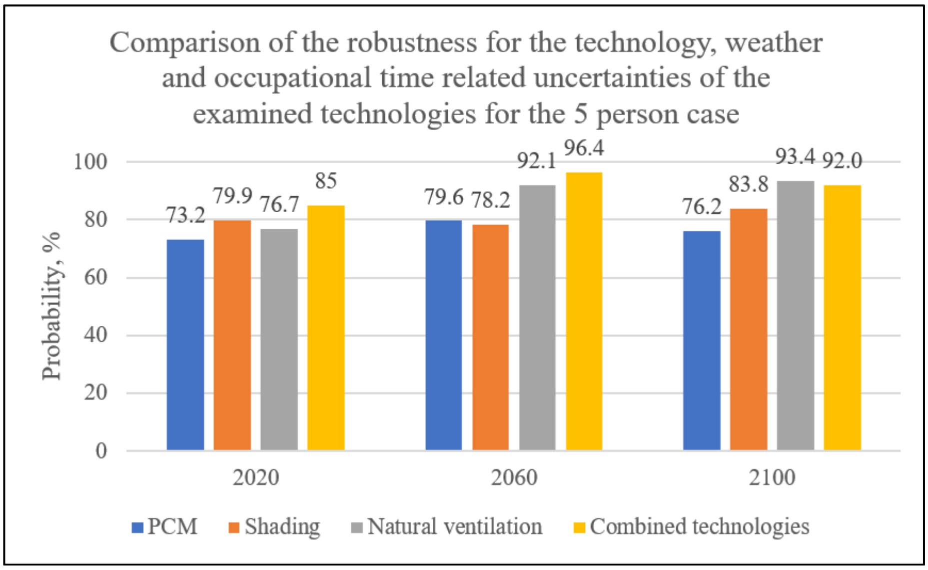


Figure 28. The robustness of the examined technologies against the technology, weather and occupational time related uncertainties for the 5-person cases.

This was determined by calculating the probability that the deterministic analysis results are achieved in the corresponding uncertainty analysis.

For the analyzed cases with two persons, all the technologies show similar robustness. The case with the combined technologies for 2100 shows a slightly lower robustness, which can probably be attributed to a good baseline result. The cases with five occupants show similar results as well, with the shading and the combination of technologies having the highest robustness for the majority of the cases.

9.2 Robustness against climate change

The robustness against climate change was determined by calculating the probability that the 2020 deterministic analyses results are achieved by the corresponding uncertainty analyses considering 2060 and 2100 weather data.

The robustness calculation for global warming resulted in significantly different values for the examined technologies (see Figure 29). The natural ventilation shows zero robustness against climate change, which means that there is zero probability that the deterministic analysis result of the 2020 is achieved in the uncertainty analysis for the 2060 and 2100 case. This happens when the baseline result of the 2020 case is lower than the lowest result of the uncertainty analysis for the 2060 and 2100 case. The same is true for the PCM technology, except the 2060 case with five occupants.

The shading, on the other hand, shows very high robustness against global warming. It resulted in even higher robustness than the case with the combined technologies, except the 2100 model with five occupants.

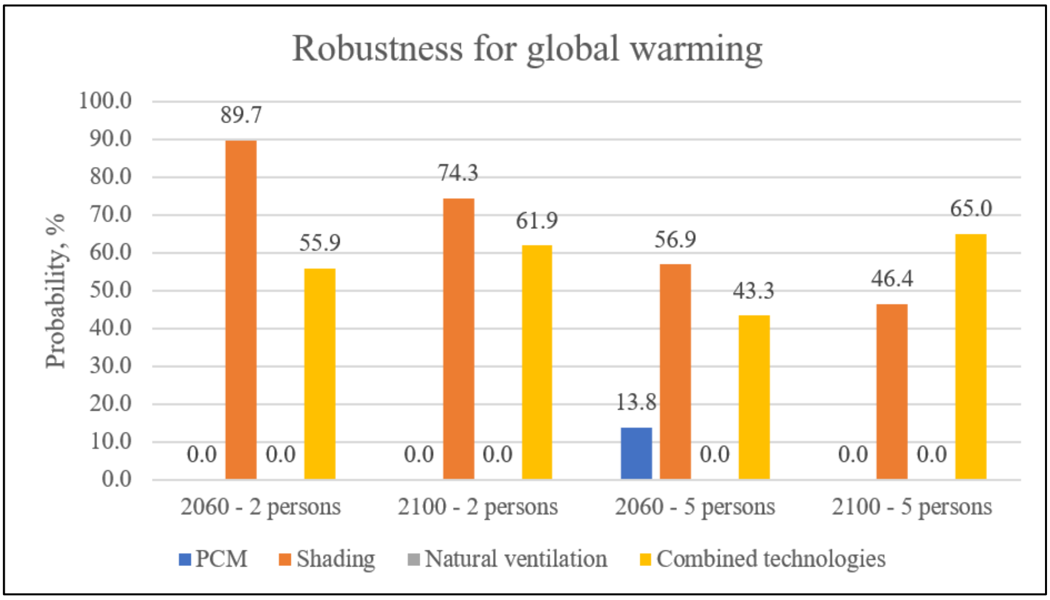


Figure 29. The robustness of the examined technologies against the global warming.

9.3 Robustness against higher occupant density

The robustness against higher occupant density was determined by calculating the probability that the deterministic analyses results for the two person cases are achieved by the corresponding uncertainty analyses with 5 persons.

In this case, the combination of technologies proved to be the most robust, by achieving very high robustness for all the examined cases. The three analyzed technologies show lower robustness against a higher occupant density, with the following average results:

- PCM: 35%
- Shading: 32.7%
- Natural ventilation: 43.3%

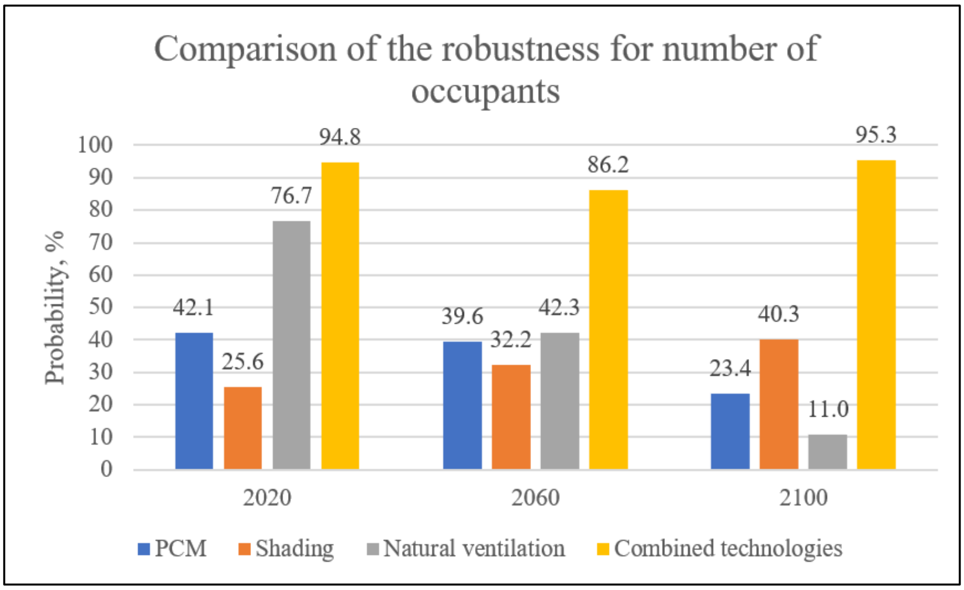


Figure 30. The robustness of the examined technologies against higher occupant density.

9.4 Comparison of the number of hours above the limit temperatures of the Danish Building Regulations

The number of hours above 27 and 28 °C was determined based on the deterministic analyses. The values for the examined technologies are compared in Figure 31 and Figure 32.

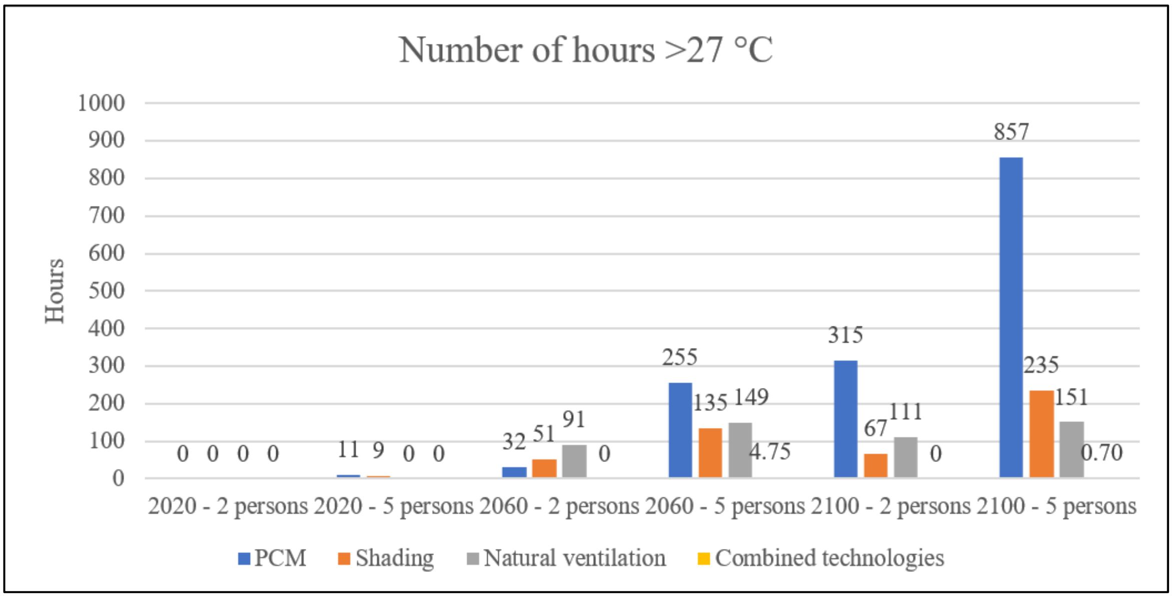


Figure 31. Comparison of the number of hours above 27 °C for the examined technologies.

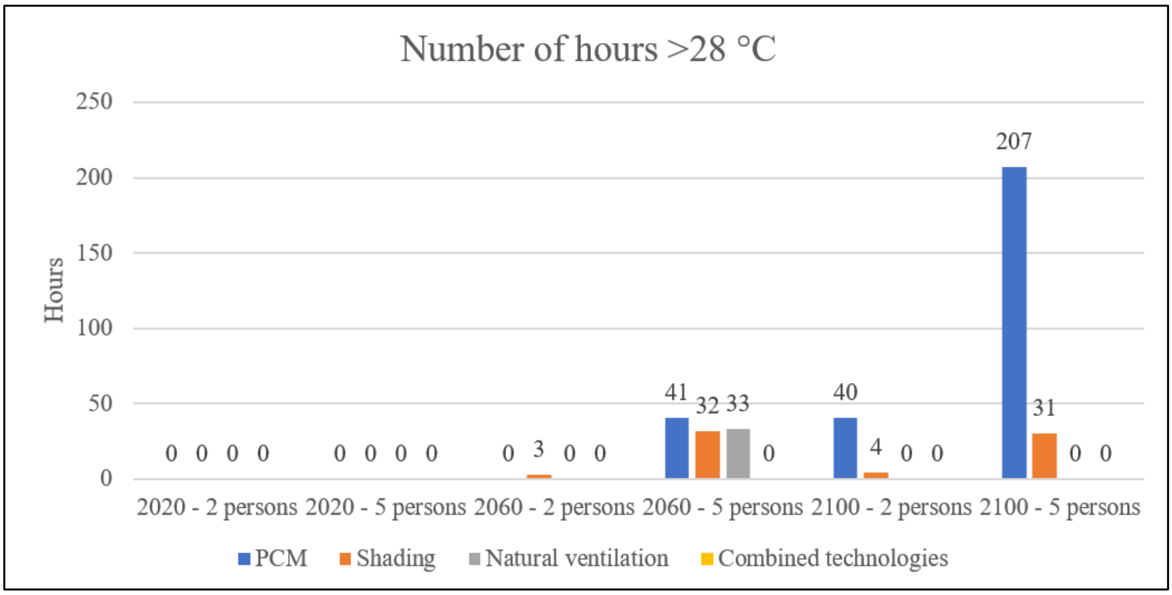


Figure 32. Comparison of the number of hours above 28 °C for the examined technologies

Based on the comparison, the combined technologies can provide the best comfort according to the Building Regulations. For the number of hours above 27 °C, the natural ventilation and the shading has similar values, while in case of the hours above 28 °C, the natural ventilation shows slightly better results, since it is above the limits of the regulation only in one case. The PCM technology proved to be the worst by a big margin based on both the number of hours above 27 and 28 °C.

