Numerical simulations of thermal comfort in an atrium

The impact of thermal mass and atrium dimensions

Master’s thesis in the Master’s programme Structural engineering and Building Technology

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MASTER'S THESIS ACEX30

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Cover:
The reference building used in this report, located in Umeå Sweden. Photo: Fredrik Larsson 2010-06-01

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ABSTRACT

Energy is used in residential buildings to provide thermal comfort and lightning for occupants. By including a glazed space within a residential building, the building has an ability to capture solar heat, which reduces the energy demand for heating the building during certain parts of the year. In this way, glazed spaces can sometimes be used to save energy in residential buildings and improve the energy performance and to provide a space for social interaction.

This study investigates how thermal comfort in atriums is affected by several design parameters and how these should be changed in order to improve thermal comfort without using mechanical heating, cooling or ventilation. A reference building, consisting of two residential buildings with a glazed space in between, is used to perform a parametric study of the impact of thermal mass of building material, glazing material, atrium type, atrium dimension, building orientation, solar shading and natural ventilation. The parametric study is performed by numerical simulations in the software IDA ICE. The results are mainly based on operative temperatures, which are evaluated according to the standard SS-EN 15251.

The study shows that the glazed space in the reference building has low operative temperatures during the winter and high operative temperatures during the summer. The most upper floor level is the most critical floor level since it has the coldest operative temperature during the winter and the warmest operative temperature during the summer. A higher thermal mass inside the glazed space is beneficial when the outdoor temperature and solar radiation is high during the summer, and when the outdoor temperature and solar radiation is low during the winter. However, a higher thermal mass is not beneficial when the outdoor temperature and solar radiation is low during the summer and when the outdoor temperature and solar radiation is high during the winter. In terms of dimensions, an increased atrium length is not beneficial when the solar radiation is high during the summer, due to the increased window area on the roof. However, it was shown that the atrium dimension width (i.e. distance between the residential buildings) does not have a major impact of the operative temperature in the atrium.

Key words: thermal comfort, atrium, glazed space, solar energy, operative temperature, passive heating, passive cooling

Numeriska simuleringar av termisk komfort i ett atrium
Effekten av termisk massa och atriets dimensioner

Examensarbete inom masterprogrammet Structural Engineering and Building Technology

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SAMMANFATTNING

Energi används i bostadshus för att ge termisk komfort och belysning för boende. Genom att inkludera ett glasat utrymme i ett bostadshus har byggnaden möjlighet att fånga solvärme, vilket minskar energibehovet för uppvärmning av byggnaden under vissa delar av året. På detta sätt kan glasade utrymmen ibland användas för att spara energi i bostadshus och förbättra energiprestanda och ge utrymme för social interaktion.

Denna studie undersöker hur termisk komfort i atrium påverkas av flera designparametrar och hur dessa bör ändras för att förbättra termisk komfort utan att använda mekanisk uppvärmning, kylning eller ventilation. En referensbyggnad, bestående av två bostadshus med ett glasat utrymme emellan, används för att utföra en parameterstudie av inverkan av byggnadsmaterials termiska massa, glasmaterial, atriumtyp, dimension av atrium, byggorientering, solskuggning och naturlig ventilation. Parameterstudien utförs genom numeriska simuleringar i programvaran IDA ICE. Resultaten är huvudsakligen baserade på operativa temperaturer, som utvärderas i enlighet med standarden SS-EN 15251.

Studien visar att det glasade utrymmet i referensbyggnaden har låga operativa temperaturer under vintern och höga operativa temperaturer under sommaren. Den övre våningen är den mest kritiska våningen eftersom den har den kallaste operativa temperaturen under vintern och den varmaste operativa temperaturen under sommaren. En högre termisk massa i det glasade utrymmet är fördelaktigt när utomhustemperaturen och solstrålningen är hög under sommaren och när utomhustemperaturen och solinstrålningen är låg under vintern. En högre termisk massa är emellertid inte fördelaktig när utomhustemperaturen och solinstrålningen är låg under sommaren och när utomhustemperaturen och solstrålningen är hög under vintern. När det gäller dimensioner är en ökad längd av atriet inte fördelaktig när solstrålningen är hög under sommaren på grund av en ökad fönsterarea på taket. Det visade sig emellertid att atriets bredd (dvs. avståndet mellan bostadshusen) inte har någon större påverkan på den operativa temperaturen i atriet.

Nyckelord: termisk komfort, atrium, glasade utrymmen, solenergi, operative temperatur, passiv uppvärmning, passiv kylning

Contents

Preface

This master's thesis, performed as a part of the Master of Science programme Structural Engineering and Building Technology, has been conducted at the division of Building Technology from January to June 2020.

This project has been carried out after an initiative from Paula Wahlgren, who also has been supervising the work together with Fredrik Domhagen, at the Department of Architecture and Civil Engineering, Chalmers University of Technology.

The work contributes to the Spaces project, which is a project on glazed geometries for improved indoor climate and social interaction. The project is a collaboration between Chalmers University of Technology and Sweco Architects with participants Paula Wahlgren, Kajsa Crona, Ruxandra Bardas-Dunare, Fredrik Domhagen, Toivo Säwén and Alesia Wessfeldt.

All tests have been carried out in the software IDA ICE. I would like to express my appreciation to the company EQUA Simulation AB who have provided me with support for the use of the software IDA Indoor Climate and Energy 4.0.

Göteborg June 2020

Johanna Hansson

Notations

A	Area [m^2]
c	Specific heat capacity [J/(kg·K)]
c_{eq}	Equivalent specific heat capacity [J/(kg·K)]
D	Diffusion factor [-]
d	Thickness [m]
$g - value$	Solar heat gain coefficient [-]
H	Height [m]
L	Length [m]
R_{se}	External thermal surface resistance [(m^2·K)/W]
R_{si}	Internal thermal surface resistance [(m^2·K)/W]
T_{in}	Indoor air temperature [°C]
T_{out}	Outdoor dry-bulb air temperature [°C]
U	Thermal transmittance [W/(m^2·K)]
V	Volume [m^3]
ε	Emissivity [-]
τ_{sol}	Solar transmittance [-]
τ_{vis}	Visible transmittance [-]
ρ	Density [kg/m^3]
ρ_a	Density of air [kg/m^3]
ρ_{eq}	Equivalent density [kg/m^3]
λ	Thermal conductivity [W/(m·K)]
λ_{eq}	Equivalent thermal conductivity [W/(m·K)]

1 Introduction

The building sector accounts for 40 % of the energy demand in EU (Ardente F, Beccali M, Cellura M, Mistretta M., 2006) and 40-50 % of the total greenhouse gas emissions (Prasad D, Hill M., 2004). The energy efficiency communication of EU has determined a goal to decrease energy consumption in building by 30% in 2030, and to reduce greenhouse gas emissions by 40% compared to 1990 (European Commission, 2014). Sweden has also set a goal to lower the consumed energy in buildings by 20% in 2020 and 50% in 2050 compared to 1995 (Boverket, 2009). Meanwhile, a faster urbanization is taking place in many cities and a lot of new buildings are needed. Therefore, it is important to design new buildings in a more sustainable way.

Energy in residential buildings is used to provide comfortable thermal and lighting environment for occupants (Pitts, Adrian, 2013). One way to design a more sustainable building could be by including a glazed space within residential buildings. Glazed spaces in buildings are used for transportation, such as entrance areas or stairways, as living spaces, such as glazed balconies, or as meeting area, such as atriums. One of the advantages of glazed spaces is the ability to capture solar heat, which reduces the energy demand for heating the building during certain parts of the year. In this way, glazed spaces can save energy in residential buildings.

During the winter when the there is a heat demand, solar radiation can contribute to reducing this heat demand. However, in other times during the year the solar radiation can become so great that the indoor temperature rises above the desired values and can result in a need of cooling. Glazed space can lead to temperatures above and below the desired value during some parts of the year. In order to be able to design a sustainable building, it is important to find solutions to minimize these deviant temperatures without compromising the reduced energy demand for heating and cooling. Technical solutions or measures to reduce energy requirements must not impair the function, indoor environment or technical quality of the building.

Glazed spaces in buildings can be used to improve the environmental sustainability. However, the result is affected by several aspects, such as climate, building and glazing properties and ventilation strategy. Acceptable temperatures in the building can easily be maintained by mechanically heating and cooling. However, in order to maintain efficient energy use, the use of mechanical heating, cooling or ventilation should be minimized. Instead, the building should be adapted to create thermal comfort throughout the year.

A sustainable building should provide optimal levels of thermal comfort while using as low amount of energy as possible. To achieve this high performance, many variables need to be considered, e.g. thermal mass in glazed space, thermal insulation, and solar shading when designing buildings. In order to design a sustainable building, it is important to find solutions to avoid these deviant temperatures without compromising the reduced energy demand for heating and cooling.

1.1 Aim

The main purpose of this study is to investigate how building design parameters should be designed to improve the thermal comfort in a glazed space between two buildings, i.e. in atriums. The main purpose can be divided into several sub-purposes, which are summarized by the following questions:

a) What is the impact of thermal mass?
b) What is the impact of glazing material?
c) What is the impact of atrium type, i.e. how the glazed parts are distributed?
d) What is the impact of the atrium dimension?
e) What is the impact of building orientation?
f) What is the impact of solar shading?
g) What is the impact of natural ventilation?

1.2 Limitations and assumptions

This study contains some limitations and assumptions. These are presented below.

- This study does not consider any economic or social aspects.
- This study considers glazed spaces in residential buildings, other types of buildings is not considered.
- This study does not consider any heat gains or losses through thermal bridges or air leakages.
- The study does not consider any mechanical heating, cooling or ventilation.
- The thermal comfort is evaluated as indoor environment although the atrium is between indoor and outdoor, since there is no other evaluation tool to use.

1.3 Methodology

A literature study is done to investigate how a building should be designed to achieve thermal comfort by passive heating and cooling. Further on, a numerical study of a reference building is made by simulations using the software IDA ICE. The reference building is an existing building in Umeå consisting an atrium. The reference building is evaluated to determine problems and opportunities with glazed spaces. Thereafter, a parametric study is made to determine how building parameters affect the thermal comfort in glazed spaces. Quantitative results of thermal comfort are evaluated. IDA ICE (EQUA Simulation AB, 2016) is used to calculate the thermal indoor climate for buildings by using a dynamic multi-floor simulation. IDA ICE uses a geometrically model of the reference building in 3-dimensions, which is divided into different floor levels. The building components walls, roof, doors and slab are described having both heat capacity and thermal conductivity. Windows can be placed in the exterior walls and roof and are described having a U-value, solar heat gain coefficient, solar transmittance, internal and external emissivity and a frame percentage. To simulate the building's indoor climate, a climate file is chosen in the software. The climate file consists of hourly data of temperature, relative humidity, wind direction, wind speed, direct solar radiation and diffuse radiation.

2 The Spaces project

The spaces project is a project on glazed geometries for improved indoor climate and social interaction. The project is a collaboration between Chalmers University of Technology and Sweco Architects. The project is an ongoing investigation of glazed geometries in residential buildings as a solution to enhancing social interaction between occupants and decreasing the use of resources. The hypothesis is that a more adapted volume of glazed geometries can increase well-being and social interaction in residential building without increasing the energy use.

Initially in the project, examples of glazed geometries in existing buildings were identified. The project investigated eight different glazed spaces in residential buildings, which were either atriums, glazed balconies or glazed roof tops. The buildings with an atrium are Bovieran, Gårdsåkra, Höstvetet, Musteriet and Sjöjungfrun. The geometry and location of each building is presented in Table 2.1 below.

So far, only the initial stage of the project has been finished and will be used as support in this study. The aim of the initial stage of the Spaces project was to determine parameters and relations that are of importance to the success or failure of a glazed space in terms of indoor climate and social interaction.

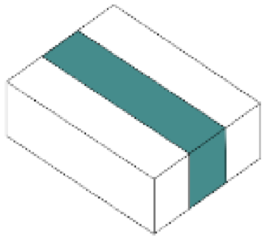
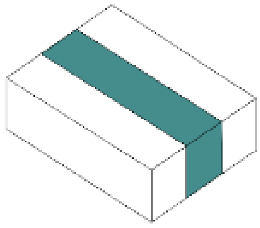
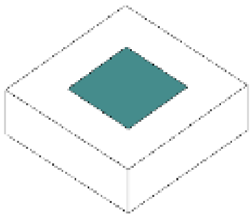
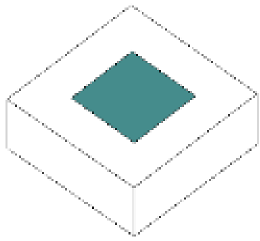
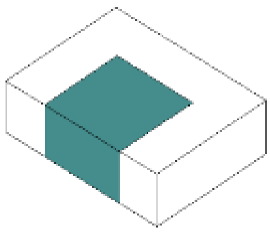
The initial stage of the project is based on study visits, interviews and surveys. The interviews and surveys focused on thermal comfort, daylight, air quality, geometry, social and human aspects and urban farming. The material from the interviews and surveys was processed in a workshop, where trends and results were extracted.

A common trend that could be extracted after the initial stage of the project was that most of the occupants were satisfied with the thermal comfort in the glazed spaces during spring and autumn. However, there were some complaints about the thermal comfort in summer and winter. In several cases, there was a desire to raise the indoor temperature during the winter to create a better thermal comfort. However, in a few cases the temperature during the winter were considered to be good. Several of the glazed spaces became warm in the summertime, especially on the upper floors.

Bovieran, Gårdsåkra and Höstvetet, which are the three largest spaces, had good thermal comfort during the summer. Bovieran has an additional glass wall facing north, automatically openable hatches in the roof, solar control coating on windows and large amounts of plants, soil and moisture. Gårdsåkra has openable roof windows and movable solar shading that are automatically controlled and large thermal mass in the flooring material of the atrium which is mainly concrete.

Sjöjungfrun is chosen to be used as a reference building in this study in order to evaluate the thermal comfort in a glazed space.

Table 2.1 Evaluated buildings in the Spaces project with an atrium.

Building	Location	Glazed space geometry
Sjöjungfrun	Umeå	
Gårdsåkra	Eslöv	
Höstvetet	Stockholm	
Musteriet	Stockholm	
Bovieran	Hönö	

3 Thermal comfort

The main purpose of a building is that people should be able to stay in it and thus also provide thermal comfort for the occupants. Thermal comfort is a measure of how people experience the thermal climate in a room, which is influenced by air temperature, air velocity, mean radiant temperature and air humidity as well as physical activity and clothing according to Swedish standards institute (2006). These parameters have specific characteristics and impact on thermal comfort. Although each of the parameters can be separately measured, the human body responds to them holistically.

The indoor air temperature is defined as the room temperature. It can be controlled by bringing outside air into a space or by increasing or decreasing the amount of solar radiation within the building by adjusting solar shading devices. Although indoor air temperature can be measured precisely and objectively, the comfort perception of the tenants will differ depending on the outdoor air temperature, the amount of solar radiation and the activity level of each occupant.

The air velocity is defined as the velocity of air movement at one point within the space. Air movements affect the occupants' thermal comfort in two ways, it conducts heat from the skin surface of a tenant to the cooler room air and it helps to evaporate sweat from the skin surface of a tenant to the room air. A high air velocity can be perceived as a disruptive draft for the occupants and it is therefore a desire to keep it as low as possible.

The mean radiant temperature is a measure of the radiated energy by objects or surfaces. It is perceived as heat on the occupants' skin and acts independently of the air temperature. Therefore, a tenant may feel thermal discomfort from the radiant heat even though the air temperature in the room is within comfortable limits. One of the greatest heat sources affecting the mean radiant temperature is solar radiation.

Air humidity is the measure of the amount of water vapor in the air. It can be given as a percentage of the actual vapor in the air compared to the maximum amount of vapor possible in fully saturated air for a certain temperature. The human body uses evaporation of the skin as a cooling mechanism to regulate the body temperature. Therefore, occupants usually find overly humid air to be uncomfortable. However, to dry indoor air is also found to be uncomfortable, so a balance must be achieved.

Metabolic rate is a measure of the energy conversion in the body at a specific activity level. Metabolic rates vary depending on the occupant's physical characteristics and their activity level. The metabolic rate of a tenant who is exercising will be higher than a tenant who is sitting. Due to different metabolic rates, each occupant will experience the thermal comfort differently in the same environment. The metabolic measurement is the metabolic unit met.

Clothing is the simplest form of insulation and has a large influence on the experienced thermal comfort. It also has some influence on the power emitted by a tenant. Clothing forms a barrier that creates a layer of trapped body heat between the skin and the clothing. The heat insulating ability of clothing is measured in the clothing unit clo.

The thermal comfort is a perceived sensation and a subjective experience. Therefore, several methods have been developed to objectively measure the satisfaction with the thermal climate. The thermal comfort can be measured by PMV and PPD, which are indices used to predict the number of occupants who statistically would experience thermal discomfort in a certain condition. The thermal comfort indices PMV and PPD is described more in detail in 3.1. To assure thermal comfort within an atrium, the standard SS-EN 15251:2007 is used in this study. The standard is a European standard established as a Swedish standard, where the criteria for the thermal climate in a building is based on the thermal comfort indices PMV and PPD.

3.1 PMV and PPD

PMV stands for Predicted Mean Vote and indicates the expected average experience of the thermal climate in a room of a group of people. The index predicts the mean value of the votes of a large group of persons on a 7-point thermal sensation scale, where -3 corresponds to a cold thermal sensation and +3 corresponds to a hot thermal sensation.

Table 3.1 Seven-point thermal sensation scale (Swedish standard, 2006).

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
- 1	Cold
- 2	Cool
- 3	Slightly cool

PPD stands for Percentage of Dissatisfied People and indicates the percentage of a group of people who are expected to be dissatisfied with the thermal climate. The index predicts the number of thermally dissatisfied persons among a large group of people. The PPD can be obtained from the PMV. The relationship between PPD and PMV is shown in figure 3.1, where the curve represents the proportion of people who are thermally dissatisfied for a certain PMV-value.

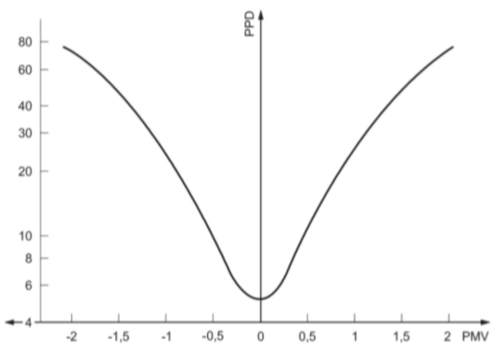


Figure 3.1 Relationship between PMV and PPD (Swedish standard, 2006).

3.2 Requirements

The criteria for the thermal comfort according the Swedish standard (2007) are based on PMV and PPD. A certain value of PPD and PMV corresponds to certain comfort category of the indoor environment. There are four comfort categories; best, good acceptable and unacceptable. The ranges of PPD and PMV for each comfort category are given in Table 3.2.

Table 3.2 Comfort categories for design of building (Swedish standard, 2007).

Comfort category	Description	PPD [%]	PMV
I	Best	< 6	- 0.2 < PMV < + 0.2
II	Good	< 10	- 0.5 < PMV < + 0.5
III	Acceptable	< 15	- 0.7 < PMV < + 0.7
IV	Unacceptable	< 25	- 1.0 < PMV < + 1.0

According to the Swedish standard (2007), it is possible to establish a corresponding range of operative temperatures by an assumed combination of activity and clothing, an assumed 50 % relative humidity and low air velocities and express the criteria as a temperature range. The operative temperature is the average of the air temperature and radiation temperature at a certain point, which is an estimation of the temperature that a person experiences in a room. Each comfort category corresponds to a design operative temperature interval.

During cooling season in buildings without mechanical cooling, the upper and lower temperature limits for the thermal environment is specified by a so-called adaptive method. The method takes occupants adaptation effects and expectations to warmer conditions into account, which is strongly related to outdoor climate condition. The allowable range for the lower limit during cooling season is defined when the running mean outdoor temperature is between the 15 °C and 30 °C. The allowable range for the upper limit during cooling season is defined when the running mean outdoor temperature is between 10 °C and 30 °C. The design values of the allowable ranges of the operative temperature are presented in Table 3.3.

Table 3.3 Design values of indoor operative temperature during cooling season in residential buildings (Swedish standard, 2007).

Comfort category	Lower limit	Upper limit
I	$T_{op,min} = 0.33 \times T_{rm} + 18.8 - 2$	$T_{op,max} = 0.33 \times T_{rm} + 18.8 + 2$
II	$T_{op,min} = 0.33 \times T_{rm} + 18.8 - 3$	$T_{op,max} = 0.33 \times T_{rm} + 18.8 + 3$
III	$T_{op,min} = 0.33 \times T_{rm} + 18.8 - 4$	$T_{op,max} = 0.33 \times T_{rm} + 18.8 + 4$

The temperature limits for each comfort category during the heating season is defined as for buildings with mechanical cooling system. The limit for each comfort category in a living space in a residential building is presented in Table 3.4.

Table 3.4 Design values of the indoor operative temperature during heating season in residential buildings (Swedish standard, 2007).

Comfort category	Lower limit
I	21.0
II	20.0
III	18.0

4 Passive heating and cooling

The temperature in a space depends on the heat loads and losses. When the heat losses are larger than the heat loads, a heat deficit will eventually take place. To increase the temperature and obtain thermal comfort, heating energy is required to heat the atrium. When the heat loads are greater than the heat losses, a heat surplus will eventually take place and thermal discomfort can occur. To restore thermal comfort, cooling energy is required to cool down the atrium.

According to the Spaces project, atrium in residential buildings in a Swedish climate can results in warm temperatures during the summer and cold temperatures during the winter. The relative high U-value of windows results in the warm glazed surfaces during summer and the cold glazed surfaces during winter, which affect the thermal comfort in the atrium. Additionally, the ability to let solar radiation into the atrium can contribute to over temperatures during summer. Glazed space can lead to temperatures above and below the desired value during some parts of the year. Passive heating and cooling can be used to improve the thermal comfort in the atrium.

Passive heating is based on reducing heat losses and increasing heat loads, while passive cooling is based on reducing heat loads and increasing heat losses. Heat loads and losses in an atrium, apart from mechanical heating and cooling, occur through internal heat gain and losses, radiation heat gain and losses, transmission heat gain and losses and ventilation heat gain and losses.

Several parameters of the atrium can be designed in different ways in order to improve the thermal comfort in the atrium. The construction of the atrium affects how the indoor climate inside responds to the outdoor climate and therefore affects the thermal comfort. The construction of the atrium includes several design parameters, such as thermal mass, thermal insulation performance of different parts, glazing shape and size.

4.1 Internal heat gains and losses

Internal heat is the heat that is supplied to the indoor air directly by occupants, equipment and lightning and indirectly by the walls, floors, ceilings and furnishings. The internal heat is supplied to the indoor air as soon as the temperature of the surfaces is higher than the indoor air. However, heat is taken from the indoor air as soon as the temperature of the surfaces is lower than that of the indoor air.

4.1.1 Thermal mass

Thermal mass can be described as the atrium capacity of heat storage. Thermal mass of an atrium is a measure of its ability to store and release thermal energy. Thermal mass will absorb thermal energy when the surroundings are warmer than the mass and release thermal energy when the surroundings are cooler than the mass. When the outside air temperatures are changing throughout the day, a large thermal mass can even out these daily temperature changes by providing the atrium with thermal inertia against outdoor temperature changes. In this way, thermal mass can help reduce peaking heat loads and losses. On the other hand, a small thermal mass will result in rapid temperature rise and fall.

The thermal mass depends on the volumetric heat capacity, thickness, density and area of the interior part of the atrium envelope and furnishings. To obtain a large thermal mass the exposed materials should have high specific heat capacity and high density and a large exposed surface area. Building with large thermal mass typically use heavy and dense materials, such as brick, concrete and tiles. Buildings with lower thermal mass typically use lighter materials and structural supports with less mass content, such as timber, light steel, fiber cement and plywood.

4.2 Radiation heat gains and losses

Solar radiation is radiant energy emitted by the sun that enters the building and is converted into heat when it hits a solid surface and the temperature of the surface rises, which is gradually heating the building. Properties of glazing materials, glazing area, shading and building orientation has great importance to the incoming solar radiation.

4.2.1 Glazing material

The glazing surfaces of the atrium is the only part that permit solar radiation to enter the building. Solar radiation can pass through a window as both direct and diffuse radiation. Direct radiation is the radiation that hits a window and passes straight through it. Diffuse radiation is the radiation that is reflected on the surroundings, such as the ground or sky, and then hits the window and is absorbed by the window and then transferred to the building in the form of convection or long-wave radiation.

The glazing properties that decide how much solar radiation can enter the building is defined by the solar heat gain coefficient and solar transmittance. The solar heat gain coefficient quantifies the amount of solar radiation admitted into a building through glass and is expressed as a number between 0 and 1, where 0 means that no radiation is admitted and 1 means that no radiation is blocked. The solar transmittance is the proportion of direct radiation entering the atrium through the window. The solar transmittance is always smaller than solar heat gain coefficient.

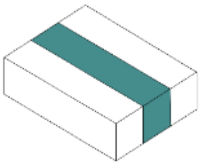
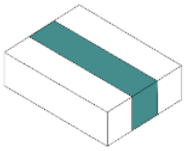
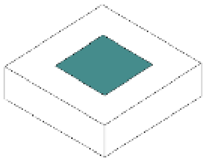
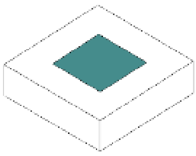
4.2.2 Glazing geometry

An atrium can be designed in different ways, which affects the thermal comfort of the atrium. The shape of the atrium can be designed in different ways, both by different atrium dimensions and types.

The dimension of the glazing area of the atrium can affect how large the heat load and heat loss become and thus affect the thermal comfort of the atrium. One way of describing the atrium dimension is through shape factors. A shape factor refers to a value that is influenced by the shape of the atrium and can be expressed in different ways.

The atrium type can be categorized by amount of parts facing the interior respectively exterior climate. Among the buildings examined in the Spaces project, three different categories can be found; linear atrium, semi-enclosed atrium and centralized atrium. A linear atrium has three parts facing the exterior climate, two exterior walls and the roof. A semi-enclosed atrium has two parts facing the exterior climate, one exterior wall and the roof. A centralized atrium only has one part facing the exterior climate, the roof.

Table 4.1 Atrium type of the evaluated buildings in the Spaces project.

Building	Glazed space geometry	Interior parts	Exterior parts	Atrium type
Sjöjungfrun		2	3	Linear
Gårdsåkra		2	3	Linear
Bovieran		3	2	Semi-enclosed
Höstvetet		4	1	Centralized
Musteriet		4	1	Centralized

4.2.3 Shading

Solar shading can contribute to minimize the solar heat gains through the glazed areas of the atrium. Solar shading can be used to avoid solar radiation and thereby the overheated periods. The solar shading can consist of different devices and material that has different properties. Existing buildings, trees and plants can also provide significant shading for a building.

Solar shading can be placed both interior within the glazed area and on the exterior side of the building. Some examples of interior solar shading devices are venetian blind, roller shade, pleated blind, screen and shutter. Some examples of exterior solar shading devices are venetian blind, drop arm awning and markisolette.

The properties of the solar shading device depend on its material properties and parameters of the device. Different material of the devices has both thermal and optical properties that affect the thermal comfort of the building.

4.2.4 Location and building orientation

All buildings receive solar radiation at some extent. However, the amount of solar radiation that reaches a building in a certain location varies according to the geographic location, time of day and year, landscape and weather. The dimension and location of existing buildings and plantings can also affect thermal comfort by contribution to site shading. Building orientation is the positioning of a building in relation to seasonal variations of the solar access. The most favorable location of the building can be determined by taking the climate and site context into account and can help improving the thermal comfort.

The earth rotates around its own axis once a day, which causes the outdoor temperature to vary daily. The earth also rotates around the sun once a year, which causes the outdoor temperature to vary annually. The rotation of the earth around its own axis causes the sun to reach a building at various angles during the day, from 0° when the sun is just above the horizon to 90° when the sun is directly above the building and finally to 180° when the sun is just above the horizon again. A building surface receives maximum solar radiation when the sunlight hits the building vertically. The rotation of the earth around the sun causes the sun to reach a building at different angles during the year. During the northern winter, the northern part of the earth leans away from the sun, which results in a building located here receiving less sunlight. During the northern summer, the northern part of the earth leans towards the sun, which leads to a building located here receiving more sunlight.

4.3 Transmission heat gains and losses

The atrium envelope is the parts that encloses the atrium, which borders either the exterior climate or the climate of other rooms in the building. These parts of the building can be designed in different ways and have different properties which affect how the atrium responds to the adjacent climate thus the thermal comfort in the atrium. Transmission heat losses is the heat transport out of the atrium through the envelope when the indoor air is warmer than the outdoor air. The heat transport through the building envelope takes place through walls, ceilings, floors, windows and doors. The heat transport is proportional to the temperature difference between inside and outside and is limited by thermal insulation of the envelope.

4.3.1 Thermal insulation

The thermal insulation of the atrium is the reduction of heat transfer over the envelope and it can be described by the heat transfer coefficient (U-value). Providing thermal insulation in the building envelope can effectively decrease the heat transfer. This principle applies to both the walls, roof and windows. The insulating capability of a material is measured as the inverse of thermal conductivity. Low thermal conductivity means a high resistance value and is therefore equivalent to high insulating capability. There is normally a reduced insulation thickness at connections between different building components, which leads to bigger heat losses, and are called thermal bridges.

The thermal properties of the materials are dependent on the materials density, specific heat capacity and thermal conductivity. Of all the envelope elements, the glazing parts have the largest thermal exchange. The relatively high U-value of the glass leads to relatively cold and warm temperatures compared to exterior walls in cold respectively warm weather. The glazing system consists of various number of glass pane and gap layers of air. By replacing the air with a noble gas, which has a lower thermal conductivity than air, the heat transport through windows can be reduced.

4.3.2 Building geometry

The geometry of an atrium can affect how large the heat addition and heat loss become and thus affect the thermal comfort of the atrium. The relation between geometry, building size and thermal comfort can be defined by shape factors. A shape factor refers to a value that is influenced by the shape of the building and can be expressed in different ways. Buildings which are more compact have smaller thermal envelope area in proportion to their volume and therefore lower heat losses during the heating season.

4.4 Ventilation heat gains and losses

Buildings are ventilated by removing polluted air at the same time as supplying fresh air. Ventilation heat losses occur through heat transport with the air leaving the building. Air moves when there is a pressure difference at a certain location and can be both intentional and unintentional made. The air pressure difference can be caused by the wind, temperature differences or mechanical devices, and is referred as wind pressure, stack effect and mechanical ventilation respectively.

The intentional air movements are referred as ventilation system, which consists of intentionally made openings, which are placed to allow air inlet or outlet from the building. Ventilation system based on wind pressure and stack effect is called natural ventilation, since it is based on natural forces and the air is not treated.

The unintentional air movements are referred as air leakages, which consists of unintentional made openings, such as cracks and leakages of the building. Since the unintentional openings also can let air in or out of the building, they participate in the building ventilation. Consequences of unintentional ventilation are increased heat losses from the building, uncontrolled intake of polluted air and malfunctioning of the ventilation system.

4.4.1 Natural ventilation

The ventilation rate of a building based on natural ventilation is determined by the pressure difference due to wind and stack effect. These natural forces are unpredictable, and it is therefore difficult to regulate the ventilation. If there are no openings in the building envelope, there will be no air exchange between the indoor and outdoor. However, as soon as a window or a door is open, the air will move.

Wind is a result of pressure differences in the atmosphere. Wind speed develops gradually from 0 m/s at the ground level to a fully developed speed at a certain height above the ground. Figure 4.1 shows the wind induced air movements in a building with two openings, where the plus-signs represent pressure and the minus-signs represent suction. The wind causes an increasing air pressure on the wall of the windward side, and a decreasing air pressure on the wall of the leeward side, i.e. there will be suction. If the building consists of a flat roof, the wind causes a decreasing air pressure on the roof, i.e. there will be suction. However, for roof with an angle above 30°, the pressure on the leading face tends to become positive and cause a pressure at the roof. The wind pattern can be described by the wind speed and the wind direction.

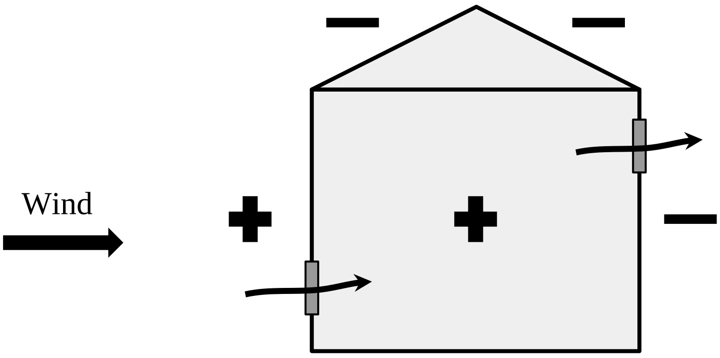


Figure 4.1 Wind induced air movements and pressure.

Stack effect causes air movements due to differences in air density. The air pressure depends on the air density, which is directly affected by the air temperature. When there is a difference in temperature between indoor and outdoor air, there is also a density difference, which results in a vertical pressure difference. If there is no temperature difference between indoor and outdoor there is no pressure difference over the building envelope and therefore no air movements. The greater the temperature difference and the height of the structure, the greater pressure difference and stack effect. A warmer air has a lower density and creates a lower pressure, while a colder air has a higher density and creates higher pressure. When the pressure difference is less than zero, there is an over pressure, and the air is leaving the building. When the pressure difference is more than zero, there is a under pressure and the air is entering the building.

Figure 4.2 shows the air movements due to stack effect in a building with two openings, where the indoor temperature is warmer. When it is colder outside than inside, there will be an over pressure at the upper part of the building and a under pressure at the lower part of the building. In the lower part of the building, cold and dry air is sucked in. In the upper part of the building, warm and humid air is pushed out.

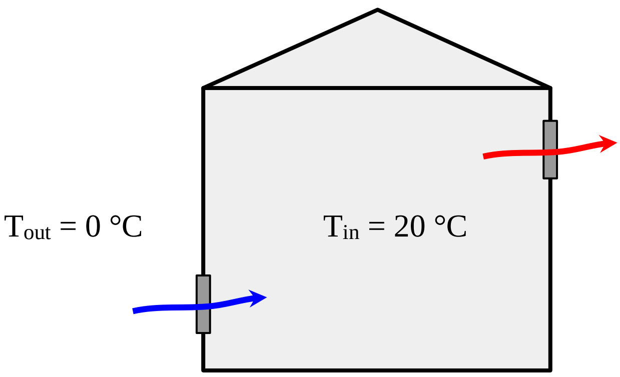


Figure 4.2 Air movements due to stack effect.

4.4.2 Air leakage

Air leakage is the heat transport that takes place with air that leaks through cracks and holes in the building envelope. The air leakage generation also involves the risk of draft which may need to be compensated with higher room temperature in order to achieve the desired thermal comfort. With an accurate construction technique, the air leakage can be very small. The ideal is a fully airtight building that is properly ventilated.

5 Model of reference building

In order to evaluate how thermal comfort in an atrium can be improved without any mechanical heating, cooling or ventilation system, a parametric study is made on a building from the Spaces project. The building Sjöjungfrun is chosen to use as a reference building in the parametric study, see Figure 5.1. An estimation of the building dimension and components is used in the study. Additionally, the climate of the location of the existing building is used. However, the ventilation strategy, plants in the atrium, occupant loads, etc. of the reference building is not used.

Figure 5.1 The reference building Sjöjungfrun (Fredrik Larsson, 2010).

The software IDA Indoor Climate and Energy 4.7 made by EQUA Simulation AB, henceforth referred to as IDA ICE, will be used for the parametric study. IDA ICE calculates the energy use as well as thermal climate for buildings by using a dynamic multi-floor simulation of a building in 3 dimensions (EQUA Simulation AB, 2016).

The reference building needs to be transformed into a geometrical model that can be used and analyzed in the software. Further on, the building can be divided into different zones. The indoor climate and is affected by outdoor climate, as well as the geographical position of the building and indoor heat loads and losses.

Walls, roof, doors and slab are described having both heat capacity and thermal conductivity. Windows can be placed in the exterior walls and roof and are described having a U-value, solar heat gain coefficient (g-value), solar transmittance (τ_{sol}), internal and external emissivity (ε) and a frame percentage.

IDA ICE takes both effects due to wind and stack effect into account at the same time. The pressure is calculated on each facade and in each zone and the flow that occurs depends on the pressure difference, the partitions and how tight the building envelope is.

To simulate the thermal comfort, IDA ICE uses a climate file from a certain location. The climate file consists of hourly measurements of dry bulb temperature, relative, humidity of air, wind direction, wind speed, direct solar radiation and diffuse radiation. The location of the chosen climate data is expressed in longitudinal and latitudinal direction and with the height above the sea.

The wind speed and direction are taken from the chosen weather file. The wind pressure on each facade is calculated from the weather file data together with pressure coefficients given per facade and a function that considers the height of the building body in relation to the altitude location of the weather station. The pressure difference due to stack effect is taking the height, air density and gravity force into account. Openings can handle bidirectional flow due to density differences.

5.1 Building geometry

The reference building is a square building with a duo pitched roof with a roof lantern above. The building consists of two five-story buildings facing each other, which are built together so that a linear atrium is formed between them. The building has a width and length of 36 meter. The pitched roof is determined by measurements of heights of the building. The height of the external wall is 14 meters and the height of the roof is 5 meters, which results in a total height of 19 meters and 15.5° angled roof. The lantern is simplified by placement of windows on the pitched roof.

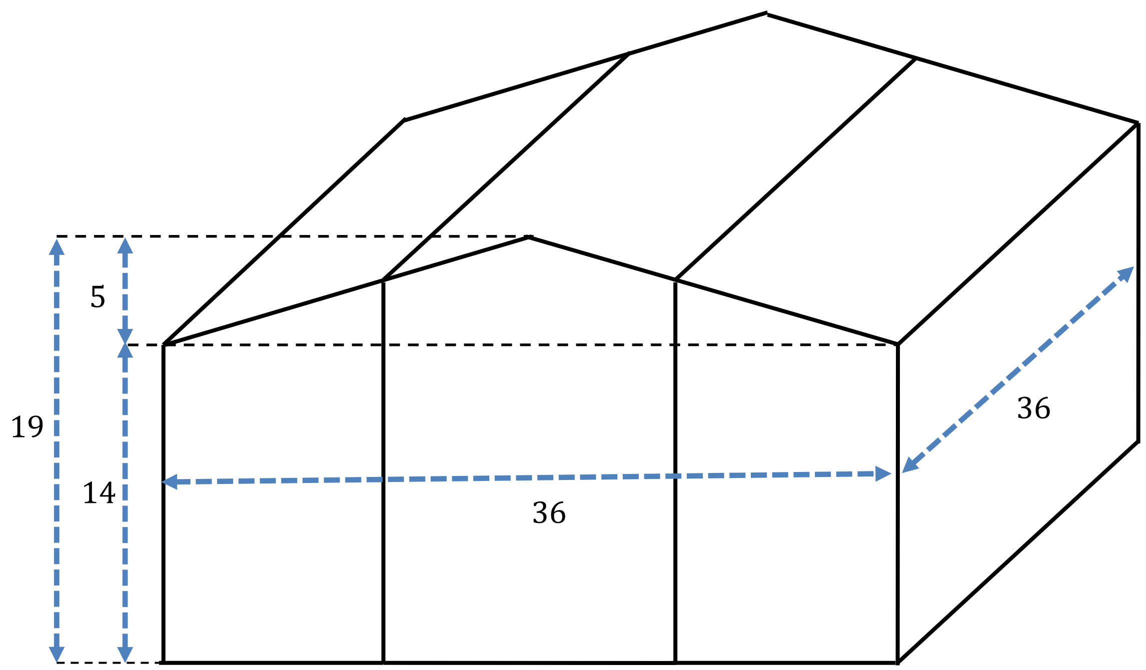


Figure 5.2 Geometry of the reference building.

Different parts of the building have different properties. To be able to describe these and calculate the results for different parts of the building, it is divided into different zones. The reference building is divided into three main zones in IDA ICE, which are referred as living area 1, atrium and living area 2. Further on, the atrium is divided into five sub-zones, one for each floor level. These are referred as floor 1, floor 2, floor 3, floor 4 and floor 5.

The building division of the reference building and the created zones in IDA ICE is presented in Figure 5.3. The red squares illustrate the main zones of the reference building, while the green squares illustrated the sub-zones of the atrium. When the calculations are performed in IDA ICE, the existing zones are living area 1, floor 1, floor 2, floor 3, floor 4, floor 5 and living area 2.

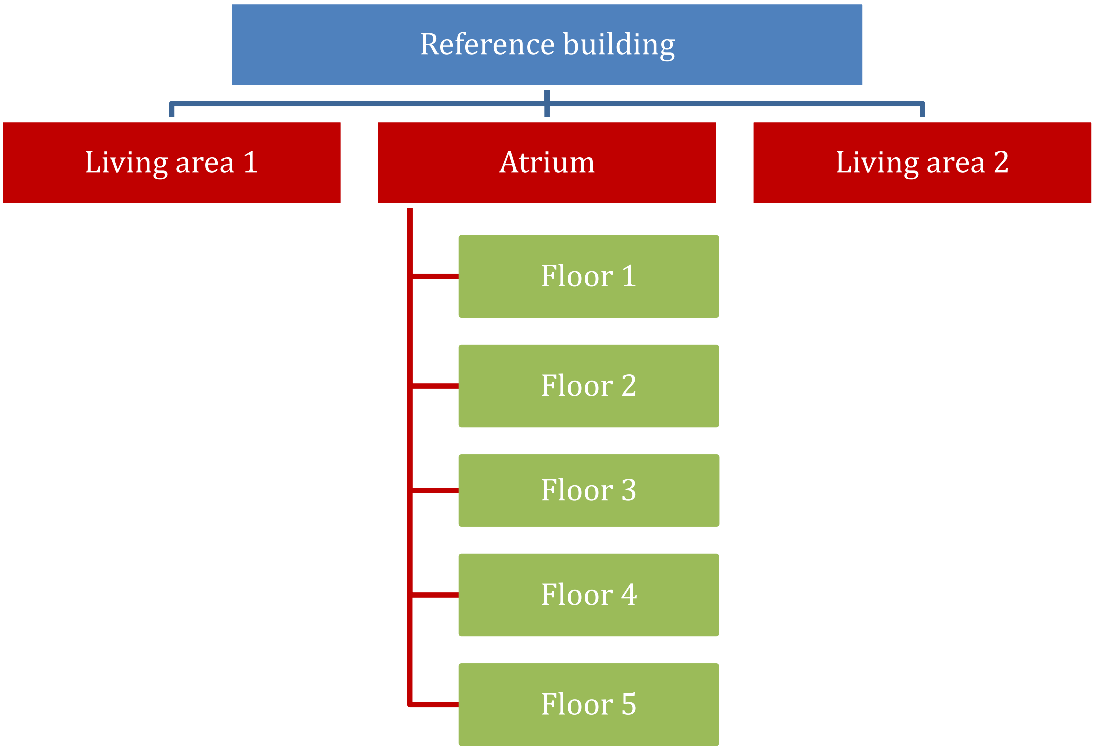


Figure 5.3 Building division in IDA ICE.

The atrium has a width of 14 meters and consists of five floor levels. Floor 1,2,3 and 4 has a height of 3 meters, while floor 5 has a height of 7 meters. The interior walls are facing living area 1 respectively living area 2.

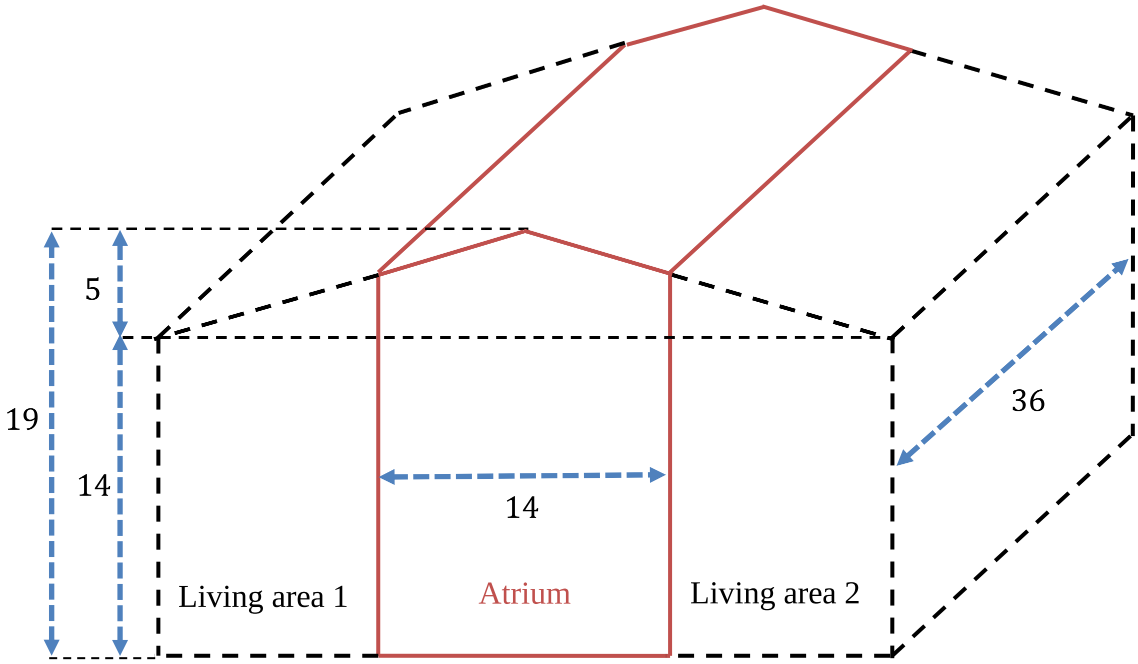


Figure 5.4 Geometry of the atrium, where the measurements are expressed in meters.

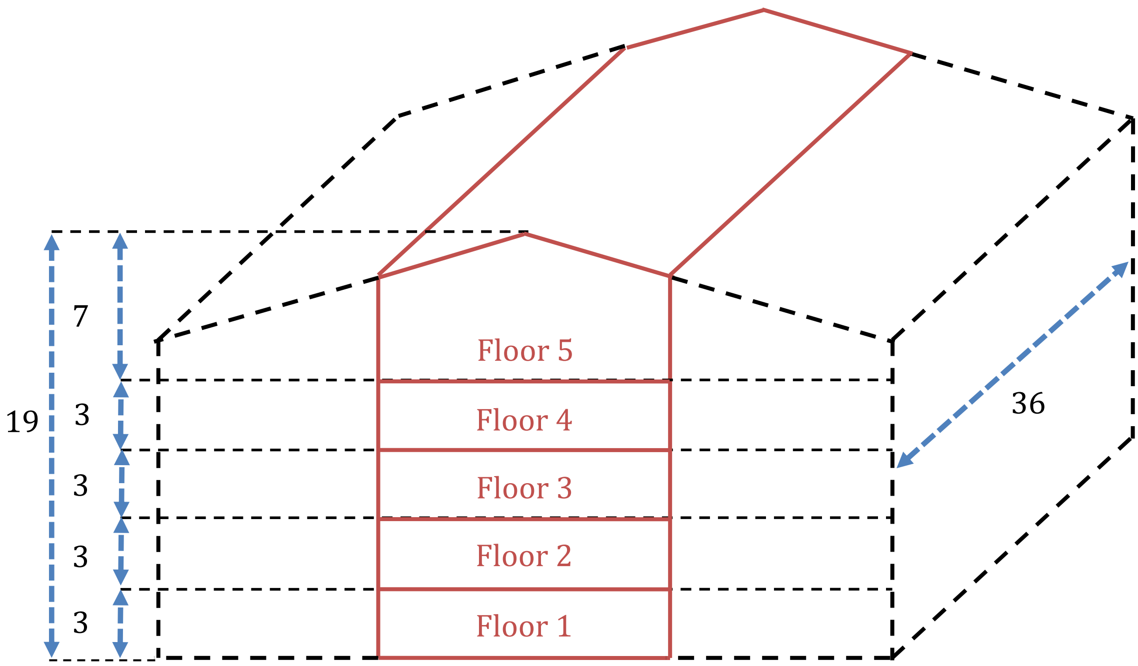


Figure 5.5 Geometry of each floor level within the atrium, where the measurements are expressed in meters.

Floor 1 has eight windows and two doors on both exterior walls. Floor 2,3,4 and 5 has ten windows on both exterior walls. Additionally, floor 5 has 30 windows on the roof. Figure 5.6 and 5.7 shows an illustration of the windows and doors of the external wall respectively roof, where the blue squares illustrate the windows and the grey squares illustrate the doors. The exact size and position of the windows and doors on the external walls of each floor is presented in Appendix A.

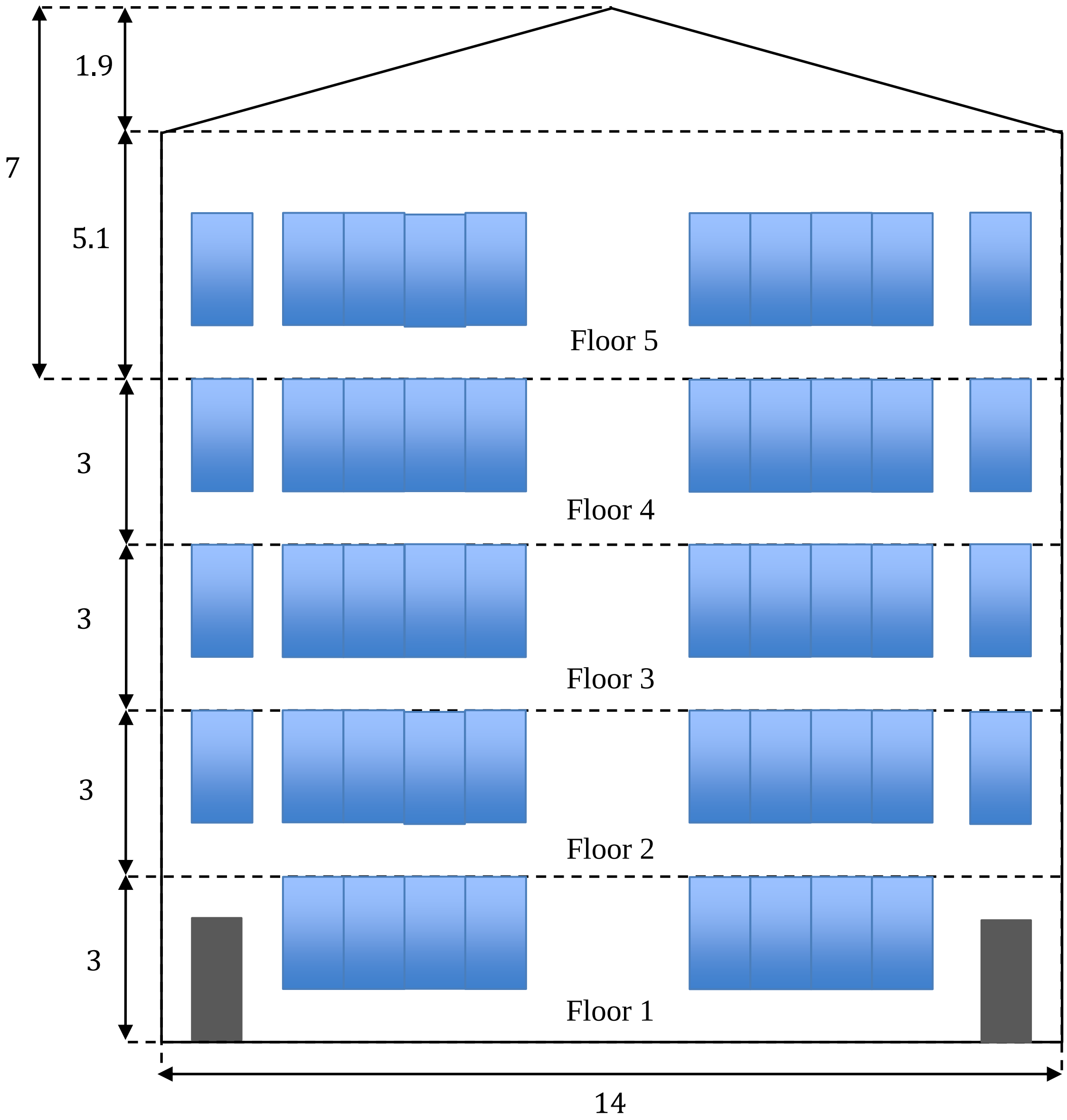


Figure 5.6 Placement of windows and doors on the exterior wall of the atrium, where the measurements are expressed in meters.

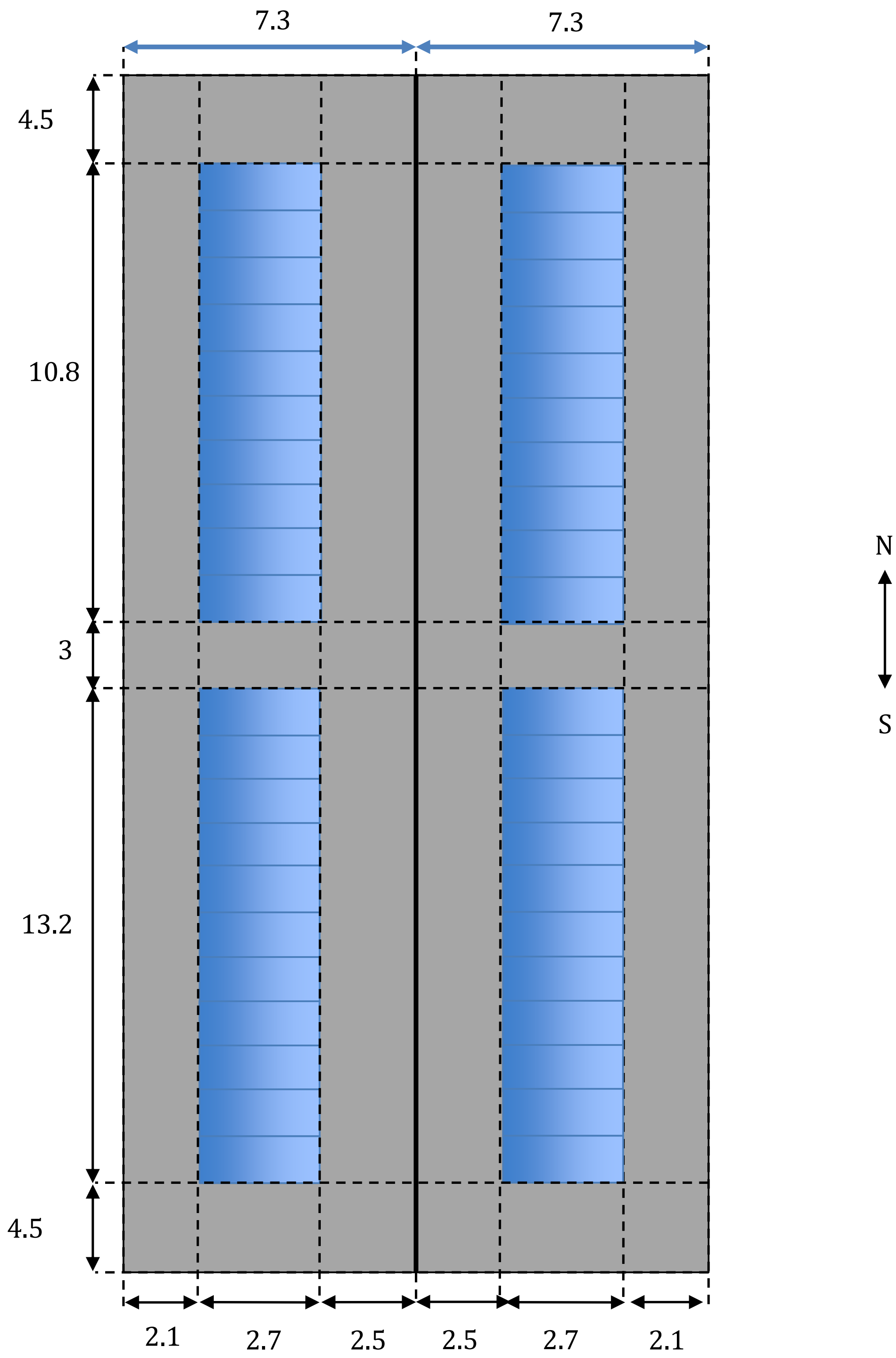


Figure 5.7 *Placement of windows on the roof of the atrium, where the measurements are expressed in meters.*

The ground floor in floor 1 is a solid floor, while floor 2,3,4 and 5 has balconies along the walls, which together creates openings from the ground to the roof. The openings are modelled as horizontal openings in IDA ICE with a Cd-factor of 0.65. The Cd-factor is the discharge coefficient for the opening flow (EQUA Simulation AB, 2016). The exact size and position of the openings of each floor is presented in Appendix A.

Figure 5.8 Solid floor and openings in the reference building (Spaces project, 2020).

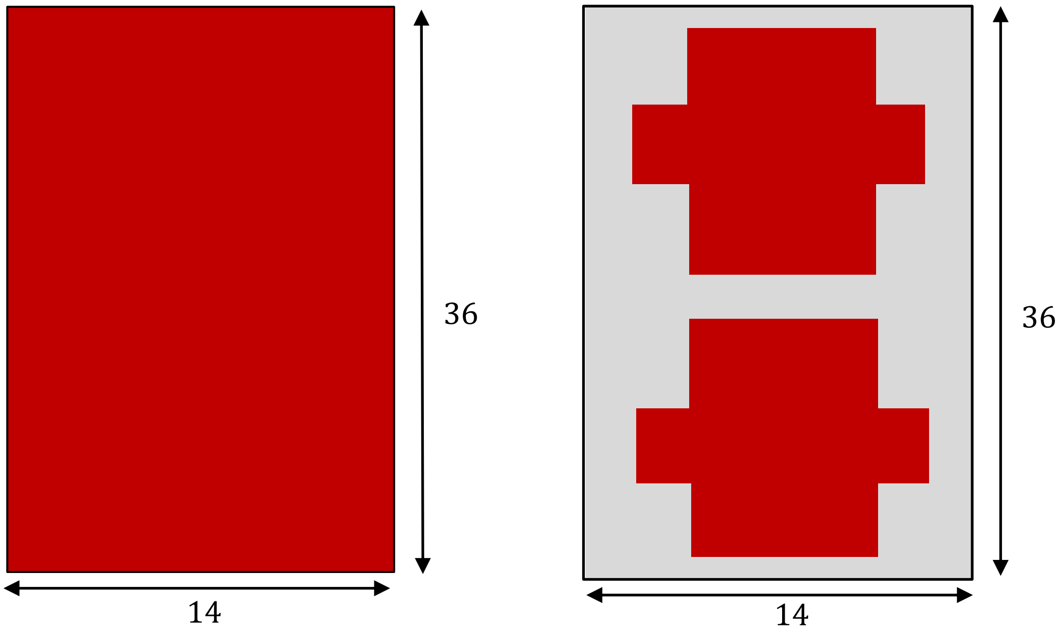


Figure 5.9 Dimensions of solid floor and openings in the reference building.

