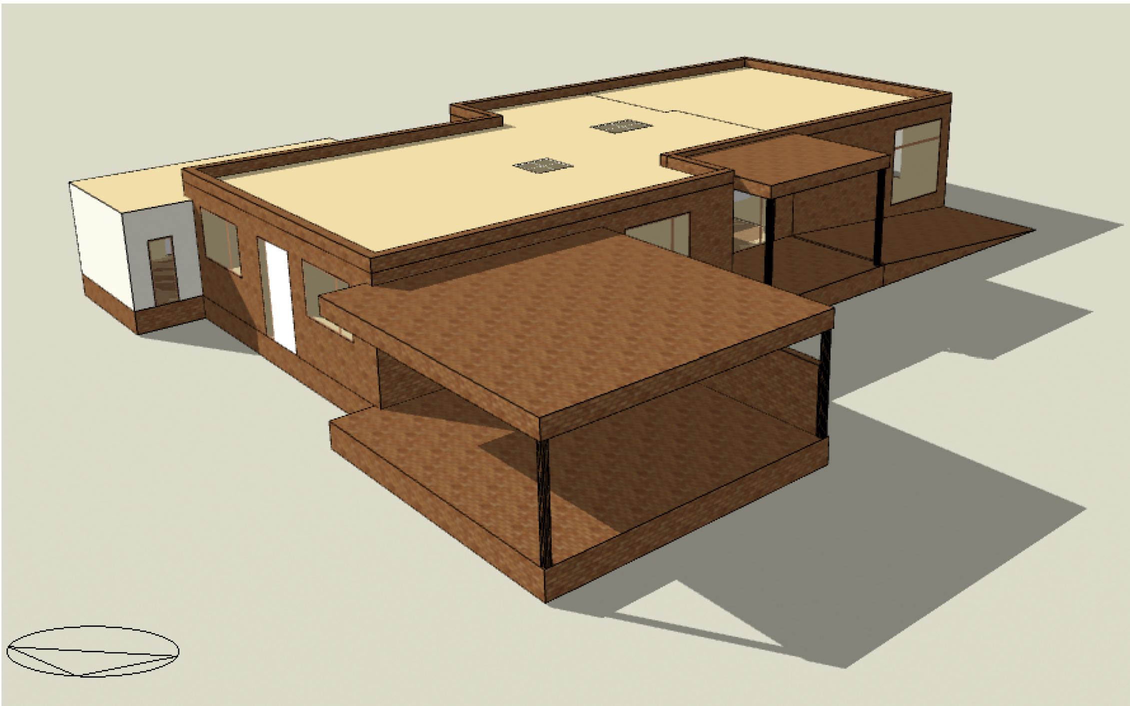
Parametric Analysis of Building Related Resilient Cooling Technologies against Global Warming



Master Thesis
Civil Engineering
Indoor Environmental and Energy Engineering
Aalborg University
4^{th} of June 2020

AALBORG UNIVERSITY
STUDENT REPORT

10. Semester
Indoor Environmental and Energy Engineering
Civil Engineering
Thomas Manns Vej 23
9220 Aalborg East

Title:

Parametric Analysis of Building Related Resilient Cooling Technologies against Global Warming

Project:

Master thesis

Project period:

September 2019 - June 2020

Author:

Anastasios Rovithakis

Supervisors:

Per Kvols Heiselberg
Chen Zhang

Number of pages: 100
Appendix: 15
Submitted 22-05-2020

Synopsis:

The purpose of this thesis is to test different passive cooling technologies to make a building resilient to future global warming scenarios.

The aim for the passive cooling technologies is to find a solution for each one with the constrain that it does not lead to more energy consumption than the initial building's existing one, and also decreases the building's discomfort hours using ASHRAE standards.

The following three passive cooling technologies were tested: Solar Radiation Control, Natural Ventilation and Micro Climate Control. For each one of these technologies an optimisation process was conducted to find a solution with the right combination of parameters offering the least amount of discomfort hours and satisfying the above mentioned constrains.

Once an optimal solution was found for each one of the three passive cooling technologies it was individually tested to determine how it performs against future global warming weather files. These files were generated using the programs Meteonorm and CCWeatherGen to test two different ways of future weather file generation processes. Finally the three individual passive cooling technologies were combined in one to have the best possible resilience and compared with the original model of the building.

Preface

This long Master's thesis project is done during the time span of 9^{th} and 10^{th} semesters for the field of Indoor Environmental and Energy Engineering. The thesis focuses on analysing and optimizing the effects of different parameters of building related passive cooling technologies to create an indoor environment with the least possible over temperature hours while maintaining the same initial energy consumption. After the optimal solutions for the chosen passive cooling technologies were found, it was tested how resilient the building can become with the implementation of these technologies against future global warming scenarios.

Figures, equations and tables are numbered after the chapter number and placement in that chapter. For example, figure 3.5 refers to the fifth figure in chapter 3. When referred to equations the reference is enclosed in brackets. This report uses the IEEE-method as the literature reference and the literature list can be seen in the end of the report.

The following programs have been used as documentation in the report: Design Builder and Excel.

Anastasios Rovithakis

<arovit18@student.aau.dk>

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1 Introduction

Buildings are among the main causes of climate change because they represent the largest energy consuming sector in most countries of the World. On the other hand, global warming can exert significant negative effects on building energy performance, in terms of thermal comfort worsening and increase of energy needs for space conditioning which is why in this thesis a resilient building needs to be designed specifically for cooling purposes.

When it comes to the use of passive cooling technologies, they require more sophisticated approaches and are less studied than the passive heating ones. That is because passive cooling is more dependent on climate like control of air temperature, velocity and humidity. Thus passive solar heating will always make a positive contribution to the overall thermal performance of a building, whereas improper choice of a cooling technique could create an unpleasant internal environment. In addition, thermal comfort requirements during summer are different for each climate type. As an example, hot dry climates require different cooling strategies to hot humid climates. The choice of the appropriate cooling technique depends not only on the local climatological conditions, but also on the building type and the occupancy patterns. [4].

1.1 Definition of Resilience

The proposed resilience definition can be interpreted as the ability of the system to withstand a change or a disruptive event by reducing the initial negative impacts (absorptive capability), by adapting itself to them (adaptive capability) and by recovering from them (restorative capability).Enhancing any of these features will enhance system resilience.

Figure 1.1 shows the above mentioned two phases of resilience.

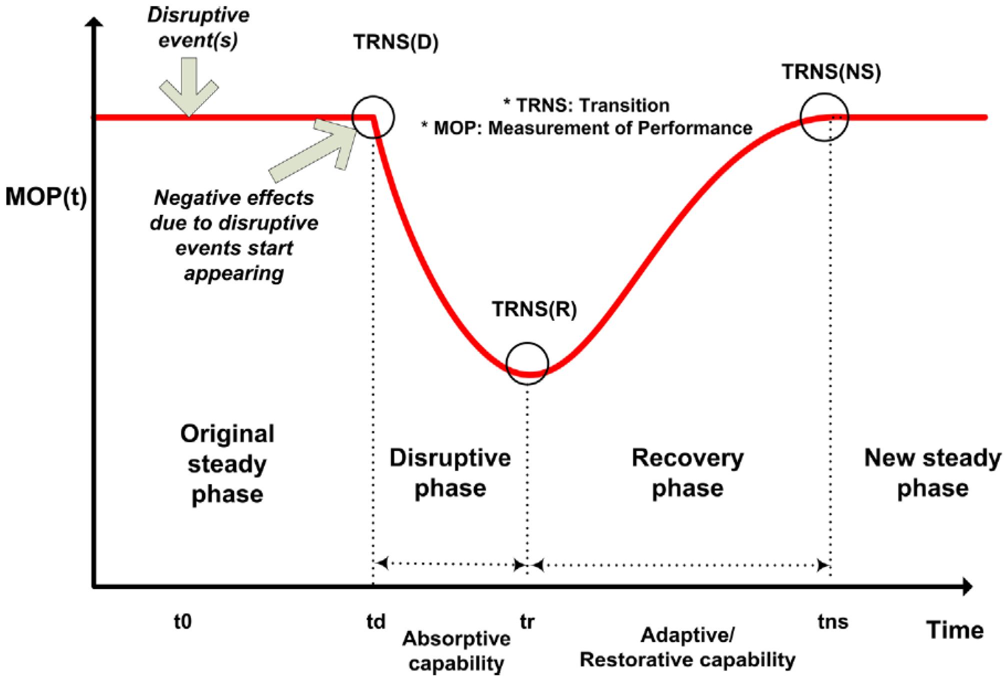


Figure 1.1. System resilience transitions and phases [2].

Absorptive capability refers to an endogenous ability of the system to reduce the negative impacts caused by disruptive events and minimize consequences. In order to quantify this capability, robustness can be used, which is defined as the strength of the system to resist disruption. This capability can be enhanced by improving system redundancy, which provides an alternative way for the system to operate.

Adaptive capability refers to an endogenous ability of the system to adapt to disruptive events through self organization in order to minimize consequences. Emergency systems can be used to enhance adaptive capability. Restorative capability refers to an ability of the system to be repaired. For example, installing real-time automated monitoring systems [2].

1.1.1 Differences between Resilience and Robustness

Resilience provides a broad scientific basis for understanding persistence and transformation in complex systems. Resilience concepts can be used both to help define the decision making context for short term decisions and to provide understanding of how this context may change or transform over longer periods.

In contrast, robustness control provides a narrower, systematic analytical framework for short to medium term decision and policy design questions under uncertainty given performance measures and the decision making context informed by basic theory from feedback systems.

Generally, robustness focuses on designing fail safe systems within a defined range of uncertainty, and resilience emphasizes trying to build fail safe systems capable of learning, self organizing, and adapting to change. The use of multiple redundant systems in engineered systems is, to some extent, built in adaptation. However, there is no real adaptation to changing conditions. These backup subsystems provide the same functionality to sustain the system exactly as it was before the change. Resilience would emphasize overlapping redundancy in which subsystems can perform similar functions with the capacity to modify higher level functions slightly in the face of change. In this way, resilient systems can learn, self organize, and evolve with change [3].

1.2 The Applied Methodology

The criteria to test the overall resilience of a building could be based on the expected percentage of time that human comfort will be achieved. Such criteria for residential buildings include when it comes to the thermal environment the amount of over temperature hours based on the ASHRAE standards. Other criteria which will not be used in this thesis are for the atmospheric environment the CO_2 concentration should not exceed 500 ppm above the outdoor concentration while the relative humidity should be between 25% and 60%. For the visual indoor environment the focus will be on supplying the right amount of light while avoiding glare. The amount of daylight into the building should not be below 2 % around the workstations, where the acceptable amount of glare can be described from the useful daylight illuminance, which tells how much of the time in percent the daylight level is useful. Useful daylight level is between 100 lux and 2000 lux where values above or under this limit are classified as too much daylight or not enough daylight.

When it comes to the energy for the building, the position, orientation, activity, lighting and construction of the building's main frame will remain the same as the specifications for the actual building.

Many passive cooling technologies like solar shading, natural ventilation and micro climate control will be tested one by one to determine if they can influence positively the building's resilience against global warming. Specifically when it comes to the technologies that will be tested since there are many parameters that influence them, firstly optimization of each passive cooling technology will be performed to with the least possible over temperature hours while maintaining the same initial energy consumption and being cost effective at the same time. Once the optimal solution is found using the actual weather data for the city of Horsens, Denmark it will be tested to determine if it makes the building resilient against potential global warming scenarios. Finally all used passive cooling technologies will be combined for the creation of the final building.

The actual testing for resilience is going to happen by comparing the results for the over temperature hours between the initial building with the actual weather file as well as the building equipped with the passive cooling technologies with the worst case future weather file scenario. The goal for every single one of the technologies to be characterized as resilient is to determine if it is able to provide results for the over temperature hours of future global warming climate data similar or less than those of the actual weather data.

1.3 General Information for the Studied Building

The project objective of the already constructed family house (Bolig 2020) was as mentioned in the document [11] to develop and demonstrate a new generation of housing that fulfills the coming 2020 regulations, where solutions are presented on those problems that have been seen with existing housing built according to the 2020 regulation and the Passive House Standard. Some of the problems mentioned above are poor indoor climate, high indoor temperatures and an actual energy consumption considerably higher than predicted are reported. The main reason for the high energy consumption is seen as "inappropriate" use of the building by the occupants, demanding more than 20°C inside, opening windows and doors during summertime and opening windows in the bedrooms also during winter night.

The solutions to these problems that implemented are the following: 1) The building envelope is optimized to reduce unwanted passive solar gains to the minimum. 2) The ventilation system is demand controlled so that inlet of fresh air follows the occupants, 3) The occupants are able to choose to cool down selected bedrooms on summer evenings by utilizing cooling generated from the hot water heat pump. 4) A small heat pump with variable speed drive is installed for space heating, allowing the output to be modulated to fit the small heat loads. 5) The earth coils for the heat pump are experimentally integrated with the foundation of the house, thereby reducing investment costs significantly.

The building envelope design is optimized by giving priority to the East and North windows, and windows to the south and west will have automatic exterior shading. Three pane windows with high light transmittance and low solar heat gain factor are also used.

The ventilation system with heat recovery is extended so that fresh air to each room can be individually controlled, so that fresh air can follow occupation rather than being constant per room. Furthermore, when windows or doors in a room are opened, then heating and ventilation to that room is automatically cut off. This reduces the negative effect of a natural user behavior on the energy consumption for heating and ventilation.

Existing Building Characteristics and Conditions 2

In this chapter the building's existing conditions for the construction, materials, energy consumption as well as the conditions and comfort criteria for the indoor environment are shown. To find all these results the program Design Builder was used in order to compare them with the results from global warming weather data and therefor test the resilience of the house bolig 2020 after implementing the passive cooling technologies.

2.1 Building Constructions

In this section the materials used in different construction elements are mentioned.

Building envelope

The tables 2.1 2.2 2.3 2.4 showcase the materials for the different elements of the building envelop.

External wall	Thickness [m]	λ [W/mK]	R [m^2K/W]	U-value [W/m^2K]
Facade stone	0.11	0.6	0.18	0.153
Protection and Insulation layer	0.19	0.034	5.588	
Porebeton	0.1	0.18	0.56	
Internal Layer wall	0.01	0.35	0.029	

Table 2.1. Construction of the external walls and the U-value.

Internal partition	Thickness [m]	λ [W/mK]	R [m^2K/W]	U-value [W/m^2K]
Porebeton	0.1	0.18	0.816	1.226

Table 2.2. Construction of the internal partition and the U-value.

Ground floor	Thickness [m]	λ [W/mK]	R [m^2K/W]	U-value [W/m^2K]
Wooden floor	0.01	0.18	0.056	0.082
Concrete (floor)	0.04	1.8	0.022	
Concrete (floor)	0.08	1.8	0.044	
EPS	0.32	0.031	10.32	
Sand crowl space	0.15	0.1	1.5	

Table 2.3. Construction of the ground floor and the U-value.

Flat roof	Thickness [m]	λ [W/mK]	R [m^{2}K/W]	U-value [W/m^{2}K]
OSB panel	0.02	0.066	0.303	0.087
Air gap	0.05	-	0.18	
Paper wool insulation	0.43	0.041	10.488	
Vapor Barrier	0.0002	0.4	0.0005	
Plasterboard ceiling	0.03	0.35	0.0857	
Air gap	0.0370	-	0.18	
Gypsum acoustic ceiling	0.013	0.21	0.0619	

Table 2.4. Construction of the roof and the U-value.

Windows

In table 2.5 is shown the different parameters for the window used .

	U-value [W/m^{2}K]	g-value [-]	Window to wall [%]
External glazing (Vetro triplo prova 5)	0.554	0.216	30
Roof glazing (Skylights da definire)	2.178	0.682	
Internal glazing (Vetro interno di progetto)	2.166	0.675	

Table 2.5. Window properties.

2.1.1 Description of HVAC system

In general the systems of the house include a floor heating system and a compact unit providing ventilation and sanitary hot water. Additionally, automatically controlled external shading, natural ventilation grids and skylights intend to create a pleasant indoor environment, while reducing the energy consumption of the dwelling.

Specifically figure 2.1 shows the different systems comprising the HVAC for the Bolig 2020. Three main loops are present the domestic hot water loop represented by the yellow lines, the air loop represented by black lines and district heating loop depicted by the red lines.

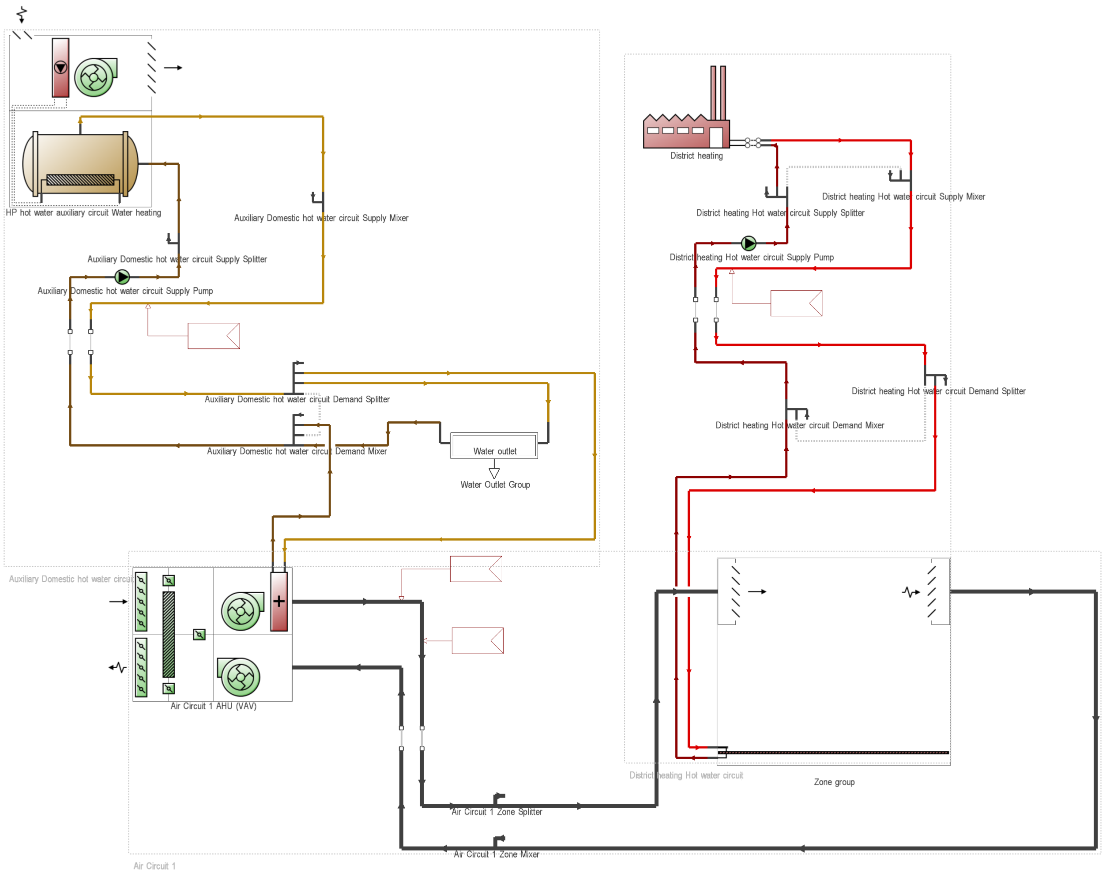


Figure 2.1. Depiction of Detailed HVAC System for the Bolig 2020.

For the domestic hot water loop system the hot water is created from a heating coil. Part of the hot water is used for the water outlet inside the house and part of it to heat up the heat coil inside the air loop system.

The air loop is consisting of an air to water heat pump, provides ventilation with heat recovery 85% and production of domestic hot water as well as an inlet fan providing hot air from the heat coil in the ventilation system of the house as well as an outlet fan extracting air from the house. The ventilation system allows individual control of the air supply in all living areas and the supplied airflow is adjusted based on the CO_2 and relative humidity level in each room. The unit is always running with a minimum airflow when the house is unoccupied or when the indoor conditions do not demand a higher air supply. Finally, the ventilation is deactivated when the windows and doors are opened to provide natural ventilation.

The main heating of every zone of the house is provided in the form of heated floors which are being fueled by the district heating system. Every zone of the house has the same loops that are used to provide heat and ventilation in the house but no cooling or contaminant extraction.

2.1.2 System set points and control strategy

The building's mechanical ventilation system with heat recovery (85%) as well as the floor heating system have individual control of the supply air in all living and sleeping areas as well as individual control of exhaust from the kitchen, bathroom and utility room. Ventilation is supplied to the room depending on presence, so that the fresh air follows the occupants. Presence is recorded as the CO_2 concentration of the air. If the CO_2 concentration in the room is higher than the outdoor one, using a set point of 800 ppm the ventilation system is activated. Extraction from the wet rooms can be controlled either manually or via the moisture content of the individual room, kitchen, bathrooms and utility room. The basic extraction from the kitchen must be at least 20 l/s whereas for the bathroom should be 15 l/s and 10 l/s for the utility room. Due to the CO_2 control in the individual rooms, ventilation is automatically interrupted in the rooms where the occupants open doors or windows. This is to reduce ventilation loss from the dwelling due to the occupant's use of the dwelling. Residents typically open windows and doors to the living rooms in the summer, and for the winter, many people want to sleep in front of an open window in the winter too, thus the fresh air supply will stop being supplied these rooms. The control system must reduce ventilation to approximately half or $0.15l/m^2s$ when a room is uninhabited. A room is uninhabited when windows and doors are closed and when the CO_2 value has fallen below 800 ppm. When the room is inhabited, the CO_2 level will rise to over 800 ppm and the ventilation will be activated at a high level. When there is no one at home, as signaled by the burglar alarm being turned on, all ventilation goes into hibernation. The mechanical ventilation which is providing 10 l/s-person has set points for CO_2 and relative humidity that were set to activate when CO_2 concentration was at 900 ppm, relative humidity at 70%, bathroom relative humidity at 60% and close when CO_2 concentration was at 700 ppm, relative humidity at 50%, bathroom relative humidity at 50%. Concerning the heating system, it is activated in all rooms with a set point temperature of 21°C whereas the cooling which is provided by natural ventilation is set at 25°C [12].

A natural ventilation system has been developed that will ventilate the building when it gets too hot, typically at high sunlight. Outdoor air is taken into selected rooms via a ventilation shutter and returns are made via skylights. The ventilation shutter consists of a fixed exterior shutter with mosquito nets, as well as an internal side-hung insulated shutter that opens when ventilation is needed. Both the ventilation shutter and the skylight are equipped with motor drives. Ventilation shutters are installed in the rooms where over temperature in the summer can be caused by sun exposure like the living room kitchen and master bedroom. The size of the ventilation shutter is basically 5% of the room window area. The skylight window must at least have a free opening area corresponding to the size of the ventilation shutter. The natural ventilation and shading systems can be controlled and activated automatically when the internal temperature exceeds 25°C [12].

The building is equipped with a heat recovery system on hot domestic water. A heat recovery coil is installed in the drain from the two showers. The function is that the cold tap water that is led to the cold water port in the mixer is preheated via heat exchange with the hot drain water from the shower. A heat recovery of the shower water of 30 - 50% can be achieved depending on the operating conditions [12].

In general the building has two main control functionalities when it comes to optimizing the indoor climate and reducing energy consumption based on use of the occupants. These two control functionalities which are either occupied or uninhabited are defined using the theft protection and have the following two operating conditions [12]:

When the residence is uninhabited:

- Ventilation is reduced to 50% of the standard requirement.
- Opening of ventilation shutters and associated skylight window when the room temperature in the room in question exceeds the selected set point of 25°C.
- Closing the outside sun shade when the temperature in a given room exceeds the selected set point of 25°C.
- Automatic light switching off in all rooms.

When the residence is occupied:

- Controlling ventilation depending on user behavior, as described earlier with a CO_2 concentration in the air in living rooms and sleeping rooms of a maximum limit of 800 ppm is used.
- For the natural ventilation and exterior shutters control the residents must be able to manually override the system and decide whether natural ventilation in the individual room should be open or closed. The system returns to automatic control when the occupants leave the home.
- When the hood in the kitchen is activated, the extractor is switched so that priority is given to extraction from the kitchen and the extraction and supply fan are run up to a selected maximum level. The extra supply air volume is added to the kitchen living room.

Occupancy Profiles

In the original study for the Bolig 2020 (conducted by Cristina Carpino) three occupancy profiles were modelled and compared in order to calibrate the model as precisely to the actual house as possible. The construction of the user profiles implied the definition of the schedules of presence at home, the use of the heating system, the production of domestic hot water, and the use of appliances.

The first model, defined as Compliance profile, was based on the indications provided by current Danish regulations and it represents a simplified model generally used for the design of the building. In particular, a load of 1.5 W/m^2 is prescribed for persons, 3.5 W/m^2 have to be considered for electricity, and a consumption of 250 l/m^2year is estimated for DHW uses.

The second model, characterised by a quite higher level of detail and named Standard profile, is defined on the basis of average values obtained from surveys. This model can be used to describe a building occupied by a typical family using the house according to a standard use.

The third model which is used for this project, labelled Actual profile, was defined using energy use data, house monitoring data and information collected through a face to face interview during which occupants were asked to figure a typical daily routine and to explain how they interact with the systems. That way is tailored on the measured data and it offers the highest compatibility with the current occupancy, returning the closest energy use to the measured one. Therefore, the daily routine of the two occupants can be summarised as follows: both leave the house around 8:00 in the morning, have breakfast and lunch outside; they return in the evening around 18:00 and go to sleep at different hours, earlier the husband (around 21:00) and later the wife (around 23:00). The rooms of the house that are usually occupied are the kitchen/dining room, the living room, the master bedroom, the bathroom 1, and the utility room, where the laundry is located. Sporadically, room 2 and bathroom 2 are used. Indoor monitoring data were used in order to build hourly occupancy schedules. Specifically hours with higher CO_2 concentration were considered as occupied. For the DHW production, a total consumption of 10.56 m^3 was recorded in the analysed period. Therefore, an average consumption of 1.76 m^3 per month is obtained, corresponding to a DHW demand of 58.67 l/day. The DHW production temperature is fixed to 40°C. The frequency of consumption was analysed to identify at what time during the day the DHW is used. For this purpose, the 24 hour daily interval was divided into 5-minute time steps, corresponding to the data monitoring frequency. Electricity meters are installed in order to monitor the main appliances. Thanks to the registered consumption, it was possible to define typical usage schedules for cooking plate, cooker, dishwasher, washing machine, and dryer [8].

2.2 Characteristics of the Building and Building Site

In this section the more general building characteristics and the site surrounding it are presented.

2.2.1 Site characteristics

The site of the building is in Horsens, Denmark at an elevation of 81 m above sea level and the orientation of the site is 37° from North. The site's ground has a small decreasing slope with the highest point starting from the North side at 81.77 m and the lowest in the South side at 80.5 m as seen in figure 2.2. In table 2.6 the floor area of the site as well as the major house spaces are shown.

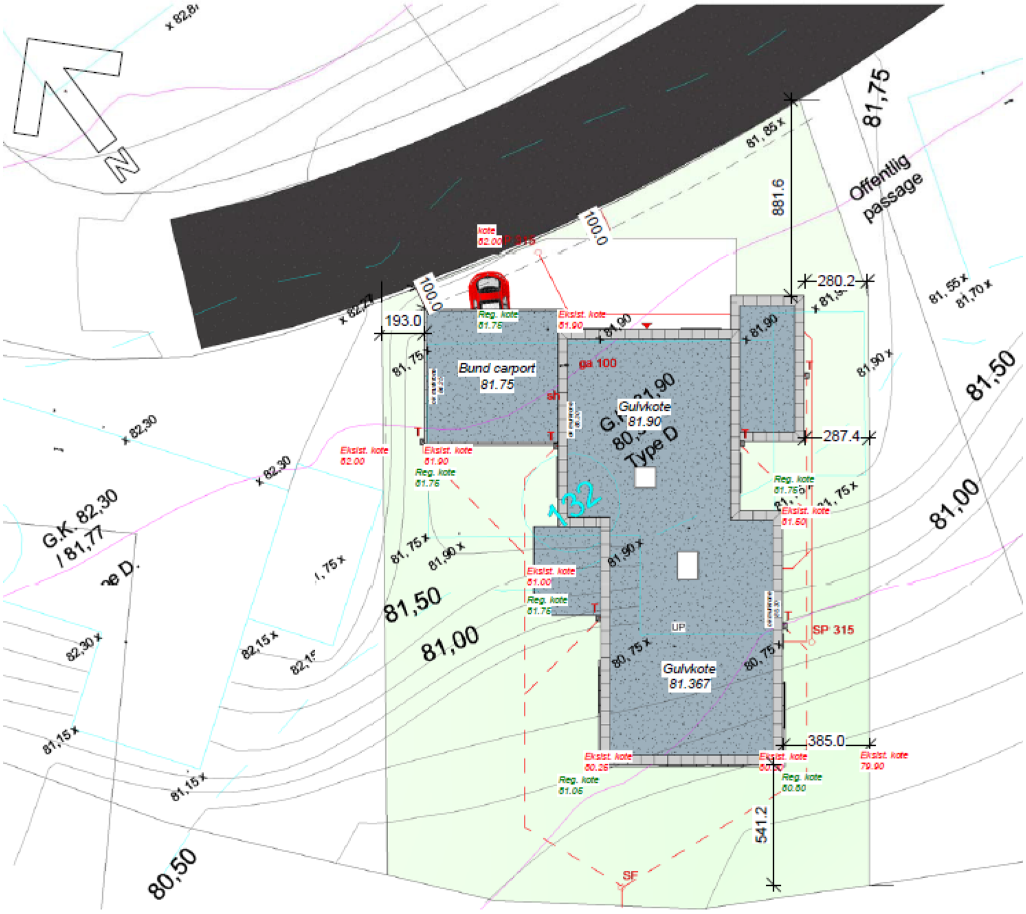


Figure 2.2. Depiction of site area for the Bolig 2020.

	Floor area [m^2]
Ground	673
Building living space	160
Carport	35.8
Shed	19.5
Covered terrace	12

Table 2.6. Area of different parts of bolig 2020 and its site.

2.2.2 Site weather data

In this subsection the base file of weather data for Bolig's 2020 site is presented as seen in figure 2.3. This weather file is based on real measurements for the location Horsens Denmark and it is used to gather the initial data for different comfort criteria in order to test the original building conditions. These initial comfort criteria data in later chapters will be compared with the corresponding data using global warming weather files while incorporating the tested passive cooling technologies.

Figure 2.3. Depiction of the base weather conditions in the site area for the Bolig 2020.

From figure 2.3 can be seen that the lowest daily temperature of the year is −8°C occurring on 12th of January, the highest is 31°C on 21st of July while the average is 9°C. The wind speed is varying between the lowest value of 0.3 m/s and the highest value of 10.5 m/s with the average being 3.7 m/s. When it comes to the wind direction it varies from Northeast to Northwest with the prevailing wind direction being Southwest. Finally the yearly direct solar radiation as calculated from the measured weather file is ranging from a minimum value of 0 kWh/m^2 to a maximum of 12 kWh/m^2 with an average of 3 kWh/m^2 whereas the diffuse solar radiation is ranging from 0 kWh/m^2 to 4 kWh/m^2 with an average of 1 kWh/m^2.

Resilient Cooling Technologies 3

Resilient cooling technologies can be divided in two general categories. The passive cooling which are most of the times used first to prevent heat gain and the natural cooling to further contribute to the cooling overall by removing the excess heat by natural measures in case the passive cooling is not enough. Both passive and natural cooling have many design solutions which will be analysed in the subsections below.

3.1 Passive Cooling

3.1.1 Micro climate

Buildings are directly affected by the micro climate which is the local climate at building site or cities and can be separated in local effects, solar gain and airflow. The local effects are referring to potentially special properties of the site for example if it is located in a suburban area with lots of greenery a cool island effect will be created which is the result of cooler temperatures due to the presence of greenery like vegetation and plants to the building. This is happening due to the fact that plants in general are responsible for providing shade for the surroundings as seen in figure 3.1. Specifically for this studied house trees will be planted all over its perimeter except from the driveway side to model their effect of shading on the house. Moreover different heights of trees will be tested to determine the ideal one.

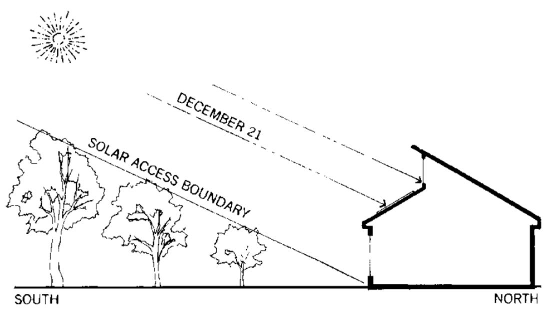


Figure 3.1. Potential use of trees for natural ventilation [5].

Another side effect of trees that is equally important and will be tested is their effect on natural ventilation since they can be used as wind barriers as seen in figure 3.2 thus affecting the natural ventilation of the building.

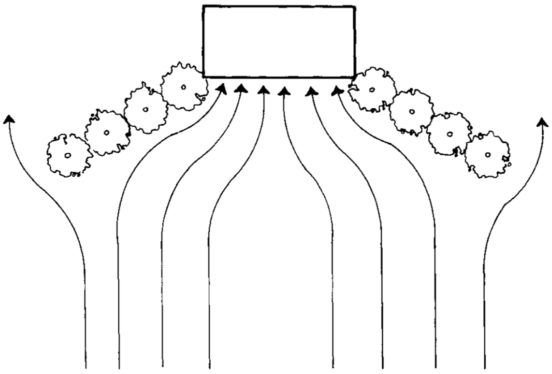


Figure 3.2. Potential use of trees for natural ventilation [5].

To do that trees will be simulated for the East, West and South facades both individually and combined to determine which design is the optimal one. The building has a flat roof which is ideal for turning it into a green roof in order to test how the heat transfer through the roof will influence the resilience of the building towards cooling. The solar gain is mainly responsible for temperature increase in buildings. Controlling the micro climate is a great way of making buildings resilient to weather changes while at the same time minimizing the use of non renewable sources for energy consumption.