10. Conclusion

10.1 Final conclusion

In this project, the resilience of three cooling techniques (external shading, natural ventilation and PCM) was investigated, with a focus on climate change and increased occupant loads. A technology was considered more resilient if it provided better comfort and was more robust – this was determined by conducting uncertainty analyses.

Before the uncertainty study, the most influential parameters were found using local sensitivity analysis:

- For the shading: the uncertainty in the setpoint and in the mechanical ventilation rate
- For the natural ventilation: the setpoint
- For the PCM: the melting temperature and the mechanical ventilation rate was found to be the most important

The comfort was evaluated based on the adaptive criteria of DS/EN 15251 using the POR value, and according to the requirements of BR18 (number of hours above 27 and 28 °C). In terms of the POR results, the shading, natural ventilation and the combination of the three technologies can provide good comfort. When considering the requirements of the building regulations, the shading and natural ventilation provided similar results, breaching the limits several times when using future weather data. The combined technologies, however, provided acceptable comfort based on BR18 as well, in every case. The PCM technology proved to be the worst in terms of comfort, regarding both the adaptive criteria and the limits of BR18.

The robustness analyses showed that the combination of technologies is the most optimal, while the shading also performed well:

- Considering the robustness against the technology, weather and occupational time related uncertainties, all technologies provided similar results.
- The PCM and natural ventilation have almost no robustness against climate change, while the shading and the combined technologies show similar values.
- However, in terms of the robustness against a larger occupant load, the combination of technologies gave outstanding results.

Based on the comfort and robustness analyses made, it was found that the combination of technologies shows the highest resiliency. In terms of the individual technologies, shading provided the best results, followed by the natural ventilation.

10.2 Proposals for further thesis development

The last chapter of this report presents suggestions for further development of the subject of resilient cooling. After four months working with different angles of the topic, the authors propose the following:

- There is a variety of other cooling methods that can be investigated. For the first round, the authors recommend night ventilation and air to earth heat exchanger. Nevertheless, before starting on a new technology, it is vital to get familiar with the capabilities and limitations of the DesignBuilder software.
- There are different methodologies that can be used for the determination of important parameters of the technologies. In this thesis, the authors varied the value of each input with +10%, but it would be even more precise to use ranges instead. The ranges for shading and natural ventilation were investigated and can be found in Appendix 12.7-12.8.
- With the possibility to analyse hourly simulation results in the DesignBuilder UA tool, the research performed in this report can be improved in the following way:
  - More key performance indicators can be determined (i.e. degree hours). The biggest obstacles in this case are the limitations of the DesignBuilder software, however, there is a possibility to use other programs (i.e. JEPlus).
  - Given the right software, the overheating and undercooling hours could be analysed separately for the UA results as well. This way, the evaluation would be more precise.
- The robustness against uncertainties related to occupancy time, climate change and technologies were investigated together in this report. However, taking into consideration the required time, these could be examined separately, with separate uncertainty analyses.
- For this thesis, thermal comfort was investigated solely. Nevertheless, there are other aspects that should be considered when implementing cooling in a residential building, especially regarding the sustainability of the solutions. The authors of this thesis created a table, that summarizes all the KPIs and influential factors which shall be considered when designing for cooling. For the above-mentioned table, see Appendix 12.9.
- In this report, only three out of four main components of resilience were evaluated. For further project development, it is suggested to evaluate rapid recovery of different cooling solutions, as that would give a complete picture of resiliency and create a possibility to develop guidelines for resilient cooling design.

We hope that our suggestions will be useful for the future generations of Building Energy Design students and we wish them all the best with the development of the subject.

11. Bibliography

ASCHEHOUG, Ø, ANDRESEN, I., HAGHIGHAT, F., HEISELBERG, P., LI, Y., OLESEN, B.W., PERINO, M., PRINCIPI, P., SILVA, F.M.D., YOSHIE, R. and ZHANG, J., 2008. *Integrating Environmentally Responsive Elements in Buildings - State-of-the-art Review : Vol. 1. State-of-the-art Report.*

BELLERI, A., LOLLINI, R. and DUTTON, S.M., 2014. Natural ventilation design: An analysis of predicted and measured performance. *Building and Environment,* **81**, pp. 123-138.

BREESCH, H. and JANSSENS, A., 2010. Performance evaluation of passive cooling in office buildings based on uncertainty and sensitivity analysis. *Solar Energy,* **84**(8), pp. 1453-1467.

CARPINO, C., LOUKOU, E., HEISELBERGB, P. and ARCURIA, N., 2018. *Energy performance gap of a nZEB: influence of occupancy modelling.* Calabria & Aalborg: University of Calabria & Aalborg University.

CHI-HSIANG WANG and LAM PHAM, Resilience and Robustness. *Abstract,* .

CORE WRITING TEAM, PACHAURI, R.K. and MEYER, L.A., 2014. *Climate Change 2014: Synthesis Report.* Geneva, Switzerland: IPCC.

CORE WRITING TEAM, PACHAURI, R.K. and REISINGER, A., 2007. *Climate Change 2007: Synthesis Report.* Geneva, Switzerland: IPCC.

CORE WRITING TEAM and WATSON, R.T., 2001. *Climate Change 2001: Synthesis report.* Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press.

DESIGNBUILDER, 2020-last update, DesignBuilder Help. Available: https://designbuilder.co.uk/helpv6.0/#GetStarted.htm%3FTocPath%3DGet%2520Started%7C_____0.

EBC EXECUTIVE COMMITTEE SUPPORT SERVICES UNIT, 2019. *Resilient Cooling - EBC ANNEX 80 Factsheet.* EBC Executive Committee Support Services Unit.

EDUCBA, 2019-last update, Percentile Rank Formula. Available: https://www.educba.com/percentile-rank-formula/2020].

EUROPEAN COMITTEE FOR STANDARDIZATION, 2007. *DS/EN 15251.*

GIVONI, B., 2011. Indoor temperature reduction by passive cooling systems. *Solar Energy,* **85**(8), pp. 1692-1726.

HEISELBERG, P., BROHUS, H., HESSELHOLT, A.T., RASMUSSEN, H.E.S., SEINRE, E. and THOMAS, S., 2007. *Application of Sensitivity Analysis in Design of Sustainable Buildings.* Chongqing University.

HERRERA, M., NATARAJAN, S., COLEY, D.A., KERSHAW, T., RAMALLO-GONZÁLEZ, A.P., EAMES, M., FOSAS, D. and WOOD, M., 2017. A review of current and future weather data for building simulation. *Building Services Engineering Research and Technology,* **38**(5), pp. 602-627.

IEN CONSULTANTS, 2016-last update, Housing 2020 with low energy consumption and high user comfort. Available: https://energiteknologi.dk/da/project/bolig-2020-med-lavt-energiforbrug-og-hoej-brugerkomfort.

JOHRA, H. and HEISELBERG, P., 2016. *Description and Validation of a MATLAB: Simulink Single Family House Energy Model with Furniture and Phase Change Materials.* Aalborg: .

KEIDING, L., GUNNARSEN, L., ROSDAHL, N., MACHON, M., MØLLER, R. and VALBJØRN, O., 2003. *Miljøfaktorer i danskernes hverdag : med særligt fokus på boligmiljø.* Coppenhagen: Kbh. : Statens Institut for Folkesundhed.

KIM B. WITTCHEN, 2004. *Vurdering af potentialet for varmebesparelser i eksisterende boliger.* 1st edn. By og Byg Statens Byggeforskningsinstitut.

KNUDSEN, H.N. and KRISTENSEN, L., 2010. *Power Point præsentation: Fremtidens Parcelhuse med fokus på brugertilfredshed.*

KOLOKOTRONI, M. and HEISELBERG, P., 2015. *Ventilative Cooling - State of the art review.* Aalborg, Denmark: Department of Civil Engineering, Aalborg University.

KUZNIK, F., VIRGONE, J. and NOEL, J., 2008. Optimization of a phase change material wallboard for building use. *Applied Thermal Engineering,* **28**.

LEE, E., SUH, S. and SHON, J., 1998. A comprehensive method for calibration of volumetric positioning accuracy of CNC-machines. *The International Journal of Advanced Manufacturing Technology,* **14**(1), pp. 43-49.

LIU, M., 2018. *PASSIVE COOLING, NATURAL COOLING AND THERMAL MASS - Lecture notes.*

LIU, M., 2015. Sensitivity analysis. *European journal of operational research,* , pp. 869-887.

LOUKOU, E., HEISELBERG, P.K., JENSEN, R.L. and JOHRA, H., 2019. Energy performance evaluation of a nearly Zero Energy Building and the reasons for the performance gap between expected and actual building operation. *IOP Conference Series: Earth and Environmental Science,* **352**, pp. 12017.

MATHEMATICS, *SCHOOL OF ENGINEERING & BUILT ENVIRONMENT.*

MAZO, J., EL BADRY, A.T., CARRERAS, J., DELGADO, M., BOER, D. and ZALBA, B., 2015. Uncertainty propagation and sensitivity analysis of thermo-physical properties of phase change materials (PCM) in the energy demand calculations of a test cell with passive latent thermal storage. *Applied Thermal Engineering,* **90**, pp. 596-608.

MINISTRY OF TRANSPORT, BUILDING AND HOUSING, 2017. *Building Regulations 2018 (BR18).*

NATIONAL INSTITUTE OF BUILDING SCIENCES, 2018-last update, Building Resilience. Available: https://www.wbdg.org/resources/building-resiliency.

O'DONNAVAN, A., O'SULLIVAN, P., HEISELBERG, P., HOLZER, P., PSOMAS, T., JUSTO-ALONSO, M., KOLOKOTRONI, M., POMIANOWSKI, M., ZHANG, G., CARRILHO DA GRACA, G., BREESCH, H., BELLERI, A. and FLOURENTZOU, F., 2018. *Ventilative Cooling Design Guide.* Aalborg, Denmark: Department of Civil Engineering, Aalborg University.

OLESEN, M., SKOVGAARD MADSEN, K., ANKJÆR LUDWIGSEN, C., BOBERG, F. and CHRISTENSEN, T., 2014. *Fremtidige klimaforandringer i Danmark.*

OROPEZA-PEREZ, I. and ØSTERGAARD, P.A., 2018. Active and passive cooling methods for dwellings: A review. , pp. 531–544.