5.2 Building components

This chapter describes the building components of the reference building and their material properties. The building components of the reference building are mainly based on wooden material. The construction of walls, roof, floors, door and windows are presented below.

Figure 5.10 Building components in the reference building (Spaces project, 2020).

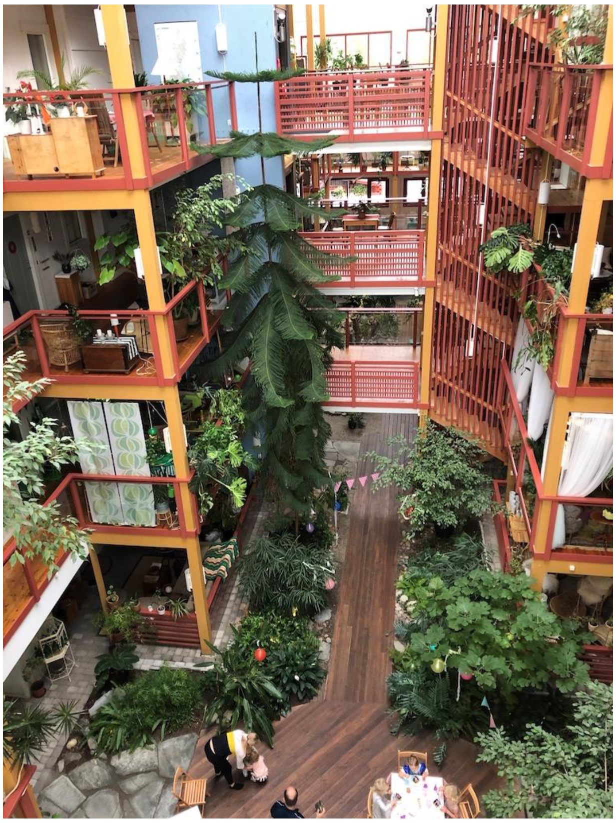


Figure 5.11 Building components in the reference building (Spaces project, 2020).

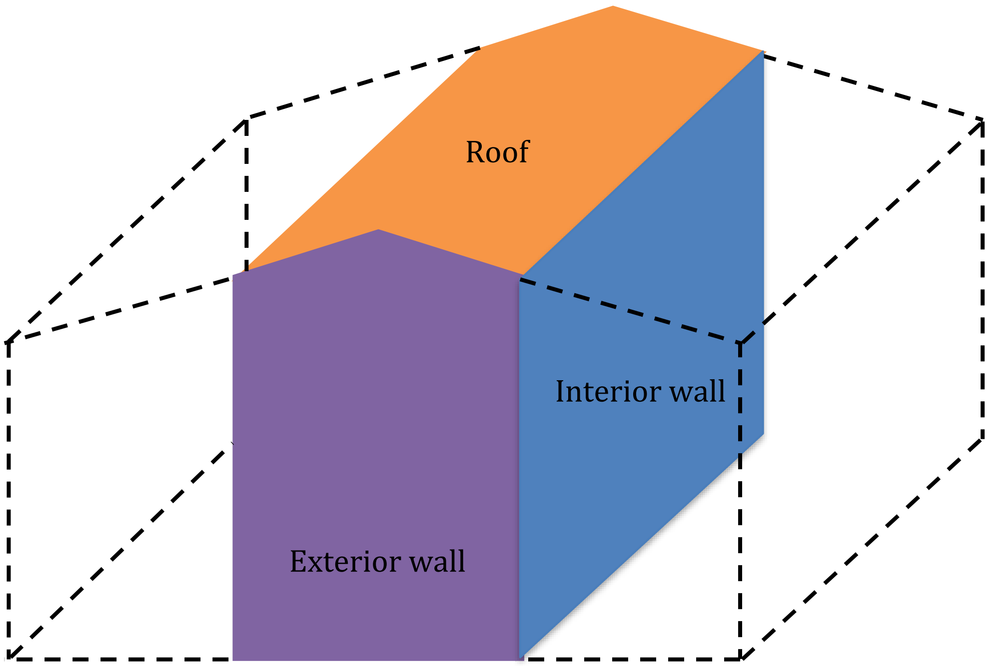


Figure 5.12 Placement of exterior wall, interior wall and roof.

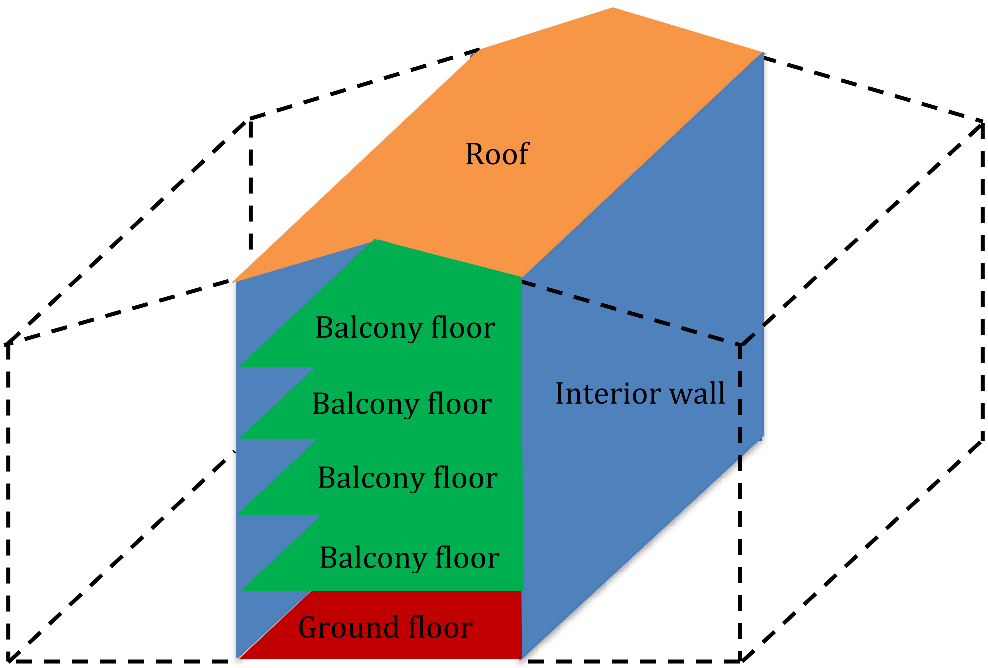


Figure 5.13 Placement of ground floor, balcony floor, interior wall and roof.

5.2.1 Exterior wall

The walls between the atrium and the exterior environment are referred as exterior wall. The construction of the exterior wall is shown in Figure 5.14. The outer wood panel, standing spars and the air gap are disregarded since the air gap is assumed to be ventilated by outdoor air. Equivalent values for λ, ρ and c are used for the insulation layers with wooden studs, see Appendix A for calculations. The material properties of the exterior wall are presented in Table 5.1.

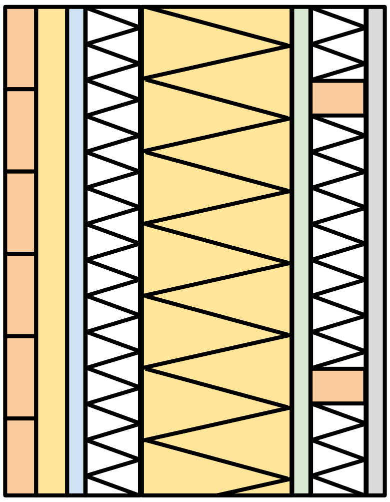


Figure 5.14 Construction of exterior wall.

Table 5.1 Material properties of exterior wall.

Layer material (from outside)	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Weather board	10	0.22	800	800	
Insulation	45	0.036	20	750	
Wood studs c600 (45x120) and insulation	120	0.044	56	806	0.19
Wood studs c600 (45x45) and insulation	45	0.044	56	806	
Wood panel	20	0.14	500	1500	

5.2.2 Interior wall

The walls between the atrium and the living floors are referred as interior wall. The construction of the interior wall is shown in Figure 5.15. Equivalent values for λ, ρ and c is used for the insulation layer with wooden studs, see Appendix A for calculations. The material properties of the interior walls are presented in Table 5.2.

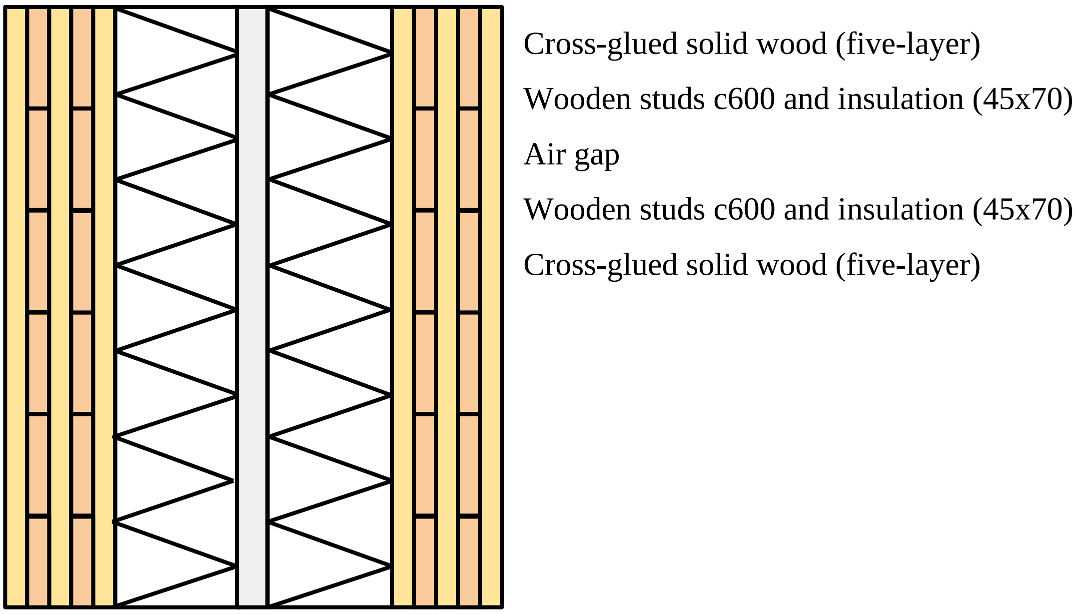


Figure 5.15 Construction of interior wall.

Table 5.2 Material properties of interior wall.

Layer material (from inside)	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Cross-glued solid wood	95	0.12	500	1300	
Wood studs c600 (45x70) and insulation	70	0.044	56	806	
Air gap	20	0.11	1.2	1006	0.20
Wood studs c600 (45x70) and insulation	70	0.044	56	806	
Air gap	20	0.11	1.2	1006	

5.2.3 Roof

The roof between the atrium and external environment are referred as roof. The construction of the roof is shown in Figure 5.16. The air gap and the layers between the air gap and the external environment are disregarded since the air gap is assumed to be ventilated by outdoor air. Equivalent values for λ, ρ and c are used for the insulation layers with wooden roof trusses and wooden studs, see Appendix A for calculation. The properties of the roof are presented in Table 5.3.

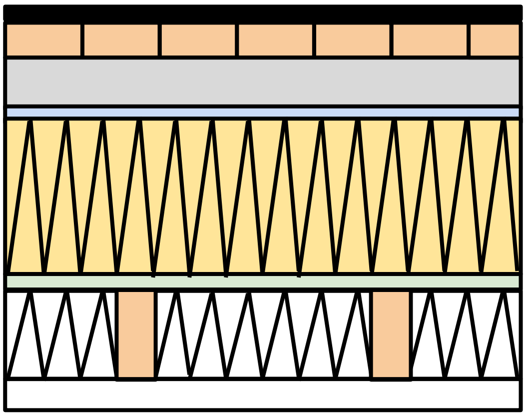


Figure 5.16 Construction of roof.

Table 5.3 Material properties of roof.

Layer material (from outside)	d [mm]	λ [W/(m·K)]	ρ [kg/m³]	c [J/(kg·K)]	U_{tot} [W/(m²·K)]
Weather board	4	0.22	850	800	0.28
Wood trusses c1200 (45x90) and insulation	90	0.04	38	778	
Wood studs c600 (45x45) and insulation	45	0.044	56	806	
Wood panel	20	0.14	500	1500	

5.2.4 Ground floor

The external floor at the ground in the atrium is referred as ground floor and is constructed as a concrete ground slab. The construction of the ground floor is shown in Figure 5.17. The calculated heat resistance of the ground is expressed in two layers in IDA ICE; 0.5 m layer of the outermost layer material and 0.1 m virtual layer below that with a neglectable heat capacity and a heat conductivity calculated to represent the rest of the heat resistance. The ground layers under the basement slab goes down to a virtual temperature, which is calculated according to the standard as a weighted average value of the annual and the monthly mean air temperatures, including a calculated time lag. The material properties of the ground floor are presented in Table 5.4.

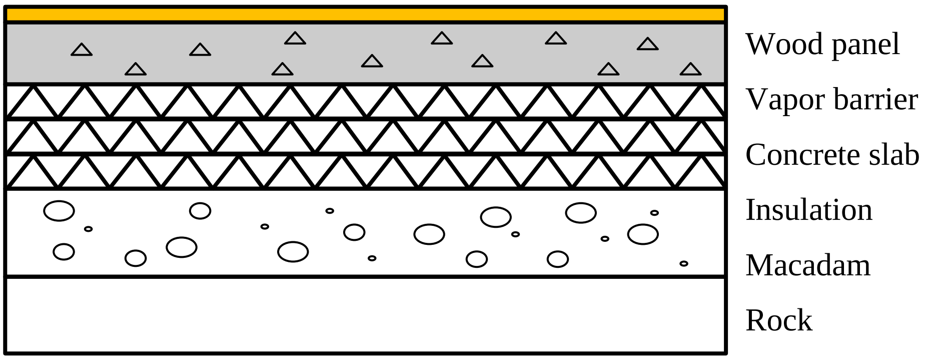


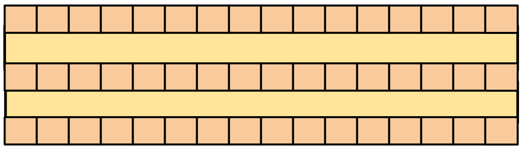
Figure 5.17 Construction of ground floor.

Table 5.4 Material properties of ground floor.

Layer material (from inside)	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Wood	20	0.14	500	1500	
Concrete	100	1.7	2300	880	
Insulation	150	0.036	20	750	0.21
Macadam	150	3	2700	880	
Rock	500	3.5	2500	800	

5.2.5 Balcony floor

The floors of the balconies in the atrium are referred as balcony floor. The balcony floors can be seen in the picture of the reference building. The construction of the floor is shown in Figure 5.18. The material property of the balcony floor is presented in Table 5.5.



Cross-glued solid wood (five-layer)

Figure 5.18 Construction of balcony floor.

Table 5.5 Material properties of balcony floor.

Layer material	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Cross-glued solid wood	95	0.12	500	1300	1.0

5.2.6 Window on wall

The windows on the external walls are referred as window on wall. The properties of the window depend on the glazing system and frame. The glazing system is a 2-pane glazing, which consists of a layer of clear glass, an air gap and another layer of clear glass. The area of the frame is expressed as a fraction of the total window area and is set to 10% with a frame U-value of 2.0 W/m^2°C. The glazing properties for the windows on the external walls is presented in Table 5.6.

Table 5.5 Glazing system of window on wall.

Layer	Material	d [mm]
Pane	Clear glass	6
Gap	Air	12
Pane	Clear glass	6

Table 5.6 Window properties of window on wall.

G [-]	τ_{sol} [W/(m^2·K)]	τ_{vis} [-]	ε [-]	U_{glas} [W/(m^2·K)]
0.712	0.597	0.786	0.837	2.859

The window on wall is chosen to have an external shading. The shading is modelled as a drop arm awning device. The properties of the shading material are presented in Appendix A. The shading device is modelled with a control strategy. The shading receives a signal between 0 and 1, where 1 is when the shading is drawn, and the window is fully shaded and 0 is when the shading is not drawn, and the window is not shaded at all. The shadings are not drawn in the reference case.

5.2.7 Window on roof

The windows on the roof are referred as window on roof. The properties of the window depend on the glazing system, frame and the properties of the interior shading. The glazing system is a 2-pane glazing, which consists of a layer of clear glass, an air gap and another layer of clear glass. The area of the frame is expressed as a fraction of the total window area and is set to 10% with a frame U-value of 2.0 W/m^2°C. The glazing properties for the windows on the roof is presented in Table 5.8.

Table 5.7 Glazing system of window on roof in the reference building.

Layer	Material	d [mm]
Pane	Clear glass	6
Gap	Air	12
Pane	Clear glass	6

The windows on the roof is chosen to have interior shadings to avoid maintenance and problems with snow etc. The interior shading on the roof windows is modelled as an interior roller shading device. The material properties of the shading device are given in Appendix A. The shading device is modelled with the same control strategy as for the window on walls. In the reference case, the shadings are not drawn.

Table 5.8 Window properties of window on roof in the reference building.

Window	D [-]	G [-]	τ_{sol} [W/(m^2·K)]	τ_{vis} [-]	ε [-]	U_{glas} [W/(m^2·K)]
Without shading	0.0	0.712	0.597	0.786	0.837	2.859
With shading	1.0	0.418	0.033	0.044	0.837	2.258

5.2.8 Door

The doors between the atrium and external environment are referred as door. The material properties of the door are presented in Table 5.9.

Table 5.9 Material properties of door.

Layer material (from inside)	d [mm]	λ [W/(m·K)]	ρ [kg/m³]	c [J/(kg·K)]	U_{tot} [W/(m²·K)]
Wood	0.004	0.14	500	1500	
Aluminum	0.001	218	2700	900	
Insulation	0.215	0.036	20	750	1.2
Aluminum	0.001	218	2700	900	
Wood	0.004	0.14	500	1500	

5.3 Climate

The climate of the reference building is dependent on location and weather file. Weather data is supplied by weather data files containing information on actual measured weather. The climate of each location is described by a climate file. The climate file consists of 8784 hours, which is 366 days, to be able to handle leap years. The IDA ICE source file consists of hourly values of the following quantities:

- Time from the beginning of year [hours]
- Dry bulb air temperature [°C]
- Relative humidity [%]
- Wind speed, x-component, positive for wind from south to north [m/s]
- Wind speed, y-component, positive for wind from west to east [m/s]
- Direct normal radiation [W/m^2]
- Diffuse radiation on a horizontal surface [W/m^2]
- Sky cover [%]

5.3.1 Location

The location of the reference building is Umeå. The position chosen in IDA ICE is presented in Table 5.10. According to the spaces project, the reference building is in a semi-urban environment, which has a large lawn of surrounding building, mostly housing. The building is therefore chosen to be semi-exposed and located in a suburban environment without any surrounding buildings in IDA ICE. The wind pressure coefficients for a semi-exposed building and the terrain coefficients for a suburban environment is presented in Appendix A.

Table 5.10 Location and environmental parameters of the reference building.

Country	Sweden
City	Umeå
Longitude	20.3 E
Latitude	63.8 N
Elevation	9 m
Wind pressure coefficient	Semi-exposed
Terrain categories	Sub-urban

5.3.2 Design reference year

The climate of a typical year is described by a climate file provided by ASHRAE (2001). The design reference year contains yearly measured climate data for a whole year. The dry-bulb temperature and direct normal radiation during the design reference year, summer period and winter period is presented below. All other weather quantities of the design reference year are shown in Appendix A.

According to the weather file, the dry-bulb temperature and direct normal radiation varies over the design reference year in Umeå. The warmest temperature is 28.1 °C and occur at 8th of August. The coldest temperature is -26.9 °C and occur at 22th of December. The highest direct normal radiation is 1006 W/m^2 and occur at the 8th of August, which is the same day as the day with maximum outdoor temperature. The lowest direct normal radiation is 0 W/m^2.

The design parameters are evaluated during a summer and winter period since the major problems occur during these time periods according to the Spaces project. The climate of the chosen time periods is further described in 5.3.2.1 and 5.3.2.2.

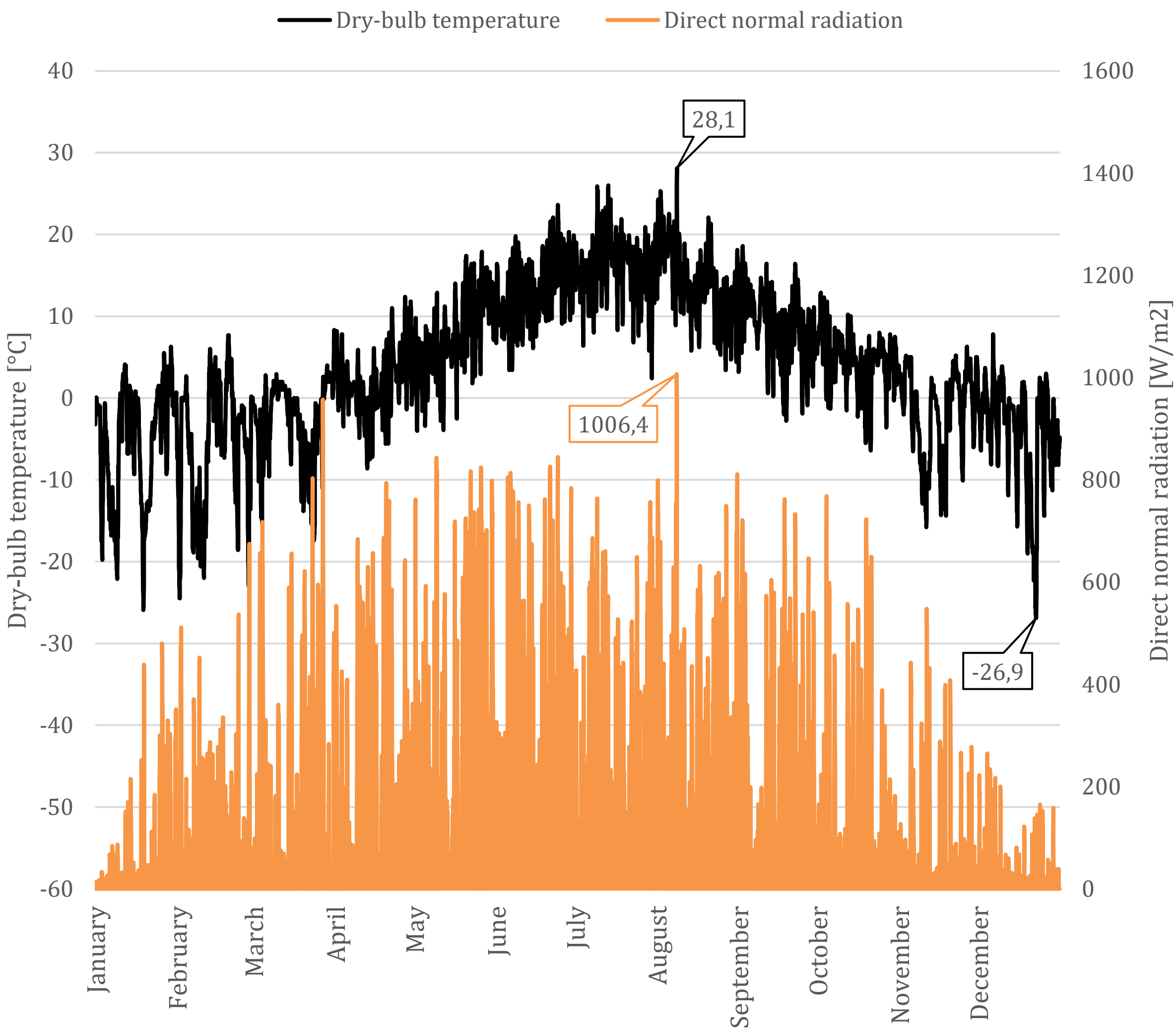


Figure 5.19 Dry-bulb temperature and direct normal radiation during design reference year.

5.3.2.1 Summer period

The summer period is chosen so that the day with the maximum outdoor temperature is included. Therefore, the summer day is chosen to be 8th August, the summer week is chosen to be 6th-12th August and the summer month is chosen to be August. The outdoor temperature and solar radiation of each summer period is presented in Figure 5.20-5.22.

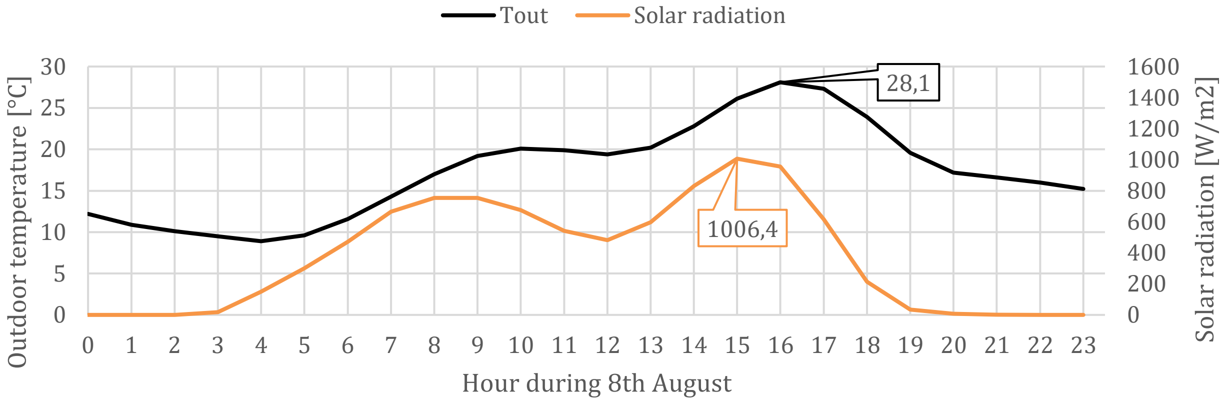


Figure 5.20 Outdoor temperature vs solar radiation during summer day.

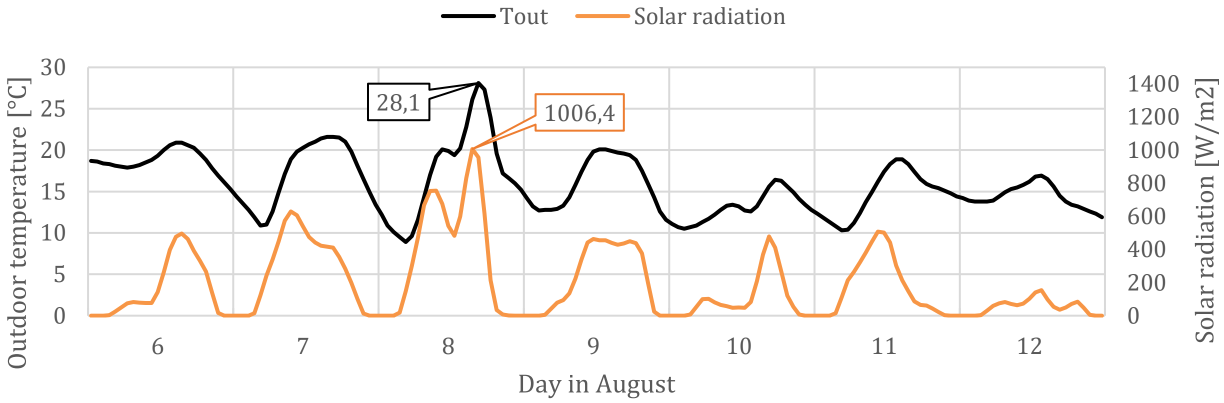


Figure 5.21 Outdoor temperature and solar radiation during summer week.

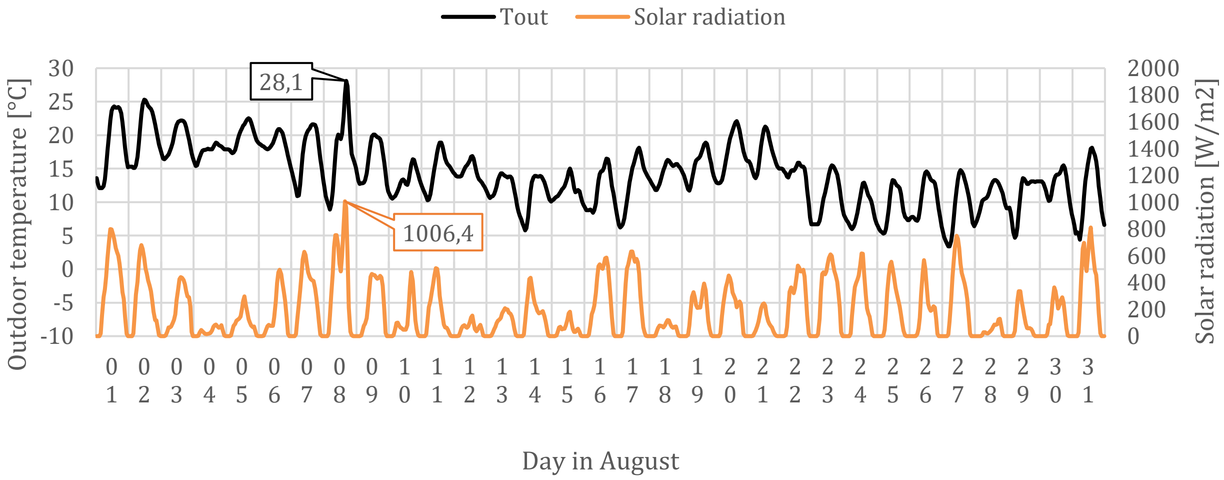


Figure 5.22 Outdoor temperature and solar radiation during summer month.

5.3.2.2 Winter period

The winter period is chosen so that the day with the minimum outdoor temperature is included. Therefore, the winter day is chosen to be 22th December, the winter week is chosen to be 20-26th December and the winter month is chosen to be December. The outdoor temperature and solar radiation of each winter period is presented in Figure 5.23-5.25.

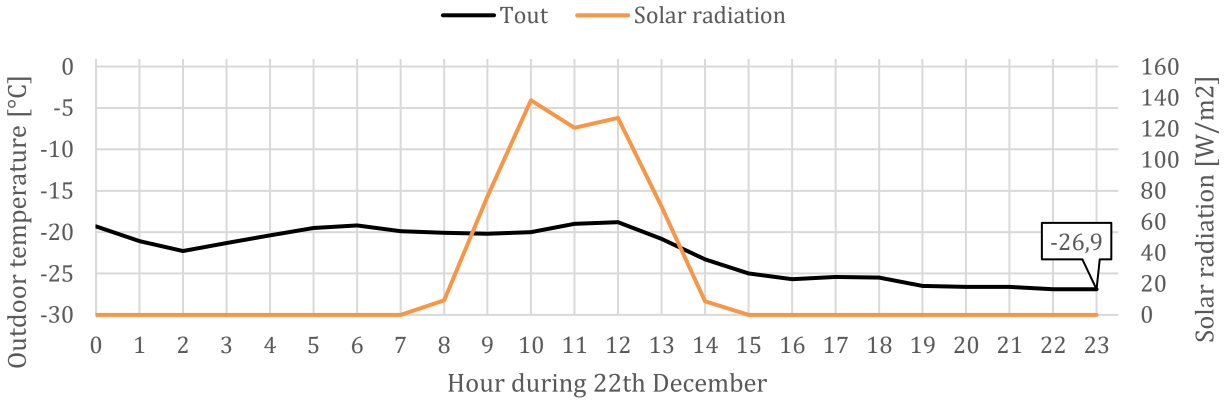


Figure 5.23 Outdoor temperature and solar radiation during winter day.

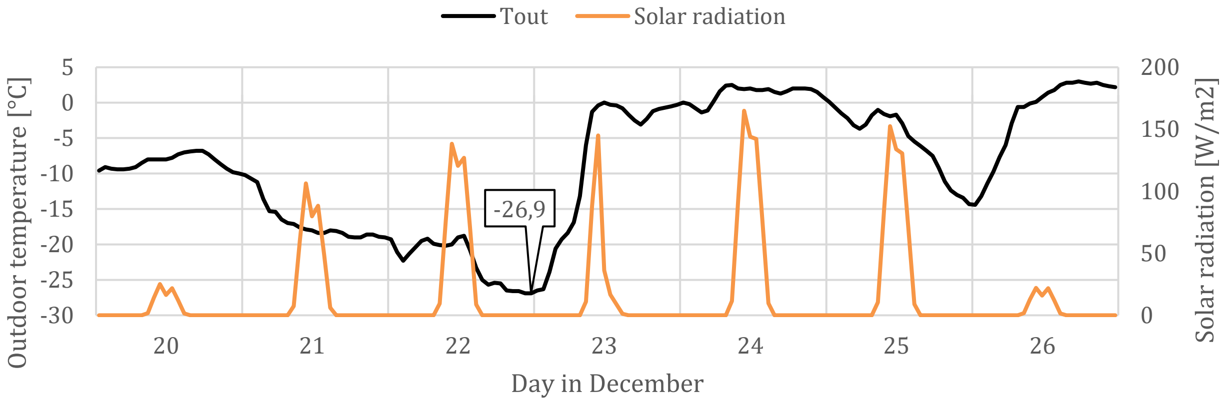


Figure 5.24 Outdoor temperature and solar radiation during winter week.

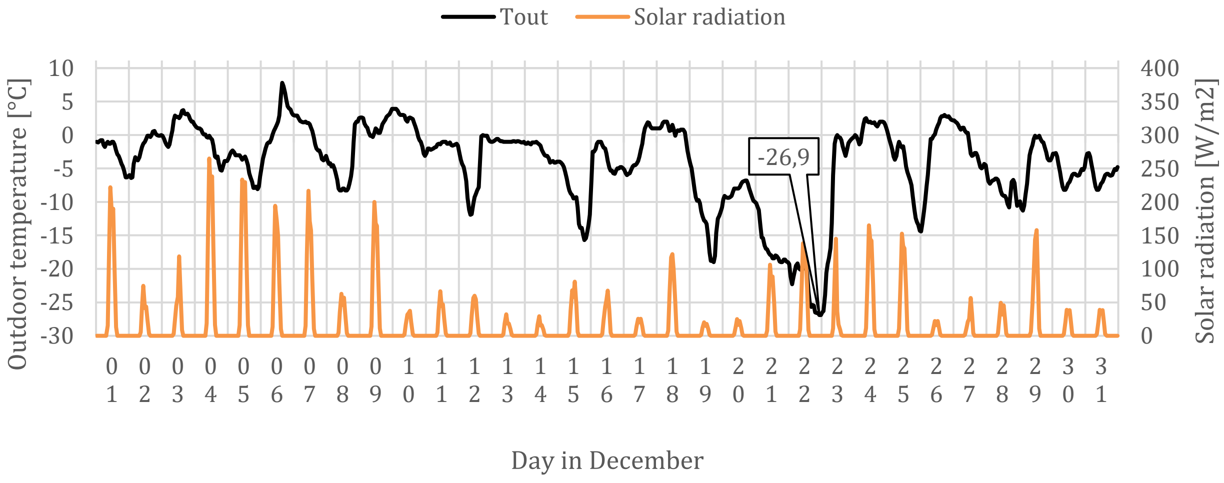


Figure 5.25 Outdoor temperature and solar radiation during winter month.

5.4 Heat loads and losses

In order to evaluate the thermal comfort without any mechanical devices, the atrium is modelled without any mechanical heating, cooling or ventilation system. However, in order to create a constant indoor temperature in living floor 1 and 2, these floors are equipped with an ideal heater and cooler with a power of 10 kW. The heating and cooling set-points is set to 20.99 °C respectively 21 °C, so that a constant temperature of approximately 21 °C is created in the living floors.

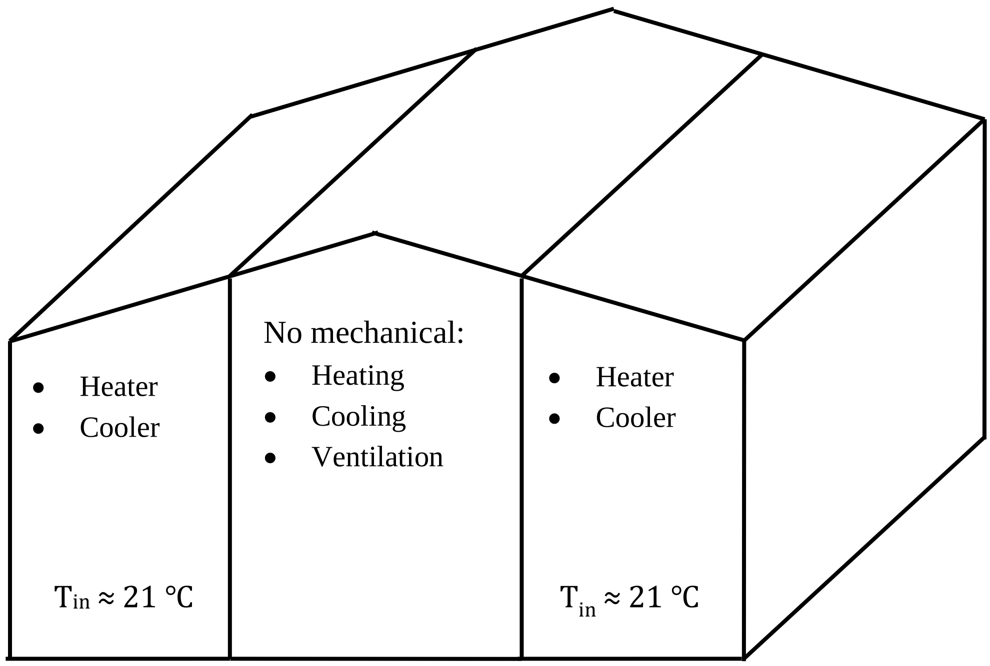


Figure 5.26 HVAC-systems in the reference building.

5.4.1 Air infiltration and thermal bridges

The reference building is assumed to have a complete airtight envelope. The envelope air tightness at 50 Pa is set to 0.0 l/(s·m^2) in IDA ICE. Additionally, the reference building is assumed to not consist of any thermal bridges. The loss factor (ψ-value) for the construction elements is set to 0.0 W/(m·K) in IDA ICE.

5.4.2 Equipment and light

None of the floors in the reference building is modelled with any equipment or light. The atrium floor is assumed to not consist of any equipment or light. Since the living floors is modelled to have an approximately constant indoor temperature, equipment and light does not affect the results.

5.4.3 Occupancy

Living area 1 and 2 has no occupancy. The atrium floor is modelled with 1 occupant on each floor, which are placed on one of the balconies, see Figure 5.27 and 5.28, with a center of gravity of 0.6 m above the floor, which is illustrating a person sitting.

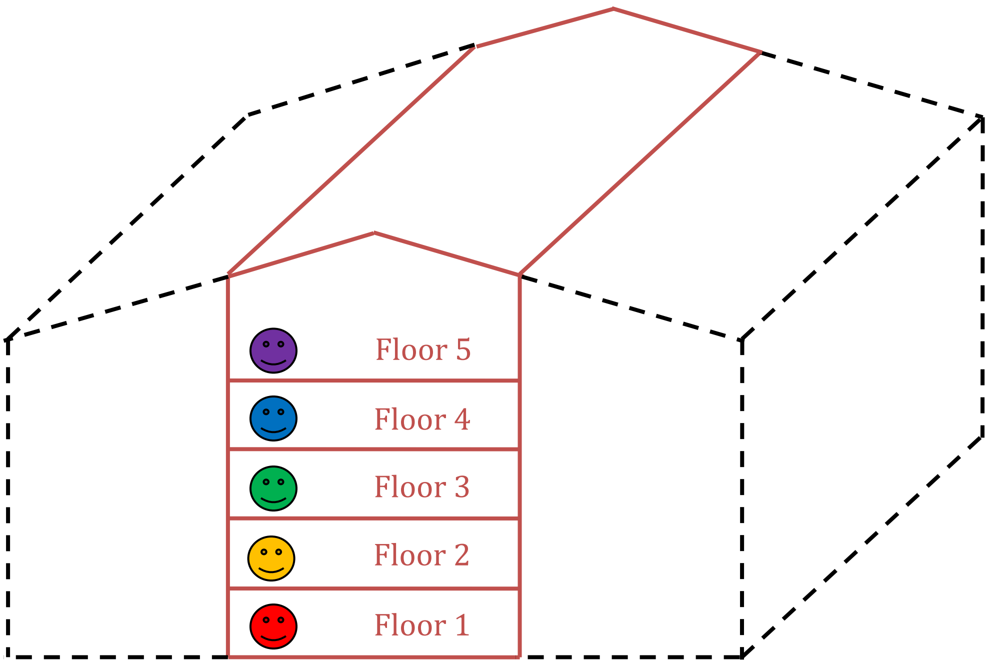


Figure 5.27 Occupant location in the atrium.

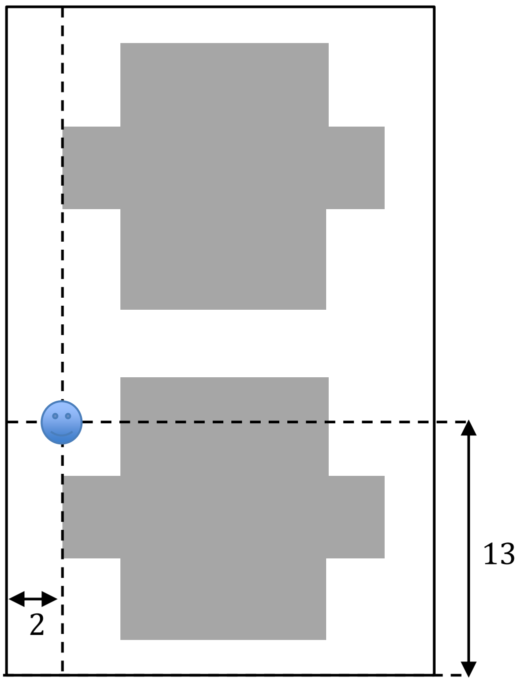


Figure 5.28 Occupant location in each floor level, where the measurements are expressed in meters.

5.4.4 Internal heat

Each occupant has an activity level of 1 met (sitting person). 1 met corresponds to 58.2 W/m^2 body surface in IDA ICE and the body surface corresponds to 1.8 m^2 in IDA ICE, which results in a power of 104.76 W.

$$58.2\ \frac{W}{m^2} \times 1.8\ m^2 = 104.76\ W \qquad \text{(Equation 5.1)}$$

The clothing level is determined by a method in IDA ICE that adapting clothing to a sensed PMV. An upper and lower bound on clo are given as an input data. The lower bound represent the acceptable lower clothing limit in the given environment and the upper bound represent the accepted upper clothing limit. The algorithm treats the occupant as a proportional controller, when PMV is at the lower bound the person will wear maximum clothing and when PMV is at the upper bound the person will wear minimum clothing. 1 clo equals a heating resistance of 0.155 (m^2·K)/W in IDA ICE.

Table 5.11 Lower and upper bound of maximum and minimum clothing.

Clo tolerance	PMV	Clothing	Clo
PMV lower bound	-1	Maximum clothing	1.1
PMV upper bound	+1	Minimum clothing	0.6

5.4.5 Natural ventilation

Natural ventilation can be modelled by openable windows and doors. IDA ICE considers wind effects and the stack effect at the same time. The pressure is calculated on each facade and in each zone. The flow that occurs depends on the pressure difference, how tight the building envelope is and the partition, such as the windows, doors and openings between zones. The openings can handle bidirectional flow due to density. However, for the reference building, the windows and doors are assumed to always be closed. In the parametric study, the discharge coefficient, Cd-factor, for the opening flow for each window, door and opening is 0.65.

The pressure difference due to the wind is calculated from the wind speed and direction from the weather file data together with pressure coefficients given per facade and a function that considers the height of the building body in relation to the altitude location of the weather station. The pressure coefficient on the internal and external walls depends on the geometry and location on the building. The wind speed is dependent on the terrain category, height above the ground and the reference wind speed 10 meter above the ground level. The terrain category consists of two terrain parameters, a0 and aexp. These coefficients are based on the environment of the building and on how exposed the building is. The pressure difference due to the stack effect is dependent on the air density and height.

6 Design parameters

A parametric study of the reference building is made in order to investigate how thermal comfort is affected and can be improved by several design parameters in an atrium without any mechanical heating, cooling or ventilation system. Each design parameter is investigated during the design reference year and a warm and cold period. The evaluation is mainly based on comparisons of the operative temperature.

The investigated design parameters are thermal mass, glazing material, atrium type, atrium dimension, building orientation, natural ventilation and solar shading. Thermal mass is investigated by a comparison of the reference building and a similar building with higher thermal mass. Glazing material is investigated in terms of solar heat gain coefficient, g-value, and thermal insulation capacity, U-value. Atrium type is investigated by a comparison of the reference building, which is a linear atrium, with a semi-enclosed atrium and a centralized atrium. Atrium dimensions is investigated by increased the height, width and length of the reference building by allowing an increased volume. Building orientation is investigated by a step-rotation of the building. Solar shading natural ventilation are investigated by comparing schedules of shading and opening.

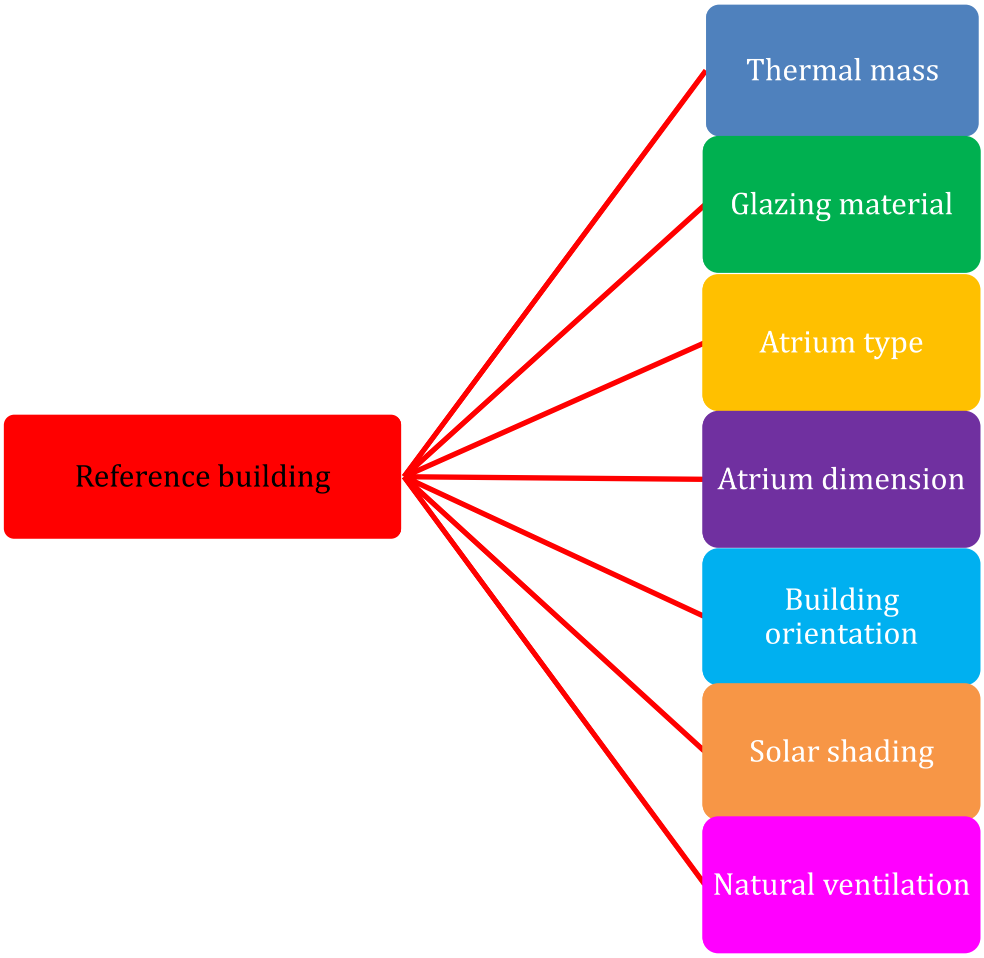


Figure 6.1 Design parameter evaluation.

6.1 Thermal mass

The exterior and interior walls, balcony floors and slab of the reference building are modelled in wood. The impact of the thermal mass is investigated by changing these components from wood to concrete. Due to different material properties of the exposed indoor surface areas, the components have different thermal mass. In case 1, the material of the interior and exterior walls is exchanged from wood to concrete. The interior walls are shown in green lines and the exterior walls is shown in purple color in Figure 6.3. In case 2, the material of the balcony floors and slab is exchanged from wood to concrete. The balcony floors are shown in red lines and the slab is shown in blue line in Figure 6.3. In case 3, the material of the interior walls, exterior walls, balcony floors and slab are exchanged from wood to concrete. The material properties and construction of each building component in the cases with higher thermal mass is presented below.

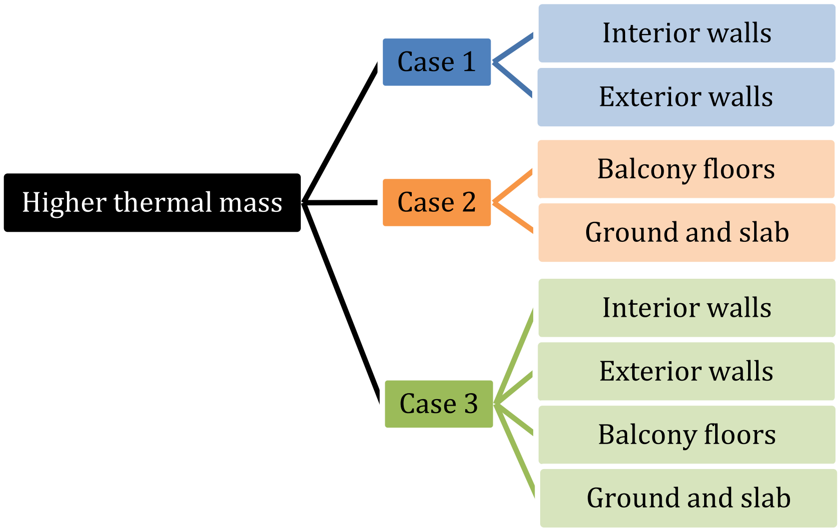


Figure 6.2 Thermal mass evaluation.

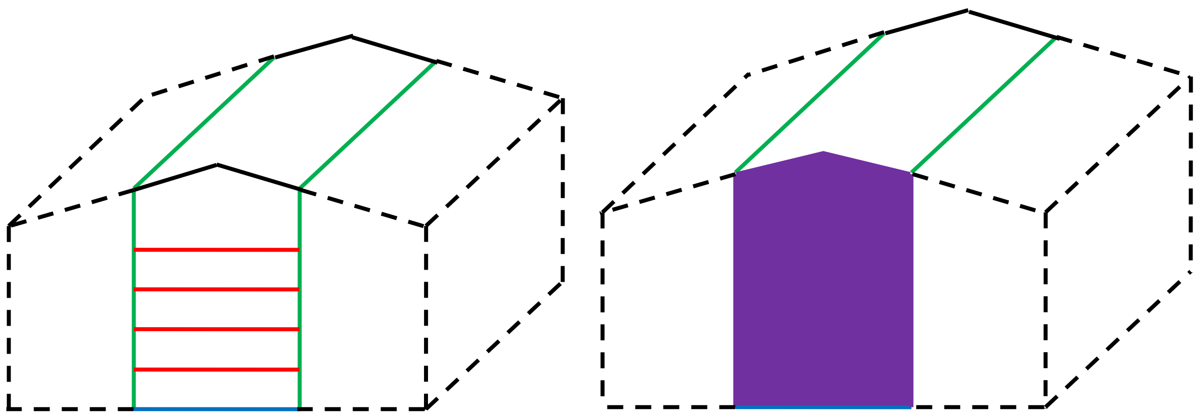


Figure 6.3 Exterior walls in purple colour, interior walls in green lines, balcony floors in red lines and slab in blue line.

The wall and floor area are approximately of equal size for the atrium. However, in the top floor, the wall area is larger than the floor area. The higher thermal mass may therefore have a larger impact than the floors when evaluating the top floor.

Table 6.1 Wall and floor areas in atrium floor and floor 5.

	Atrium floor	Floor 5
A_{wall} [m^2]	1733	533
A_{floor} [m^2]	1768	316
A_{wall}/A_{floor} [-]	0.98	1.69

6.1.1 Exterior wall

The construction of the interior wall with higher thermal mass consists of a concrete layer, insulation layer and another concrete layer, see Figure 6.4. The material properties of each material layer and the total U-value of the exterior wall are presented in Table 6.2. However, the U-value of the exterior wall in the cases with higher thermal mass is the same as in the reference case.

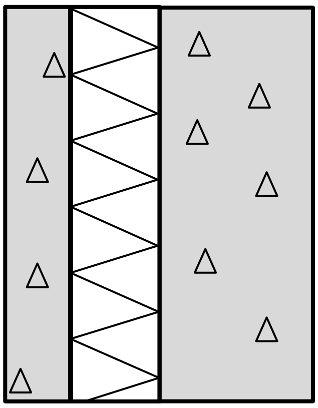


Figure 6.4 Construction of exterior wall with higher thermal mass.

Table 6.2 Material properties of exterior wall with higher thermal mass.

Layer material (from outside)	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Concrete	70	1.7	2300	880	
Insulation	180	0.036	20	750	0.19
Concrete	150	1.7	2300	880	

6.1.2 Interior wall

The construction of the interior wall with higher thermal mass is constructed as the exterior wall with higher thermal mass, which consists of a concrete layer, insulation layer and another concrete layer, see Figure 6.4. However, the thickness of the layers differs. The material properties of each material layer and the total U-value of the interior wall are presented in Table 6.3. The U-value of the interior wall in the cases with higher thermal mass is the same as in the reference case.

Table 6.3 Material properties of interior wall with higher thermal mass.

Layer material (from inside)	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Concrete	100	1.7	2300	880	0.20
Insulation	170	0.036	20	750	
Concrete	100	1.7	2300	880	

6.1.3 Balcony floor

The construction of the balcony floor with higher thermal mass consists of concrete, see Figure 6.5. The material property of the concrete and the total U-value of the balcony floor is presented in Table 6.4. The U-value of the balcony floor in the reference case is not the same as in the cases with higher thermal mass. However, since the atrium has an opening on every floor plan, the different U-values will not have a major impact on the results.

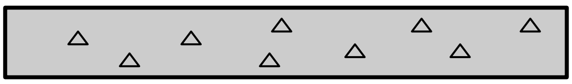


Figure 6.5 Construction of balcony floor with higher thermal mass.

Table 6.4 Material properties of balcony floor with higher thermal mass.

Layer material	d [mm]	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	U_{tot} [W/(m^2·K)]
Concrete	550	1.7	2300	880	2.1

6.1.4 Ground floor

The construction of the ground floor with higher thermal mass is shown in Figure 6.6. The material properties of the ground floor are presented in Table 6.5.

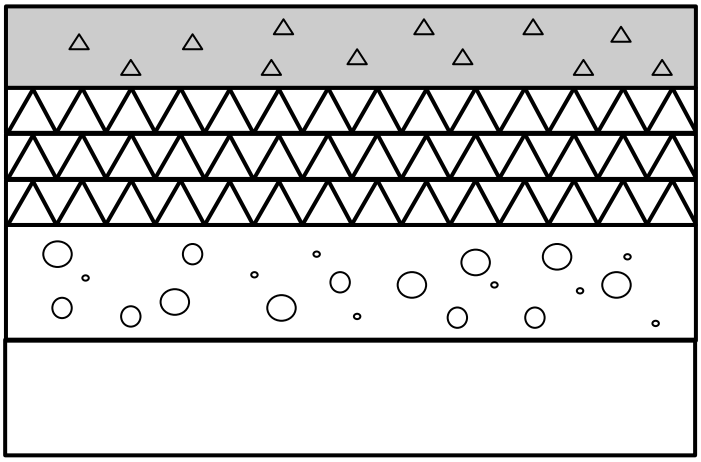


Figure 6.6 Construction of ground floor with higher thermal mass.

Table 6.5 Material properties of ground floor with higher thermal mass.

Layer material (from top of floor)	d [mm]	λ [W/(m·K)]	ρ [kg/m³]	c [J/(kg·K)]	U_{tot} [W/(m²·K)]
Concrete	100	1.7	2300	880	0.21
Insulation	155	0.036	20	750	
Macadam	150	3	2700	880	
Rock	500	3.5	2500	800	

6.2 Glazing material

The windows in the reference building are modelled as a 2-pane glazing. The impact of glazing material is investigated by comparing the glazing system of the reference building with lower g-value, lower U-value and a 3-pane glazing. The construction of each evaluation case is presented in Table 6.6 and the material properties are presented in Appendix B. The systems have different glazing properties, which are presented in Table 6.7.

Table 6.6 Construction of evaluation cases.

Case	Layer	Material	d
2-pane glazing (Reference)	Pane	Clear glass	6
	Gap	Air	12
	Pane	Clear glass	6
Lower g-value	Pane	Clear glass with lower g-value	6
	Gap	Air	12
	Pane	Clear glass with lower g-value	6
Lower U-value	Pane	Clear glass with lower U-value	6
	Gap	Argon	12
	Pane	Clear glass with lower U-value	6
3-pane glazing	Pane	Clear glass	6
	Gap	Air	12
	Pane	Clear glass	6
	Gap	Air	12
	Pane	Clear glass	6

Table 6.7 Glazing properties of evaluation cases.

Case	G [-]	τ_{sol} [W/(m^2·K)]	τ_{vis} [-]	ε [-]	U_{glas} [W/(m^2·K)]
2-pane glazing (Reference)	0.71	0.60	0.79	0.84	2.86
Decreased g-value	0.62	0.60	0.79	0.84	2.86
Decreased U-value	0.71	0.60	0.79	0.84	1.87
3-pane glazing	0.62	0.464	0.79	0.84	1.87

6.3 Atrium type

The reference building consists of a linear atrium. The impact of atrium type is investigated by comparing the reference building with a semi-enclosed atrium and centralized atrium. All evaluation cases have equal length, width and heights of the atrium. However, the glazing and door areas differs between the cases.

Table 6.8 Geometry of evaluation cases.