3.1.2 Solar radiation Control

In this subsection the different solar shading based passive cooling solutions are mentioned. These solutions in chapter 5 will undergo an optimization process to find out which of those is the most energy efficient solution while meeting the thermal comfort criteria and being cost efficient.

During the day and year the sun will follow different paths on the sky. The highest sun path for summer solstice is on June 21, resulting in the highest amount of solar radiation especially for the south and west facing facades since they receive much more solar radiation. The middle sun path for the equinoxes on March and September 21 and the lowest sun path for winter solstice on December 21 as seen in figure 3.3.

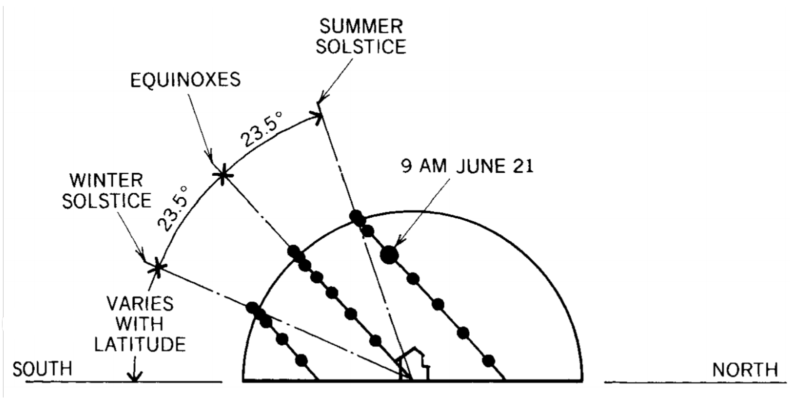


Figure 3.3. The different yearly sun positions [5].

Meaning that is possible to take advantage the fact that the altitude angle is much larger in summer than in winter in order to use passive solutions mentioned below, like overhangs for the windows to prevent the direct radiation. Other than the direct radiation the building needs to be protected by the diffuse solar radiation where in hot climates can be just as important as well as the reflected solar radiation from highly reflected materials of adjacent buildings. When it comes to the direct solar component it can be best controlled by exterior shading devices. The diffuse solar component since it has a large exposure angle from which the radiation comes can be best controlled by indoor shading devices. Finally the reflected solar component can be minimised by the use of trees in order to act as a barrier for the radiation. Below the devices and shading solutions for solar radiation control are mentioned.

Permanent Devices

Overhangs are architectural elements that can either be part of the roof or stand alone elements protruding from the main building structure in order to provide shading for lower windows and building levels. The main use of this solution is to block the direct solar radiation especially during the summer months when the sun's position is the highest seen in figure 3.4 . Overhangs is an affordable solution with minimum maintenance.

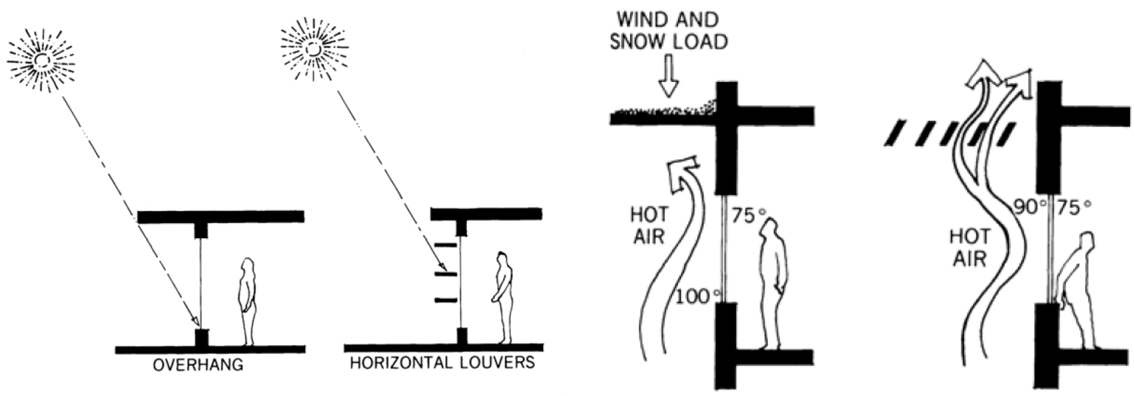


Figure 3.4. Implementation of permanent shading devices [6].

However overhangs can also "trap" hot air close to the window and can also create additional structural stress to the building from extreme snowfall or wind speed seen in figure 3.4. To minimise these problems horizontal louvres can be implemented as they allow wind and snow to pass right through.

These solutions are not very effective for the majority of time as well as for the East and West facing windows. For those orientations vertical fins can be added to reduce the low solar angle of incidence problem. However vertical fines can limit the view to the outside and make the window washing harder [5].

Movable Devices

These devices are able to adapt better to the changing sun angles unlike the permanent ones while at the same time providing glare control and can be divided into the following:

Screens are usually motorized semi-opaque fabric constructions on the external side of windows providing shade and glare protection for the room inside. Screens typically require more maintenance than overhangs since they are not very rigid constructions and have moving parts that are vulnerable to the elements. However they are more effective than overhangs since it is possible to be controlled by solar radiation or temperature sensors for the best result possible.

Venitian blinds are constructions that can be implemented on the internal side or in between the window panes or on the external side of windows providing shade and glare protection. However unlike screens they are not very effective for cooling purposes being on internal side of windows since solar radiation can easily penetrate the glass and thus heat up the room. By placing the blinds on the external side this problem can be reduced as they offer the best solar radiation control but at the same time they are more vulnerable to the elements. Finally the placement of blinds in between window panes offers both outstanding solar radiation control and less maintenance.The main disadvantages is their difficult access in case of malfunctioning, the increased cost and the obscuring of the view to the outside.

Protective Glazing

Windows are built up of two or more layers of glass that are working by reflecting back to the environment a small amount of radiation they received, absorbing part of the solar radiation and transmitting the rest of it seen in figure 3.5.

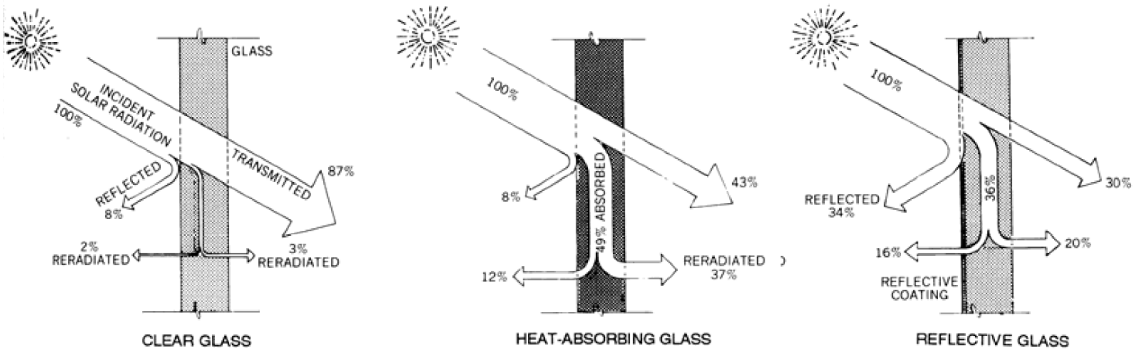


Figure 3.5. Implementation of permanent shading devices [4].

The heat transmission in a sealed glazed unit occurs by means of conduction and convection in the cavity and by radiation from the warm glass to the cold glass. In an ordinary double glazed unit heat transmission by radiation accounts for approximately 2/3 of the total heat transmission between glass layers. Therefore for cooling purposes the reflection part of the solar radiation needs to be increased by using reflective coating. That solution even though it provides cooling it also decreases the natural lighting so to combat that a low emission coating can be used as it transmits less short wave radiation [4].

3.1.3 Building Form and Layout

The building form must be designed with the purpose to keep as much heat during winter as possible and at the same time accept the least amount of radiation during summer.

The ability of a building to store heat can be determined by its thermal capacity which is directly correlated to the building's volume. Whereas the rate at which the building gains or loses heat can be determined by the exposed surface area. This means that a high volume to surface ratio a building will heat up slowly, as it offers small exposed surface for the control of both heat losses and gains.

The layout of the building's interior determines also the ventilation conditions throughout it. An elongated design with the right placing of openings is considered optimal especially when the air flow path does not get restricted from the separation of spaces or large furniture. A good rule of thumb for the room positioning is that the biggest rooms should be on the windward side seen in figure 3.6.

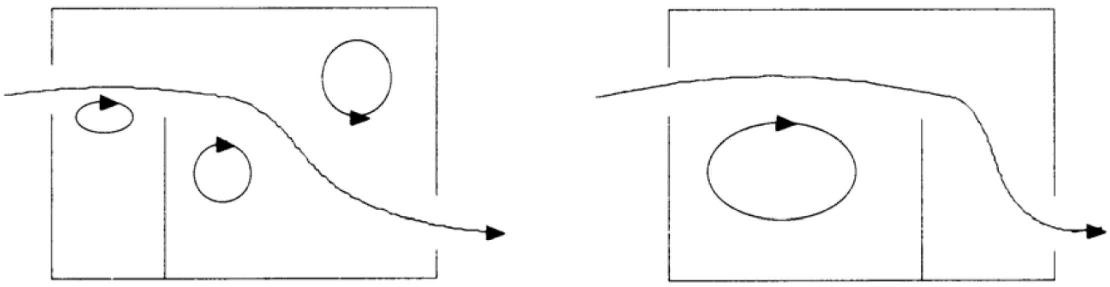


Figure 3.6. The wrong and correct positioning of spaces respectively [4].

Stratification can be provoked with high ceilings, which can be useful especially in hot climates. The cooling effect of the room height is greater in spaces with very high ceilings, where stratification of the air allows the occupants to inhabit the lower cool space.

3.1.4 Heat Avoidance

The buildings should be designed with heat avoidance in mind. This can happen by the right choice of color as lighter colors reflect more of the solar radiation as well as using materials with high emissivity like plastic. Especially useful is the insulation as it improves summer comfort by lowering the building's temperature of the inner surface. The roof receives the highest amount of solar radiation so the placement of insulation there is particularly effective. The main disadvantages are that insulation is relatively costly and demands careful design to avoid thermal bridges and condensation. The goal is to create a building with sufficient mass in order for the heat absorbed at the exterior surface during the day to not reach the interior of the building, but to return back to the surroundings when the exterior surface temperature drops at night. Effective cooling can also be provoked on buildings with high surface area to volume ratio as it facilitates space for many windows thus providing natural ventilation which can also affect daylight positively. Another way to reduce heat gains in the building is by reducing the envelope's infiltration which is also directly correlated to humidity and condensation levels in the house. The infiltration rate depends not only on the wind velocity but also on the difference between indoor and outdoor temperatures [4].

3.1.5 Internal Heat Gain Control

Unwanted heat gains can be created by internal heat sources like artificial lighting, equipment and occupants. By using the available natural daylight instead of the artificial one lighting heat gains can be reduced thus reducing the cooling loads needed, while at the same time reducing the electricity consumed for lighting. When it comes to the light entering a building is composed of diffuse sunlight which is the usable part of daylight and the direct sunlight which is responsible for creating glare. For the best results and particularly when daylight enters from the roof, it is important to shade openings to avoid heat production. Humans is another variable both when it comes to production of some heat loads which can be combated by avoiding high occupancy density as well as not dressing appropriately according to the weather conditions thus demanding more energy consumption for cooling than they need. Finally electric equipment can also contribute to the increased heat gains in a building so more energy efficient devices should be used and preferably located in unoccupied ares with the appropriate amount of ventilation [4].

3.2 Natural Cooling

In case the passive cooling techniques mentioned above turn out not sufficient enough to prevent heat gain the natural cooling techniques mentioned below can be used to remove the excess heat.

3.2.1 Natural Ventilation

Natural ventilation has many uses ranging from reducing the cooling loads and improving thermal comfort criteria to providing the required levels of fresh air and control indoor pollutants. Natural ventilation can occur mainly due to difference in pressure between the building's inlets and outlets, but also from density differences due to temperature and moisture differences. Natural ventilation can be greatly influenced by the site's environmental conditions like the prevailing wind direction, speed, temperature and the surrounding topography in general. After understanding the site's environmental conditions the building should be designed accordingly to enhance the airflow in it. With a proper design natural ventilation can turn out more effective than mechanical ventilation as it is able to provide 15-30 air changes per hour. For providing the best cooling as possible the incoming air should be at a lower temperature that the indoor air temperature. However, even though the incoming air could have a higher temperature than the inside, thermal comfort conditions for the occupants can be met, since the airflow enhances evaporative and convective heat losses. On the other hand air humidity is the most important limiting factor for the application of natural ventilation techniques. For places with high levels of humidity natural ventilation should be avoided and instead the use of conventional air-conditioning systems is necessary in order to remove the excess humidity from indoor air.

Natural ventilation is also very effective during the night, when outdoor air temperatures are usually lower than the indoor ones. Air flow through the building during the night, when the outside air temperature is low, other than lowering the indoor ambient temperature is also responsible for storage of cooling in the building's mass. That way the building is kept cool during the next day, as the building's mass is able to absorb the heat of the day.

3.2.2 Evaporative Cooling

Evaporative cooling which is most effective in dry climates works by turning the sensible heat in the air flow to latent heat in the form of small water droplets and it can work either directly or indirectly.

The direct method works by directly spraying water droplets into the warm outdoor air seen in figure 3.7, thus causing moisture to evaporate and cool the air. The main drawback of such system is that it increases the moisture content and thus it cannot be used in regions with high humidity levels.

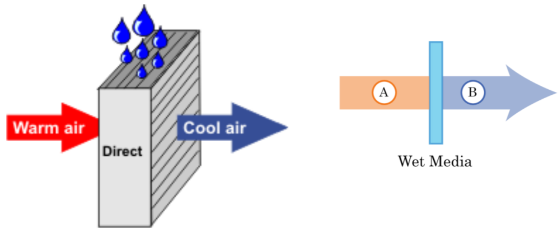


Figure 3.7. Implementation of direct evaporative cooling [7].

To minimise the drawbacks of the direct system it possible to use an indirect system, in which air is cooled without addition of moisture by passing through a heat exchanger seen in figure 3.8. However the indirect system has a reduction in efficiency of the evaporation process as it depends on the temperature of the air and of the wet surface.

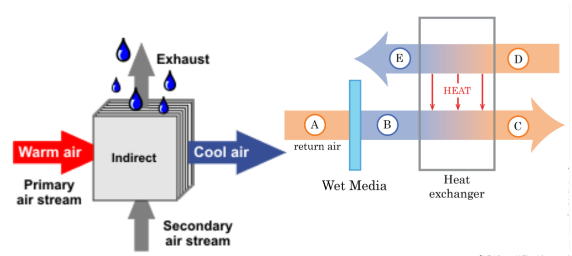


Figure 3.8. Implementation of indirect evaporative cooling [7].

Traditionally in dry climates direct cooling could be incorporated by placing jars of water on wind towers where incoming air passes through them thus cooling the incoming airflow as seen in figure 3.9.

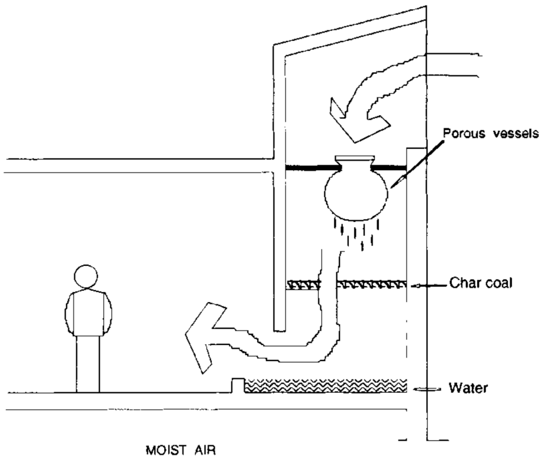


Figure 3.9. Implementation of traditional direct evaporative cooling [4].

Whereas indirect evaporation is used to cool the roof of the building either by keeping a thin layer of water (Water-film) on the roof surface or by using a water spray to keep the roof wet. The building is then cooled, because the radiant temperature of the roof, and of the indoor air coming in contact with the roof, is lowered [4].

3.2.3 Ground Cooling

Ground cooling is an effective way of making a building more resilient to temperature changes as the ground has a much higher thermal capacity to store the excess heat and thus stay cooler than the ambient temperatures by having an almost constant temperature during the day. There are two main ways of using the ground for cooling purposes either indirectly or directly.

When it comes to indirect ground cooling an earth to air ex-changer is used usually in the form of pipes in order to remove the building's excess heat using the ground as a heat sink and at the same time cool air is transferred in the building as seen in figure 3.10.

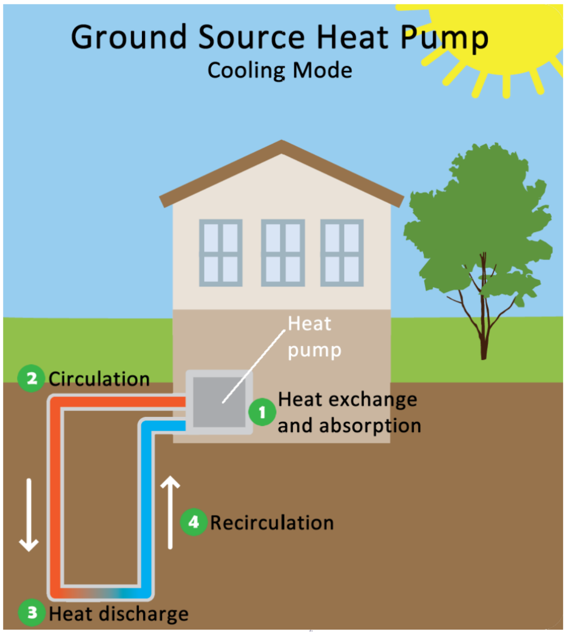


Figure 3.10. Implementation of indirect ground cooling [7].

Direct ground cooling refers to when the building is directly in contact with the ground. This design increases the conductive exchange between the ground and building surfaces, it has low maintenance as well as environmental benefits. However it suffers from reduced daylight and indoor air quality.

The actual house and thus model of it has direct ground cooling system incorporated. To minimize the drawbacks of this system only the lower part of the building's South, East and West facades (until the height of the lower part of windows) are in contact with the ground. This is done so the building's temperature could be reduced since these facades receive the most solar radiation thus using the ground to store some of the excess amount while at the same time not obscuring the view to the outside [7].

3.2.4 Radiative Cooling

Using this type of cooling the heat of the day can be absorbed and then released back to the environment during the night as seen in figure 3.11. Radiative cooling can be divided in direct and indirect cooling and is effective due to the lower sky temperatures when compared to anything on the ground.

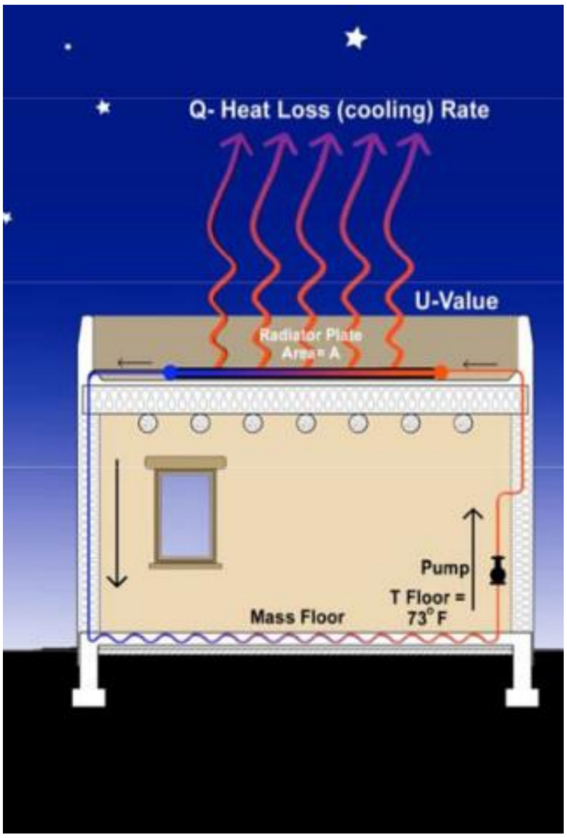


Figure 3.11. Implementation of radiative cooling [7].

Direct radiative cooling uses the roof as a heat sink during day and a heat source during night in order to release the excess heat during the night with the use of insulation.

Indirect radiative cooling is the same principle but uses a flat plate with water or air. Long wave radiation coming from the zenith of the sky is less than the one coming from the horizon. The optimum position of a flat plate radiative cooler is thus horizontal and does not depend on the latitude of the site [7].

4 Model Calibration

In this chapter the model calibration and validation is presented. For the calibration of the model a manual approach is followed, where the simulated effect of different input parameters such as weather data and natural ventilation is shown and graphically compared with the actual measured data from the bolig 2020. In this thesis the cooling potential from the different resilient cooling technologies are most important so the model calibration is made comparing the simulated with the measured results for the building's indoor air temperature with extra emphasis given to the cooling season results. For the final calibrated model of the house the graphical comparisons between simulated and measured data for the individual rooms will also be presented together with the validation indexes mentioned below.

4.1 Initial Model Calibration Procedure

Building energy models is complex and composed of a large number of input data. When modeling a building within a simulation program, the accuracy especially relies on the ability of the user to input the parameters (input data) that results in a good model of the actual building energy use. Given the large number of parameters involved, the process of calibrating a detailed energy model is a highly undetermined problem. A common technique is to use a "trial and error" method to calibrate a building model, which is mainly driven by experience assumptions, but can lead to time consuming and unsolved problems [13].

In this section the simulated model's internal temperature will be compared to the actual measured one. Also many different formulas (MBE, NMBE, CV(RMSE), GOF) will be used to calculate errors based on ASHRAE Guideline 14 and the results will be compared to the limits defined both from ASHRAE as well as other verification protocols like FEMP Criteria and IPMVP. The limits for acceptably calibrated model from these protocols can be seen in figure 4.1.

Data Type	Index	FEMP Criteria	ASHRAE Guideline 14	IPMVP
Calibration criteria				
Monthly criteria %	$NMBE$	±5	±5	±20
	$CV(RMSE)$	15	15	-
Hourly criteria %	$NMBE$	±10	±10	±5
	$CV(RMSE)$	30	30	20

Figure 4.1. Acceptable limits for model calibration [10].

4.1.1 Model Validation Indexes

In this subsection the math formulas for the indexes mentioned in figure 4.1 are explained in detailed.

MBE (Mean Bias Error)

MBE (Mean Bias Error), as its name indicates, is the average of the errors of a sample space. Generally it is a good indicator of the overall behavior of the simulated data with regards to the regression line of the sample. Positive values mean that the model under predicts measured data, and a negative one means over prediction. However, the main problem with this index is that it is subject to cancellation errors where the sum of positive and negative values could reduce the value of MBE. Equation 4.1, shows the MBE indicators for the yearly and summer periods [9].

$$\begin{aligned} MBE_{year} &= \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} = -0.31^{\circ}C \\ MBE_{summer} &= \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} = -1.1^{\circ}C \end{aligned} \tag{4.1}$$

m_i	The measured values [^oC]
s_i	The simulated values [^oC]
n	The number of measured data points [-]

MBE is not an index used by ASHRAE Guidelines, FEMP and IPVMP for model calibration but nonetheless it shows the average difference between measured and simulated data for the two periods specified as well as the fact that the model over predicts slightly.

NMBE (Normalized Mean Bias Error)

NMBE (Normalized Mean Bias Error) is a normalization of the MBE index that is used to scale the results of MBE, making them comparable. It quantifies the MBE index by dividing it by the mean of measured values ($\bar{m}$), giving the global difference between the real values and the predicted ones. As in the case of MBE, positive and negative values mean the under or over prediction of this normalization. NMBE is also subject to cancellation errors thus the use of this index alone is not recommended [9].

$$\begin{aligned} NMBE_{year} &= \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \cdot 100\% = -1.4\% \\ NMBE_{summer} &= \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \cdot 100\% = -0.4\% \end{aligned} \tag{4.2}$$

m_i	The measured values [^oC]
$\bar{m}$	The mean of measured values [^oC]
s_i	The simulated values [^oC]
n	The number of measured data points [-]
p	The number of adjustable model parameters, for calibration purposes, should be zero [-]

The results for the NMBE index for the yearly and summer period as shown in equation 4.2 are well below the acceptable limits for ASHRAE as well as the other protocols based on figure 4.1. However since this index is subject to cancellation errors the following CV(RMSE) index will also be tested.

CV(RMSE) (Coefficient of Variation of the Root Mean Square Error)

CV(RMSE) (Coefficient of Variation of the Root Mean Square Error) measures the variability of the errors between measured and simulated values. It "gives an indication of the model's ability to predict the overall load shape that is reflected in the data". It is not subject to cancellation errors, and hence, AHSRAE Guidelines, FEMP and IPMVP use it with NMBE to verify the accuracy of the models [9].

$$\begin{aligned} CV(RMSE)_{year} &= \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \cdot 100\% = 5.6\% \\ CV(RMSE)_{summer} &= \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \cdot 100\% = 8.9\% \end{aligned} \tag{4.3}$$

m_i	The measured values [^oC]
$\bar{m}$	The mean of measured values [^oC]
s_i	The simulated values [^oC]
n	The number of measured data points [-]
p	The number of adjustable model parameters, for calibration purposes, should be one [-]

The results for the CV(RMSE) index for the yearly and summer period as shown in equation 4.3 are again well below the acceptable limits for ASHRAE as well as the other protocols based on figure 4.1. Since those two indexes are acceptable the model can be considered validated based on the different protocols tested.

GOF (Goodness-Of-Fit)

Another statistical index not used by ASHRAE Guidelines, FEMP and IPVMP, but which have been found to be useful for calibration purposes is the Goodness-Of-Fit index (GOF). GOF (Goodness-Of-Fit) measures how well the simulated values fit the measured ones. Lower values mean lower dispersion, so the regression line of the model is closer to the real one. As can be seen, this statistical index combines the overall behavior of CV(RMSE) and NMBE. Therefore, in order to obtain a good value of GOF, the other indices also need to be good [9].

$$\begin{aligned} GOF_{year} &= \frac{\sqrt{2}}{2} \cdot \sqrt{CV(RMSE)^2 + NMBE^2} = 4.1\% \\ GOF_{summer} &= \frac{\sqrt{2}}{2} \cdot \sqrt{CV(RMSE)^2 + NMBE^2} = 6.3\% \end{aligned} \tag{4.4}$$

4.1.2 Weather Influence

The original model of the Bolig 2020 was using the 30 year reference weather file from Meteonorm library for the location of Ry for the simulations. These can lead in discrepancies in the results, because the measured data for the building's internal temperature were made using the actual measured weather data for the year 2018 for the location of Horsens. So in this subsection these two weather files are tested to determine how they influence the model calibration.

Here the importance of different weather files is shown. The house bolig 2020 is built in the area of Horsens Denmark. The first weather file is from the area of Horsens and has actual measurements for the year 2018. The second weather file has been taken from the program Design Builder's library for the area of Ry which is very close to Horsens and consists of files from multiple years. Each month has been selected to be representative of that month for the period of record. The selection of months is usually based on a weighting of temperature, humidity, wind, and solar.

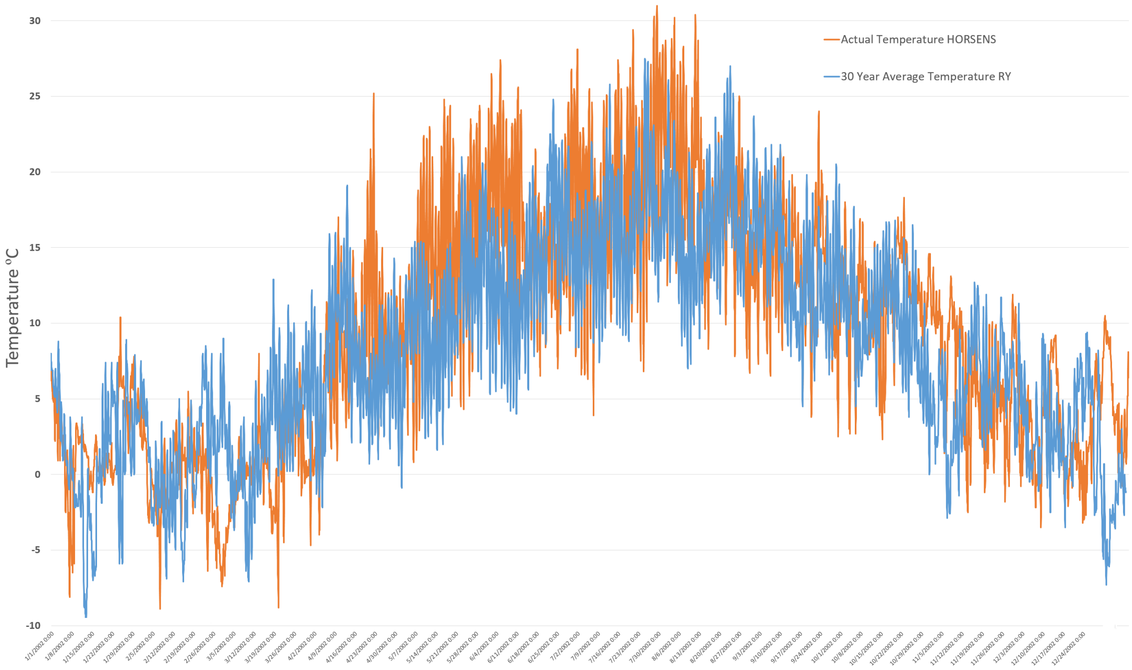


Figure 4.2. Hourly comparison between the actual weather data from Horsens and the 30 year average weather data from Ry.

As seen in figure 4.2 the actual measured weather file from Horsens is much hotter as it has an average summer temperature of 20°C with a maximum of 31°C whereas the weather file from Ry has an average summer temperature of 15°C with a maximum of 27°C.

Internal Temperature Comparison with the Ry weather file.

In figure 4.3 the simulated results for the entire house depicted with blue color are shown using the weather file from Ry and without changing any parameters to the original model of the Bolig 2020. The results depicted with orange color are actual measured results for the entire house.

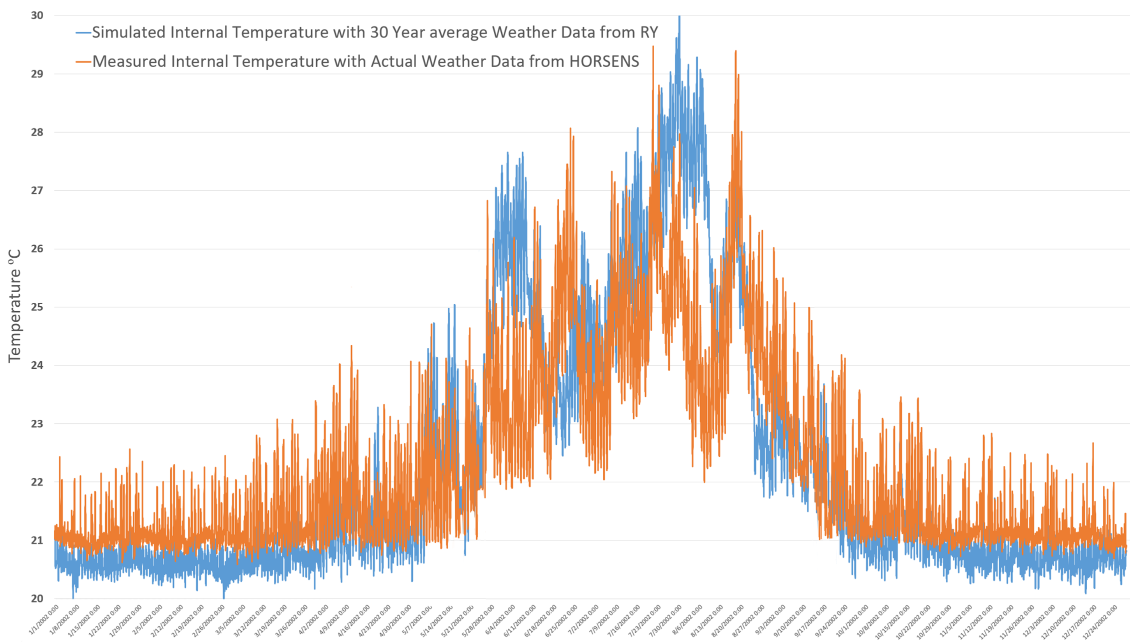


Figure 4.3. Hourly comparison between the simulated results from the original model using the Ry weather file and the actual measured results.

In general figure 4.3 shows that the two set of temperature data are following the same trend. However it is clear that the simulated results are showing cooler temperatures as the weather file from Ry is also cooler than the actual one from Horsens.

Entire House	Indexes
-0.02	MBE_{year}
-1.1	MBE_{summer}
-0.07	$NMBE_{year}$
-3.69	$NMBE_{summer}$
5.4	$CV(RMSE)_{year}$
8.3	$CV(RMSE)_{summer}$
3.8	GOF_{year}
6.4	GOF_{summer}

Table 4.1. The different calibration indexes for the entire house with the weather data from Ry.

The results for the different validation indexes in table 4.1 were calculated using the equations from subsection 4.1.1. The main indexes NMBE and CV(RMSE) are below the limits so technically the model can be considered calibrated. However judging by the graph 4.3 the simulated results are clearly not following the measured ones and that can also be reflected by the relatively high CV(RMSE) index. When it comes to the extremely low MBE and NMBE indexes they are most likely subjected to cancellation errors.

Internal Temperature Comparison with the Horsens Actual Weather File.

For the figure 4.4 the actual weather file from Horsens is used again without changing any other parameters from the original model of the house. The simulated results for the entire house are depicted with green color and the results depicted with orange color are the actual measured results for the house.