PARYS, W., BREESCH, H., HENS, H. and SAELENS, D., 2012. Feasibility assessment of passive cooling for office buildings in a temperate climate through uncertainty analysis. *Building and Environment,* **56**, pp. 95-107.

POUL E. KRISTENSEN, 2017. *Sketch for the management strategy for ventilation and heating for Bolig 2020.* IEN Consultants.

SALTELLI, A., RATTO, M., ANDRES, T., CAMPOLONGO, F., CARIBONI, J., GATELLI, D., SAISANA, M. and TARANTOLA, S., 2008. *Global Sensitivity Analysis. The Primer.* London: John Wiley & Sons Ltd.

SPITZ, C., MORA, L., WURTZ, E. and JAY, A., 2012. Practical application of uncertainty analysis and sensitivity analysis on an experimental house. *Energy & Buildings,* **55**, pp. 459-470.

YILDIZ, Y. and ARSAN, Z.D., 2011. Identification of the building parameters that influence heating and cooling energy loads for apartment buildings in hot-humid climates. *Energy,* **36**(7), pp. 4287-4296.

ZHANG, C., 2017. *User Profiles Bolig 2020.* Aalborg: Aalborg University.

ZSEMBINSZKI, G., MORENO, P., SOLÉ, C., CASTELL, A. and F.CABEZA, L., 2014. Numerical model evaluation of a PCM cold storage tank and uncertainty analysis of the parameters. *Applied Thermal Engineering,* **67**(1-2), pp. 16-23.

12. Appendixes

12.1 Appendix for technologies and KPI-s

SINK	MEDIUM	DISTRIBUTION		TERMINAL DEVICE
1. Outdoor Air	**Air**	Natural Vent.	Day	-
			Night	
		Mechanical Vent.	Day	Diffuser
			Night	
2. Ground	**Air**	Natural Vent.		Diffuser
		Mechanical Vent.		Diffuser
	Water	Water Circulation		Floor/Roof Cooling
				Convective Panels
				Radiation Panels
3. Sky	**Air**	Mechanical Vent.		Diffuser
	Water	Water Circulation		Floor/Roof Cooling
				Convective Panels
				Radiation Panels

Table 34. Division of cooling technologies according to natural sinks (Per Heiselberg 2019).

Heat sinks:

"Heat sink is a process where the indoor heat gains are transported into a sink, which is then used as a heat releaser. There is no heat storage in the heat sink. Examples of natural heat sinks include: water body, ground or other massive bodies, to which heat is driven during the daytime and then released during the nighttime." (Oropeza-Perez, 2017)

Technology	Limitations	Price/Cost (US prices)	Possibility of making in the Design Builder
Natural Ventilation	-Applicable in all building types. -In regions with moderate wind speeds (outlet can be supported by fan if necessary) (Givoni, 2011).	-For fans the prices are between 10 and 250 euro (Oropeza-Perez, 2017).	**YES**
Nocturnal Vent.	-Applicable in all building types. - In regions without sufficient wind speed at night, outlet can be supported by fan if necessary. -Its effectiveness ventilation cooling depends on the diurnal temperature swing. Applicable in regions with diurnal swings of more than about 8°C. -In colder climates, it can improve the comfort of the occupants when sleeping but the ability to lower the indoor temperatures during the day is limited (Givoni, 2011).	-For fans the prices are between 10 and 250 euro (Oropeza-Perez, 2017).	**YES**
Radiant Cooling	-Applicable only to low-rise buildings when using roof as the cold collector. -Most effective in regions that have clear sky conditions during the evening/nighttime. -Corrugated metal roofs have to be covered with insulation that is fire protected. -Includes insulation that has to be movable either manually or automatically (Givoni, 2011). -The performance of the system depends on the amount of insulation and thermal mass of the building -Affected negatively by high relative humidity. -Insulation should be firmly attached to avoid being blown away.	-The system is expected to be very expensive, especially if the insulation is to be moved automatically (Fernandez, 2015).	**YES** (for the attic space above the house) **NO** (for the water filled bags and movable insulation)
Radiant cooling panels	-Prone to condensation. -Commercially not that available.	-30-35 dollars to be installed (Messana, 2019).	**Not found (YES?)**
Direct Evaporative Cooling Evaporative Cooling Tower Spraying Droplets of Water on the Roof	-Not applicable in hot humid areas. -Includes implementation of for example a small pond in the house or a cooling tower. -Usually needs fan at the top to increase the cooling power. -Popular in the US and Mexico in but not in Europe. -Performance dependent on the dry bulb temperature depression.	-One ceramic porous wall to cool 120m^2 can cost approx. 1800 euro at the stage of implementation with the advantage of having practically no maintenance.	**Not found (YES?)**

	-Surface temperature of the building part is lower, but the inside temperature is not significantly lower (Givoni, 2011).		
Indirect Evaporative Cooling	-Can be used in all the climates. -Requires a heat exchanger. -Significant water consumption. -Cooling process limited by the WB temperature. -Not so typical for application in residential buildings. -Potential limited due to the difference between DBT and WBT.	-1 to 15 American dollars per cfm.	**YES**
Direct Ground Cooling	-Economic limitations, daylight aspects, condensation especially in humid climates and indoor air quality. -Soil should be in direct contact with the construction part without additional insulation layer in between, meaning the system is applicable only in regions with hot summers and mild winters with very rare rains (Givoni, 2011).	-Not found (strictly depending on the system type).	**NO**
Indirect Ground Cooling Air to Earth Heat Exchanger	-Involves a hybrid system (a fan is required to circulate the air inside the building). -Humidity should be taken into consideration as condensation can occur in the pipes (Wilson, 2015).	-Usually 5-6% of the house construction costs.	**YES**

Table 35 Possible cooling technologies description (Givoni 2011)

Shading - no matter on which side of the glazing it is placed, the purpose of shading is to control/limit solar radiation, which in the end is transformed into an internal heat gain. There is a wide array of shading possibilities including overhangs, external blinds, shutters, building self-shading and curtains. In order to apply proper shading, factors such as building's location, sun position, sky condition and visual comfort have to be examined (Oropeza-Perez, 2017).

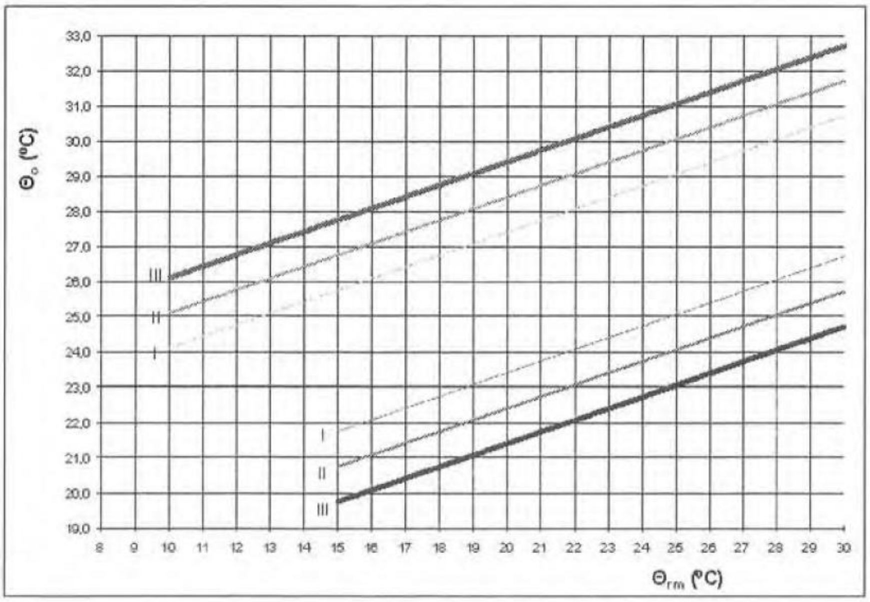
Natural ventilation - the introduction of outdoor air into the room, driven either by wind pressure or buoyancy (stack effect). These two natural forces can be used for natural ventilation separately or together and create natural air inlet and outlets. For cooling purposes, natural ventilation can be used as cooling of the inside air (if the temperature inside is higher than the temperature outside), cooling of the structure through convention or direct cooling over skin using evapotranspiration. (Oropeza-Perez, 2017)

Phase change materials (PCM) - materials, that have a very low melting point. The phase of the material changes due to heat absorption or release. The shift of its state happens mainly from solid to solid, solid to liquid and liquid to gas. There is a small range of the material's temperature variation, as it is mainly the latent heat that is stored in the structure. (Oropeza-Perez, 2017)

Table 1 — Description of the applicability of the categories used

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

Table 36. Comfort categories in buildings (European Comittee for Standardization 2007)



Key

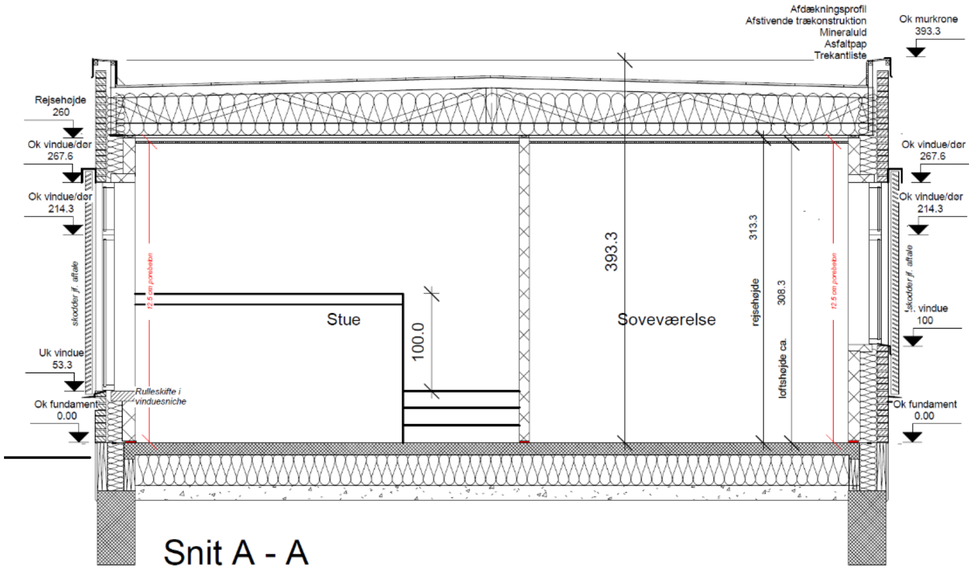
Θ_{rm} = Outdoor Running mean temperature °C.

Θ_0 = Operative temperature °C.