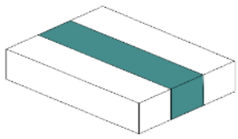
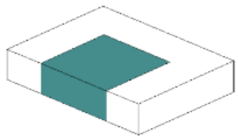
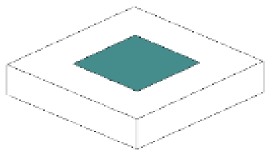
Case	Geometry	L	W	H_{edge}	H_{tot}
Linear atrium (Reference)		37	14	17	19
Semi-enclosed atrium		37	14	17	19
Centralized atrium		37	14	17	19

Table 6.9 Glazing and wall area of the atrium and the top floor in each evaluation case.

Case	A_{glas}		A_{wall}	
	Roof	Walls	Interior wall	Exterior wall
Linear atrium (Reference)	130	174	1228	326
Semi-enclosed atrium	130	86	1480	163
Centralized atrium	130	0	1733	0
Case	$A_{glas,top\ floor}$		$A_{wall,top\ floor}$	
	Roof	Walls	Interior wall	Exterior wall
Linear atrium (Reference)	130	36	364	133
Semi-enclosed atrium	130	18	448	66
Centralized atrium	130	0	533	0

6.4 Atrium dimension

The impact of atrium dimensions is investigated by comparing the geometry of the reference building with an increased height, width and length by allowing an increased volume. However, the adjacent rooms of atriums have the same width and length. The new dimensions of each evaluation case are presented in Figure 6.8, 6.9 and 6.10. The placement of the added windows is presented in Appendix B.

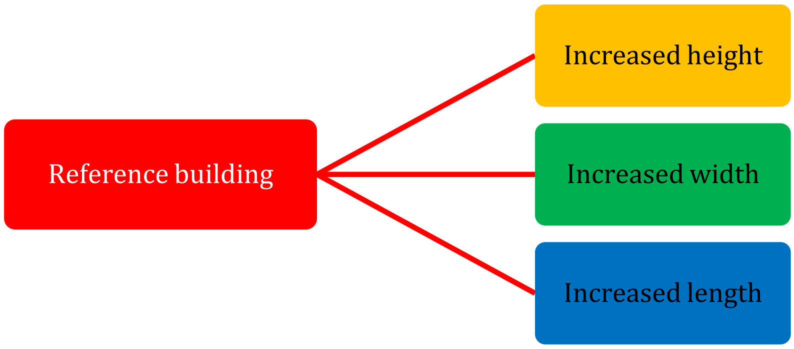


Figure 6.7 Atrium dimensions evaluation.

For the case with increased height, one floor level is added to the atrium. The geometry of the atrium is as the reference case, but with an increased height of three meters and consists of six floors. This results in that 20 new windows on wall are added to the atrium. The top floor has the same geometry and the occupant location as the top floor of the reference case.

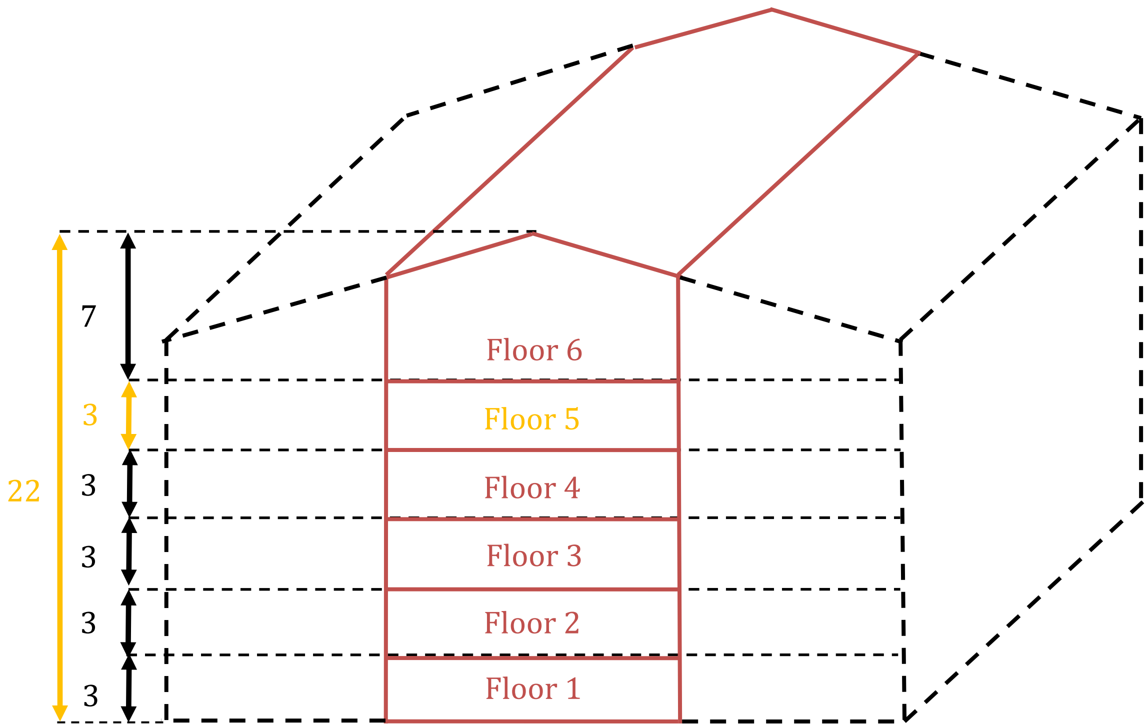


Figure 6.8 Dimensions for the case with increased height, where the measurements are expressed in meters.

The width is increased so that equal window area is added to the atrium as in the case with increased height. This results in 20 added windows on the atrium wall.

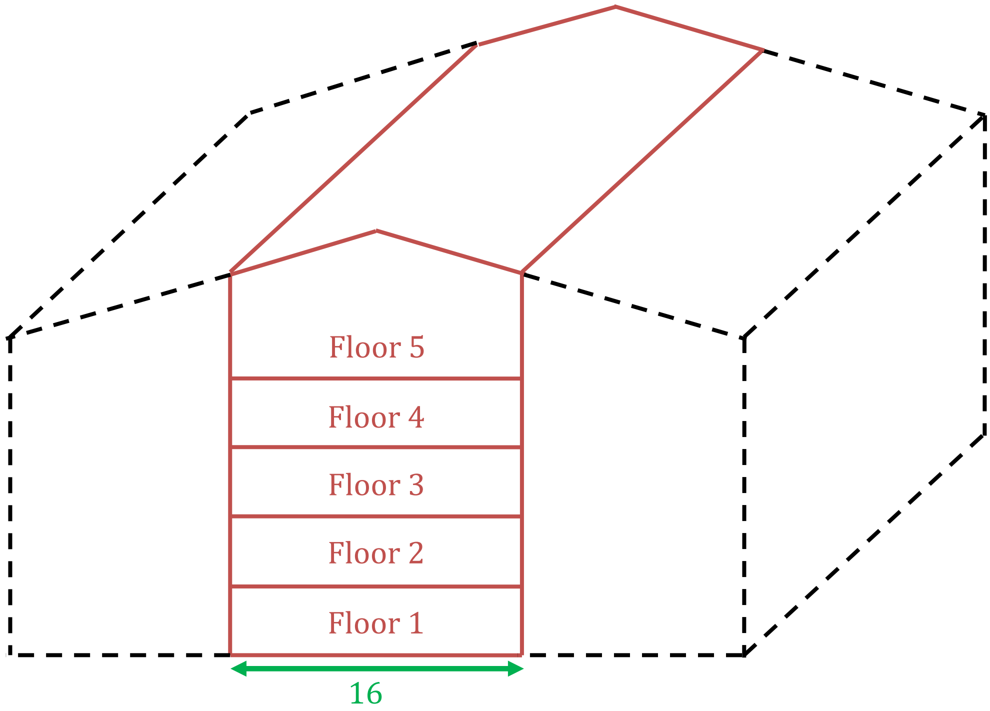


Figure 6.9 *Dimensions for the case with increased width, where the measures are expressed in meters.*

Since windows on roof has different size than windows on wall, the length is increased so that approximately equal window area is added to the atrium as in the other cases. This results in 12 added windows on the atrium and a slightly larger window area.

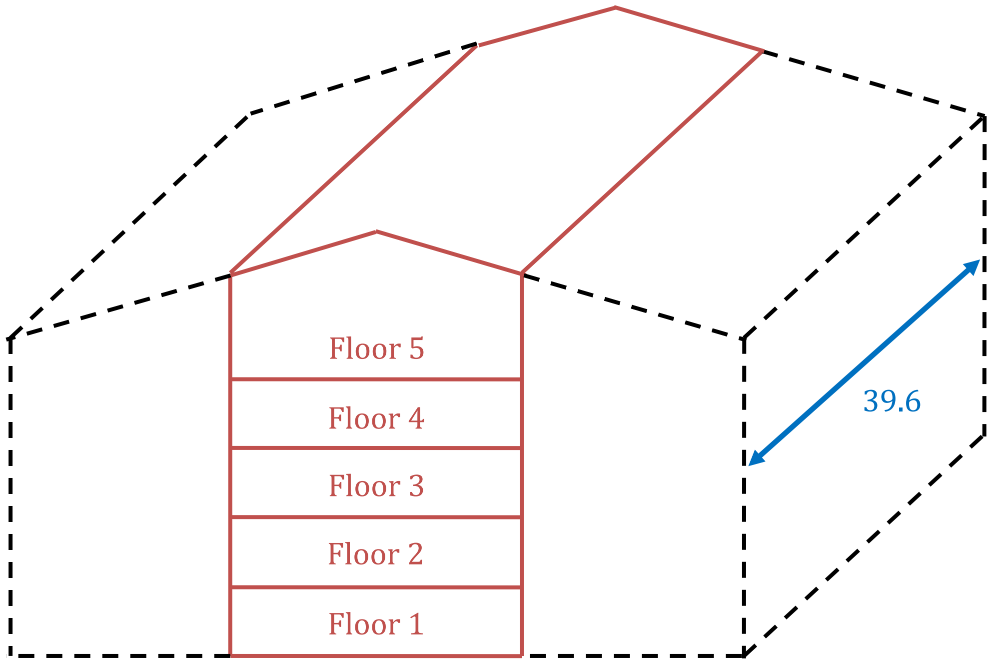


Figure 6.10 *Dimensions for the case with increased length, where the measures are expressed in meters.*

The new dimensions of the top floor are presented in Table 6.10 and the new areas of the top floor are presented in Table 6.11.

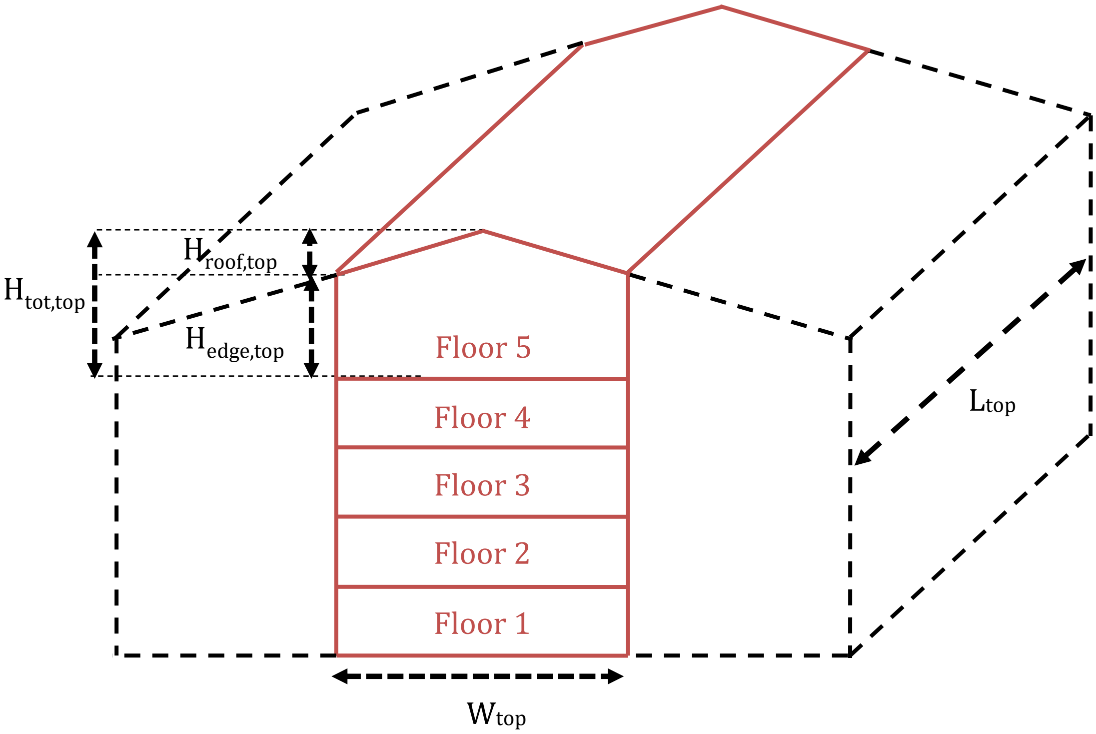


Figure 6.11 Atrium dimension.

Table 6.10 Geometry of the top floor level of the evaluation cases.

Case	W_{top} [m]	L_{top} [m]	$H_{edge,top}$ [m]	$H_{roof,top}$ [m]	$H_{tot,top}$ [m]	V_{top} [m^3]
Reference	14	36	2	5	7	3037
Increased height	14	36	2	5	7	3037
Increased width	16	36	2	5	7	3393
Increased length	14	39.6	2	5	7	3340

Table 6.11 Areas of the top floor level of the evaluation cases.

Case	$A_{floor,top}$ [m^2]	$A_{env,top}$ [m^2]	$A_{window,top}$ [m^2]	$A_{exterior,top}$ [m^2]
Reference	316	1559.3	165.6	691.7
Increased height	316	1559.3	165.6	691.7
Increased width	388	1706.4	172.8	786.2
Increased length	366.4	1698.4	204.48	744.0

6.5 Building orientation

The orientation of the reference building is presented in Figure 6.12. The exterior walls of the atrium consist of glazed parts and are facing the outdoor climate in south and north direction, while the interior walls are facing a typical indoor climate in the east and west direction. The impact of building orientation is investigated by a step-rotation of the building. However, only a half rotation of the building is made since the geometry of the building is bi-laterally symmetrical. An illustration of each evaluation case is presented in Appendix B.

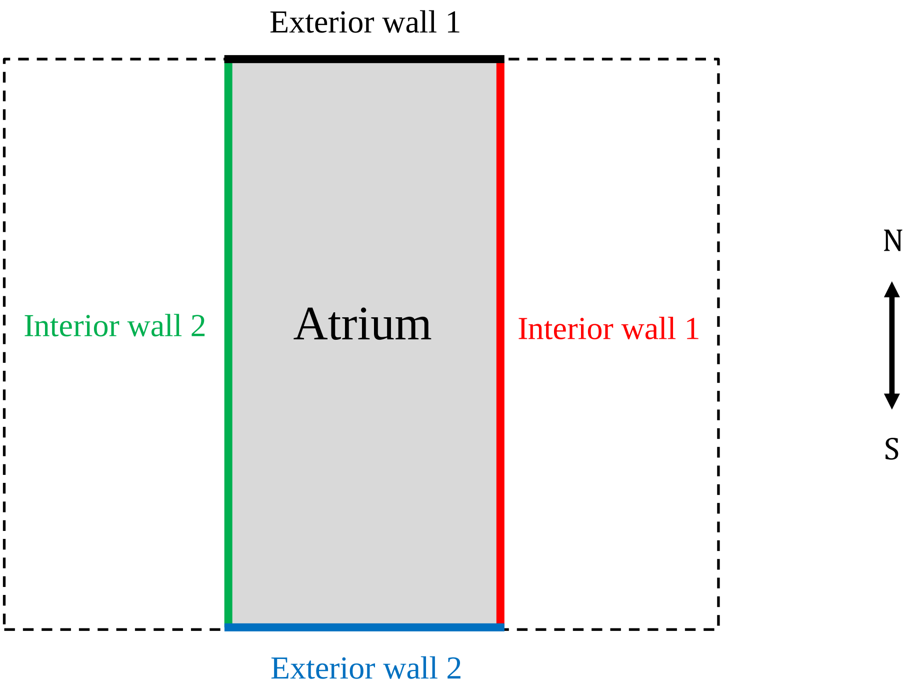


Figure 6.12 Name of the atrium walls.

Table 6.12 Investigated cases of building orientation.

Case	Exterior wall 1	Internal wall 1	Exterior wall 2	Interior wall 2
0° (Reference)	North	East	South	West
45°	North/East	South/East	South/West	North/West
90°	East	South	West	North
135°	South/East	South/West	North/West	North/East
180°	South	West	North	East

6.6 Solar shading

The solar shading of the reference building is modelled to never be drawn. The impact of solar shading is investigated by comparing the reference building with shadings always drawn and with a schedule of the solar shadings. The presence of shading decreases the U-value, g-value, solar transmittance and visible transmittance. The properties of the shading materials are presented in Appendix A.

The shading device operates in the range from 0 to 1, where 1 is when the shading is completely drawn and 0 is when the shading is completely open. In the case where the shadings are always drawn, the shadings are drawn both during the warm and cold periods. However, the shadings should decrease the temperature in the atrium during the warm period and increase the temperature in the atrium during the cold period. The case with a schedule is therefore divided into one case during the warm period and one during the cold period. During the warm period, the shadings are drawn when the incident solar radiation exceeds 100 W/m^2 on the outside of the window. During the cold week, the shadings are drawn when the sun is no longer up, which is approximately between 15.00-08.00.

Table 6.13 Evaluation cases of shading schedule.

<table>
<tr><th colspan="2">Case</th><th>Description of shading schedule</th></tr>
<tr><td colspan="2">Never drawn (Reference)</td><td>Shadings are never drawn</td></tr>
<tr><td colspan="2">Always drawn</td><td>Shadings are always drawn</td></tr>
<tr><td rowspan="2">Schedule</td><td>Warm period</td><td>Shading are drawn when the incident solar radiation exceeds 100 W/m^2 on the outside of the glazing</td></tr>
<tr><td>Cold period</td><td>Shadings are drawn between 15.00 – 08.00</td></tr>
</table>

6.7 Natural ventilation

The windows are modelled to always be closed in the reference building. The impact of natural ventilation is investigated by comparing the reference building with an opening schedule of windows, where the windows are open according to a PI temperature control. The investigation is only evaluated for the warm period since it only can decrease the temperature within the atrium.

The opening of a window operates in the range from 0 to 1, where 0 is corresponds to fully closed windows and 1 corresponds to fully open windows. When the window is open according to a PI temperature control, the opening is controlled by both interior and exterior air temperatures. The windows are opened when the mean indoor temperature within the atrium is higher than the cooling setpoint, which is set to 25 °C, and the outdoor temperature is lower than the atrium temperature. The PI temperature control is illustrated in Figure 6.13.

Table 6.14 Investigated cases of natural ventilation.

Case	Description of opening schedule
Always closed (Reference)	Windows are always closed
PI control	Windows are open according to PI temperature control

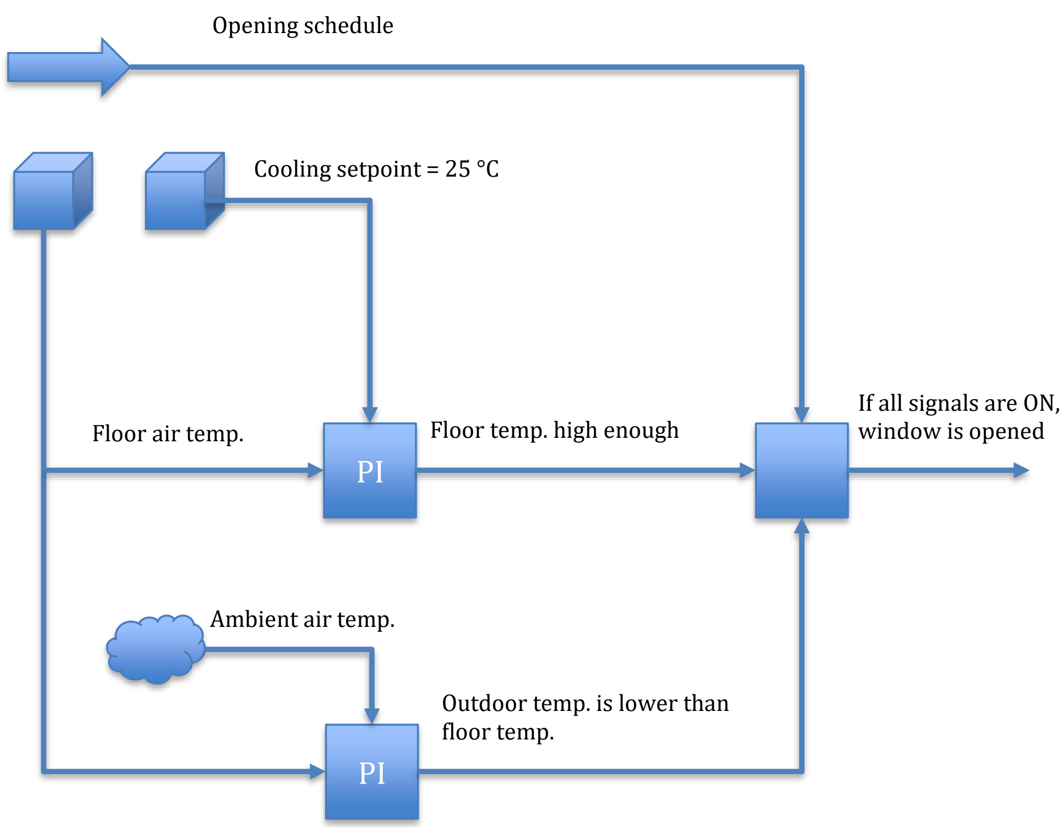


Figure 6.13 PI temperature control of windows.

7 Results

The thermal climate in the atrium depends on the outdoor temperature and the presence of the sun. When the outdoor temperature and presence of the sun is high, there is a risk of overheating, especially on the upper floors, and there is a desire to lower the temperature to achieve thermal comfort according to the standard. When the outdoor temperature and presence of the sun is low, there is a risk of cold temperatures, and a desire to raise the temperature to achieve thermal comfort according to the standard.

Previous conclusions from the interviews in the Spaces project is that:

- The operative temperature is too warm during the summer in all floor plans.
- The operative temperature is too cold during the winter in all floor plans.
- The most critical location is the top floor during both summer and winter.

The result of the thermal comfort in the reference building and evaluation cases of the design parameters are presented in this chapter. The thermal comfort is mainly evaluated through the operative temperature. The results of the evaluation of the design parameters is also presented with other variables. Table 7.1 presents a description of different temperature and radiation variables used in this chapter and Table 7.2 present a description of different heat gain variables used in this chapter.

The results are presented during different investigation periods. The result of the design reference year is presented with monthly mean values, while the result of the summer and winter period is presented with hourly mean values. The maximum and minimum operative temperature and occupancy hours per comfort category of each design parameter is presented in Appendix C. As mentioned before, the upper and lower operative temperature limits is based on a living area in a residential building and not limits for a glazed space.

Table 7.1 Description of temperature and radiation variables.

Denotation	Description
T_{air}	Mean air temperature [°C]
T_{op}	Operative temperature [°C]
T_{surf}	Mean surface temperature [°C]
T_{out}	Dry-bulb outdoor temperature [°C]
Solar radiation	Direct normal radiation [W/m^2]

Table 7.2 Description of heat gain variables.

Denotation	Description
Q_{window}	Net heat gain through external windows, i.e. through long and short-wave radiation as well as via transmission trough pane and frame [W]
$Q_{window,transmission}$	Heat gain via transmission through windows and frames [W]
$Q_{window,radiation}$	Heat gain via radiation through windows [W]
$Q_{opening}$	Heat supplied via air from openings [W]
$Q_{internal}$	Heat gained through internal walls, floors and ceiling [W]
$Q_{envelope}$	Heat gained through external walls, floors and roof [W]
$Q_{occupant}$	Heat from people in the floor, excluding heat from perspiration [W]

7.1 Reference building

The result of the reference building is presented during the design reference year. The operative temperature is within the limits for thermal comfort during some parts of the year. However, the operative temperature is too warm during the summer and too cold during the winter to achieve thermal comfort according to the standard.

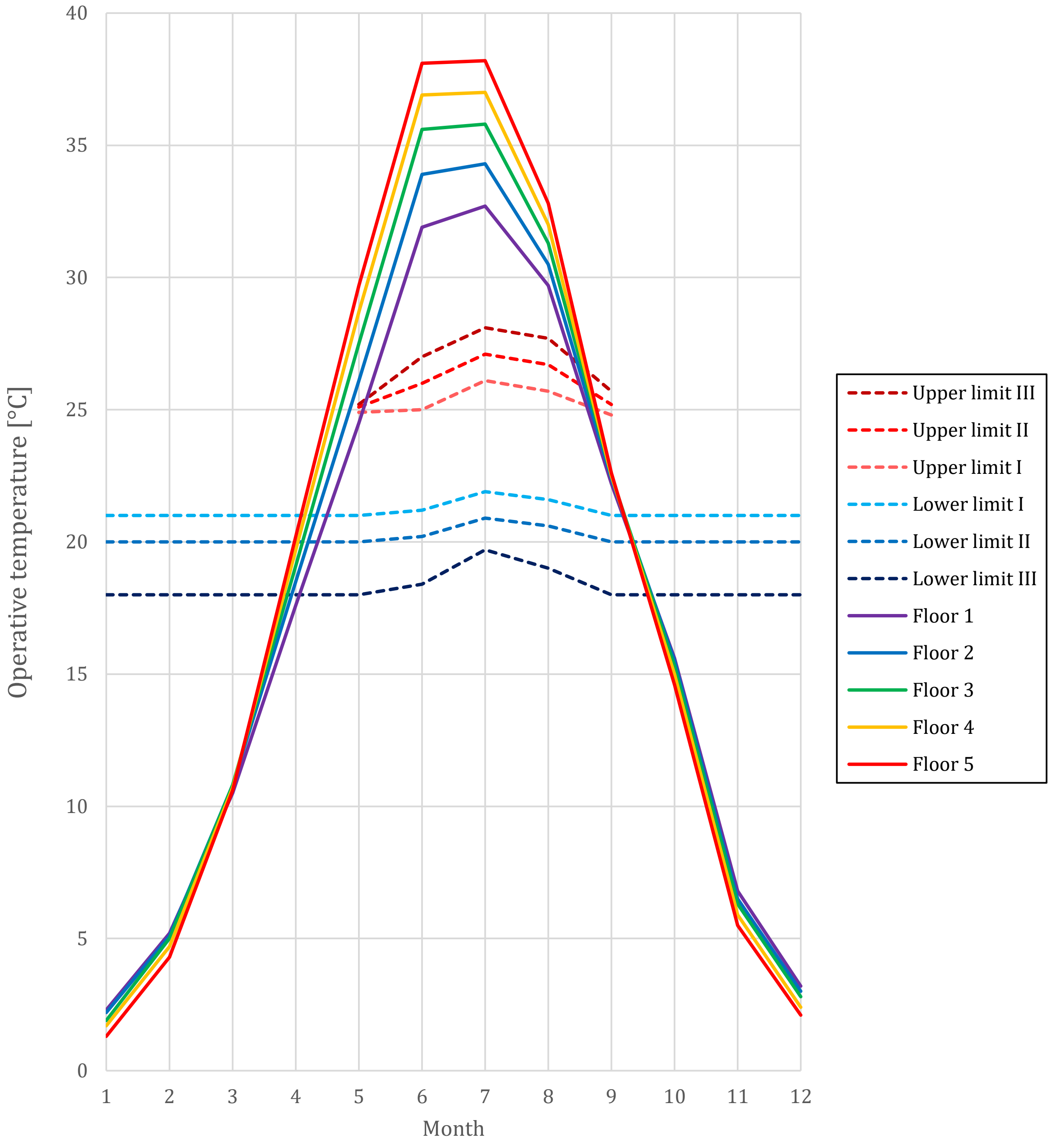


Figure 7.1 Monthly mean operative temperature in each floor level, and comfort limits during the design reference year.

The curve of the operative temperature follows the curve of the window heat gain over the year. The window heat gain is largest during the summer, which results in the warmest operative temperature. The window heat loss is largest during the winter, which results in the coldest operative temperature.

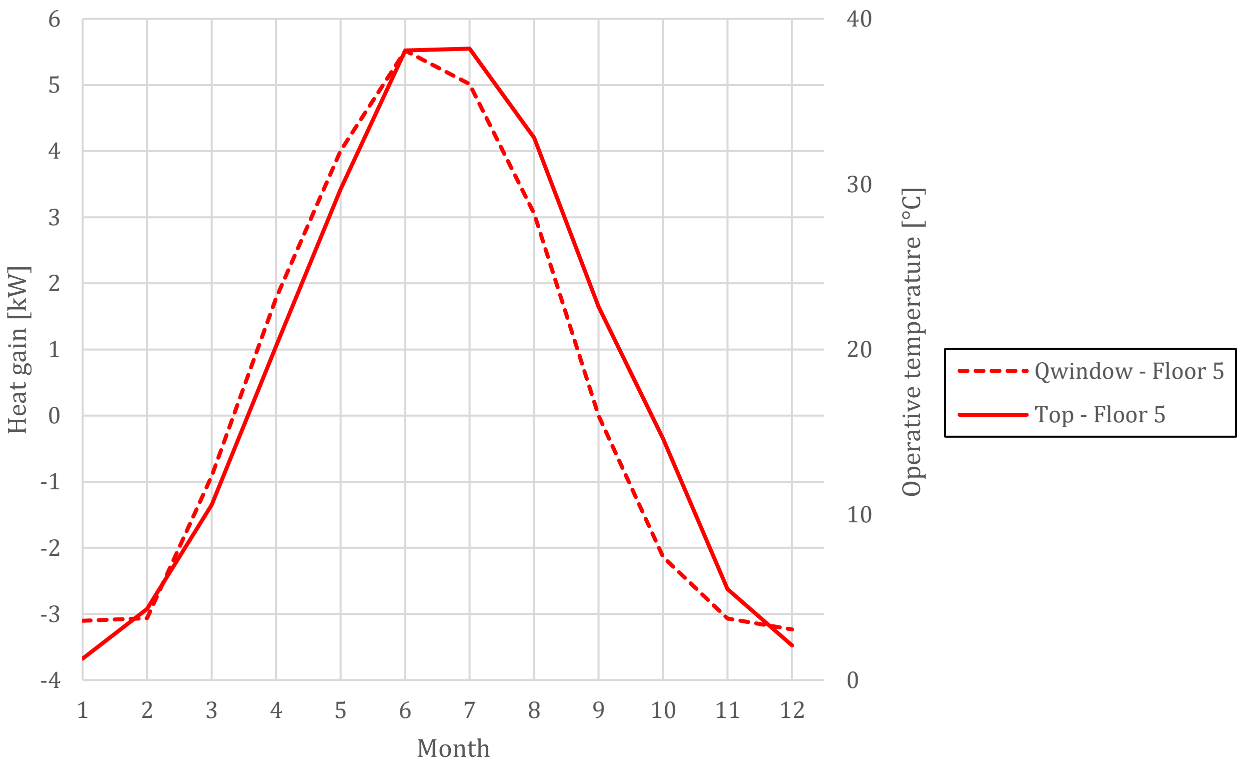


Figure 7.2 Window heat gain vs operative temperature in floor 5 during the design reference year.

The previous conclusions from the interviews in the spaces project is correct regarding too warm and cold operative temperature during summer respectively winter. The operative temperature is too high during the summer and too low during the winter to achieve thermal comfort according to the standard. Due to the large glazing area, the heat gains through the windows are largest during the summer and the heat losses through the windows are largest during the winter. The increased heat gains during summer and heat losses during winter results in too warm respectively too cold operative temperature in the atrium according to the standard.

7.2 Most critical location

Thermal comfort is dependent on where the occupant is located. The impact of the occupant location is evaluated by an investigation of the thermal comfort in different locations in the atrium, both floor level and position on the most critical floor level.

The results of the most critical location considering floor level and position on floor level during the summer and winter period will be presented in this chapter. The summer period is examined during the summer week and the winter period is examined during the winter week.

The previous conclusion from the interviews in the Spaces project regarding the most critical location is also correct. The top floor is the most critical floor level during both summer and winter, due to a larger glazing area. However, the temperature difference between the floor levels are larger during the summer than during the winter.

During the summer, the top floor has the warmest operative temperature in the atrium. This is because the top floor has the largest glazing area and is the most upper floor. A larger glazing area will let more solar radiation into the room. Additionally, heat from the other floors will leak into the top floor through the openings since warm air has a lighter density and will be transported from lower floors to upper floors.

During the winter, the top floor has the coldest operative temperature in the atrium. This is because the top floor has the largest glazing area, which has higher U-value compared to the other building components and more transmission losses will occur over the windows.

The location on the top floor does not have any impact on the thermal comfort. It is more critical to be located close to the windows since the surface temperature of the windows is more affected of the outdoor temperature and solar radiation compared to the other surfaces of the atrium. However, the window placement is 1.8 meter above the floor level, which is above the occupant of all the investigated cases.

7.2.1 Floor level

The most critical location of the occupant is investigated by comparing the impact of floor level.

Table 7.3 Occupant position in each floor level.

Case	x-direction	y-direction	z-direction	Floor level
Floor 1	2	13	0.6	1
Floor 2	2	13	0.6	2
Floor 3	2	13	0.6	3
Floor 4	2	13	0.6	4
Floor 5	2	13	0.6	5

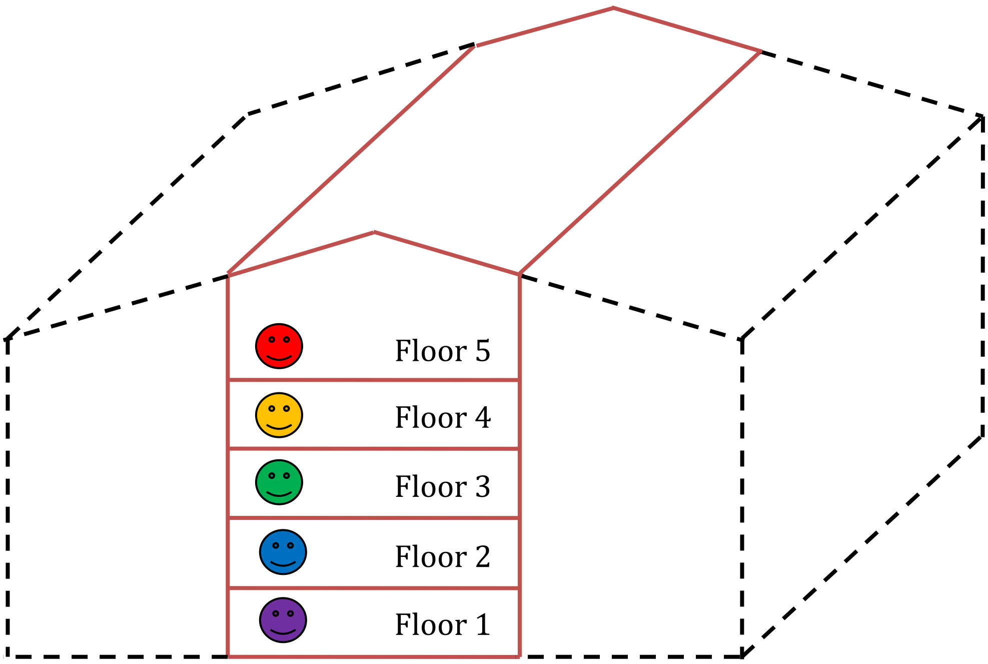


Figure 7.3 Occupant position in each floor level.

7.2.1.1 Summer period

Figure 7.4 shows the operative temperature, and the upper comfort limits during the summer week. The operative temperature is too warm during all hours of the summer week according to the standard. The warmest operative temperature occurs in floor 5 and decreases downward with the floor level.

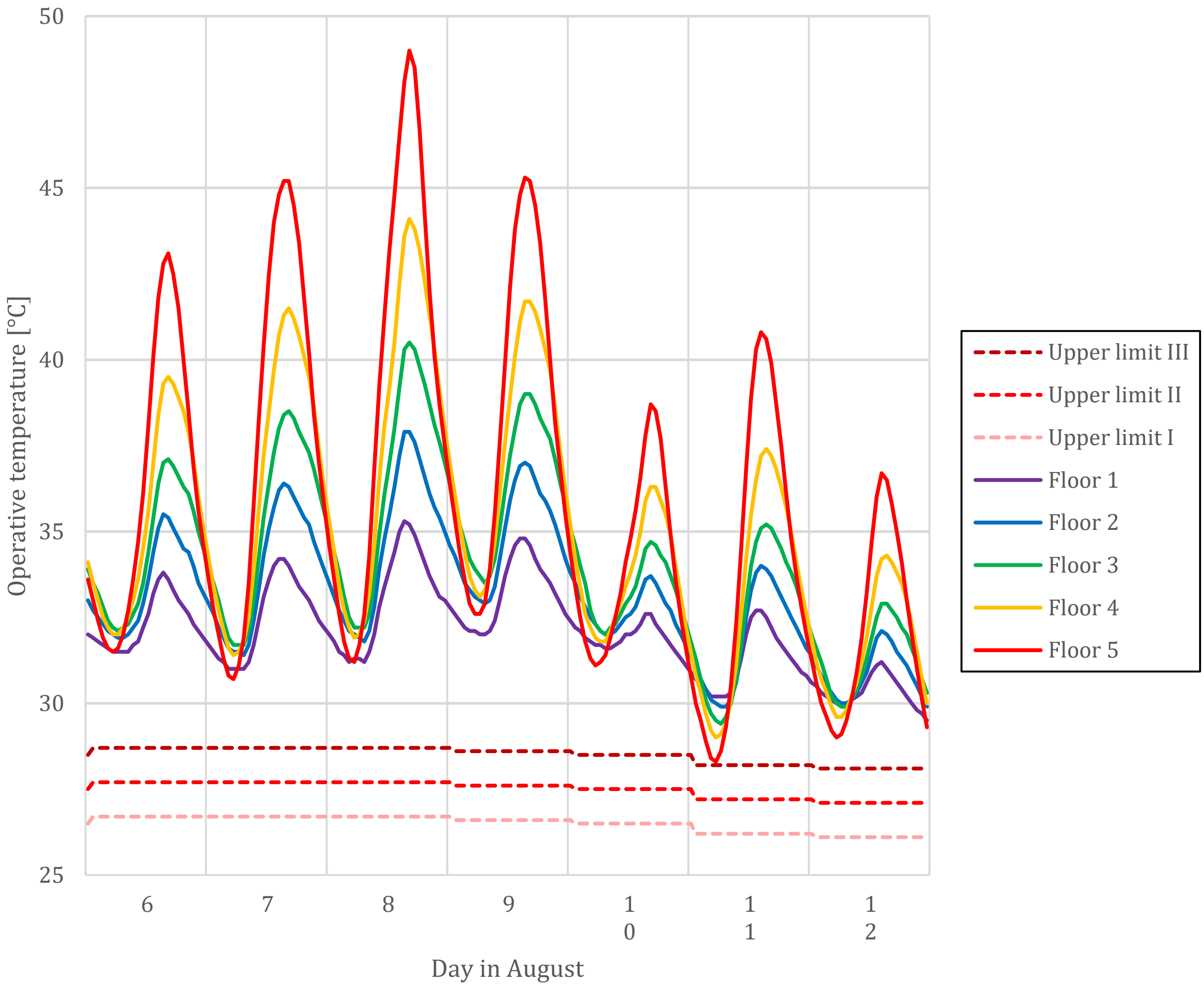


Figure 7.4 Operative temperature in each floor and upper comfort limits during summer week.

Figure 7.5 and 7.6 shows operative temperature in floor 1 and 5, and the heat gain through windows respectively openings during the summer week. During the days, the heat gains through the windows and openings are larger in floor 5. During the night, the heat losses through the windows are larger in floor 5. However, during the night, the heat losses through the openings are larger in floor 1. This results in a warmer operative temperature in floor 5 during the days and almost equal operative temperature during the nights.

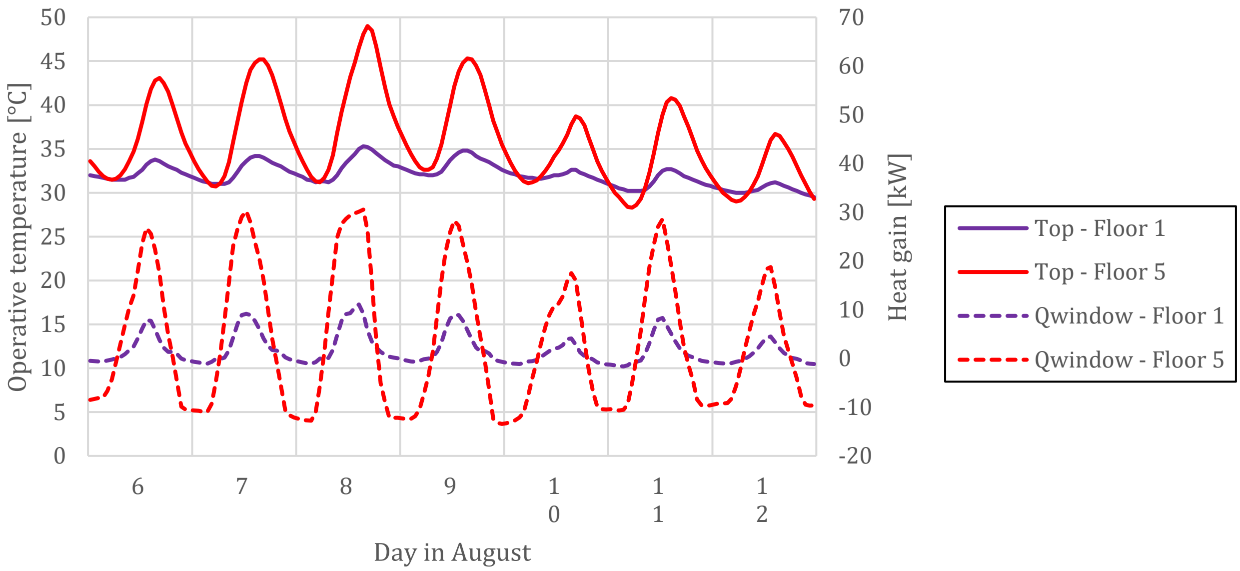


Figure 7.5 Operative temperature, and window heat gain in floor 1 and 5 during summer week.

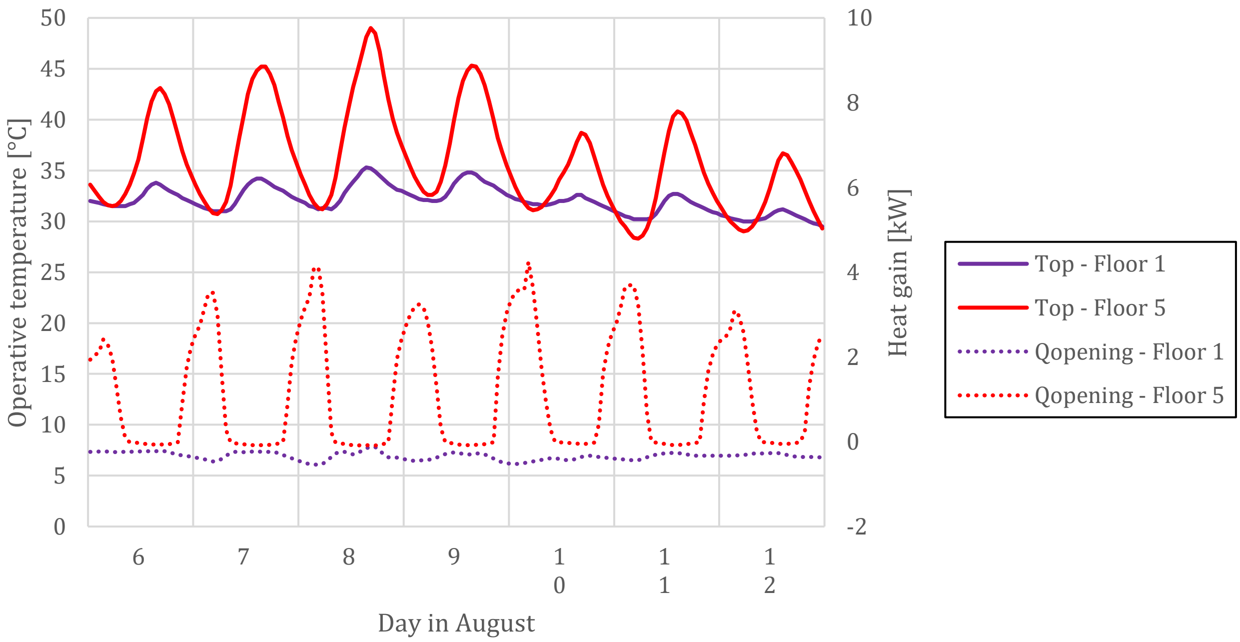


Figure 7.6 Operative temperature, and opening heat gain in floor 1 and 5 during summer week.

7.2.1.2 Winter period

Figure 7.7 shows the operative temperature and lower comfort limits during the winter week. The operative temperature is too cold during all hours of the cold week according to the standard. The coldest operative temperature in the atrium occur in floor 5. Thereafter, the coldest operative temperature of each floor increases downward.

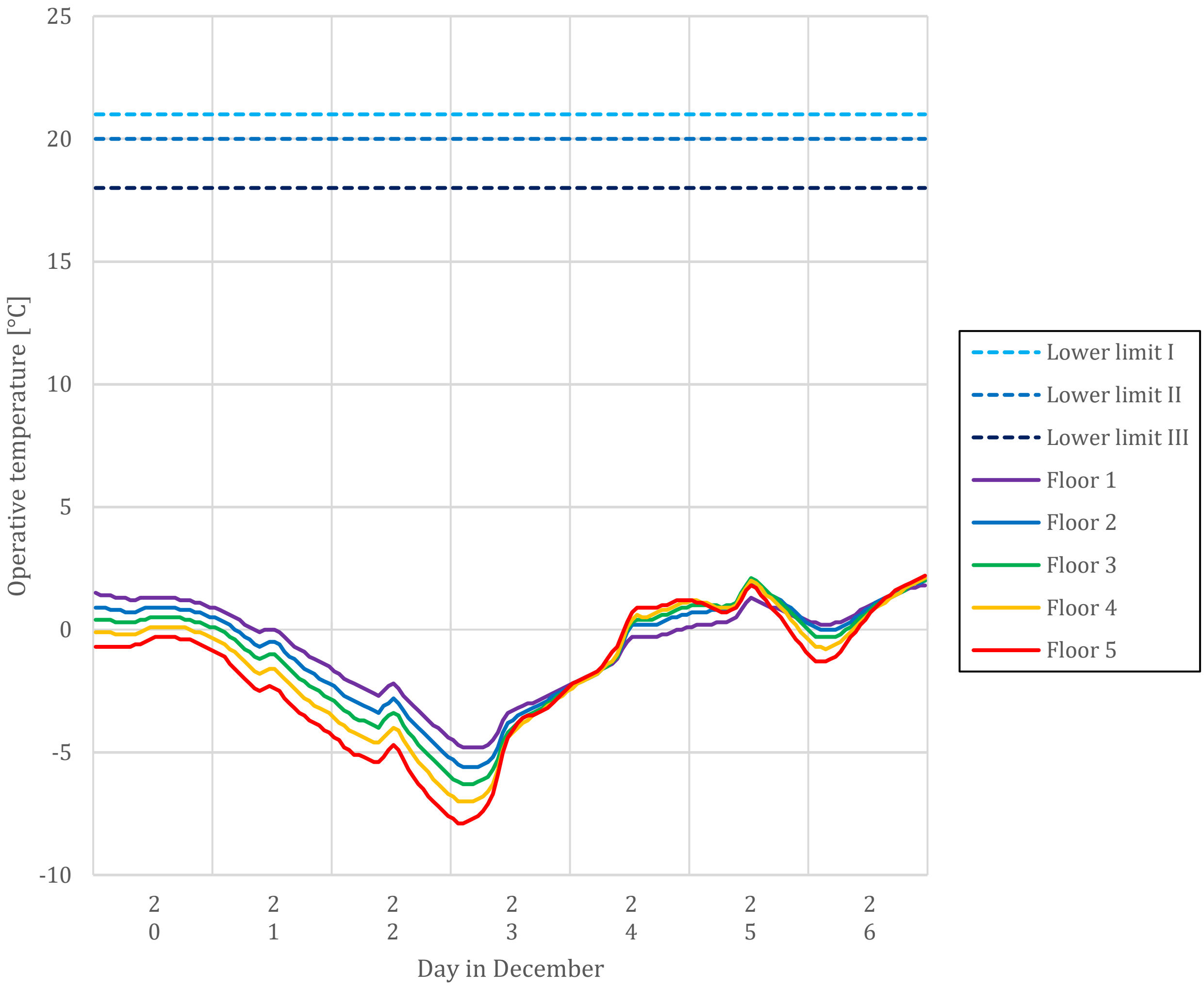


Figure 7.7 Operative temperature of each floor, and the lower thermal comfort limits during winter week.

Figure 7.8 and 7.9 shows operative temperature in floor 1 and 5, and the heat gain through windows respectively openings during the winter week. During the first three days, the heat losses through the windows are larger in floor 5. However, floor 5 is gaining heat through openings, while floor 1 is losing heat through openings. This results in a slightly lower operative temperature in floor 5. During the following days, the heat gains and losses through windows and openings are approximately equal in floor 1 and floor 5, which results in an almost equal operative temperature.

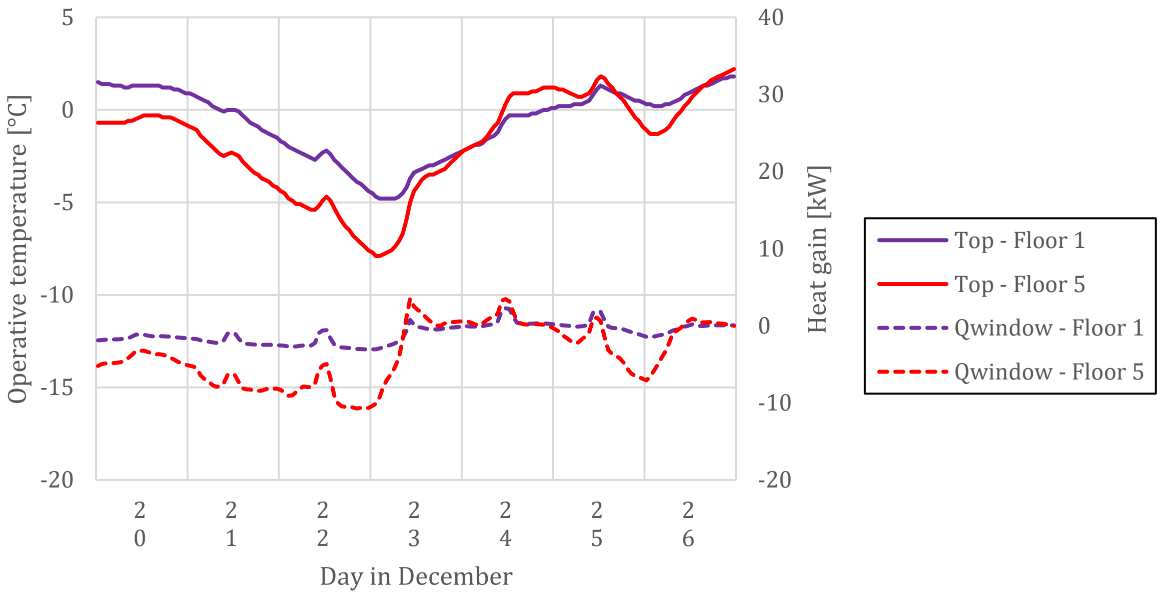


Figure 7.8 Operative temperature, and window heat gain in floor 1 and 5 during winter week.

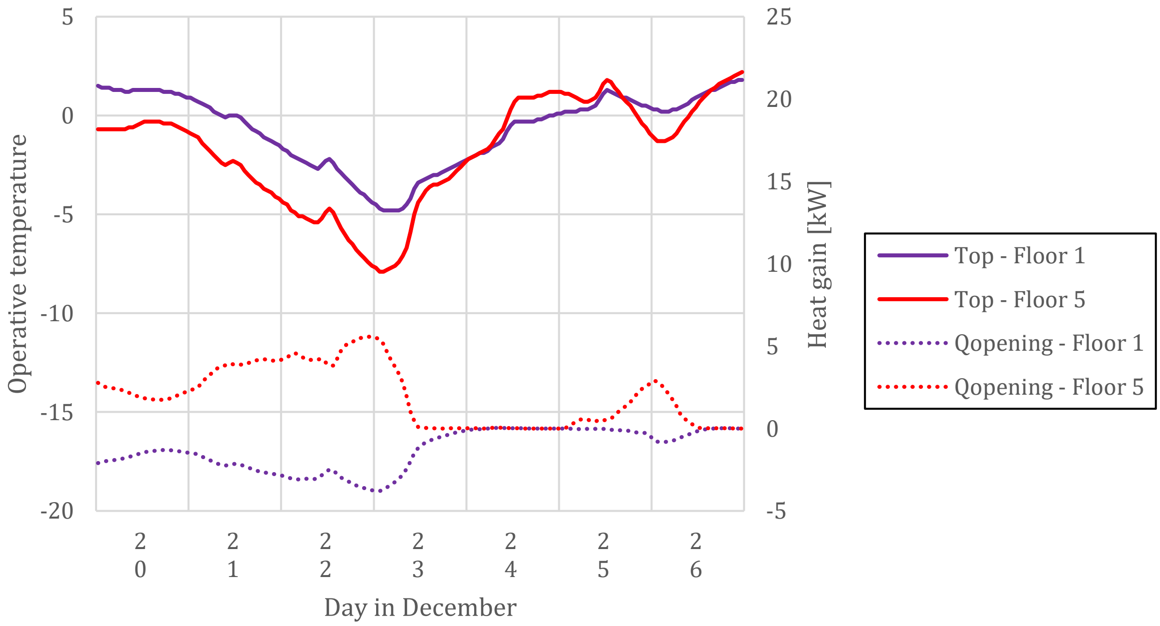


Figure 7.9 Operative temperature, and window heat gain in floor 1 and 5 during winter week.

7.2.2 Position

The most critical location of the occupant is investigated by comparing the impact of position on floor 5. In the reference case, the occupant is sitting on one of the balconies, which is located close to the center of the room. In the case “Standing”, the occupant is standing instead of sitting on the balcony. In case “Standing close to window”, the occupant is standing close to one the windows on the south exterior wall. In the case “Sitting close to window”, the occupant is sitting close to one of the windows on the south exterior wall.

Table 7.4 Position of different location cases.

Case	x-direction	y-direction	z-direction
Reference	2	13	0.6
Standing	2	13	0.9
Close to window	4	0.5	0.6

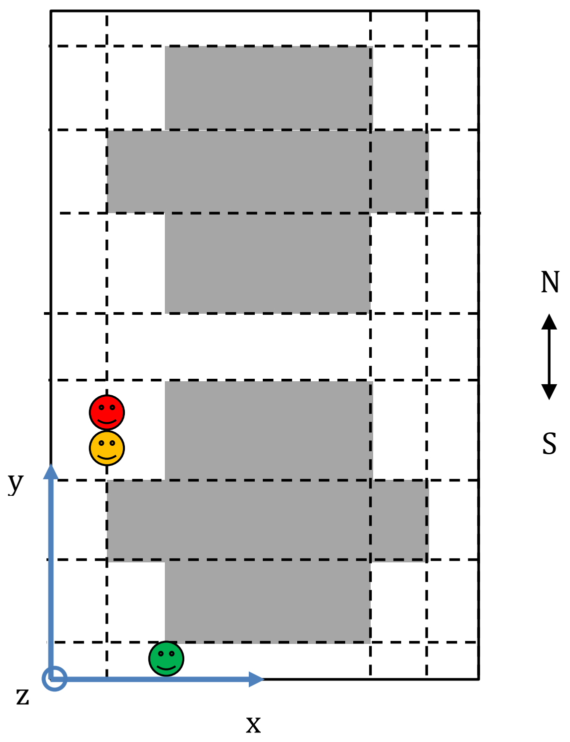


Figure 7.10 Occupant position in x-direction for the evaluation cases.

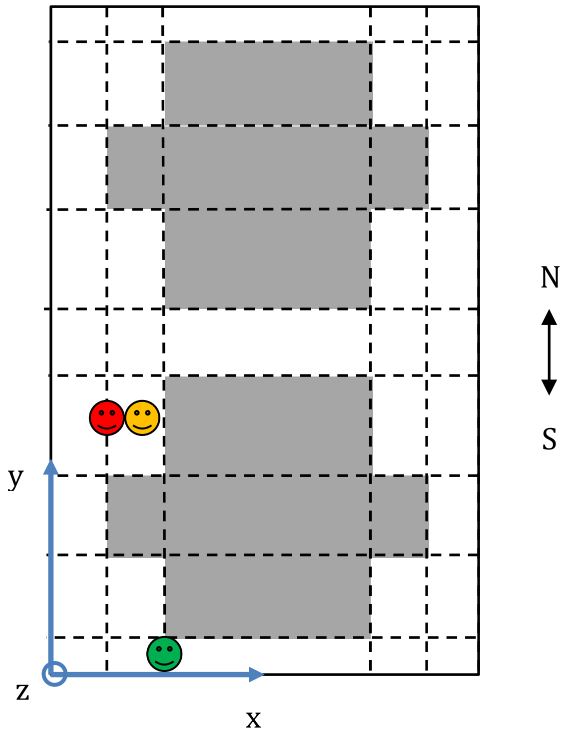


Figure 7.11 Occupant position in y-direction for the evaluation cases.