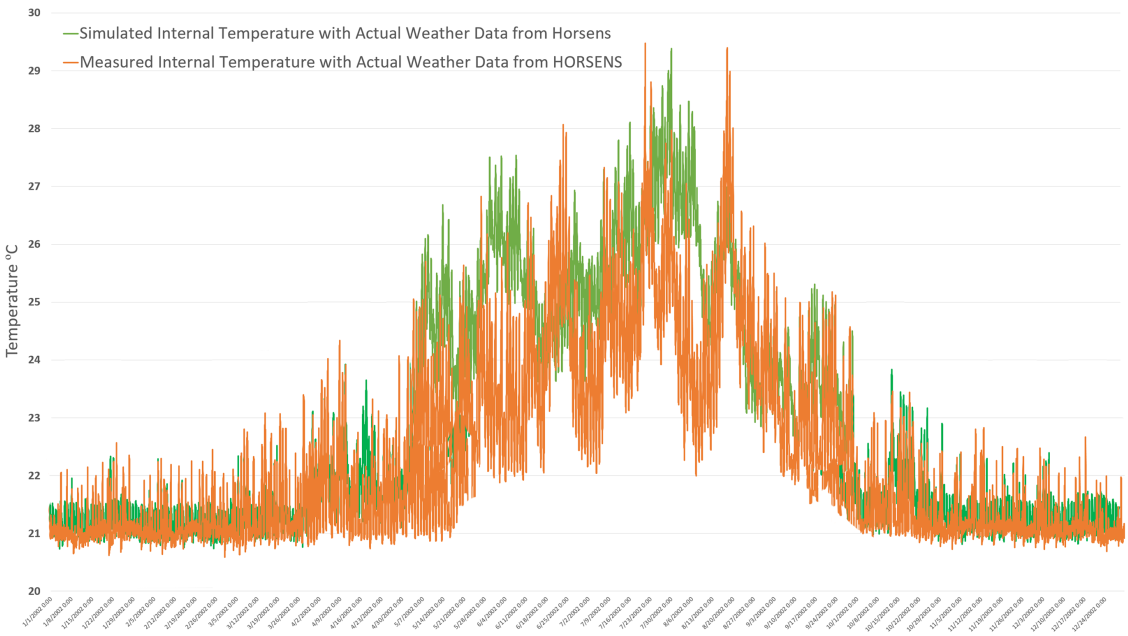


Figure 4.4. Hourly comparison between the simulated results from the original model using the actual weather file from Horsens and the measured results.

Using the actual weather file has shifted the simulated data upwards as this weather file is warmer. As seen in figure 4.4 the new simulated data depicted with green color are following the measured ones much closer and the general trend is much more accurate. Now the simulated data are showing a good calibration for the winter time however for the summer time there are some periods where the simulated data values are out of the range from the measured ones.

Entire House	Indexes
-0.6	MBE_{year}
-1.1	MBE_{summer}
-2.7	$NMBE_{year}$
-5.6	$NMBE_{summer}$
5.2	$CV(RMSE)_{year}$
8.1	$CV(RMSE)_{summer}$
4.2	GOF_{year}
7.1	GOF_{summer}

Table 4.2. The different calibration indexes for the entire house with the actual weather data from Horsens.

Again using the equations from subsection 4.1.1 the validation indexes in table 4.2 were calculated. The negative MBE and NMBE indexes show that the model is over predicting compared to reality. Even though the index CV(RMSE) got smaller when compared to the corresponding one from table 4.1 it is clear that specifically for the summer period the model is not as calibrated judging by the graph 4.4.

4.2 Final Calibrated Model

The original study [8] for the Bolig 2020 had made a calibrated model of the house using the program Design Builder for the winter period and specifically for energy use and energy performance, this means that some parameters like the natural ventilation or the operation of the shading devices have not been considered. Even though the previous model iterations based on the weather data turned out to be calibrated according to the indexes, some parts of the simulated data were outside the range of the measured ones. That is why it is important to not rely solely on the indexes alone but also have a graphical representation comparing the simulated to the measured results for the internal temperature of the house. In order to have an even better calibrated model specifically for the summer period, the opening of windows was turned on as in the original model the windows were always of. The windows were set up to open when the internal temperature exceeded 25°C as this limit was also set up in the actual house and followed the occupancy schedule. The operation of shading devices was also turned on for the rooms with overheating potential like the living room, master bedroom and kitchen which are the same rooms that have shading devices in the actual house. This was done for calibration purposes so that the model of the house could be as closely matched with the actual house, even though solar shading will be separately studied and optimized in the next chapter.

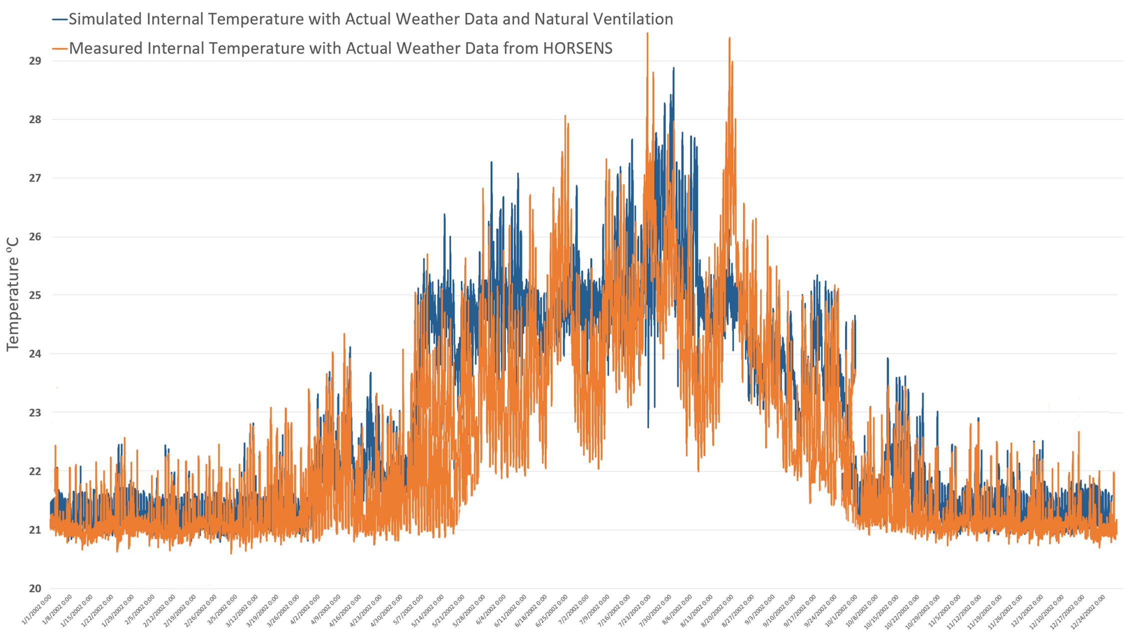


Figure 4.5. Hourly comparison of the simulated internal temperature adjusted for the summer period with the measured one.

After calibrating the model for natural ventilation can be seen in figure 4.5 that the simulated data follow the measured ones better during the winter and summer period.

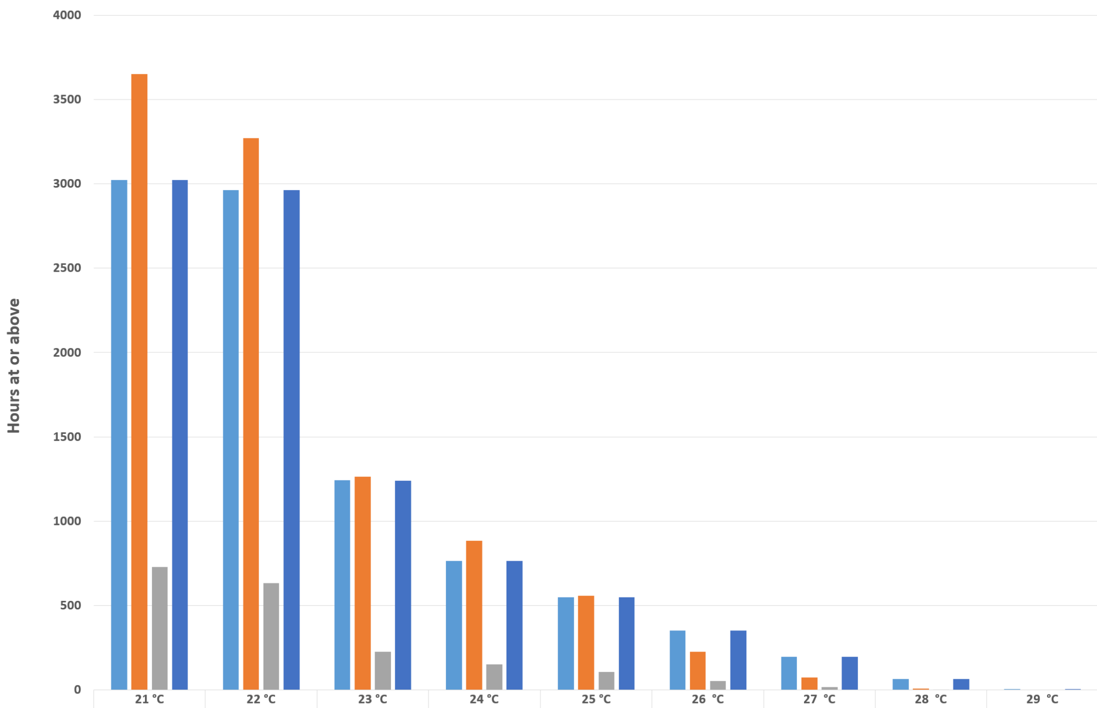
Entire House	Indexes
-0.5	MBE_{year}
-1.2	MBE_{summer}
-2.3	$NMBE_{year}$
-3.7	$NMBE_{summer}$
4.6	$CV(RMSE)_{year}$
6.7	$CV(RMSE)_{summer}$
3.6	GOF_{year}
5.4	GOF_{summer}

Table 4.3. The different calibration indexes for the entire house.

The validation indexes in table 4.3 for the final calibrated model and specifically the CV(RMSE) are the smallest indicating an even better prediction of the real internal temperatures. According to the MBE and NMBE indexes the model shows slight signs of over-prediction compared to reality. This final model has a better representation of the actual Bolig 2020 systems for winter but more importantly for the summer period. This is essential to accurately simulate the effects of the resilient cooling technologies in chapter 5.1.3 to the internal temperature of the house. In the following figures 4.8 and 4.9 the results for the internal temperature comparison are shown for the individual rooms of the house.

Over temperature results for the final calibrated model

In order to test the different resilient cooling technologies, the over temperature results are used. The program Design Builder is only able to calculate these results at room level which is why is necessary to select a representative room. Looking at figure 4.6 the over temperature results for the occupied rooms are presented as the rest of the rooms in the house did not have occupancy profiles and thus over temperature results could not be calculated from the program. Judging from figure 4.6 The rooms with the highest over temperatures are the Living room in the Kitchen both having 6 hours at 29°C, while the coldest room is bathroom 1 having just 3 hours at 28°C. However the master bedroom and the Living room are chosen to be the representative rooms for the entire house as they have temperatures in between the two extreme cases of the other rooms and they are also the rooms that the occupants spend the most time.



	21 °C	22 °C	23 °C	24 °C	25 °C	26 °C	27 °C	28 °C	29 °C
Living room	3022	2964	1242	765	548	352	196	66	6
Master bedroom	3650	3272	1265	884	558	226	75	8	0
Bathroom 1	730	633	225	152	108	53	16	3	0
Kitchen	3022	2964	1241	765	548	352	196	66	6

Figure 4.6. Hours at or above temperature for the different occupied rooms of Bolig 2020.

In figure 4.7 the comparison of temperature distribution and specifically the hours at or above temperature between the actual house and the final calibrated model for the Master bedroom and the Living room are presented. This temperature distribution graph will be used in chapter 5.1.3 in order to see how effective the resilient technologies are in reducing the general heat load.

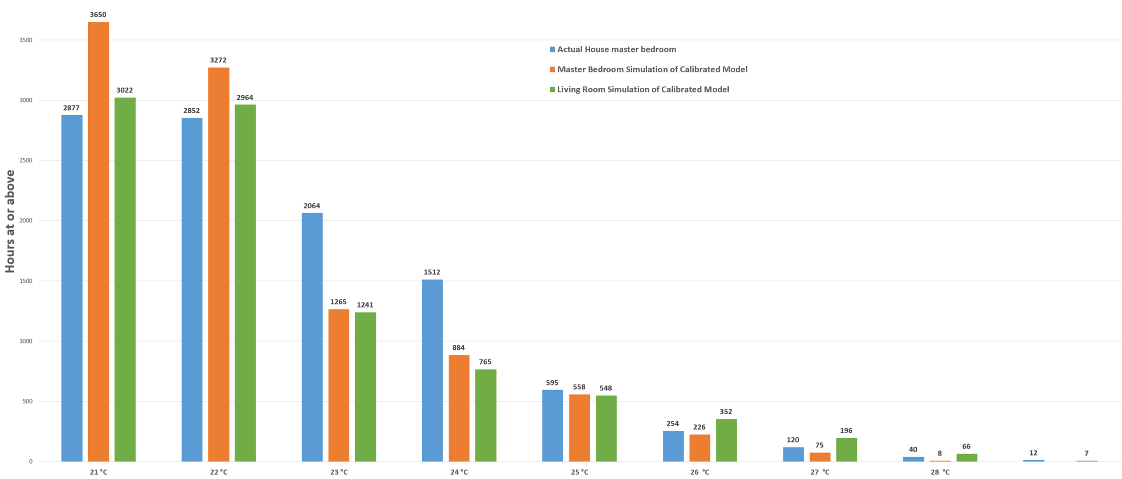


Figure 4.7. Hours at or above temperature for the Master bedroom and Living room.

It can be seen from figure 4.7 that the hours at or above for the entire range of temperatures are very close between the actual house and the final calibrated model. For some of the temperatures like 21°C and 22°C the simulated model over predicts whereas for the others the actual house shows slightly higher numbers. The biggest difference between the two sets of results can be observed at temperature 23°C and with the simulation predicting 799 hours or 33 days less than the actual house and at 24°C predicting 628 hours or 26 days less than the actual house. However for the summer period represented by the temperatures 25°C 26°C 27°C 28°C and 29°C the two sets of results are very close indicating that the calibrated model can be trusted when it comes to testing the resilient cooling technologies for the summer period. Finally the calibrated model shows that the maximum temperature for the house is 28°C whereas the actual house also has 12 hours at 29°C. These over temperature results from the simulation of calibrated model now represent the base case when comparing the resilient cooling technologies with the actual and future weather data.

4.2.1 Internal temperature comparisons for the individual occupied rooms

In figure 4.8 the four graphs for the individual occupied rooms are shown in order to further determine if the model is also calibrated down to room level. From the graphs it is clear that the simulated results follow the measured ones closely. In general most of the rooms suffer from over temperature reaching 30°C. However looking at the graph for bathroom 1 it is clear that this room has by far the coolest temperatures.

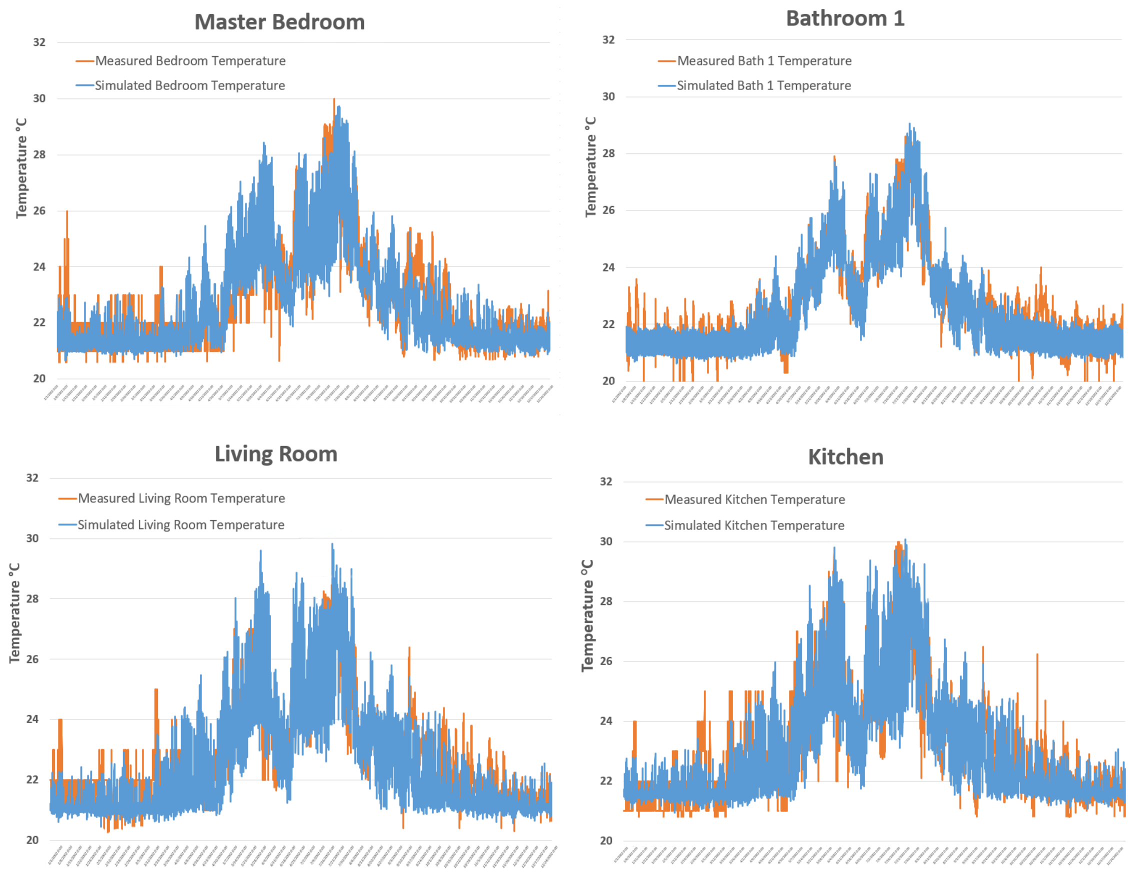


Figure 4.8. Hourly temperature comparison between the simulated and measured results for the individual occupied rooms.

Other than the generally high temperatures of the rooms it is important that the model accurately represents reality and thus can be trusted when testing the different resilient cooling technologies to find out how well they can reduce the over temperatures. Table 4.4 shows the results for the different indexes of the individual rooms .

Master Bedroom	Bathroom 1	Living Room	Kitchen	Indexes
0.1	0.3	0.5	0.3	MBE_{year}
-0.2	0.1	0.2	0.2	MBE_{summer}
0.3	1.5	1.9	1.3	$NMBE_{year}$
-1.2	0.5	0.7	1.1	$NMBE_{summer}$
4.9	3.8	4.8	4.9	$CV(RMSE)_{year}$
6.7	4.5	6.1	6.3	$CV(RMSE)_{summer}$
3.5	2.9	3.7	3.6	GOF_{year}
4.8	3.2	4.3	4.5	GOF_{summer}

Table 4.4. The different calibration indexes for mainly used rooms of the house.

Comparing the results from table 4.4 to the ones from the entire house can be seen that have been lowered even more. This is due to the fact that by examining the individual rooms when compared to the entire house, the errors are reducing as the internal temperature for the individual rooms does not get averaged. Looking at the indexes for the different rooms even though all of them are well below the acceptable limits, the Master Bedroom has the highest CV(RMSE) error meaning that it is the room with the least good fitted simulated results.

4.2.2 Internal temperature comparisons for the individual unoccupied rooms

In figure 4.9 the four graphs for the individual unoccupied rooms are shown. This house has one master bedroom, living room, kitchen and bathroom that are used by the couple. However there are three extra bedrooms and a second bathroom that are not being used since this couple does not have kids. The range for the internal temperature for these rooms is similar to rooms in graph 4.8 with also similar over temperature problems. Room 1 is the hottest with temperatures reaching 31°C.

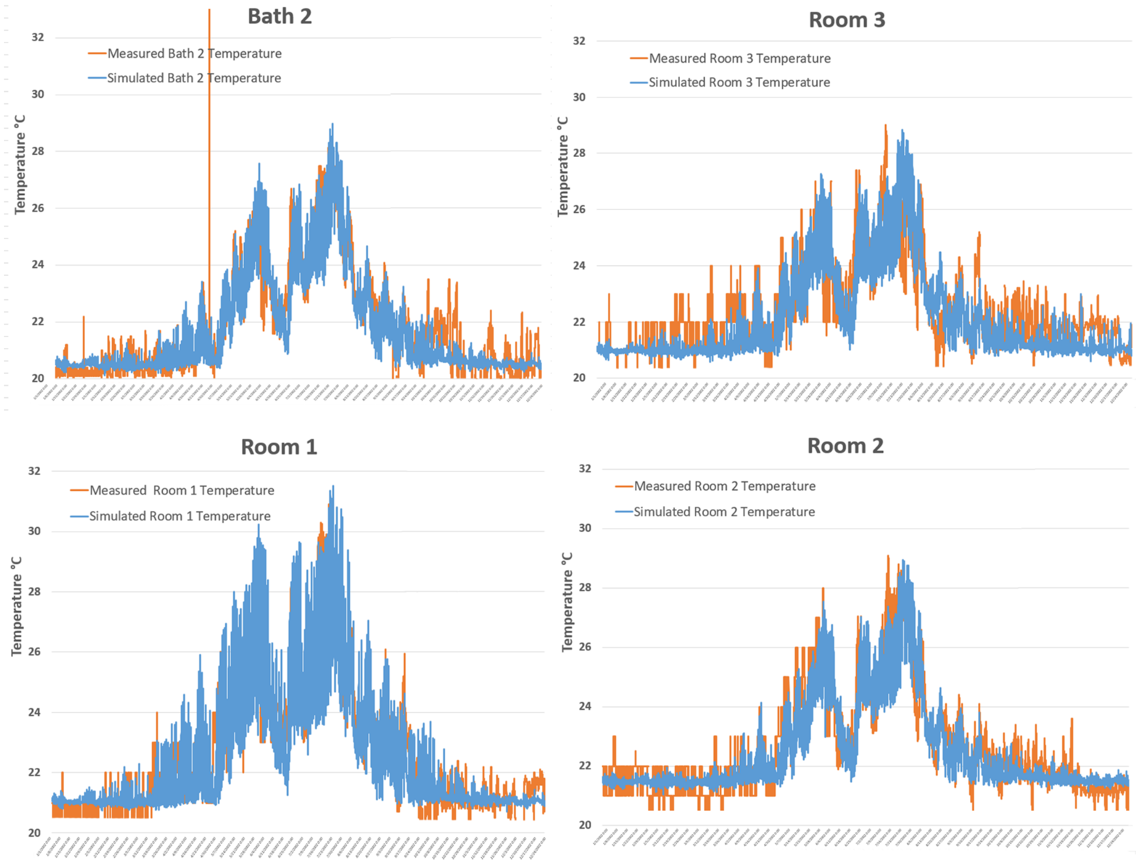


Figure 4.9. Hourly temperature comparison between the simulated and measured results for the individual unoccupied rooms.

However looking at these four graphs, the simulated results follow the measured ones much better during the summer period than the winter one. The simulated results for these four rooms have a much more stable behaviour during winter period since they were modelled with the same heating, cooling set points and HVAC settings but without occupancy profiles or any use of equipment. However the measured results for these unoccupied rooms have greater fluctuations during winter period which is indicating a plausible sporadic occupancy when cleaning them for example which is probably responsible for these fluctuations. Moreover specifically the graph for Bath 2 has some measurement errors as indicated by the huge spike in the measured results as well as some extreme fluctuations in the second half winter period. Other than these slight misalignments between the measured and simulated results during the winter periods the model represents reality rather well which is important for the future optimization of the resilient cooling technologies. Table 4.5 shows the results for the different indexes of the individual rooms .

Bath 2	Room 3	Room 1	Room 2	Indexes
0.5	0.3	0.3	0.2	MBE_{year}
-0.8	-0.1	0.7	0.3	MBE_{summer}
1.5	1.3	1.3	0.7	$NMBE_{year}$
-3.1	-0.3	2.9	1.4	$NMBE_{summer}$
5.1	4.3	4.9	3.7	$CV(RMSE)_{year}$
7.2	5.4	6.6	5.1	$CV(RMSE)_{summer}$
3.7	3.2	3.5	2.7	GOF_{year}
6.5	3.9	5.1	3.7	GOF_{summer}

Table 4.5. The different calibration indexes for mainly used rooms of the house.

Comparing the results from table 4.5 to the ones from table 4.4 can be seen that are in the same over all range with the exception of Bath 2 as that was the one with the largest variations. Looking at the indexes for the different rooms even though all of them are well below the acceptable limits, the Room 2 has the lowest CV(RMSE) error meaning that it is the room with the best fitted simulated results.

Results and Optimization 5

Optimization of many parameters will be run for Solar Radiation Control, Natural Ventilation and Micro Climate Control individually for the actual weather file and compare the internal temperatures with and without resilient cooling techniques. These three were chosen because the main goal of this thesis is to test resilient cooling technologies that are easy to adapt and do not require changes in the main structure of the building. This is important as not all buildings were designed and constructed with resilience towards global warming in mind and thus these resilient cooling technologies can be implemented after the building's construction is finished with immediate results. The same procedure will be done for global warming weather files to see if the internal temperatures using resilient cooling in global warming scenarios are similar to the ones using resilient cooling in the actual weather file.

Design Builder uses a Genetic Algorithm (GA) for the optimisation process, which is widely used as a "fast and elitist multi-objective" method providing a good trade off between a well converged and a well distributed solution set. It works by first randomly initialising the population. Chromosomes (design variants) are sorted and put into fronts based on Pareto non-dominated sets. Generally, solutions which are far away (not crowded) from other solutions are given a higher preference in the selection process to help create a diverse solution set and avoid crowding. The best designs are picked from the current population and put into a mating pool. In the mating pool, tournament selection, crossover and mating is carried out. The mating pool and current population is combined. The resulting set is sorted, and the best chromosomes are passed into the new population. The solution set is the highest ranked Pareto non-dominated set from all populations.

According to the Design Builder program's help file for the optimisation process, "the recommended settings are 100 generations with a population size of at least 10 in each, growing as Pareto solutions are added meaning that at least 100 x 10 = 1000 simulations will be run. However if time is an issue it is usually worth keeping an eye on the solutions as they come in to check whether convergence has been achieved."

The selection of the optimal solution according to the over temperature hours will be conducted based on the ASHRAE Standard 55-2004 [10]. The discomfort hours have an acceptable limit that should not exceed 5% of the people's occupation time in the house. Based on the people's occupation schedule in subsection 2.1.2, the people occupy the house from 18:00 to 8:00. According to these information the overall discomfort hours should not exceed the acceptable yearly limit of 255 hours and since the original calibrated model has 89 discomfort hours as seen in the following sections, all final solutions should have less discomfort hours than that.

5.1 Solar Radiation Optimisation

In this section the different parameters of the solar radiation cooling technology are analysed for the final calibrated model. These parameters will later be used as inputs for the optimisation process in order to achieve the following optimisation objectives, which are to find the parameter combination that provides the most cooling potential by having the lowest internal temperatures and being cost effective as well as energy efficient at the same time.

5.1.1 Design input Variables for Solar Radiation Control

Model parameter	Parameter variation	Unit	Values	Distribution
Permanent Devices	Projection length	[m]	No shading from permanent device Overhang : 0.5; 1.0; 1.5 Projection Louvre: 0.5; 1.0; 1.5 Side fins: 0.5; 1.0; 1.5 0.5m projection + 0.5m overhangs and sidefins	Discrete
Movable Devices	Conductivity, Solar transmittance, Solar reflectance	[W/m K], [-], [-]	No shading from movable device Blind with medium reflectivity slats: 0.9; 0; 0.5 Blind with high reflectivity slats: 0.9; 0; 0.8 Blind with low reflectivity slats: 0.9; 0; 0.2 MicroLouvre: 0.9; 0; 0.05 Venetian blinds - light (modelled as diffusing): 0.1; 0.6; 0.2 Shade roll - light opaque: 0.1; 0.05; 0.5 High reflectance - low transmittance shade: 0.1; 0.1; 0.8 Low reflectance - low transmittance shade: 0.1; 0.1; 0.2	Discrete
Protective Glazing	Conductivity, Solar transmittance, Solar reflectance	[W/m K], [-], [-]	Original windows: 1; 0.27; 0.39 Absorptive glass: 0.9; 0.12; 0.17 Reflective glass: 0.9; 0.09; 0.22	Discrete

Table 5.1. The chosen solar radiation control input parameters for Bolig 2020.

When the input parameters are chosen it is necessary to define a proper range and distribution. These inputs are tested for every room individually in order to optimise the entire house. For the chosen input parameters from table 5.1 the genetic algorithms using the program Design Builder are utilised to see the effects of the different input parameters on the outputs, but first a more detailed description of the different input parameters is presented.

Permanent devices input parameters

To reduce and avoid excess temperatures inside the building, shading in the form of permanent devices can be implemented. The range for these devices is only controlled by their projection length which is set vary from 0.5 m to 1.5 m with a step size of 0.5 m as these three lengths are the most common ones. Other than these three values for all the inputs an option for no shading as well as a combination of different technologies is set up. All the inputs have a discrete distribution as single values are used and tested for the optimisation.

Movable devices input parameters

For a more precise control of the excess temperatures inside the building, shading from movable devices can be implemented. Here, the same discrete distribution is used but the range of the different devices is controlled and categorised using the conductivity, solar transmittance and solar reflectance properties. The goal here was to select from the most common solutions for movable devices the ones with the most representative combination of properties by having both high, low and middle values of the above metioned properties.

Due to the fact that these are movable devices a set point for activation and deactivation has to be defined. It is chosen to be controlled by the temperature using the set point of 25°C as this is how these devices were controlled in the actual building.

Protective glazing input parameters

A window consists of different parameters which can affect the excess temperatures and the amount of daylight. When the conductivity, solar transmittance and solar reflectance are changed the whole window characteristics are changed, which means that new values for the above mentioned properties are given. Conductivity describe the ability to transfer the solar energy through the glass, where solar transmittance is how much of the solar radiation gets transmitted inside. On the other hand Solar reflectance shows the amount of solar radiation that is being reflected back to the environment as depicted in figure 5.1.

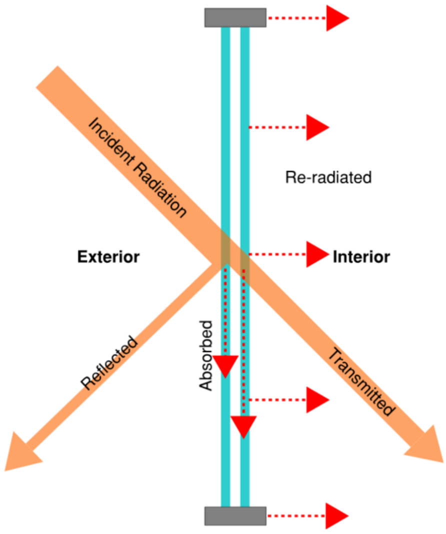


Figure 5.1. Depiction of the window properties [14] .

For cooling purposes the values for conductivity and solar transmittance should be low whereas values for solar reflectance should be as high as possible. The simulation uses a discrete distribution for the windows properties, because the windows are often selected from a company's catalogue. Usually the manufacturer provides windows with specified conductivity, solar transmittance and solar reflectance properties. Therefor, a discrete distribution with three different window types is chosen. The windows are picked out from the Design builder catalogue.

5.1.2 Optimisation process for solar radiation

The objectives for the optimisation are to minimise the cost of the total building construction and the discomfort hours however to select the optimal solution the total site energy consumption needs to be minimised as well. The discomfort hours data is based on whether the humidity ratio and the operative temperature is within the region shown in ASHRAE Standard 55-2004 in Figure 5.2 and 5.3. The graphs below are based on the following tables which extend the ASHRAE values to zero humidity ratio. When it comes to the discomfort hours they are calculated using the standards based on both winter as well as summer clothing as the optimization process is run for the entire year.

Air Temp(degC)	Humidity Ratio
23.6	0.012
26.8	0.012
28.3	0.000
25.1	0.000

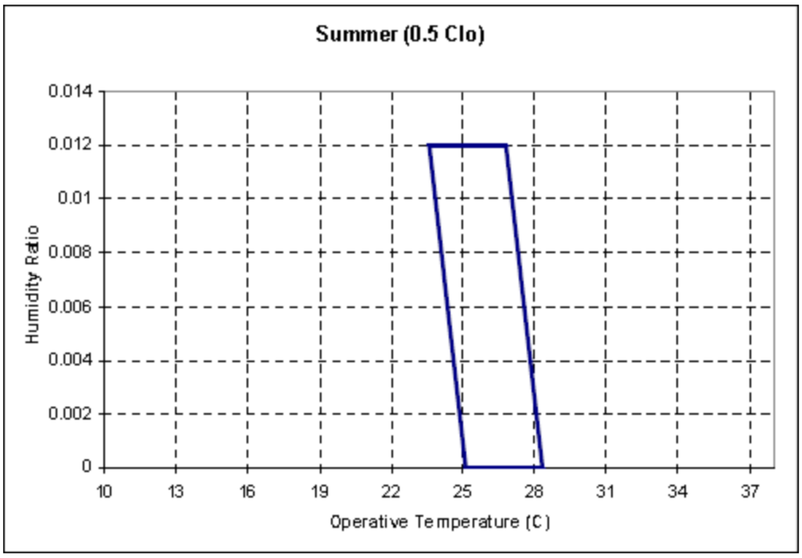


Figure 5.2. ASHRAE Standard for summer discomfort hours.

The minimum comfort temperature with winter clothes when the air is very dry is 21.7°C which may be lower than some heating temperature set points. Likewise in the summer when the air is very humid operative temperatures above 26.8°C are considered too hot with summer clothes.

Air Temp(degC)	Humidity Ratio
19.6	0.012
23.9	0.012
26.3	0.000
21.7	0.000

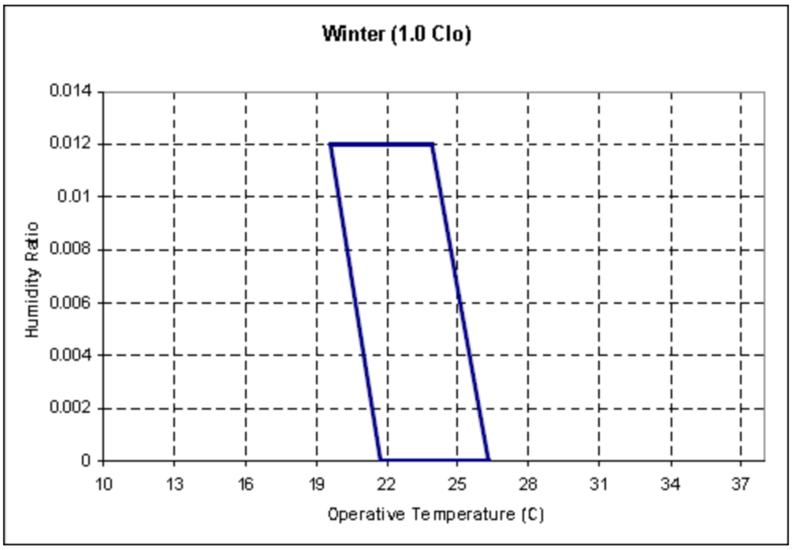


Figure 5.3. ASHRAE Standard for winter discomfort hours.