Figure 33. Design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature (European Comittee for Standardization 2007)

12.2 Appendix for the building description

12.2.1 Building construction



Building Element	Construction	U-value, [W/m²K]
Foundation	• Stepped Foundation • Edge Foundation Skawblock 39x50/34 • Plinth 100/400 • Concrete Foundation 12mPa 390 mm • Min. 90 cm Below the Terrain • Foundation under Load Bearing Internal Walls 230x190 mm	
Floor	• Flooring • Concrete 120 mm • EPS insulation (λ=31) 320 mm • Compressed Sand Pad • Radon Seal • Radon Venting (Penetration Through the Concrete Slab)	0.082
Roof	• Slope 1.5 Degree • Roofing Felt • OSB Plate 18mm • Air Gap 50 mm • Paper Wool Insulation (λ=34) 430 mm • Beams and Rafters • Vapor Barrier PE Film 0.2 mm	0.087

	• Plasterboard Ceiling with Acoustic Panels	
Internal Wall	• Concrete 120/125 mm	1.226
External Wall	• Brick Outer Leaf 110 mm • Insulation (λ=34) 190 mm • Concrete Inner Leaf 100/125 mm	0.153
Windows	• Wooden/Aluminum Frame • 3-layer Low Energy Glass Pane • VELFAC	0.5-0.6
Doors	• Wooden/Aluminum • VELFAC	0.5-0.6
Skylight	• VELUX Skylights with Electrical Control	2.3

Table 37. Construction description examined house (Larsen, 2017)

12.2.2 Blower door test

Airflow with 50 Pa (+/-1%)	l/s/m^2	l/s
Under pressure	0.53	84
Overpressure	0.52	83
Average	0.52	84

Table 38. Blower door test results (Kristensen, 2017)

Conditions: The house is of 160 m^2. 9 degrees of Celsius outside and 21 degrees Celsius inside when the test was conducted.

Address: Kildebjerg Sovej 32, 8680 Ry

12.2.3 Ventilation system damper opening

Step 1	Open dampers < 3
Step 2	2 < open dampers < 6
Step 3	5 < open dampers < 9
Step 4	8< open dampers

Table 39. Damper opening of the ventilation system (Kristensen, 2017)

12.2.4 Sensors for indoor climate monitoring

	Temperature [°C]	CO_2 level [ppm]	Relative humidity [%]	Damper opening [min/ max]
Master Bedroom	V	V	V	V
Wardrobe closet	V			V
Living Room	V	V	V	V
Kitchen/ Dining Room	V	V	V	V
Room 1	V	V	V	V
Room 2	V	V	V	V
Room 3	V	V	V	V
Bathroom 1	V		V	V
Bathroom 2	V		V	V
Utility Room	V		V	V

Table 40. Sensor location in the examined house (Kristensen, 2017)

Note: It was discovered that there were high discrepancies between the CO_2 levels, even when the house was not occupied. The reason for that could be the use of virtual sensors, which provided not reliable results.

12.3 Appendix for internal loads and schedule of them

12.3.1 Internal loads

The chosen relevant people load and electricity profiles for the model can be found in Table 41, Table 42 and Table 43. Tables based on gathered and measured data. (Carpino, et al., 2017)

Calculation Type	Load Profile for Compliance Calculations	Load Profile for Average Use Case	Load Profile for Actual Use Case
People	1070 kWh/m^2 for 2 people 2675 kWh/m^2 for 5 people	1402 kWh/m^2 for 2 people	920 kWh/m^2 for 2 people being in the house 14 hours per day

Table 41 User profiles (Zhang, 2017)

Calculation Type	Load Profile for Compliance Calculations	Load Profile for Average Use Case	Load Profile for Actual Use Case
Electricity	4906 kWh/year corresponding m2 load: 3.5 W/m2	4258 kWh/year for a size of 160 m2 and average 2.62 person	1500 kWh/year predicted from 3 month average data

Table 42. Electricity profiles (Zhang, 2017)

Appliances	Room	W/m^2	N° of uses per week	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Usage hours
Cooking plate	Kitchen/Living room	0.95	3	v	v	v					18:30 – 20:30
Cooker	Kitchen/living room	7.49	2	v		v					19:00 – 21:00
Dishwasher	Kitchen/Living room	3.82	2			v				v	20:00 – 23:00
Washing machine	Utility room	67.32	3	v					v	v	19:00 – 22:00
Dryer	Utility room	65.16	2	v						v	12:30 – 14:00 18:30 – 22:00

Table 43. Device profile (Carpino, et al., 2017)

12.3.2 Schedules of the internal loads

Schedule name: Laptop usage		
Schedule:Compact,		
_Laptop_Rooms_5p,		
Fraction,		
Through: 31 Dec,		
For: AllDays,	Frequency	
Until: 16:00	0	
Until: 17:00	1	
Until: 20:00	0	
Until: 22:00	1	
Until: 24:00	0	

Figure 34. Schedule of the laptop usage in the rooms for 5 people case

Schedule name: Room occupancy (5 pp)		
Schedule:Compact,		
_Occ_Rooms_5p,		
Any Number,		
Through: 31 Dec,		
For: AllDays,	Frequency	
Until: 6:00	1	
Until: 16:00	0.000001	
Until: 17:00	1	
Until: 20:00	0.000001	
Until: 24:00	1	

Figure 35. Schedule of the occupancy in the rooms for 5 people case

Schedule name: Bedroom occupancy (2 pp)		
Schedule:Compact,		
_Occ_MasterBedroom_2p5p,		
Any Number,		
Through: 31 Dec,		
For: AllDays,	Frequency	
Until: 7:00	2	
Until: 21:00	0.000001	
Until: 23:00	1	
Until: 24:00	2	

Figure 36. Schedule of the occupancy in master bedroom for 2 and 5 people case

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_13hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 19:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays,	
Until: 7:00	0.000001
Until: 10:00	2
Until: 12:00	0.000001
Until: 14:00	2
Until: 19:00	0.000001
Until: 20:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_15hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 17:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays,	
Until: 7:00	0.000001
Until: 10:00	2
Until: 12:00	0.000001
Until: 14:00	2
Until: 15:00	0.000001
Until: 18:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Figure 37. 13h and 15h schedule for the occupancy in living room for 2 people

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_16hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 16:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 10:00	2
Until: 12:00	1
Until: 14:00	2
Until: 15:00	1
Until: 18:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_16.3hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 15:30	0.000001
Until: 16:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 10:00	2
Until: 12:00	1
Until: 15:00	2
Until: 18:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Figure 38. 16h and 16.3h schedule for the occupancy in living room for 2 people

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_17hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 14:00	0.000001
Until: 16:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 11:00	2
Until: 12:00	1
Until: 14:00	2
Until: 15:00	1
Until: 17:00	0.000001
Until: 18:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_19.5hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	2
Until: 10:00	1
Until: 12:00	0.000001
Until: 15:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 11:00	2
Until: 12:00	1
Until: 15:00	2
Until: 16:00	1
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Figure 39. 17h and 19.5h schedule for the occupancy in living room for 2 people

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_2p_23hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 11:00	2
Until: 12:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 21:00	2
Until: 23:00	1
Until: 24:00	0.000001

Figure 40. 23h schedule for the occupancy in living room for 2 people

Schedule name: Living room occupancy		
Schedule:Compact,		
_Occ_Living_room_5p_13hrs		
Any Number,		
Through: 31 Dec,		
For: Weekdays	Frequency	
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 16:00	0.000001	
Until: 18:00	2	
Until: 19:00	3	
Until: 20:00	2	
Until: 22:00	1	
Until: 24:00	0.000001	
For: Weekends AllOtherDays		
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 10:00	4	
Until: 11:00	3	
Until: 12:00	0.000001	
Until: 13:00	3	
Until: 17:00	0.000001	
Until: 18:00	3	
Until: 19:00	4	
Until: 20:00	3	
Until: 21:00	2	
Until: 22:00	1	
Until: 24:00	0.000001	

Schedule name: Living room occupancy		
Schedule:Compact,		
_Occ_Living_room_5p_15hrs		
Any Number,		
Through: 31 Dec,		
For: Weekdays	Frequency	
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 16:00	0.000001	
Until: 17:00	2	
Until: 18:00	4	
Until: 19:00	5	
Until: 20:00	3	
Until: 22:00	2	
Until: 23:00	1	
Until: 24:00	0.000001	
For: Weekends AllOtherDays		
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 10:00, 4,	4	
Until: 11:00, 3,	3	
Until: 12:00, 0.0(	0.000001	
Until: 13:00, 5,	5	
Until: 14:00, 4,	4	
Until: 15:00, 3,	3	
Until: 16:00, 1,	1	
Until: 17:00, 0.0(	0.000001	
Until: 18:00, 3,	3	
Until: 19:00, 4,	4	
Until: 20:00, 3,	3	
Until: 21:00, 2,	2	
Until: 22:00, 1,	1	
Until: 24:00, 0.0(	0.000001	

Figure 41. 13h and 15h schedule for the occupancy in living room for 5 people

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_5p_16.3hrs,	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 7:00	0.000001
Until: 8:00	5
Until: 13:30	0.000001
Until: 15:00	1
Until: 16:00	2
Until: 17:00	3
Until: 18:00	4
Until: 19:00	5
Until: 20:00	4
Until: 21:00	3
Until: 22:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 8:00	5
Until: 10:00	4
Until: 12:00	3
Until: 13:00	5
Until: 15:00	4
Until: 16:00	3
Until: 16:30	0.000001
Until: 17:00	1
Until: 18:00	3
Until: 19:00	4
Until: 20:00	3
Until: 21:00	2
Until: 22:00	1
Until: 24:00	0.000001

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_5p_16hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays,	Frequency
Until: 7:00	0.000001
Until: 8:00	5
Until: 15:00	0.000001
Until: 16:00	2
Until: 17:00	3
Until: 18:00	4
Until: 19:00	5
Until: 20:00	4
Until: 21:00	3
Until: 22:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 7:00	0.000001
Until: 8:00	5
Until: 10:00	4
Until: 12:00	3
Until: 13:00	5
Until: 14:00	4
Until: 16:00	3
Until: 17:00	0.000001
Until: 18:00	3
Until: 19:00	4
Until: 20:00	3
Until: 21:00	2
Until: 22:00	1
Until: 24:00	0.000001

Figure 42. 16h and 16.3h schedule for the occupancy in living room for 5 people

Schedule name: Living room occupancy		
Schedule:Compact,		
_Occ_Living_room_5p_17hrs		
Any Number,		
Through: 31 Dec,		
For: Weekdays	Frequency	
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 14:00	0.000001	
Until: 15:00	2	
Until: 17:00	3	
Until: 18:00	4	
Until: 20:00	5	
Until: 21:00	4	
Until: 22:00	2	
Until: 23:00	1	
Until: 24:00	0.000001	
For: Weekends AllOtherDays		
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 11:00	4	
Until: 12:00	3	
Until: 14:00	5	
Until: 15:00	4	
Until: 16:00	3	
Until: 17:00	0.000001	
Until: 18:00	4	
Until: 19:00	5	
Until: 20:00	3	
Until: 21:00	2	
Until: 22:00	1	
Until: 24:00	0.000001	

Schedule name: Living room occupancy		
Schedule:Compact,		
_Occ_Living_room_5p_19.5hrs		
Any Number,		
Through: 31 Dec,		
For: Weekdays	Frequency	
Until: 7:00	0.000001	
Until: 8:00	5	
Until: 15:00	2	
Until: 16:00	3	
Until: 18:00	4	
Until: 20:00	5	
Until: 21:00	4	
Until: 22:00	2	
Until: 23:00	1	
Until: 24:00	0.000001	
For: Weekends AllOtherDays		
Until: 7:00	0.000001	
Until: 9:00	5	
Until: 12:00	4	
Until: 14:00	5	
Until: 18:00	4	
Until: 20:00	5	
Until: 21:00	4	
Until: 22:00	3	
Until: 24:00	0.000001	

Figure 43. 17h and 19.5h schedule for the occupancy in living room for 5 people

Schedule name: Living room occupancy	
Schedule:Compact,	
_Occ_Living_room_5p_23hrs	
Any Number,	
Through: 31 Dec,	
For: Weekdays	Frequency
Until: 6:00	0.000001
Until: 8:00	5
Until: 14:00	3
Until: 15:00	4
Until: 20:00	5
Until: 21:00	4
Until: 22:00	2
Until: 23:00	1
Until: 24:00	0.000001
For: Weekends AllOtherDays	
Until: 6:00	0.000001
Until: 8:00	5
Until: 12:00	4
Until: 14:00	5
Until: 18:00	4
Until: 20:00	5
Until: 21:00	4
Until: 22:00	3
Until: 24:00	0.000001

Figure 44. 23h schedule for the occupancy in living room for 5 people

12.4 Appendix for spearman's rank correlation coefficient

The Spearman's rank correlation coefficient is a calculated in a same way as the correlation coefficient, however, the two variable arrays that are analyzed are first ranked (listed in order i.e., from the highest value to the lowest value).