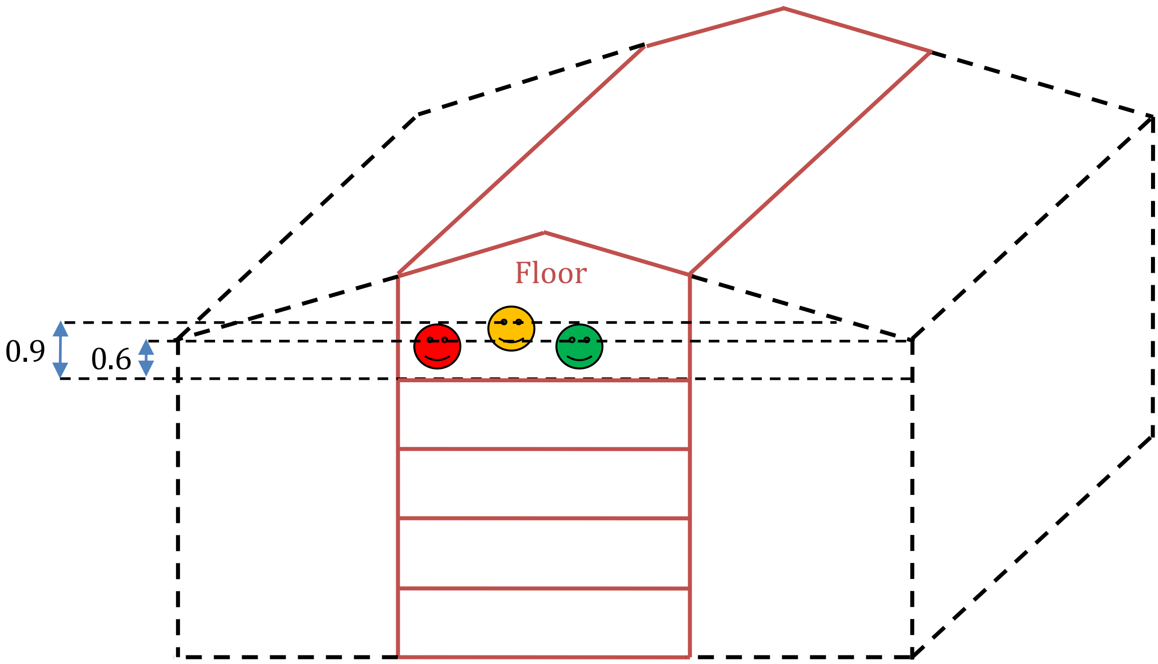


Figure 7.12 Occupant position in z-direction for the evaluation cases.

7.2.2.1 Summer period

Figure 7.13 shows the operative temperature in floor 5 for all evaluation cases, and the upper comfort limits during the summer week. The operative temperature is equal in all evaluation cases. The occupant position on the floor level does not have any impact on the operative temperature during the summer week.

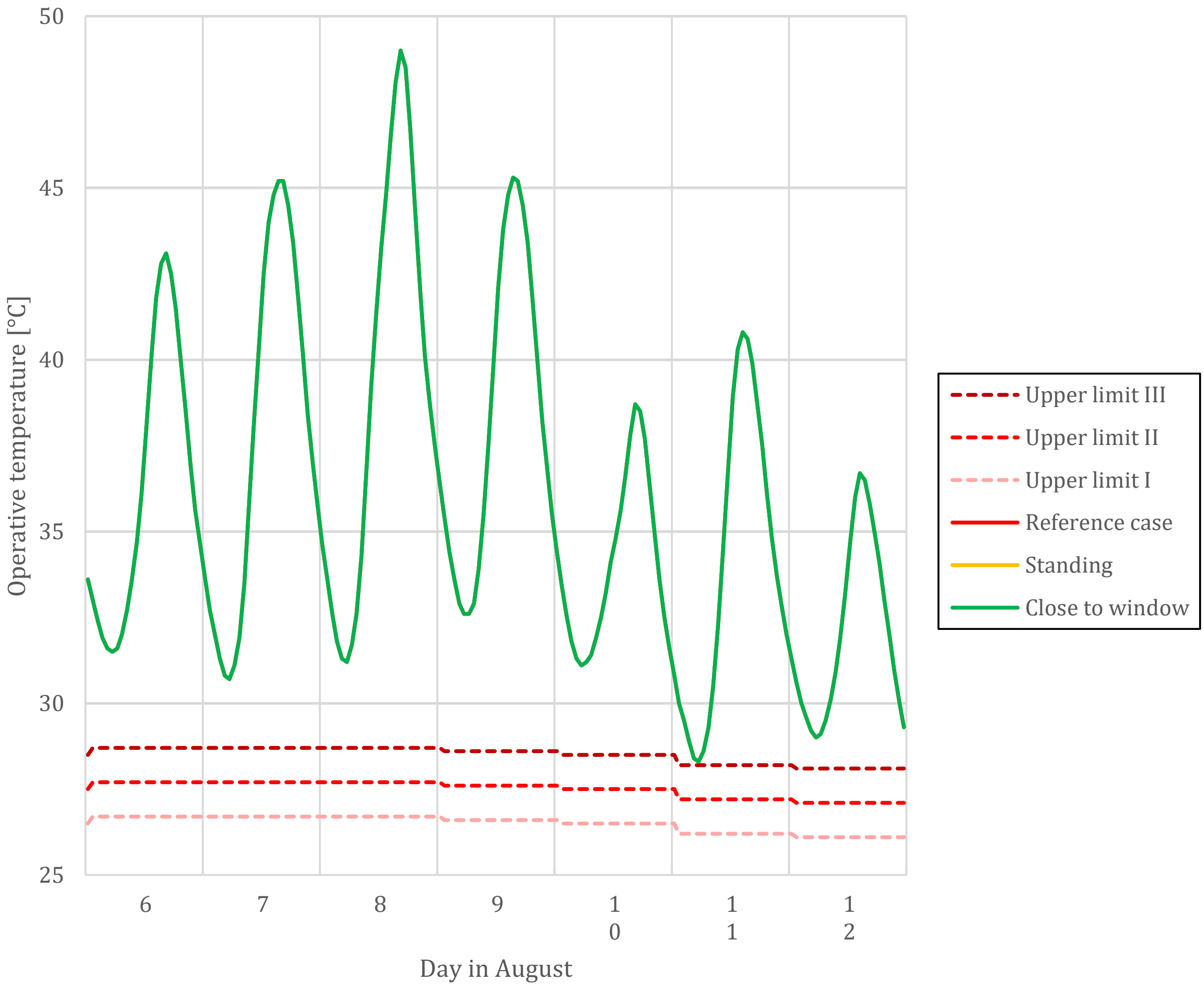


Figure 7.13 Operative temperature, and the upper thermal comfort limits in floor 5 during summer week.

7.2.2.2 Winter period

Figure 7.14 shows the operative temperature in floor 5 for all evaluation cases and the lower comfort limits during the winter week. The operative temperature is equal in all cases. The occupant position on the floor level does not have any impact on the operative temperature during the winter week.

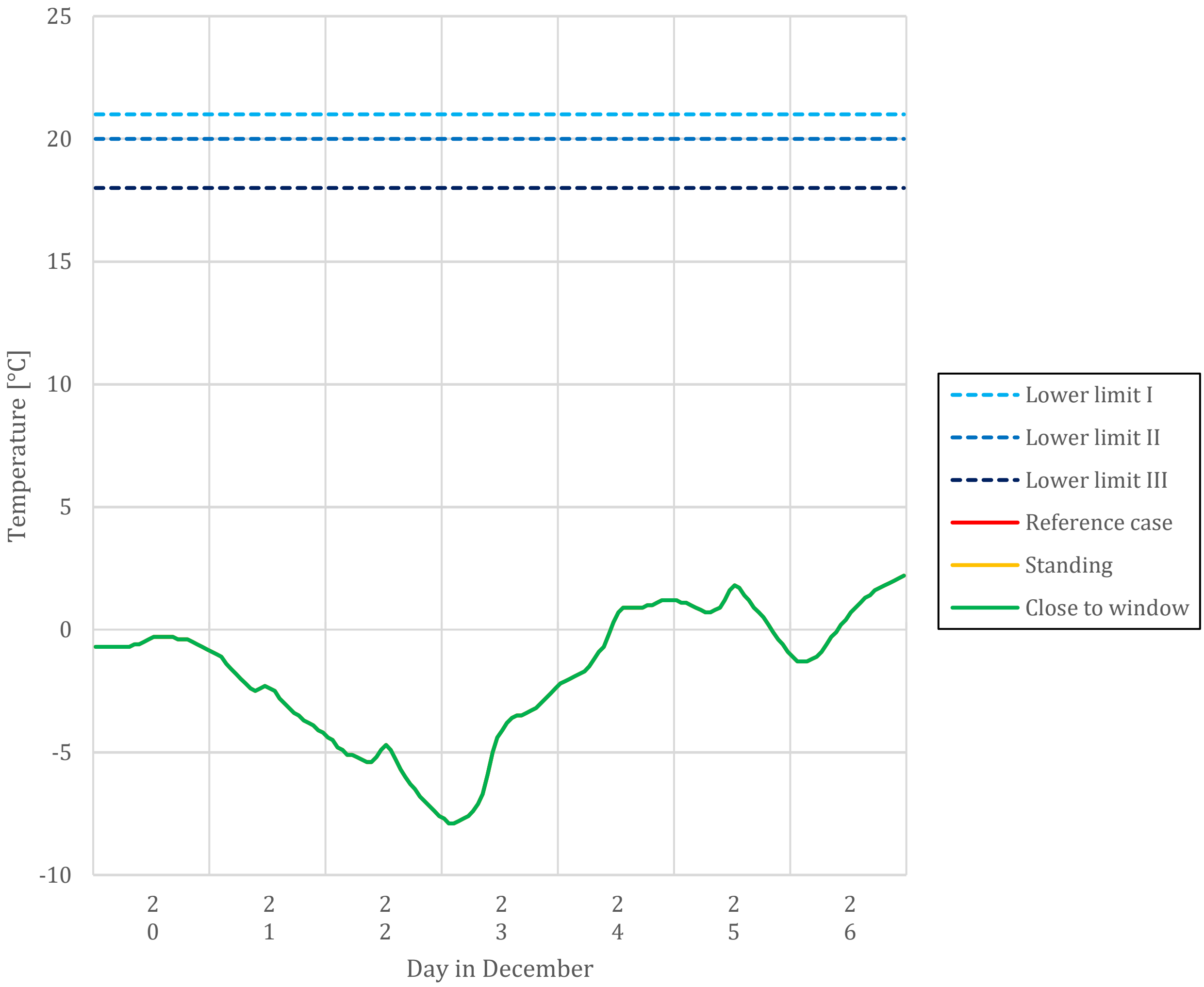


Figure 7.14 Operative temperature in floor 5, and lower thermal comfort limits during the winter week.

7.3 Thermal mass

The impact of thermal mass is investigated by comparing the reference building with three cases with higher thermal mass, which were described in 6.1. A building with increased thermal mass can store and release heat. Therefore, the summer period is examined during the summer month and the winter period is examined during the winter month.

The operative temperature in the atrium is highly dependent on the thermal mass. The operative temperature oscillates less in the cases with higher thermal mass and the maximum and minimum operative temperature is lower respectively higher compared to the reference case. The higher the thermal mass is, the more the temperature oscillations decreases.

The operative temperature is dependent on the surface temperatures and the indoor mean air temperature, which are is affected by the thermal mass. For the reference case, the operative temperature varies according to the outdoor temperature and solar radiation. For the cases with higher thermal mass, the operative temperature varies much smaller according to the outdoor temperature.

During the summer, when the solar radiation and outdoor temperature is generally higher, a higher thermal mass is beneficial when the outdoor temperature and solar radiation is higher. However, a lower thermal mass is beneficial when outdoor temperature and solar radiation is lower. It is advantageous to have a higher thermal mass during warmer days since the maximum temperature is decreased. However, it will also increase the minimum operative temperature during the night.

During the winter, when the solar radiation and outdoor temperature is generally lower, a higher thermal mass is beneficial when the outdoor temperature and solar radiation is lower. However, during cold and sunny days it can sometimes be advantageous to have lower thermal mass since the temperature within the building will be heated up faster compared to a building with higher thermal mass. A higher thermal mass is almost always beneficial during the winter since the outdoor temperature and solar radiation is almost always low.

7.3.1 Summer period

Figure 7.15 shows the operative temperature in floor 5 in all evaluation cases, and the upper thermal comfort limits during the summer month. The operative temperature of the reference case is within the comfort limits during some hours of the summer month. However, in all cases with higher thermal mass, the operative temperature is too warm to achieve thermal comfort according to the standard.

The operative temperature oscillates less in the cases with higher thermal mass. The maximum and minimum operative temperature of the cases with higher thermal mass is lower respectively higher compared to the reference case. The minimum operative temperature and the maximum operative increases respectively decreases in the following order; reference case, case 1, case 2 and case 3. The operative temperature difference in floor 5 decreases in the same order.

The maximum operative temperature of all cases is 50.1 °C and occur 1st of August in the reference case. The time period 30 july-2 August is therefore investigated more in detail and is called the warmer period during summer. The minimum operative temperature is 22 °C and occur 29th of August in the reference case. The time period 27-30 of August is therefore also investigated more in detail and is called colder period during summer.

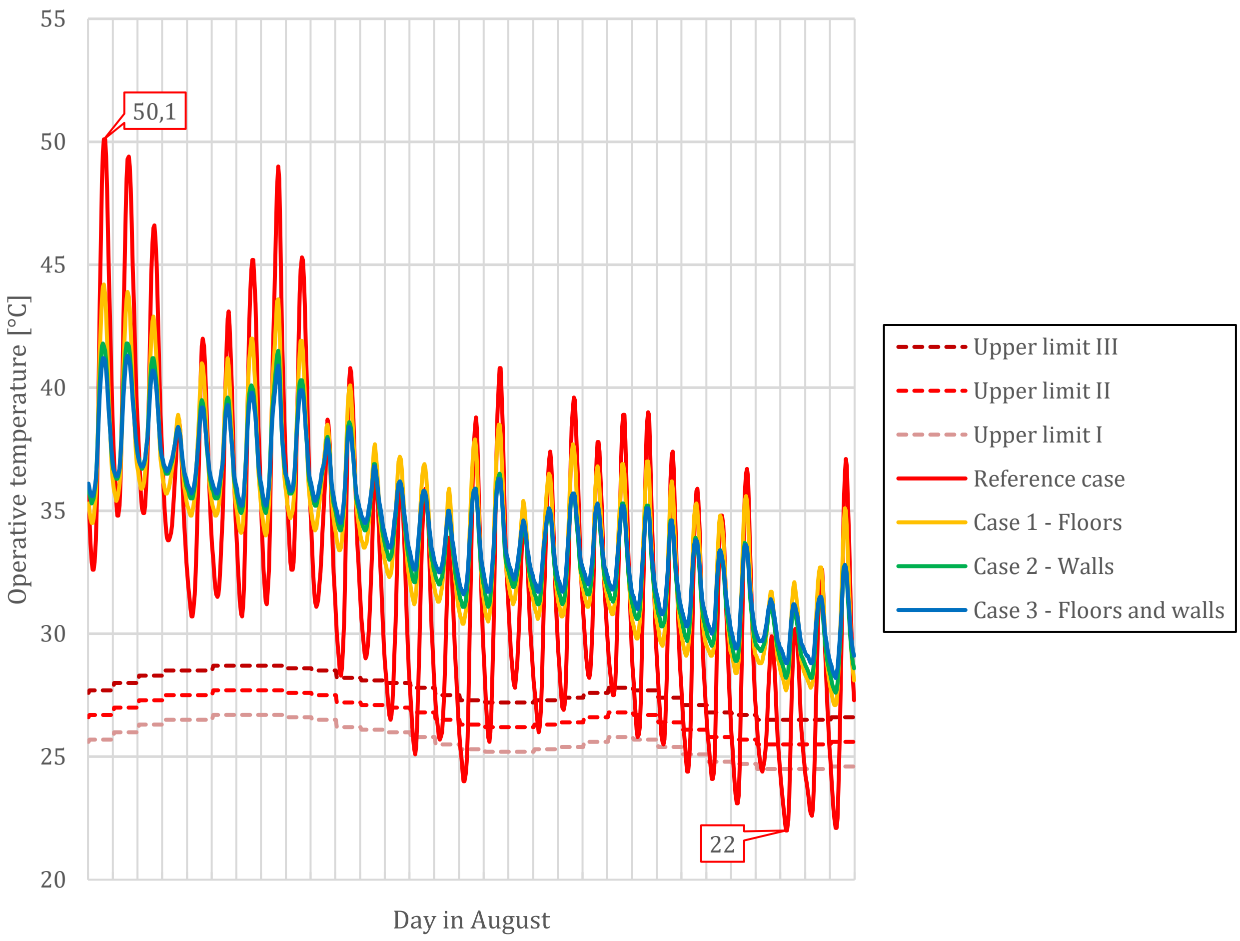


Figure 7.15 Operative temperature in floor 5, and the upper thermal comfort limits during the summer month.

7.3.1.1 Warmer period during summer

In the reference case, the operative, mean air and mean surface temperature of floor, roof and walls are approximately of equal size. However, the mean surface temperature of the windows is lower compared to the other mean surface temperatures. The temperatures vary with the outdoor temperature and solar radiation. In case 3, the operative, mean air and mean surface temperature of floor, roof and walls varies more in relation to each other but less in relation to the outdoor temperature and solar radiation in comparison to the reference case. However, the mean surface temperature of the windows is varying with the outdoor temperature and solar radiation and reaches higher temperature than the other surfaces during some hours of the studied period.

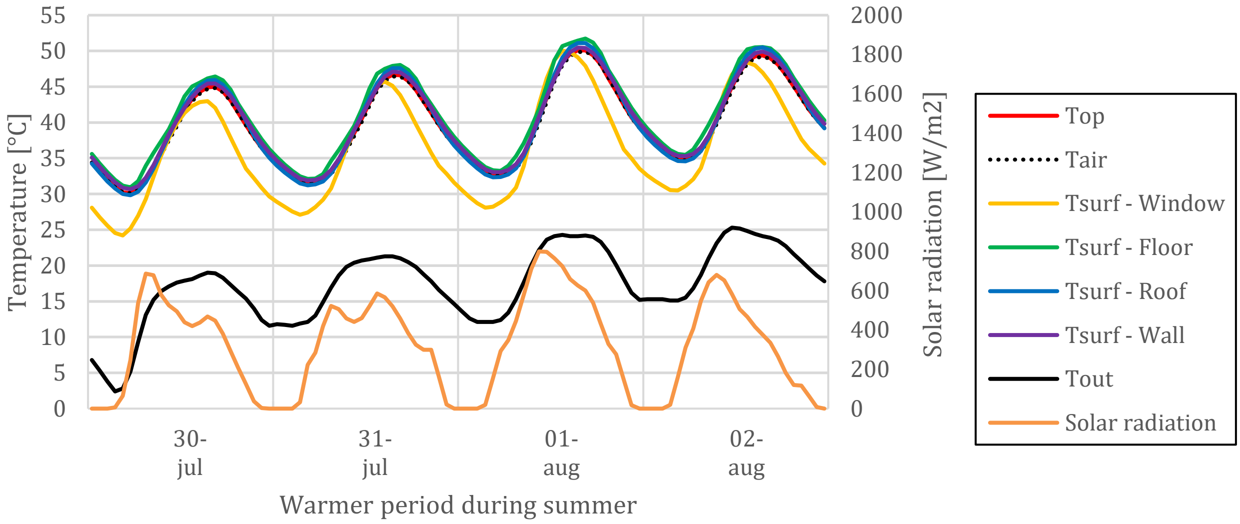


Figure 7.16 Operative temperature, mean air temperature and surface temperature of floor 5 in the reference case, and the outdoor temperature and solar radiation of warmer period during summer.

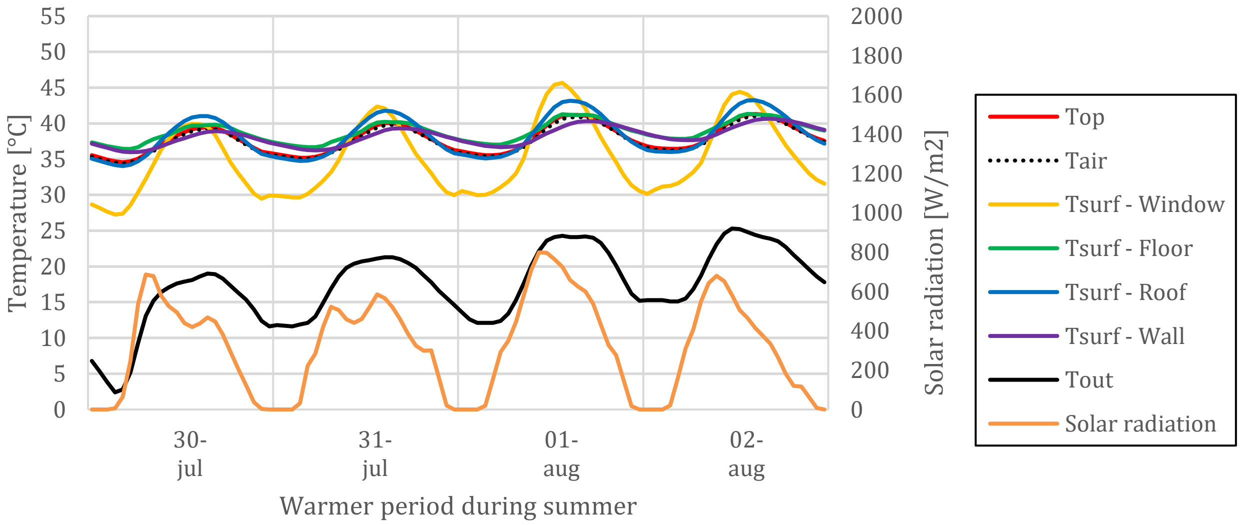


Figure 7.17 Operative temperature, mean air temperature and surface temperature of floor 5 in case 3, and the outdoor temperature and solar radiation during of warmer period during summer.

When the solar radiation and outdoor temperature is lower, case 3 releases more heat than the reference case. When the solar radiation and outdoor temperature is higher, case 3 stores more heat than the reference case.

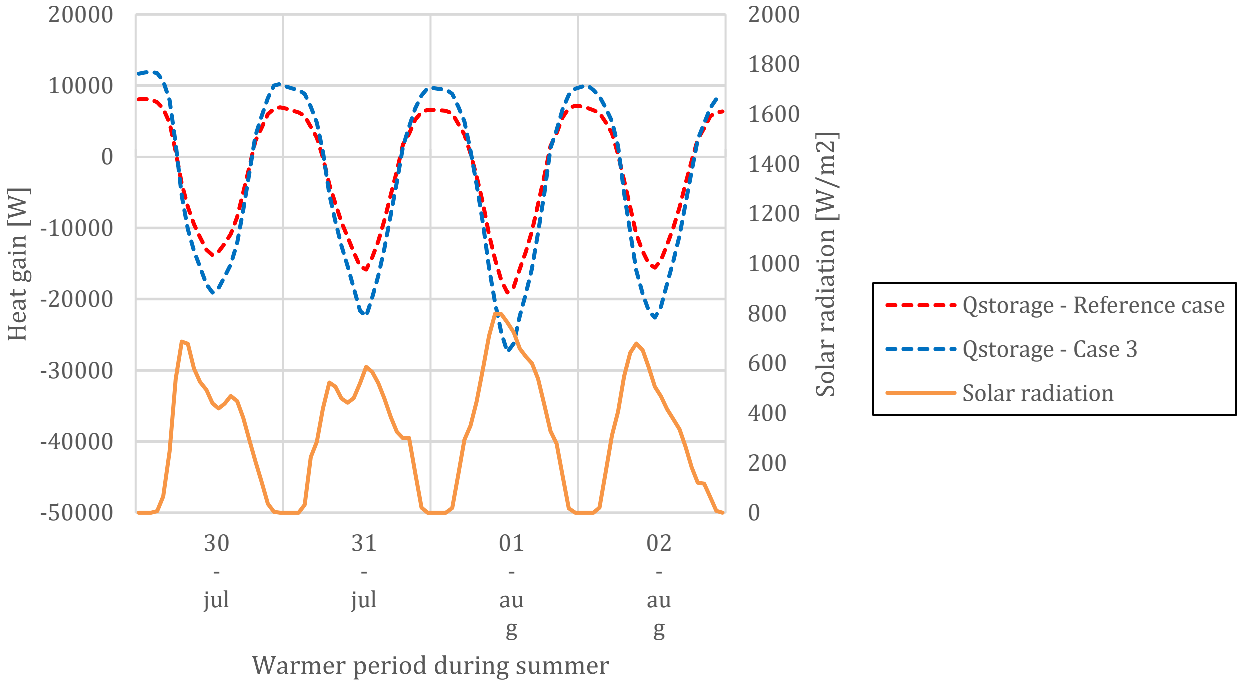


Figure 7.18 Storage heat gain in floor 5, and the solar radiation of warmer period during summer.

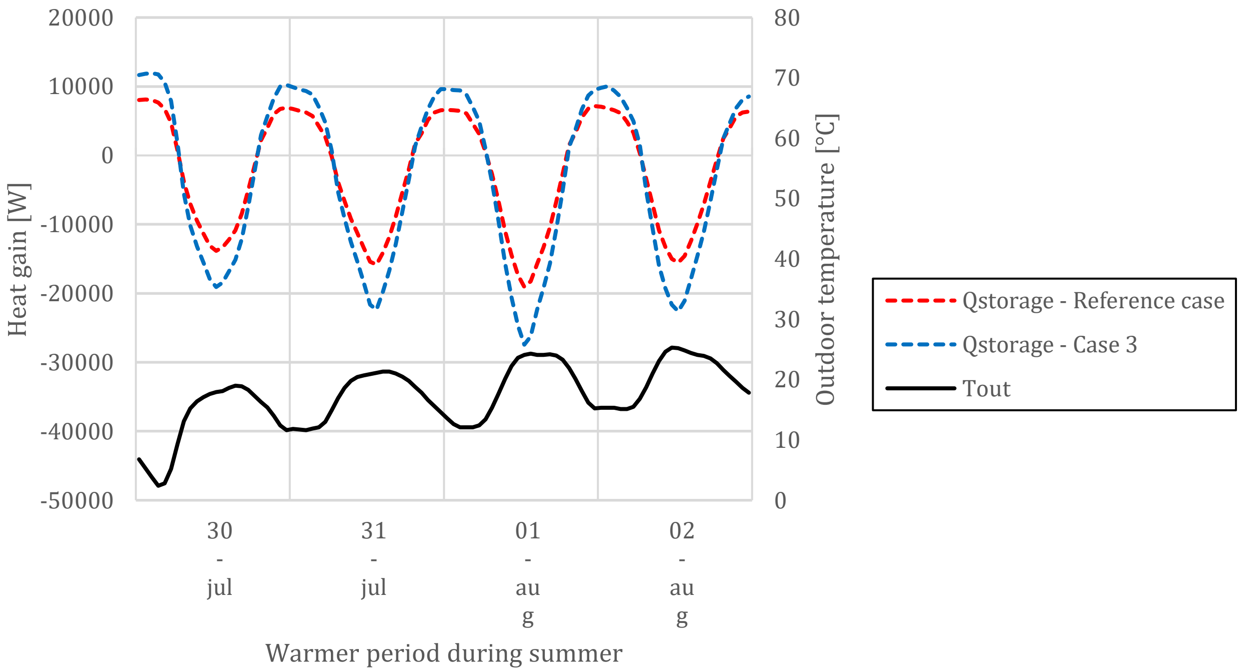


Figure 7.19 Storage heat gain in floor 5, and the outdoor temperature of warmer period during summer.

Figure 7.20 shows the storage heat gain and operative temperature in floor 5 of the reference case and case 3. The ability to release heat, when there is no solar radiation and the outdoor temperature is lower, increase the operative temperature in the atrium. The ability to store heat, when the solar radiation and outdoor temperature is higher, decrease the operative temperature in the atrium.

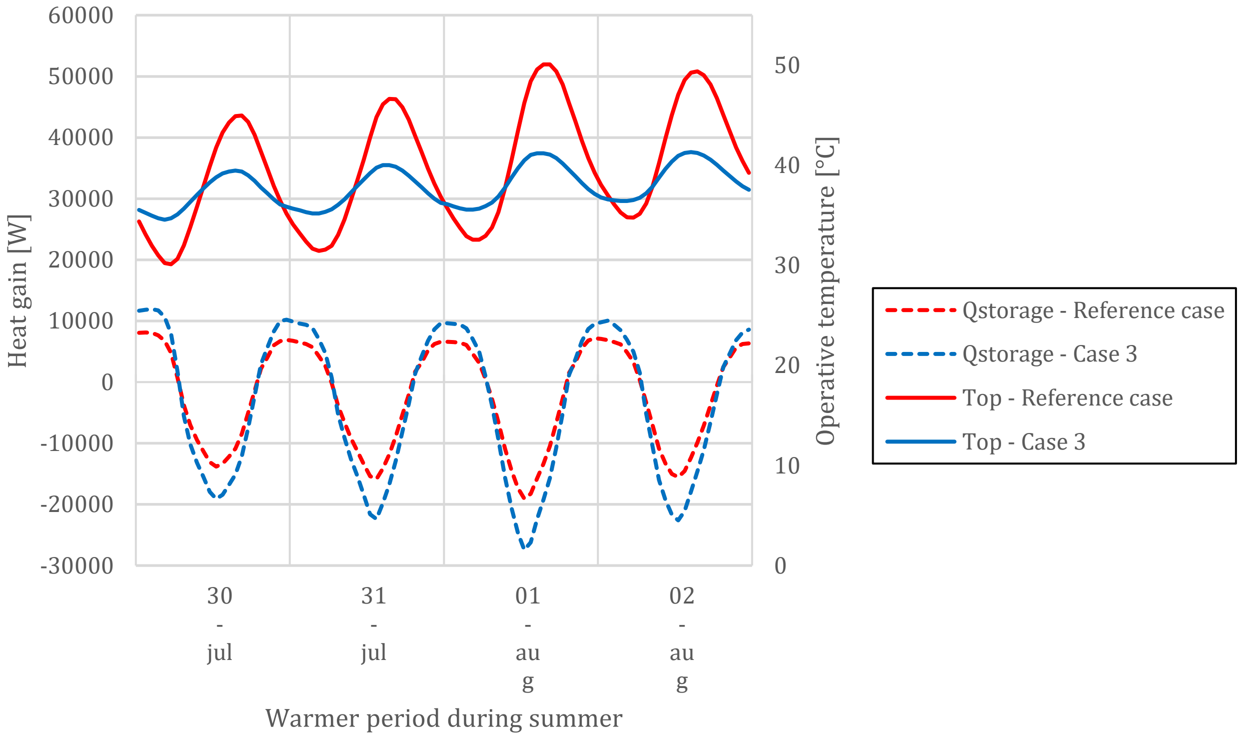


Figure 7.20 The storage heat gain, and the operative temperature in floor 5 of warmer period during summer.

7.3.1.2 Colder period during summer

In the reference case, the temperatures are approximately of equal size. However, the mean surface temperature of the windows is smaller compared to the other surfaces. The temperatures vary with the outdoor temperature and solar radiation. In case 3, the temperatures vary more in relation to each other but less in relation to the outdoor temperature and solar radiation in comparison to the reference case. However, the mean surface temperature of the windows is varying with the solar radiation and reaches higher temperature than the other surfaces during some hours of the studied period.

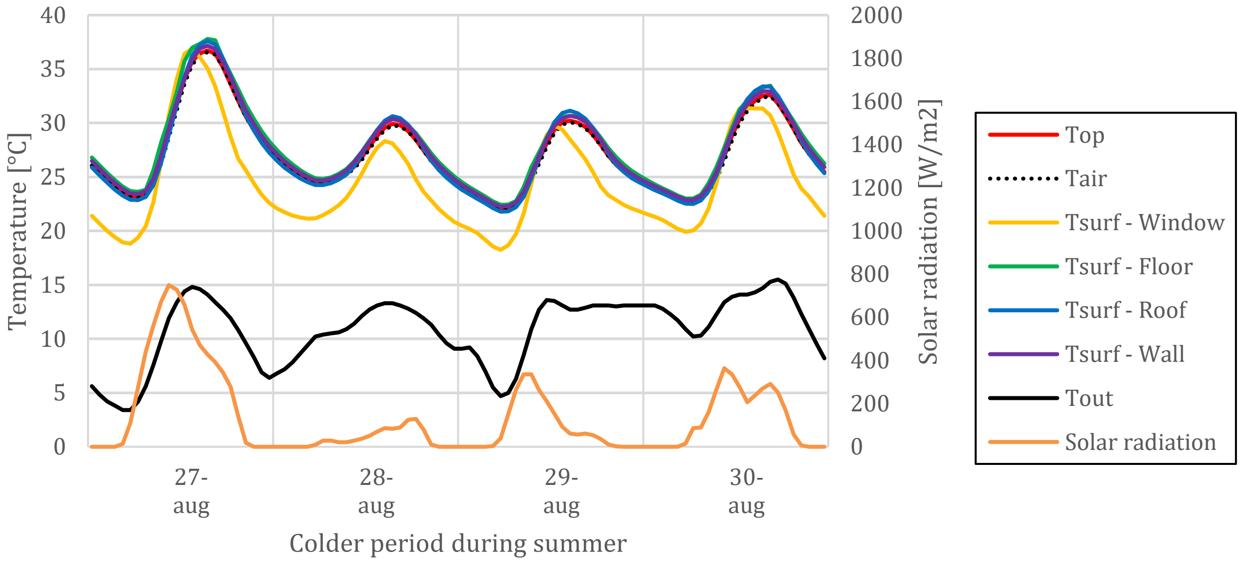


Figure 7.21 Operative temperature, mean air temperature and surface temperature of floor 5 in the reference case, and the outdoor temperature and solar radiation of colder period during summer.

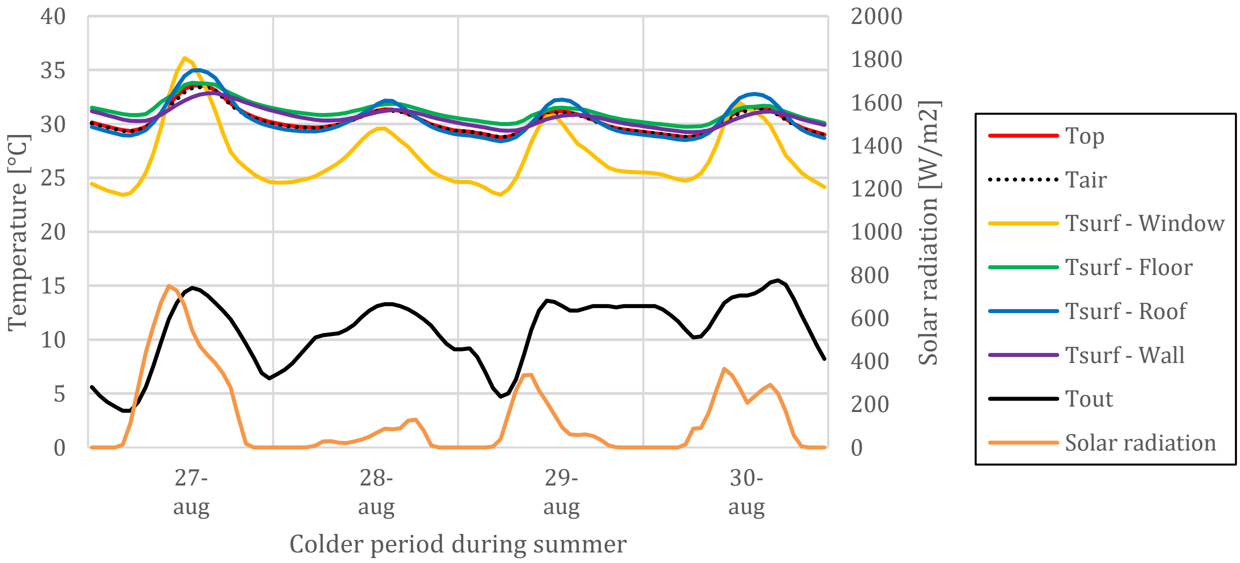


Figure 7.22 Operative temperature, mean air temperature and surface temperature of floor 5 in the reference case, and the outdoor temperature and solar radiation of colder period during summer.

Figure 7.23 and 7.24 shows the storage heat gain of the reference case and case 3, and the solar radiation respectively outdoor temperature. During the first day, when the solar radiation is higher than the following days, the atrium stores and releases more heat in case 3 compared to the reference case. During the second day, when the solar radiation is lower than the day before, the atrium releases more heat in case 3 than the reference case but stores almost equal amount of heat.

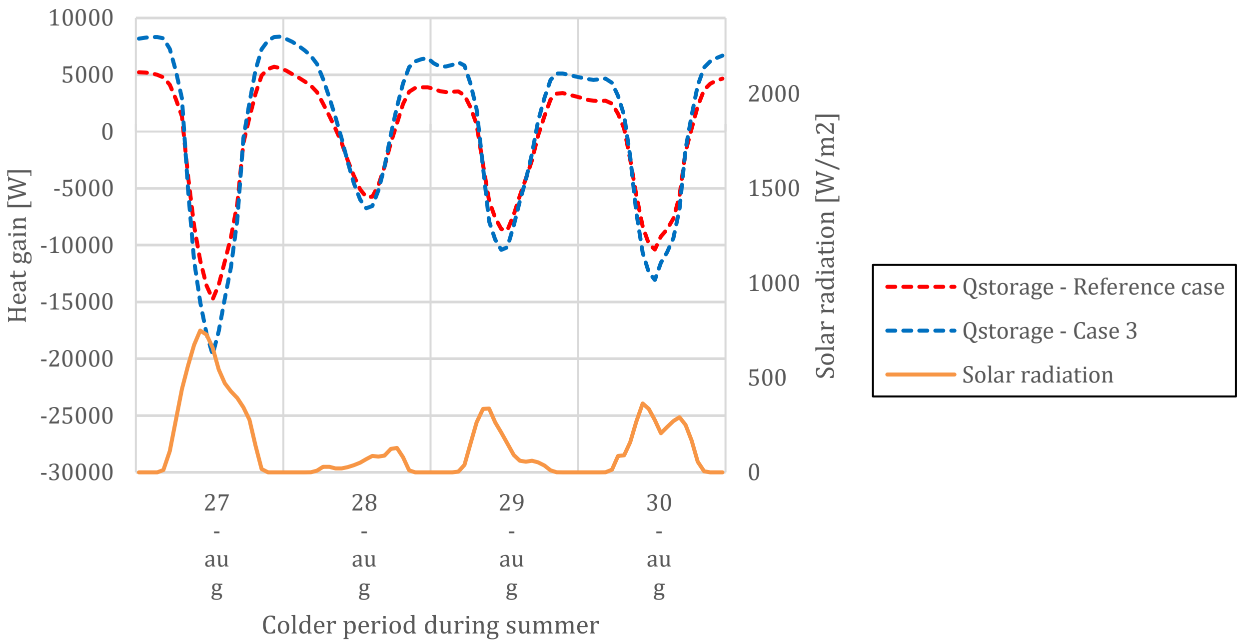


Figure 7.23 Storage heat gain in floor 5 of the reference case and case 3, and the solar radiation of colder period during summer.

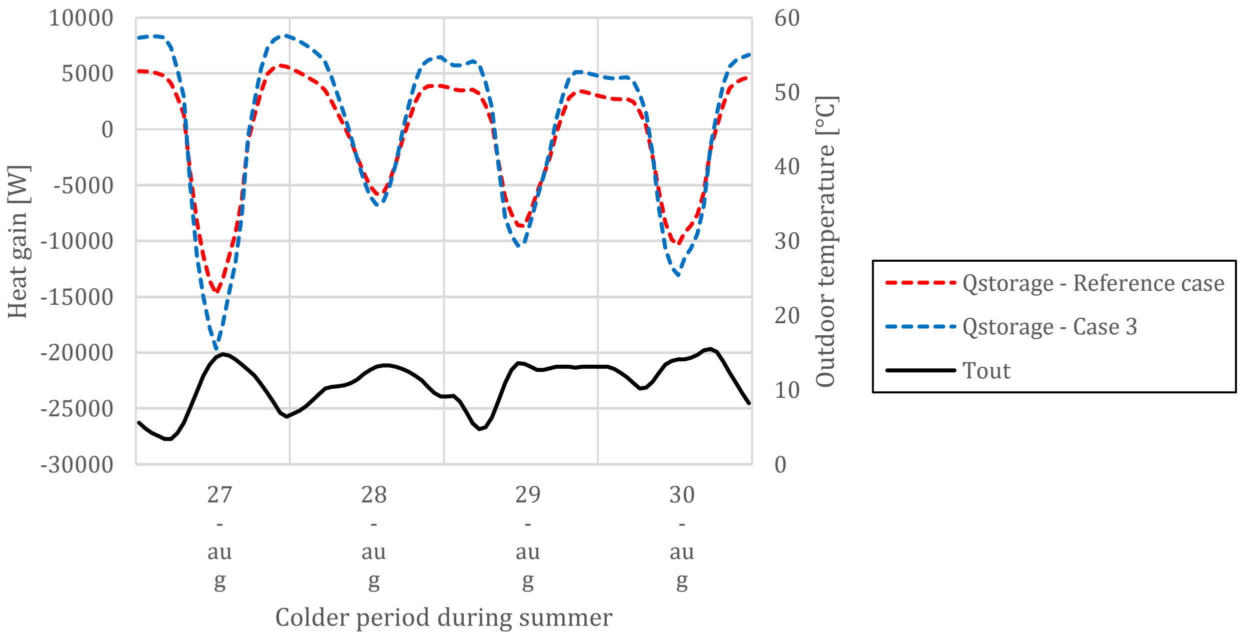


Figure 7.24 Storage heat gain in floor 5 of the reference case and case 3, and the outdoor temperature of colder period during summer.

Figure 7.25 shows the storage heat gain, and the operative temperature of the reference case and case 3. During the first day, the atrium stores and releases less heat in the reference case than in case 3. This results in a higher operative temperature in the reference case than in case 3. During the following 3 days, the reference case stores almost equal amount of heat as case 3 but releases more heat. This results in a lower operative temperature in the reference case than in case 3.

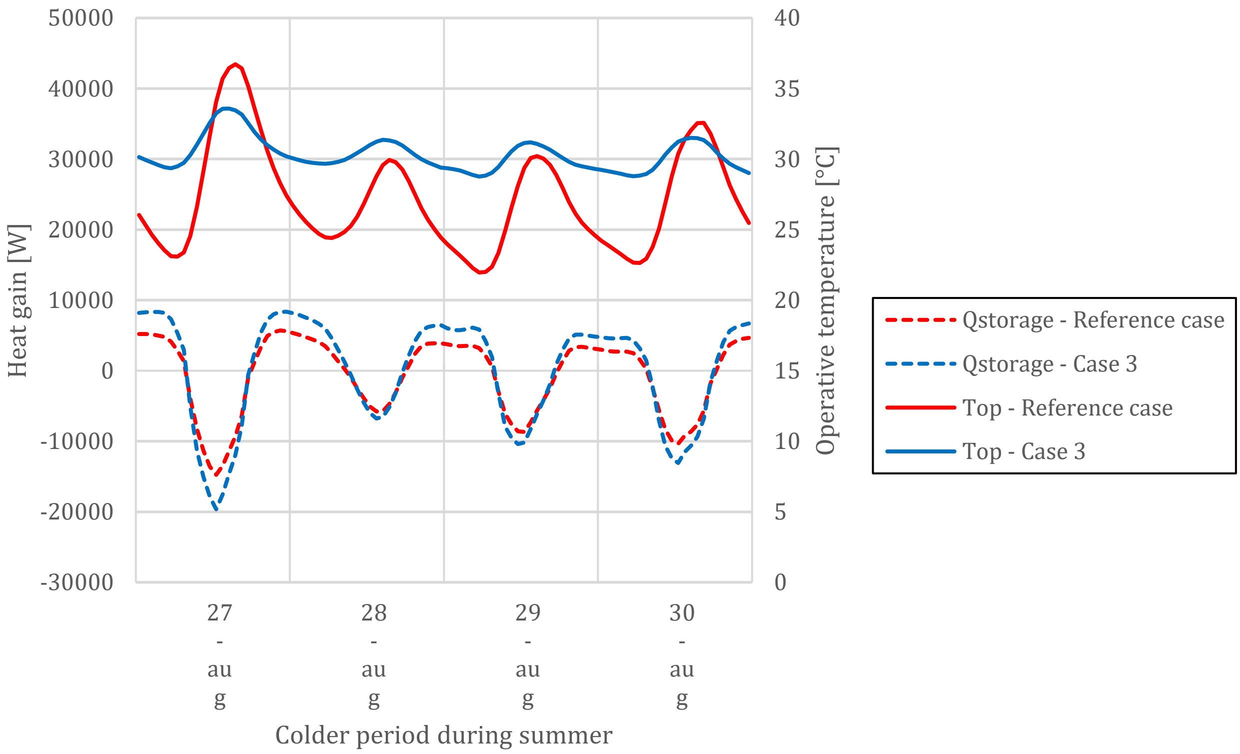


Figure 7.25 Heat storage and operative temperature in floor 5 of the reference case and case 3, and the outdoor temperature of colder period during summer.

7.3.2 Winter period

Figure 7.26 shows the operative temperature in floor 5 in all cases during the winter month. The operative temperature is too low in all cases to achieve thermal comfort according to the comfort limits.

The operative temperature oscillates less in the cases with higher thermal mass. The minimum operative temperature of the cases with higher thermal mass is higher compared to the reference case. The minimum operative temperature increases in the following order; reference case, case 1, case 2 and case 3.

The maximum operative temperature of all cases is 6.7 °C and occur 1st of December in case 3. During the 7th of December, the operative temperature is higher in the reference case compared to the other cases. The time period 5-8th December is therefore investigated more in detail and is called warmer period during winter. The minimum operative temperature of all cases is -7.9 °C and occur 22th of December in the reference case. The operative temperature of the reference case during that day decreases fast and much in relation to the other cases. The time period 20-23th December is therefore also investigated more in detail and is called colder period during winter.

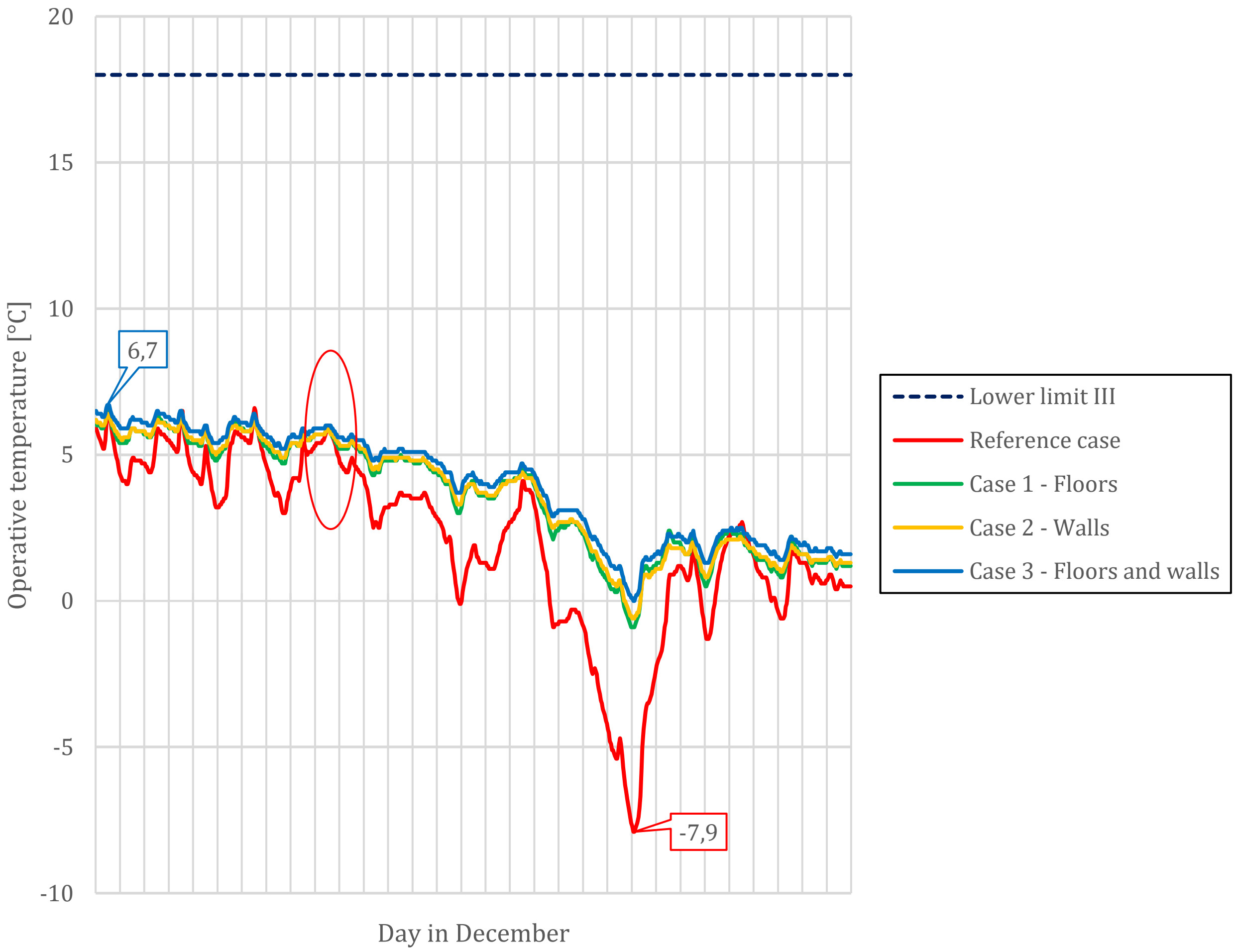


Figure 7.26 Operative temperature and lower comfort limit III in floor 5 during the winter month.

7.3.2.1 Warmer period during winter

The operative, mean air and mean surface temperature of the windows, floors, roof and walls vary more with the outdoor temperature and solar radiation in the reference case than in case 3.

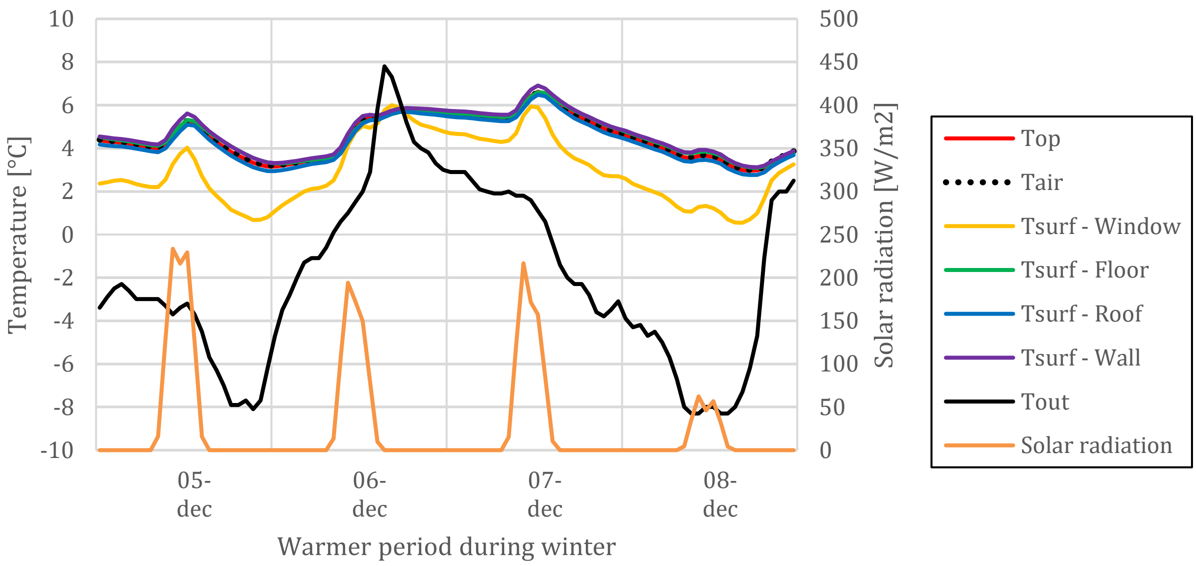


Figure 7.27 Operative temperature, mean air temperature and surface temperature of floor 5 in the reference case, and the outdoor temperature and solar radiation of warmer period during winter.

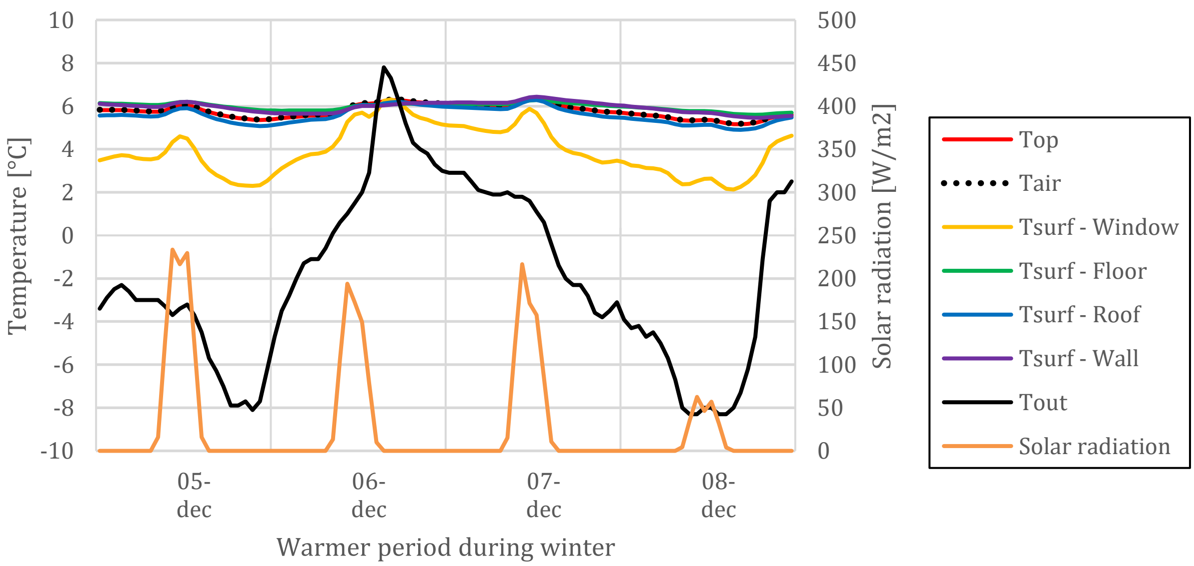


Figure 7.28 Operative temperature, mean air temperature and surface temperature of floor 5 in case 3, and the outdoor temperature and solar radiation of warmer period during winter.

Figure 7.29 and 7.30 shows the storage heat gain in floor 5 for the reference case and case 3, and the solar radiation respectively outdoor temperature. When the solar radiation and outdoor temperature is lower, case 3 releases more heat than the reference case. When the solar radiation is higher and outdoor temperature lower, the reference case stores more heat than case 3. However, when the solar radiation and outdoor temperature is higher, case 3 stores more heat than the reference case.

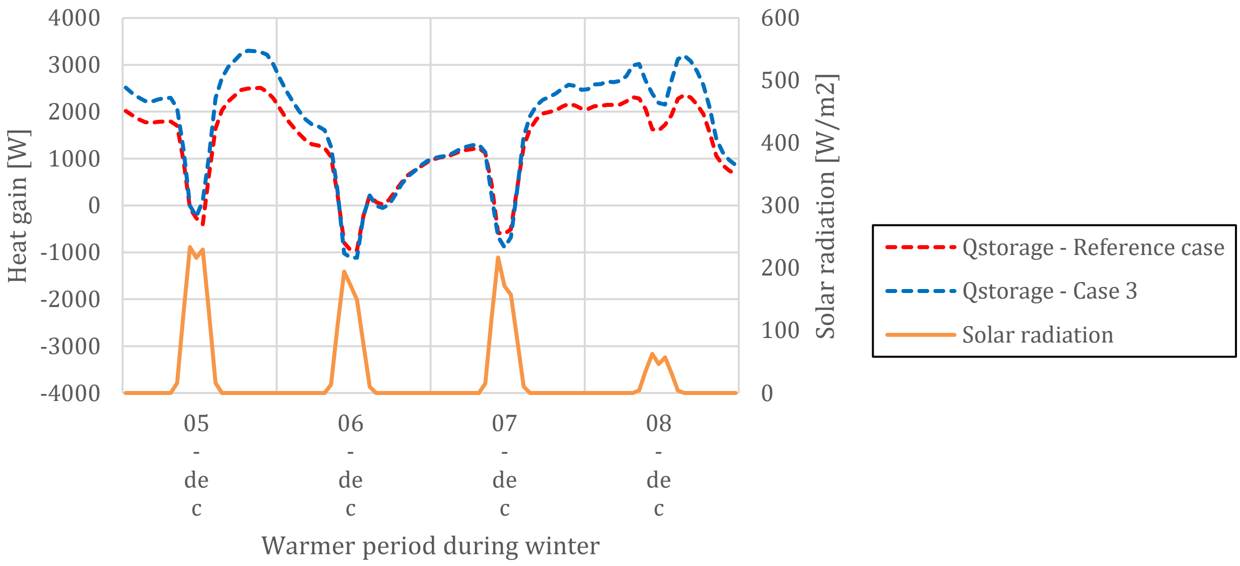


Figure 7.29 Storage heat gain in floor 5, and the solar radiation of warmer period during winter.

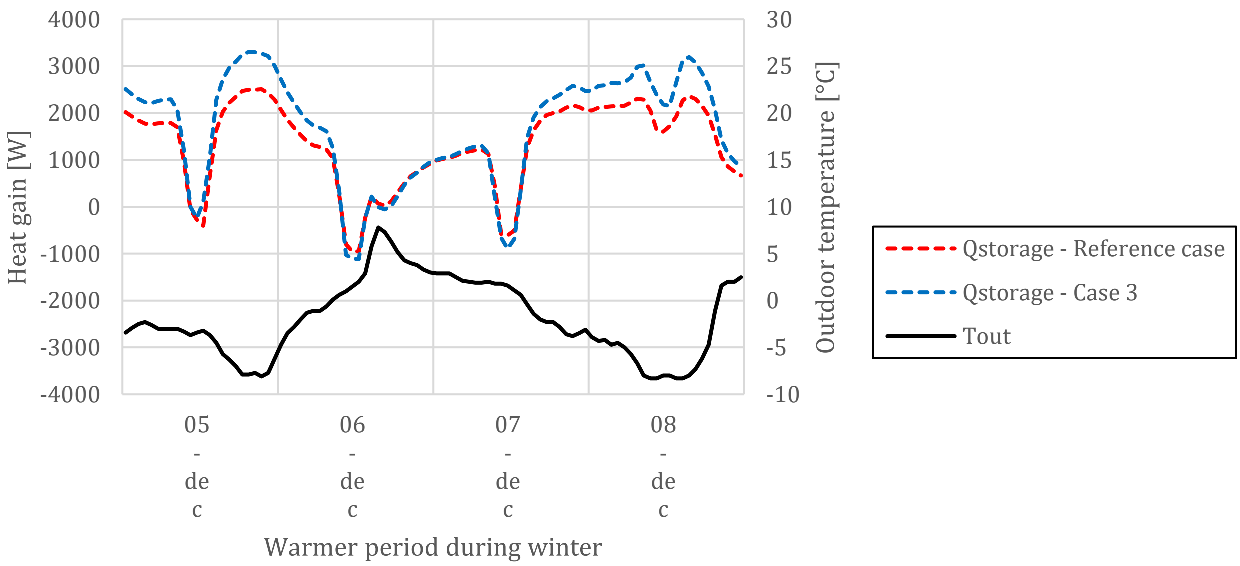


Figure 7.30 Storage heat gain in floor 5, and the outdoor temperature of warmer period during winter.