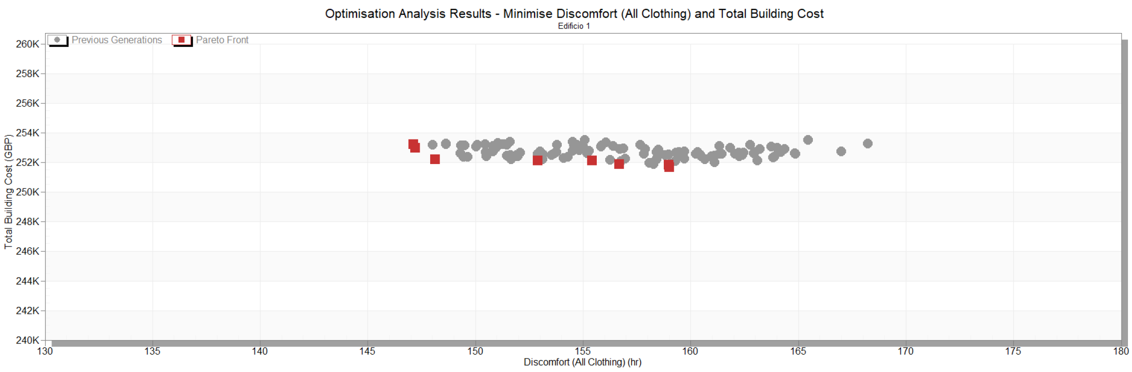
After the optimisation objectives and the different input variables shown in table 5.1 were set, the optimization is ready to start. No extra constraints were added because the goal was to find all possible solutions in order to minimize the two specified objectives.

5.1.3 Solar radiation control results

In this subsection the results for the solar radiation optimization are presented. The optimization is done in several stages in order to observe which set of parameters is the most influential for the end model. After running a lot of trial optimizations it was observed that after 150 simulations no more optimal solutions were added in the pareto front which meant that all possible best solutions where found. So it is decided that 250 simulations in total are enough to find the necessary best solutions. Initially the optimisation process regarding minimising the total building cost was run in order to determine which combination of solar shading parameters is the most cost effective. However to find the optimal solution the optimisation process regarding minimising the total site energy consumption was run to find a solution that does not consume more energy than the original calibrated model.

Optimisation results regarding cost minimisation

The movable devices as well as the glazing options are in the same optimisation category in the Design Builder program. As can be seen from the figure 5.4 all the different solutions do not have a wide spread when it comes to the cost as these modifications do not have high maintenance or operation cost. The main aspect contributing to the total building cost is the installation and the cost per m^2. Most of the spread of solutions is happening on the x axis which is the discomfort hours. The movable devices were controlled according to the occupancy of every room and activated when the internal temperature exceeded 25°C.



Status

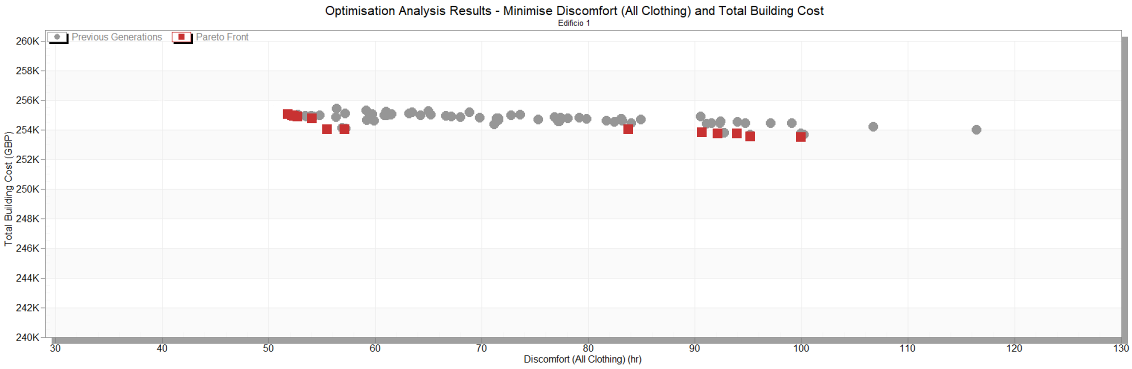
Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total Building Cost (GBP)	Window blind type Living room	Window blind type Master bedroom	Window blind type Kitchen an Room 3	Window blind type Room 1	Window blind type Room 2 and Utility room
Optimal Designs									
11	1	Optimal Designs	147,1273	253204,901	High reflectance - low transmittance shade	Blind with high reflectivity slats	Low reflectance - low transmittance shade	Blind with low reflectivity slats	Blind with high reflectivity slats
2	0	Optimal Designs	147,2054	252939,934	Blind with high reflectivity slats	High reflectance - low transmittance shade	Low reflectance - low transmittance shade	<None>	High reflectance - low transmittance shade
86	7	Optimal Designs	148,1391	252171,887	High reflectance - low transmittance shade	Blind with low reflectivity slats	<None>	<None>	<None>
61	5	Optimal Designs	152,8929	252120,673	<None>	<None>	<None>	Blind with high reflectivity slats	High reflectance - low transmittance shade
71	6	Optimal Designs	155,4080	252114,576	<None>	Blind with high reflectivity slats	High reflectance - low transmittance shade	High reflectance - low transmittance shade	<None>
32	3	Optimal Designs	156,6807	251839,777	<None>	<None>	High reflectance - low transmittance shade	High reflectance - low transmittance shade	<None>
150	11	Optimal Designs	158,9737	251812,439	<None>	Blind with high reflectivity slats	<None>	<None>	<None>
10	1	Optimal Designs	159,0171	251660,788	<None>	<None>	<None>	Blind with high reflectivity slats	<None>

Figure 5.4. Optimization of movable devices and glazing for the Bolig 2020.

As seen from the pareto solutions (red squares) which are the optimal design solutions presented with green color in figure 5.4, the one with the least amount of discomfort hours is number 11 having 147 discomfort hours. Judging by the majority of the pareto solutions for the living room which is a South facing room the options high reflectance low transmittance shades as well as no shading are the most significant ones. For the master bedroom which is a South-West facing room the options blind with high reflectivity slats is the most important. For the rest of the rooms the best options are having either high reflectance low transmittance shades blind with high reflectivity slats or no shading at all.

In general the glazing options were not preferred for the optimal solutions whereas the most important options overall were the ones with a higher reflective coefficient.

For the permanent devices category as seen from the figure 5.5 all the different solutions follow the same trend as movable and glazing category. However judging by the different points in the figure is it permanent devices sing to be more effective than the movable ones when it comes to decreasing the discomfort hours.



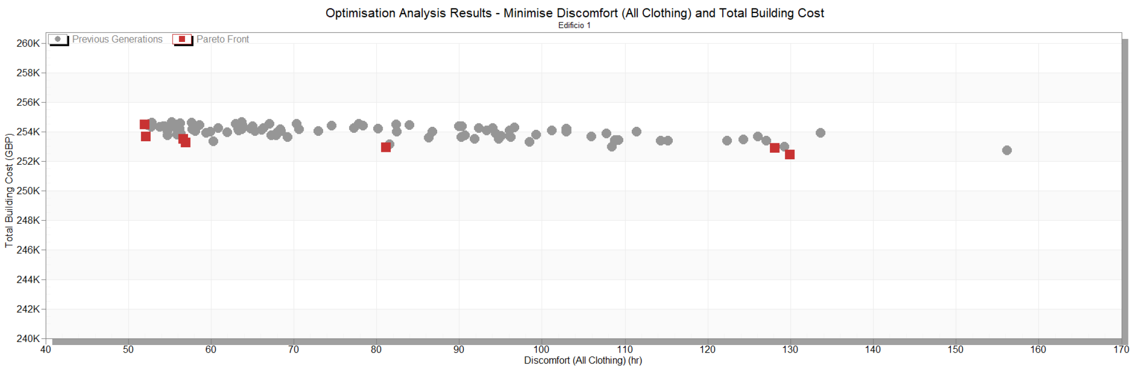
Status

Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total Building Cost (GBP)	Local shading Living room	Local shading Master bedroom	Local shading Kitchen and Room 3	Local shading Room 1	Local shading Room 2 and Utility
Optimal Designs									
47	4	Optimal Designs	51,8136	255041,008	Louvre, 1.0m projection + 1m overhangs a...	0.5m projection Louvre	Louvre, 1.0m projection + 1m overhangs a...	Overhang + sidefins (0.5m projection)	1.0m Overhang
52	4	Optimal Designs	52,1710	254958,005	Louvre, 1.0m projection + 1m overhangs a...	0.5m projection Louvre	1.0m Overhang	Overhang + sidefins (0.5m projection)	Overhang + sidefins (0.5m projection)
98	6	Optimal Designs	52,3542	254903,973	Louvre, 1.0m projection + 1m overhangs a...	0.5m projection Louvre	Louvre, 1.0m projection + 1m overhangs a...	Overhang + sidefins (0.5m projection)	0.5m Overhang
15	1	Optimal Designs	52,6968	254860,279	Louvre, 1.0m projection + 1m overhangs a...	Overhang + sidefins (0.5m projection)	1.5 m projection Louvre	2.0m Overhang	0.5m Overhang
94	6	Optimal Designs	54,0884	254760,300	Louvre, 1.0m projection + 1m overhangs a...	0.5m projection Louvre	Louvre, 1.0m projection + 1m overhangs a...	No shading	0.5m Overhang
54	5	Optimal Designs	57,1435	254024,036	Louvre, 1.0m projection + 1m overhangs a...	1.0m projection Louvre	1.0m Overhang	1.0m Overhang	No shading
41	4	Optimal Designs	83,7585	254009,340	2.0m Overhang	1.0m projection Louvre	Louvre, 0.5m projection + 0.5m overhangs...	1.0m Overhang	No shading
24	2	Optimal Designs	90,6789	253825,525	Overhang + sidefins (0.5m projection)	Louvre, 0.5m projection + 0.5m overhangs...	0.5m projection Louvre	0.5m Overhang	No shading
4	0	Optimal Designs	92,1529	253742,228	0.5m projection Louvre	Louvre, 0.5m projection + 0.5m overhangs...	0.5m Overhang	2.0m Overhang	No shading
59	5	Optimal Designs	93,9476	253728,807	1.0m Overhang	1.0m Overhang	2.0m Overhang	1.0m Overhang	No shading
88	6	Optimal Designs	95,1916	253514,255	2.0m Overhang	Overhang + sidefins (0.5m projection)	No shading	1.0m Overhang	No shading
65	5	Optimal Designs	99,9755	253495,425	Overhang + sidefins (0.5m projection)	No shading	0.5m projection Louvre	Louvre, 0.5m projection + 0.5m overhangs...	No shading
65	5	Optimal Designs	99,9755	253495,425	Overhang + sidefins (0.5m projection)	No shading	0.5m projection Louvre	Louvre, 0.5m projection + 0.5m overhangs...	No shading

Figure 5.5. Optimization of permanent devices for the Bolig 2020.

Using combinations of permanent devices as seen from solution 47 in figure 5.5 it is possible to reach 51 discomfort hours. Judging by the majority of the pareto solutions for the South East and West facing rooms a combination of projection louvres and overhangs is providing the least discomfort hours. Whereas for the North facing rooms which are the Utility room and room 2 it is either overhangs or no shading.

For the model in figure 5.6 the two previously mentioned categories were combined. It is chosen for the final optimisation to choose for every room one solution from the movable devices and glazing category and another solution from permanent devices category. 25°C.



Status

Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total Building Cost (GBP)	Local shading Living room	Local shading Master bed...	Local shading Kitchen an...	Local shading Room 1	Local shading Room 2 an...	Window blind Living room	Window blind Master bed...	Window blind Kitchen an...	Window blind Room 1	Window blind type
Optimal Designs														
72	6	Optimal D...	51,9666	254460,644	Louvre, 1.0m projection +...	Overhang + sidefins (0.5...	1.5 m projection Louvre	1.5 m projection Louvre	1.5 m projection Louvre	High reflectance - low tra...	<None>	Blind with high reflectivity ...	<None>	Blind with high reflectivity ...
89	7	Optimal D...	52,1281	253640,264	Louvre, 1.0m projection +...	1.5 m projection Louvre	Louvre, 1.0m projection +...	1.5 m projection Louvre	2.0m Overhang	<None>	<None>	<None>	<None>	<None>
56	5	Optimal D...	56,6771	253508,400	Louvre, 1.0m projection +...	1.5 m projection Louvre	0.5m Overhang	1.5 m projection Louvre	Louvre, 0.5m projection +...	<None>	<None>	<None>	<None>	<None>
61	5	Optimal D...	56,9694	253232,978	Louvre, 1.0m projection +...	No shading	Louvre, 1.0m projection +...	Louvre, 1.0m projection +...	1.0m Overhang	<None>	<None>	<None>	<None>	<None>
71	5	Optimal D...	81,1936	252909,662	1.5 m projection Louvre	No shading	0.5m Overhang	0.5m projection Louvre	No shading	<None>	<None>	Venetian blinds - light (mo...	Low reflectance - low tran...	<None>
25	2	Optimal D...	128,0879	252879,401	0.5m Overhang	No shading	0.5m Overhang	0.5m Overhang	0.5m Overhang	<None>	<None>	Blind with low reflectivity s...	High reflectance - low tra...	<None>
85	6	Optimal D...	129,9076	252409,318	No shading	1.0m Overhang	1.0m Overhang	Overhang + sidefins (0.5...	1.0m Overhang	<None>	<None>	<None>	<None>	<None>

Figure 5.6. Optimization of all possible solar radiation control devices for the Bolig 2020.

For this combined optimisation the best solution when it comes to minimizing discomfort hours is solution 72 with 51 hours. Overall by combining the two categories there is no further reduction in discomfort hours than just by using the permanent devices category. That is also evident by the fact that the optimisation decided to not include solutions from both categories for every room at the same time for most pareto designs.

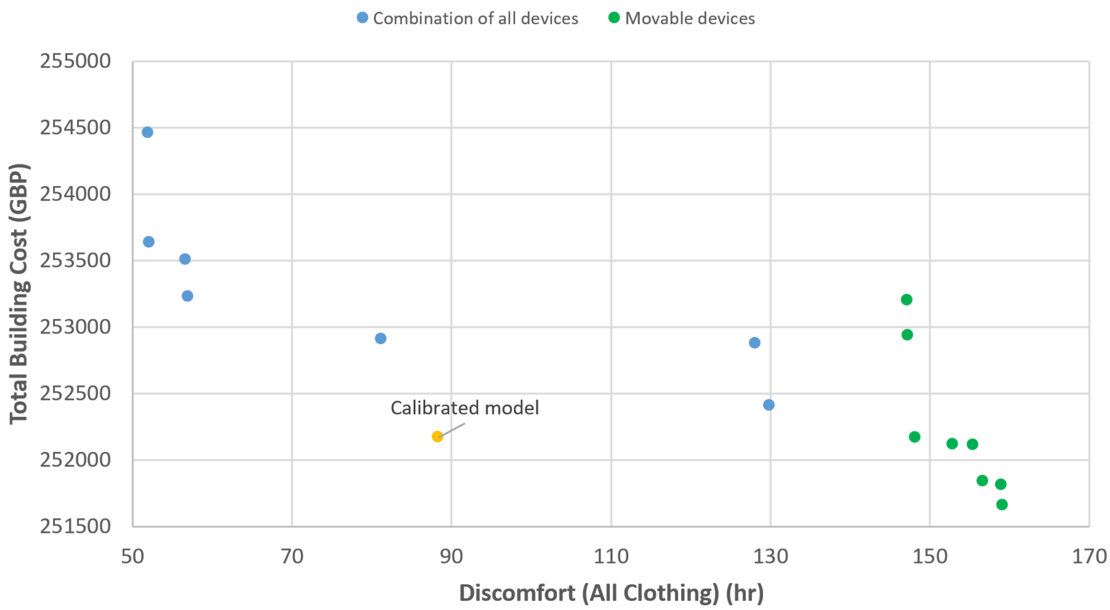
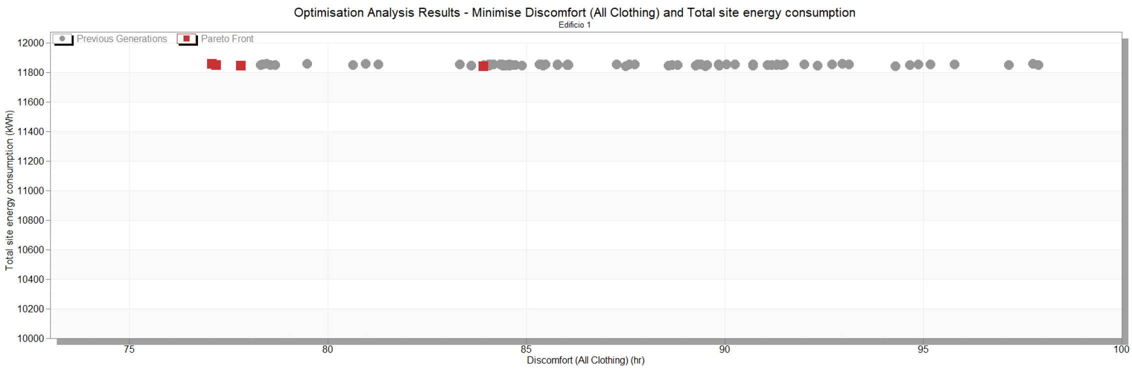


Figure 5.7. Optimization regarding the cost of all possible solar radiation control devices for the Bolig 2020.

Since figure 5.6 is a combination of both permanent and movable devices it is decided to change the y axes scale to compare the cost of the optimal pareto front solutions to original calibrated model more clearly. Judging by the graphs 5.6 and 5.7 the calibrated model represents the average cost when it comes to the movable devices and the minimum cost for the combination of all devices.

Final model optimisation regarding energy minimisation

For the final selection of the best solution the total site energy consumption should be taken into account as a constraint. The total site energy consumption according to the validated model of the house consists of energy for electricity equal to 2870 kWh and energy for district heating equal to 8981 kWh resulting in a total of 11853 kWh. The goal for the chosen solution is to select the one that does not increase the total energy consumption while at the same time has the least amount of discomfort hours. Another reason why the best solution was decided to be taken from figure 5.9 is because when running the optimisation to minimise the total cost it was found out that all solutions had a similar overall cost. In order to find the optimal solution the optimisation process seen in figures 5.8 and 5.9 was run with the objectives to minimise discomfort hours as well as minimise the total site energy consumption to be able to find the solution with an energy consumption as close to the original calibrated model as possible.

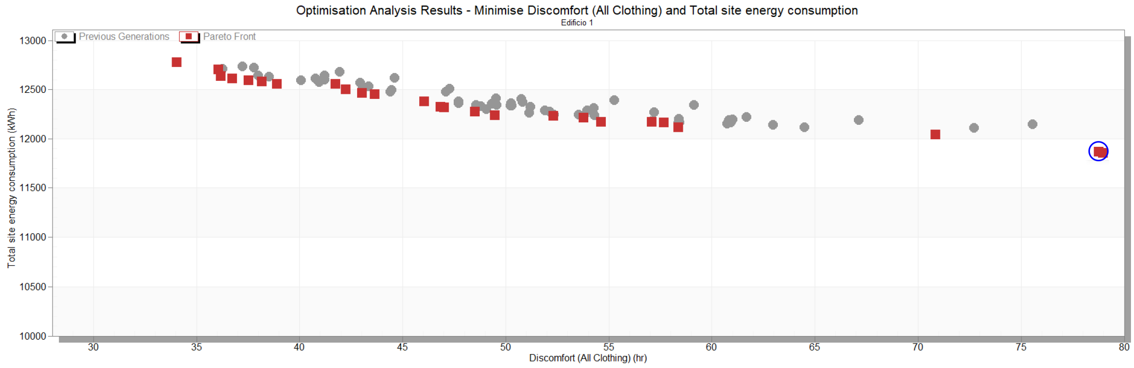


Status

Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total site energy consumption (kWh)	Window blind type Living room	Window blind type Master bedroom	Window blind Kitchen and Room 3	Window blind Room 1	Window blind Room 2 and Utility
Optimal Designs									
57	5	Optimal Designs	77,0775	11856,14	High reflectance - low transmittance shade	Blind with high reflectivity slats	High reflectance - low transmittance shade	Blind with high reflectivity slats	<None>
80	7	Optimal Designs	77,1838	11845,08	High reflectance - low transmittance shade	Blind with high reflectivity slats	High reflectance - low transmittance shade	Blind with high reflectivity slats	Blind with high reflectivity slats
106	8	Optimal Designs	77,8079	11840,95	High reflectance - low transmittance shade	Blind with high reflectivity slats	Blind with high reflectivity slats	Blind with high reflectivity slats	Blind with high reflectivity slats
70	6	Optimal Designs	83,9240	11839,53	Blind with high reflectivity slats	Blind with high reflectivity slats	Blind with high reflectivity slats	<None>	Blind with high reflectivity slats

Figure 5.8. Optimization of movable devices for solar radiation control for the Bolig 2020.

After running the optimisation in figure 5.8 for the movable devices it is clear that all optimal (pareto front) solutions have the same total site energy consumption as the original calibrated model. This is happening due to the fact that the movable devices are controlled by the internal room temperature set point of 25°C meaning that during the winter period these devices are rarely used and thus not increasing the energy consumption for heating. The best solution when it comes to having the least number of discomfort hours is solution number 57 with 77 discomfort hours.



Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total site energy consum...	Local shading Living room	Local shading Master bed...	Local shading Kitchen an...	Local shading Room 1	Local shading Room 2 an...	Window blind Living room	Window blind Master bed...	Window blind Kitchen an...	Window blind Room 1	Window blind Room 2 an...
Optimal Designs														
61	5	Optimal D...	34,0438	12778,85	Louvre, 1.0m projection +...	2.0m Overhang	Louvre, 1.0m projection +...	Louvre, 0.5m projection +...	1.0m projection Louvre	<None>	Blind with medium reflecti...	<None>	Blind with high reflectivity ...	<None>
46	4	Optimal D...	36,0675	12700,59	Louvre, 1.0m projection +...	1.0m Overhang	Louvre, 1.0m projection +...	1.0m Overhang	Overhang + sidefins (0.5...	Venetian blinds - medium ...	Blind with high reflectivity ...	Blind with high reflectivity ...	High reflectance - low tra...	<None>
56	5	Optimal D...	36,1705	12636,98	Louvre, 1.0m projection +...	1.0m Overhang	Louvre, 0.5m projection +...	2.0m Overhang	0.5m projection Louvre	High reflectance - low tra...	Blind with high reflectivity ...	<None>	<None>	<None>
43	4	Optimal D...	36,7471	12611,07	Louvre, 1.0m projection +...	0.5m Overhang	Overhang + sidefins (0.5...	Louvre, 1.0m projection +...	0.5m Overhang	High reflectance - low tra...	Blind with medium reflecti...	<None>	<None>	<None>
67	6	Optimal D...	37,5349	12592,82	Louvre, 1.0m projection +...	0.5m Overhang	2.0m Overhang	1.5 m projection Louvre	Overhang + sidefins (0.5...	Blind with low reflectivity s...	Blind with high reflectivity ...	<None>	Blind with medium reflecti...	Blind with low reflectivity s...
80	6	Optimal D...	38,1850	12580,66	1.5 m projection Louvre	0.5m Overhang	Louvre, 1.0m projection +...	1.0m projection Louvre	Overhang + sidefins (0.5...	High reflectance - low tra...	Blind with low reflectivity s...	<None>	High reflectance - low tra...	High reflectance - low tra...
32	3	Optimal D...	38,8947	12554,30	Louvre, 1.0m projection +...	1.0m Overhang	1.0m Overhang	0.5m Overhang	0.5m projection Louvre	Blind with medium reflecti...	High reflectance - low tra...	Blind with high reflectivity ...	High reflectance - low tra...	<None>
65	6	Optimal D...	41,7492	12553,56	1.5 m projection Louvre	0.5m Overhang	Louvre, 1.0m projection +...	2.0m Overhang	Overhang + sidefins (0.5...	Blind with medium reflecti...	Blind with high reflectivity ...	<None>	<None>	<None>
58	5	Optimal D...	42,2493	12502,41	1.5 m projection Louvre	Overhang + sidefins (0.5...	0.5m Overhang	1.0m Overhang	0.5m projection Louvre	High reflectance - low tra...	Blind with high reflectivity ...	Blind with high reflectivity ...	<None>	High reflectance - low tra...
63	6	Optimal D...	43,0285	12464,93	1.5 m projection Louvre	0.5m Overhang	1.5 m projection Louvre	No shading	0.5m projection Louvre	High reflectance - low tra...	<None>	Venetian blinds - medium ...	High reflectance - low tra...	<None>
74	6	Optimal D...	43,6639	12452,26	Louvre, 0.5m projection +...	0.5m Overhang	Louvre, 1.0m projection +...	1.0m projection Louvre	0.5m projection Louvre	<None>	Blind with high reflectivity ...	Venetian blinds - medium ...	<None>	<None>
81	6	Optimal D...	46,0632	12380,12	2.0m Overhang	0.5m projection Louvre	Louvre, 1.0m projection +...	2.0m Overhang	Overhang + sidefins (0.5...	High reflectance - low tra...	Blind with low reflectivity s...	<None>	High reflectance - low tra...	Blind with low reflectivity s...
51	4	Optimal D...	46,8412	12325,66	2.0m Overhang	1.0m Overhang	1.5 m projection Louvre	2.0m Overhang	1.0m Overhang	High reflectance - low tra...	Blind with low reflectivity s...	<None>	High reflectance - low tra...	<None>
57	5	Optimal D...	47,0236	12319,99	2.0m Overhang	0.5m Overhang	Louvre, 1.0m projection +...	1.0m Overhang	1.0m Overhang	High reflectance - low tra...	Blind with low reflectivity s...	<None>	High reflectance - low tra...	Blind with low reflectivity s...
69	6	Optimal D...	48,5166	12272,80	Overhang + sidefins (0.5...	0.5m Overhang	Louvre, 1.0m projection +...	No shading	Overhang + sidefins (0.5...	High reflectance - low tra...	Blind with high reflectivity ...	Blind with low reflectivity s...	<None>	Blind with low reflectivity s...
76	6	Optimal D...	49,4680	12239,11	1.0m Overhang	0.5m projection Louvre	1.0m Overhang	Louvre, 1.0m projection +...	1.0m projection Louvre	High reflectance - low tra...	Blind with medium reflecti...	<None>	Blind with high reflectivity ...	<None>
71	6	Optimal D...	52,3299	12232,80	1.0m Overhang	0.5m Overhang	Louvre, 1.0m projection +...	0.5m Overhang	1.0m Overhang	Blind with high reflectivity ...	<None>	Venetian blinds - medium ...	Venetian blinds - medium ...	Venetian blinds - medium ...
11	1	Optimal D...	53,7726	12212,15	1.0m Overhang	2.0m Overhang	1.0m Overhang	0.5m projection Louvre	1.5 m projection Louvre	<None>	High reflectance - low tra...	Blind with high reflectivity ...	Blind with medium reflecti...	<None>
19	1	Optimal D...	54,6193	12172,24	1.0m Overhang	0.5m projection Louvre	1.0m Overhang	0.5m projection Louvre	1.0m Overhang	Blind with high reflectivity ...	<None>	Blind with low reflectivity s...	High reflectance - low tra...	Venetian blinds - medium ...
37	3	Optimal D...	57,0858	12168,57	1.0m Overhang	0.5m projection Louvre	1.0m Overhang	0.5m Overhang	Overhang + sidefins (0.5...	Blind with medium reflecti...	Blind with high reflectivity ...	Blind with medium reflecti...	High reflectance - low tra...	Venetian blinds - medium ...
45	4	Optimal D...	57,6625	12166,07	1.0m Overhang	0.5m projection Louvre	1.0m Overhang	0.5m Overhang	Overhang + sidefins (0.5...	Blind with medium reflecti...	<None>	Blind with high reflectivity ...	High reflectance - low tra...	Blind with medium reflecti...
78	6	Optimal D...	58,3786	12113,21	1.0m Overhang	0.5m Overhang	1.0m Overhang	0.5m Overhang	0.5m Overhang	<None>	<None>	Venetian blinds - medium ...	High reflectance - low tra...	Venetian blinds - medium ...
3	0	Optimal D...	70,8359	12039,48	No shading	0.5m projection Louvre	Overhang + sidefins (0.5...	Overhang + sidefins (0.5...	1.0m Overhang	Blind with high reflectivity ...	Blind with low reflectivity s...	<None>	<None>	Blind with high reflectivity ...
106	7	Optimal D...	77,0775	11856,14	No shading	No shading	No shading	No shading	No shading	High reflectance - low tra...	Blind with high reflectivity ...	High reflectance - low tra...	Blind with high reflectivity ...	<None>
48	8	Optimal D...	77,1838	11845,08	No shading	No shading	No shading	No shading	No shading	High reflectance - low tra...	Blind with high reflectivity ...	High reflectance - low tra...	Blind with high reflectivity ...	Blind with high reflectivity ...

Figure 5.9. Optimization of all possible solar radiation control devices for the Bolig 2020.

Again from figure 5.9 which is a combination of both permanent and movable devices regarding energy consumption a more clear representation of the y axes is shown in figure 5.10 to compare the energy consumption of the optimal pareto front solutions as well as the original calibrated model. Judging by the graph 5.10 the calibrated model has an almost identical energy consumption to the optimal solution.

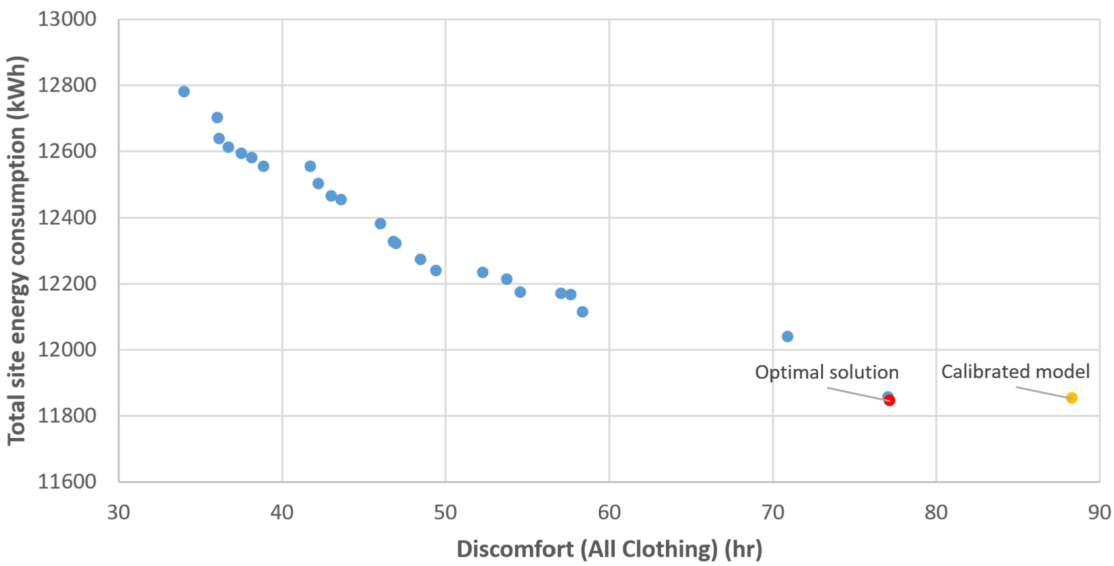


Figure 5.10. Optimization regarding the energy of all possible solar radiation control devices for the Bolig 2020.

For the final optimisation process in figure 5.10 all solar radiation devices were tested to find the optimal design regarding energy consumption. This time it is clear that the permanent devices have a direct correlation with energy consumption. Specifically using a combination of permanent and movable devices is far more efficient when it comes to reducing the discomfort hours but at the same time increasing the total site energy consumption. This is happening as the permanent devices are providing shade even during the winter period resulting in more energy consumption to obtain the same internal temperature. The optimal solution in figure 5.9 when it comes to minimising the discomfort hours is solution 61 with just 34 discomfort hours. According to the ASHRAE Standard 55-2004 [10] mentioned in the beginning of Chapter the overall discomfort hours should not exceed the acceptable yearly limit of 255 hours. For this reason solution number 106 is chosen as the final one as it has the same energy consumption as the calibrated model and at the same time is under the acceptable limit of 255 discomfort hours. This solution corresponds to the best solution of the movable devices optimisation in figure 5.8 having 77 discomfort hours and it achieves that by using only movable devices and specifically the options High reflectance - low transmittance shade for the Living room, Kitchen and Room 3 as well as the option Blind with high reflectivity slats for the Master bedroom and Room 1. Finally for the Room 2 and Utility room no shading was used.

Comparison with the base case

Figure 5.11 shows the hours at or above temperatures for the Master bedroom between the final calibrated model from section 4.2 and the final optimised solar radiation control solution.