The correlation coefficient is calculated based on eq. 5

$$corr(X,Y) = \frac{cov(X,Y)}{\sigma_x \sigma_y} = \frac{E[(X - E(X)(Y - E(Y)]}{\sigma_x \sigma_y} \quad 5$$

where:

$corr(X,Y)$: the correlation coefficient of the variables X and Y, -

$cov(X,Y)$: the covariance of the variables X and Y, -

$E(X)$: the mean of X

σ_x : standard deviation of X, -

12.5 Appendix for the weather data

12.5.1 Morphing

Morphing can be defined as adjusting the current weather data. In order to do that, the weather data for a specific site should be of a very high resolution, then the data is morphed (downsized) based on one of the two climatic models-either the regional one or the global one.

Morphing is based on historical weather observations. The applicability of the data depends mostly on the used baseline period. It has to be noted, that the heat waves are overlooked. (Herrera, 2017)

The morphing processes are as follows:

- Absolute change $x = x_0 + \Delta x_m$
- Fractional change $x = \alpha_m x_0$
- Change of the associated monthly variance of the variable $Var(x) = \alpha_m \; Var(x_0)$
- A combination of stretch and shift transformations $x = x_0 + \Delta x_m + \alpha_m(x - x_0)$

In general, the morphing processes overestimate extreme data, due to the maximum and minimum temperatures being approached separately from the mean, which should be correlated instead. (Herrera, 2017)

12.5.2 Weather generators

Most weather generators are parametric (the statistical properties and input distribution functions are pre-defined). The non-parametric ones do not need to meet any data-related assumption. The drawback is, that the extreme events might not be correctly presented, as the data used for weather generators is based on historical data. It is very improbable, that those extreme events would reoccur during the examined time and that the weather patterns would be repeated. (Herrera, 2017)

A good example of a weather generator is Meteonorm.

"Meteonorm [83] extrapolates hourly data from statistical data for a location. Where statistical data are not available, Meteonorm interpolates from other nearby sites. Meteonorm is a combination of a climate database, a spatial interpolation tool and a stochastic weather generator, with global radiation data obtained from the Global Energy Balance Archive (GEBA). This allows typical years with hourly or minutely time resolution to be created for any site." (Herrera, 2017)

12.5.3 Comparison of morphing and weather generators

Weather generators	Morphing
Based on statistics obtained from historical weather investigation	Based on historical observations
Weather data consistent with historical observations for different variables, but not suitable when considering hourly timescale	Consistent weather files
Heat waves cannot be correctly presented for most of the cases	Heat-wave frequency and other weather aspects are ignored
Can be used for the estimation of extreme temperatures	Extreme data tends to be overestimated
Suitable for any location	Limited by the weather station location and baseline availability

Table 44. Comparison of morphing procedure and weather generators (Herrera, 2017)

12.6 Appendix for the Local Sensitivity analyses of Natural ventilation

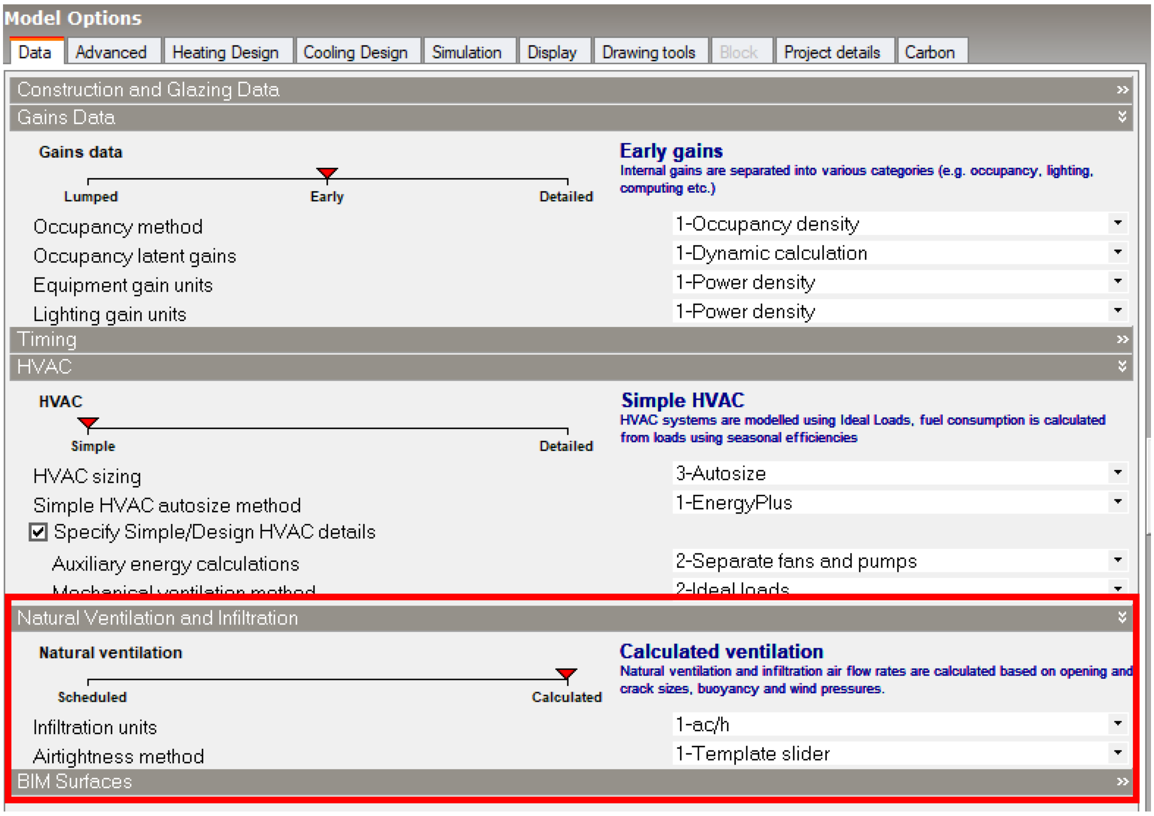
Figure 45. Case house elevations with marked window openings (Lasse Larsen Byggefirma 2017).

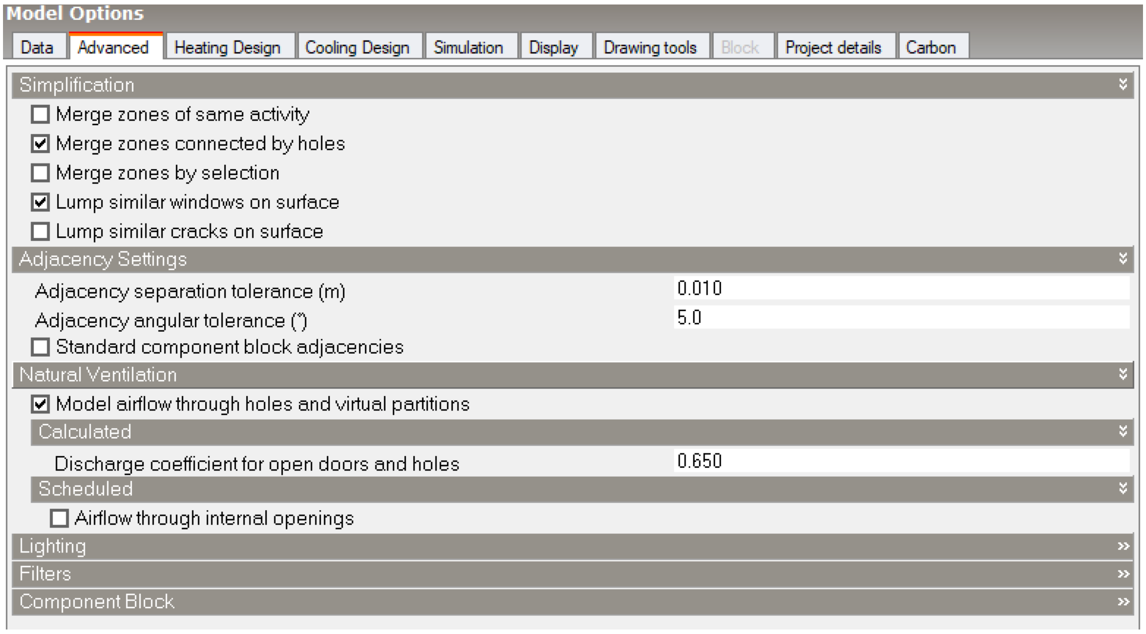
12.6.1 Ventilation system description

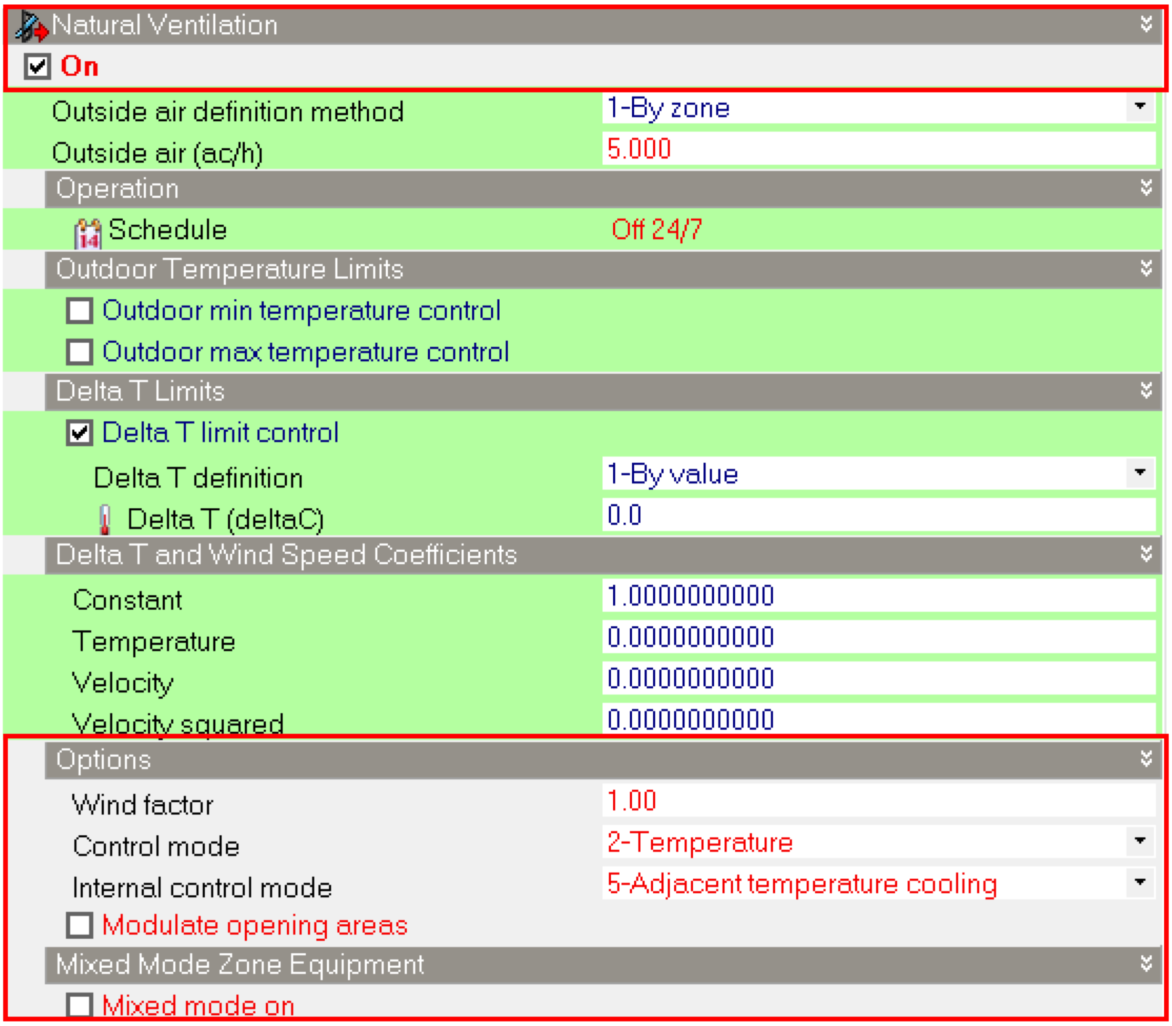
"Management of natural ventilation and solar shading is based on EUDP. The nat. ventilation control is based on CO_2, RH and occupancy. The natural system is activated, when there is no need for heat recovery. The activation happens before the mechanical ventilation increases. The condition for the natural ventilation to be activated is, that it must not be a source of nuisance for the occupants. In order to provide natural ventilation to the house, some of the windows have been equipped with grids. The grids take up to 5% of the window area and are in rooms with overheating risk. The glazing located behind the grids can be opened in multiple steps, so the fresh air supply can be controlled. Additionally, two skylights were installed in the living room and kitchen, and act as an outlet for the returning air. (…) Venting can occur when the house is locked and unoccupied. Fresh air is introduced into selected rooms via a newly developed ventilation shutter from Velfac. The shutters are fitted with a motor drive." (Heiselberg, 2018)