Figure 7.31 shows the storage heat gain and operative temperature in floor 5 for the reference case and case 3. The increased and more stable surface temperatures in case 3 gives the atrium ability to store and release more heat. When there is solar radiation and the outdoor temperature is higher, the storage heat gain is approximately equal in both cases. However, when there is no solar radiation and the outdoor temperature is lower, the storage heat gain in case 3 is higher than the reference case.

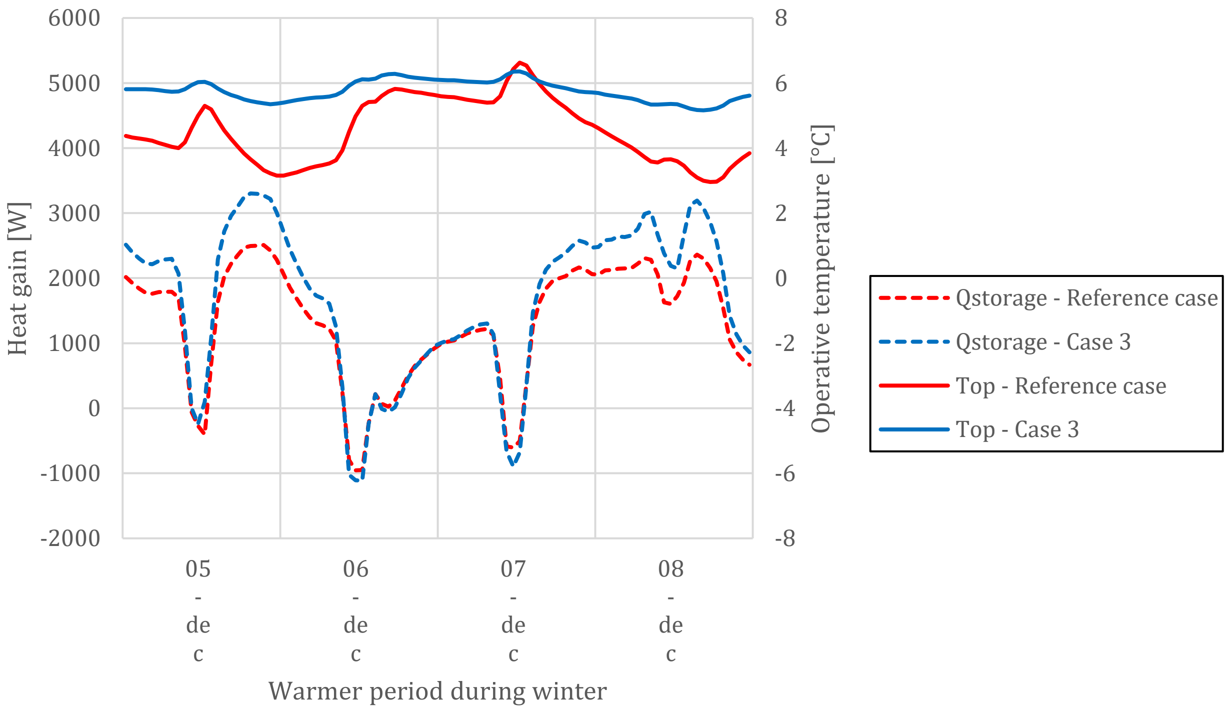


Figure 7.31 Storage heat gain and the operative temperature in floor 5 of warmer period during winter.

7.3.2.2 Colder period during winter

The temperatures in the reference case varies more with the outdoor temperature and solar radiation compared to case 3.

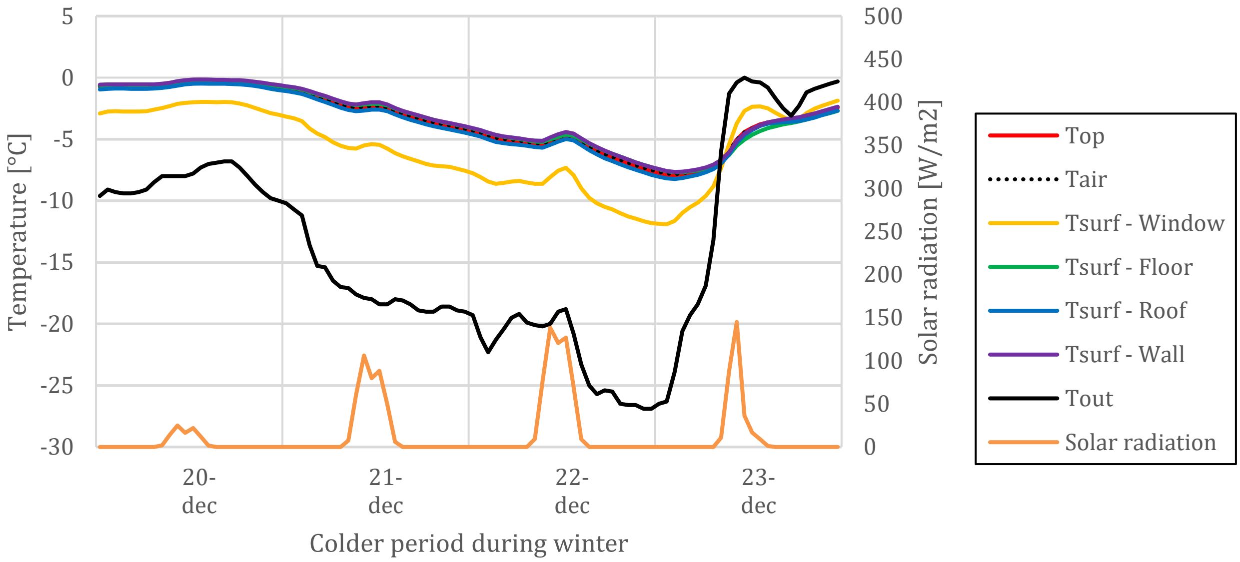


Figure 7.32 Operative temperature, mean air temperature and surface temperature of floor 5 in the reference case, and the outdoor temperature and solar radiation of colder period during winter.

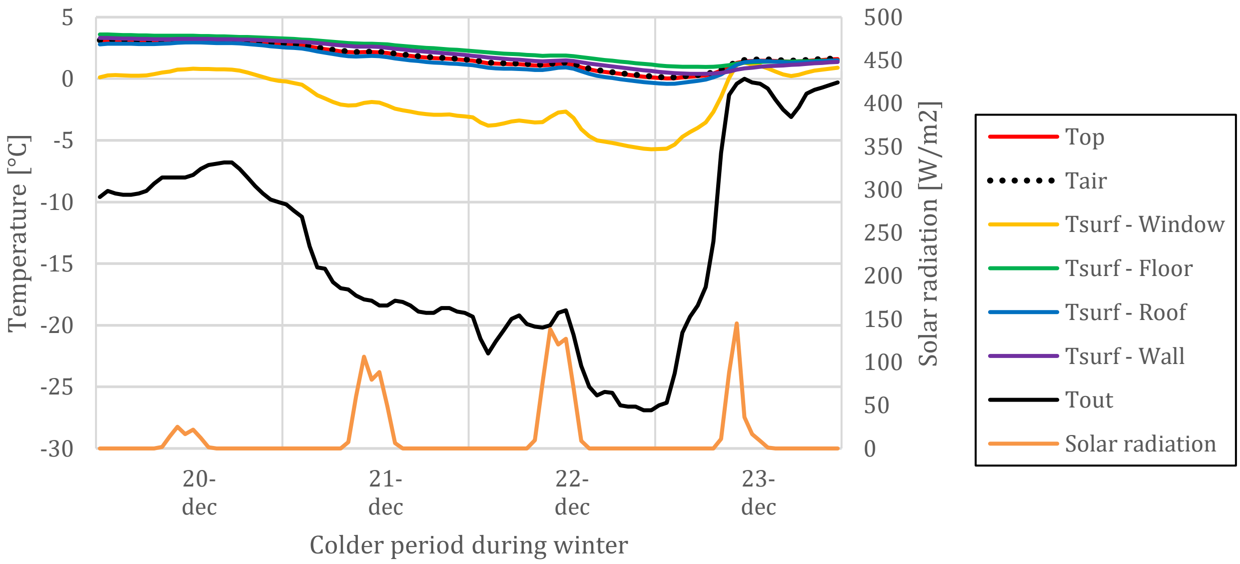


Figure 7.33 Operative temperature, mean air temperature and surface temperature of floor 5 in case 3, and the outdoor temperature and solar radiation of colder period during winter.

Figure 7.34 and 7.35 shows the storage heat gain in floor 5 for the reference case and case 3, and the solar radiation respectively outdoor temperature. When the solar radiation and outdoor temperature is lower, despite the absence of solar radiation, case 3 releases more heat than the reference case. However, when the solar radiation is higher and outdoor temperature is higher, both case stores approximately equal amount of heat.

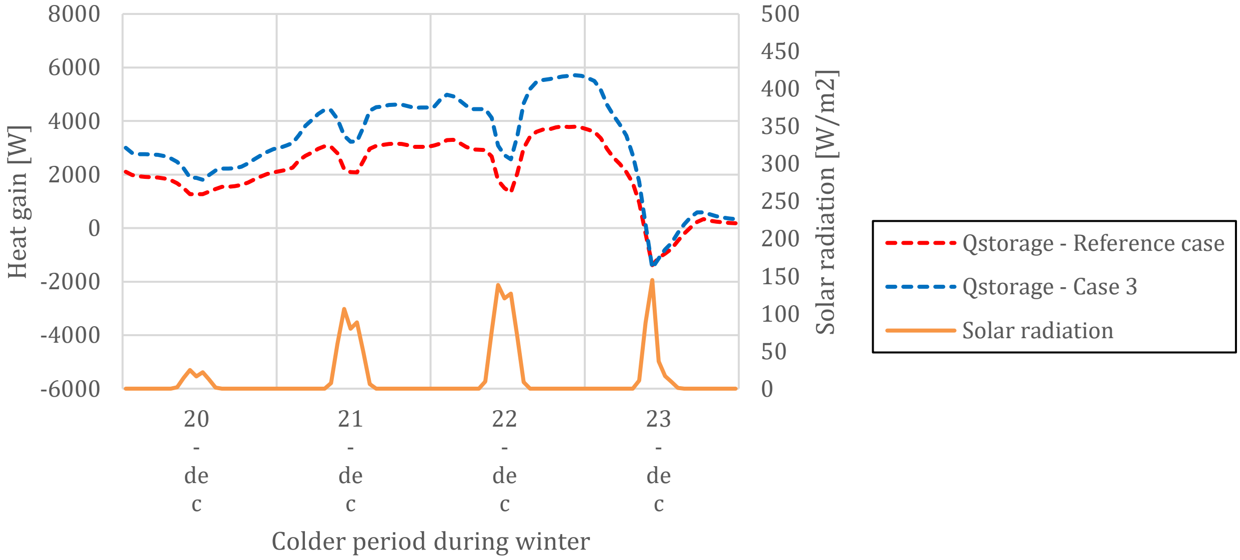


Figure 7.34 Storage heat gain in floor 5, and the solar radiation of colder period during winter.

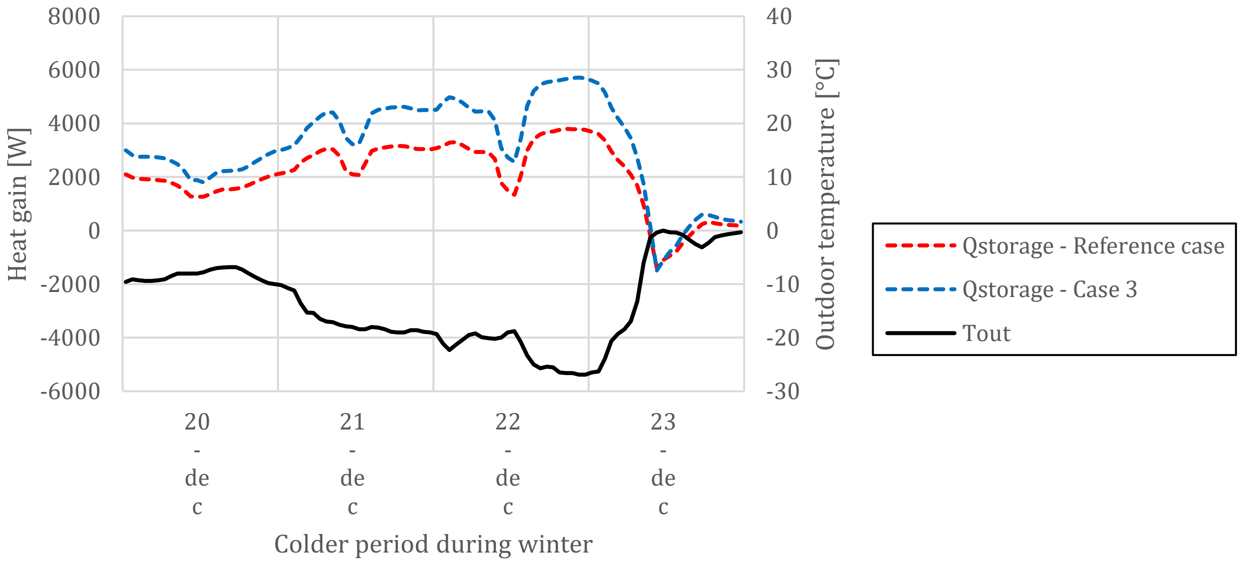


Figure 7.35 Storage heat gain in floor 5, and the outdoor temperature of colder period during winter.

Figure 7.36 shows the heat storage and operative temperature in floor 5 for the reference case and case 3. The ability to store and release heat when needed results in a more stable operative temperature in case 3.

When there is solar radiation and the outdoor temperature is higher, the storage heat gain is negative since the atrium store the heat. When there is no solar radiation and the outdoor temperature is lower, the storage heat gain is positive since the atrium is releasing heat to the atrium. Since case 3 has higher thermal mass than the reference case, it can release more heat.

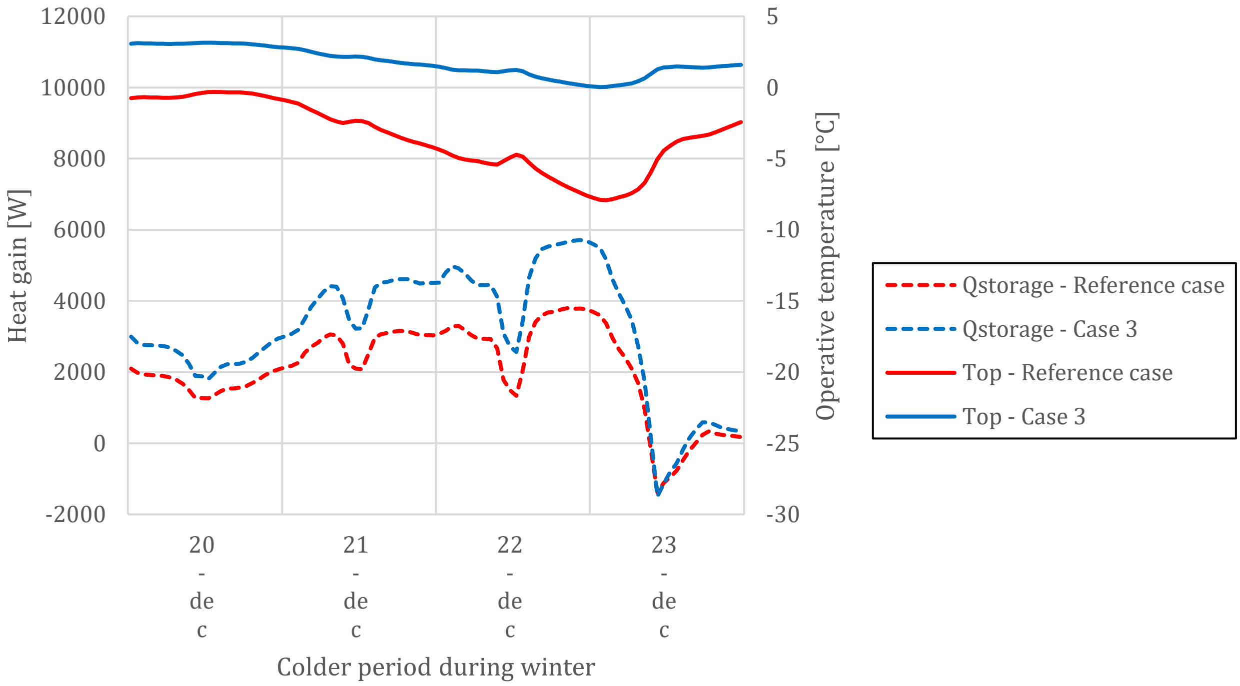


Figure 7.36 Storage heat gain, and the operative temperature in floor 5 of colder period during winter.

7.4 Glazing material

The impact of glazing material is investigated by comparing the reference building, which has a 2-pane glazing, with a glazing system with lower g-value, lower U-value and with a 3-pane glazing. The glazing material is investigated during the summer and winter week. In order to compare the impact of G- and U-value with each other, the heat gain through windows is divided into transmission heat gain and radiation heat gain.

A lower g-value decreases the operative temperature in the atrium during both the summer and winter week due to less radiation heat gain through windows. A lower g-value is therefore beneficial during summer, but not beneficial during the winter. A lowered g-value helps to shade the atrium.

A lower U-value increases the operative temperature in the atrium during both the summer and winter week due to less transmission heat gains and losses through windows. A lower g-value is therefore not beneficial during summer, but beneficial during the winter. A lowered U-value helps cooling the atrium.

A 3-pane glazing, which means lower g- and U-value, increases the operative temperature in the atrium during both the summer and winter week. This is because the impact of a lower U-value decreases the transmission heat losses through the windows more than the impact of a lower g-value decreases the radiation heat gain through the windows. A 3-pane glazing is therefore not beneficial during the summer, but beneficial during the winter.

7.4.1 Summer period

Figure 7.37 shows operative temperature in zone 5 for all cases and the upper comfort limits. The operative temperature in the case with lower g-value is within the comfort limits during some hours. However, in all other cases, the operative temperature is too warm to achieve thermal comfort according to the standard.

The case with lower U-value has the maximum operative temperature during the whole period, while the case with lower g-value has the minimum operative temperature during the whole period. The maximum operative temperature decreases in the following order: lower U-value, reference case, lower G- and U-value and lower g-value. The minimum operative temperature increases in the following order; lower g-value, reference case, lower G-and U-value and lower U-value. The maximum operative temperature of all cases is 54.4 °C and occur 8th August in the case with lower U-value. The coldest operative temperature of all cases is 26.7 °C and occur 11th August in the case with lower g-value. The case with lower g-and U-value has a lower maximum operative temperature than the reference case during all days, except the warmest day. The time period 8-9th August is therefore investigated more in detail.

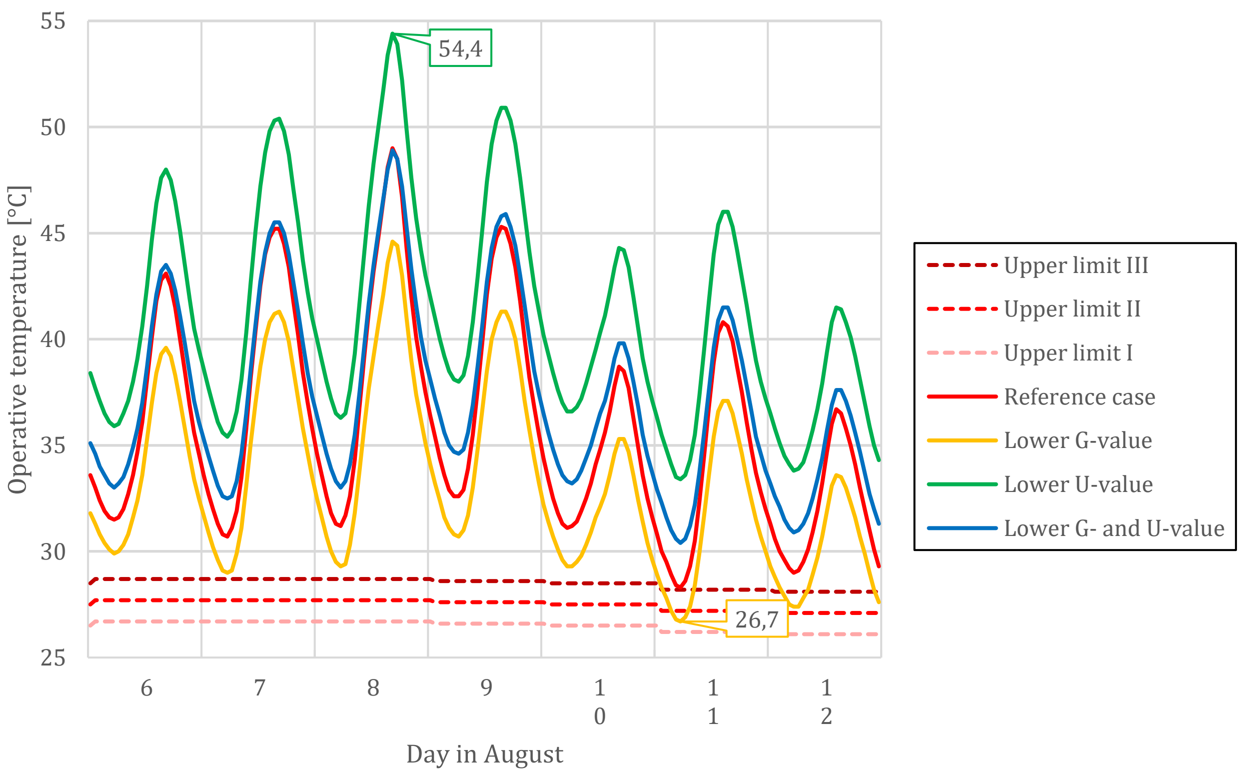


Figure 7.37 Operative temperature in floor 5, and the upper thermal comfort limits during the summer week.

The reference case has the largest transmission heat losses through windows, while the case with lower G- and U-value has the smallest transmission heat losses through windows. When the outdoor temperature is increasing, the transmission heat losses through windows are decreasing.

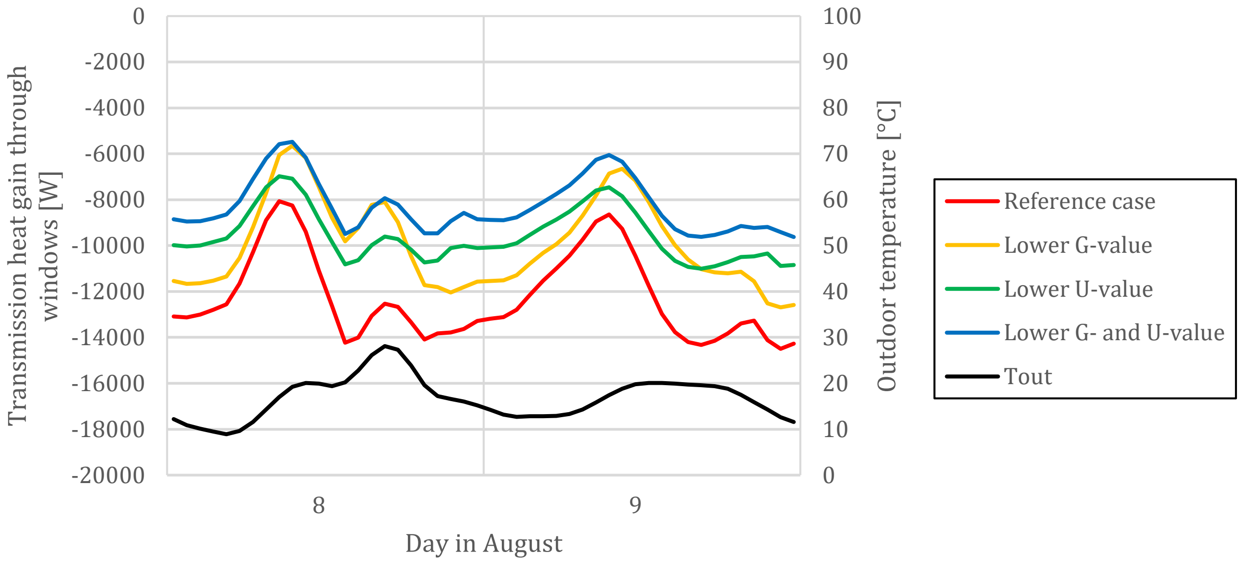


Figure 7.38 Transmission heat gain through windows in floor 5, and the outdoor temperature during the warmest day and the day after.

All cases have approximately equal amount of radiation heat gain when there is no solar radiation. However, when the solar radiation is higher, the reference case has and the case with lower U-value has the largest radiation heat gain through windows, while the case with lower g-value has the lowest radiation heat gain through windows.

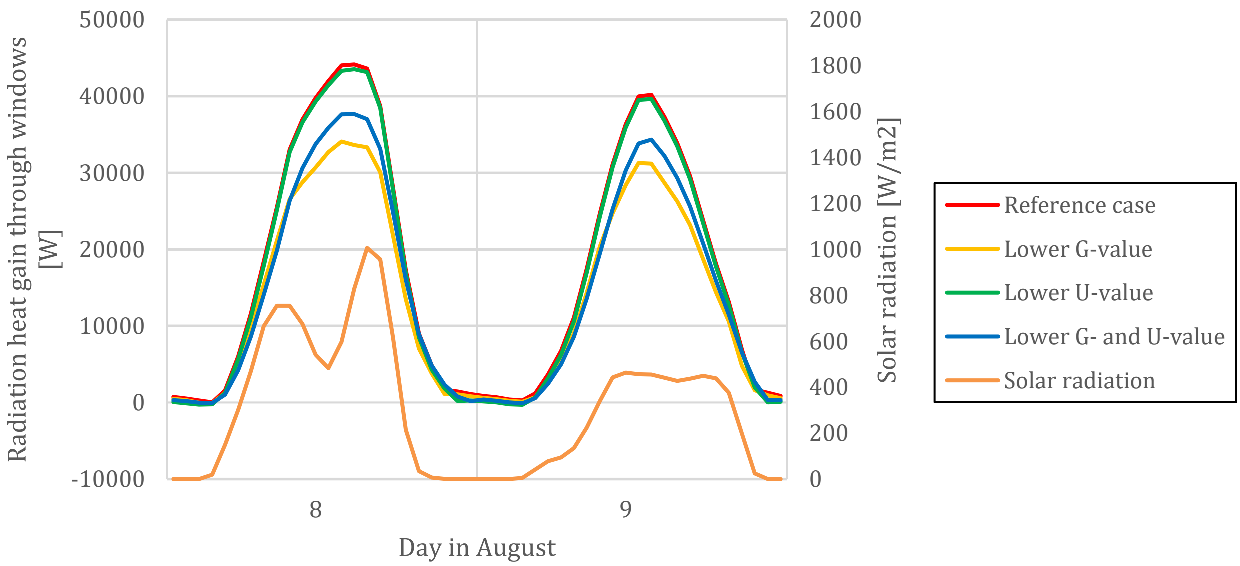


Figure 7.39 Radiation heat gain through windows in floor 5, and the solar radiation during the warmest day and the day after.

When composing the transmission heat gain and radiation heat gain, the net heat losses is largest in the reference case. This is due to large transmission losses through the windows. The net heat gains are largest in the case with lower U-value. This is due to a combination of large radiation heat gain, but smaller transmission heat losses through the windows than the reference case.

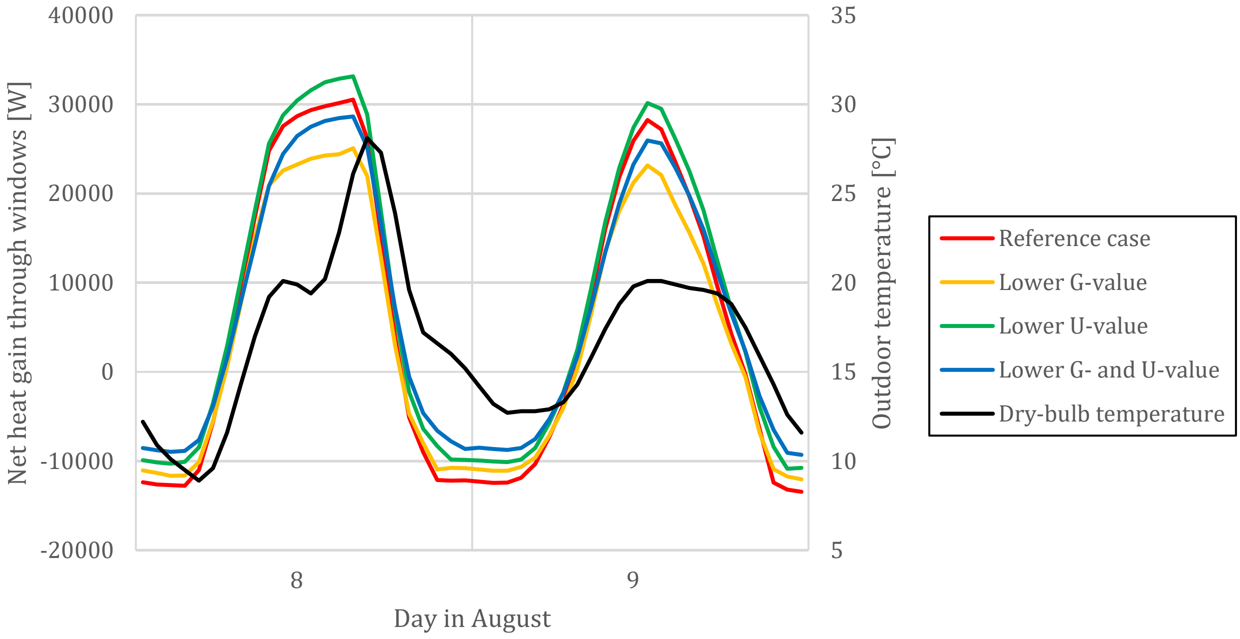


Figure 7.40 Net heat gain through windows in floor 5, and the outdoor temperature during the warmest day and the day after.

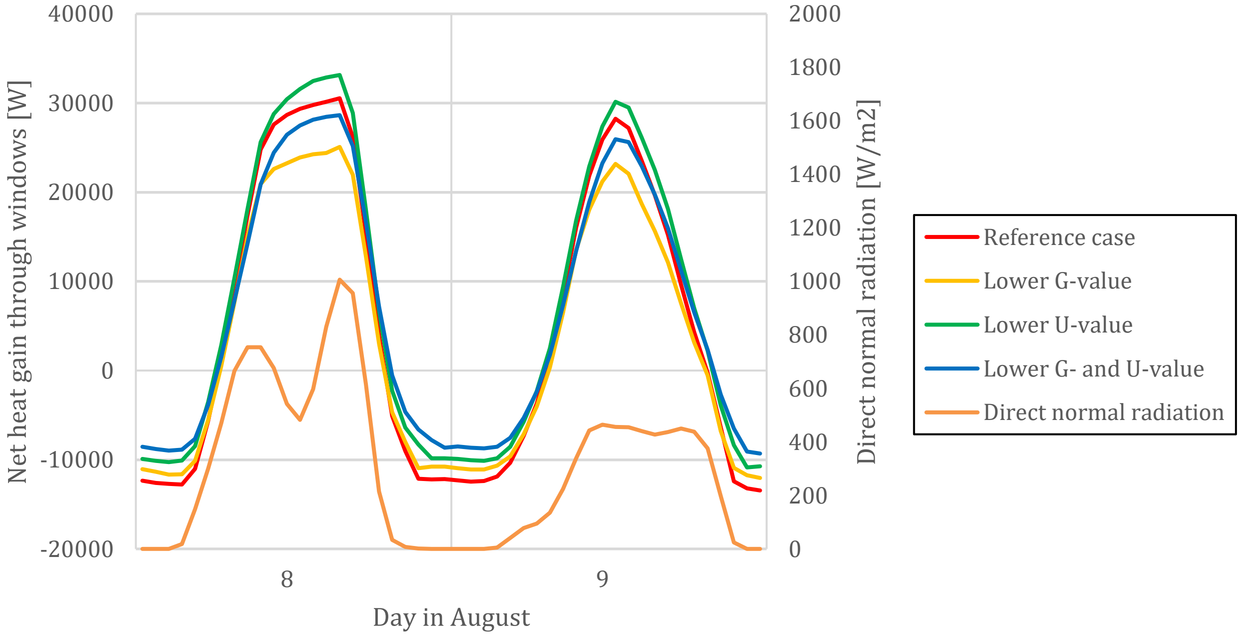


Figure 7.41 Net heat gain through windows in floor 5, and the solar radiation during the warmest day and the day after.

A lower g-value results in lower operative temperature compared to the reference case, due to a lower radiation heat gain. A lower U-value results in higher operative temperatures compared to the reference case, due to the combination of large radiation heat gain but smaller transmission heat losses through the windows than the reference case. A lower g- and U-value results in approximately equal operative temperature as the reference case when the solar radiation and outdoor temperature is higher, and a slightly higher operative temperature compared to the reference case when the outdoor temperature and solar radiation is lower. This is due to that the reference case has larger transmission heat losses, but also larger radiation heat gains.

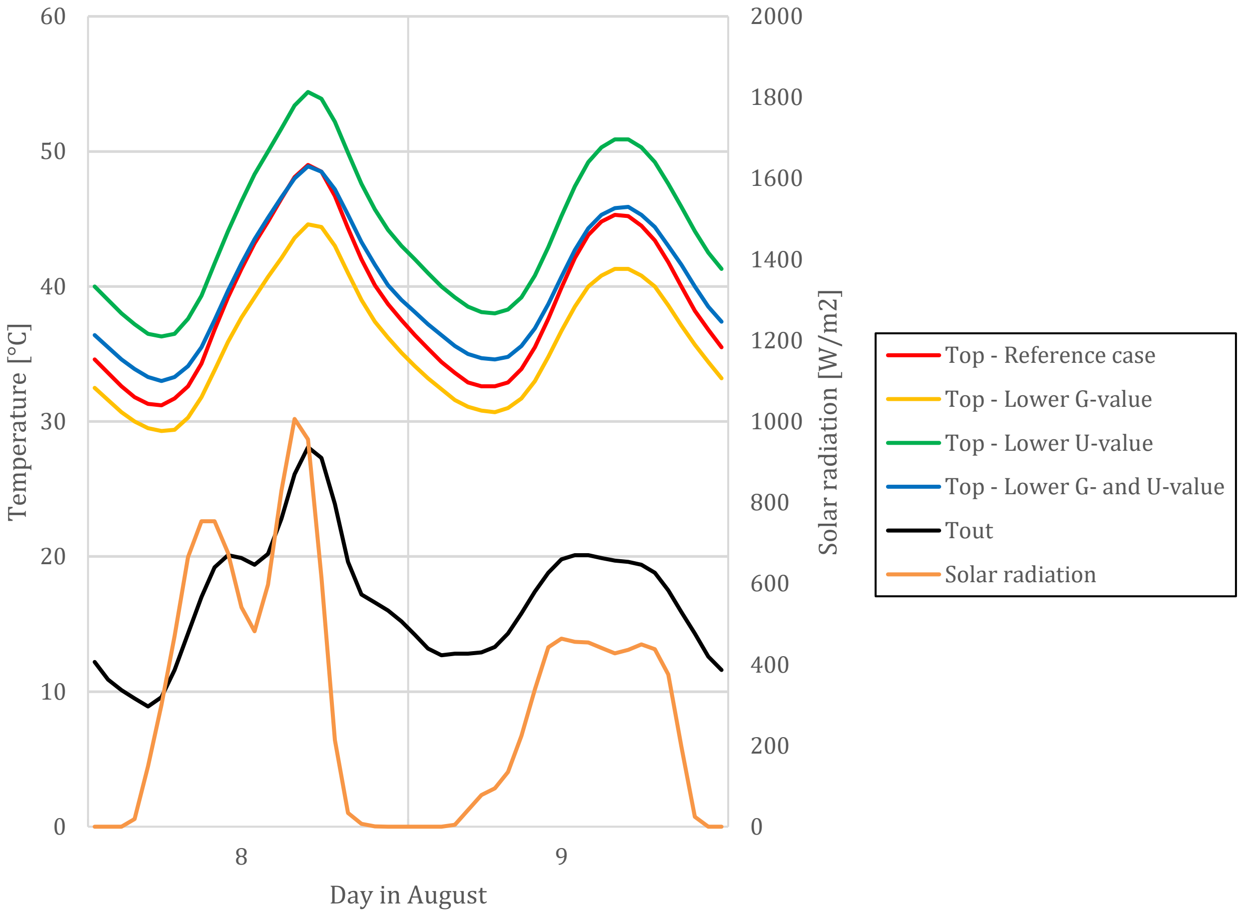


Figure 7.42 Operative temperatures in floor 5, and the outdoor temperature and solar radiation during the warmest day and the day after.

7.4.2 Winter period

Figure 7.43 shows operative temperature in zone 5 for all cases and the lower limit III according to the standard. The operative temperature is too cold in all cases during all hours to achieve thermal comfort according to the standard.

The case with lower G- and U-value has the maximum operative temperature during the whole period, while the case with lower g-value has the minimum operative temperature during the whole period. The maximum operative temperature of all cases is 3.1 °C and occur 26th December in the case with lower g- and U-value. The coldest operative temperature of all cases is -8 °C and occur 23th December in the case with lower g-value. The time period 22-23th August is therefore investigated more in detail.

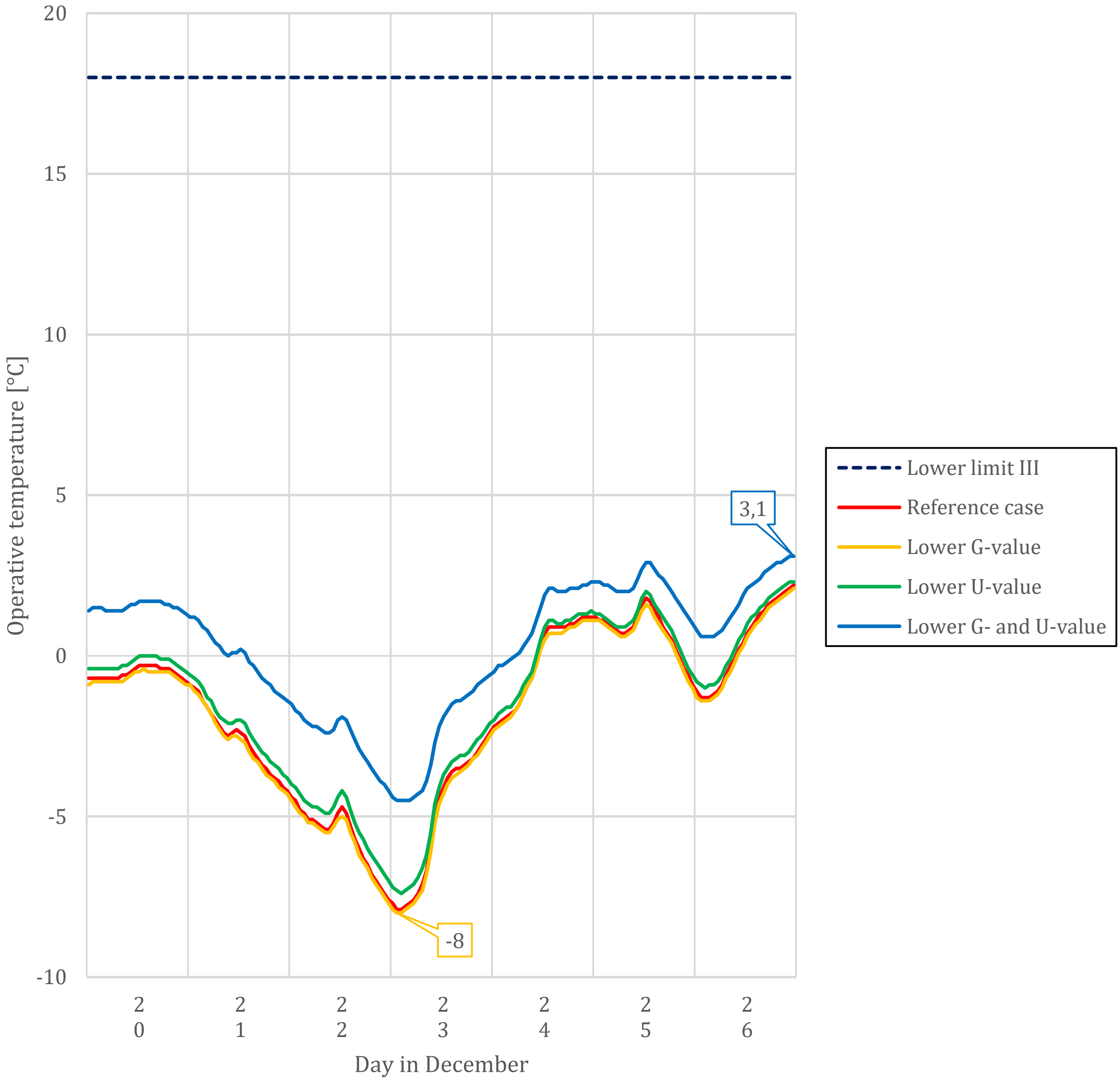


Figure 7.43 Operative temperature and lower thermal comfort limit III in floor 5.

The reference case and the case with lower g-value has the largest transmission heat losses and gains through windows, while the case with lower U-value and lower G- and U-value has the smallest transmission heat losses and gains through windows.

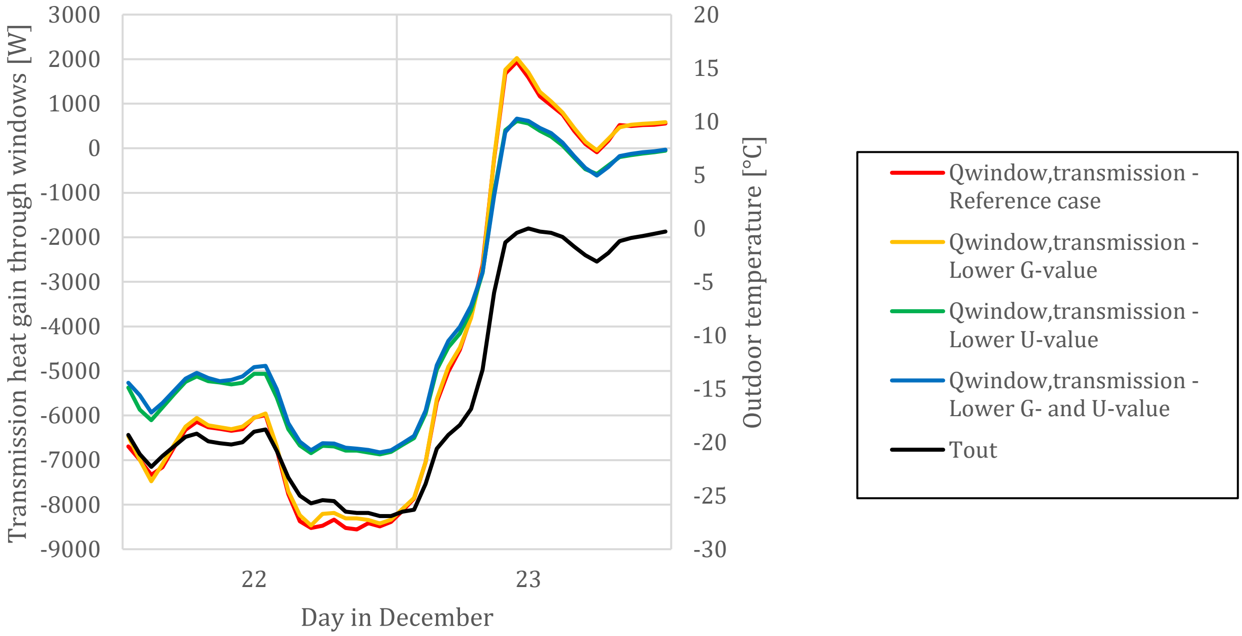


Figure 7.44 Transmission heat gain through windows in floor 5, and the outdoor temperature during the coldest day and the day after.

When the solar radiation is higher, the case with lower U-value has the largest radiation heat gain through windows, while the case with lower g-value has the lowest radiation heat gain through windows.

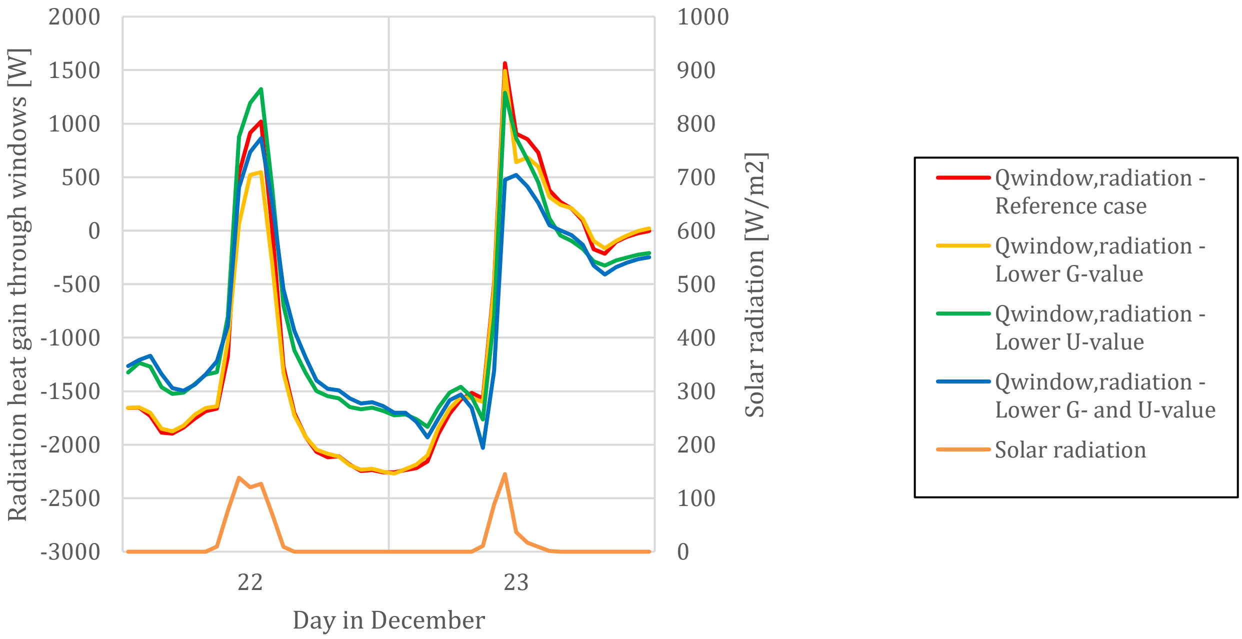


Figure 7.45 Radiation heat gain through windows in floor 5, and the solar radiation during the coldest day and the day after.

A lower g-value results in approximately equal net heat gains and losses through windows. A lower U-value and lower g-and U-value results in lower net heat gains and losses through windows.

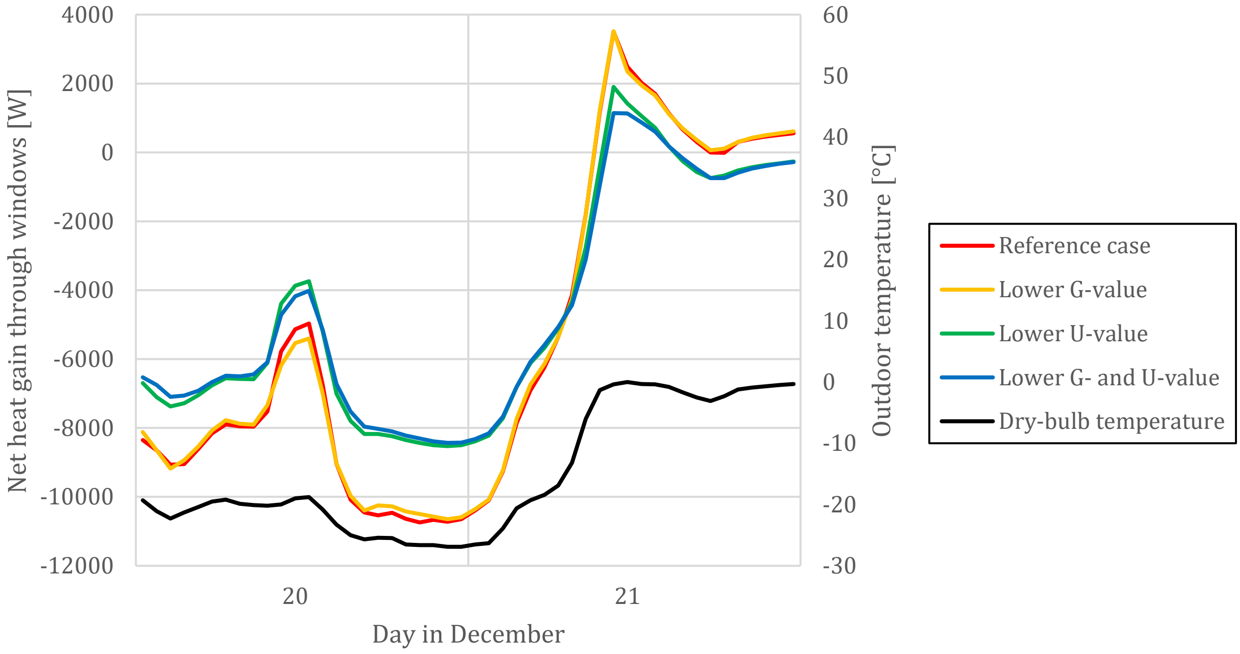


Figure 7.46 Net heat gain through windows in floor 5, and the outdoor temperature during the coldest day and the day after.

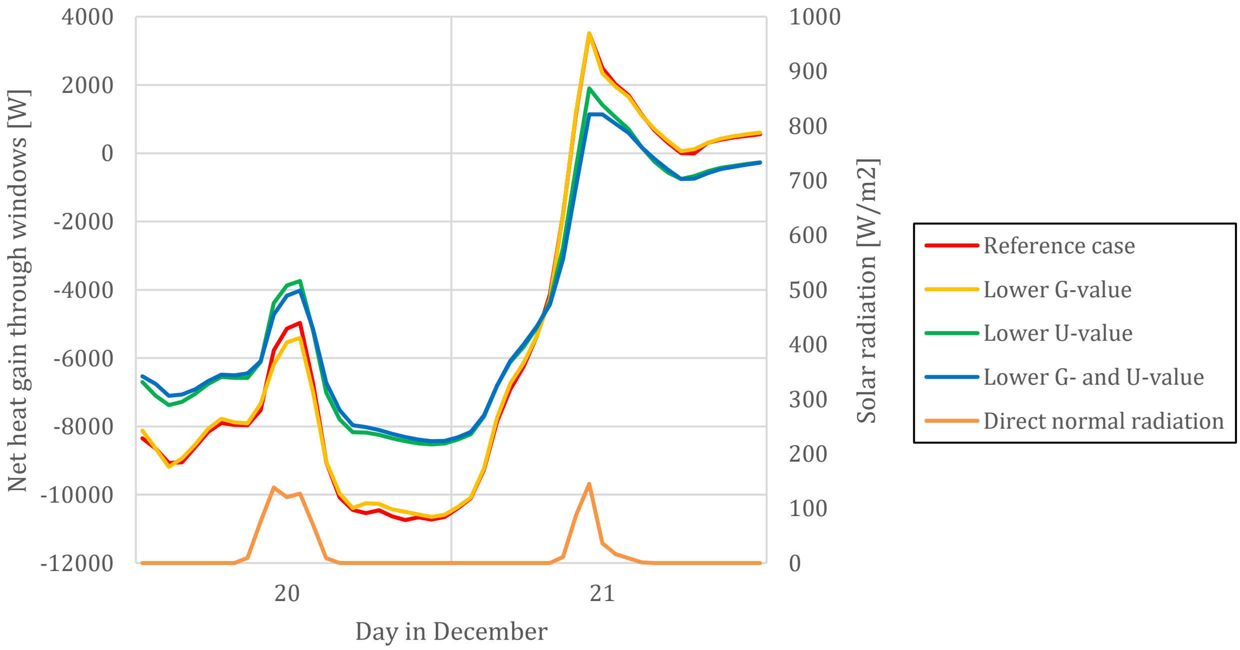


Figure 7.47 Net heat gain through windows in floor 5, and the solar radiation during the coldest day and the day after.

A lower g-value results in approximately equal net heat gains and losses through windows. An equal net heat gains and losses through windows results in an approximately equal operative temperature. A lower U-value and lower g-and U-value results in lower net heat gains and losses through windows. A lower net heat gains and losses through windows results in a higher operative temperature.

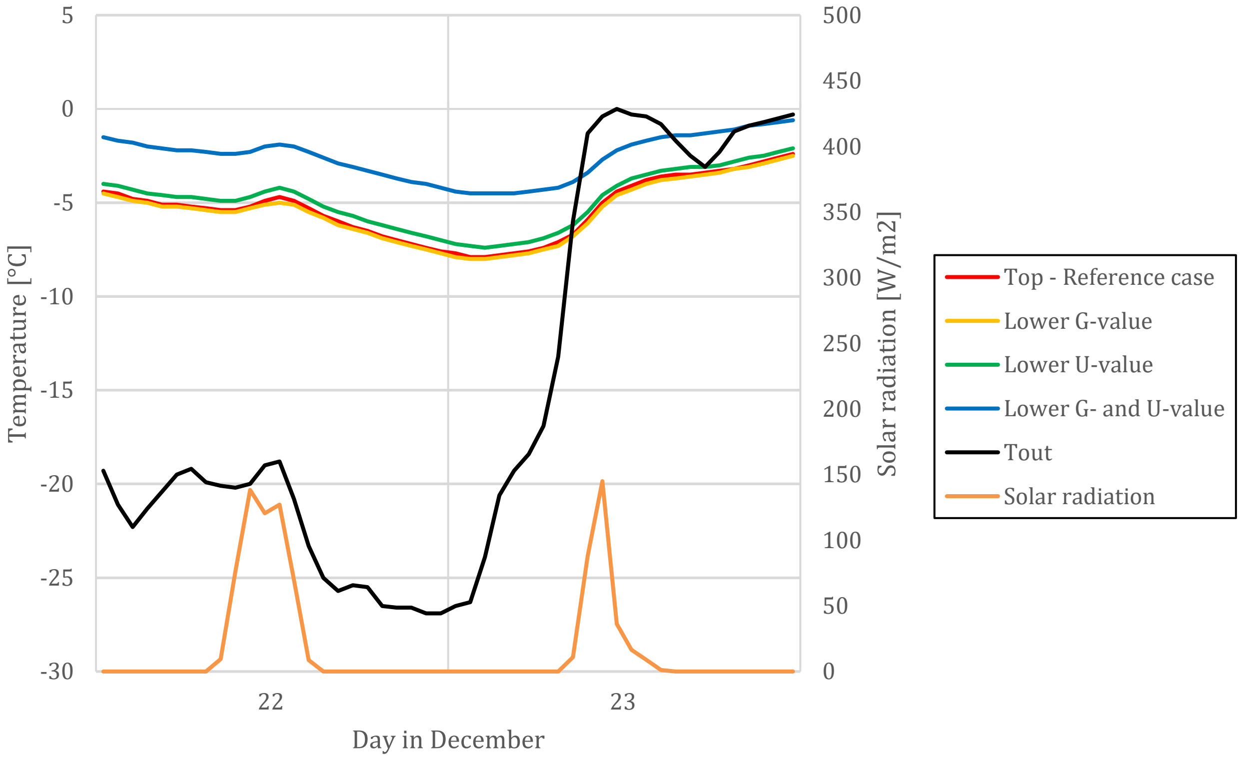


Figure 7.48 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the coldest day and the day after.

7.5 Atrium type

The impact of atrium type is investigated by comparing the reference building, which is a linear atrium, with a semi-enclosed atrium and a centralized atrium. The atrium type is investigated during the summer and winter week. The top floor in the linear atrium has the largest window area and exterior wall area and the smallest interior wall area. The top floor in the centralized atrium has the smallest window area and exterior wall area and the largest interior wall area.

The linear atrium has two glazed sides and two sides facing an indoor climate. The two glazed sides are facing south and north. The semi-enclosed atrium has one glazed side and three sides facing an indoor climate. The glazed side is facing south.

Table 7.5 Glazing and wall area of top floor in each evaluation case.

Case	$A_{glas,top\ floor}$		$A_{wall,top\ floor}$	
	Roof	Walls	Interior wall	Exterior wall
Linear atrium (Reference)	130	36	364	133
Semi-enclosed atrium	130	18	448	66
Centralized atrium	130	0	533	0

A centralized atrium has colder operative temperature during the summer and warmer operative temperature during the winter compared to the linear and semi-enclosed atriums. A centralized atrium is therefore more beneficial during both summer and winter.

A centralized atrium has colder operative temperature during the summer due to the smaller glazing area and larger interior wall area. Since the glazing area has lower U-value, more glazing area the atrium results in more transmission heat gain through the windows during the summer. Since the outdoor temperature is warmer than the indoor temperature in the ambient building parts during the summer, more interior wall area results in more transmission heat losses.

A centralized atrium has warmer operative temperature during the summer due to the smaller glazing area and larger interior wall area. Since the glazing area has lower U-value, more glazing area the atrium results in more transmission heat losses through the windows during the winter. Since the outdoor temperature is colder than the indoor temperature in the ambient building parts during the winter, more interior wall area results in more transmission heat gains.

7.5.1 Summer period

The operative temperature is too warm during all hours in all cases to achieve thermal comfort according to the standard. The warmest operative temperature off all cases is 49.6 °C and occurs 8th August in the semi-enclosed atrium. The coldest operative temperature of all cases is 28.3 °C and occur 11th August in the linear atrium, which is the reference case.