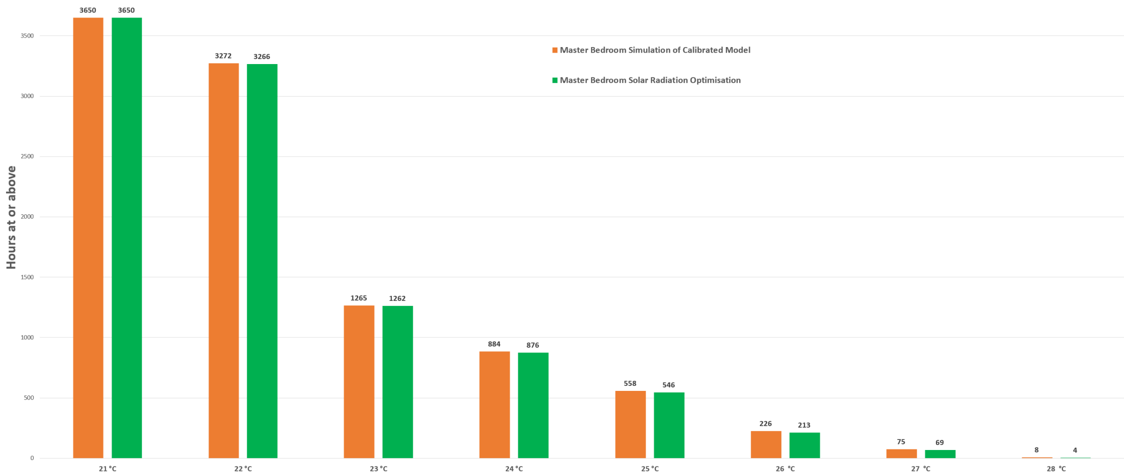


Figure 5.11. Temperature distribution for the Master bedroom between the calibrated and the solar radiation optimised models.

Figure 5.12 shows the hours at or above temperatures for the Living room between the final calibrated model from section 4.2 and the final optimised solar radiation control solution.

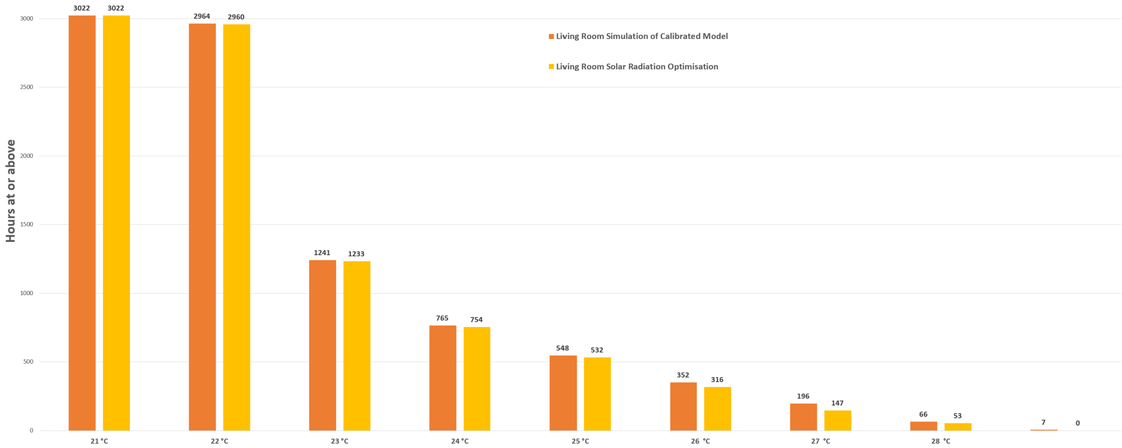


Figure 5.12. Temperature distribution for the Living Room between the calibrated and the solar radiation optimised models.

From the figure 5.11 and 5.12 can be seen that the optimisation for solar radiation control has not made a drastic positive change in the Bolig 2020 thermal comfort. That is because the solution was chosen based on not having a negative impact in the total site energy consumption which also meant that it did not have the least possible discomfort hours. Even though the house has acceptable comfortable levels of over temperature further optimisation of the following resilient cooling technologies is conducted in order to make the final building as resilient to global weather change as possible.

5.2 Natural Ventilation Optimisation

Natural ventilation is part of the natural cooling technologies and can easily be implemented by every house by opening the windows.

5.2.1 Design input variables for natural ventilation

The goal for every resilient cooling technology tested is to not change the structure and construction of the main building in order for these technologies to be easy to implement after the building construction. This means that even though natural ventilation can be controlled and optimised by many ways only the windows opening percentage is optimised here.

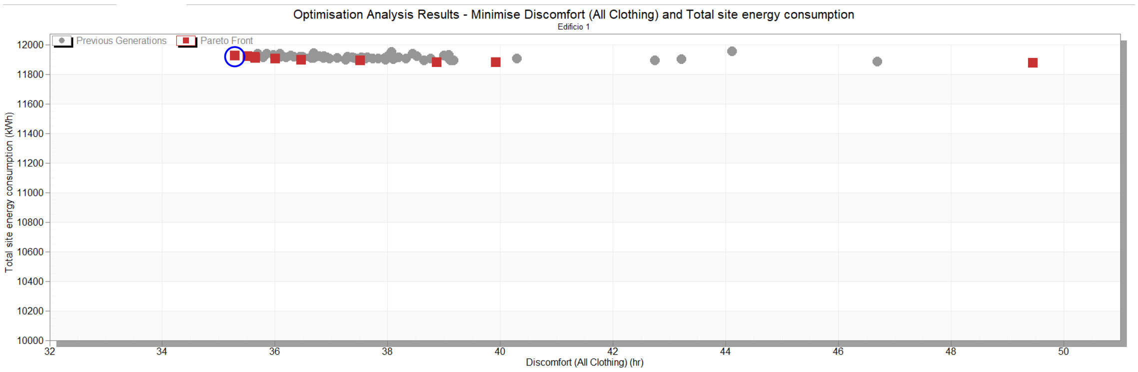
Model parameter	Parameter variation	Unit	Values	Distribution
% External Window Opens	Area percentage	[%]	0 - 100 Step size = 1	Discrete

Table 5.2. The chosen natural ventilation input parameters for Bolig 2020.

For the chosen input parameter it is necessary to define a proper range and distribution. This input is tested for every room individually in order to optimise the entire house. From table 5.2 can be seen that the optimisation process is able to choose between all possible window opening percentages using a discrete distribution with a step size of 1 to have enough detail for the end results.

5.2.2 Natural ventilation results

Since all the windows used for the natural ventilation optimisation are the already existing ones the optimisation process has no effect in the total building cost. That is why it is decided the objectives for this optimisation are to make sure the optimal solution does not affect the total site energy consumption and at the same time to have the least amount of discomfort hours.



Status

Iteration	Generation	Status	Discomfort (All Clothing) (hr)	Total site energy consumption (kWh)	% Window opens Living room	% Window opens Master bedroom	% Window opensKitchen and Room 3	% Window opens Room 1	% Window opens Room 2 and Utility
75	5	Optimal Designs	35,2862	11922,82	86,000	40,000	91,000	73,000	67,000
50	4	Optimal Designs	35,5118	11921,49	87,000	53,000	97,000	48,000	59,000
37	3	Optimal Designs	35,6406	11916,52	77,000	22,000	97,000	48,000	58,000
52	4	Optimal Designs	35,6503	11908,70	73,000	25,000	93,000	48,000	66,000
8	0	Optimal Designs	36,0044	11905,82	93,000	29,000	42,000	21,000	69,000
14	1	Optimal Designs	36,4640	11894,43	59,000	54,000	58,000	21,000	66,000
56	5	Optimal Designs	37,5199	11890,79	73,000	27,000	17,000	39,000	64,000
48	4	Optimal Designs	38,8735	11880,79	74,000	17,000	85,000	52,000	0,000
46	4	Optimal Designs	39,9237	11878,68	73,000	7,000	32,000	26,000	3,000
15	1	Optimal Designs	49,4519	11876,07	6,000	33,000	42,000	7,000	58,000

Figure 5.13. Optimisation of window % opening for the Bolig 2020.

Figure 5.14 is a clearer representation of the optimal solution energy results from figure 5.13.

Figure 5.14. Optimisation regarding the energy of window % opening for the Bolig 2020.

After running the optimisation seen in figure 5.14 it is clear that all solutions do not affect total site energy consumption as the window openings are controlled by the internal temperature. This is true as the energy consumption of all pareto front solutions are falling in the category of error which is calculated to be 5% according to the validation indexes from chapter 4 resulting in an error of $\pm 600kWh$. That is why solution number 75 is chosen as the optimal one as it has the least amount of discomfort hours equal to just 35 hours. Since the original calibrated model had a window opening percentage area of 5% the internal temperature was not able to be regulated very fast so the optimal solution has in general increased opening area percentages for all rooms ranging from 40% to 91%.

Comparison with the base case

Figure 5.15 shows the hours at or above temperatures for the Master bedroom between the final calibrated model from section 4.2, the final optimised solar radiation control solution and the natural ventilation optimised solution.

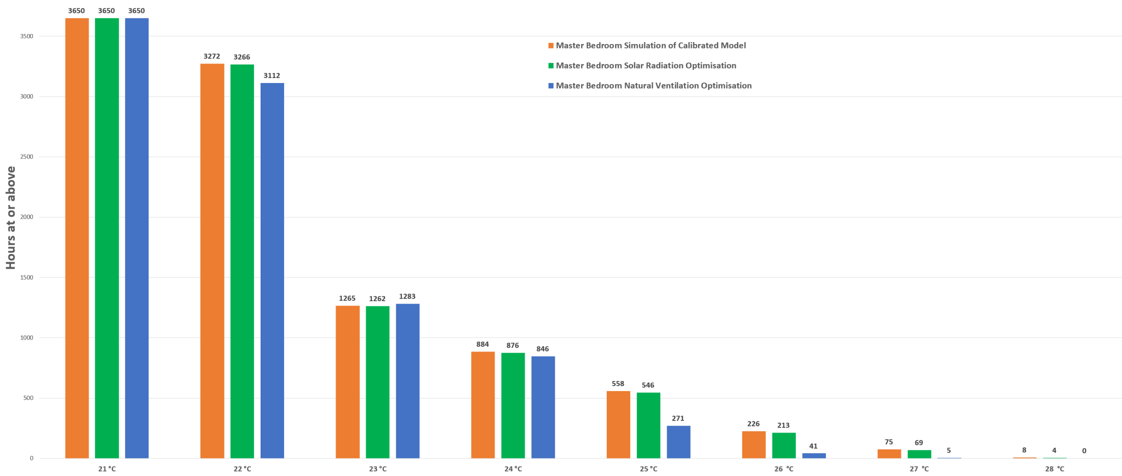


Figure 5.15. Temperature distribution for the Master bedroom between the calibrated, the solar radiation and natural ventilation optimised models.

Figure 5.16 shows the hours at or above temperatures for the Living room between the final calibrated model from section 4.2, the final optimised solar radiation control solution and the natural ventilation optimised solution.

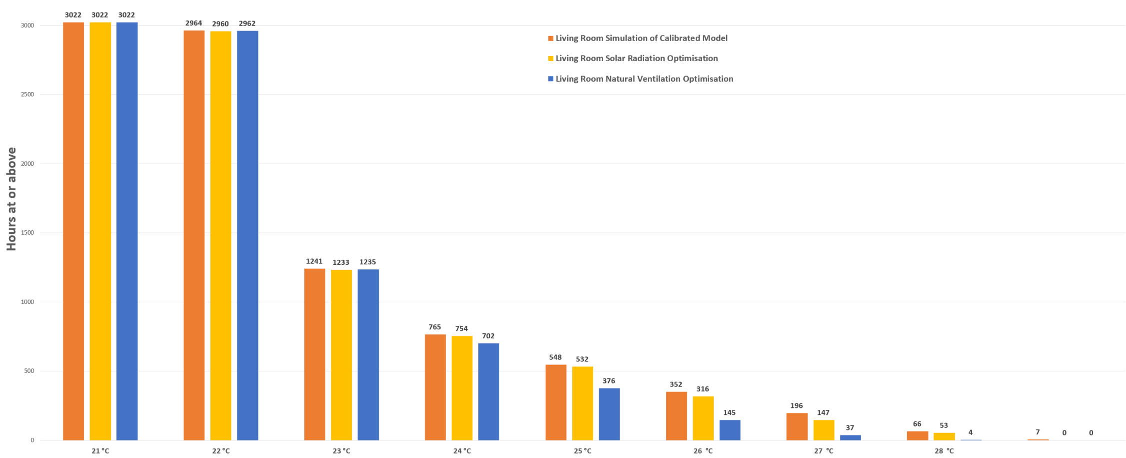


Figure 5.16. Temperature distribution for the Living Room between the calibrated, the solar radiation and natural ventilation optimised models.

After applying the optimal solution found from the optimisation process to the model the temperature distribution was calculated and compared with the rest of the models. The implementation of natural ventilation has a significant positive impact in reducing the over temperatures. Specifically from figure 5.15 and 5.16 can be seen that by applying natural ventilation mostly the high temperatures at or above 25°C show the highest reduction to more than half from the original, while leaving the lower, comfortable ones at more less the same levels. Even though the house now has much more comfortable levels of over temperature further optimisation of the micro climate is conducted in order to make the final building even more resilient to global weather change.

5.3 Micro Climate Control Optimisation

For the micro climate control different parameters that affect the indoor environment are tested. These parameters are used as inputs for the optimisation process in order to achieve the same optimisation objectives, which are to find the parameter combination that provides the most cooling potential by having the lowest internal temperatures and being cost effective as well as energy efficient at the same time.

5.3.1 Design input variables for micro climate control

In the premises of controlling the micro environment mainly the effects of planting trees in the building site's perimeter are tested. These effects include modelling of the extra shade that is provided from the trees as well as the changes in the wind amount for ventilation. Theses two main effects have a direct impact on thermal comfort in the house. In the program Design builder external objects like trees can be modelled using component blocks as seen in figures 5.17 and 5.18 depicted as extruded rectangles in the site's perimeter. This is presented in more detail in subsection 5.3.2.

Model parameter	Parameter variation	Unit	Values	Distribution
Tree planting orientation	Orientation	[Degree]	E, W, S E&W, E&S, W&S W&E&S	Discrete
Tree height	Height	[m]	1, 2, 3, 4, 5 10, 15	Discrete
Tree type	Solar transmittance (Defoliated and Foliated)	[%]	Chestnut: 57; 9 Linden: 54; 8 Birch: 59; 14 Cherry: 48; 13 Pine: N/A; 12	Discrete

Table 5.3. The chosen micro climate control input parameters for Bolig 2020.

The effects of these inputs in table 5.3 regarding the external environment are tested for the Master Bedroom. The three main model parameters are tested in separate stages in order to optimise each one. A detailed description of the different input parameters is presented below.

Tree planting orientation

The first optimization that is conducted for the micro climate control is about finding the optimal placing for the trees. In general the trees were planted in the perimeter of the actual house. Since on the North side can not be blocked as it is the entrance to the main road the site has the rest three sides available to plant trees.

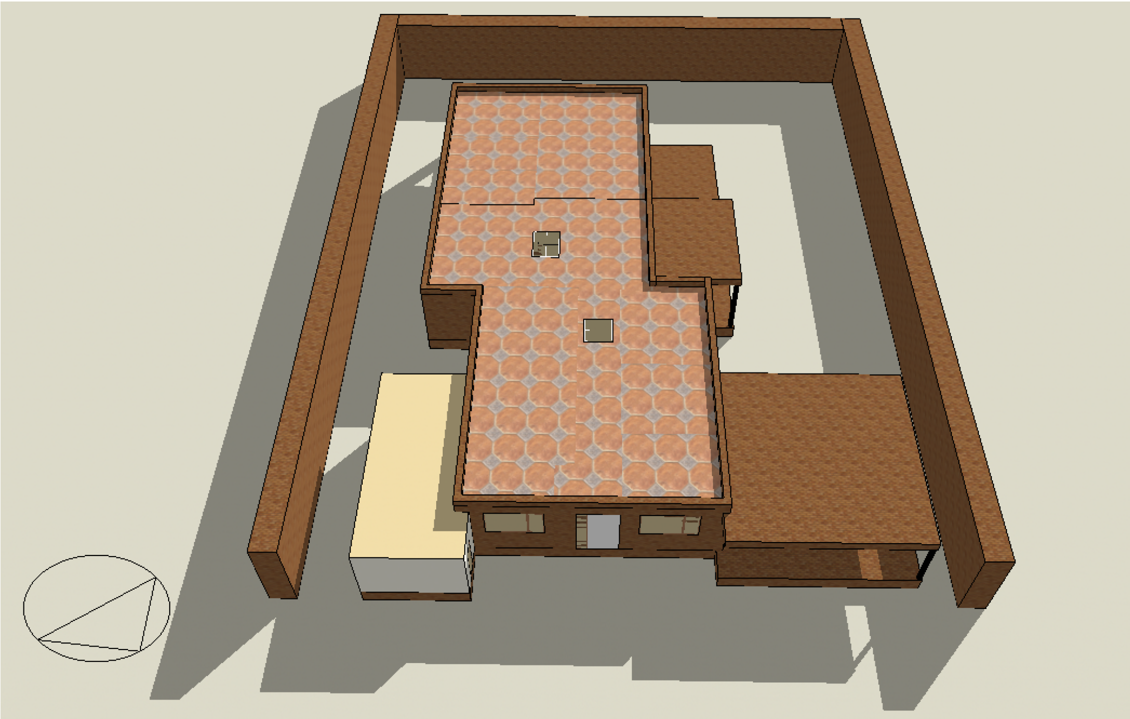


Figure 5.17. Optimisation of tree orientation for the Bolig 2020.

For the optimization the trees were planted in all possible combinations of the different sides to find the optimal one as seen in figure 5.17. By planting trees in all sides the building will have the highest amount of shading, however that will introduce more energy consumption especially during the winter time. For that reason the optimal solution that will be found below should not produce more energy consumption while at the same time is cost effective and has the least amount of discomfort hours.

Tree height

After an optimal solution is found for the tree planting orientation, the actual tree height is optimised for that optimal solution.

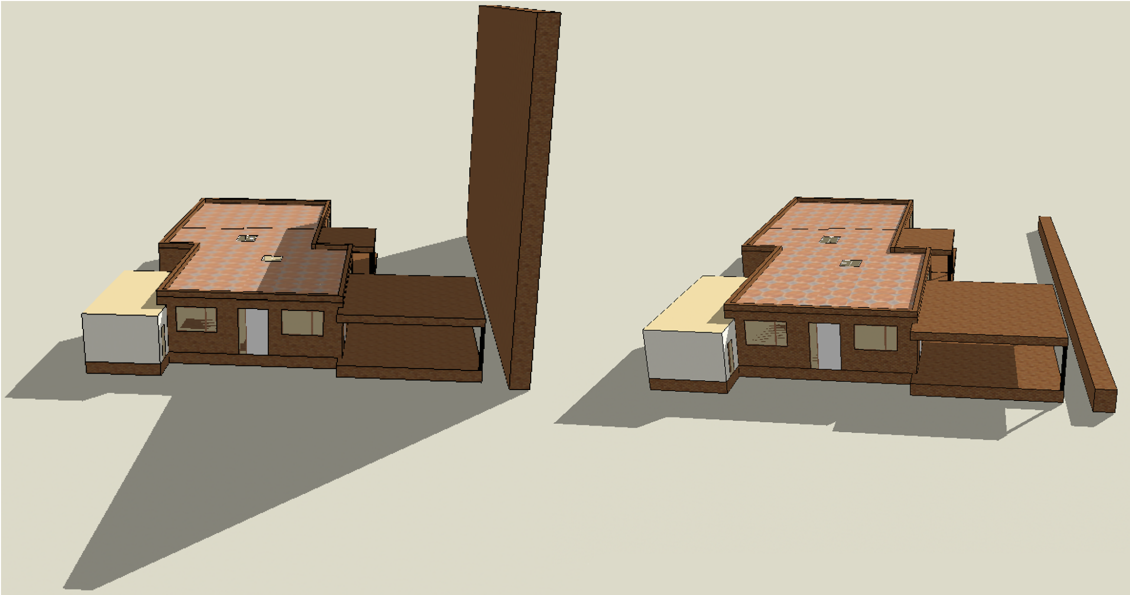


Figure 5.18. Optimisation of tree height for the Bolig 2020.

In figure 5.18 the two extreme heights of 15m on the left and 1m on the right are seen. For the optimization different Heights will be used between the 2 extreme ones mentioned above. These two extreme heights were chosen to represent typical tree heights. The significant effects of shading from the taller trees are clear when compared to the shorter ones for the same time of day.

Tree type

The optimal solution from the tree planting orientation as well as the tree height will be used for the optimization of the tree types. For this study since the building is located in Denmark different endemic trees are tested.

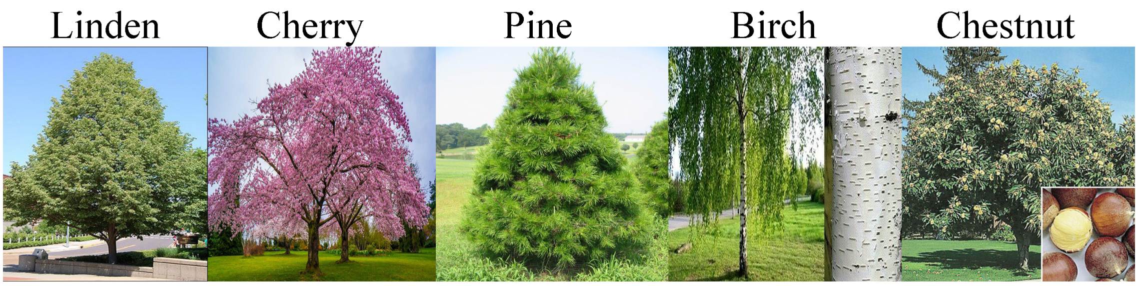


Figure 5.19. Optimisation of tree types for the Bolig 2020.

In figure 5.19 the five different tree types are shown. These trees were chosen in order to test the effects of deciduous trees that lose their leaves in the winter as well as evergreen ones. By losing their leaves the deciduous trees are able to provide less shading during winter time when it is needed, however the evergreens have the benefit of blocking the winter winds thus providing a more sheltered environment all year.

5.3.2 Optimisation process for micro climate control

As for all tested resilient cooling technologies the goal for this one is again to find a solution that does not increase the already existing energy consumption while at the same time decreases the discomfort hours and it is cost efficient. To test the effects from the micro climate in the program Design Builder it is essential to use component block which are the extruded rectangular objects seen in figures 5.18 and 5.17. Using these component blocks it is able to simulate the effects of adjacent objects like trees on the main building. The most important things to set up in the component blocks in order to model trees are as seen in figure 5.20 the maximum transmittance value and the transmittance schedule. When it comes to the maximum transmittance it ranges between the values of 0 meaning there in no transmittance and 1 which describes fully opaque objects. A value close to 0 represents the summer period when the trees still have all their leaves so the solar transmission through them is minimum and the opposite is true for the winter period when all the leaves are fallen. The transmittance schedule is used to define the variation between the lowest in highest transmittance values in order to represent the change of seasons and was modeled according to the findings from the paper [15].

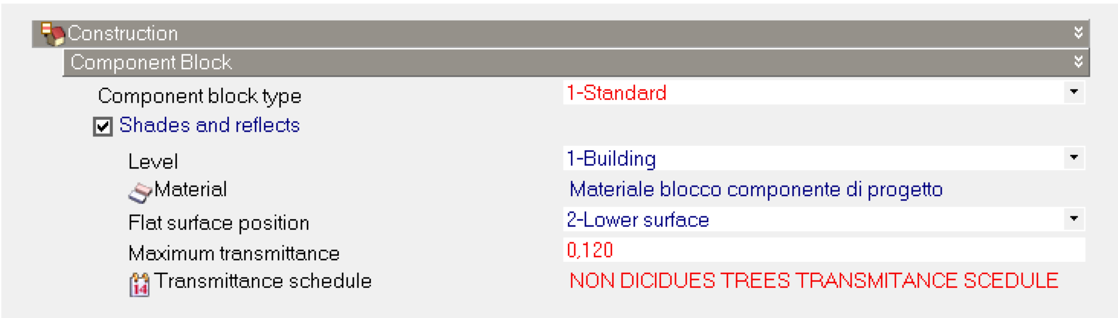


Figure 5.20. Component block construction to simulate the effects from trees.

Other than studying the effects from trees a green roof was constructed in order to reduce the overall energy consumption by providing more insulation. In order to model the green roof one more layer was added in the existing roof construction of the building. The program Design Builder has in it's gallery a material that can model green roofs with the properties seen in figure 5.21.

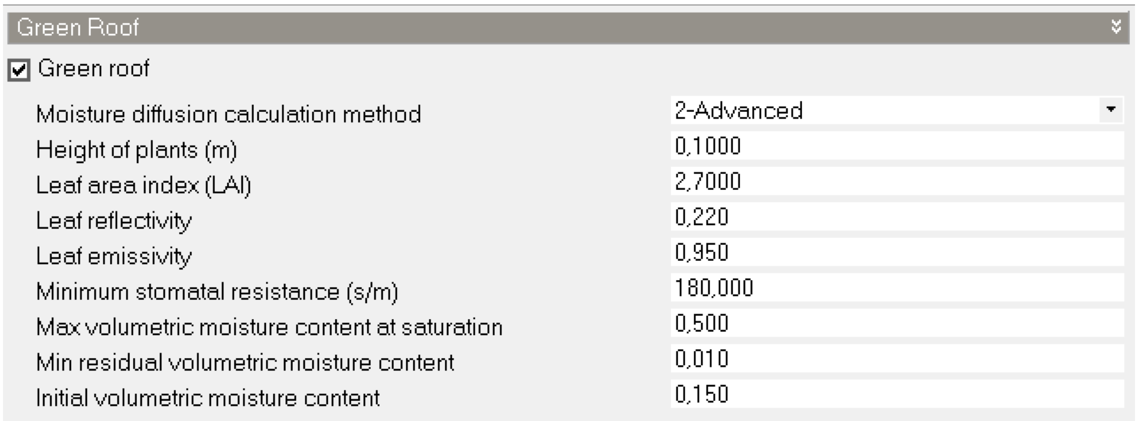


Figure 5.21. Component block construction to simulate the effects from trees.

The overall optimisation process for the micro climate control was achieved in three main stages. In the first stage the component blocks mentioned above were placed in different positions around the perimeter of the building site. This is done as different orientations or a combination of those provide more or less shading in the house. The optimal solution that was found for the proper orientation was used for the optimization for the height of the trees. At this stage the height of the actual trees have a direct influence to the overall thermal comfort of the house as higher trees provide more shade for a longer period of time. For the final stage the combined best solution from the two previous stages was used in order to determine the optimal tree type. This was done in order to test the effects from deciduous trees, where the solar transmittance increases during the winter period when the leaves are falling thus increasing the valuable heat gain. The evergreen tree type was also tested due to the additional benefit of blocking the winter winds.

5.3.3 Micro climate control results

In figure 5.22 the optimisation results for the optimal tree position are shown.

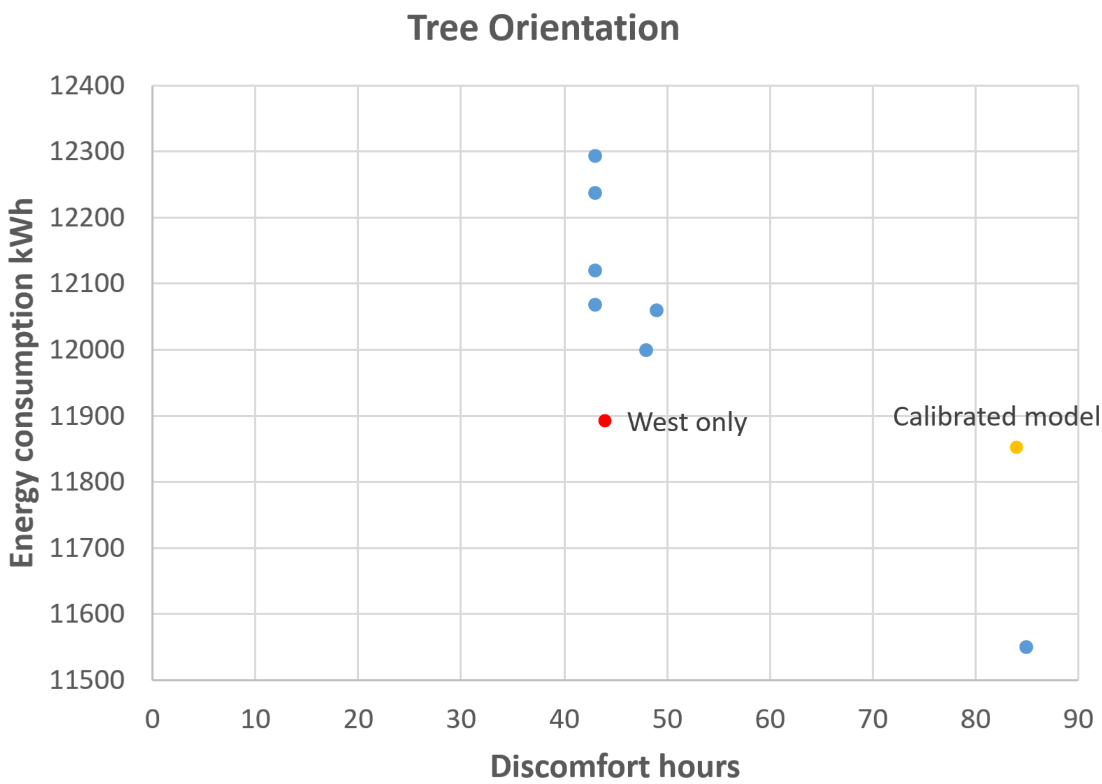


Figure 5.22. Optimisation of tree orientation for the Bolig 2020.

In table 5.4 the numeric results used for figure 5.22 are presented.

Case	Discomfort hours	Total site energy consumption [kWh]
Original calibrated model	84	11852
Green roof only	85	11550
East only	48	11999
West only	44	11892
South only	49	12059
East and West	43	12068
East and South	43	12237
West and South	43	12119
East West and South	43	12293

Table 5.4. Output results for tree orientation.

From the results in table 5.4 can be seen that just by adding another layer of green roof in the roof construction the total site energy consumption gets reduced a lot while the discomfort hours increase slightly by one hour compared to the original calibrated model. The green roof was decided to be present for all of the rest position combinations since it had a significant impact in reducing the energy consumption. When it comes to the tree position can be seen that out of the East, West and South orientations the South orientation provides then most discomfort hours where the West one provides the least amount of discomfort hours as well as energy consumption. The building is accumulating heat during the day so by shading from the West side the excess heat load of the day can be alleviated. Finally by using a combination of all the other sides the results for the discomfort hours show diminishing returns in the improvement while at the same time the total side energy consumption increases even more. Moreover having trees planted in just one orientation is the most economic solution when compared to planting them in all three sides of the site's perimeter. These are the reasons why the West side combined with the green roof was chosen as the optimal solution to be used in the next optimization for the tree height.

In figure 5.23 the optimisation results for the optimal tree height are shown.

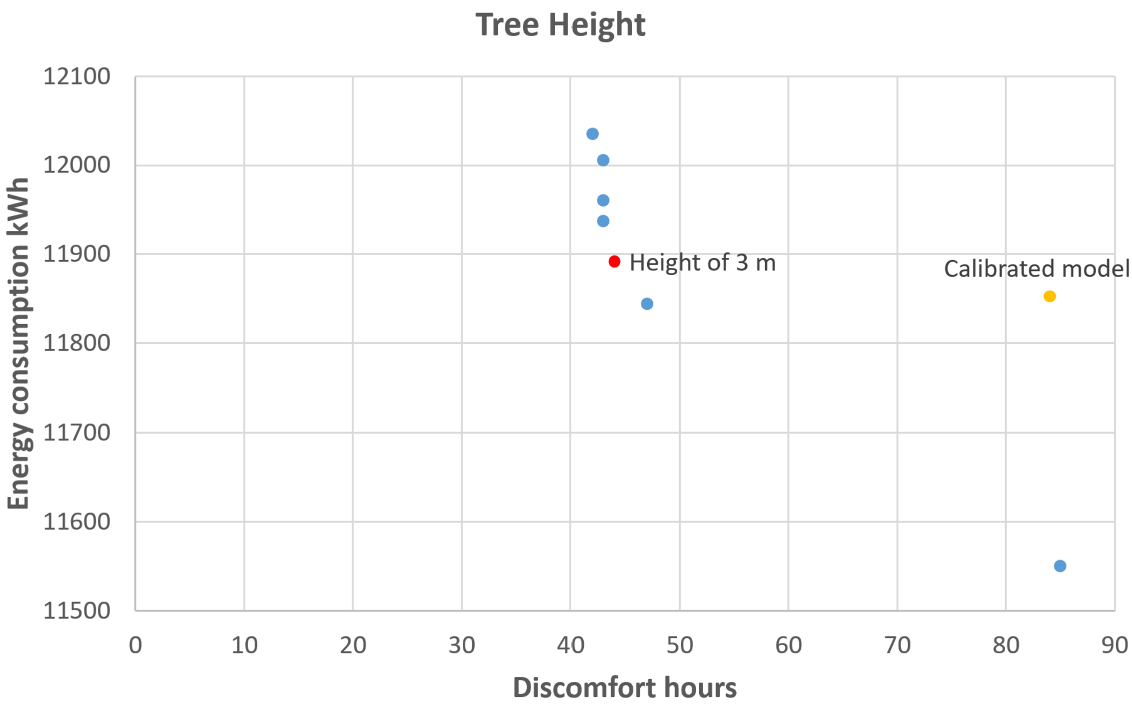


Figure 5.23. Optimisation of tree height for the Bolig 2020.

In table 5.5 the numeric results used for figure 5.23 are presented.

Case	Discomfort hours	Total site energy consumption [kWh]
Original calibrated model	84	11852
Height of 1 m	85	11550
Height of 2 m	47	11844
Height of 3 m	44	11892
Height of 4 m	43	11937
Height of 5 m	43	11960
Height of 10 m	43	12005
Height of 15 m	42	12035

Table 5.5. Input parameters for tree height.

The table 5.5 shows that compared to the original calibrated model when increasing the height of the trees by one meter the energy consumption decreases considerably however the discomfort hours increase slightly by one hour. When increasing the height to more than one meter the discomfort hours decrease considerably and create a plateau at the height of 3 meters. After this height there is no more considerable decrease in the discomfort hours however the energy consumption increases a lot. That is why the height of 3 meters on the West side is chosen as the optimal solution to be used in the final optimisation as it provides a similar energy consumption to the original model While having the least amount of discomfort hours at the same time.

In figure 5.24 the optimisation results for the optimal tree position are shown.