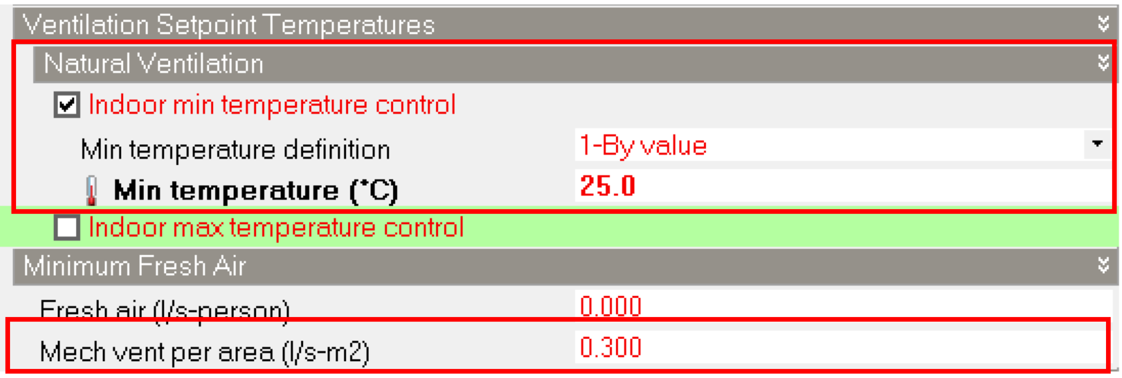
12.6.2 Modelling in the Design Builder-Automatically controlled natural ventilation

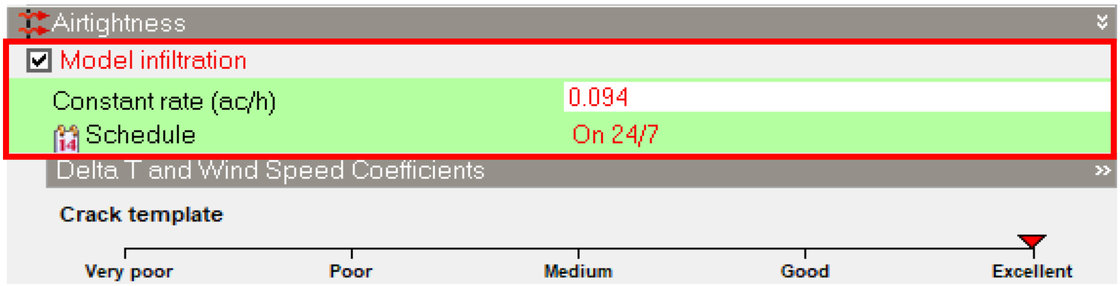
Model Options - Building and Block

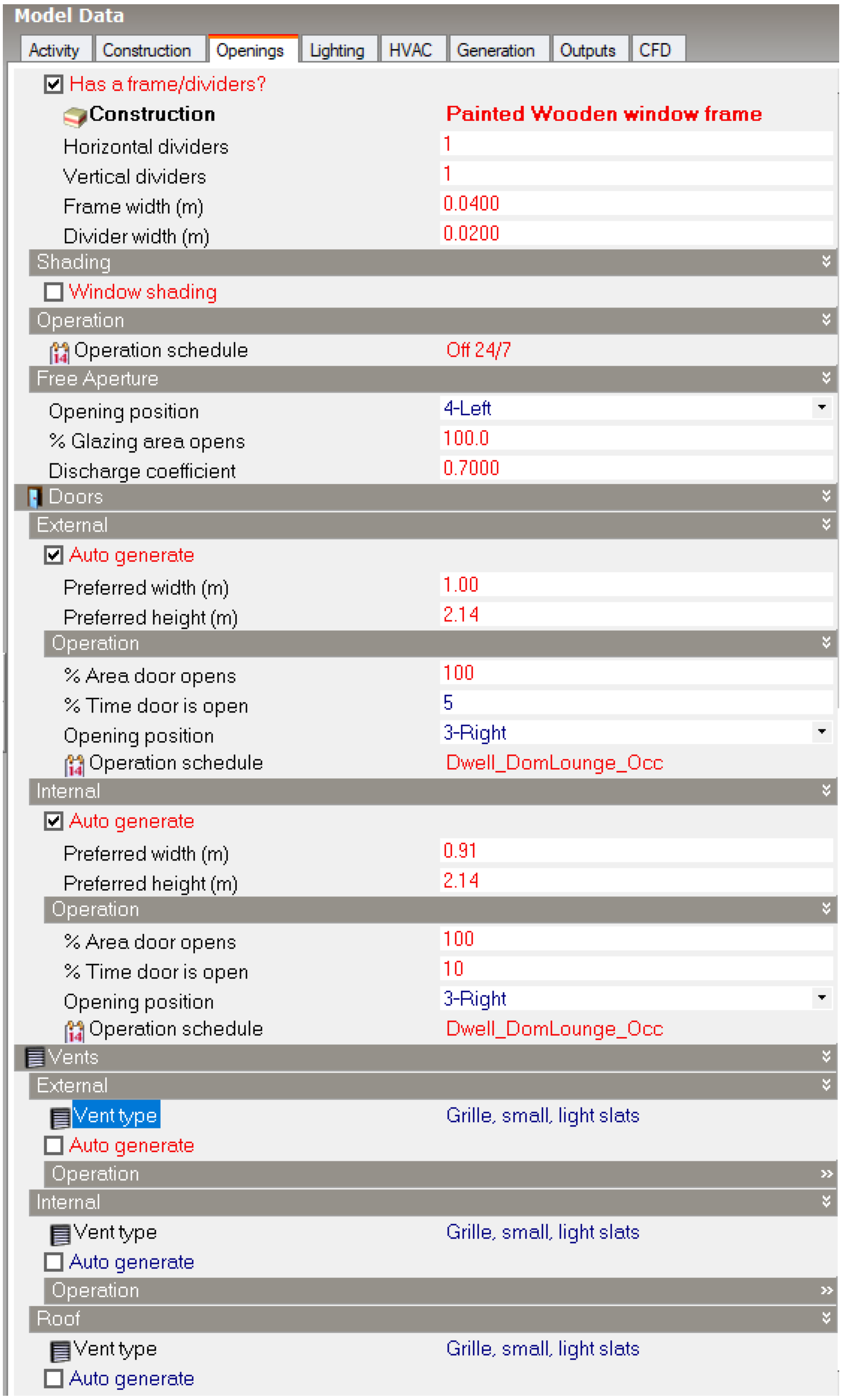



Model Options
Data
Advanced
Heating Design
Cooling Design
Simulation
Display
Drawing tools
Block
Project details
Carbon
Simplification
Merge zones of same activity
Merge zones connected by holes
Merge zones by selection
Lump similar windows on surface
Lump similar cracks on surface
Adjacency Settings
Adjacency separation tolerance (m)
0.010
Adjacency angular tolerance (°)
5.0
Standard component block adjacencies
Natural Ventilation
Model airflow through holes and virtual partitions
Calculated
Discharge coefficient for open doors and holes
0.650
Scheduled
Airflow through internal openings
Lighting
Filters
Component Block

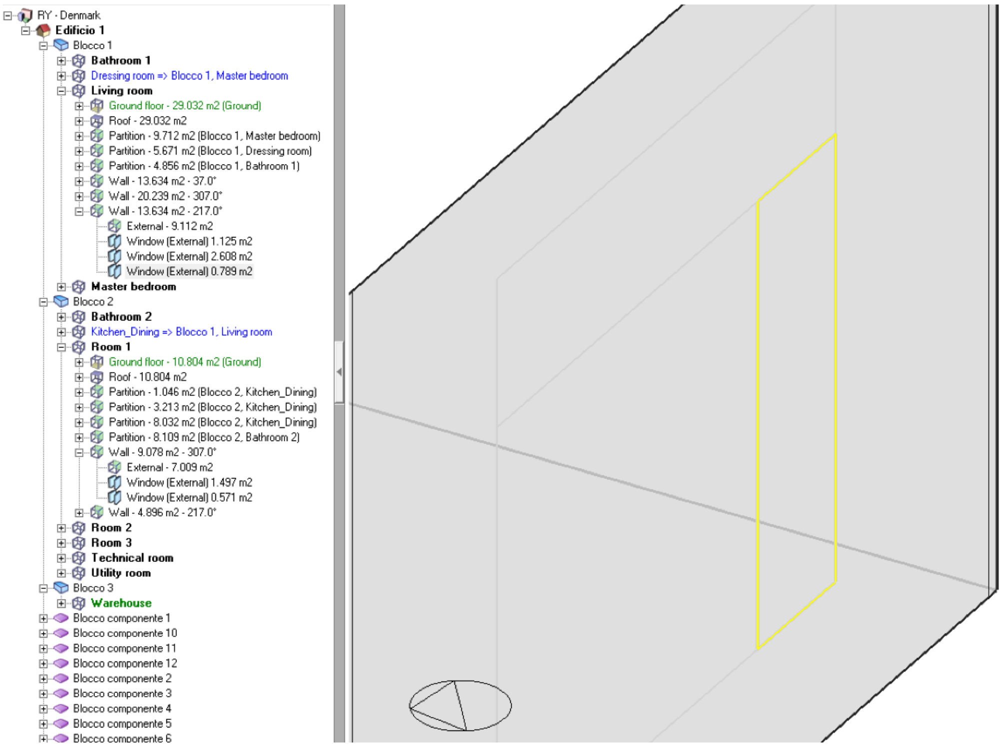

Natural Ventilation
On
Outside air definition method
1-By zone
Outside air (ac/h)
5.000
Operation
Schedule
Off 24/7
Outdoor Temperature Limits
Outdoor min temperature control
Outdoor max temperature control
Delta T Limits
Delta T limit control
Delta T definition
1-By value
Delta T (deltaC)
0.0
Delta T and Wind Speed Coefficients
Constant
1.0000000000
Temperature
0.0000000000
Velocity
0.0000000000
Velocity squared
0.0000000000
Options
Wind factor
1.00
Control mode
2-Temperature
Internal control mode
5-Adjacent temperature cooling
Modulate opening areas
Mixed Mode Zone Equipment
Mixed mode on