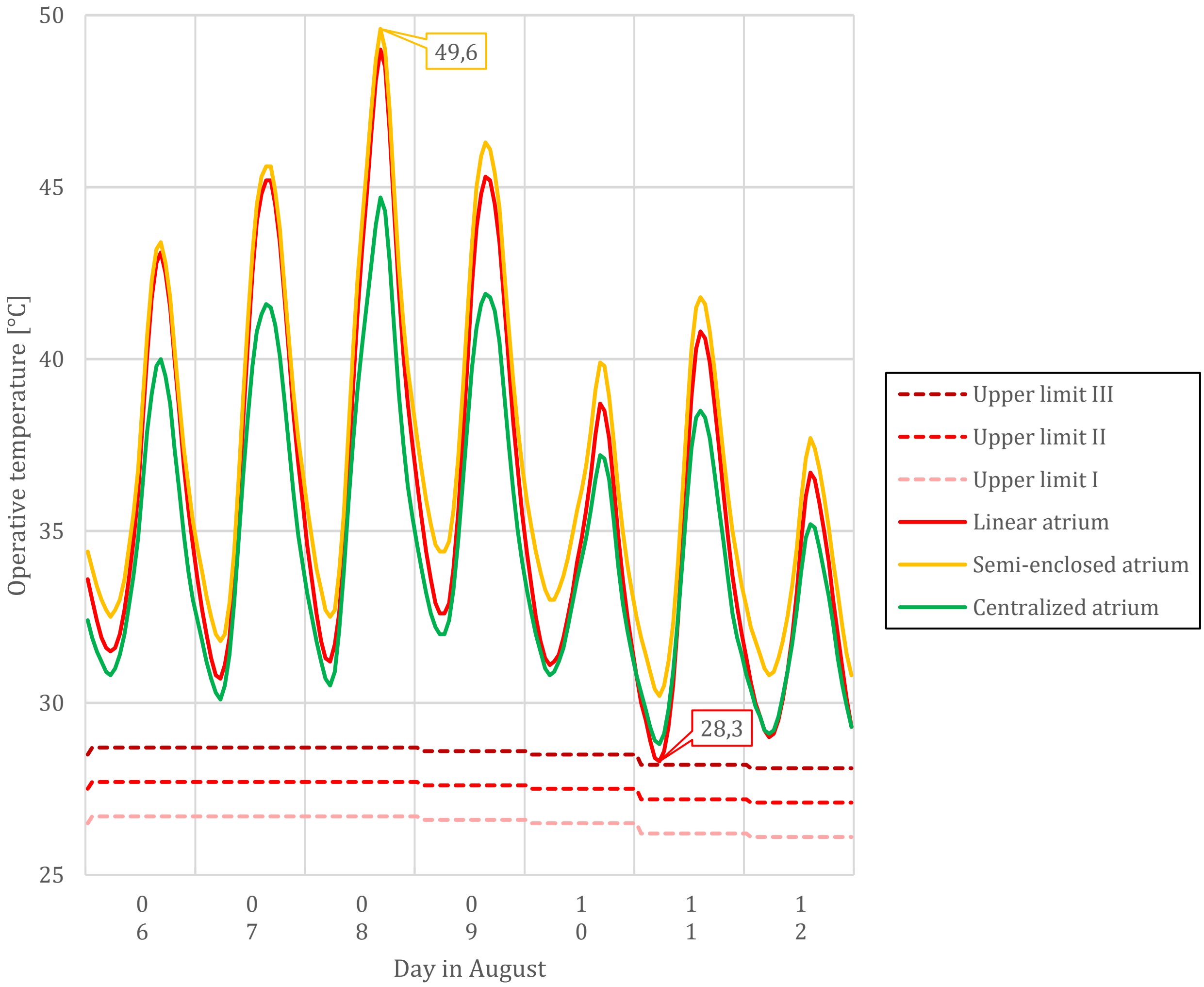


Figure 7.49 Operative temperature in floor 5, and the upper thermal comfort limits during the summer week.

When there is no solar radiation and the outdoor temperature is lower, the operative temperature is coldest in the centralized atrium. However, when the solar radiation is lower during the day at 10th August and the outdoor temperature is decreasing, the linear atrium has a lower operative temperature than the centralized atrium during the night. When there is solar radiation and the outdoor temperature is higher, the operative temperature is warmest the semi-enclosed atrium.

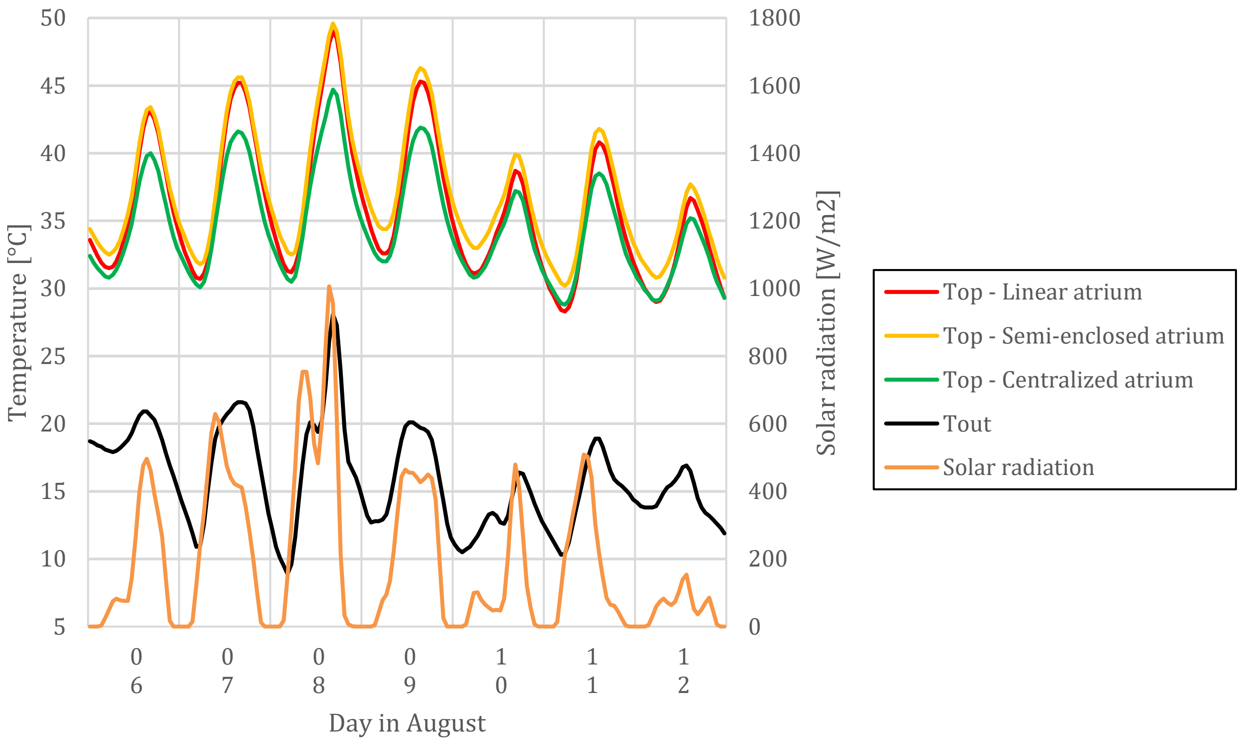


Figure 7.50 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the summer week.

7.5.2 Winter period

The operative temperature is too cold during all hours in all cases to achieve thermal comfort according to the standard. The warmest operative temperature off all cases is 6.3 °C and occurs 26th December in the centralized atrium. The coldest operative temperature of all cases is -7.9 °C and occur 23th December in the linear atrium, which is the reference case.

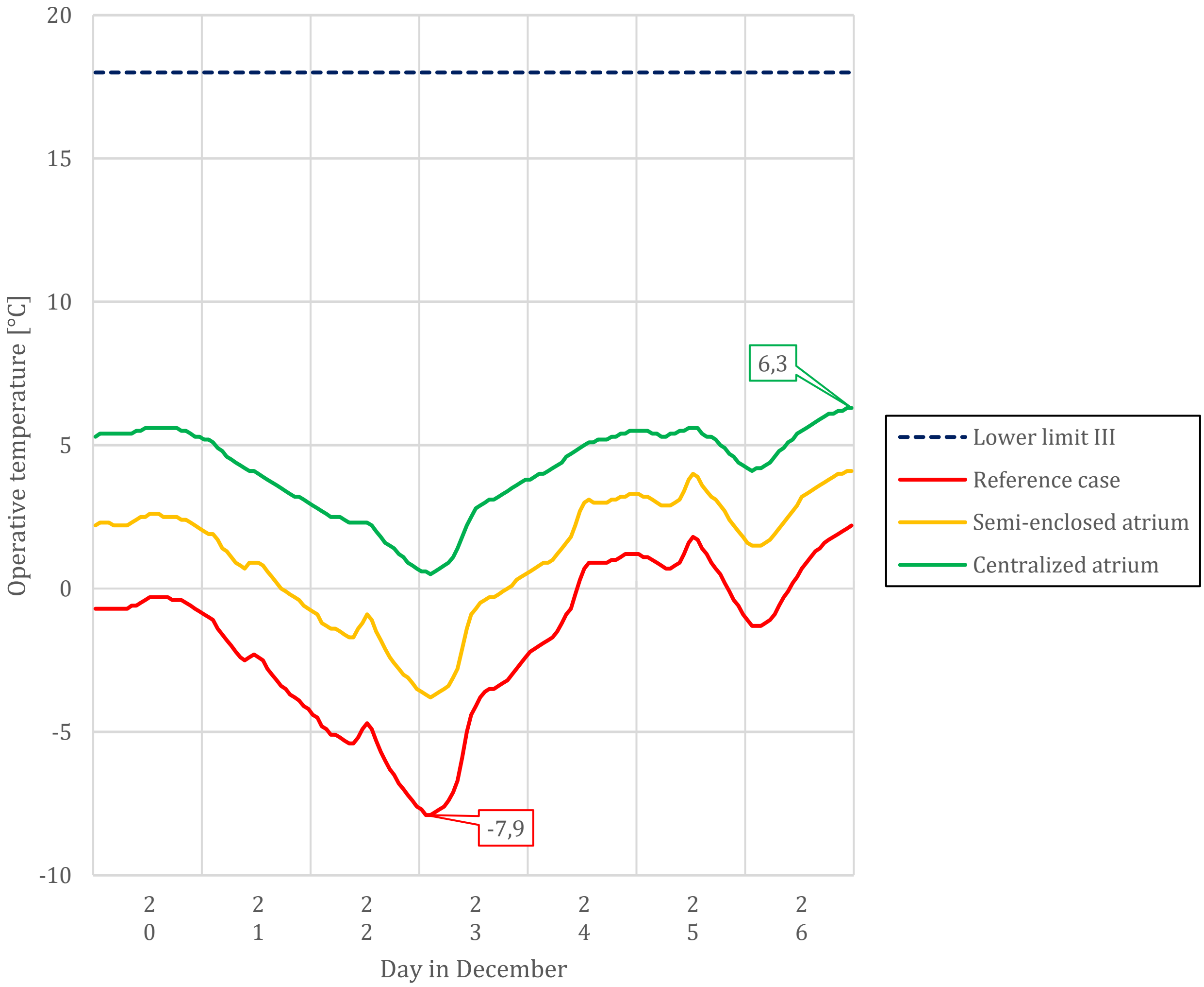


Figure 7.51 Operative temperature in floor 5, and the lower thermal comfort limit III during the winter week.

The centralized atrium has a higher operative temperature than the semi-enclosed atrium all the time, while the semi-enclosed atrium has a higher operative temperature than the linear atrium all the time.

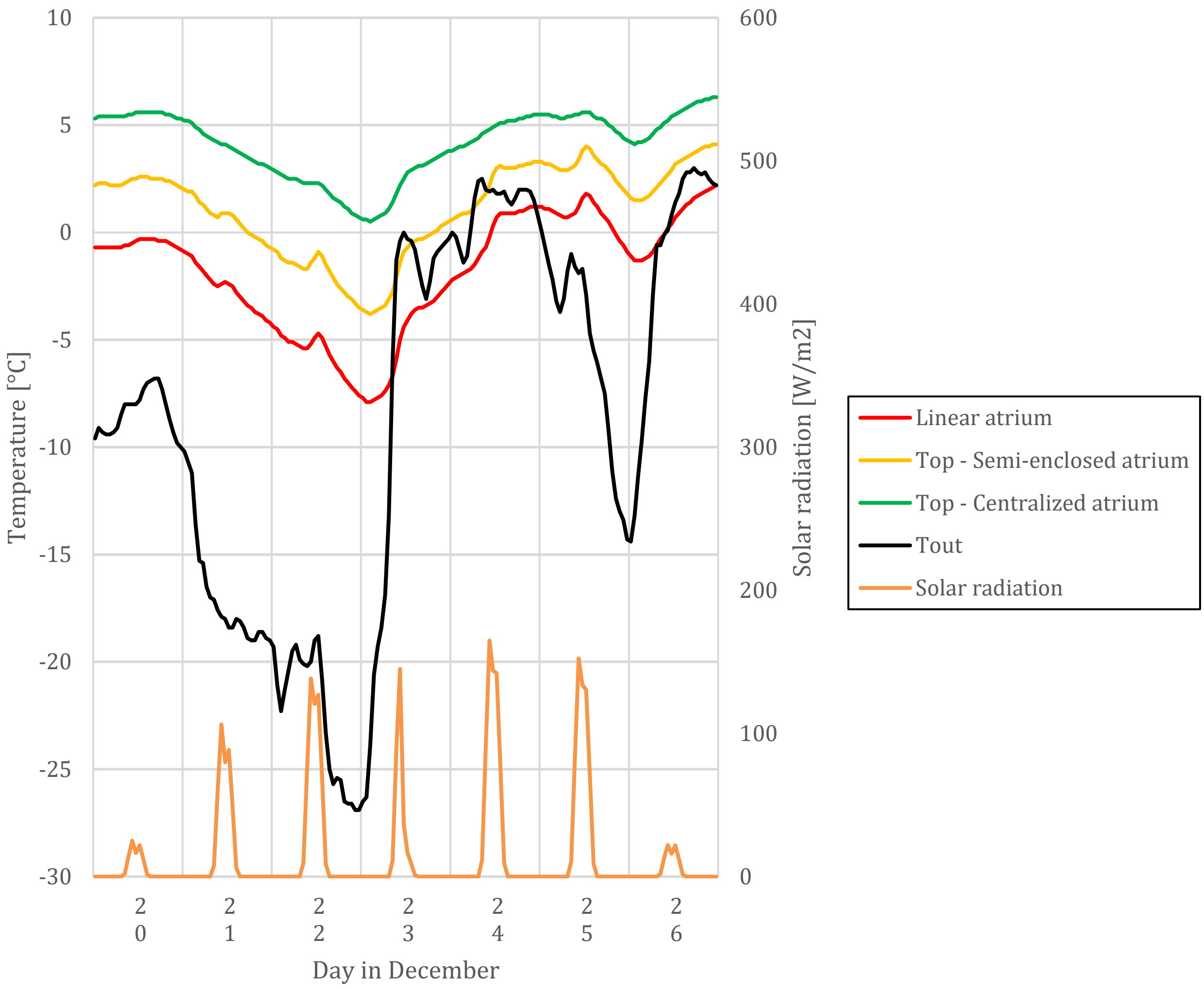


Figure 7.52 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the winter week.

7.6 Atrium dimension

The impact of atrium dimension is investigated by comparing the reference building with increased height, width and length. The summer period is examined during the summer week and the winter period is examined during the winter week.

The reference case and the case with increased height has equal geometry of the most upper floor. The case with increased width has the largest floor and envelope area. The case with increased length has largest window area.

Table 7.6 Floor area, envelope area, window area and area facing the outdoor environment of the top floor.

Case	$A_{floor,top}$ [m²]	$A_{env,top}$ [m²]	$A_{window,top}$ [m²]	$A_{exterior,top}$ [m²]
Reference	316	1371.3	165.6	691.7
Increased height	316	1371.3	165.6	691.7
Increased width	388	1518.4	172.8	786.2
Increased length	366.4	1510.4	204.48	744.0

The reference building with an increased length has the warmer operative temperature during both summer and winter. However, the operative temperature difference is larger during the summer than during the winter.

During the summer, when the solar radiation and outdoor temperature is generally higher, the case with an increased length is not beneficial when the outdoor temperature and solar radiation is high. This is due to a larger window area, which results in larger heat gains through windows. The operative temperature in the atrium is more sensitive to solar radiation than to the outdoor temperature during the summer. The largest heat gain in the atrium is the heat gain through windows, which is more dependent of solar radiation than the outdoor temperature during the summer.

During the winter, when the solar radiation and outdoor temperature is generally lower, there is no major difference between the cases when the solar radiation and outdoor temperature is either high or low.

7.6.1 Summer period

The operative temperature is too warm during all hours in all cases to achieve thermal comfort according to the standard.

The warmest operative temperature of all cases is 50.2 °C and occur 8th of August in the case with increased length. This day is therefore investigated more in detail. The coldest operative temperature is 28.3 °C and occur 11th of August in the reference case. The warmest operative temperature during the warmest day decreases in the following order; increased length, increased height and reference case and increased width.

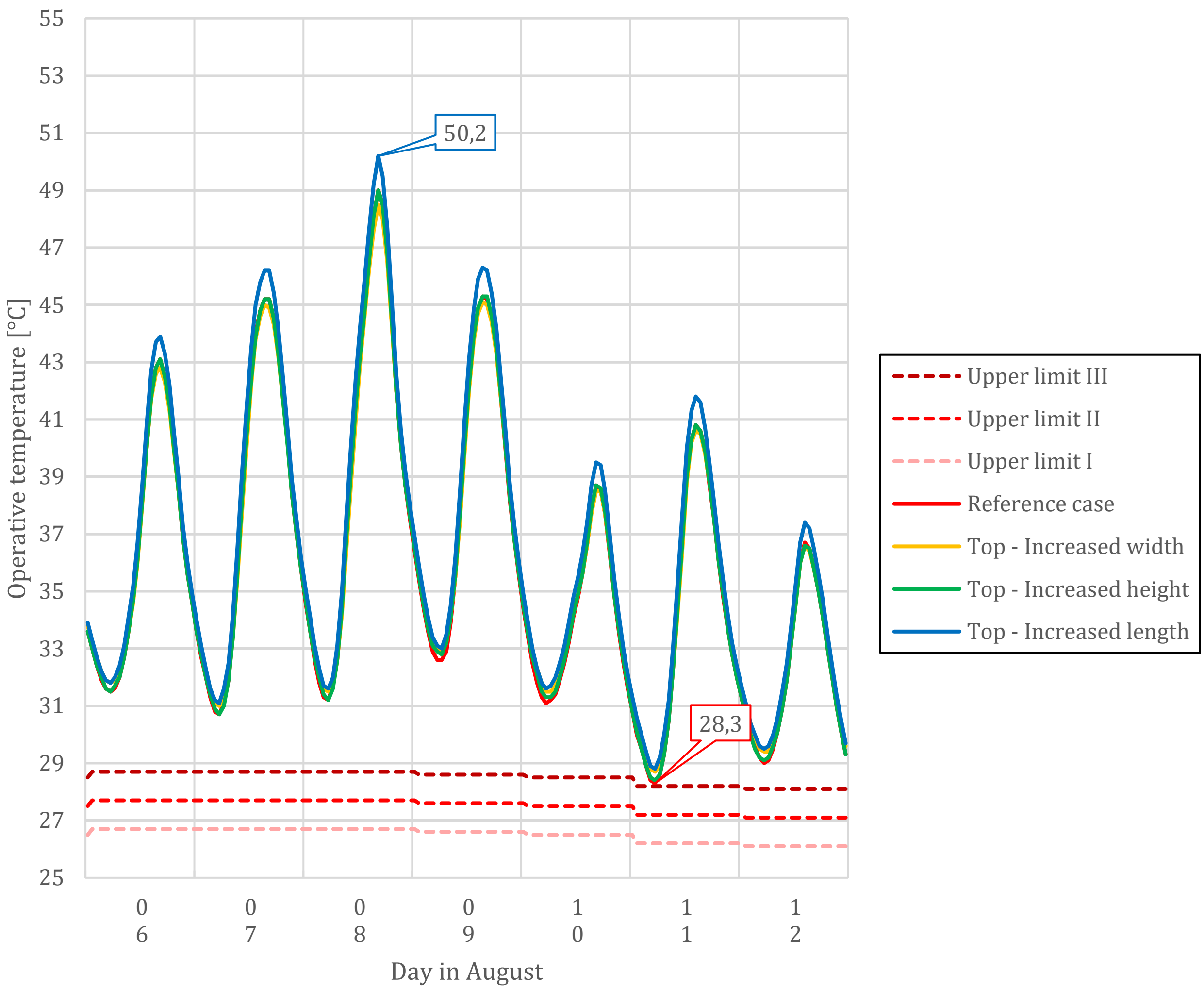


Figure 7.53 Operative temperature in floor 5 and the upper comfort limits.

When there is no solar radiation and the outdoor temperature is lower, the operative temperature is approximately equal in all cases. When the solar radiation and outdoor temperature is higher, the case with increased length has the warmest operative temperature. When there is no solar radiation and the outdoor temperature is decreasing, the operative temperature is decreasing and approximately of equal size. When the solar radiation and the outdoor temperature is increasing, the operative temperature is increasing. When the solar radiation and the outdoor temperature is decreasing, the operative is decreasing and are eventually of approximately equal size again.

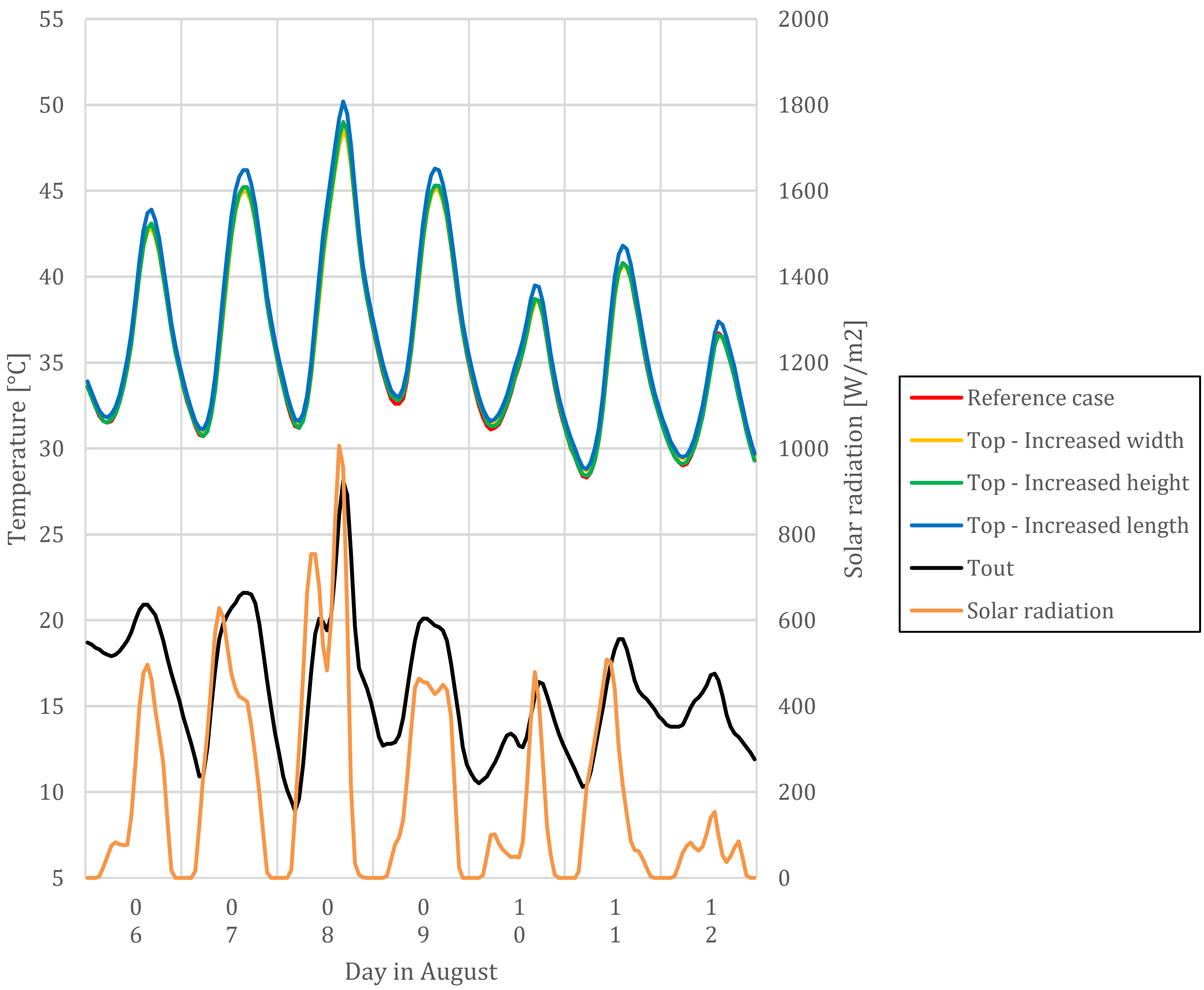


Figure 7.54 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the summer week.

The heat gains and losses can be divided into heat gain through windows, storage, envelope, openings and occupants. Figure 7.55 shows the heat gains and losses through windows, storage, envelope and openings in floor 5 for each case. The maximum heat gain occurs through the windows. Thereafter, the maximum heat gain decreases in the following order; storage, openings, envelope and occupant. Since the maximum heat gain range occur through the windows, the windows have the largest impact of the operative temperature in the atrium.

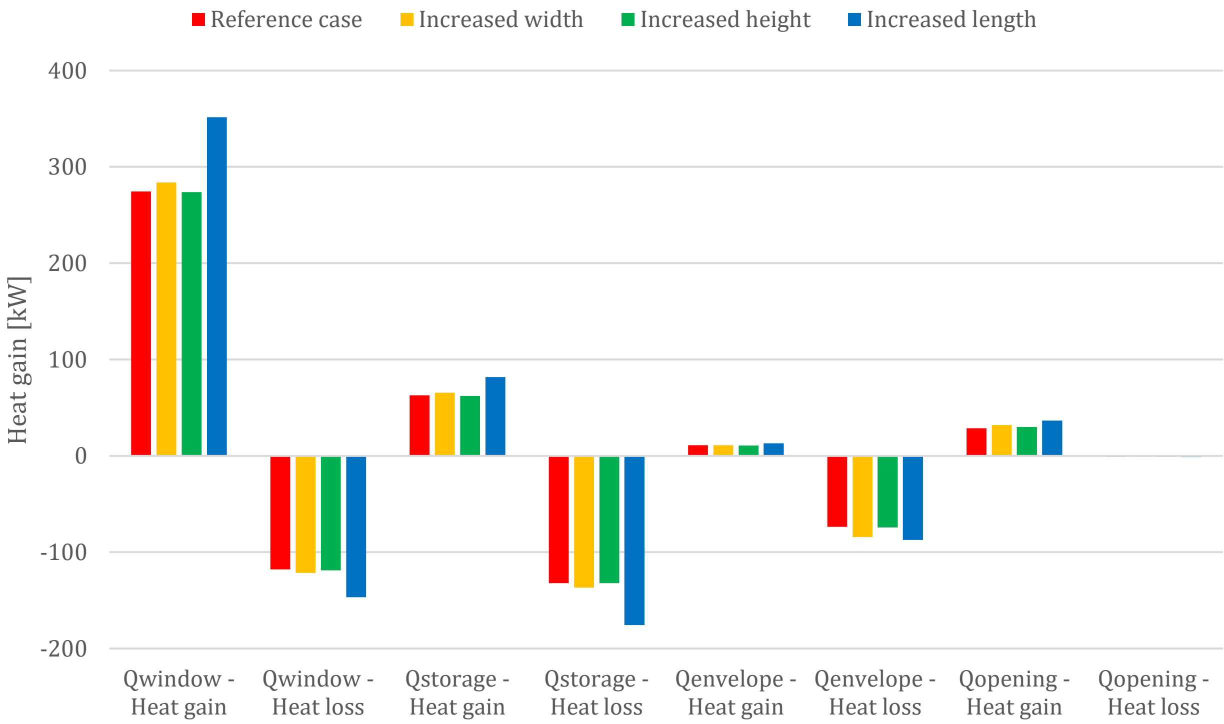


Figure 7.55 Heat gain per category during the warmest day.

The heat gains and losses through windows is largest in the case with the increased length due to the largest window area. The reference case and the case with increased height has equal window area, which results in almost equal heat gain and losses through windows. During mid-day, when the solar radiation is decreasing and the outdoor temperature is approximately constant, the heat gain through windows is increasing more in the case with increased width compared to the other cases.

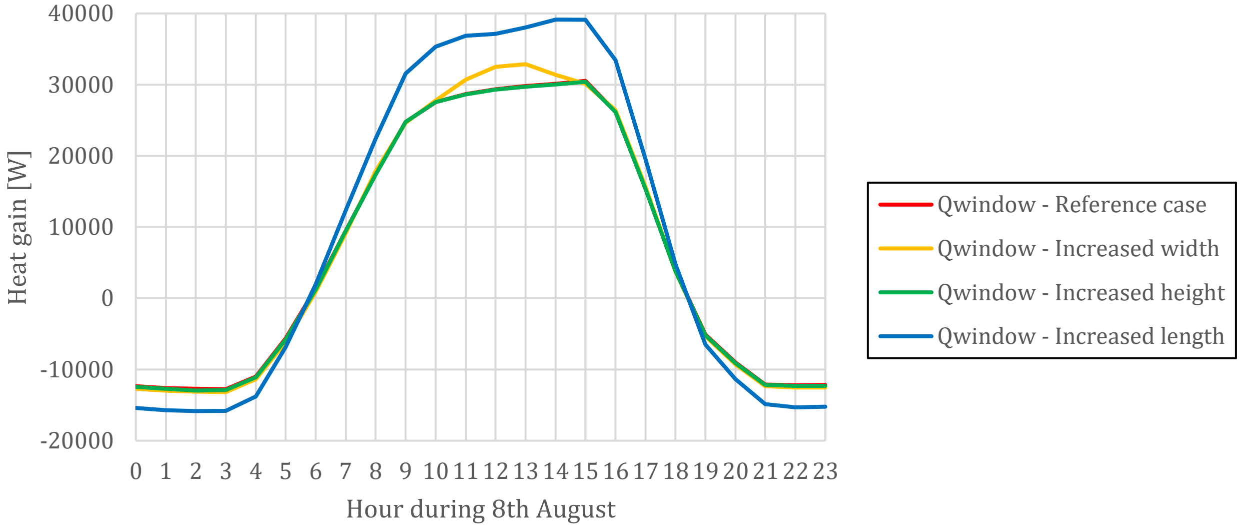


Figure 7.56 Heat gain through windows in the top floor.

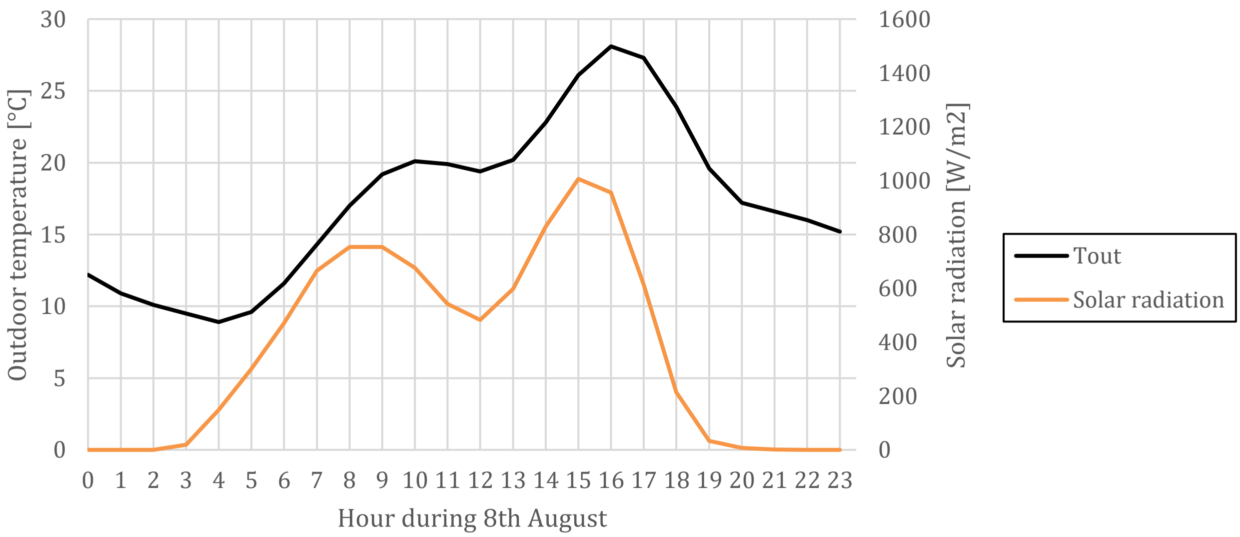


Figure 7.57 Outdoor temperature vs solar radiation during 8th August.

The case with increased length is gaining and losing more heat through storage during the warmest day compared to the other cases, which are gaining and losing almost equal amount of heat. This is because it has a larger window area which let more solar radiation into the atrium and a large envelope area which can store and release the heat from solar radiation. The reference case, the case with increased width and the case with increased height gains almost equal amount of heat since they have almost equal amount of window area. However, when the solar radiation is decreasing and the outdoor temperature is approximately constant, the case with increased width loses more heat through storage since it has a larger envelope area.

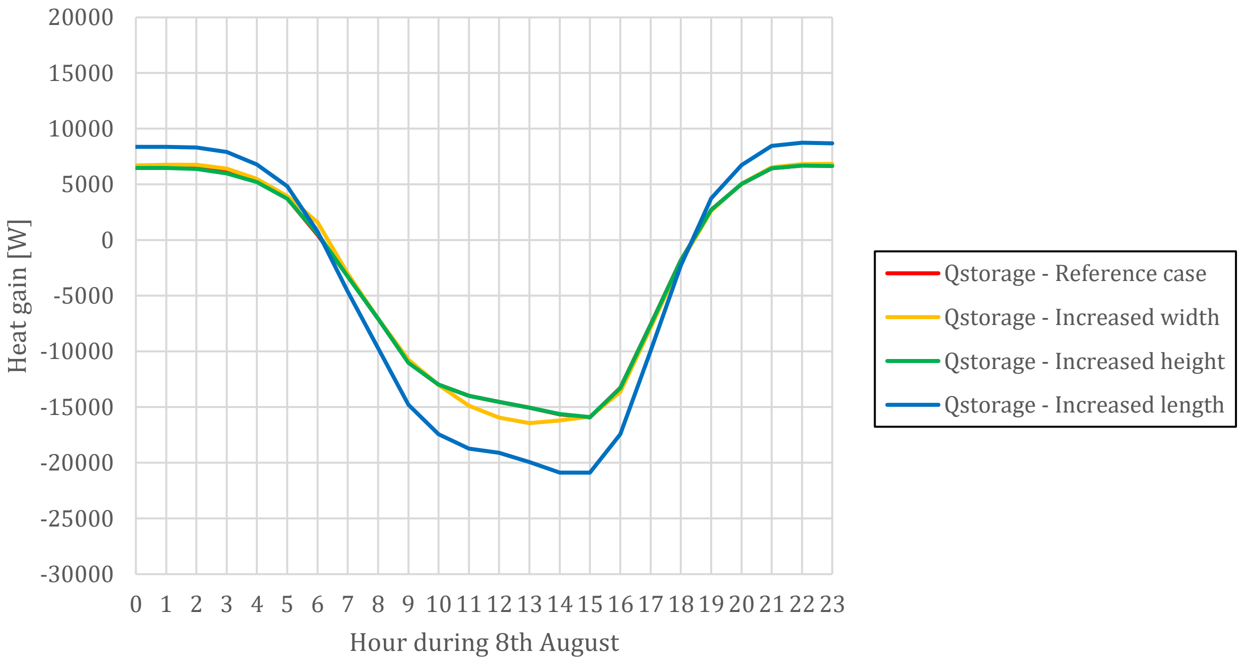


Figure 7.58 Heat gain through storage in the top floor.

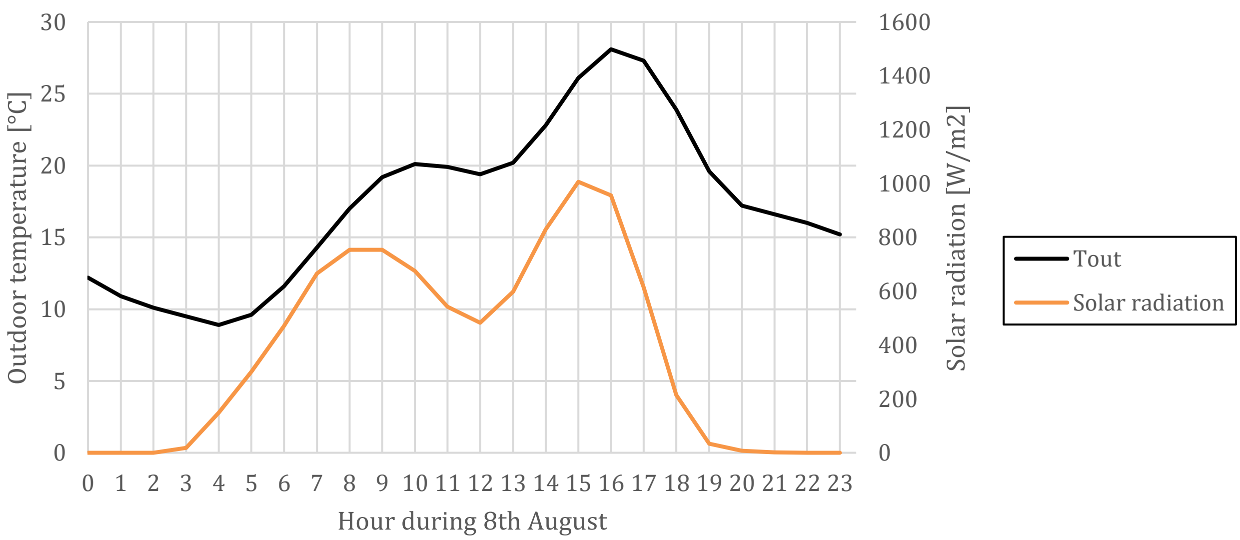


Figure 7.59 Outdoor temperature vs solar radiation during 8th August.

The case with increased length and width are gaining and losing more heat through the envelope compared to the other cases. When the solar radiation and outdoor temperature is increasing, the heat loss is increasing the most in the case with increased length since this case has the highest operative temperature. When the solar radiation is decreasing and outdoor temperature is approximately constant, the heat losses is decreasing the least in the case with increased width since this case has a larger area facing the exterior climate compared to the other cases.

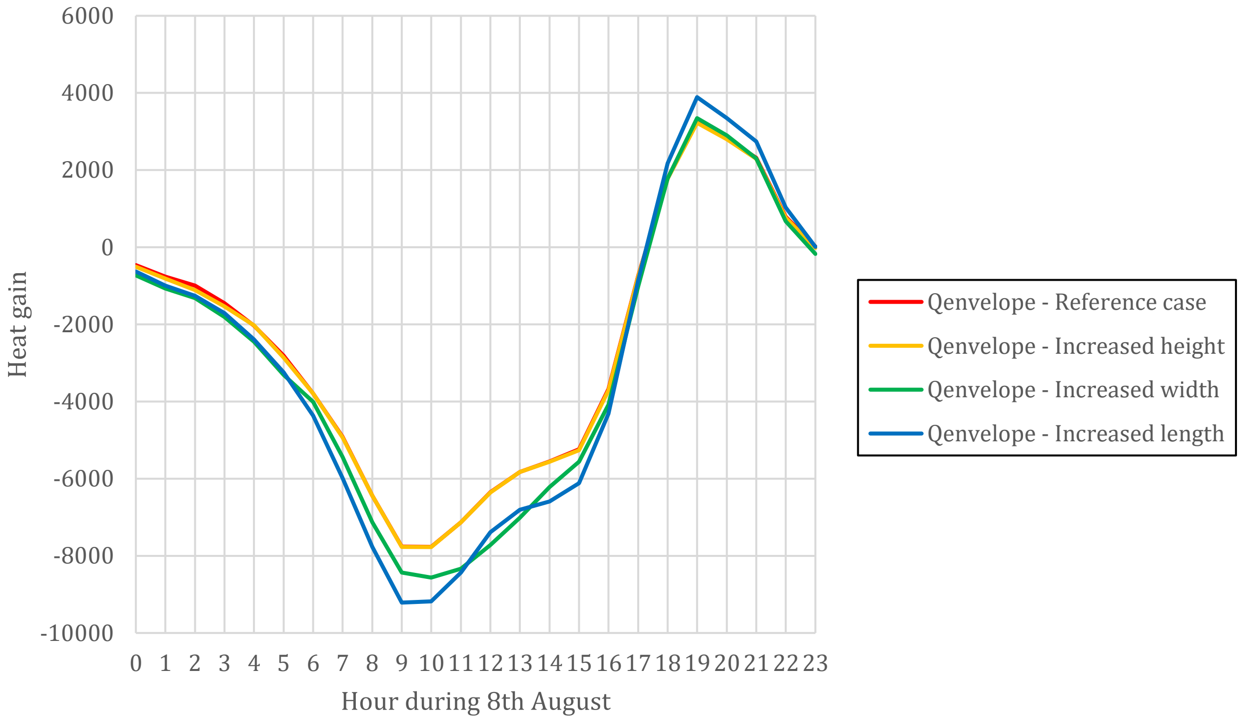


Figure 7.60 Envelope heat gain in the top floor.

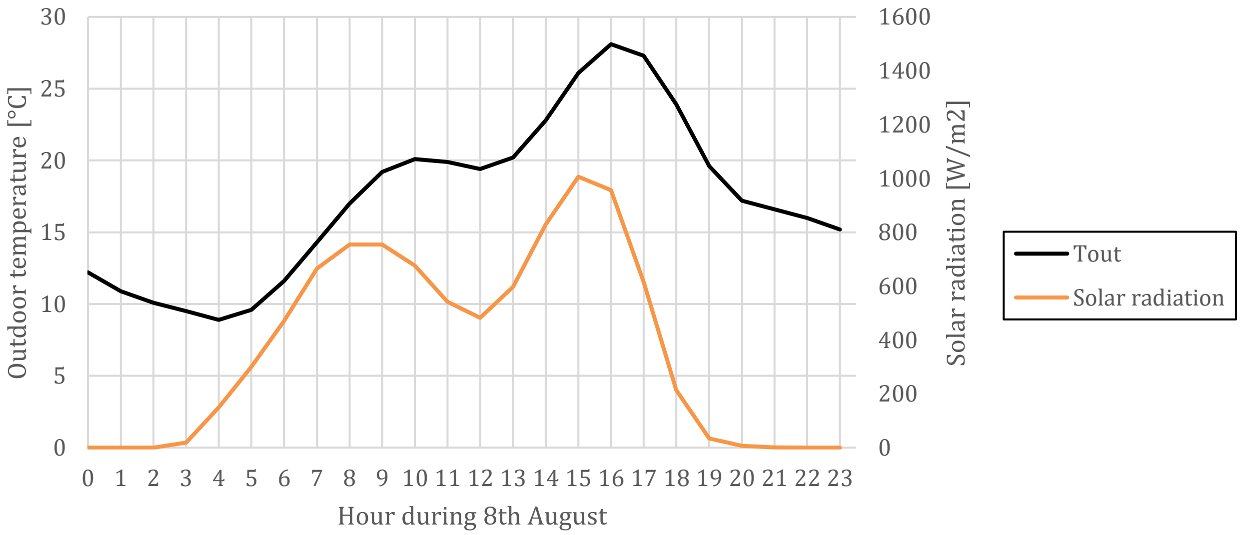


Figure 7.61 Outdoor temperature vs solar radiation during 8th August.

When composing the heat gain through windows, storage, envelope and openings, the largest heat gain and losses occur in the case with increased length. The largest heat gain difference between the cases occurs during the day. This results in a higher operative temperature in the case with increased length during the day and almost equal operative temperature during the night.

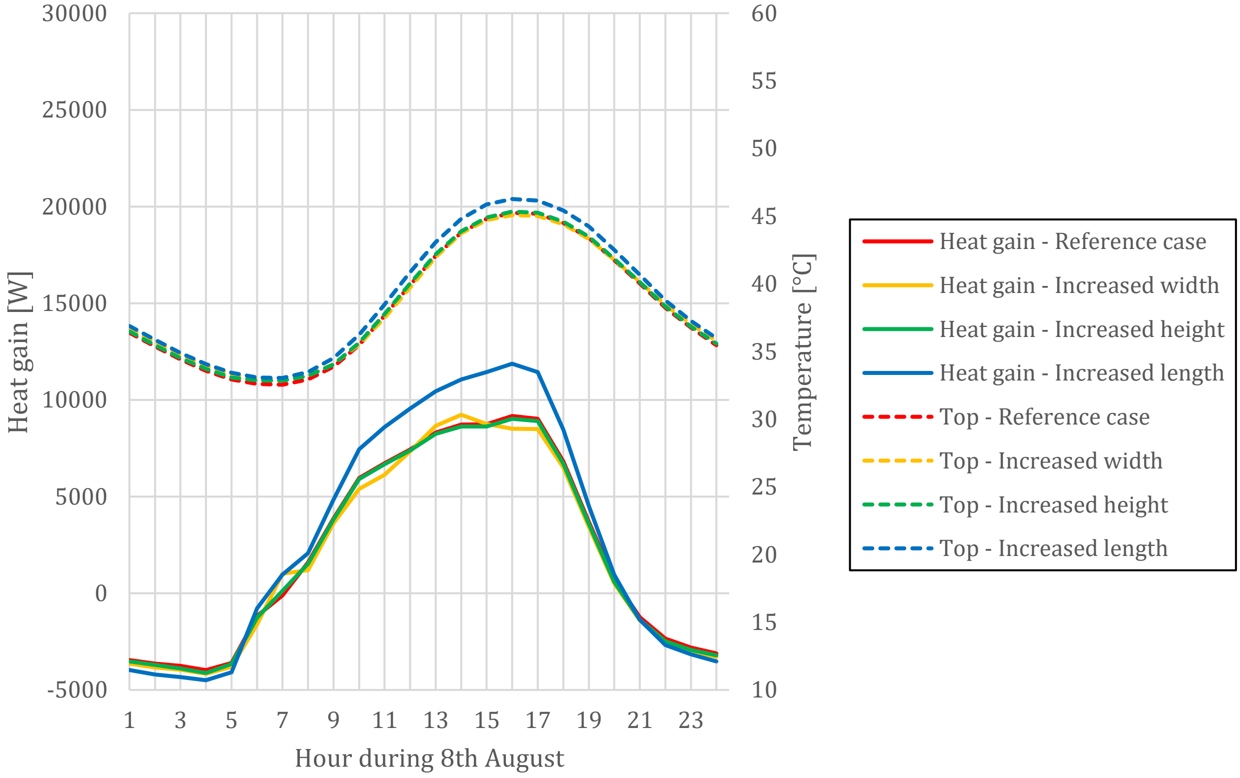


Figure 7.62 Heat gain vs operative temperature in floor 5.

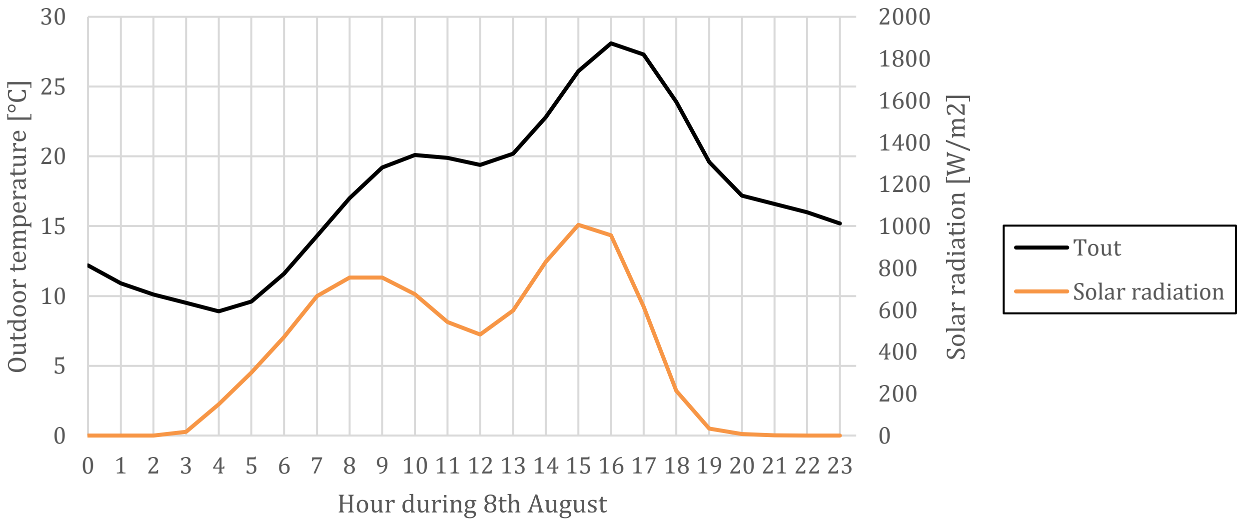


Figure 7.63 Outdoor temperature vs solar radiation during 8th August.

7.6.2 Winter period

The operative temperature is too cold during all hours in all cases to achieve thermal comfort according to the standard. The coldest operative temperature of all cases is -8 °C and occur 23th of December in the case with increased width. Since the minimum outdoor temperature day occur 22th December and the minimum operative temperature in the atrium occur 23th December, these two days is investigated more in detail. The warmest operative temperature of all cases is 2.3 °C and occur 26th of December in the case with increased height. The coldest operative temperature during the coldest day decreases in the following order; increased length, increased height and reference case and increased width.

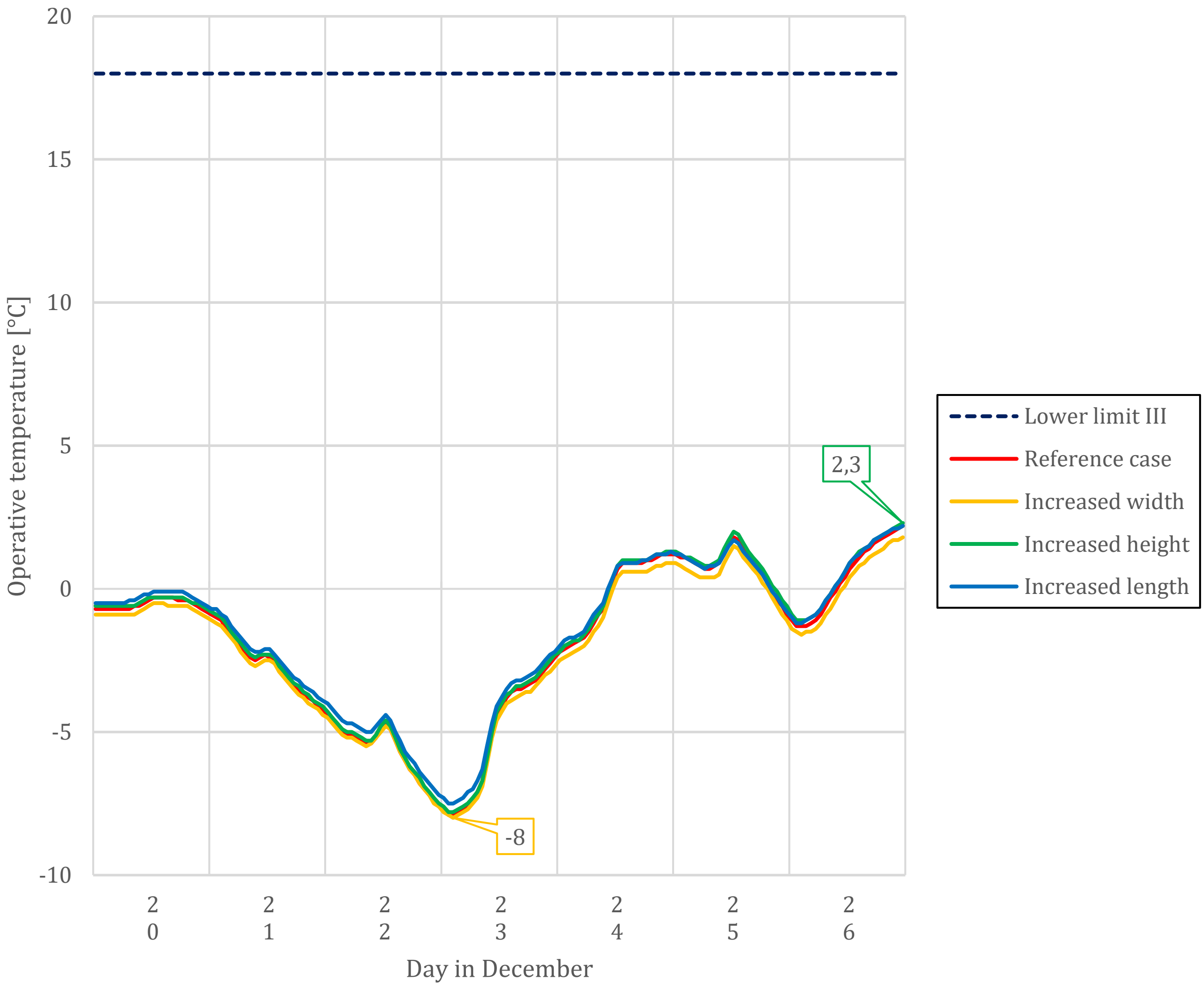


Figure 7.64 Operative temperature in floor 5 and thermal lower thermal comfort limit III during winter week.

The operative temperature is approximately equal in all cases during both days. When the solar radiation and outdoor temperature is increasing and decreasing, there is no major difference between the temperatures.

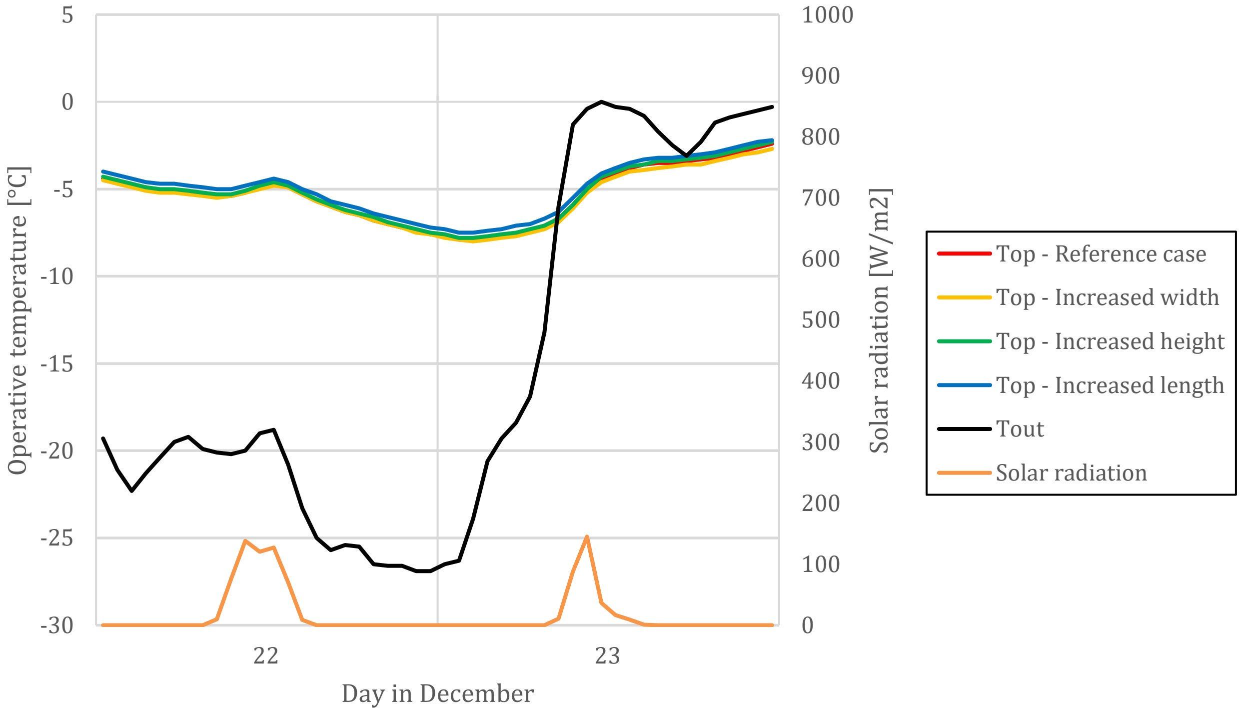


Figure 7.65 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the coldest day and the day after.

7.7 Building orientation

The impact of building orientation is investigated by comparing the position of the reference building with 45° offset, 90° offset, 135° offset and 180° offset. The summer period is examined during the summer week and the winter period is examined during the winter week.

The operative temperature is more dependent on the building orientation during the summer than during the winter. The case with 0° offset and 180° offset, see Figure 7.66 and 7.67, has the coldest operative temperatures during the summer. However, during the winter, the operative temperature is approximately equal in all cases except the case with 90° offset. Therefore, the building orientation of all other cases does not have a major impact. The building orientation should be designed with 0° offset or 180° offset to achieve the coldest operative temperatures during the summer and warmest operative temperatures during the winter. The glazed parts of the building should be orientated to the south and north to achieve the most acceptable occupancy hours according to the standard.

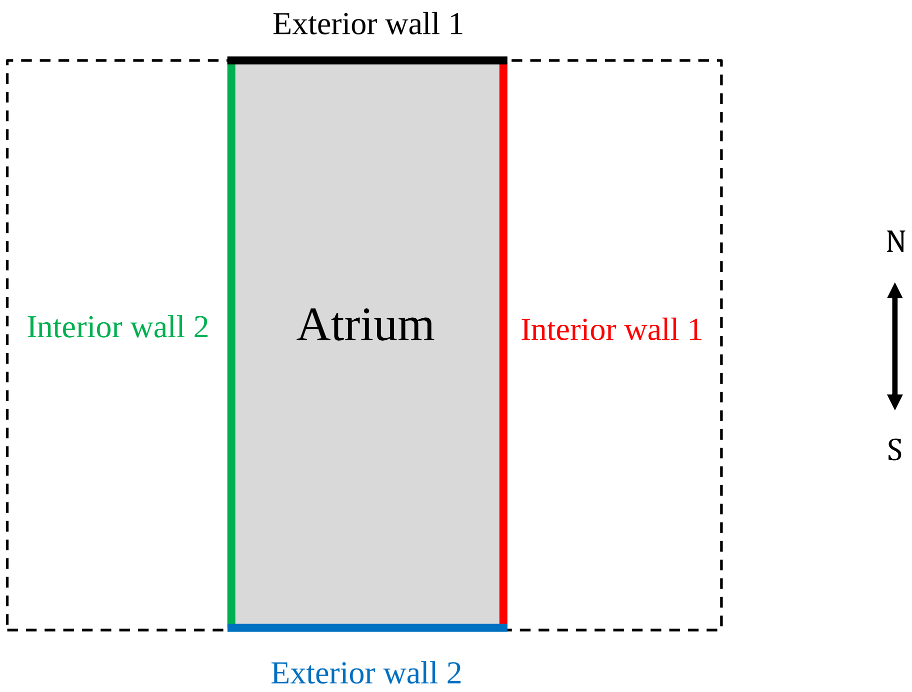


Figure 7.66 Reference case with 0° offset, where the exterior walls consists of glazed parts and the interior walls are facing a typical indoor climate.