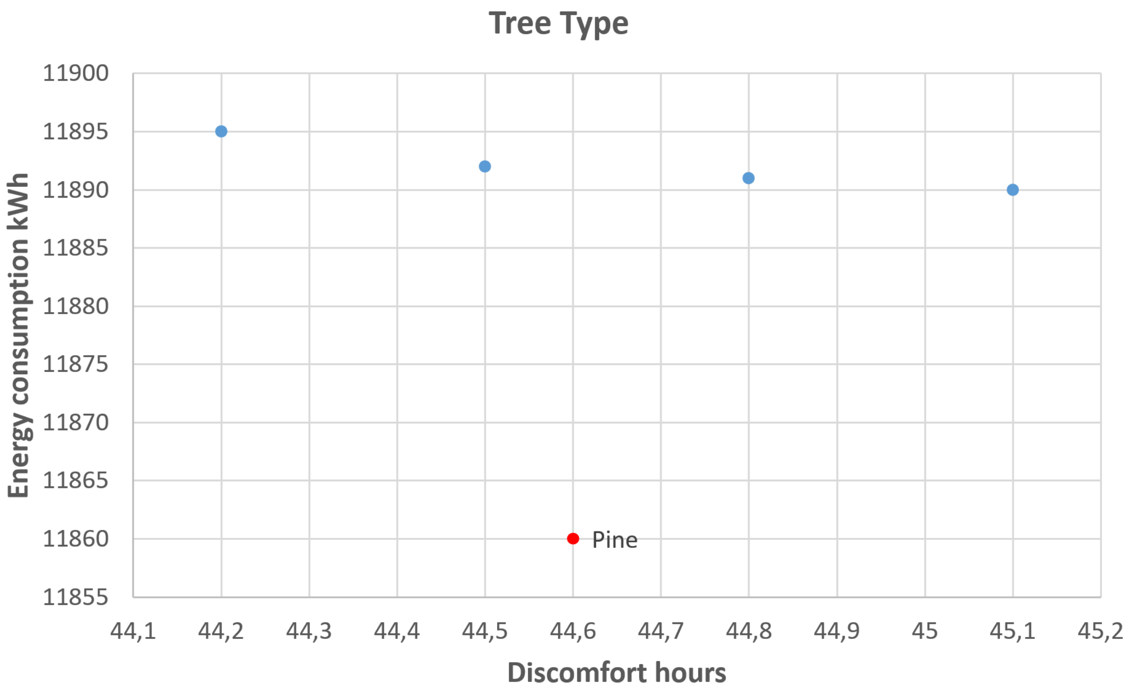


Figure 5.24. Optimisation of tree types for the Bolig 2020.

In table 5.6 the numeric results used for figure 5.24 are presented. The defoliated and foliated data for total transmissivity are for endemic trees in the Scandinavian countries according to the paper [15].

Case	Defoliated Total Transmissivity [%]	Foliated Total Transmissivity [%]	Discomfort hours	Total site energy consumption [kWh]	Cost per tree
Chestnut	57	9	44.5	11892	100
Linden	54	8	44.2	11895	70
Birch	59	14	45.1	11890	60
Cherry	48	13	44.8	11891	50
Pine	N/A	12	44.6	11860	40

Table 5.6. Input parameters for different tree types.

From the results in figure 5.24 it is evident that all different tree types have approximately the same effect on the discomfort hours since they are ranging from 44.2 and 45.1. When it comes to energy consumption all the different tree types provide solutions that do not consume more energy than the original calibrating model, with the Pine tree specifically has slightly lower energy consumption. This is happening as it is in the evergreen category of trees that never lose their leaves and thus it is able to provide a more sheltered solution from the external winter winds. Moreover according to the table 5.19 the Pine tree has the lowest cost per tree which also makes it the most affordable option. However for the final solution of the entire micro climate control category all possible tree types can be chosen to be planted in the West side of the site's perimeter with a height of 3 meters as all solutions are falling in the category of error which is calculated to be 5% as previously mentioned resulting in an error of $\pm 2 hours$. For the final optimal solution for the micro climate control the Pine tree is selected though as it has slightly less energy consumption and is compared below with the rest of the optimal resilient cooling technologies solutions.

Comparison with the base case

Figure 5.25 shows the hours at or above temperatures for the Master bedroom between the final calibrated model from section 4.2, the final optimised solar radiation control solution, the natural ventilation optimised solution as well as the micro climate control final solution.

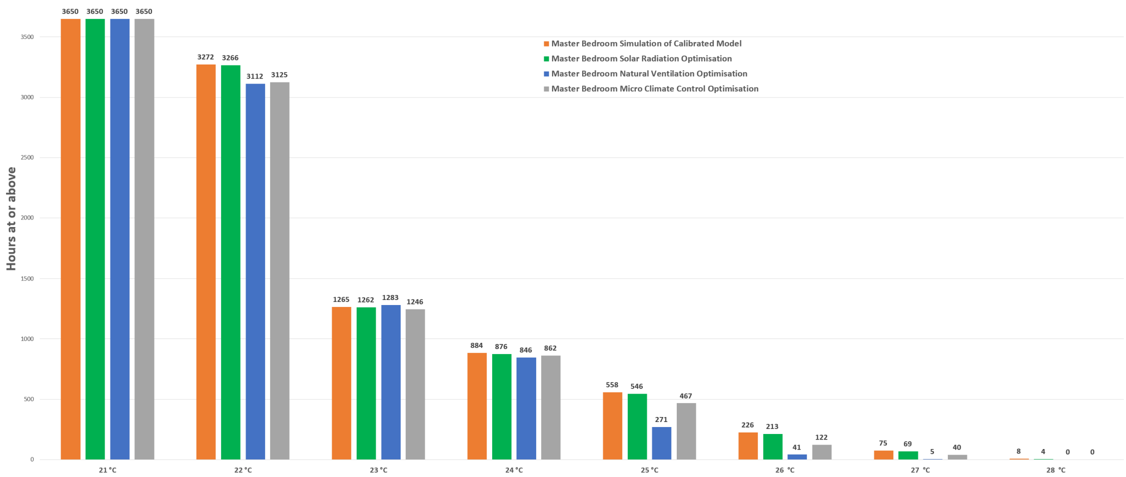


Figure 5.25. Temperature distribution for the Master bedroom between all tested resilient cooling technologies.

Figure 5.26 shows the hours at or above temperatures for the Master bedroom between the final calibrated model from section 4.2, the final optimised solar radiation control solution, the natural ventilation optimised solution as well as the micro climate control final solution.

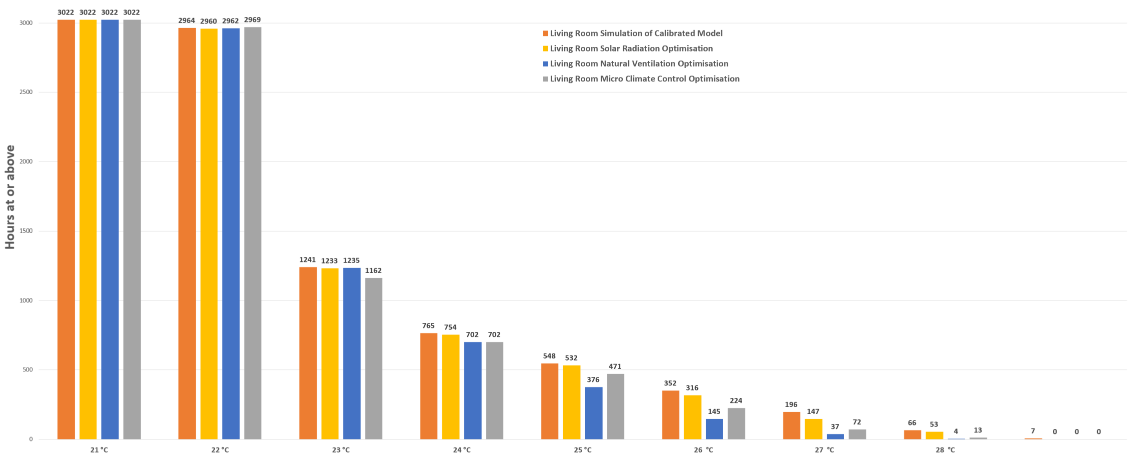


Figure 5.26. Temperature distribution for the Living Room between all tested resilient cooling technologies.

After applying the optimal solution found from the optimisation process to the model the temperature distribution was calculated and compared with the rest of the models. The implementation of micro climate has an overall significant positive impact in reducing the over temperatures. Specifically from figure 5.25 and 5.26 can be seen that by implementing micro climate control the same trend is observed where mostly the high temperatures at or above 25°C show the highest reduction to more than half from the original, while leaving the lower, comfortable ones at more less the same levels. When comparing the different resilient cooling technologies with the calibrated model can we seen that the solar radiation control provides the least reduction in internal temperatures whereas the natural ventilation solution provides the most reduction. Finally when it comes to the micro climate control the internal temperatures are ranging between the other two resilient cooling technologies.

6 Generation and Comparison of Future Weather Files

In this chapter future global warming weather files are created. Specifically two different methodologies for future weather generation are tested and explained. The first is called synthetic time series which is used by the program Meteonorm and the second is called morphing time series which is used by the program CCWeatherGen. A lot of different variations of parameters are tested for both programs to generate different weather files with different properties. All the generated weather files were categorized and compared to find the most extreme one for later testing on the existing building to determine whether or not the building is resilient to global weather change.

6.1 Methodologies for Creating Future Weather Files

Using average data to produce weather files provides no information about the natural variability of the weather, which is of primary importance when trying to consider extreme or atypical weather conditions. This is needed because extreme weather events such as, heat waves, drought periods, or cold snaps are essential for modelling overheating in buildings, analysis of thermal comfort or estimating peak energy use. Extreme weather events are likely to become more frequent in the future as a result of climate change

Weather files ideally need to:

- Contain examples of typical conditions
- Contain examples of extreme conditions
- Be at the temporal resolution required by simulation packages (typically a 1 hour or higher resolution)
- Be at a geographic resolution that matches changes in weather due to local topography in the country of interest
- Express the effect of the urban micro-climate
- Contain examples of possible future climates, ideally considering the effects of climate change
- Need to have a proven track record with industry

There are limitations when using observed data for typical and extreme weather files like observed historical weather data which are the principal source of data for all the weather files. The first limitation applies to both typical and extreme weather files, and is based on the fact that weather files are based on a relatively small number of weather stations with a heterogeneous spatial distribution. The applicability of this data far from the observation site is reduced [16].

The second set of limitations is specifically related to weather files representing extreme weather conditions. The primary limitation of extreme weather files is how to overcome the fact that extreme weather is, by definition, a low frequency event. So, a time series collected to create the typical weather years are not long enough to provide sufficient information about the frequency and intensity of extreme weather events that might only occur once every 50 or 100 years. Also characteristics of weather time series change over time, further complicating the extreme events analysis. The use of historical data implies that no information is contained on how climate change may affect weather patterns and extreme weather events [16].

6.1.1 Synthetic time series

Weather generators like the program Meteonorm use computer algorithms that produce a long time-series of weather variables with statistical properties comparable to existing historical records. Weather generators can also simulate meteorological variables at different time scales. Weather generators are often developed in two steps: firstly, by modelling of daily precipitation and then generating the remaining variables of interest based upon the rain occurrence. These variables often are maximum and minimum temperature (Tmax, Tmin), and solar radiation (R). Other variables such as wind direction and speed are then derived from the key variables. The decision of either a wet or dry day depends on the amount of rainfall observed; dry is used if the rainfall is below a certain threshold (usually, 0.02 mm); otherwise the day is classified as wet. For each month different model parameters are used to represent the seasonal variations in both the magnitude of climate variables and their cross-correlations (correlations between single variables over different periods of time).

The primary limitation of weather generators is that they are based upon statistics derived from historical observations of weather. This means that it is unlikely that extreme events will be correctly represented, as these will rarely, if at all, have occurred during the short historic record used to create the generator. In addition, there is the inherent assumption that future weather patterns will be the same as those observed historically.

In theory, weather generators can be used to generate enough data to evaluate the probability of extreme weather events. Observed time series represent one single ‘realisation’ of the climate, whereas a weather generator can create many ‘realisations’ and hence, potentially, a wider range of feasible situations [16].

6.1.2 Morphing time series

The alternative to using climate projections is to adjust (morph) current weather files or even raw time series data taken at weather stations which is done using the program CCWeatherGen. The starting point of this method is obtaining high-resolution weather data for a specific site. These data are then morphed using projections from either a global or a regional climate model. This process is often used for the analysis of building energy use or assessing resilience under different future climate scenarios. Morphed weather files use historical observations of weather to represent the present-day climate. This produces meteorologically consistent weather files, but ignores some aspects of future climate change, such as the changing frequency of heat waves. The use of a standard baseline historical time series means that the applicability of any future weather files is constrained by baseline data availability. Additionally, if the baseline data to be morphed is already in the form of a TRY, TMY or similar weather file, then there is also the inherent assumption that any climatic change that occurred between the baseline period of the weather file and the baseline period of the climate projections is negligible. The morphed time series are constructed by 'shifting' and 'stretching' the observed variables using factors produced from the climate change projections.

The morphing procedure tends to overestimate extreme data as it approaches maximum and minimum temperatures independently from the mean when they should be correlated. This is one of the reasons why weather generator methods are known to be better suited to investigating extreme temperatures. In addition, weather generators offer a consistent, finer spatial resolution than morphing, which is reliant on the number and locations of weather stations whereas, at least in theory, a weather generator can be run for any location [16].

6.2 Weather Files Categorization Process

To categorize the future weather files by the occurrence of heatwaves, a system has developed specifically for the Danish weather. This system categorizes the future weather based on the frequency of occurrence of certain weather phenomena like heat waves which are described below.

6.2.1 Categorisation based on defined attributes

The following attributes were defined based on the findings from the World Meteorological Organization and modified for the Danish climate. This happened as people tend to adapt to their local climate. For example a threshold considered extreme in one part of the world could be considered quite normal in another. To overcome this problem, thresholds based on percentile values can also be defined [19].

Maximum Year Temperature

The maximum temperature for every year tested was found as a general simple first comparison between the different years.

Heatwave Frequency and Duration

A heat wave is when the mean value of the highest recorded temperatures, measured over three consecutive days, exceeds 28°C.

- Heatwave frequency is the number of heatwave days relative to number of days in a year or [number of heatwave days/365]·100 (%)
- Heatwave duration is the number of days of the longest heatwave of the year (days)

Tropical Day

It is meteorologically a tropical day when the minimum temperature of the day somewhere in the country that is also overnight never drops to or below 20°C.

Summer Day

It is meteorologically a summer day when the day's maximum temperature rises above 25°C somewhere in the country. Since this happens almost only during the daytime, it is most often called a summer day

Using the above mentioned categorization criteria the results for all the different weather files are shown in figure 6.1. These future weather files can be split in two main categories.

The files generated by the CCWeatherGen program which uses the morphing method, produced the most extreme weather files. In this category there are only two options to generate future weather files based on a 2050 and 2080 scenario. Using this program a initial weather file is needed to be morphed so the Actual Weather file and the Reference weather file were used. The Actual Weather file represents the measured weather for one year at the location of the actual building whereas the Reference Weather file is based on the 30 year period 1981-2010 from the Meteonorm library for the location of Ry as seen in figure B.1. By using these two initial weather files four future weather files were produced and shown in figure 6.1.

In the next category are the future weather files generated by the Meteonorm program. This program can only use the 30 year Reference Weather file from Ry. Using the Meteonorm program there are more options to generate future weather files. There are three main IPCC scenarios for future periods which are the B1, A1B and A2 and can be seen in figure B.3. All these scenarios were generated for the years 2020, 2050, 2070 and 2100 and for each one a typical and an extreme version were created. To create the typical version looking at figure B.3 the following settings were used: Temperature model was set to Standard (hour), In the temperature - 10 year monthly extreme values category, the Extremas section was set to Averages (default) and in the Radiation - 10 year monthly extreme values category, the Extremas section was set to Averages (default). To create the extreme version looking at the same figure the following same settings were changed: Temperature model was changed to 10 year extreme (hour), In the temperature - 10 year monthly extreme values category, the Extremas section was changed to Yearly maxima and in the Radiation - 10 year monthly extreme values category, the Extremas section was changed to Yearly maxima.

	Heatwave Index				
	Maximum year temperature °C	Heatwave Frequency (%)	Heatwave Duration (days)	Tropical Day (days)	Summer Day (days)
Actual Weather	31	1.4	5	0	32
CCWeatherGen 2080 (Actual Year)	35.9	3.8	7	20	59
CCWeatherGen 2050 (Actual Year)	34.4	0	0	10	40
Reference Weather	27.5	0	0	0	8
CCWeatherGen 2080 (Reference Year)	31.3	1.1	4	10	36
CCWeatherGen 2050 (Reference Year)	29.7	0	0	0	15
B1 2020 Typical	27.8	0	0	0	8
B1 2050 Typical	28.6	0	0	0	9
B1 2070 Typical	30.4	0	0	1	12
B1 2100 Typical	28.2	0	0	4	8
B1 2020 Extreme	31.3	0	0	0	11
B1 2050 Extreme	30.3	0	0	4	10
B1 2070 Extreme	30.4	0	0	3	18
B1 2100 Extreme	32.2	0	0	5	20
A2 2020 Typical	28	0	0	0	10
A2 2050 Typical	28.8	0	0	0	9
A2 2070 Typical	30.8	0	0	0	18
A2 2100 Typical	31	0	0	3	21
A2 2020 Extreme	31.6	0	0	2	11
A2 2050 Extreme	32.1	0	0	0	17
A2 2070 Extreme	32	0	0	4	21
A2 2100 Extreme	32.8	0	0	7	25
A1B 2020 Typical	25.8	0	0	0	2
A1B 2050 Typical	28.8	0	0	0	11
A1B 2070 Typical	28.4	0	0	2	14
A1B 2100 Typical	29.8	0	0	1	21
A1B 2020 Extreme	29.3	0	0	1	12
A1B 2050 Extreme	32.4	0	0	3	14
A1B 2070 Extreme	32.6	0	0	2	21
A1B 2100 Extreme	32.5	0	0	5	28

Figure 6.1. Categorization of future weather files using all possible combination of settings from Meteonorm and CCWeatherGen programs.

Judging from the table 6.1 it is clear that even though the actual weather has 5 heatwave days all the other future weather scenarios with the exception of the CCWeatherGen 2080 (actual year) are a lot cooler without any heatwaves.

Comparing the weather file with the actual measure data with the 30 year reference weather file from Meteonorm library it is seen that the reference weather file is cooler than the actual weather file and that result corresponds with the figure 4.2 from subsection 4.1.2 where the initial comparison was conducted. This result also explains why all Meteonorm future weather files are also cooler than the actual weather file as Meteonorm uses a 30 year average file to generate future global warming weather files. The actual weather file is from the year 2018 and it is possible that this year was hotter than the 30 years that the reference year is based on.

However since there are more aspects to a weather file than just some indexes the figure 6.2 was created which is a box plot of all the weather files representing range of the majority of temperatures.

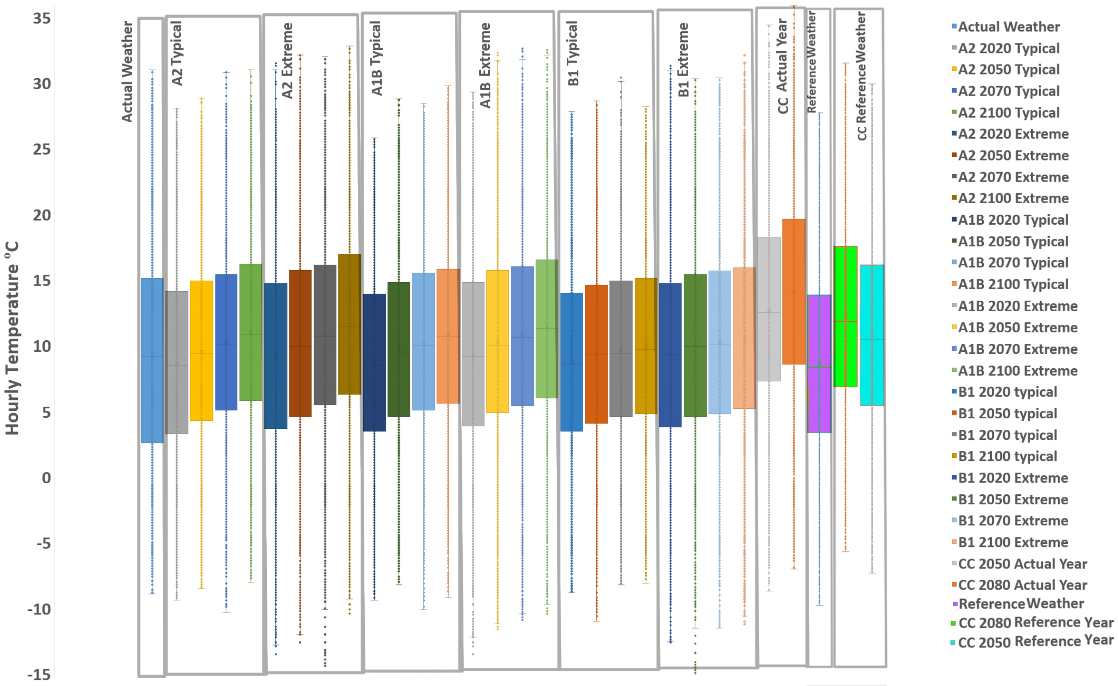


Figure 6.2. The same future weather files using a box plot for better visualisation.

From figure 6.2 can be seen that the majority of weather files are mostly the same with the actual weather with the exception of of the A2 2100 extreme and the two CCWeatherGen files. However when compared with the reference weather file all of them are higher as they are based on that one. Since the main goal is to test the resilience of the building, the results from the worst case scenarios are compared in the next chapter.

6.2.2 Comparison of weather file characteristics

The following figures 6.3 and 6.4 compare the actual weather file with the worst case scenario from the CCWeatherGen and the Meteonorm programs respectively, for a more visual comparison.

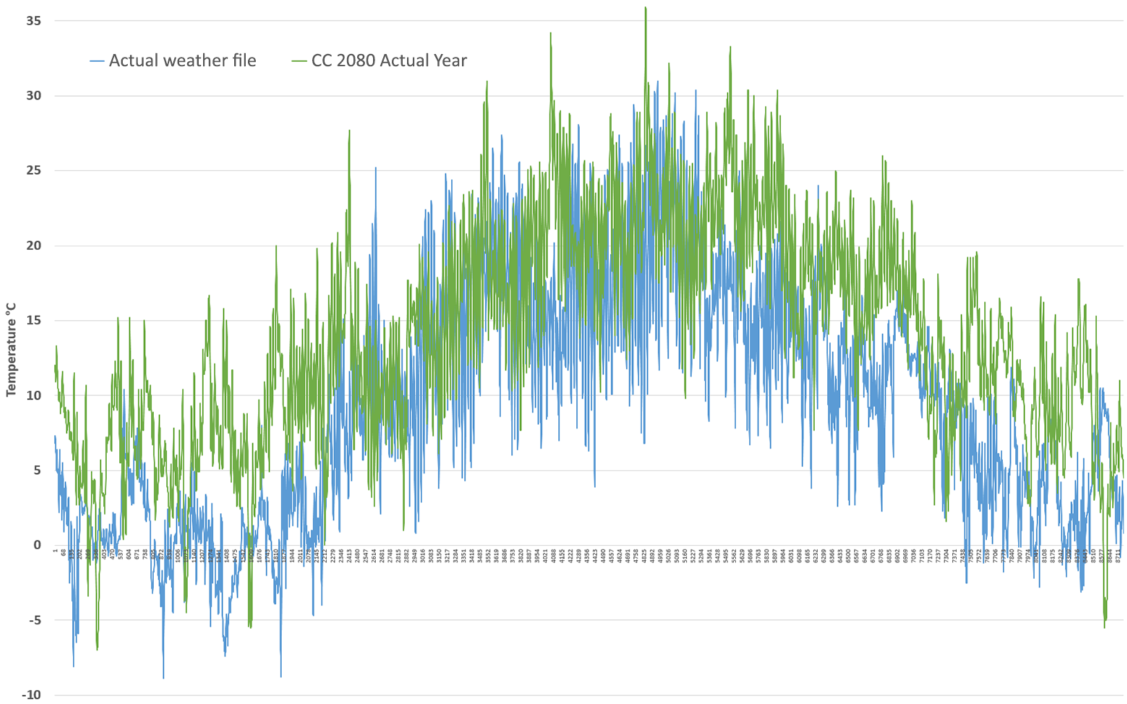


Figure 6.3. Comparison between the actual weather and the worst case scenario from the CCWeatherGen program.

Since the weather file in figure 6.3 from the CCWeatherGen program is made with the morphing method it has a distinct general increase in the average values compered to the actual weather file. These generally increased averages are the ones responsible for affecting the building's performance the most as they provide a constant source of excess heat which is tougher for the building to cope.

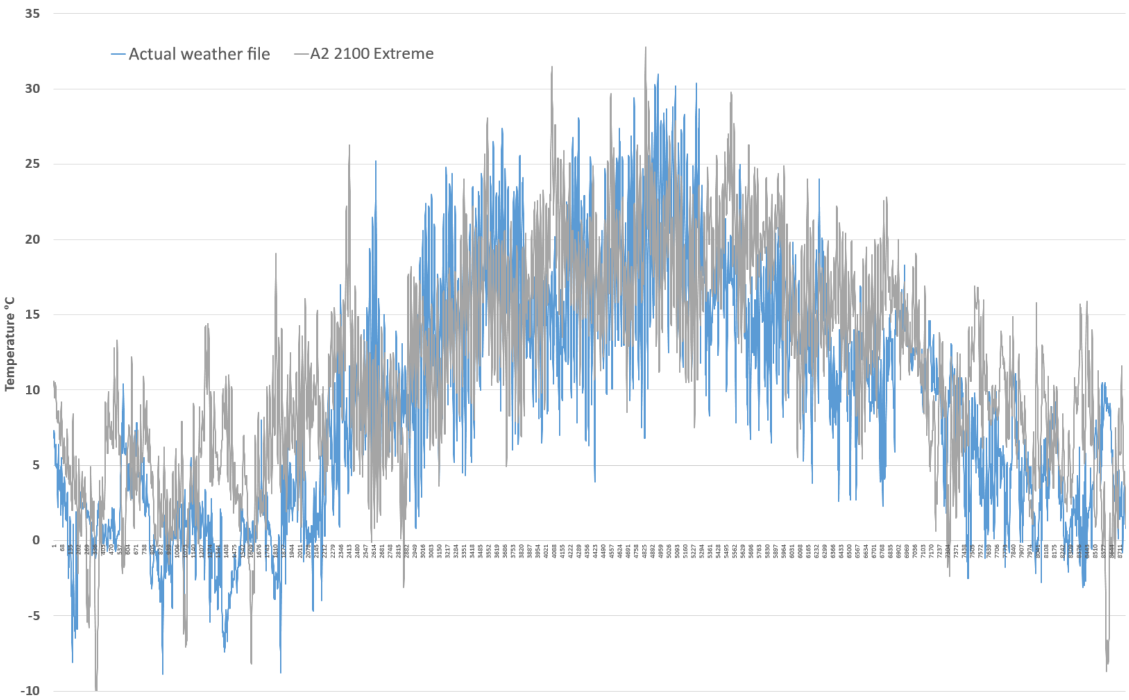


Figure 6.4. Comparison between the actual weather and the worst case scenario from the Meteonorm program.

On the other hand the behaviour of the A2 2100 extreme weather file (which is based on the reference instead of the actual weather file) generated from Meteonorm as seen in figure 6.4 is closer to the actual weather file. That is because it has undergone a transformation based on the reference weather file that has made it almost as hot as the actual weather file. It only has a few hours of higher temperatures than the actual one but for most of the time it ranges within the limits of the actual file. This is great for accuracy purposes but at the same time is not ideal for testing the effects of global warming as the building in not affected negatively by a few hours of slightly higher temperatures.

Since all optimisation process in chapter 5.1.3 is made using the actual weather file (which is hotter than the reference one) to have more representative results of an initially tougher building scenario only the future weather files hotter than the actual weather file are considered in the results of the following chapter.

Cumulative comparison of other weather file attributes

So far the temperature pattern and characteristics was the main focus of weather file comparison. However there are other weather file attributes that affect the building performance greatly. By plotting the cumulative data for global radiation, temperature and wind speed in the following figures 6.5, 6.6 and 6.7 a clear answer regarding the behaviour of the different weather files on the building model emerges. The following three figures explain why using the future weather files generated from Meteonorm turned out to be colder than the actual (measured) weather data and only the most extreme weather file (CC 2080) using the CCWeatherGen program and the morphing method was sufficiently hot to test the building resilience.

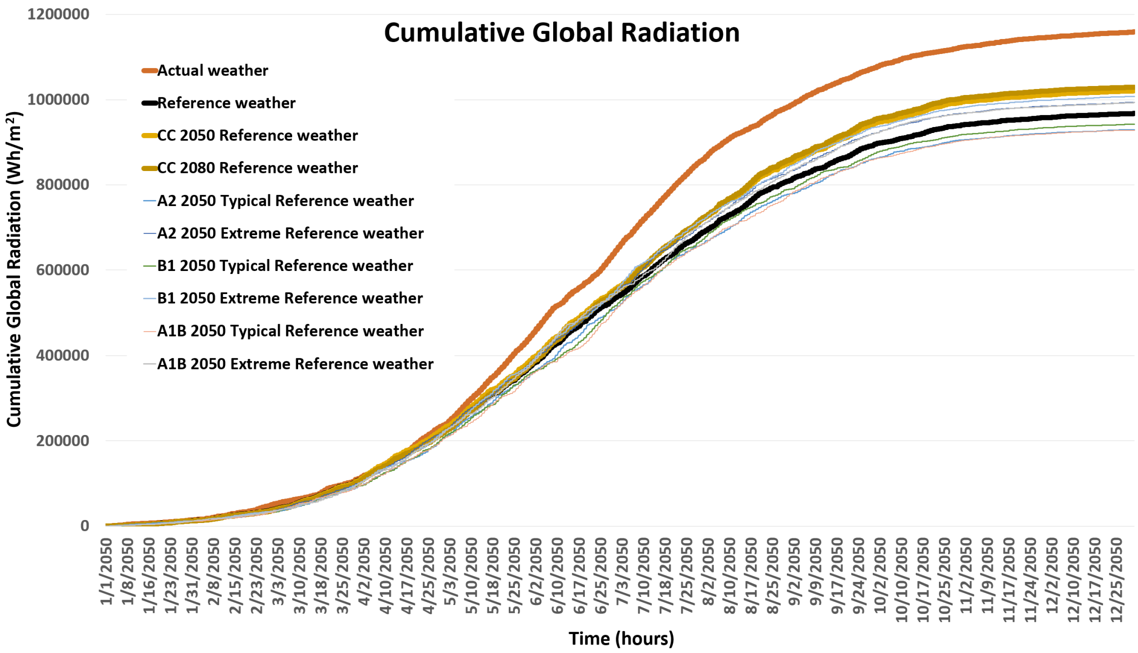


Figure 6.5. Cumulative global radiation comparison of all future weather file categories at year 2050 with the actual and 30 year reference weather file from the Meteonorm library.

Figure 6.5 shows the cumulative global radiation results for all future weather file categories at year 2050 together with the actual and 30 year reference weather files. For all these three figures the bold lines represent the actual (measured), reference (based on 30 years from Meteonorm library), the CC 2050 and the CC2080 (which was used for modeling) weather files, where as the thin lines represent all the files from Meteonorm at year 2050. It is important to observe in figure 6.5 that all Meteonorm files (thin lines) have very similar global radiation levels to the reference (bold black line) and some of them have even less than the reference. Another important observation is that the CCWeatherGen program responsible for producing the CC 2050 and CC 2080 weather files did not change the global radiation levels even though the CC 2080 was supposed to have higher levels to represent a more harsh future scenario. Finally the actual weather file has the highest levels of global radiation below that are the two files from the CCWeatherGen program and the least amount of global radiation are possessed by the Meteonorm and reference weather files. When global radiation reduces (which happens for all future weather files as they are based on the reference weather file) the indoor environment is affected positively.

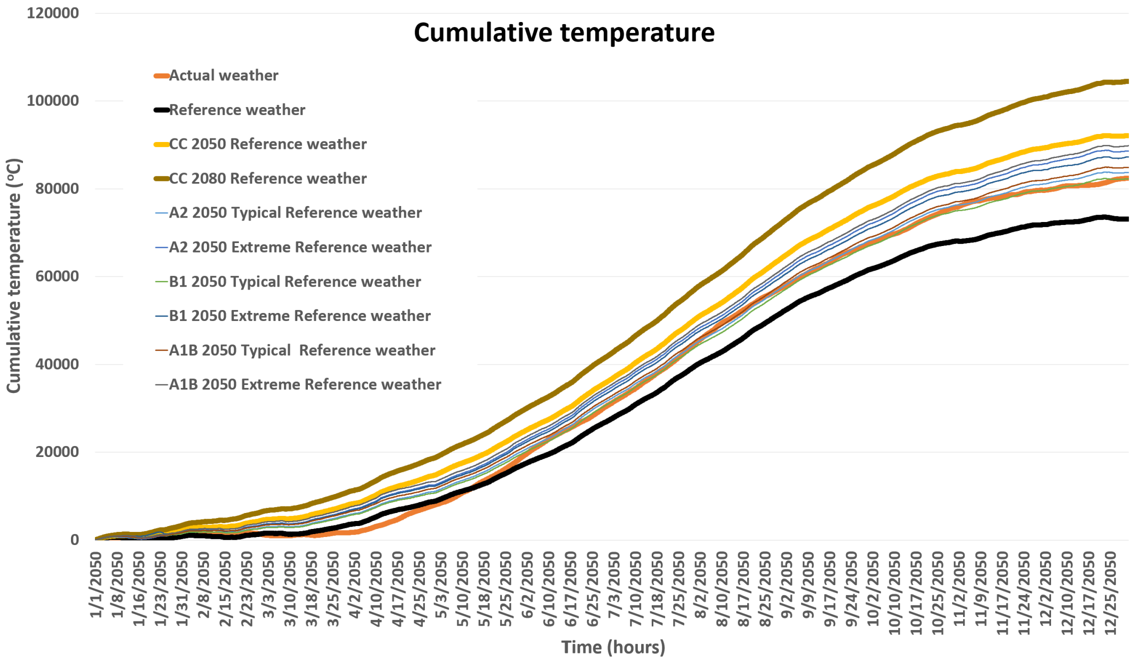


Figure 6.6. Cumulative temperature comparison of all future weather file categories at year 2050 with the actual and 30 year reference weather file from the Meteonorm library.