Ventilation Setpoint Temperatures
Natural Ventilation
Indoor min temperature control
Min temperature definition
1-By value
Min temperature (°C)
25.0
Indoor max temperature control
Minimum Fresh Air
Fresh air (l/s-person)
0.000
Mech vent per area (l/s-m2)
0.300


Airtightness
Model infiltration
Constant rate (ac/h)
0.094
Schedule
On 24/7
Delta T and Wind Speed Coefficients
Crack template
Very poor
Poor
Medium
Good
Excellent


Model Data
Activity
Construction
Openings
Lighting
HVAC
Generation
Outputs
CFD
Has a frame/dividers?
Construction
Painted Wooden window frame
Horizontal dividers
1
Vertical dividers
1
Frame width (m)
0.0400
Divider width (m)
0.0200
Shading
Window shading
Operation
Operation schedule
Off 24/7
Free Aperture
Opening position
4-Left
% Glazing area opens
100.0
Discharge coefficient
0.7000
Doors
External
Auto generate
Preferred width (m)
1.00
Preferred height (m)
2.14
Operation
% Area door opens
100
% Time door is open
5
Opening position
3-Right
Operation schedule
Dwell_DomLounge_Occ
Internal
Auto generate
Preferred width (m)
0.91
Preferred height (m)
2.14
Operation
% Area door opens
100
% Time door is open
10
Opening position
3-Right
Operation schedule
Dwell_DomLounge_Occ
Vents
External
Vent type
Grille, small, light slats
Auto generate
Operation
Internal
Vent type
Grille, small, light slats
Auto generate
Operation
Roof
Vent type
Grille, small, light slats
Auto generate

The vents for the automatically controlled ventilation were modelled at the window level, by assigning operation schedule, opening position, percentage of the openable glazing area and window discharge coefficient.



12.6.3 Modelling in the Design Builder-Automatically controlled natural ventilation

The manually controlled ventilation was modelled in the same way up until the window level. For that part, the ventilation shutters in the windows are off and only openable window parts have their schedules assigned according to the occupancy schedule of the rooms, that they serve. The same parameters are defined for these window parts as for vents. The skylights are assumed to be closed.

12.7 Appendix for shading input parameters PDF for Uncertainty Analyses

Changed input	PDF	Min.	Mean	S.D.	Max.	Unit	Literature(PDF)/Description
Type [-]							
Position [-]							
Control type [-]							
Inside air temperature [^{o}C]	Normal distribution (±0.5)		25	0.25		oC	Wout Building and Environment 2012
Slat angle control [-]							
Operational schedule [day]	Uniform distibution	13 h			23 h		6 different schedule for the living room
Equipment load [W/m^2]	Triangle distribution	8	12		18	W/m2	Natural_ventilation_design_An_analysis_o
Occupant load [people/m^2]	Different models	2 people and 5 people					2 different model made
Local shading [-]							
Shading from other objectives [-]							
*Weather data (3 different year will be evaulated)	Bernoulli	Probability of second option: (extreme) 10 %					DesignBuilder,https://en.wikipedia.org/wiki/Bernoulli_distribution
Slat:reflectance [-]							
Slat: with [m]	Continues uniform(±20µm)	0.04498	Wont use bcs to love the changes		0.04502	m	Lee1998_Article_AComprehensiveMethodForCalibra
Slat: separation [m]	Continues uniform(±20µm)	0.03957			0.03961	m	Lee1998_Article_AComprehensiveMethodForCalibra
Slat: thickness [m]							
Slat: distance from glass [m]							
Mech. Ventilation ACH [l/s/m^2]	Continues uniform(±10%)	0.27			0.33	l/s/m2	Wout Building and Environment 2012 (Ati favourite)

Figure 46. Shading input parameters probability density functions (PDF)

12.8 Appendix for natural ventilation input parameters PDF for Uncertainty Analyses

Changed input	PDF	Min.	Mean	S.D.	Max.	Unit	Literature(PDF)/Description
Infiltration [1/h] **(don't include)**			6.5/2.6	3/1.9		[1/h]	Feasibility assessment of passive cooling for office buildings in a temperate
Window to wall ratio [%]							climate through uncertainty analysis
External doors dimensions [m^2]							
Internal doors dimensions [m^2]							
Inside air temperature [^oC]	Normal distribution (±0.5)		25	0.25		oC	Wout Building and Environment 2012
% of the area the external door opens							
% of the area the internal door opens							
Opening position (windows and doors)							
% of the glazing area that opens (windows)							
Outside air ach [1/h]							
Operational schedule [day]	Uniform distribution	13 h			23 h		6 different schedule was made based on Denmark Statictics
Equipment load [W/m^2] (not include)	Triangle distribution	8	12		18	W/m2	Natural_ventilation_design_An_analysis_o
Occupant load [people/m^2]	Different model	2 people and 5 people					Thanks to limitations two different model case was made with 2 and 5 people
Weather data (3 different year)	Bernoulli	Probability of second option: (extreme) 10 %					DesignBuilder,https://en.wikipedia.org/wiki/Bernoulli_distribution
% of time the external door is open [%]	Normal distribution (±0.5)	0.5	1.75		4	%	Study-The influence of opening windows and doors on the natural ventilation rate of a residential building
% of time the internal door is open [%]	Normal distribution (±0.5)	10	45		100	%	A SENSITIVITY ANALYSIS OF NATURAL VENTILATION DESIGN PARAMETERS FOR NON RESIDENTIAL BUILDINGS
Lighting [W/m2] (not include)	Continues uniform(±10%)	5	lighting was lowered for residential building		20	W/m2	A SENSITIVITY ANALYSIS OF NATURAL VENTILATION DESIGN PARAMETERS FOR NON RESIDENTIAL BUILDINGS
Window discharge coefficient [-]	Normal distribution (±0.5)	0.3/0.6	0.5/0.675		0.9/0.75	-	A SENSITIVITY ANALYSIS OF NATURAL VENTILATION DESIGN PARAMETERS FOR NON RESIDENTIAL BUILDINGS/UNCERTAINTY AND SENSITIVITY ANALYSIS OF NATURAL VENTILATION IN HIGH-RISE APARTMENT BUILDINGS
Mech. Ventilation ACH [l/s/m^2]	Continues uniform(±10%)	0.27			0.33	l/s/m2	PARAMETERS FOR NON RESIDENTIAL BUILDINGS

Figure 47. Natural ventilation input parameters probability density functions (PDF)

12.9 Appendix for the Technologies and Key Performance Indicators

Indicator group	Category	KPIs (Key Performance Indicators)	Formula
System Indicators	Thermal Comfort	Percentage Outside Range (POR)	$POR = \frac{\sum_{i=1}^{Oh}(wf_i \cdot h_i)}{\sum_{i=1}^{Oh} h_i}$
System Indicators	Thermal Comfort	Degree Hours (DhC)-adaptive comfort model	$DhC = \sum_{i=1}^{Oh}(wf_i \cdot h_i)$
System Indicators	Thermal Comfort	Likelihood of Dissatisfied (LPD (LD))	$LPD(LD) = \frac{\sum_{t=1}^{T}\sum_{s=1}^{S}(p_{t,s} \cdot LD_{t,s} \cdot h_t)}{\sum_{t=1}^{T}\sum_{s=1}^{S}(p_{t,s} \cdot h_t)}$
System Indicators	Thermal Comfort	Weighted discomfort temperature index (DI)	$DI = \sum (t_i - t_{comf,sup})$
System Indicators	Thermal Comfort	Temperature efficiency (Te)	$TE = \frac{T_{out} - T_{in}}{T_{surface} - T_{in}}$
System Indicators	Thermal Comfort	Temperature difference ratio (TDR)	$TDR = \frac{T_{o,max} - T_{i,max}}{T_{o,max} - T_{o,min}}$
System Indicators	Thermal Comfort	Decrement factor (DF)	$DF = \frac{T_{i,max} - T_{i,min}}{T_{o,max} - T_{o,min}}$
System Indicators	Thermal Comfort	$Exceedance_M$	$Exceedance_M = f(B_i): B_i = 1 \Leftrightarrow (Acceptability < 80\%);\ B_i = 0 \Leftrightarrow (Acceptability \geq 80\%)$; $Exceedance_M = \frac{\sum B_i}{\sum n} \in [0;1]$
System Indicators	Thermal Comfort	Nicol Overheating Risk (NaOR)	$P(\Delta T) \equiv \frac{\exp(0.4734 \cdot \Delta\theta - 2.607)}{1+\exp(0.4734 \cdot \Delta\theta - 2.607)} \in [0.069;1]$
System Indicators	Thermal Comfort	Robinson and Haldi's Overheating Risk (RHOR)	for charging: $P_{OH}(t_n) \equiv 1 - \exp\left(-\alpha \sum_{i=1}^{n} Dh_{c,i}\right)(1 - P_{OH}(t_0)) \in [0;1]$; for discharging: $P_{OH}(t_n) \equiv \exp\left(-\beta \sum_{i=1}^{n} Dh_{c,i}\right) P_{OH}(t_0) \in [0;1]$
System Indicators	Energy Performance	Specific Primary Energy Consumption Anually ($Q_{e,vc}$)	$Q_{pe,vc} = Q_{pe,v} + Q_{pe,h} + Q_{pe,c} \cdot Q_{pe,v,sys}$
System Indicators	Energy Performance	Hourly/Daily Energy Removal at Night (Q_n)	$Q_n = \int_{t_1}^{t_2} \dot{m}_{air} C_{pair}(T_{out} - T_{exhaust})\, dt$
System Indicators	Energy Performance	Cooling Requirements Reduction (CRR)	$CRR = \frac{Q^{ref}_{el,c} - Q^{scen}_{el,c}}{Q^{ref}_{el,c}}$
System Indicators	Energy Performance	Coefficient of Performance (COP)	$COP(t) = \frac{Q_{Useful}(t)}{Q_{Consumption}(t)}$
System Indicators	Energy Performance	Potential Energy Efficiency Index (PEE)	$PEE = \frac{Q_s}{Q_t}$
System Indicators	Energy Performance	Absolute Energy Savings	
System Indicators	Energy Performance	Ventilative cooling advantage (ADV)	$ADV_{VC} = \frac{Q^{ref}_{el,c} - Q^{scen}_{el,c}}{Q_{el,v}}$
System Indicators	Energy Performance	Utilization Factor ($f_u(t)$)	$f_u(t) = \frac{Q_{Useful}(t)}{Q_{Available}(t)}$
System Indicators	Energy Performance	Natural Cooling Normalized Capacity (T_c)	$\tau_c = \frac{Q_{Useful}}{Q_{Requirement}}$
System Indicators	Energy Performance	Available Cooling Potential Index ($IP_{avail.}$)	$IP_{Available} = \int [T_{Set\ point}(t) - T_{Sink}(t)]\delta(t)\, dt$ where $\delta(t)=1$ if $T_{Sink} < T_{Set\ point}$ and $\delta(t)=0$ if $T_{Sink} > T_{Set\ point}$
System Indicators	Energy Performance	Useful Cooling Potential Index (IP_{useful})	$IP_{Useful} = \int [T_{Set\ point}(t) - T_{Inlet}(t)]\delta_1(t)\, dt$ with $\delta_1(t)=1$ if $T_{Outlet} < T_{Set\ point}$ and $\delta_1(t)=0$ if $T_{Outlet} > T_{Set\ point}$
System Indicators	Energy Performance	Building Cooling Requirement Index (IB_{req})	$IB_{Requirement} = \int [T_{Inlet}(t) - T_{Set\ point}(t)]\delta_2(t)\, dt$ where $\delta_2(t)=1$ if $T_{Inlet} < T_{Set\ point}$ and $\delta_2(t)=0$ if $T_{Inlet} > T_{Set\ point}$
Component Indicators	Mechanical Equipment	Seasonal Energy Efficiency Ratio ($SEER_{vc}$)	$SEER_{VC} = \frac{Q^{ref}_{el,c} - Q^{scen}_{el,c}}{Q_{el,v}}$
Component Indicators	Mechanical Equipment	Ventilative Cooling Advantage (ADV_{vc})	$ADV_{VC} = \frac{Q^{ref}_{el,c} - Q^{scen}_{el,c}}{Q_{el,v}}$
Component Indicators	Mechanical Equipment	Specific Fan Power (SPF)	
Component Indicators	Natural Methods	Window Opening Efficiency	