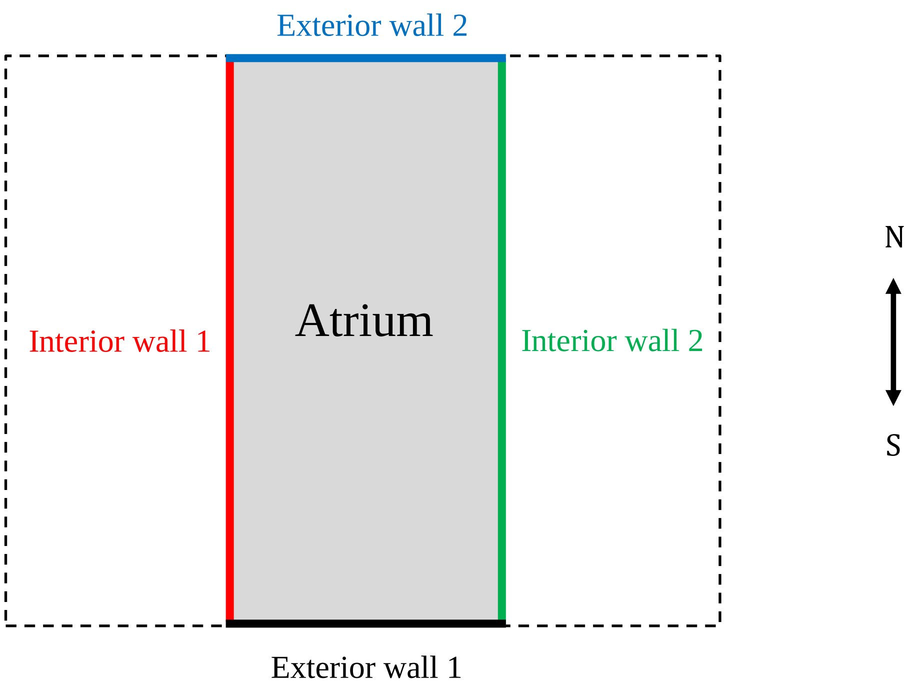


Figure 7.67 Reference case with 180° offset, where the exterior walls consists of glazed parts and the interior walls are facing a typical indoor climate.

7.7.1 Summer period

The operative temperature is too warm to achieve thermal comfort during all hours in all cases. The warmest operative temperature of all cases is 49.9 °C and occurs 8th August in the case with 45° offset. The coldest operative temperature of all cases is 28.3 °C and occurs in the reference case and the case with 180° offset.

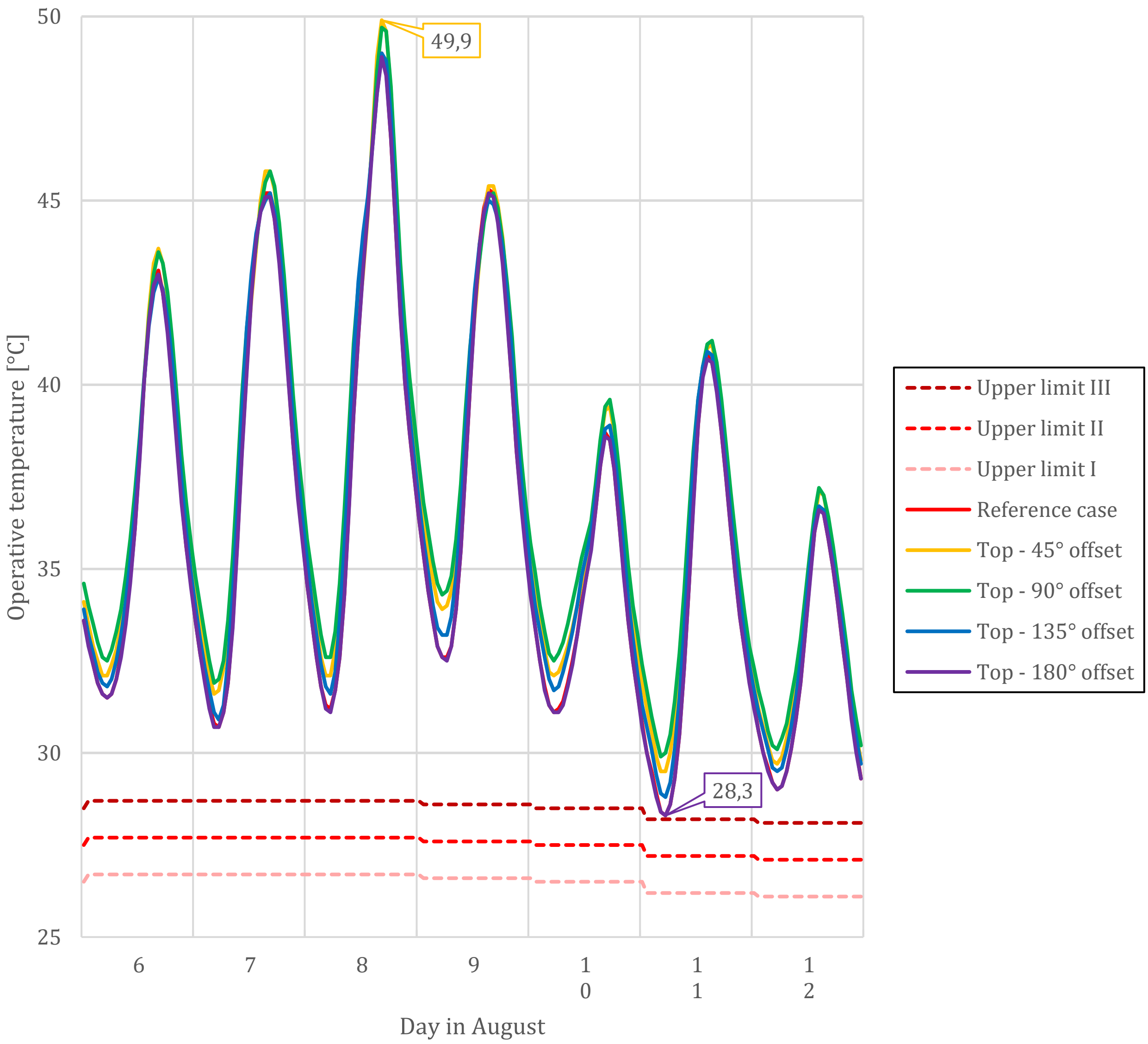


Figure 7.68 Operative temperature in floor 5, and the upper thermal comfort limits during the summer week.

7.7.2 Winter period

During the cold period, the operative temperature is too cold during all hours in all cases to achieve thermal comfort according to the standard. The warmest operative temperature is 2.2 °C and occurs 26th December in the reference case. The coldest operative temperature is -8.3 °C and occurs 23th December in the case with 90° offset.

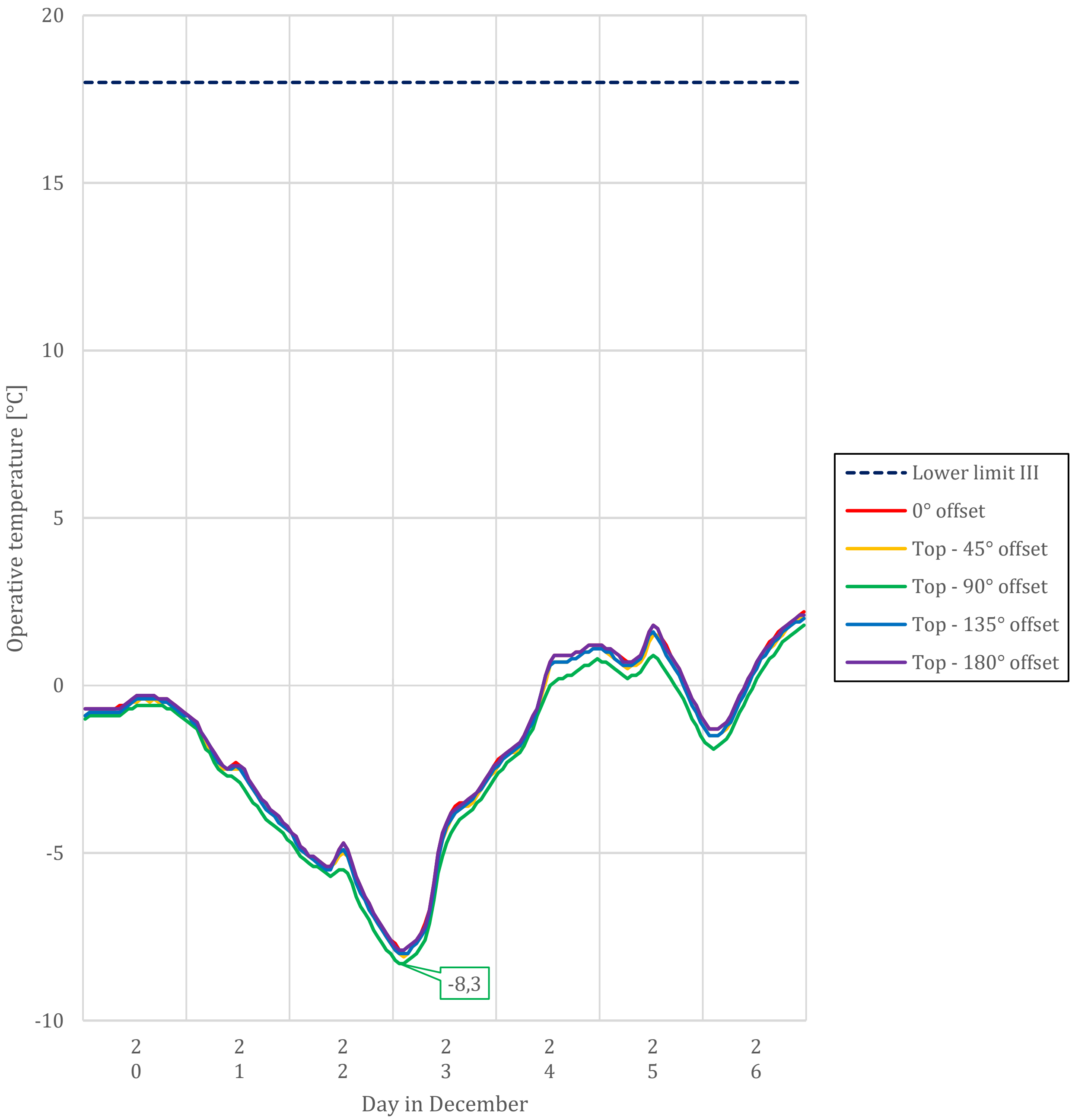


Figure 7.69 Operative temperature in floor 5, and the lower thermal comfort limit III during the winter week.

7.8 Solar shading

The impact of solar shading is investigated by comparing the reference building with shadings always drawn and with a schedule of the solar shadings. During the summer period, the shadings are drawn when the incident solar radiation exceeds 100 W/m^2 on the outside of the window. During the winter period, the shadings are drawn between 15.00-08.00. The summer period is examined during the summer week and the winter period is examined during the winter week.

Table 7.7 Evaluation cases of shading schedule.

Case		Description of shading schedule
Never drawn (Reference)		Shadings are never drawn
Always drawn		Shadings are always drawn
Schedule	Summer period	Shading are drawn when the incident solar radiation exceeds 100 W/m^2 on the outside of the glazing
	Winter period	Shadings are drawn between 15.00 – 08.00

During the summer, the solar shadings should always be drawn to achieve most acceptable occupancy hours according to the standard. However, there is no major difference of the operative temperature in the atrium when having the shadings always drawn or drawn according to the sun control.

During the winter, the solar shadings should be drawn when the absence of the sun occur to achieve most acceptable occupancy hours according to the standard. The operative temperature in the atrium is more dependent of the outdoor temperature than the solar radiation and the difference between the shadings cases is larger when the outdoor temperature is colder. A decreased transmission heat loss by a lower total U-value is more important than an increased solar heat gain by solar radiation to achieve a warmer operative temperature during the winter.

7.8.1 Summer period

The operative temperature is too warm during all hours in the reference cases to achieve thermal comfort according to the standard. However, in both cases with solar shading, the operative temperature is within the limits during some hours to achieve thermal comfort according to the standard. The warmest operative temperature of all cases is 49 °C and occur 8th of August in the reference case. This day is therefore investigated more in detail. The coldest operative temperature is 23.9 °C and occur 11th of August in the case where the shadings are always drawn.

The atrium has more acceptable occupancy hours when the shadings are used compared to when they are not used, and the minimum and maximum operative temperature is increased respectively decreased. The atrium has slightly more acceptable occupancy hours when the shadings are always drawn compared to when the shadings are drawn according to the sun control. However, the maximum and minimum temperature is approximately equal in both cases.

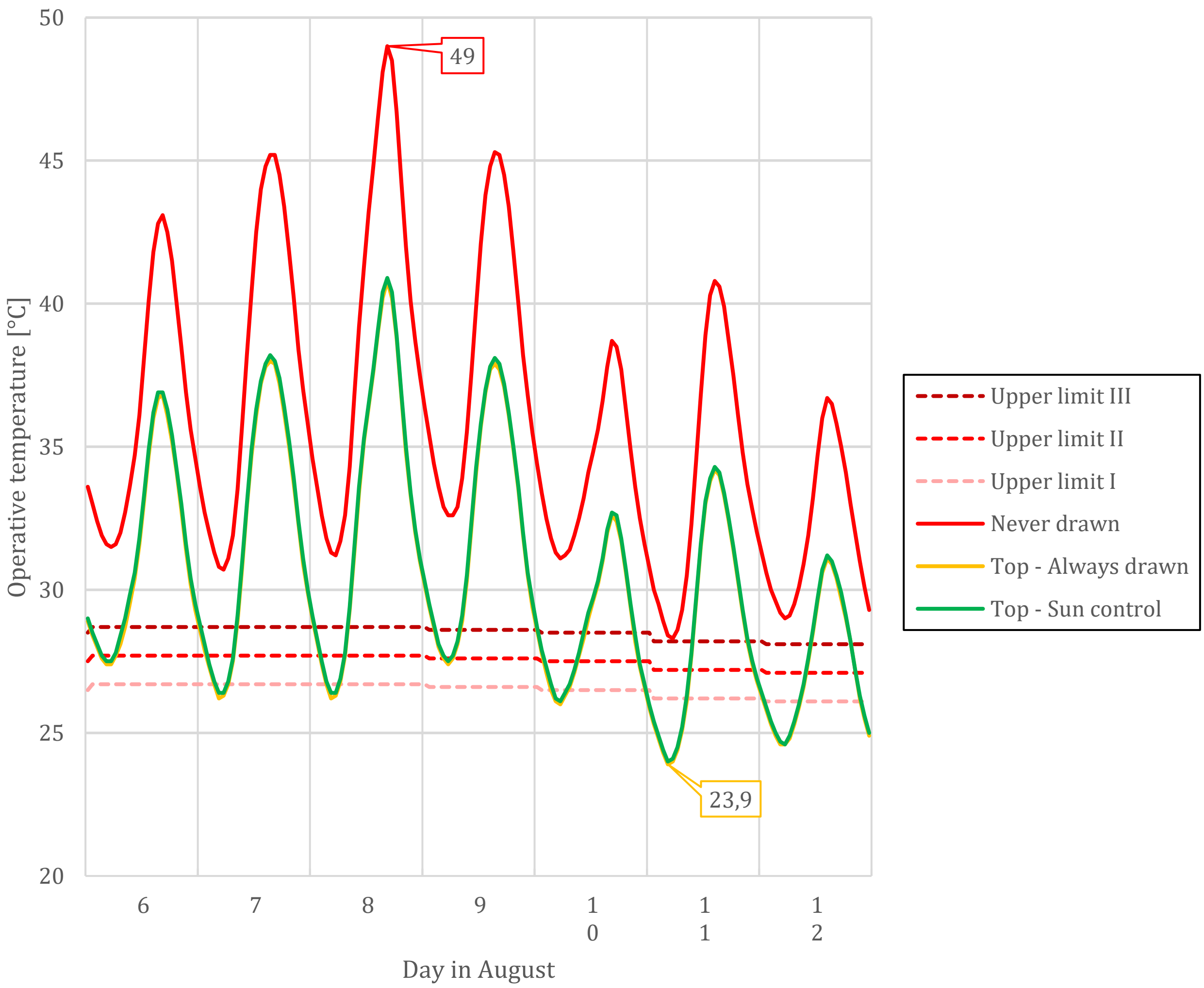


Figure 7.70 Operative temperature and thermal comfort limits in floor 5 during summer week.

The operative temperature follows the outdoor temperature and solar radiation. The operative temperature in the cases where the shadings are drawn is approximately equal despite the absence of solar radiation.

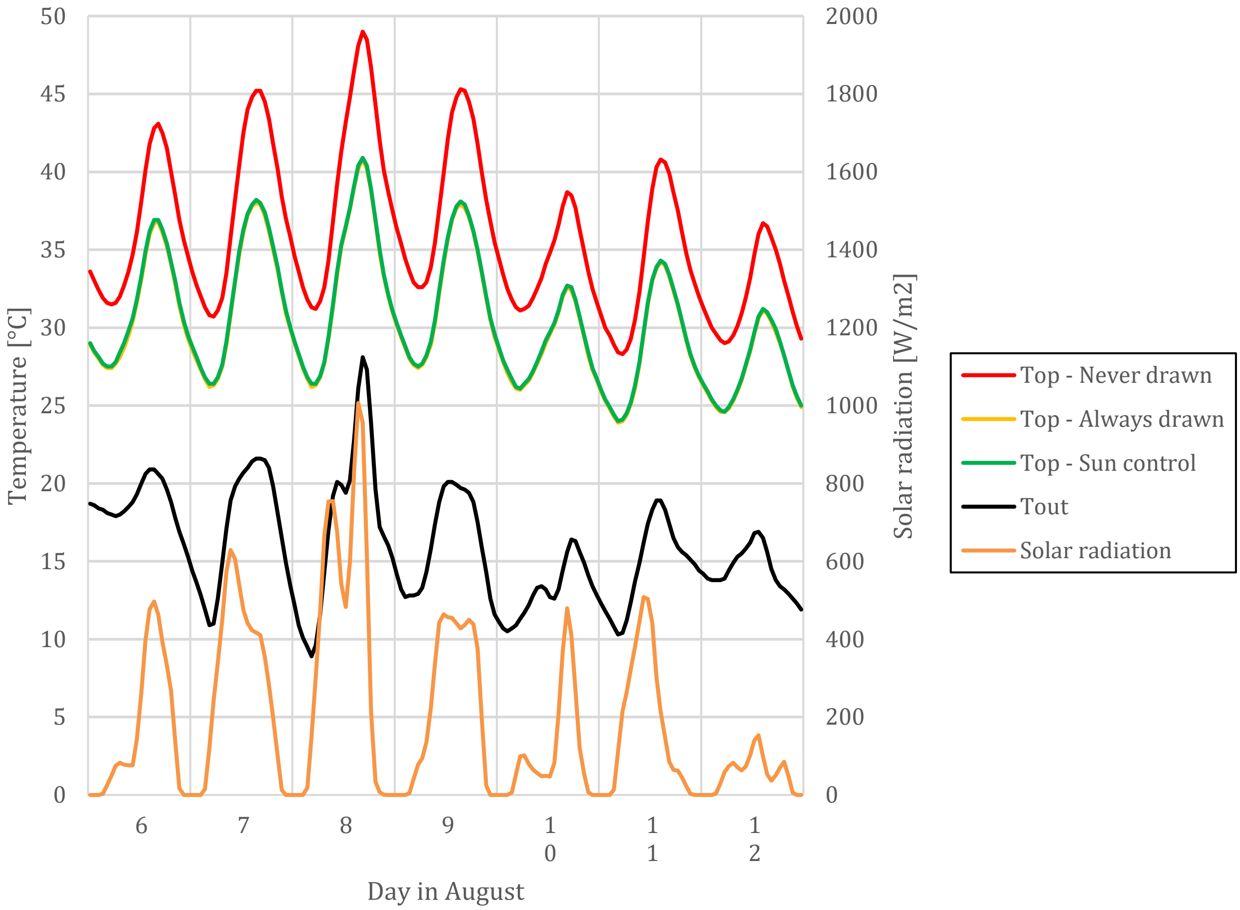


Figure 7.71 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the summer week.

7.8.2 Winter period

The operative temperature is too cold during all hours in all cases to achieve thermal comfort according to the standard. The coldest operative temperature of all cases is -8.2 °C and occur 23th of December in the case where the shadings are always drawn. This day is therefore investigated more in detail. The warmest operative temperature is 2.4 °C and occur 26th of December in the case where the shadings are drawn between 15.00 and 18.00.

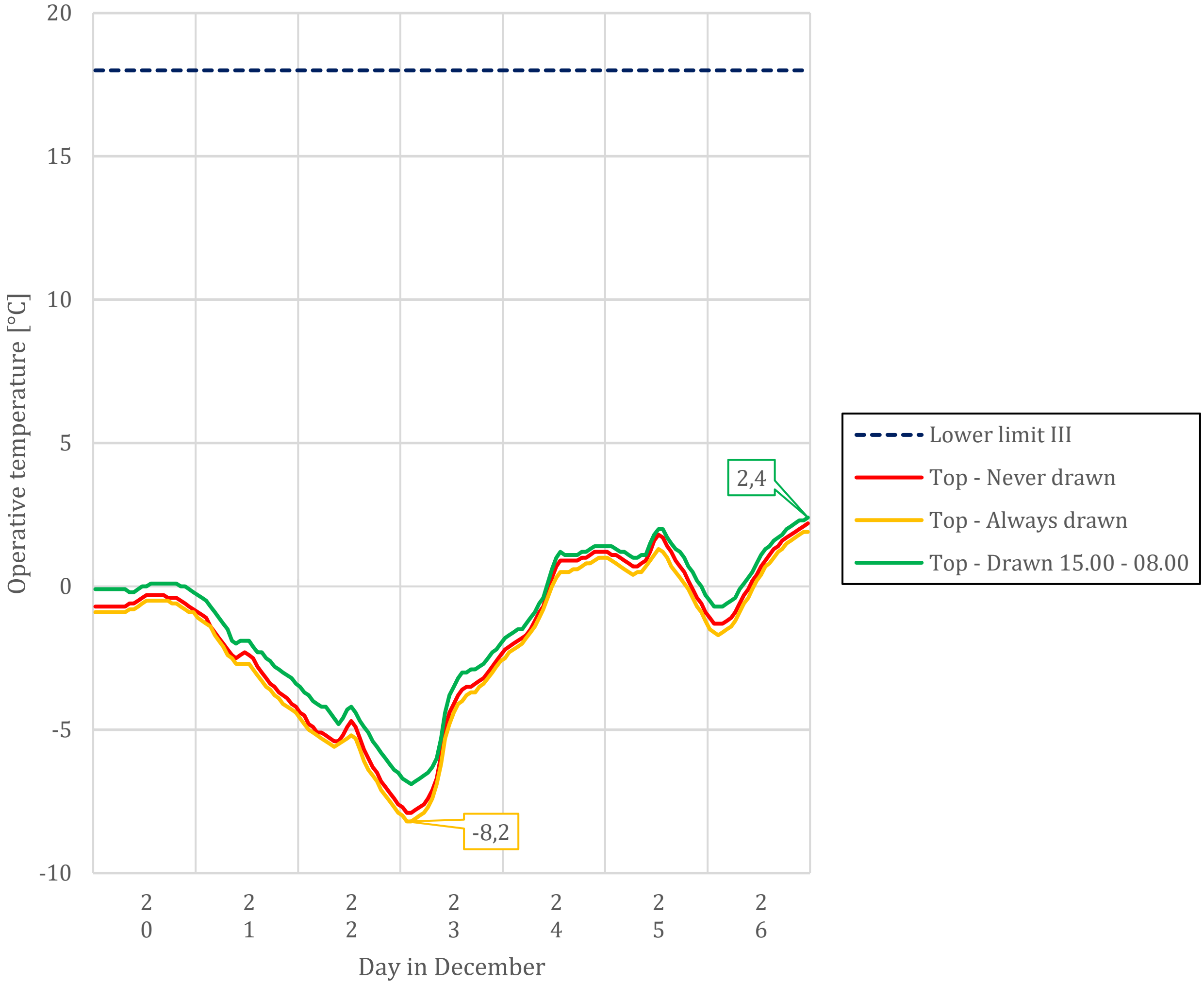


Figure 7.72 Operative temperature and thermal comfort limits in floor 5.

The operative temperature follows the outdoor temperature and solar radiation. When the outdoor temperature is colder, there is a larger difference of the operative temperature between the cases compared to when the outdoor temperature is warmer. The operative temperature in the cases where the shadings are drawn is approximately equal despite the absence of solar radiation.

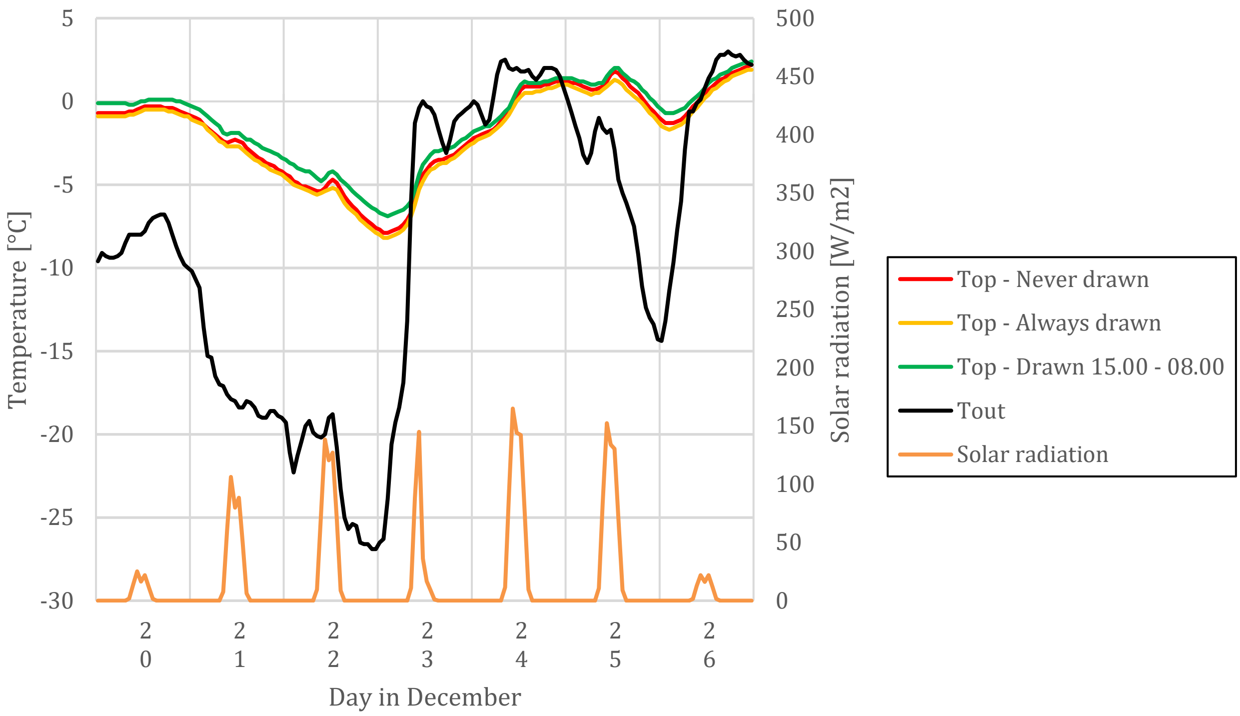


Figure 7.73 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the winter week.

7.9 Natural ventilation

The impact of natural ventilation is investigated by comparing the reference building, where the windows are always closed, with a natural ventilation system where the windows are always open and with windows opened according to a PI temperature-controlled ventilation system. The summer period is examined during the summer week and the winter period is examined during the winter week.

Natural ventilation is a good way to decrease the operative temperature when the outdoor temperature is lower than the indoor temperature. The case with a PI temperature-controlled ventilation results in acceptable operative temperatures according to the standard. However, if the warmest day would be warmer, the natural ventilation would not be efficient, since the windows would not be open when the outdoor temperature is warmer than the indoor temperature.

The operative temperature is too warm during all hours in the reference cases to achieve thermal comfort according to the standard. However, in both cases with natural ventilation, the operative temperature is within the limits during some hours to achieve thermal comfort according to the standard. The warmest operative temperature of all cases is 49 °C and occur 8th of August in the reference case. The coldest operative temperature is 10 °C and occur 8th of August in the case where windows are always open.

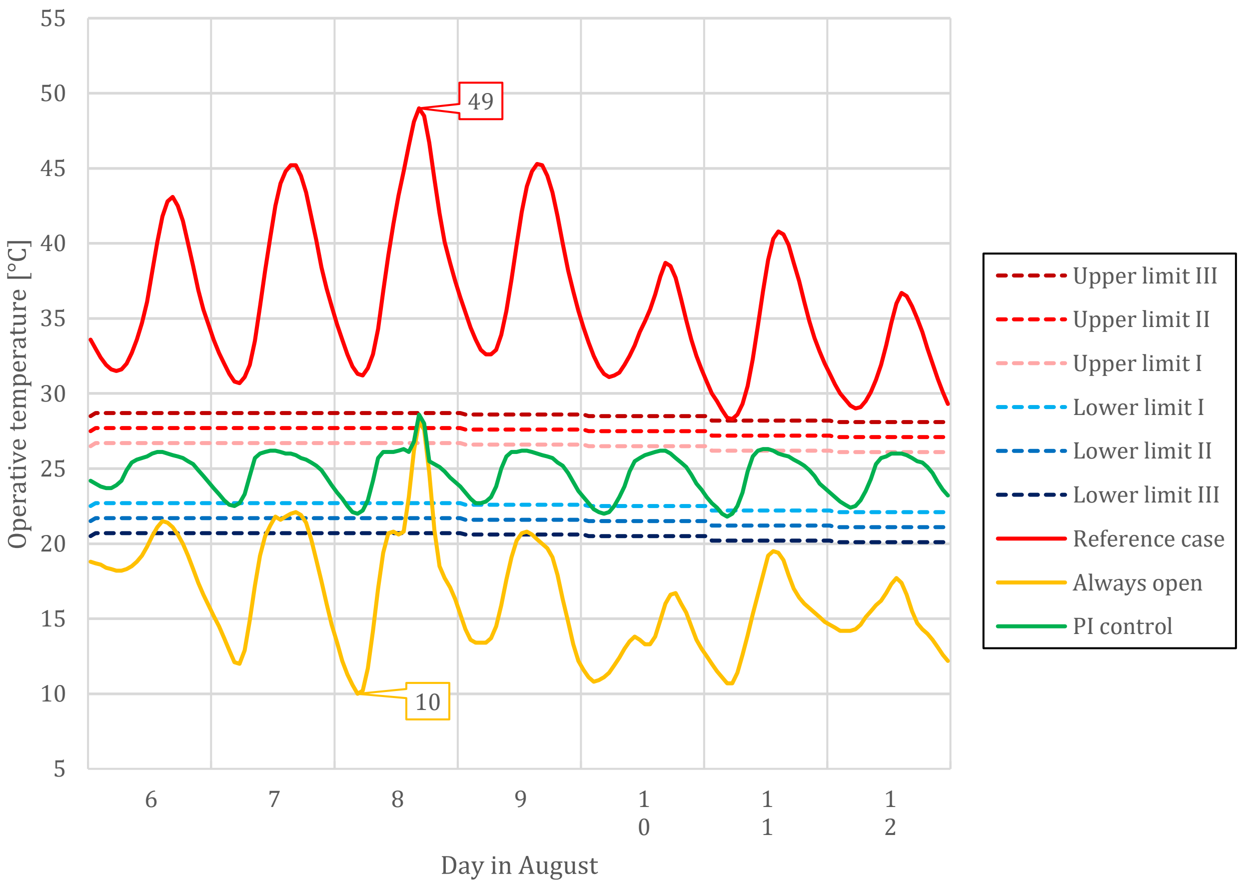


Figure 7.74 Operative temperature in floor 5, and the thermal comfort limits during the summer week.

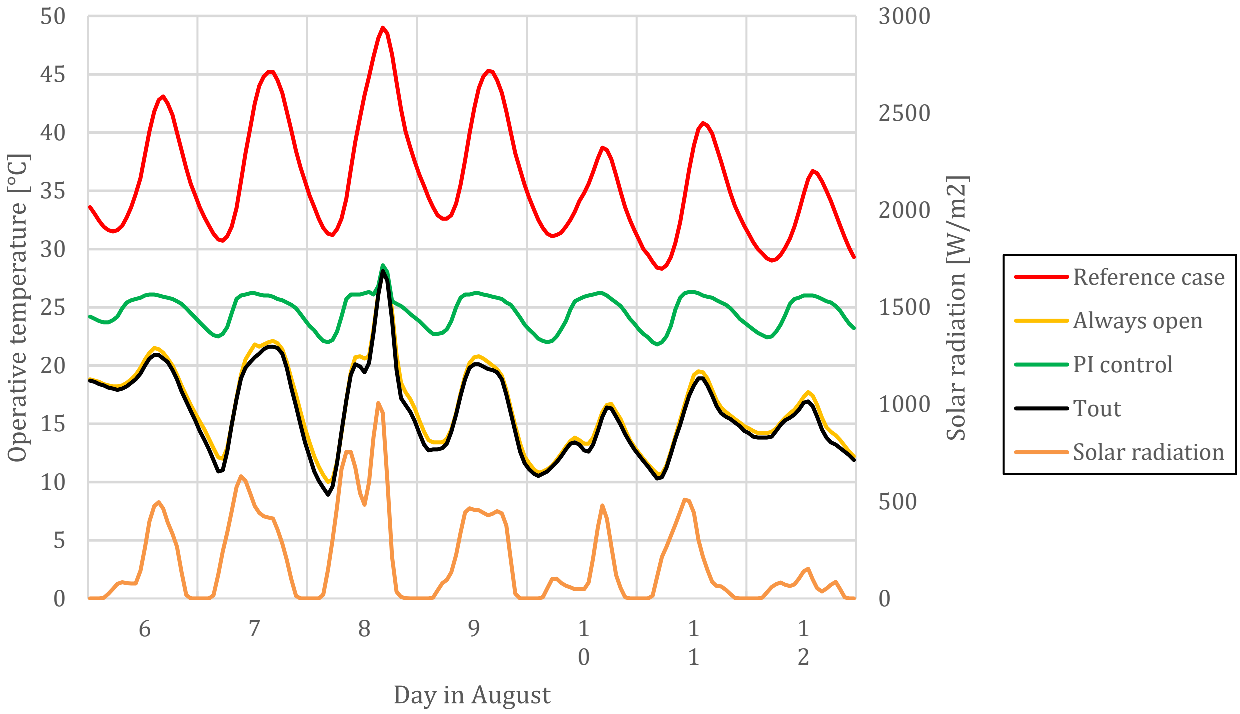


Figure 7.75 Operative temperature in floor 5, and the outdoor temperature and solar radiation during the summer week.

8 Conclusion

An atrium consists of an increased glazing area compared to a standard building, which results in more varying temperatures indoors. The relatively high U-value and the glazing properties that let solar radiation into the building results in too warm temperatures during the summer and too cold temperatures during the winter if the area is to be used to live in.

A higher thermal mass of the atrium is almost always beneficial since the decreased temperature oscillation decreases the maximum temperatures in the atrium.

A glazing material with a lower g-value is beneficial during the summer since it decreases the operative temperature in the atrium due to less radiation heat gain through windows. Also, a 3-pane glazing, which means lower g- and U-value, is beneficial during the winter since it increases the operative temperature in the atrium due to a less transmission heat losses through the windows.

A centralized atrium is, compared to a linear or semi-enclosed atrium, beneficial during both summer and winter since it has colder operative temperature during the summer and warmer operative temperature during the winter. This is due to a smaller glazing area and larger interior wall area.

The reference building with an increased length has a warmer operative temperature during both summer and winter due to an increased glazing area. However, the operative temperature difference between the reference building and the longer building is larger during the summer than during the winter. The reference building with increased length is therefore not beneficial.

The operative temperature is more dependent on the building orientation during the summer than during the winter. The building orientation should be designed with 0° offset or 180° offset to achieve the coldest operative temperatures during the summer and warmest operative temperatures during the winter. The glazed parts of the building should thus be orientated to the south and north to achieve the most acceptable occupancy hours according to the standard.

During the summer, the solar shadings should always be drawn to achieve most acceptable occupancy hours according to the standard. The solar shadings also lower the U-value and, consequently, during the winter, the solar shadings should be drawn when there is no solar radiation to achieve most acceptable occupancy hours according to the standard.

Natural ventilation is a good way to decrease the operative temperature when the outdoor temperature is lower than the indoor temperature. The indoor temperature is always warmer than the outdoor temperature during the summer period. However, if the outdoor temperature is warmer than the indoor temperature, natural ventilation cannot decrease the indoor temperature in the atrium.

9 Discussion

The usage of the top floor, availability of glazing material, daylight deprivation and some further investigations is discussed in this chapter.

9.1 Usage of top floor

According to the results, the top floor is the most critical level when considering thermal comfort in terms of operative temperature. The top floor in the reference building consists of technical rooms and storage and are not intended to use as living areas or staying for a longer time. When designing an atrium, the top floor should not be used as an area for the occupants to stay in for a longer time if the temperatures become as high and low as in the reference building.

9.2 Availability of glazing material

According to the results, an ultimate glazing material would have low g-value and high U-value to optimize the operative temperature in the atrium in summertime. A window with low g-value and high U-value is not very common on the market. To use such window would therefore be expensive. A glazing system with even more panes could also increase the operative temperature in wintertime. However, such windows would be heavier for the structural system to carry and be more expensive.

9.3 Daylight deprivation

It was shown that solar shading is efficient to improve the thermal comfort when the sun is shining during the summer period and when the sun is not shining during the winter period. Thermal comfort can be achieved by adding a layer outside the windows. However, this result in decreased daylight in the atrium, which is not beneficial for the occupants. The purpose with a glazed space is fulfilled during autumn and spring. However, during summer and winter, the building should be designed so that the glazed space can be transferred into a regular building design as much as possible.

According to the results, an increased height of the building would not have a major impact of the thermal comfort. However, the higher the building is, the lower the daylight factor will be for the lower floors of the building.

9.4 Further investigations

The results of the design parameters are only evaluated separately. Therefore, a further investigation is to combine the design parameters to evaluate how these are affecting each other and how an optimal atrium should be designed. For an example, the ability of thermal storage increase with an increased thermal mass and an increased atrium volume would increase the thermal mass. An increased volume with higher thermal mass may have a larger impact of the thermal comfort when combining these parameters.

The reference building is in Umeå, which has especially more and less sun hours during the summer respectively winter. A possible further investigation is therefore to investigate how the operative temperature in the atrium is affected by maximum and minimum sun hours per day compared to maximum and minimum outdoor temperature.

Due to the on-going climate changes, an interesting investigation would be to evaluate how the operative temperature in the atrium would be affected of a warmer and colder climate during the summer respectively winter. It would also be interesting to investigate how the operative temperature in the atrium is affected in different locations in Sweden.

The thermal comfort in his study is based on evaluation of the operative temperature. However, thermal dissatisfaction can also be caused by local thermal discomfort, such as draught, vertical air temperature differences, floor temperature, and radiant temperature asymmetry. Local thermal discomfort should also be evaluated in order to assure thermal comfort in the atrium. For example, due to the natural ventilation through PI temperature opening control, the air flow into and out of the building will increase. Since the windows of the reference case is always closed, it has a lower air flow through the windows compared to the building with PI temperature-controlled opening. This increased airflow can be causing a local thermal discomfort.

10 References

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Appendix A - Reference building

A1 Geometry

The geometry of external walls, roof and openings is presented below. Additionally, the exact size and position of the windows and doors placed on the external walls and roof are presented.

The blue square illustrated the windows on the external walls and the grey squares illustrates the doors on the external walls.

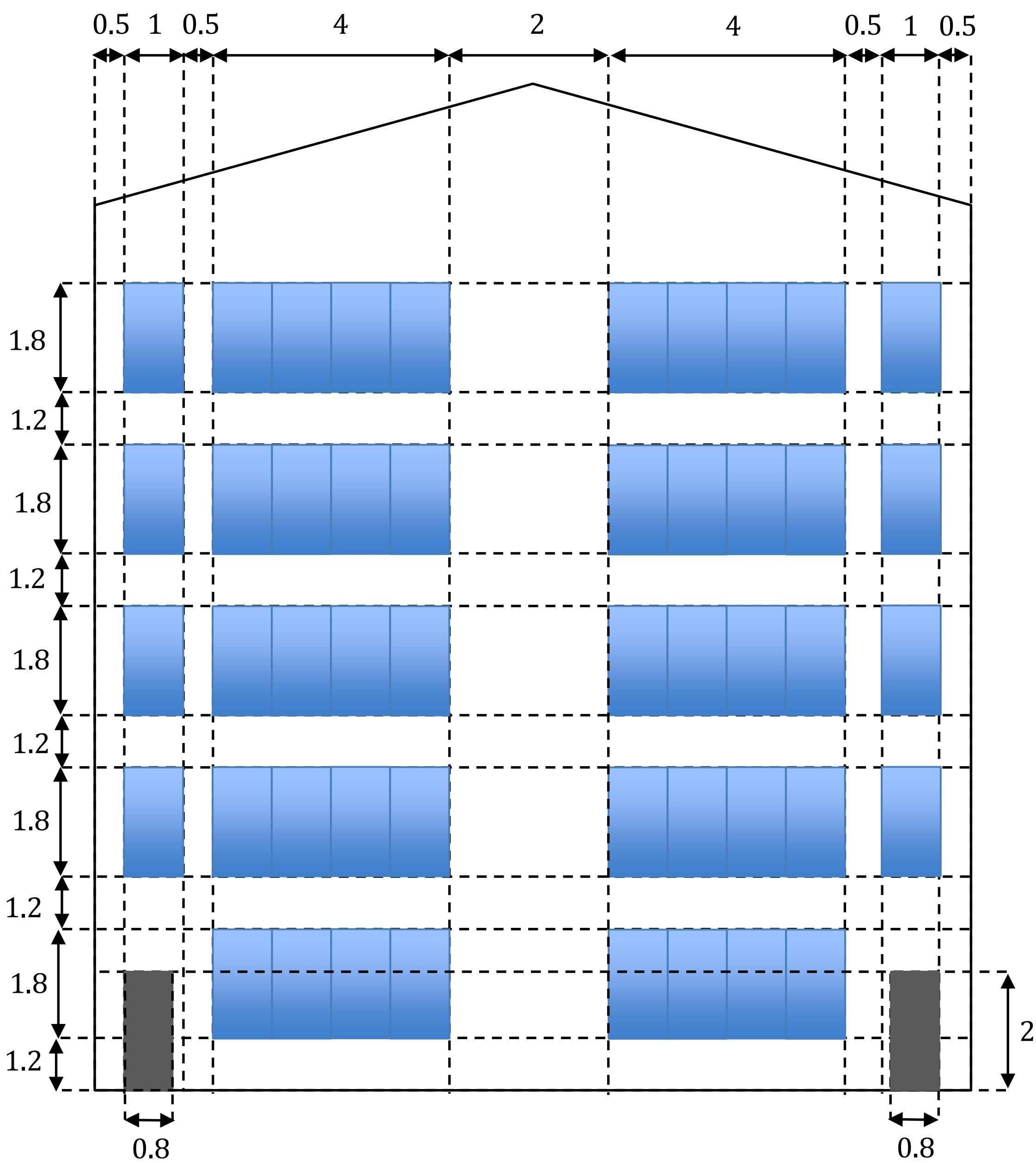

Figure A.1 Placement and geometry of windows and doors on exterior walls, where the measurements are expressed in meters.

The windows on wall have a width of 1 meter and a height of 1.8 meters. The geometry of the windows on wall is illustrated in Figure A.2. The doors have a width of 0.8 meters and a height of 2.0 meters. The geometry of the doors is illustrated in Figure A.3.

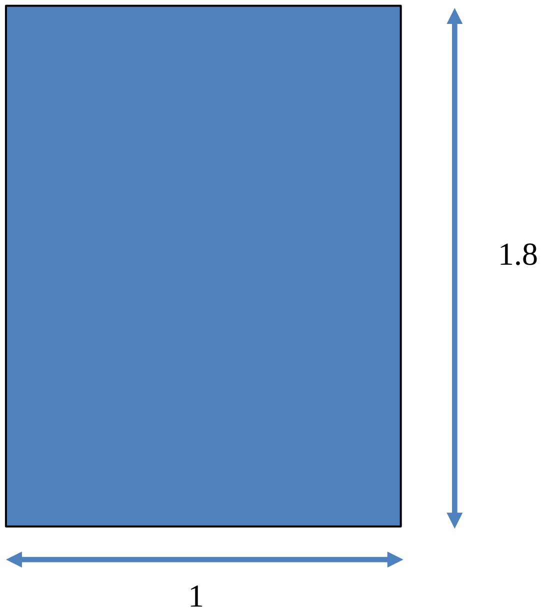

Figure A.2 Geometry of the window on wall, where the measurements are expressed in meters.

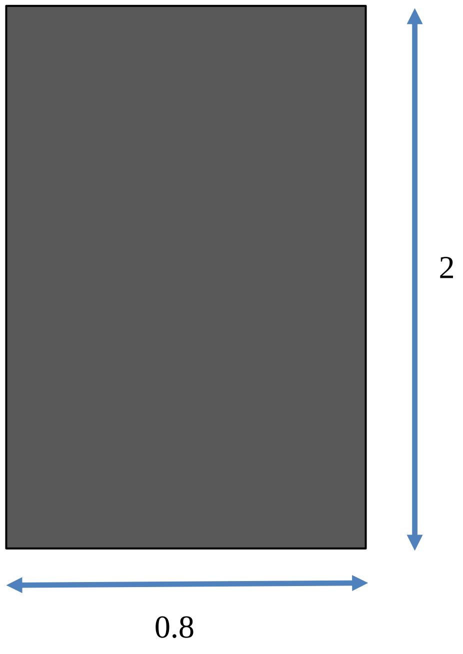

Figure A.3 Geometry of the door, where the measurements are expressed in meters.

The placement and geometry of the windows on the roof is illustrated in blue squares in Figure A.4.

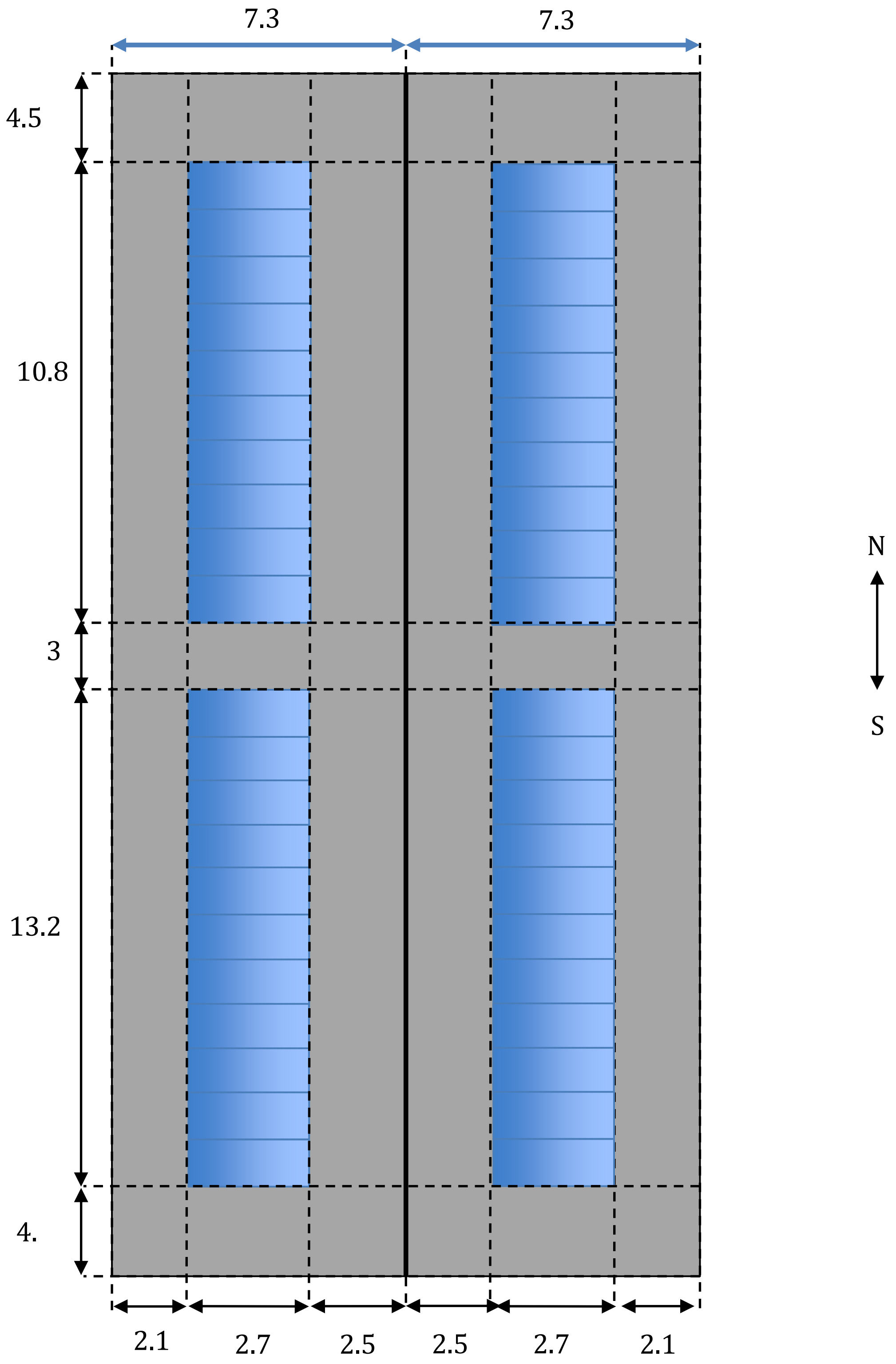

Figure A.4 Geometry of windows placed on roof, where the measurements are expressed in meters.

The windows on the roof has a width of 1.2 meters and a height of 2.7 meters. The geometry of the windows on roof is illustrated in Figure A.5.

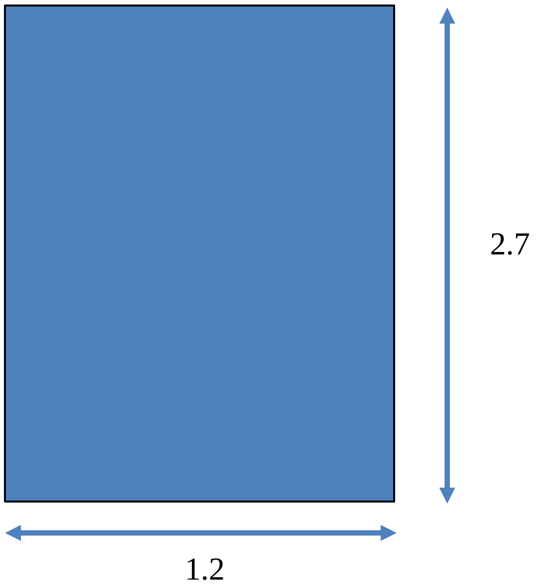

Figure A.5 *Geometry of the window on roof, where the measurements are expressed in meters.*

The geometry of floor 1 is presented in Figure A.6. The grey color represents the balcony floor and the red color represents the opening areas.

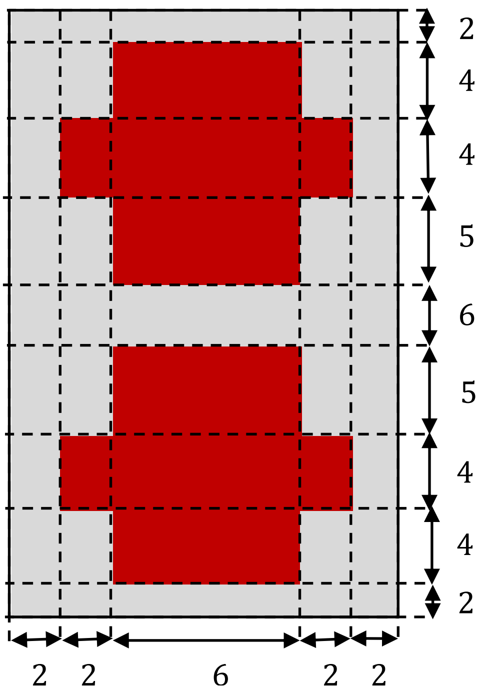

Figure A.6 *Geometry of the openings on floor 2,3,4 and 5, where the measurements are expressed in meters.*

A2 Building components

The material properties of insulation and wood is presented in Table A.1. The equivalent properties of the material layers which consists of a combination of insulation and wood is presented as a summary in Table A.2. The calculation of each of them is presented in the chapters below.

Table A.1 Material properties.

Material	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]
Insulation	0.036	20	750
Wood	0.14	500	1500

Table A.2 Equivalent properties of materials.

Component	Material	λ_{eq} [W/(m·K)]	ρ_{eq} [kg/m^3]	c_{eq} [J/(kg·K)]
Exterior wall	Wood studs c600 (45x120) and insulation	0.044	56	806
	Wood studs c600 (45x45) and insulation	0.044	56	806
Roof	Wood roof trusses c1200 (45x90) and insulation	0.040	38	778
	Wood studs c600 (45x45) and insulation	0.044	56	806

The exterior walls are constructed with a layer of wood studs and insulation. The c-distance between the wooden joists is 0.6 m. The thickness of the joists is 0.045 m. Equivalent material properties for insulation and wooden joists with c-distance of 0.6 m is calculated below.

$$\boldsymbol{c_{wood,exterior} = 0.6\ m}$$

$$\boldsymbol{d_{wood,exterior} = 0.045\ m}$$

$$\boldsymbol{d_{insulation,exterior} = c_{wood,exterior} - d_{wood,exterior} = 0.555\ m}$$

$$\boldsymbol{\lambda_{eq,exterior} = \frac{\lambda_{insulation} \times d_{insulation,exterior} + \lambda_{wood} \times d_{wood,exterior}}{c_{wood,exterior}} = 0.044\ W/mK}$$

$$\boldsymbol{\rho_{eq,exterior} = \frac{\rho_{insulation} \times d_{insulation,exterior} + \rho_{wood} \times d_{wood,exterior}}{c_{wood,exterior}} = 56\ kg/m^3}$$

$$\boldsymbol{c_{eq,exterior} = \frac{c_{insulation} \times d_{insulation,exterior} + c_{wood} \times d_{wood}}{c_{wood,exterior}} = 806\ J/(kgK)}$$

The roof is constructed with a layer of wood roof trusses and insulation. The c-distance between the wooden roof trusses is 1.2 m. The thickness of the joists is 0.045 m. Equivalent material properties for insulation and roof trusses with c-distance of 1.2 m is calculated below.

$$\boldsymbol{c_{wood,roof} = 1.2\ m}$$

$$\boldsymbol{d_{wood,roof} = 0.045\ m}$$

$$\boldsymbol{d_{insulation,roof} = c_{wood,roof} - d_{wood,roof} = 1.155\ m}$$

$$\boldsymbol{\lambda_{eq,roof} = \frac{\lambda_{insulation} \times d_{insulation,roof} + \lambda_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 0.040\ W/mK}$$

$$\boldsymbol{\rho_{eq,roof} = \frac{\rho_{insulation} \times d_{insulation,roof} + \rho_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 38\ kg/m^3}$$

$$\boldsymbol{c_{eq,interior} = \frac{c_{insulation} \times d_{insulation,roof} + c_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 778\ J/(kgK)}$$

The roof is constructed with a layer of wood studs and insulation. The c-distance between the wooden joists is 0.6 m. The thickness of the joists is 0.045 m. Equivalent material properties for insulation and wooden joists with c-distance of 0.6 m is calculated below.

$$c_{wood,roof} = 0.6\ m$$

$$d_{wood,roof} = 0.045\ m$$

$$d_{insulation,roof} = c_{wood,roof} - d_{wood,roof} = 0.555\ m$$

$$\lambda_{eq,roof} = \frac{\lambda_{insulation} \times d_{insulation,roof} + \lambda_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 0.044\ W/mK$$

$$\rho_{eq,roof} = \frac{\rho_{insulation} \times d_{insulation,roof} + \rho_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 56\ kg/m^3$$

$$c_{eq,roof} = \frac{c_{insulation} \times d_{insulation,roof} + c_{wood} \times d_{wood,roof}}{c_{wood,roof}} = 806\ J/(kgK)$$

The material properties of the material of the external shading device and the internal shading device is presented in Table A.3 and A.4.

Table A.3 Material properties of the drop arm awning shade material.

	Transmittance	Reflectance (Outside)	Reflectance (Inside)
Total shortwave [-]	0,05	0,3	0,3
Visible [-]	0,05	0,3	0,3
Diffusion [-]	1,0	1,0	1,0
Longwave [-]	0,0	0,9	0,9
d [mm]	0,6		
λ [W/(K*m)]	0,3		

Table A.4 Material properties of the generic roller shade material.

	Transmittance	Reflectance (Outside)	Reflectance (Inside)
Total shortwave [-]	0,05	0,5	0,5
Visible [-]	0,05	0,5	0,5
Diffusion [-]	1,0	1,0	1,0
Longwave [-]	0,0	0,9	0,9
d [mm]	0,6		
λ [W/(K*m)]	0,3		

A3 Climate

The reference building is assumed to be in a suburban environment and be semi-exposed. The terrain coefficient for a building in a suburban environment is presented in Table A.5. Wind pressure coefficient for a building in a semi-exposed environment is presented in Table A.6.

Table A.5 Terrain coefficients for the reference building (ASHRAE, 1993).

Terrain category	a0	aexp
Suburban	0.67	0.25

Table A.6 Wind pressure coefficients for the reference building (EQUA Simulation AB, 2016).

	0	45	90	135	180	225	270	315	Face azimuth
f1	0,25	0,06	-0,35	-0,6	-0,5	-0,6	-0,35	0,06	0
f2	0,25	0,06	-0,35	-0,6	-0,5	-0,6	-0,35	0,06	90
f3	0,25	0,06	-0,35	-0,6	-0,5	-0,6	-0,35	0,06	180
f4	0,25	0,06	-0,35	-0,6	-0,5	-0,6	-0,35	0,06	270
r1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	-0,1	0

The weather quantities dry-bulb temperature, relative humidity, wind speed in x-direction and y-direction, direct normal radiation, diffuse radiation and sky cover of the design reference year is presented below.