A similar accumulation procedure was performed for the temperature and presented in figure 6.6 for all future weather file categories at year 2050 together with the actual and 30 year reference weather files. Unlike the results for global radiation, all future weather file results for the temperature are higher than the reference weather file (bold black line). Again the CC 2080 weather file is by far the hottest and this is why it was chosen for modelling purposes whereas all future weather files at year 2050 have a similar pattern with the CC 2050 being the hottest as it was produced with the morphing method.

In this figure all future weather files have higher temperature than the actual weather whereas in figures 6.1 and 6.2 it was shown the opposite. The reason for that is because figure 6.1 represents the frequency and number of heatwaves of all weather files. The actual weather file having a higher number of heatwaves than the future weather files using the reference weather file does not necessarily mean that it will also have a higher cumulative temperature as the heatwaves are representing extreme phenomena. When it comes to figure 6.2 the box plot could not give precise information as it does not add up all temperature data but instead it is a visual representation of the majority of temperature range and the extremes of each weather file. For that reason it seemed like all future weather files generated with the Meteonorm program were mostly similar with the actual weather file where in reality those Meteonorm weather files had slightly higher temperature.

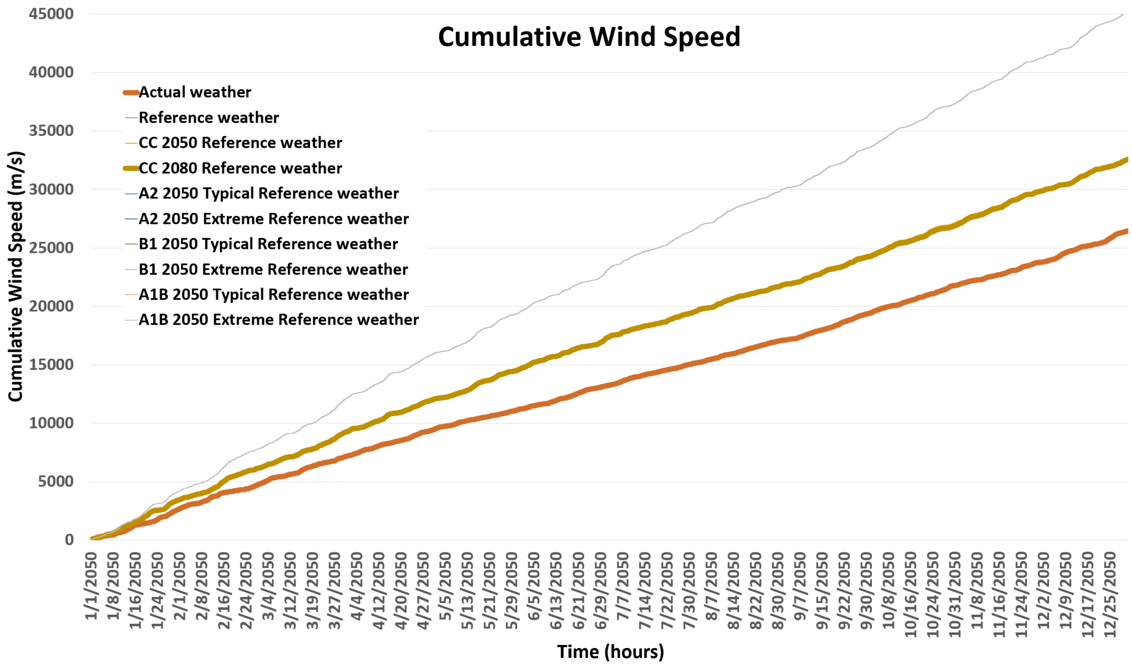


Figure 6.7. Cumulative wind speed comparison of all future weather file categories at year 2050 with the actual and 30 year reference weather file from the Meteonorm library.

The accumulation procedure for the wind speed presented in figure 6.7 for all future weather file categories at year 2050 together with the actual and 30 year reference weather files revealed some interesting results. This time there are three distinct set of results represented with three lines. The bold red line depicts the actual weather file, the bold yellow depicts the CC 2080, CC 2050 and the reference weather files and finally the thin line depicts all future weather files produced from meteonorm. From these results it is concluded that both Meteonorm an CCWeatherGen programs do not adjust the wind speed results for the future. Another important conclusion is that all Meteonorm future weather files have clearly higher wind speed which directly and positively affects natural ventilation and as a result increases passive cooling. That is why all Meteonorm weather files resulted in less over temperature hours than the actual weather file when used by the simulation program.

Overall the CC 2080 weather file is chosen to be used in the next chapter as comparison with the actual weather file to test building resilience, as it provides a similar wind speed while at the same time it has the highest temperature than any other weather file and the highest global radiation compared to the other future weather files. The CC 2080 weather file is the only one the results in higher over temperature results for the building compared to all the other weather files as well as the actual one. The main purpose is to select a weather file to test the building resilience with the worst case scenario.

Testing the Building's Resilience to Future Weather Files 7

In this chapter the building's resilience to temperature change is tested. To test the resilience the over temperature hours graph is used. If the building using the most extreme future weather file as well as utilizing all passive cooling technologies has less over temperature hours than the building using the actual weather file but no passive cooling technologies then these technologies are consider to give resilience to the building. To test this theory over temperature graphs were made for every single passive cooling technology separately and all of them combined for the best result possible. At the end the percentage improvement when using these passive cooling technologies versus not using them was calculated to have a clearer understanding of which technology was more useful.

7.1 Comparison Of Over Temperature Hours With The Actual Weather File As The Basis

In this section a comparison between the separate and combined passive cooling technologies on the building's over temperature hours is conducted to determine how each passive cooling technology is influencing the building's resilience. In the next section the actual weather file will be the basis for the building's resilience comparison against the worst case future weather file which is the CC2080. A similar comparison is held in section 7.2 between the 30 year reference weather file and the CC2080 as well the 30 year reference weather file and the A2 1100 extreme. The comparison against the actual weather file is the most important for this thesis (even though reference weather files are generally being used for building design) because the whole purpose of this thesis is make all resilience related observations on a model of the building that closely resembles the existing one.

The first figure 7.1 is a combination of all passive cooling technologies separately and combined representing the over temperature results for the Master bedroom. Every column represents the results of the actual and CC2080 weather files for every technology. That way it is seen how every passive cooling technology is affected by the weather change and which technologies offer the greater resilience for the building. It is clear that even though this future weather file has hotter temperature than the actual one all passive cooling technologies manage to provide very similar over temperature hours compared to the actual weather file. That is happening due to the two other main weather file properties which are the global radiation and the wind speed. This means that even though all future weather files have hotter temperatures than the actual weather file, it can be seen in figures 6.5 and 6.7 that these future weather files also have less global solar radiation and more wind speed than the actual weather file. These two properties are being used by the passive cooling technologies to "combat" the higher temperatures of the CC2080 and thus provide comparable over temperature hours with actual weather file which does not have that high temperatures but it has more solar radiation and less wind speed. The natural ventilation passive cooling technology stands out from the rest as it does not cope that well offering less resilience because it increases the over temperature hours a lot compared to the actual weather even though it has the least over temperature hours when using the actual weather. An explanation for this behaviour could be because this technology is based on the external environment's cooling potential and since the environment is getting warmer it loses its cooling potential.

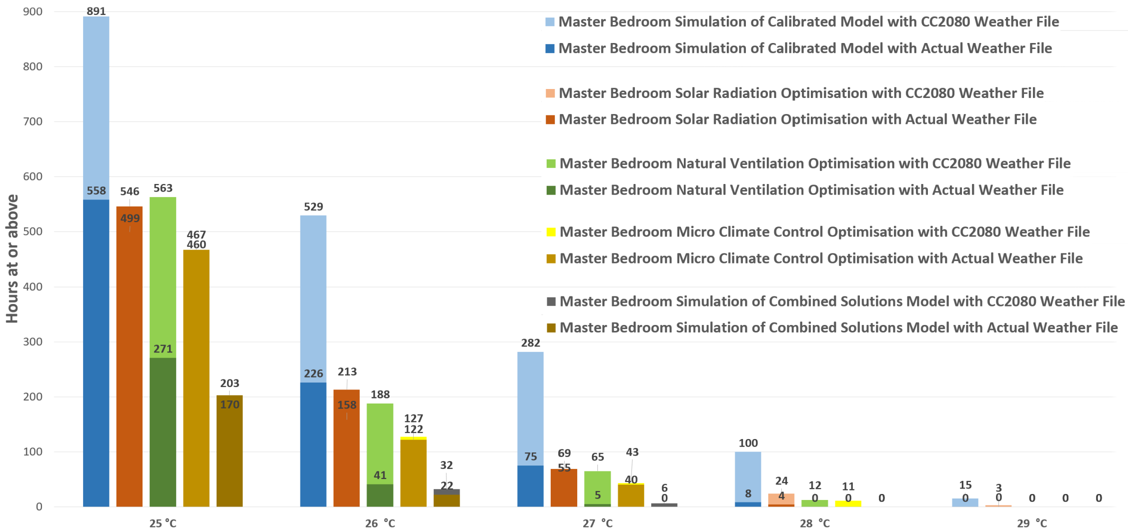


Figure 7.1. Master bedroom comparison between the initial building using the actual weather and the building with every passive cooling solution separately and combined using the worst case scenario from the CCWeatherGen program.

Figure 7.2 has the same concept of testing the different passive cooling technologies but showing the results for the Living room. The critical temperatures are in the range between 25°C and 29°C. For those critical temperatures the Living room has higher over temperature hours than the Master bedroom however the trend between the two rooms is similar with the natural ventilation offering the least resilience compared to the other passive cooling technologies. Both figures 7.1 and 7.2 show that there is an improvement overall when using each passive cooling technology separately as all columns in those figures are lower than the first column represented with blue color which is the initial building without any passive cooling technologies. In the same figures specifically for the red column representing the solar radiation control the results for the actual weather provide more over temperature hours than thus completely overlapping the CC2080 weather file results. That is happening due to the characteristics of this future weather file having less global radiation than the actual one as seen in figure 6.5. However using passive cooling technologies separately with the CC2080 weather file does not have enough improvement over the initial model of the building with the actual weather file and without any passive cooling technologies. That is why figure 7.3 was made using all passive cooling technologies combined to test the best possible resilience scenario for the building.

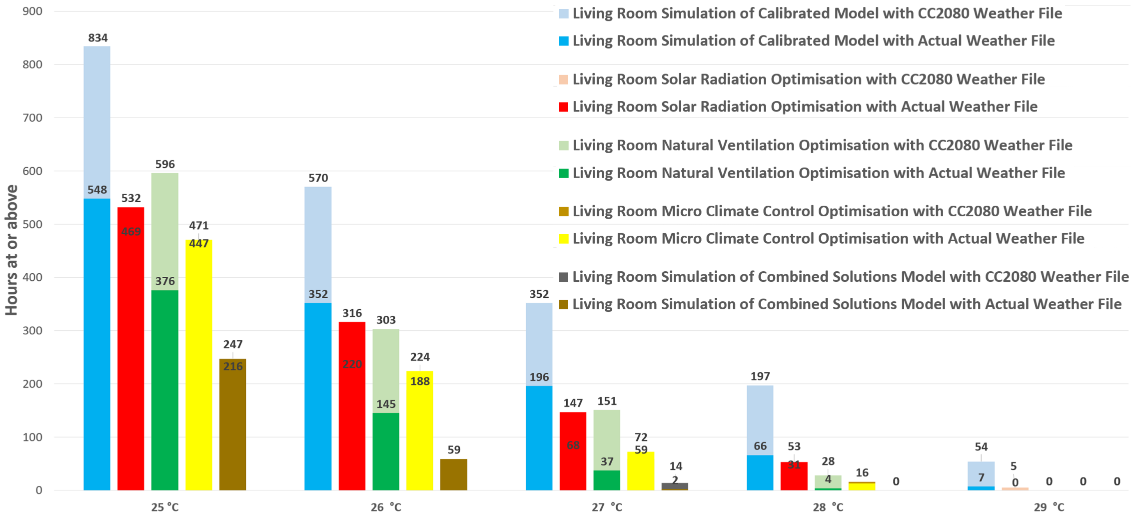


Figure 7.2. Living room comparison between the initial building using the actual weather and the building with every passive cooling solution separately and combined using the worst case scenario from the CCWeatherGen program.

After the comparison of the separate passive cooling technologies was finished all these technologies were combined in one model which had the best resilience potential possible. The two weather files were simulated again in this model with the combined passive cooling technologies as can be seen in figure 7.3. This time the final combined solution is solely compared with the initial building without any passive cooling technologies. It is clear that the final combined solution model offers considerably less over temperature hours than the original model even though the hotter CC2080 weather file was used showing that the implementation of all passive cooling technologies at the same time is offering considerably more resilience potential than just using them separately.

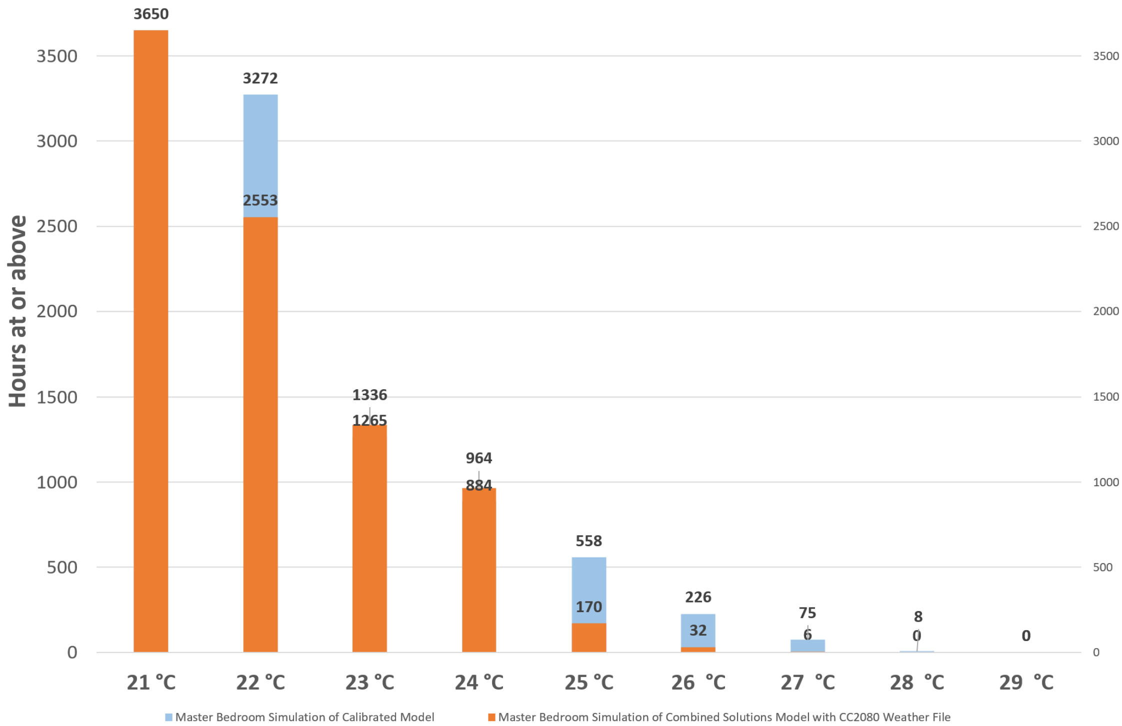


Figure 7.3. Master bedroom comparison between the initial building using the actual weather and the building with all passive cooling solutions combined using the worst case scenario from the CCWeatherGen program.

Figure 7.4 makes the same comparison as figure 7.3 but showing the results for the Living room. Again this room has overall higher temperatures than the Master bedroom but also a similarly impressive improvement in over temperature hours compared to the initial building without any passive cooling technologies.

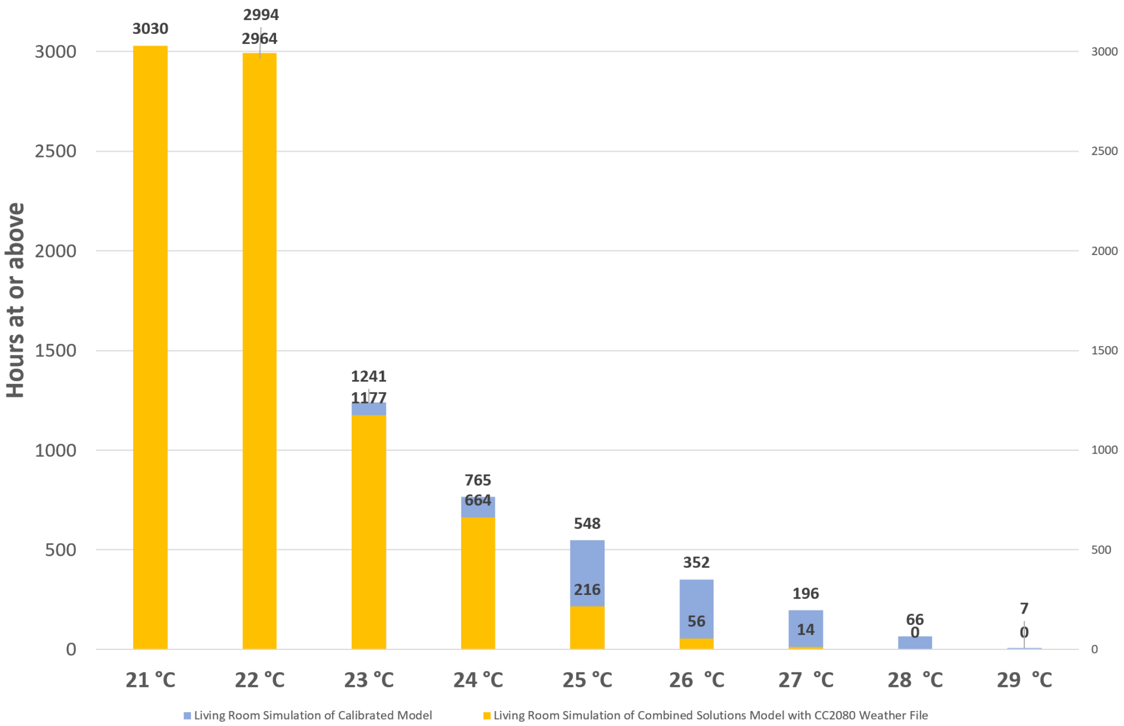


Figure 7.4. Living room comparison between the initial building using the actual weather and the building with all passive cooling solutions combined using the worst case scenario from the CCWeatherGen program.

7.1.1 Improvement Comparison

So far a visual representation of the improvement of over temperature hours was shown but to have a clearer overview of the importance of each passive cooling technology both separately and combined the following figure 7.5 was calculated. The improvement as expressed in difference of over temperature hours was calculated for each of the two weather files separately to determine if any of the passive cooling technologies provided more resilience for the hotter weather file compared to the actual weather file. Initially figure 7.5 was made for the Master bedroom and Living room separately however it was observed that the improvement percentages for the two rooms were very similar so the averages were calculated to represent the entire house.

Over Temperature Hours Difference with the CC 2080 Weather File				
	Difference Solar Radiation (hours)	Difference Natural Ventilation (hours)	Difference Micro Climate Control (hours)	Difference Combined Passive Cooling Solutions (hours)
21 °C	0	0	0	0
22 °C	-88	115	79	80
23 °C	251	-7	265	288
24 °C	335	55	333	406
25 °C	379	283	409	670
26 °C	361	304	392	506
27 °C	256	209	266	307
28 °C	121	129	135	149
29 °C	31	35	35	35

Over Temperature Hours Difference with the Actual Weather File				
	Difference Solar Radiation (hours)	Difference Natural Ventilation (hours)	Difference Micro Climate Control (hours)	Difference Combined Passive Cooling Solutions (hours)
21 °C	0	0	0	0
22 °C	5	81	71	74
23 °C	6	-1	49	108
24 °C	10	51	43	113
25 °C	14	230	84	328
26 °C	25	196	116	249
27 °C	28	115	80	135
28 °C	9	35	31	37
29 °C	7	7	7	7

Figure 7.5. Improvement as expressed in difference of over temperature hours between the CC2080 and the Actual weather file for the entire building.

The results from figure 7.5 were plotted in figure 7.6 for better understanding. On the figure 7.6 there are four dots with the following lighter blue, red, green and yellow colors representing the results of the actual weather file with the Solar Radiation, Natural Ventilation, Micro Climate Control and the Combined passive cooling technologies respectively. On the same figure there are also four darker dots of the same colors representing the results of the CC2080 weather file with the same categories of passive cooling technologies in the same order.

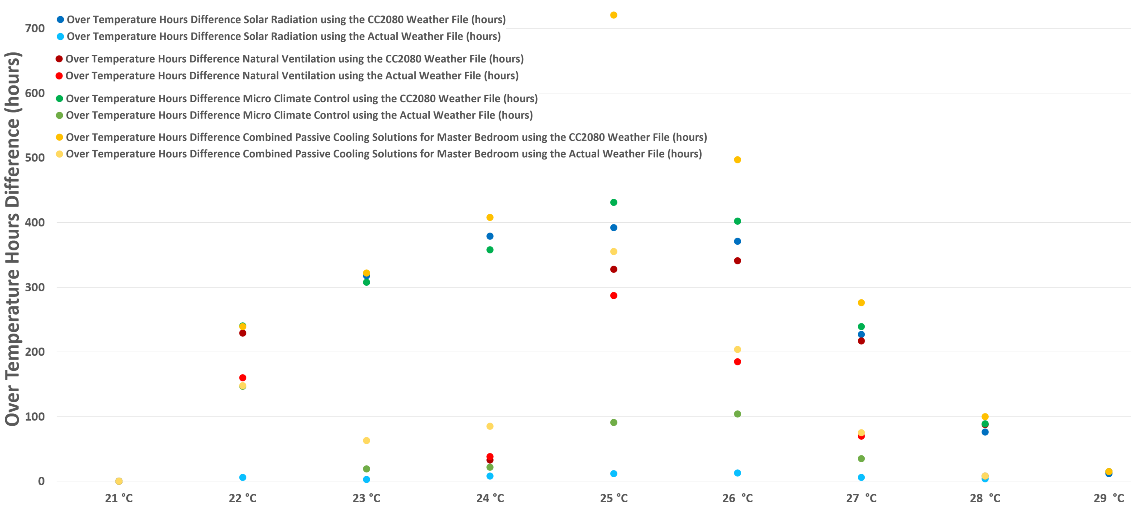


Figure 7.6. Comparison of the improvement both for every single technology and the combined solution on the building with the actual and the CC2080 weather files.

Overall it is concluded based on figure 7.6 that the best improvement when it comes to difference in over temperature hours is occurring at 25°C. Moreover an important observation is that for the darker colored dots representing the results from the CC2080 which is the worst future weather file the improvement is higher than using the actual weather.

7.2 Comparison of Over Temperature Hours with the Reference Weather File as the Basis

So far the actual weather file has been used as the initial weather file to test the building's resilience against the worst case future weather scenario, which resulted in excellent building resilience. However as it was concluded from subsubsection 6.2.2 the resilience resulted due to the extra wind speed and less global radiation of the worst case future weather file when compared to the actual one. So in this section the 30 year reference weather file from the Meteonorm library is going to be used and compared with future weather scenarios to determine if the building is still resilient, even though by doing so the initial model is no longer calibrated according to the actual real case building.

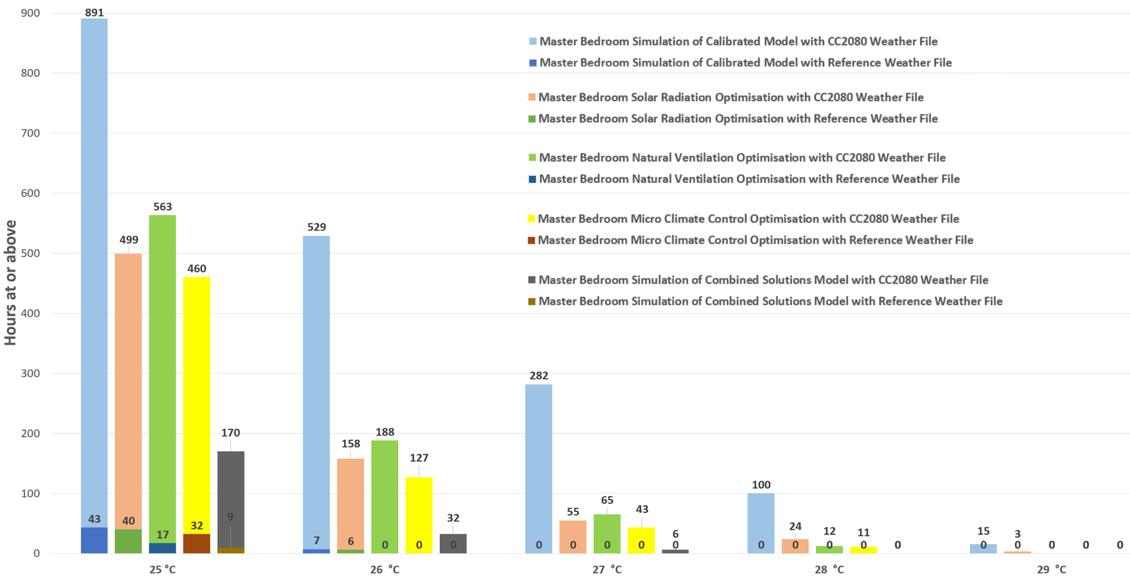


Figure 7.7. Master bedroom comparison between the initial building using the reference weather and the building with every passive cooling solution separately and combined using the worst case scenario from the CCWeatherGen program.

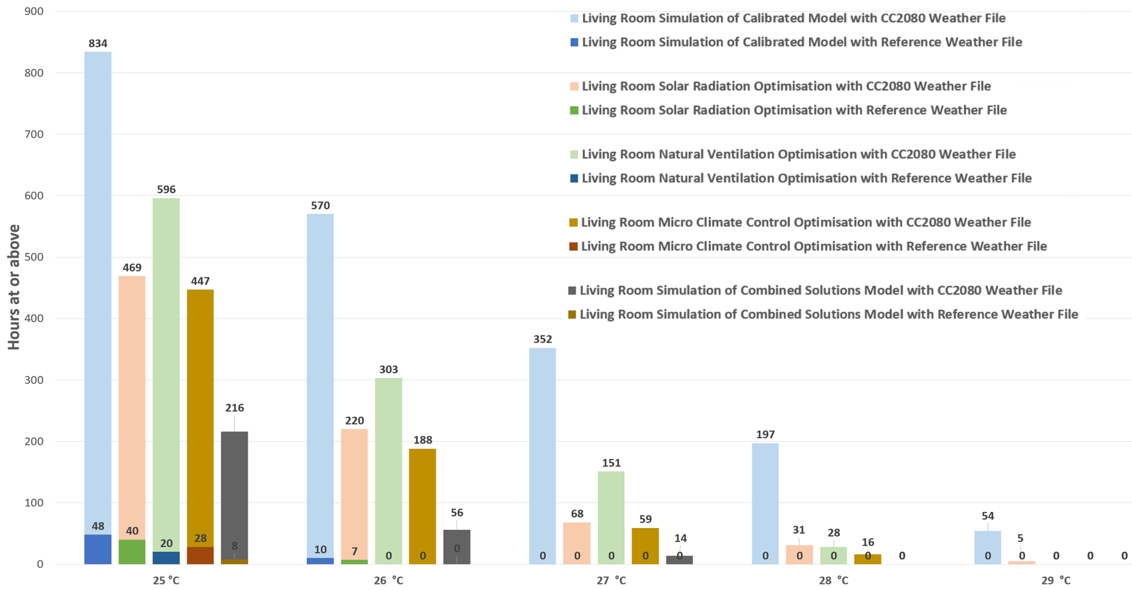


Figure 7.8. Living room comparison between the initial building using the reference weather and the building with every passive cooling solution separately and combined using the worst case scenario from the CCWeatherGen program.

In the first two figures 7.7 and 7.8 the 30 year reference weather file is compared with the CC 2080 which is the hottest future weather file. Using these two weather files the building is not resilient as the over temperature hours using the future weather file with all combined solutions are slightly more than the building with the reference weather file without any passive cooling technologies. This is happening due to the explanation of weather file characteristics in subsubsection 6.2.2 where the CC 2080 has less amount of wind speed as well as more global radiation and temperature.

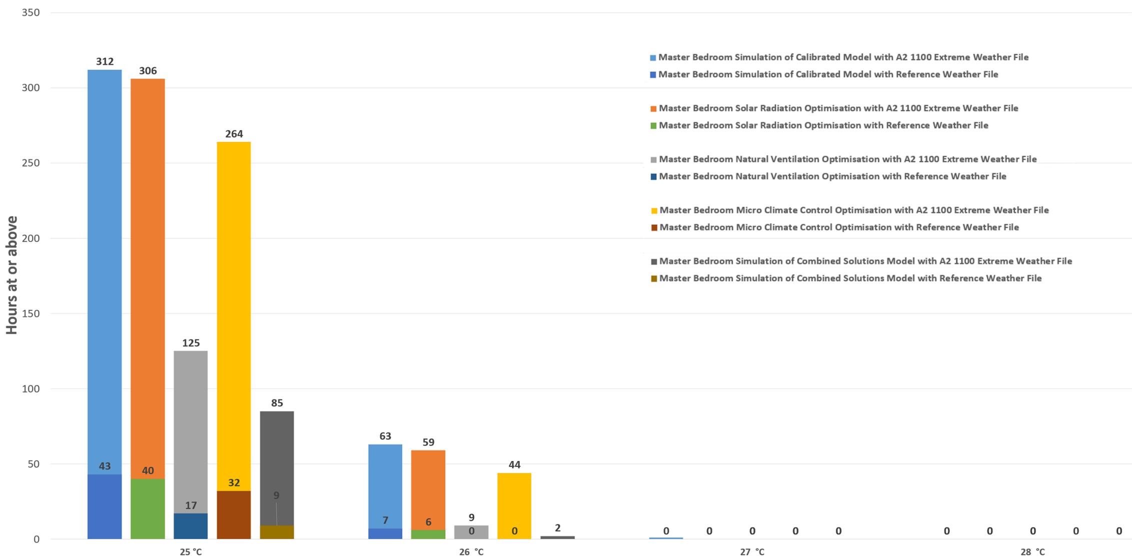


Figure 7.9. Master bedroom comparison between the initial building using the reference weather and the building with every passive cooling solution separately and combined using the worst case scenario from the Meteonorm program.

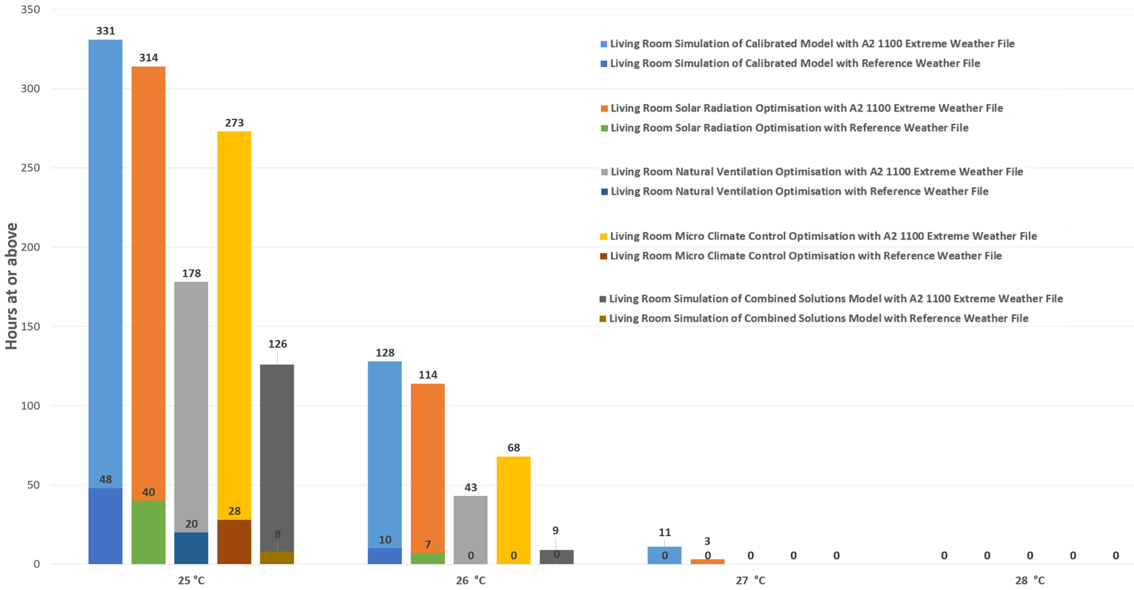


Figure 7.10. Living room comparison between the initial building using the reference weather and the building with every passive cooling solution separately and combined using the worst case scenario from the Meteonorm program.

Finally in the second two figures 7.9 and 7.10 the 30 year reference weather file is compared with the A2 2100 Extreme which is not the hottest future weather file overall but it is the hottest from the program Meteonorm. Using these two weather files, the building is slightly resilient as the over temperature hours using the future weather file with all combined solutions are slightly less than the building with the reference weather file without any passive cooling technologies. This time again based on subsubsection 6.2.2 the A2 2100 Extreme has more global radiation and temperature and it also has the same wind speed and based on that the passive cooling technologies are able to provide some resilience to the building.

8 Conclusion

In this thesis a family building in Horsens, Denmark was tried to be optimised by reducing the over temperature hours as much as possible while maintaining the original energy consumption using passive cooling technologies. This building already had implemented some passive cooling technologies like solar shading, natural ventilation and ground cooling. However the building was modeled and optimised (as far as energy consumption is concerned) for the winter period. So the main focus of this thesis was to improve the existing and add new technologies to be tested for resilience against future global warming and to improve user comfort all year round while having similar energy consumption as the original building. The chosen passive cooling technologies could be implemented at any stage of the building's construction process easily by the majority of building types and did not add much additional cost to the building's construction. That is why the solar radiation control, natural ventilation and micro climate control were chosen as passive cooling technologies to be optimised.