Cooling Strategies/Technologies
1. Passive Cooling Strategies/Technologies
Shading (Internal/External/Advanced)
Overhang
Radiant Heat Barriers (Green Roof/Vinyl)
PCM (Phase Change Materials)
Advanced Glazing (Coating/Gas/PCM)
Thermal Mass (Thermal Capacity)
Internal Heat Gain Control
2. Natural Cooling Strategies/Technologies
Heat Sink Outdoor Air Nat. Vent. Day — *Controlled Natural Ventilation/Tower Cooling*
Heat Sink Outdoor Air Nat. Vent. Night — *Night Ventilation*
Heat Sink Outdoor Air Mech. Vent. Day — *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers/Chilled Beams*
Heat Sink Outdoor Air Mech Vent. Night — *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers /Chilled Beams*
Heat Sink Ground Vent. EAHE Natural — *Direct Ground Cooling*
Heat Sink Ground Vent. EAHE Mech. — *Indirect Cooling Earth to Air Heat Exchanger/Water to Air HE*
Heat Sink Ground Water Floor/Roof/Walls
Heat Sink Ground Water Convective Panels
Heat Sink Ground Water Radiation Panels
Heat Sink Sky Ventilation Mechanical — Indirect Radiant Cooling Air Based Flat Plate Coolers
Heat Sink Sky Thermal Mass — *Direct Radiant Cooling*
Heat Sink Sky Water Floor/Roof/Walls
Heat Sink Sky Water Convective Panels
Heat Sink Sky Water Radiation Panels — *Indirect Cooling Water Based Flat Plate Coolers*
Multiple Heat Transfer (Intelligent Facades) — *Kinetic/Open Joint Vent./Double Skin/Solar/Double Glazed*

KPIs (Key Performance Indicators)	Boundary Conditions Indicators																												
	Gains		Thermal Mass					Openings			Airflow						Climate										Occupancy			
Cooling Strategies/Technologies	Internal Heat Gains with Diversity Factor	Solar Gains	Existing Building Thermal Mass	Thermal Effusivity (b)-Equivalent and Global	Level of Insulation	Part of Thermal Masss Covered by Furniture	Convective Heat Transfer Between Ventilation and Thermal Mas	Window Surface Area	Solar Transmission	Window Location	Natural Airflow	Mechanical Airflow	Building/Room Volume	Discharge Coefficient of a Window (C_d)	Flow Coefficient of a Window (C_f)	k-factor for Dampers and Physical Free Area	Precipitation	Microclimate Zone (urban/suburban/remote)	Temperature Difference Inside and Outside	Average Outdoor Temperature Range	Wind Speed and Direction	Soil Type and Properties (Ind. Temp.)	Wind Surface Pressure Coefficient (C_p)	Climatic Cooling Potential (CCP)	Balance Temperature for Cooling (T_{cu})	No of users	Adjusted Level of Activity and Clothing	Occupancy Schedule	Average Habit of Window and Door Opening
1. Passive Cooling Strategies/Technologies																													
Shading (Internal/External/Advanced)																													
Overhang																													
Radiant Heat Barriers (Green Roof/Vinyl)																													
PCM (Phase Change Materials)																													
Advanced Glazing (Coating/Gas/PCM)																													
Thermal Mass (Thermal Capacity)																													
Internal Heat Gain Control																													
2. Natural Cooling Strategies/Technologies																													
Heat Sink Outdoor Air Nat. Vent. Day *Controlled Natural Ventilation/Tower Cooling*																													
Heat Sink Outdoor Air Nat. Vent. Night *Night Ventilation*																													
Heat Sink Outdoor Air Mech. Vent. Day *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers/Chilled Beams*																													
Heat Sink Outdoor Air Mech Vent. Night *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers /Chilled Beams*																													
Heat Sink Ground Vent. EAHE Natural *Direct Ground Cooling*																													
Heat Sink Ground Vent. EAHE Mech. *Indirect Cooling Earth to Air Heat Exchanger/Water to Air HE*																													
Heat Sink Ground Water Floor/Roof/Walls																													
Heat Sink Ground Water Convective Panels																													
Heat Sink Ground Water Radiation Panels																													
Heat Sink Sky Ventilation Mechanical *Indirect Radiant Cooling Air Based Flat Plate Coolers*																													
Heat Sink Sky Thermal Mass *Direct Radiant Cooling*																													
Heat Sink Sky Water Floor/Roof/Walls																													
Heat Sink Sky Water Convective Panels																													
Heat Sink Sky Water Radiation Panels *Indirect Cooling Water Based Flat Plate Coolers*																													
Multiple Heat Transfer (Intelligent Facades) *Kinetic/Open Joint Vent./Double Skin/Solar/Double Glazed*																													

KPIs (Key Performance Indicators)	Other Indoor Environmntal Factors																									
	Daylight								Noise				Indoor Air Quality							Thermal Quality						
Cooling Strategies/Technologies	Window to Floor Area	Daylight Factor (DF)	Daylight Distribution	Possibility of Glare	G and U values of the Windows	View to the Outside	Useful Daylight Illuminance (UDI)	Room Location	Noise from the Outside	Sound Transfer Between Rooms	Reverberation Time	Percentage of Urbanization	Smells, Odours, Gasses and Microorganisms	CO_2 Pollution (ppm)	Perceived Air Quality (olf)	Humidity Level	VOCS	Infiltration Efficiency and Infiltration Factor (F_{inf})	Age of Air and Air Exchange Effectiveness (AEE)	Radiant Temp. Assymmetry (Hor. and Vert.)	Vertical Air Temperature Difference	Mean Radiant Temperature	Surface Temperature	Humidity	Air Velocity and Draught (DR)	Free Running Temperature (T_{fr})
1. Passive Cooling Strategies/Technologies																										
Shading (Internal/External/Advanced)																										
Overhang																										
Radiant Heat Barriers (Green Roof/Vinyl)																										
PCM (Phase Change Materials)																										
Advanced Glazing (Coating/Gas/PCM)																										
Thermal Mass (Thermal Capacity)																										
Internal Heat Gain Control																										
2. Natural Cooling Strategies/Technologies																										
Heat Sink Outdoor Air Nat. Vent. Day *Controlled Natural Ventilation/Tower Cooling*																										
Heat Sink Outdoor Air Nat. Vent. Night *Night Ventilation*																										
Heat Sink Outdoor Air Mech. Vent. Day *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers/Chilled Beams*																										
Heat Sink Outdoor Air Mech Vent. Night *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers /Chilled Beams*																										
Heat Sink Ground Vent. EAHE Natural *Direct Ground Cooling*																										
Heat Sink Ground Vent. EAHE Mech. *Indirect Cooling Earth to Air Heat Exchanger/Water to Air HE*																										
Heat Sink Ground Water Floor/Roof/Walls																										
Heat Sink Ground Water Convective Panels																										
Heat Sink Ground Water Radiation Panels																										
Heat Sink Sky Ventilation Mechanical *Indirect Radiant Cooling Air Based Flat Plate Coolers*																										
Heat Sink Sky Thermal Mass *Direct Radiant Cooling*																										
Heat Sink Sky Water Floor/Roof/Walls																										
Heat Sink Sky Water Convective Panels																										
Heat Sink Sky Water Radiation Panels *Indirect Cooling Water Based Flat Plate Coolers*																										
Multiple Heat Transfer (Intelligent Facades) *Kinetic/Open Joint Vent./Double Skin/Solar/Double Glazed*																										

KPIs (Key Performance Indicators)	Sustainability																	
	Social								Economical					Environmental				
Cooling Strategies/Technologies	Possibility of Self-Regulation	Automatic Regulation	Energy and Electricity Cons. of Control Tool	Availability and Usability of the Control	Fire Safety	Security Against Break-ins	Ease of Integration (Arch. and Eng.)	Compliance with Common Practices	Capital Cost Investment	Operation and Maintenance	Cost Savings (Benefits)	Technical Lifespan	Life Cycle Cost (LCC)	Impact on Urban Heat Island Effect	Global Warming Potential (GWP)	Abiotic Depletion	Water Supply and Quality	Life Cycle Assesment (LCA)
1. Passive Cooling Strategies/Technologies																		
Shading (Internal/External/Advanced)																		
Overhang																		
Radiant Heat Barriers (Green Roof/Vinyl)																		
PCM (Phase Change Materials)																		
Advanced Glazing (Coating/Gas/PCM)																		
Thermal Mass (Thermal Capacity)																		
Internal Heat Gain Control																		
2. Natural Cooling Strategies/Technologies																		
Heat Sink Outdoor Air Nat. Vent. Day *Controlled Natural Ventilation/Tower Cooling*																		
Heat Sink Outdoor Air Nat. Vent. Night *Night Ventilation*																		
Heat Sink Outdoor Air Mech. Vent. Day *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers/Chilled Beams*																		
Heat Sink Outdoor Air Mech Vent. Night *Fan/Portable Device/Air to Air or to Water Heat Pumps/AC/ Direct or Indirect Evaporative Cooling/Chillers /Chilled Beams*																		
Heat Sink Ground Vent. EAHE Natural *Direct Ground Cooling*																		
Heat Sink Ground Vent. EAHE Mech. *Indirect Cooling Earth to Air Heat Exchanger/Water to Air HE*																		
Heat Sink Ground Water Floor/Roof/Walls																		
Heat Sink Ground Water Convective Panels																		
Heat Sink Ground Water Radiation Panels																		
Heat Sink Sky Ventilation Mechanical Indirect Radiant Cooling Air Based Flat Plate Coolers																		
Heat Sink Sky Thermal Mass *Direct Radiant Cooling*																		
Heat Sink Sky Water Floor/Roof/Walls																		
Heat Sink Sky Water Convective Panels																		
Heat Sink Sky Water Radiation Panels *Indirect Cooling Water Based Flat Plate Coolers*																		
Multiple Heat Transfer (Intelligent Facades) *Kinetic/Open Joint Vent./Double Skin/Solar/Double Glazed*																		