Initially it had to be made sure that the Design Builder which was the program used for energy and internal temperature calculations gave results close to the actual measured ones. To do that different validation indexes were used like MBE (Mean Bias Error), NMBE (Normalized Mean Bias Error), CV(RMSE) (Coefficient of Variation of the Root Mean Square Error) and GOF (Goodness-Of-Fit) which are mathematical formulas used to calculate errors based on ASHRAE Guideline 14. All these indexes gave results well below the acceptable limits. However when the internal building's temperatures were simulated and compared with the actual measured ones (for better result visualisation) it was found that the simulated results do not follow the pattern of the measured ones precisely. The explanation for that is due to the lack of precise modelling of the initial building's already existing passive cooling technologies like natural ventilation and the operation of the shading devices. This happened as the model for this building was made for another study for the winter period and specifically for energy use and energy performance and so these already existing passive cooling technologies were not affecting the results. For the final calibrated model these already existing passive cooling technologies were added in the model and the actual measured weather data for that year was used which led to very precise simulated internal temperature result compared to the actual measured ones for both the winter and summer period.

For the optimisation process of the over temperature hours the Design Builder's Genetic algorithms were used, where different input parameters for every separate passive cooling technology were given a range and distribution. All potential optimal solutions were plotted in the pareto front and based on those only one was chosen with the least possible discomfort hours while maintaining the same energy consumption as the initial building. All the optimal solutions for every passive cooling technology had a lot less over temperature hours than the requirements which state that these hours need to be less than 5% of the people's yearly occupation time resulting in less than 255 over temperature hours. These optimal passive cooling technologies also fulfil the requirements to have less or equal energy consumption than the original model which is 11853 kWh.

After finding the optimal solutions for every passive cooling technology separately, they got tested to determine their performance against future global warming scenarios. Two main processes were used to generate those future weather files, the first one is called Synthetic time series method using the program Meteonorm and the second is the Morphing time series method using the program CCWeatherGen. All possible parameter variation when it comes to the generation of future weather files got tested in the building simulation to determine the effects of these different types of weather files. It was discovered that the actual weather file gave a lot more over temperature hours than all future weather files except the one called CC2080 which is the worst case scenario using the morphing method. The reason behind that is due to the fact that all future weather files are based on the 30 year reference weather file which was considerably cooler than the actual weather file. However it was decided to use the actual weather file since the building model used that one to be calibrated according to real conditions. This also meant that only the CC2080 weather file was hot enough to create challenging weather conditions to test the building's resilience.

Finally using the CC2080 weather file the building turned out to have resilience to weather changes since the building with all passive cooling technologies combined using the CC 2080 weather file which is the worst case scenario had considerably less over temperature hours than the original building without any passive cooling technologies using the cooler actual weather file. However it was later discovered that the resilience was due to the specific weather file characteristics. The CC2080 even though it was considerably hotter it also had less global radiation and higher amounts of wind speed which got taken advantage by the natural ventilation passive cooling technology and managed to make the building interior slightly cooler than the original model. That is why to test the theory that resilience strongly depends on the weather file characteristics the reference weather file was also used as the basis for comparison against the CC2080 and A2 1100 Extreme weather files. These results proved the theory especially for the comparison between the reference and CC2080 weather files as the over temperature hours of the model with all passive cooling technologies combined were more than the original model of the house without any passive cooling technologies. In general the natural ventilation passive cooling technology stands out from the rest as it does not cope that well offering less resilience because it increases the over temperature hours a lot compared to the actual weather even though it has the least over temperature hours when using the actual weather. This is probably happening as cooling potential of natural ventilation reduces when the climate gets warmer. On the other hand the micro climate control seems to provide the best resilience and the least over temperature hours. That pattern is the same for all weather file comparisons except the one between the reference and the A2 1100 Extreme where the natural ventilation passive cooling technology has the best resilience.

Discussion 9

The focus in this thesis has been to optimise a building by reducing the over temperature hours while maintaining the initial energy consumption. After that different passive cooling technologies were implemented to test the building's resilience to global warming change. For the majority of the modelling and optimisation process as well as to simulate the energy frame and indoor environment the program Design Builder has been used. A final solution for the designed building was chosen and analysed for every passive cooling technology both separately and combined. Here, it was found that the application especially of all passive cooling technologies combined resulted in a building with great resilience since the over temperature hours during the hottest future weather file were a lot less than the original building with the current weather file. However this extremely positive result is due to the use of these two specific weather files. It was discovered in subsubsection 6.2.2 that the main reason why the passive cooling technologies could provide such a good resilience is because the future weather file even though it was considerably hotter than the actual one it had way less global radiation levels and a lot more wind speed which affects the natural ventilation potential directly. When a different initial weather file was chosen like the 30 year reference one from the Meteonorm library and compared with the same most extreme one which is the CC 2080 there are no particular signs of resilience. From all that it is clear that passive cooling technologies even though they provide less over temperature hour when compared to not using them at all they do not offer additional actual resilience against future global warming.

This thesis was based on an already existing model of a real case building in Horsens, Denmark. For that reason every aspect of building performance like the energy consumption was modeled to be as close to the real case as possible. However one potential aspect that could be improved is the initial building's energy consumption using a PID system for the thermostat controlling the radiators instead of a simpler two position control which is not as accurate. This system has the benefit of continuously monitoring and adjusting the error between the specified setpoint and the measured internal temperature. It has the proportional, P, term, which is the difference between the actual value and the setpoint, the integral, I, term, which is the integral of the error over the time to adjust the valve, which is controlling the output and the derivative, D, term, which is the rate of change of the error.

Another way to generally reduce a building's energy consumption that could be tested is implementing different occupants behaviour patterns since this is the main factor that contributes to energy loss. This could be a theoretical approach since the already existing occupant behaviour patterns were used and it is generally hard to change how occupants behave. Instead of changing the occupant's behaviour an important topic to research could be how to equip the building with systems adapting to user behaviour like installing motion detectors to limit water or electricity consumption.

In this thesis only passive cooling technologies were used to test the building's resilience, however even though this solution is economic and easy to implement by most buildings, they do not provide the best possible resilience. For that reason active cooling technologies powered by green sources like sun, wind geothermal and more is another important topic to research and determine how they affect building resilience.

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Limitations Using Future Weather Files A

Ideally, current and future weather files would be correlated so that the building response to the weather files can be directly compared. However, the morphing method and the weather generator method have their own limitations in this regard and with other issues which are discussed below.

Weather generators produce time series of weather data and while many time series can be produced that are augmented with projections of climate change, the user receives no information about the climate change anomaly applied. Additionally, while weather generators can produce weather data at a 5 km spatial resolution the climate change projections have a spatial resolution of 25 km. Furthermore, the distributions of individual variables are truncated to limit extremes. As such, it is unlikely that extreme events such as heat waves and storms will be present in short time-series. This means that while the probabilistic outputs of weather generators are a powerful tool for examining the effects of the range of possible climate change on buildings, they are not ideal when planning for resilience against extreme events.

The use of climate change anomalies to morph historic observations of weather or standard composite weather files also has its own set of limitations in addition to those already mentioned above for the climate change projections. Primary among these is the availability of the baseline weather time series both in terms of spatial resolution and the time period of observations. Climate change anomalies are typically defined according to a baseline period of 1961-1990, hence using a weather file based upon a different time period (or even a shorter period) has the potential to introduce errors into the process, assuming that climate change happens in a uniform, linear manner. The morphing methodology also has the inherent assumption that the weather patterns will not change in the future. The future weather file will contain identical weather patterns to the base weather file with magnitudes of weather variables shifted and stretched by the morphing algorithms. This means that the future weather years will be comparable to the baseline years. Using many years' worth of data for a single location and morphing them might be an interesting approach to cope with the natural variability of climate. However, due to the issues associated with observations of weather, such as missing data, insufficient variables etc. it would be simpler to use a weather generator which includes climate change projections instead [16].

B Meteonorm Program User Guide

Meteonorm works by extrapolating 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. The stochastic generation of global radiation is based on a Markov chain model for daily values and an auto-regressive model for hourly or minutely data [18].

In order to generate hourly values at any desired location, stochastic models are used. The stochastic models generate intermediate data having the same statistical properties as the measured data, i.e. average value, variance, and characteristic sequence (auto-correlation). Recent research shows that data generated in this way can be used satisfactorily in place of long-term measured data [18].

The following generation procedure is adopted. Starting with the monthly global radiation values, first the daily values, then the hourly and minute values are generated stochastically. Further characteristic values, e.g. temperature, humidity, wind, longwave radiation, are derived from these as required [18].

The validation procedure for the complete model shows that coupling the various models to provide hourly values produces satisfactory results. Thus the basic procedure for generating hourly values of meteorological data at any desired location has proved to be a valid approach. On average, the model overestimates yearly average global radiation values by 0 W/m2 by the default model. The rmse comes to 6 W/m2 (4%) [18].

The software basically works in two steps. In a first step, surrounding weather stations are searched and their long-term monthly means are interpolated to the specified location as seen in figure B.1. Data derived from satellite imagery help to improve radiation parameters in regions with a low density of available ground based data [18].

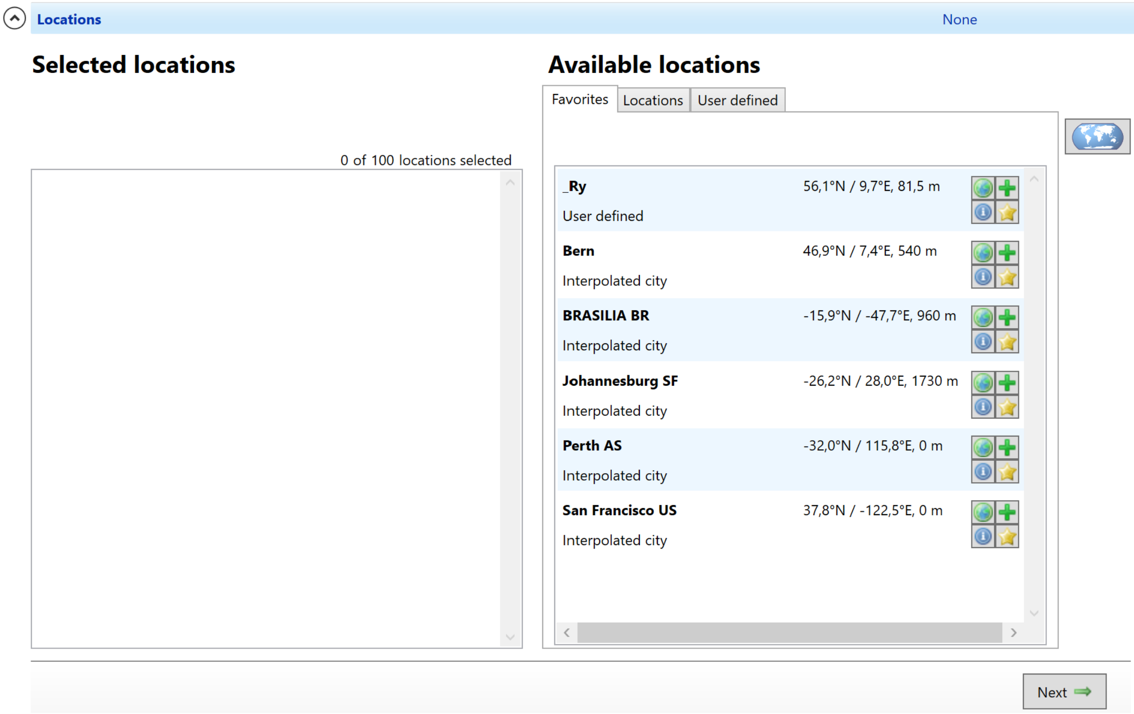

Figure B.1. Selection of the desired location.

In a second step, a stochastic weather generator runs on the interpolated monthly data to generate a typical mean year of data in hourly resolution (8760 values per parameter) for most of the output formats. Some of the output formats even require a minute-by-minute time resolution [18].

Corrections of global radiation measurements

This point as seen in figure B.2 affects only a few stations in deep valleys in the Swiss Alps where measurements are highly influenced by high horizons. The data is corrected as if there is no horizon line. This setting is only available if one of these stations is selected [18].

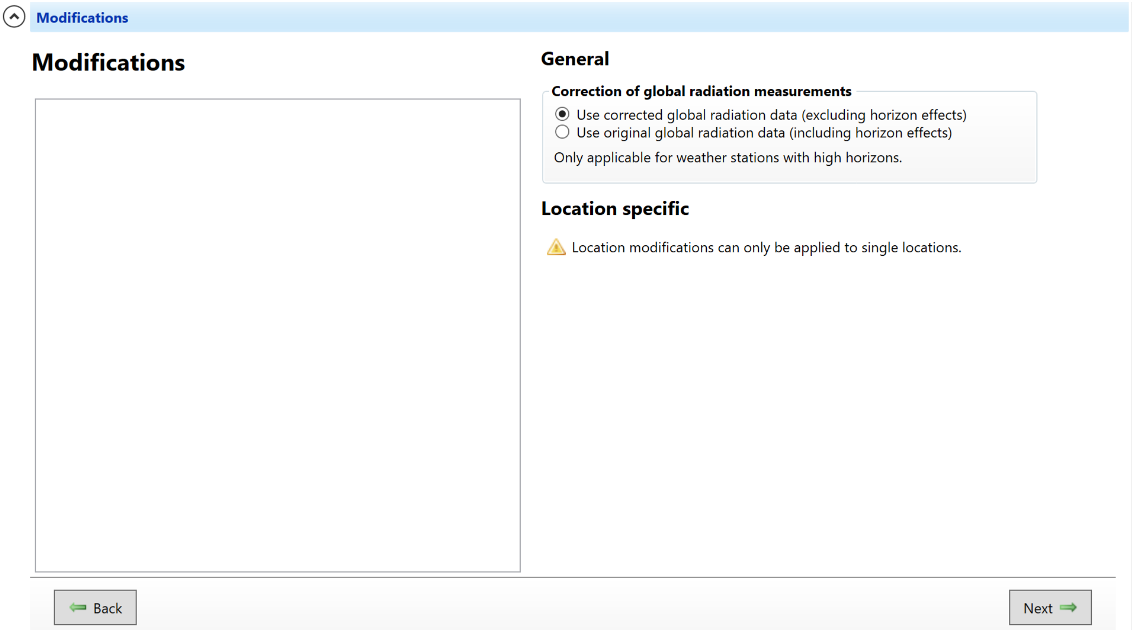

Figure B.2. Location modification settings.

Location specific

Plane orientation where the orientation and inclination of a solar panel for the calculations of the radiation components on the inclined plane can be set.

Data

As seen in figure B.3, three different scenarios B1 (low), A1B (mid) and A2 (high) are available. The anomalies of temperature, precipitation, global radiation of the periods 2011–2030, 2046–2065, 2080–2099 were used for the calculation of future time periods. The forecast changes of global radiation until 2100 with all scenarios are relatively small compared to temperature changes. They are in the range of one tenth of a percent up to some percent. The differences between the three scenarios are also relatively small. In average, the global radiation will slightly decrease. However, in the Mediterranean region the trend is positive (+ 2–4 % until 2100). The changes of the last 25 years go in the same direction but are already bigger than the forecasted anomalies for the period until 2030. However it has to be noted that the variations in the past 50 years (global dimming and brightening) have been underestimated by the climate models in the past [18].

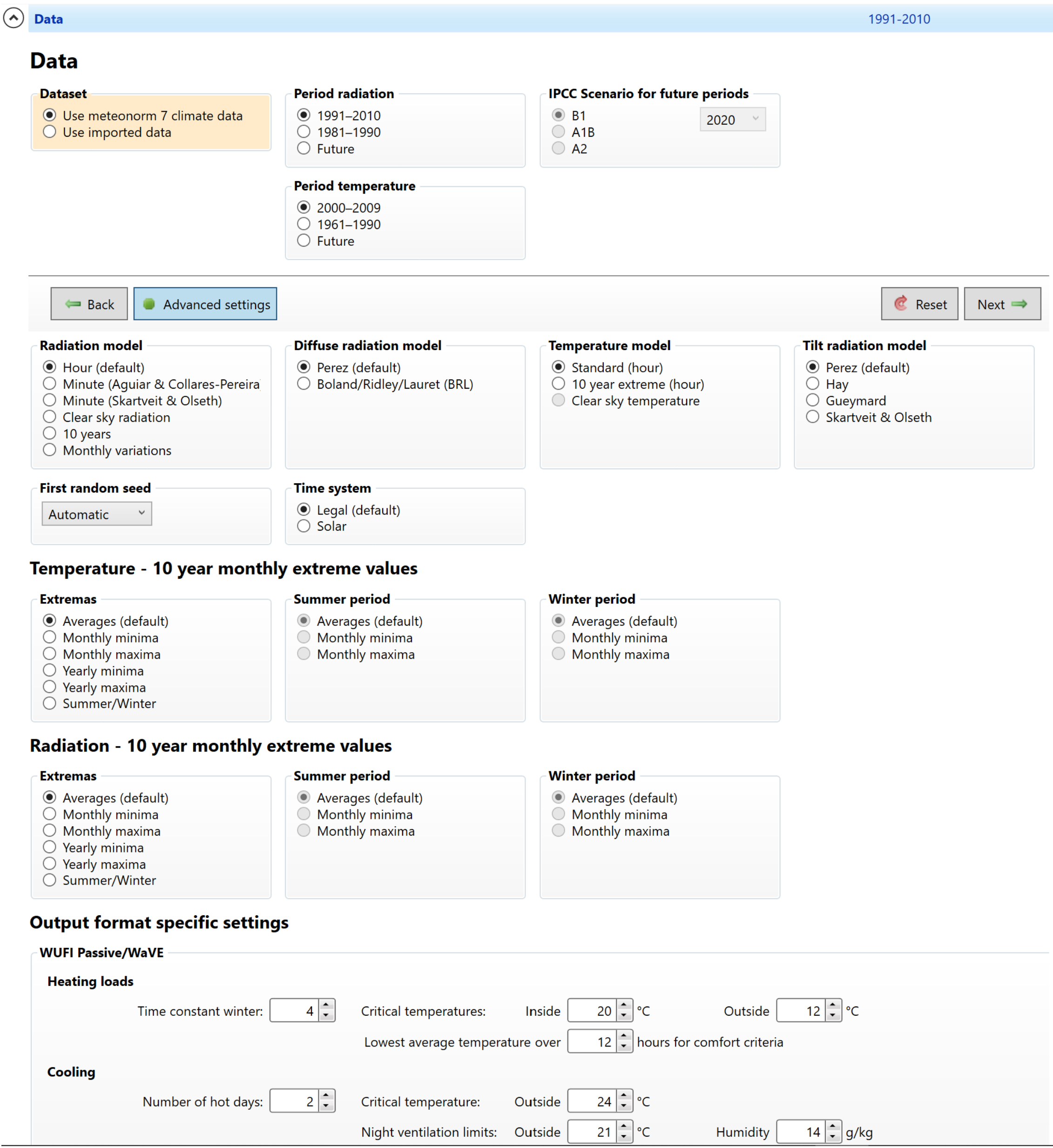

Figure B.3. All possible data to be chosen for the weather files generation process.

Advanced settings are intended for more experienced users, as they allow changing the standard setting by selecting different radiation models or other specific settings. By changing the defaults the green dot on the button "Advanced settings" changes to yellow. By pushing the Reset button all settings in the Data step are reset to their default.

Radiation model

- Default (hour). Hourly values for one typical year are generated. The chain of algorithms from (Remund, 2008) is used.
- Minute (Aguiar & Collares-Pereira). Minute values for one year are generated according the TAG model.

- Minute (Skartveith & Olseth). Minute values for one year are generated according Skartveith and Olseth (1991).
- Clear sky radiation: Calculation of maximum global radiation and corresponding diffuse radiation for clear days (cloudless sky) at hourly intervals. This affects the automatic selection of the clear day temperature model (warmest possible temperature).
- Monthly variation: This will produce a more variable year instead of a typical mean year. The monthly values are not the mean of the selected climatological period but are varied between the climatological extreme boundaries.
- 10 years: This will generate 10 single years of the 'monthly variation' type. 10 files are written to the output (10 x 8760 values).

For minute data only the special output format "Standard Minute" and "PVScout" will be available in the settings of the Output step. Only the radiation parameters are generated in minute resolution. The other parameters will be generated in hourly resolution [18].

Diffuse radiation model

- Perez (default): This is the standard model which was already used in meteonorm version 6.
- Boland/Ridley/Lauret (BRL): Added in version 7.0.

Temperature model

- Standard (hour): The default model for hourly temperature values produces hourly extremes, which correspond to mean extreme values.
- 10 year extreme (hour): This model for hourly temperature values produces hourly extremes, which correspond to 10 year hourly extreme values. This option will spread the distribution of values while the climatological mean remains the same. It is suited for simulations in which also extremely warm or cold values have to be considered (e.g. building simulations).
- Clear sky temperature: This model is selected automatically when the clear sky radiation model is chosen and cannot be selected by the user himself.

Tilt radiation model

- Perez (1986): This is the default model. It delivers the most robust and best results for generated time series.
- Hay's model (1979): This delivers slightly better results for vertical surfaces than the Perez model.
- Skartveit and Olseth model (1986)
- Gueymard's model (1987)

First random seed

10 different first random numbers of the generation algorithm of hourly radiation can be chosen. By changing this number, different time series of all meteorological parameters are

generated due to a different initialization of the stochastic process. The monthly means remain the same.

Time system

Definition of the time system in which the data is saved.

- Legal: The data is saved in local winter time.
- Solar: The data is saved in true solar time which means that the highest sun elevation angle is always at noon.

10 year monthly extreme values for temperature and radiation

For the analysis of radiation and temperature extremes at the selected location there is the possibility to simulate rare climate events. The option allows displaying the variations at a certain location.

- Averages (default): Per default an average year is generated.
- Monthly minima/maxima will take the lowest/highest monthly values for a decade. This is not equal to a P90/P10 extreme year. These are even a much rarer events.
- Yearly minima/maxima will produce a yearly value with a statistical probability of happening once in a decade (minima = P10, maxima = P90). This allows evaluating a P10 or P90 year. P10 means that there is 10% chance to have such a year or such a year occurs once in 10 years. P90 will occur 9 times in a decade.
- Summer/Winter allows selecting summer and winter periods specifically. With this function you can produce e.g. a cold winter together with a hot summer which is a worst case scenario for heating and cooling simulations.

Extremes can be simulated for temperature and global radiation only. For radiation the 10 year extreme monthly values of the 6 nearest measurement stations are interpolated to obtain the extreme conditions for each location. For temperature the extreme values are calculated using the standard deviation of the interpolated 6 nearest sites with such measurements. For the maximum values the standard deviations, multiplied by the factor 1.28, are added to the mean, for the minimum values the standard deviations are subtracted. The annual mean resulting this way does not correspond to any realistic value, because 12 ten year extreme months are not probable to follow each other [18].

Output format specific settings

For the output format PHPP/WaVE the parameters for calculating the heating and cooling degree days can be modified.

Heating loads:

- Time constant winter: equals the number of days in which a building cools down or is heated up.
- Critical temperature Inside: Aspired room temperature inside the building.
- Critical temperature Outside: Above this outside daily mean temperature heating is not needed any more.

- Lowest average hours over: Number of hours to calculate minimum temperature to satisfy the comfort criteria (e.g. 12 = 12-hours minimum is calculated)

Cooling loads:

- Number of hot days: Equals the number of days in which a building heats up (in summer).
- Critical temperature outside: Above this outside daily mean temperature cooling is needed.
- Night ventilation limits outside: Limitations of temperature and humidity to use night time cooling based on ventilation.

Output format

As seen in figure B.4 these are the setting used to create an output file with the EnerfyPlus (.epw) format to be used in the Design Builder software.

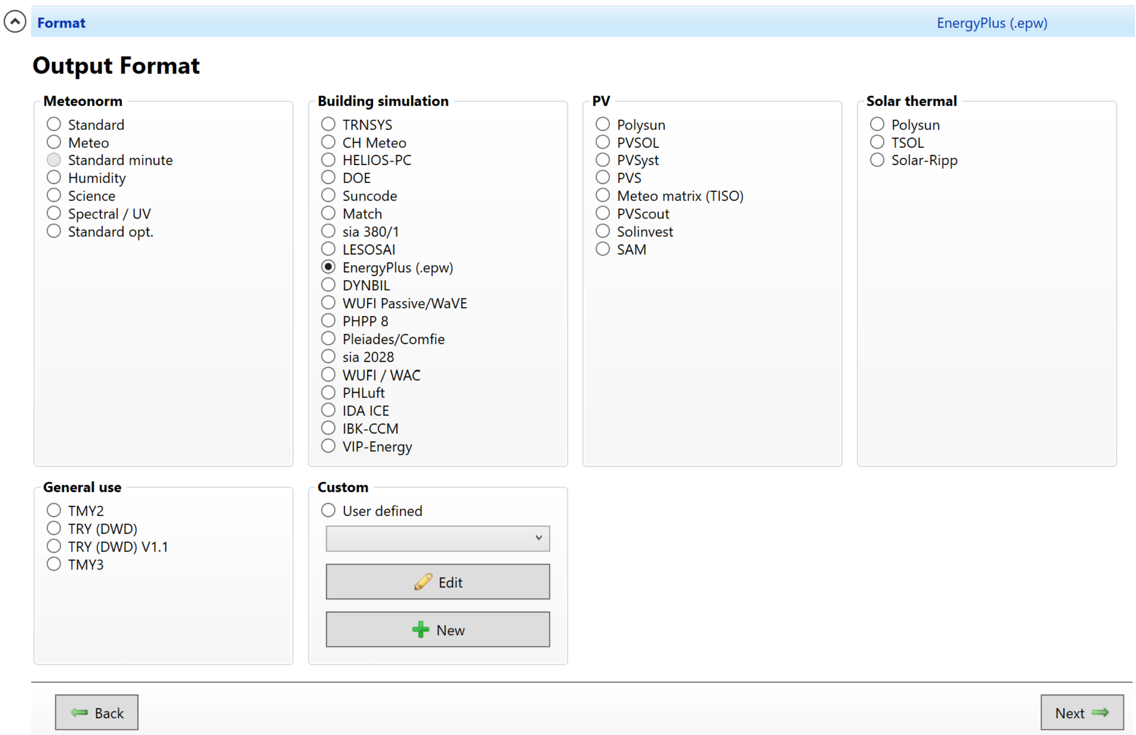

Figure B.4. Output format settings.

Output

As seen in figure B.5 this is the last step to visualise the results before finally saving them.

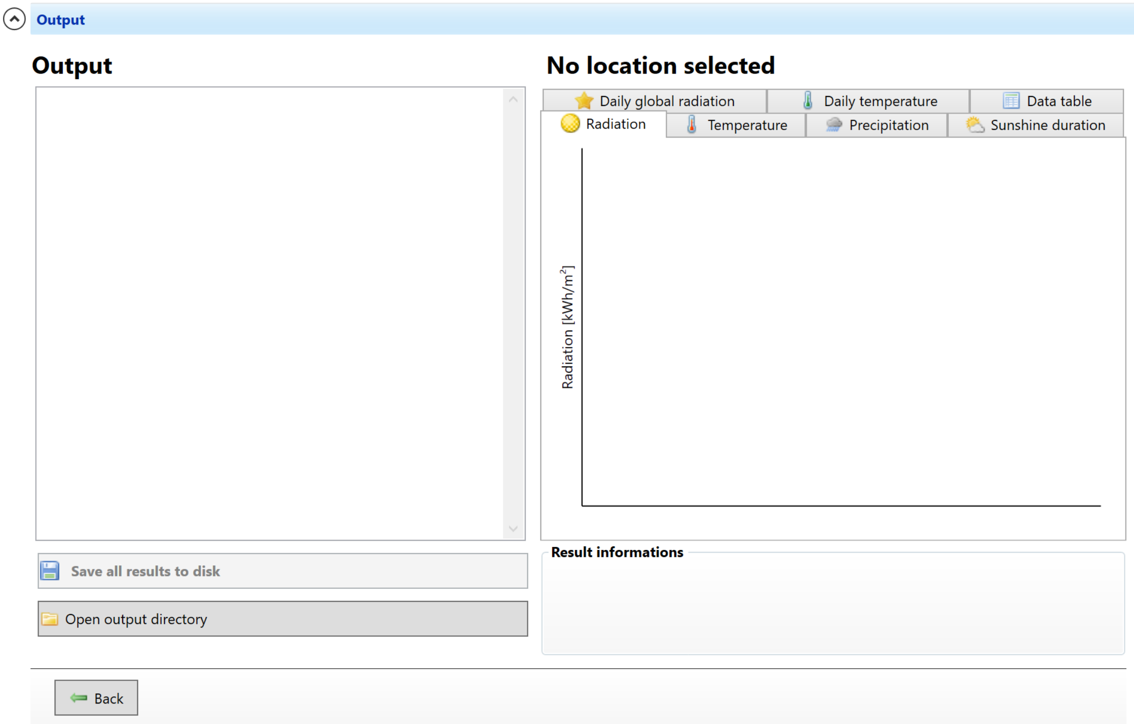

Figure B.5. Visualisation and output of generated weather file.

C CCWorldWeatherGen Program User Guide

‘Morphing’ theory is a basic concept revolving around obtaining climate anomaly projections to calculate new weather data files for building energy simulations. In 2005, Belcher, Hacker and Powell published a methodology to ‘morph’ weather data to future time frames by modifying a historical 8760 (hourly) data set based on future projections. The approach has been frequently used because it preserves real weather sequences and is specific to an observed location. The algorithms use three simple operations to modify present-day weather data; (1) a shift is applied when an absolute change to a variable is required, (2) a stretch or scaling factor when the change is projected in a percentage, and (3) a combination of both shifting and scaling may be used to adjust present-day data to reflect future projections. Creating weather data files under the ‘morphing’ methodology maintains weather sequences from the recorded data, but monthly projections from GCMs do not capture the details of diurnal patterns or allow for potential extreme anomalies. [17]

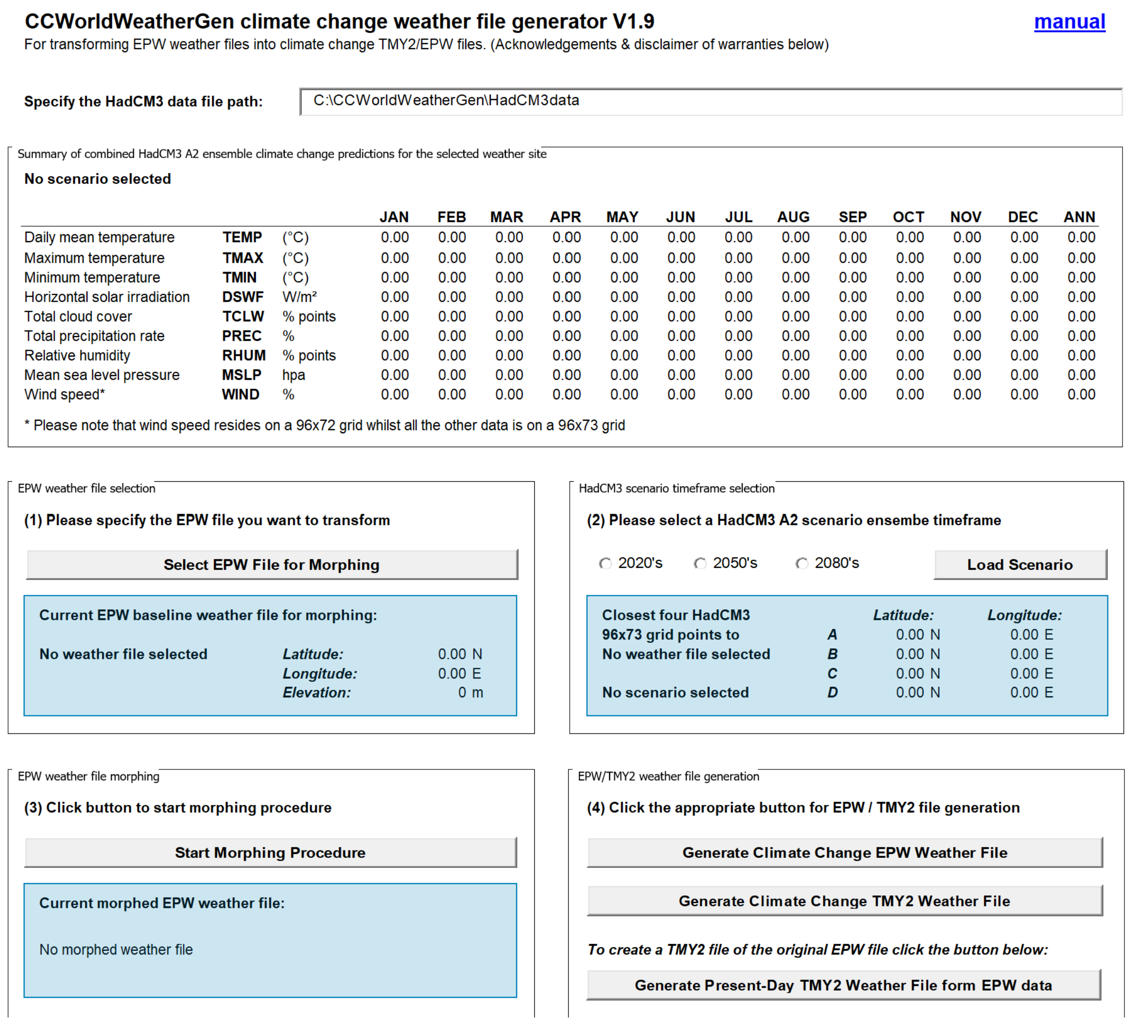

Figure C.1. All possible settings for weather file generation using the morphing method with the CCWeatherGen program.

As seen in figure C.1 to generate weather files with this program first the original weather file needs to be selected in step (1) and then there are only three options in step (2) to generate future weather files. The 2020's option generates the least extreme future weather file while the 2080's option generates the most extreme one and the 2050's lies somewhere in between the two extremes. In step (3) the morphing procedure starts and in step (4) there are some options for the output file type generation.