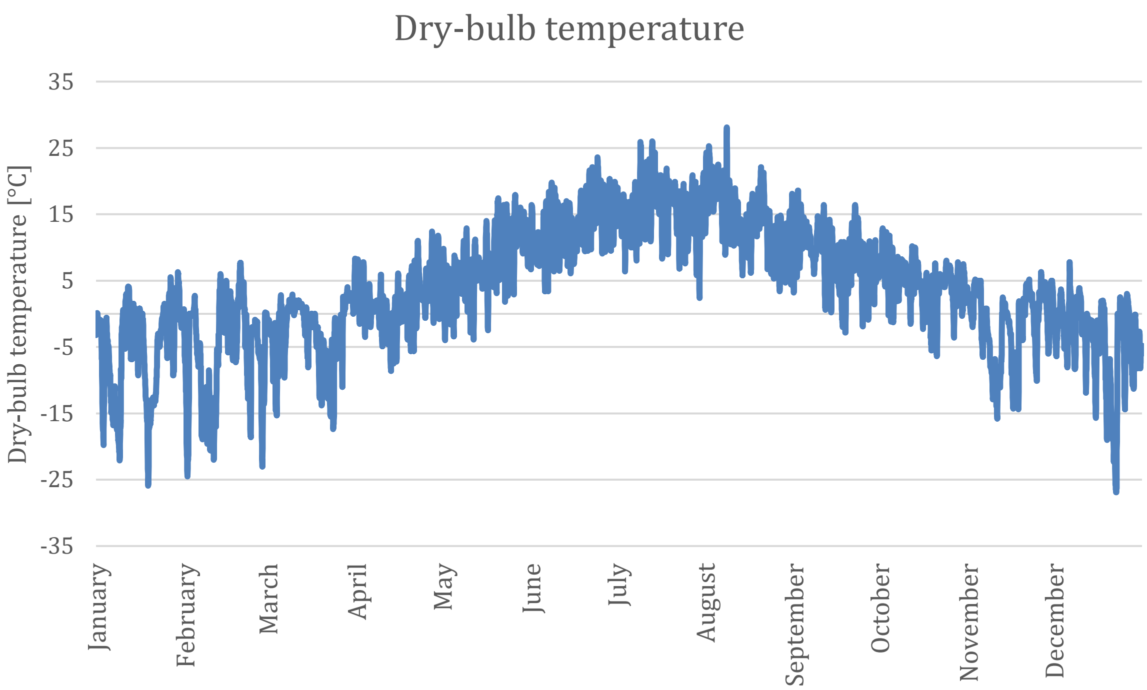

Figure A.7 Dry-bulb temperature during design reference year.

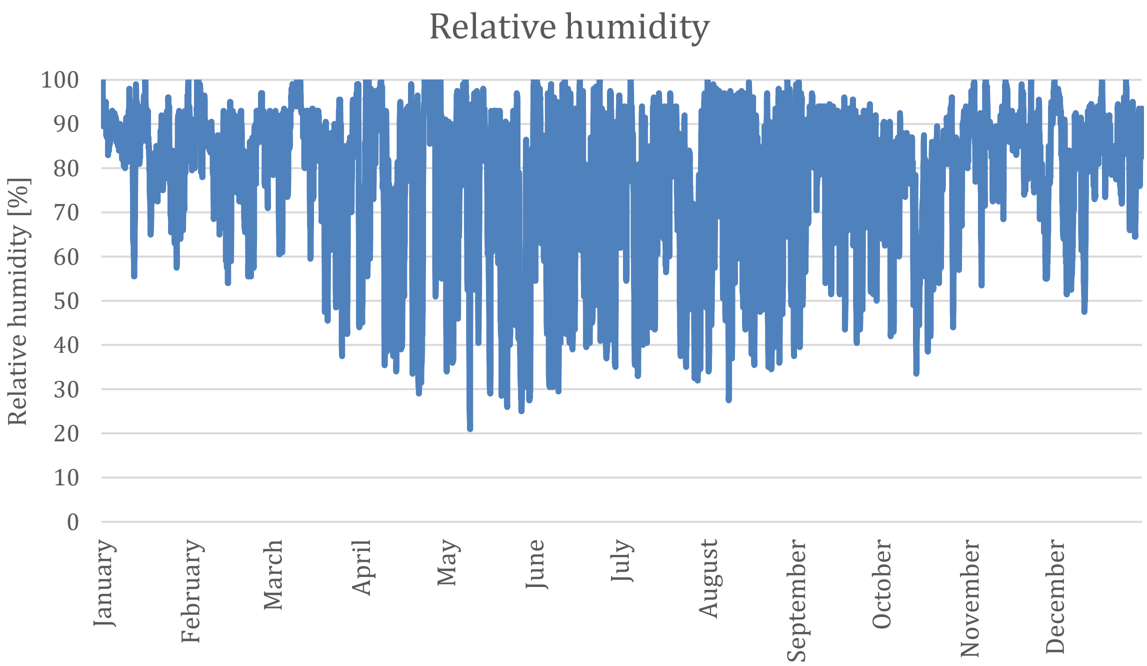

Figure A.8 Relative humidity during design reference year.

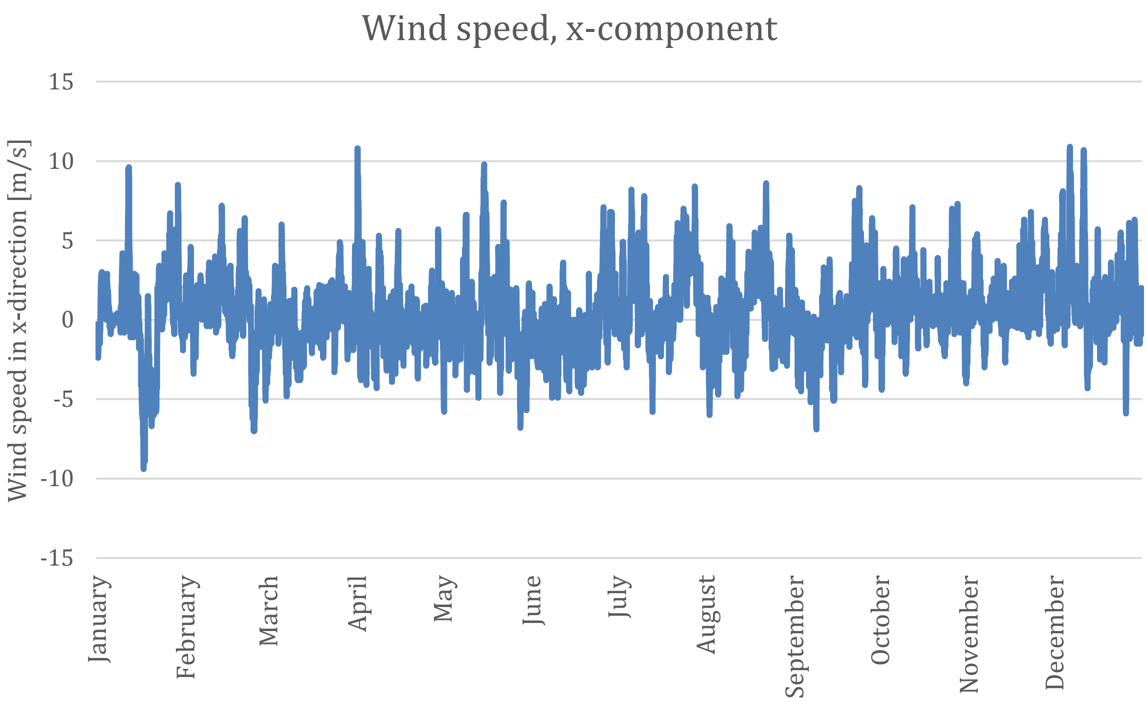

Figure A.9 Wind speed in x-direction during design reference year.

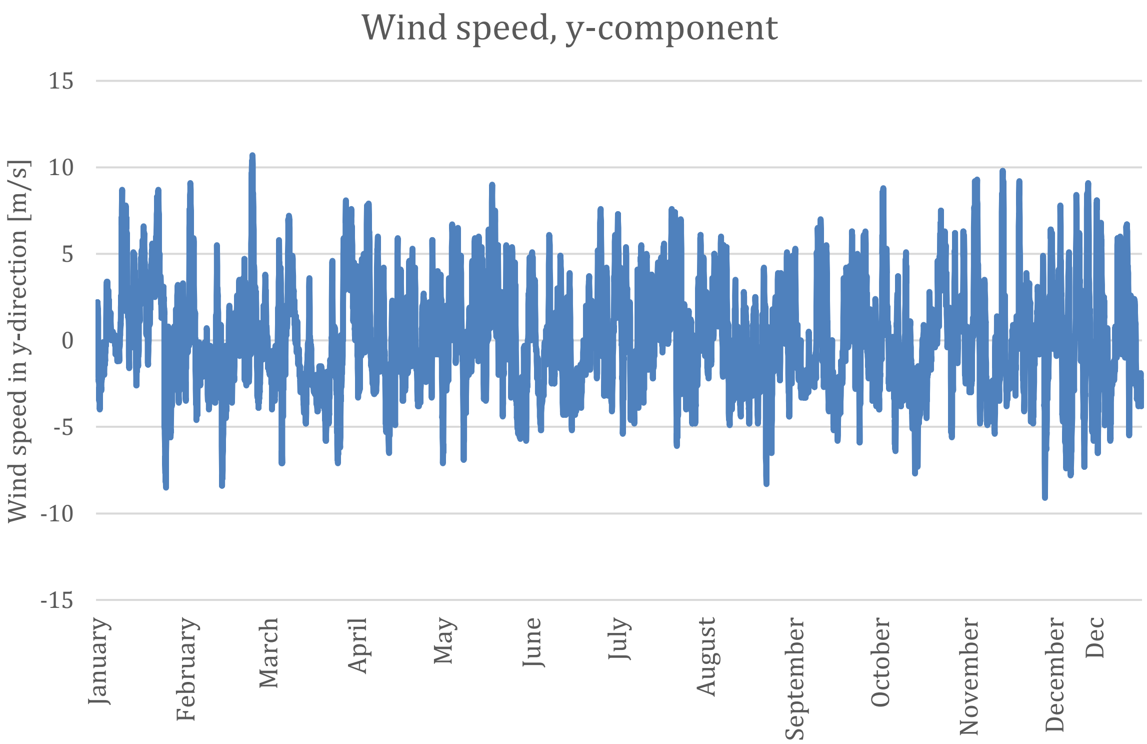

Figure A.10 Wind speed in y-direction during design reference year.

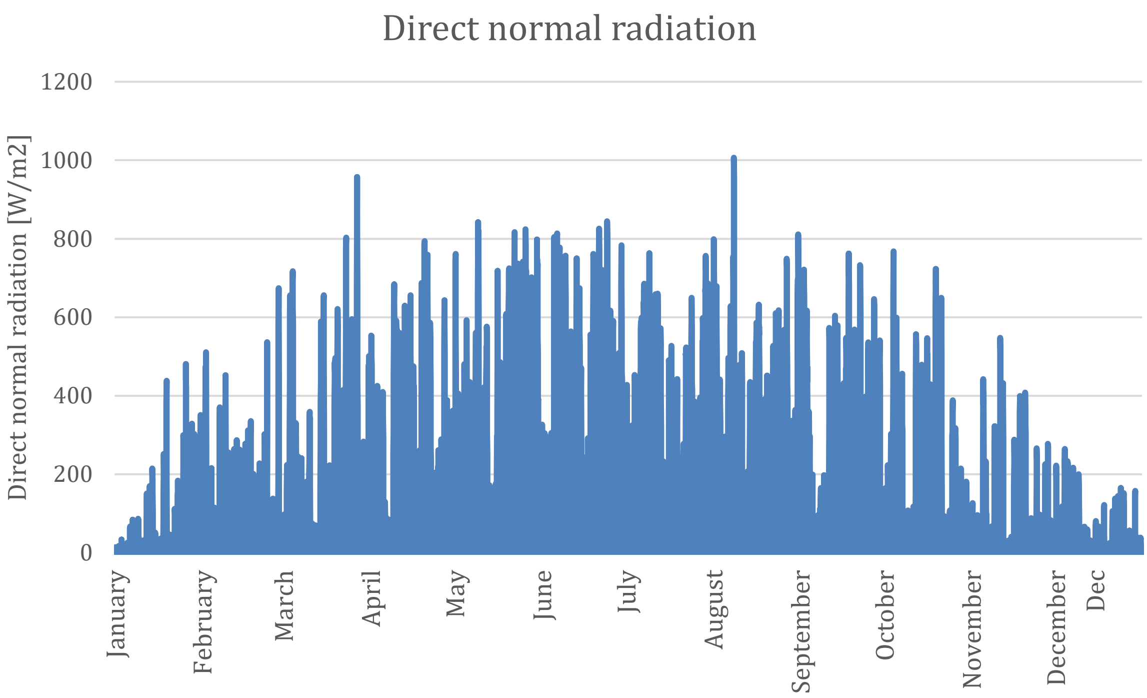

Figure A.11 Direct normal radiation during design reference year.

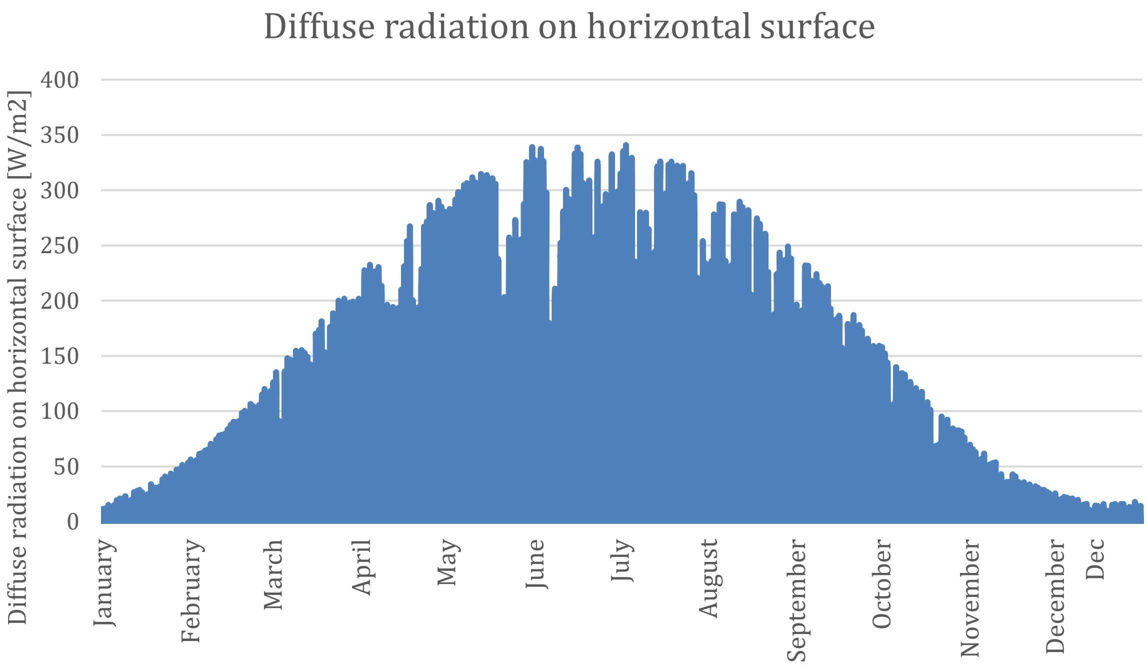

Figure A.12 Diffuse radiation on horizontal surface during design reference year.

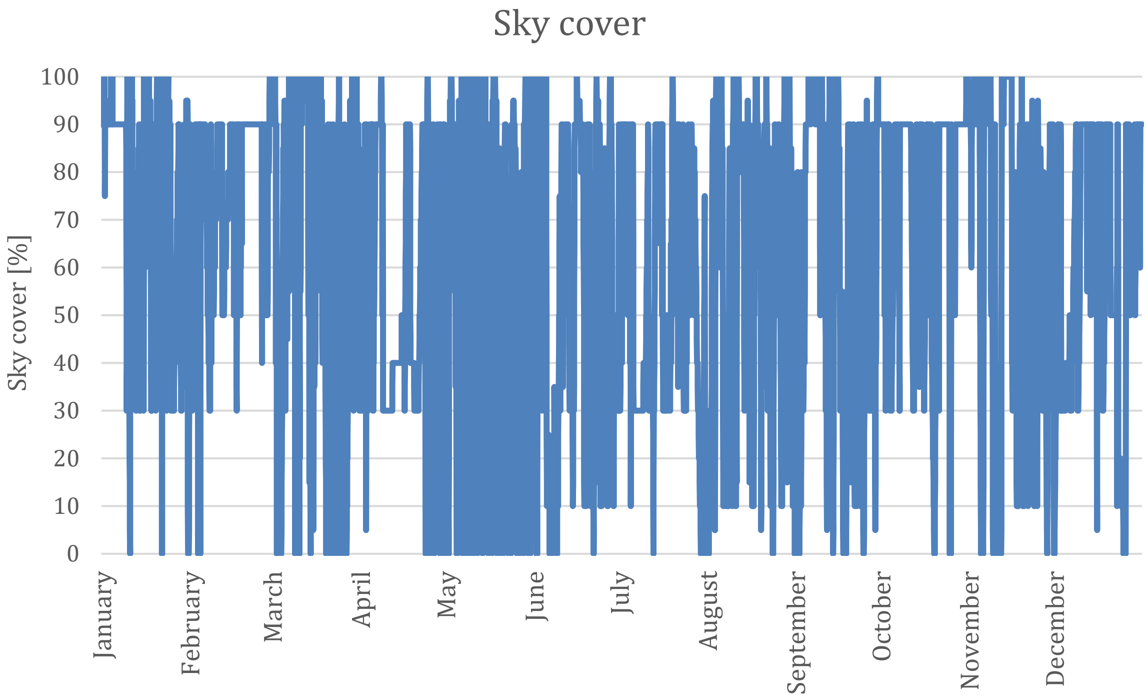

Figure A.13 Sky cover during design reference year.

Appendix B – Evaluation of design parameters

B1 Glazing material

The material properties of the clear glass pane, air layer, clear glass pane with lower g-value, argon gas layer and clear glass pane with lower U-value is presented below. The material properties of the air and argon layer is calculated according to equation B.1-B.3.

$$\text{Thermal conductivity} = a + b * T\ (K) \qquad \text{(Equation B.1)}$$

$$\text{Viscosity} = a + b * T\ (K) \qquad \text{(Equation B.2)}$$

$$\text{Specific heat at constant pressure} = a + b * T\ (K) \qquad \text{(Equation B.3)}$$

Table B.1 Material properties of clear glass pane.

	Transmittance	Reflectance (Outside)	Reflectance (Inside)
Total shortwave [-]	0.77	0.07	0.07
Visible [-]	0.88	0.08	0.08
Diffusion [-]	0.0	0.0	0.0
		Emissivity	Emissivity
Longwave [-]	0.0	0.84	0.84
d [mm]	5.715		
k [W/(K·m)]	1.0		

Table B.2 Material properties of air layer.

	a	b	At 0 °C	At 10 °C
Thermal conductivity	0.0029	7.76E-5	0.024	0.025
Viscosity [(N·s)/m^2]	3.72E-6	4.94E-8	1.72E-5	1.77E-5
Specific heat at constant pressure [J/(kg·K)]	1002.74	0.012	1006.10	1006.23

Table B.3 Material properties of clear glass pane with lower g-value.

	Transmittance	Reflectance (Outside)	Reflectance (Inside)
Total shortwave [-]	0.77	0.22	0.07
Visible [-]	0.88	0.08	0.08
Diffusion [-]	0.0	0.0	0.0
		Emissivity	Emissivity
Longwave [-]	0.0	0.84	0.84
d [mm]	5.715		
k [W/(K·m)]	1.0		

Table B.4 Material properties of argon gas layer.

	a	b	At 0 °C	At 10 °C
Thermal conductivity	0.0027	5.01E-5	0.016	0.017
Viscosity [(N·s)/m^2]	3.70E-6	6.24E-8	2.10E-5	2.17E-5
Specific heat at constant pressure [J/(kg·K)]	519.0	0.0	519.0	519.0

Table B.5 Material properties of clear glass pane with lower U-value.

	Transmittance	Reflectance (Outside)	Reflectance (Inside)
Total shortwave [-]	0.77	0.07	0.07
Visible [-]	0.88	0.08	0.08
Diffusion [-]	0.0	0.0	0.0
		Emissivity	Emissivity
Longwave [-]	0.0	0.84	0.84
d [mm]	5.715		
k [W/(K·m)]	0.065		

B2 Building orientation

Illustrations of the evaluated cases of building orientation is presented in this chapter.

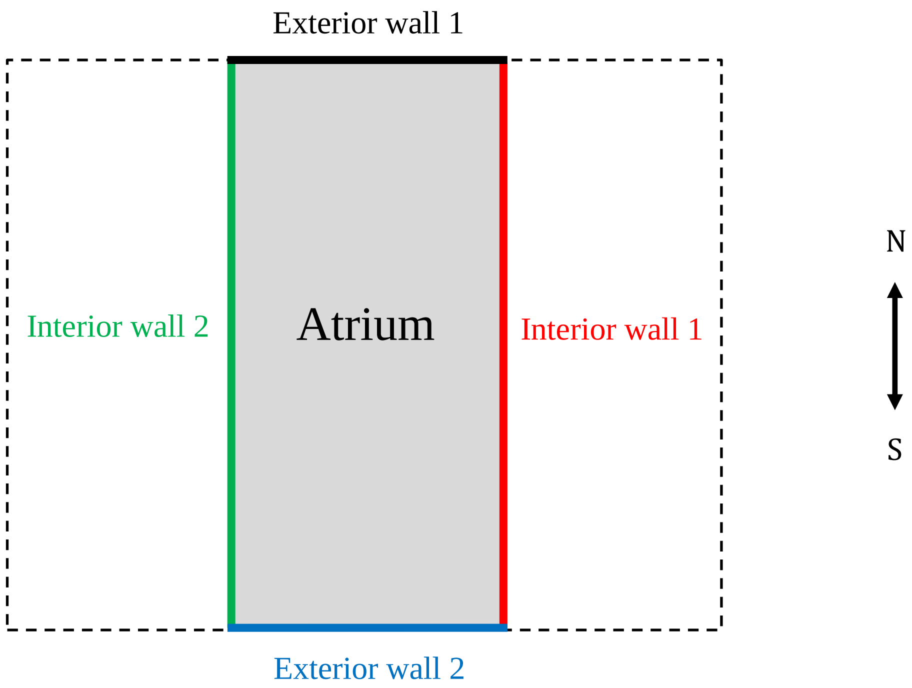

Figure B.1 Reference building with 0° offset.

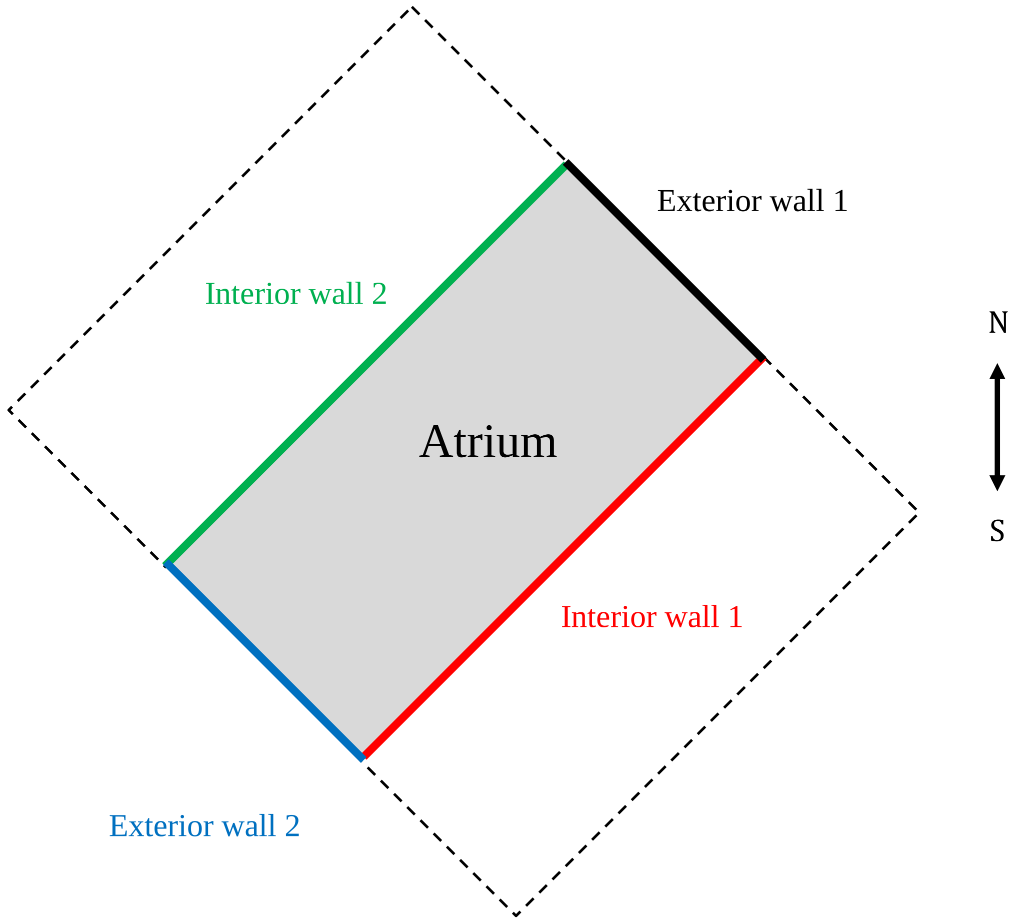

Figure B.2 Reference building with 45° offset.

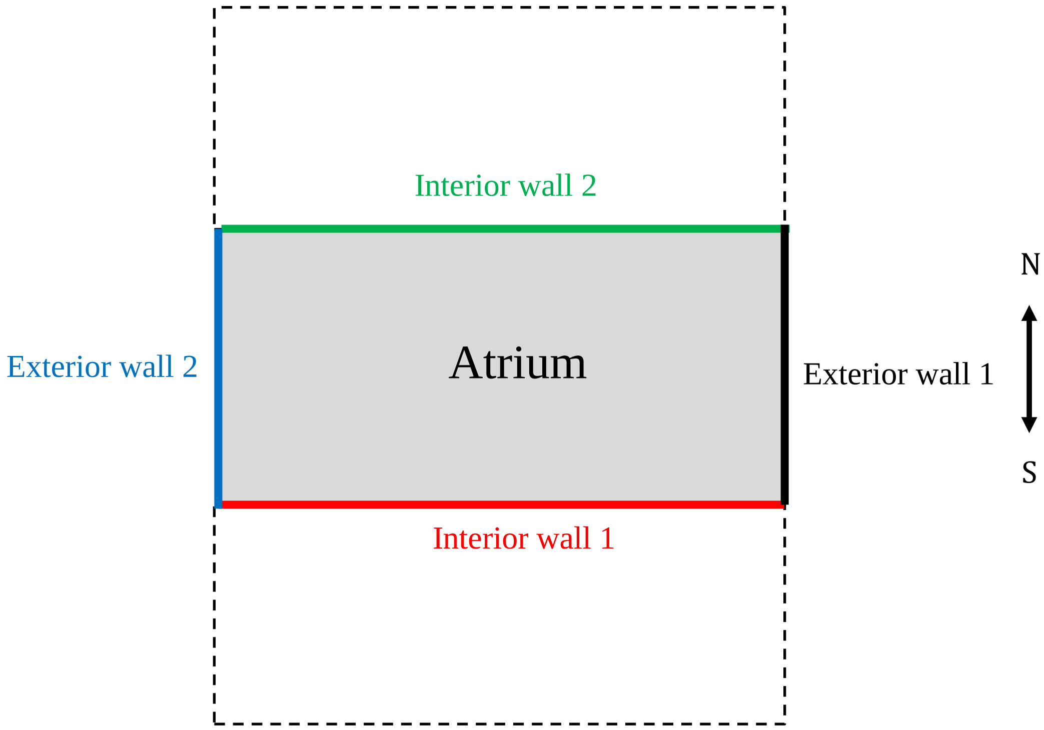

Figure B.3 Reference building with 90° offset.

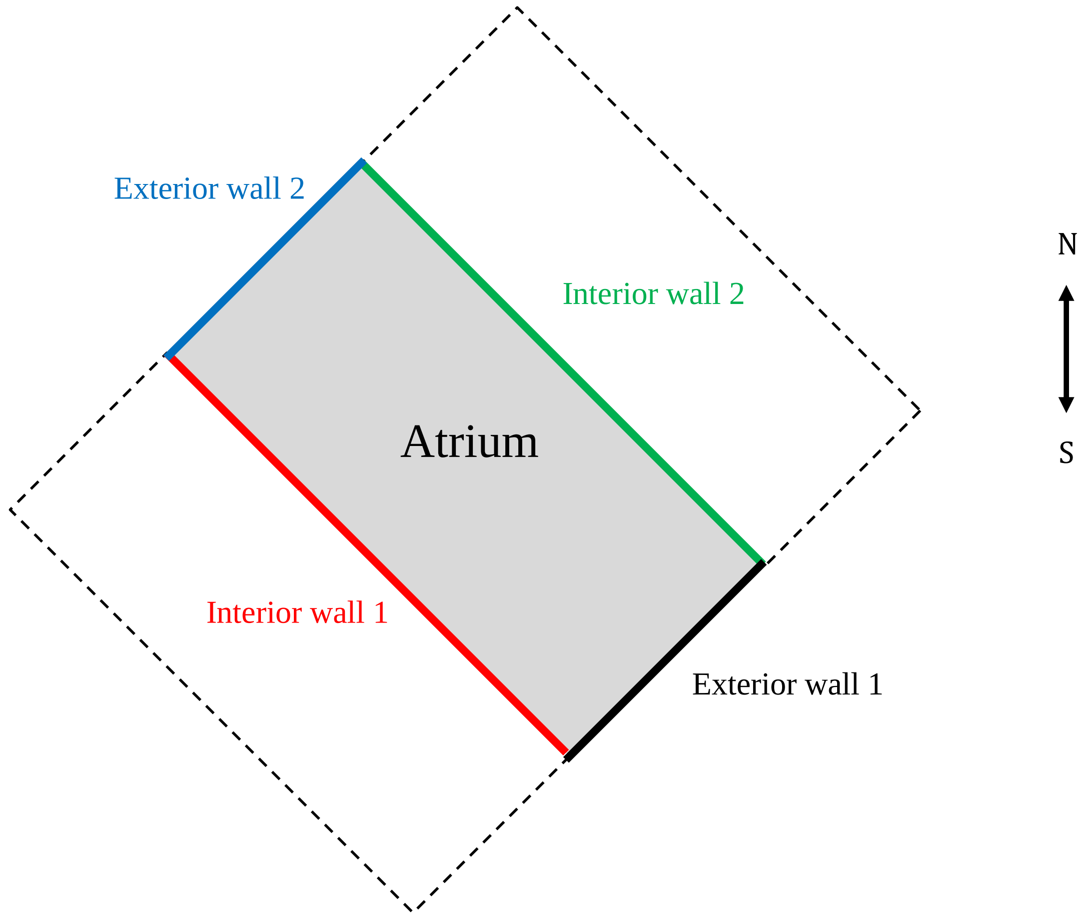

Figure B.4 Reference building with 135° offset.

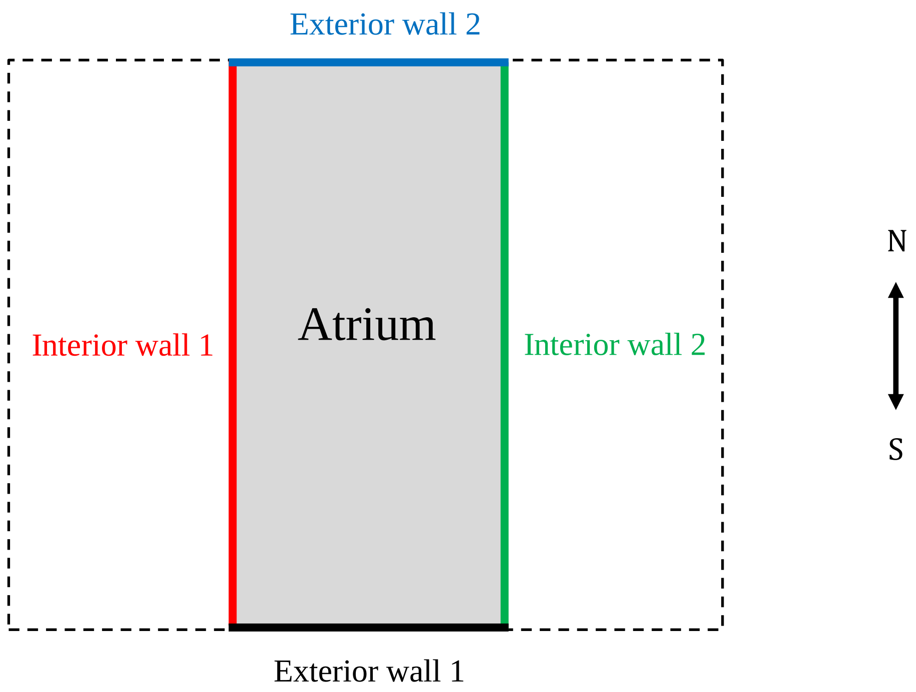

Figure B.5 Reference building with 180° offset.

B3 Atrium dimension

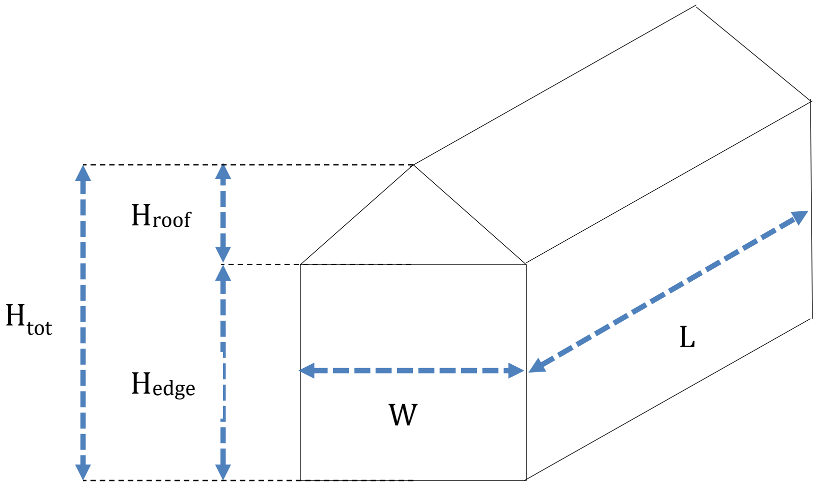

Figure B.6 Atrium dimensions.

Table B.6 Atrium geometry of evaluation cases.

Case	W [m]	L [m]	H_{edge} [m]	H_{roof} [m]	H_{tot} [m]	V [m^3]
Reference	14	36	14	5	19	9086.1
Increased height	14	36	17	5	22	9828
Increased width	16	36	14	5	19	9504
Increased length	14	39.6	14	5	19	9979.2

Table B.7 Areas of evaluation cases.

Case	A_{floor} [m^2]	A_{env} [m^2]	A_{window} [m^2]	A_{wall} [m^2]
Reference	504	1983.7	309.6	1470
Increased height	504	2120.4	345.6	1950
Increased width	576	2310.9	345.6	1716
Increased length	604.8	2351.2	348.5	1887.6

Appendix C – Results

The results of the design reference year are presented as monthly mean values. The occupancy hours during the design reference year is 366 days, which corresponds to 8784 hours. The results of the summer week and winter week are presented as hourly mean values. The investigated time period is 7 days, which corresponds to 168 hours.

Table C.1 Days and hours during each time aspect.

Time aspect	Time [days]	Time [hours]
Design reference year	366	8784
Summer month	31	744
Winter month	31	744
Summer week	7	168
Winter week	7	168

C1 Reference building

The minimum and maximum operative and the occupancy hours in the reference building is presented during the design reference year, summer week and winter week.

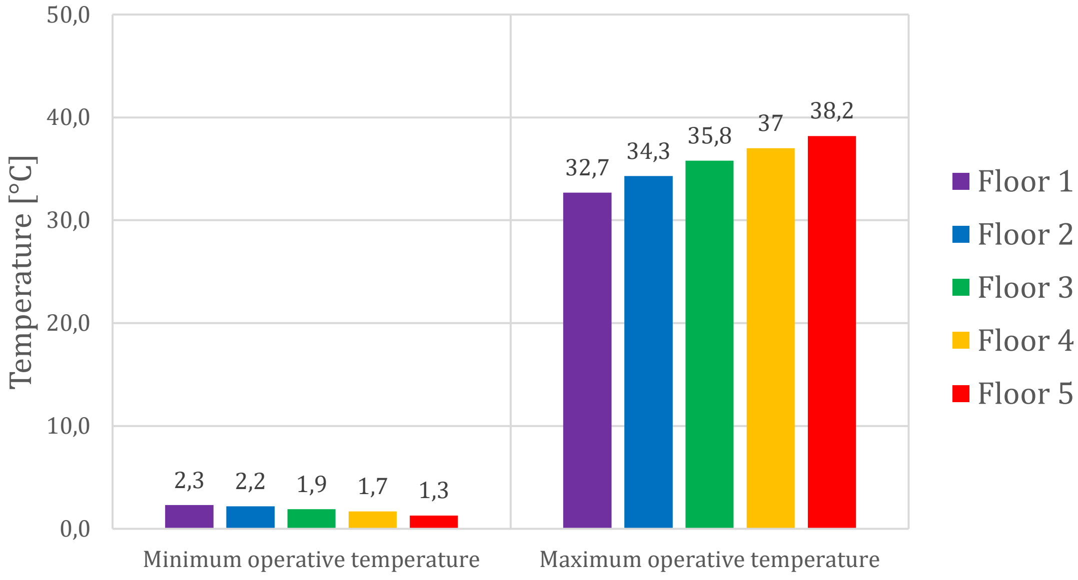

Figure C.1 Minimum and maximum operative temperatures of each floor level during design reference year.

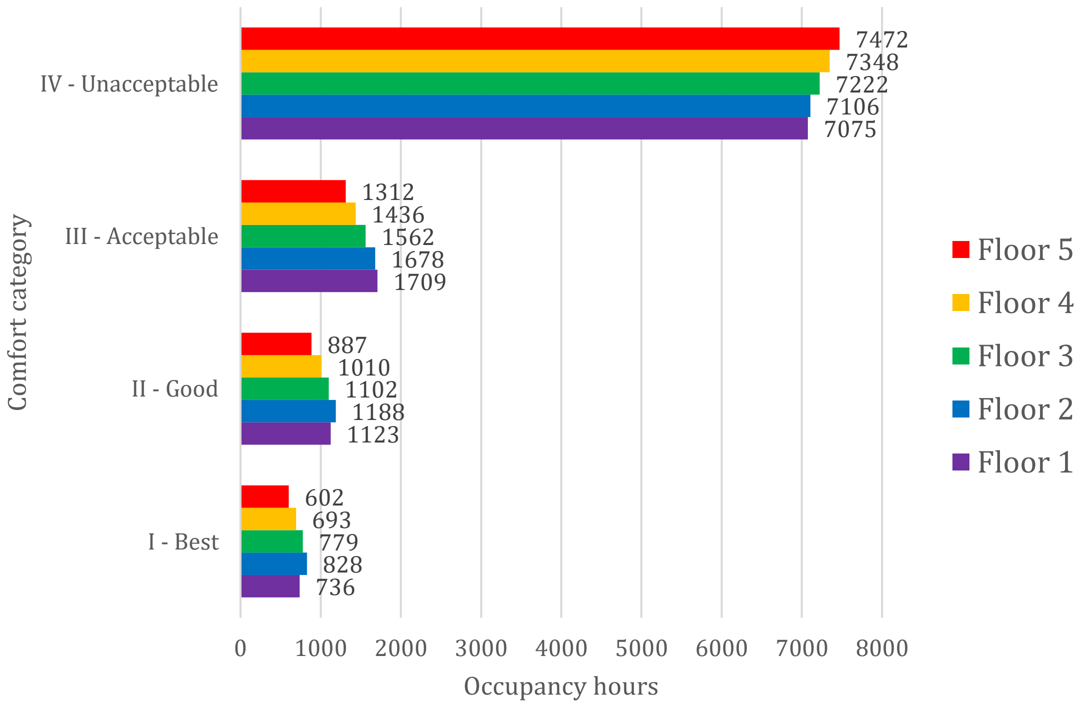

Figure C.2 Occupancy hours of each comfort category of each floor level during design reference year.

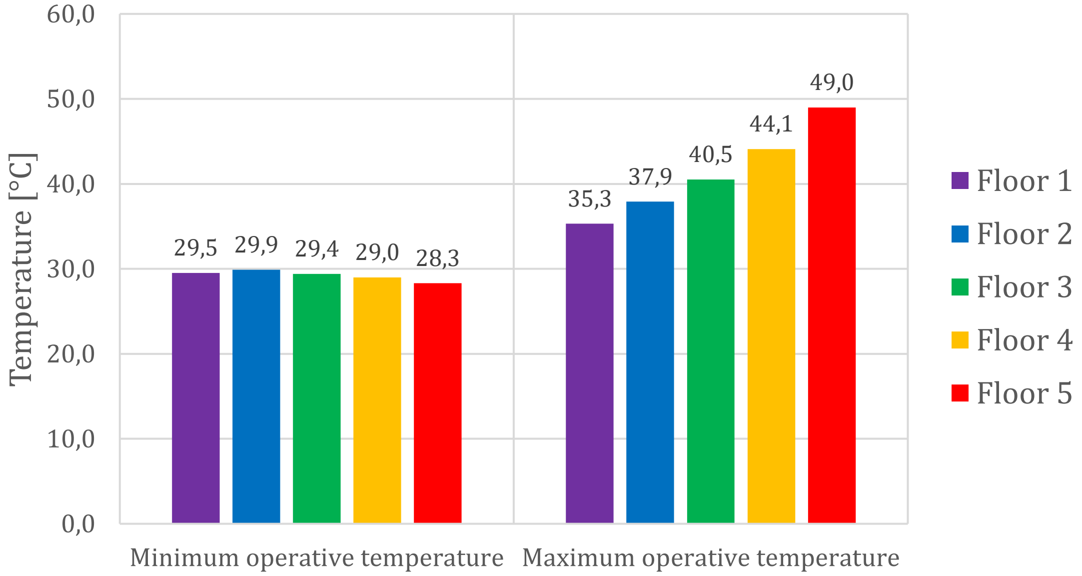

Figure C.3 Minimum and maximum operative temperatures in floor 5 during the summer week.

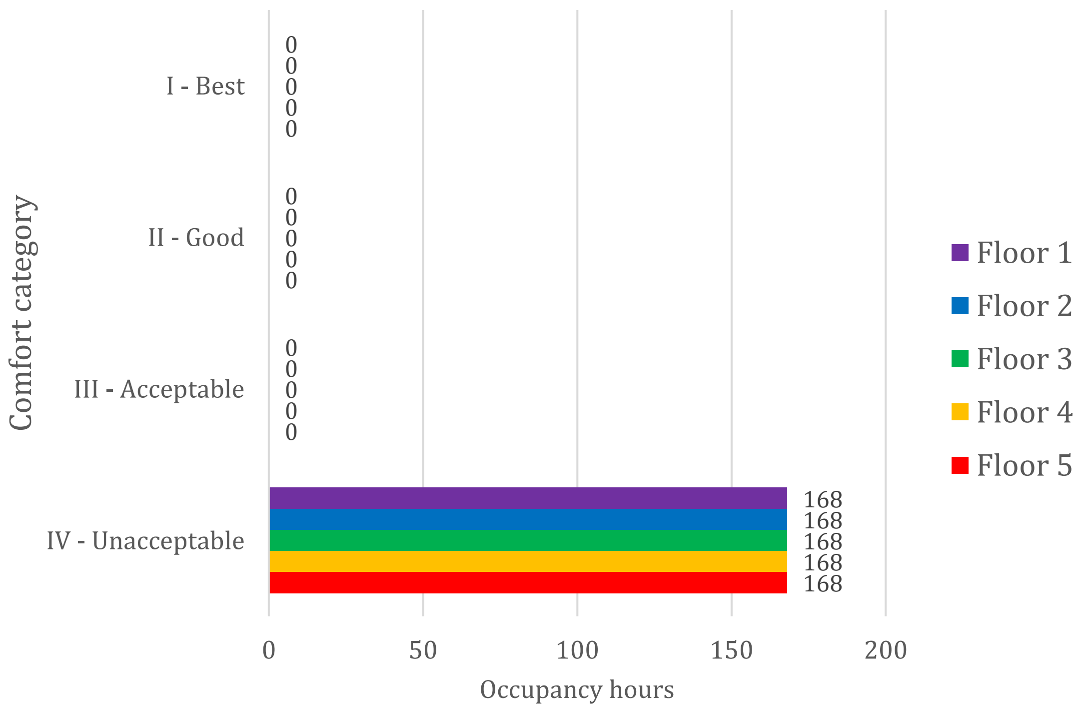

Figure C.4 Occupancy hours of each comfort category in floor 5 during the summer week.

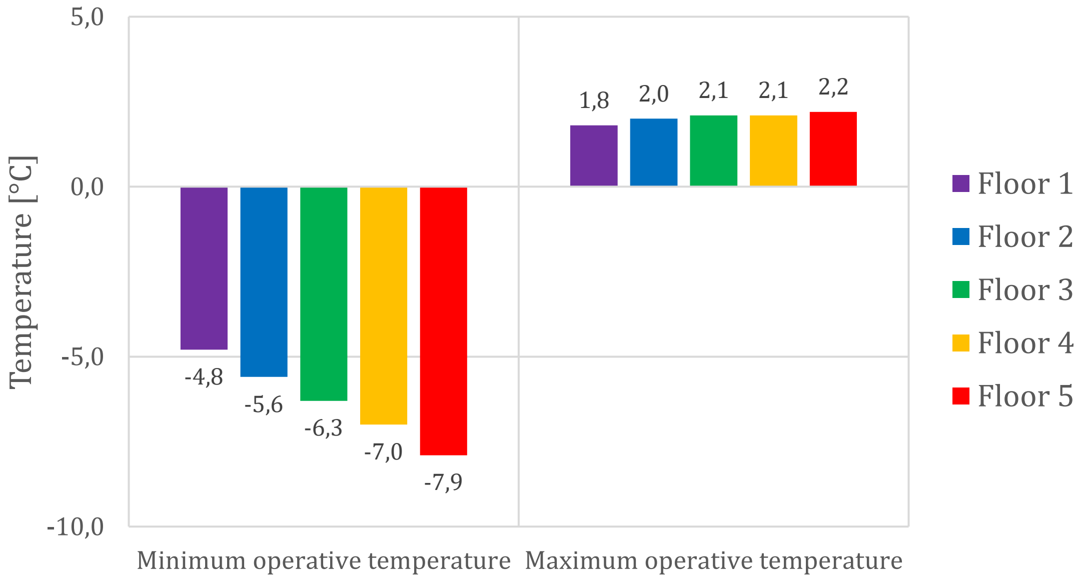

Figure C.5 Minimum and maximum operative temperatures during the winter week.

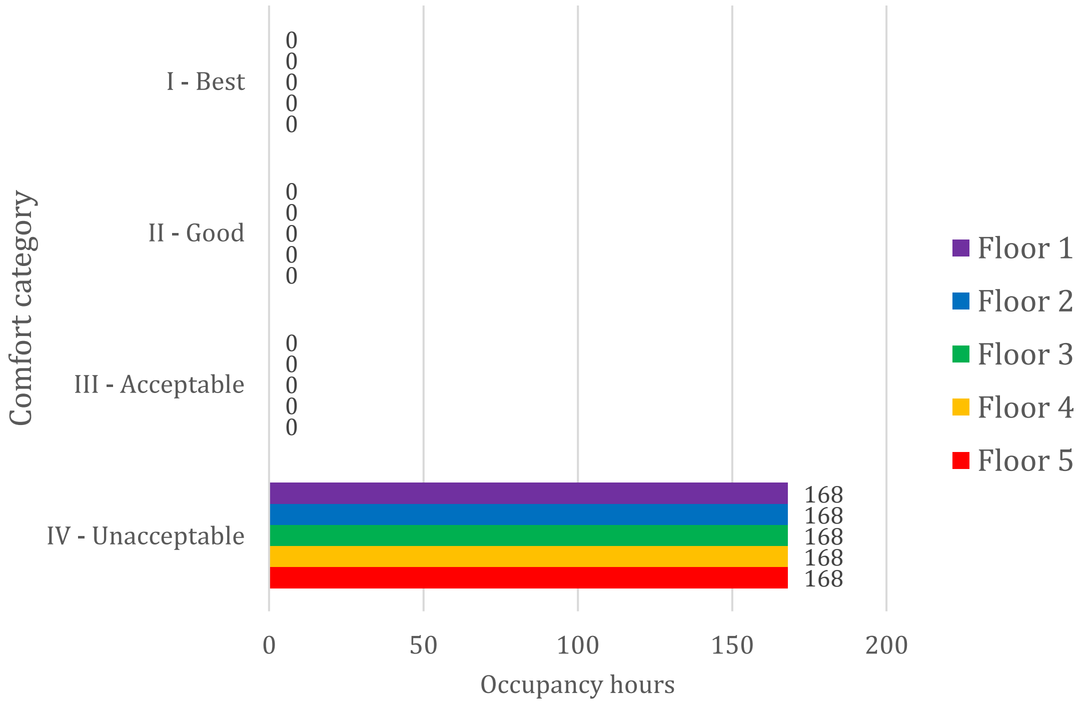

Figure C.6 Occupancy hours of each comfort category during the winter week.

C2 Thermal mass

The minimum and maximum operative and the occupancy hours of the evaluation cases with thermal mass evaluation is presented during the summer month and winter month.

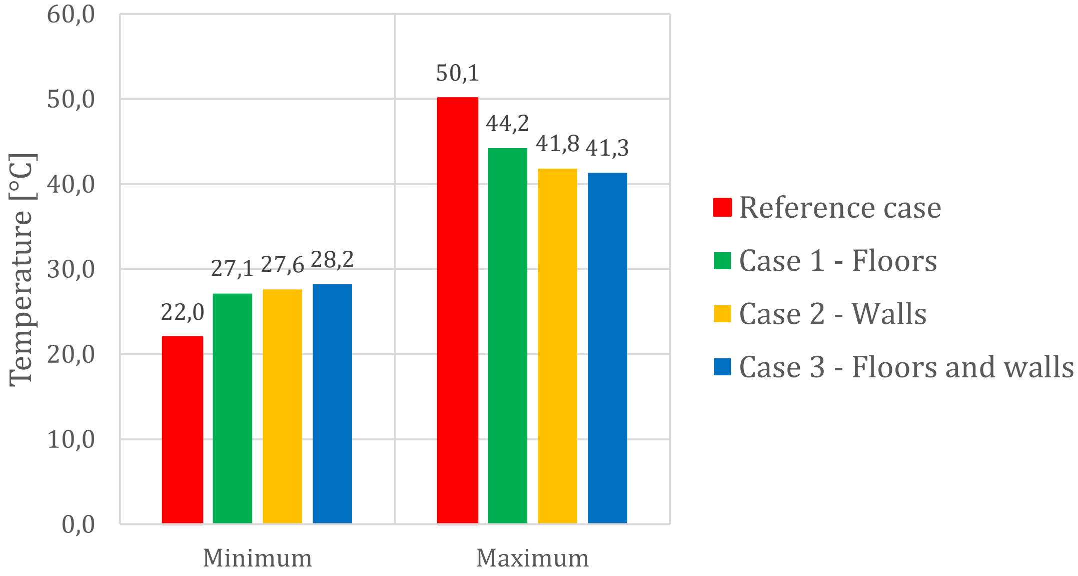

Figure C.7 Minimum and maximum operative temperature in floor 5 during the summer month.

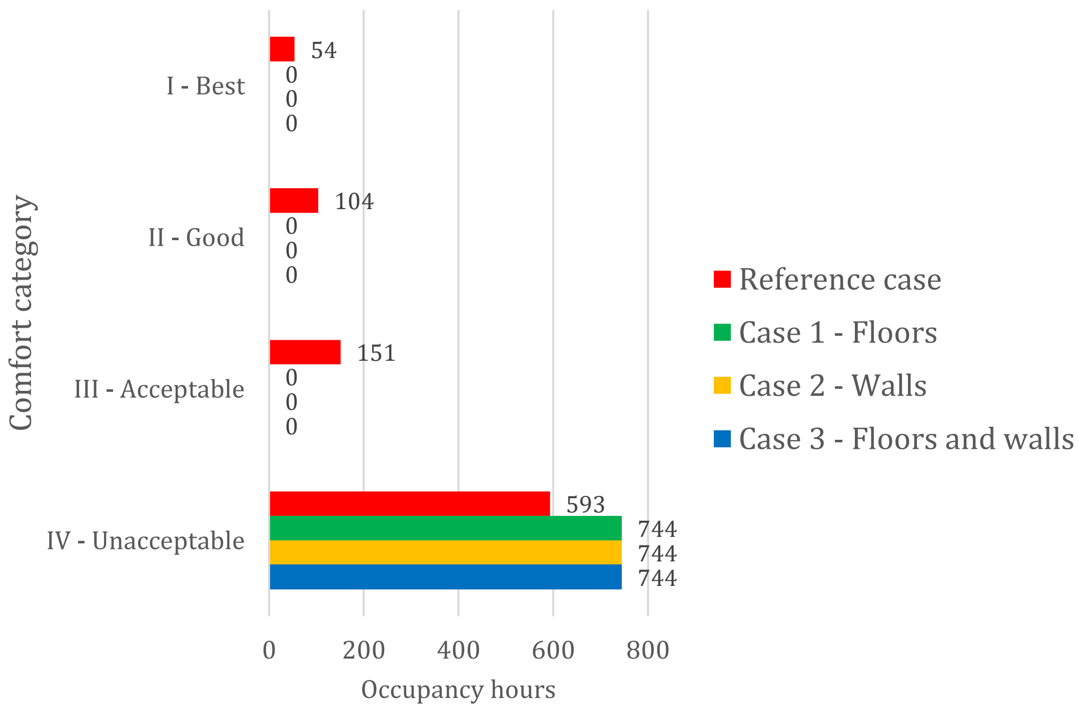

Figure C.8 Occupancy hours per comfort category in floor 5 during the summer month.

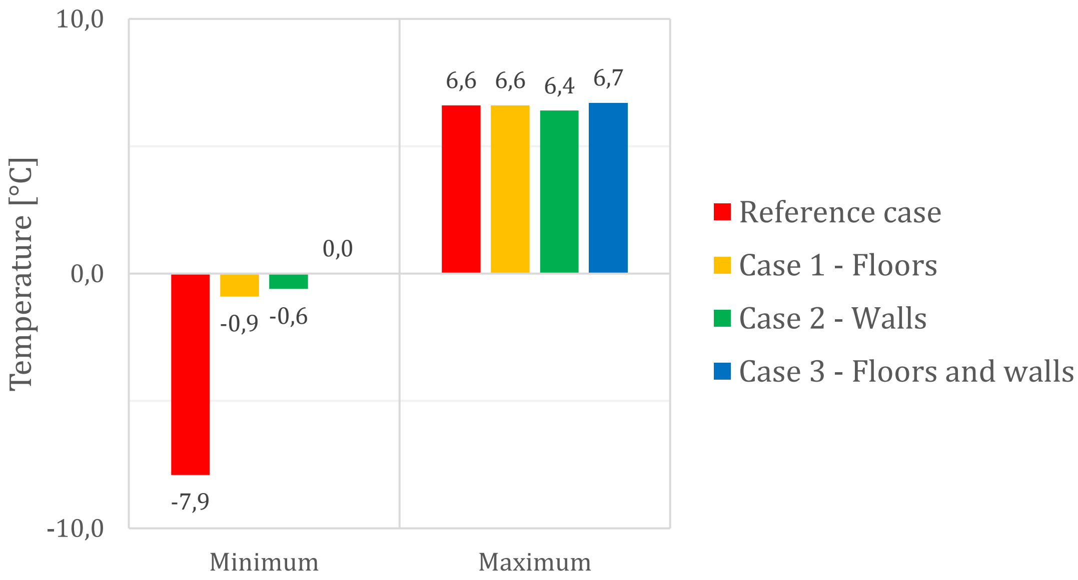

Figure C.9 Minimum and maximum operative temperature in floor 5 during the winter month.

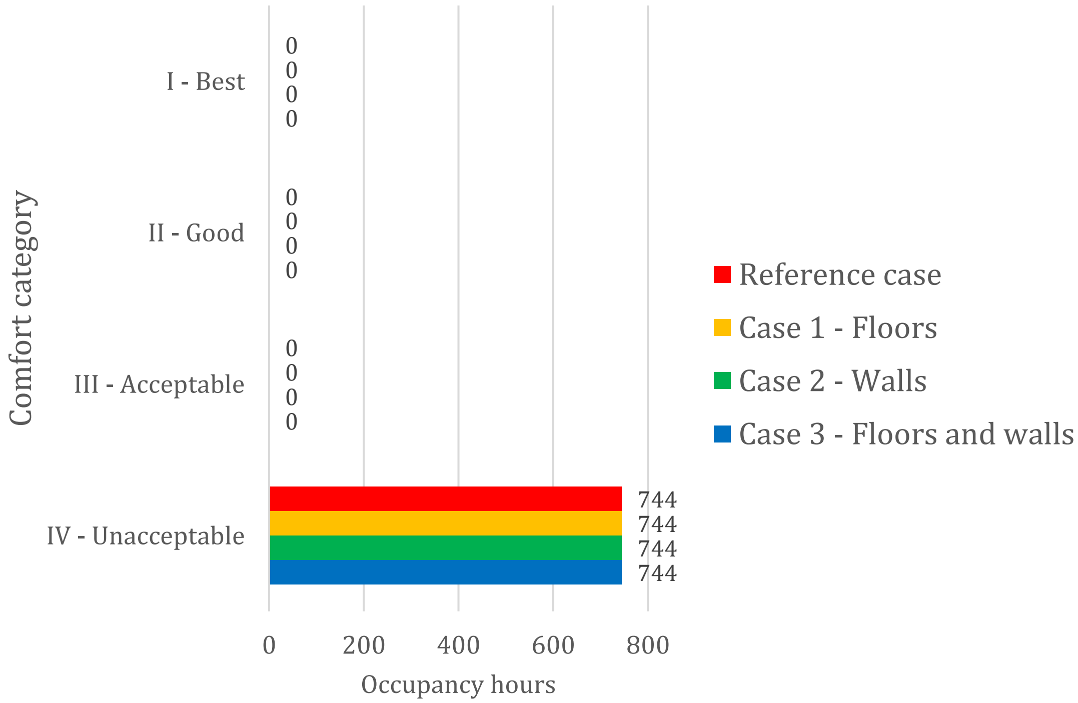

Figure C.10 Occupancy hours per comfort category in floor 5 during the winter month.

C3 Glazing material

The minimum and maximum operative and the occupancy hours of the evaluation cases with glazing material evaluation is presented during the summer week and winter week.

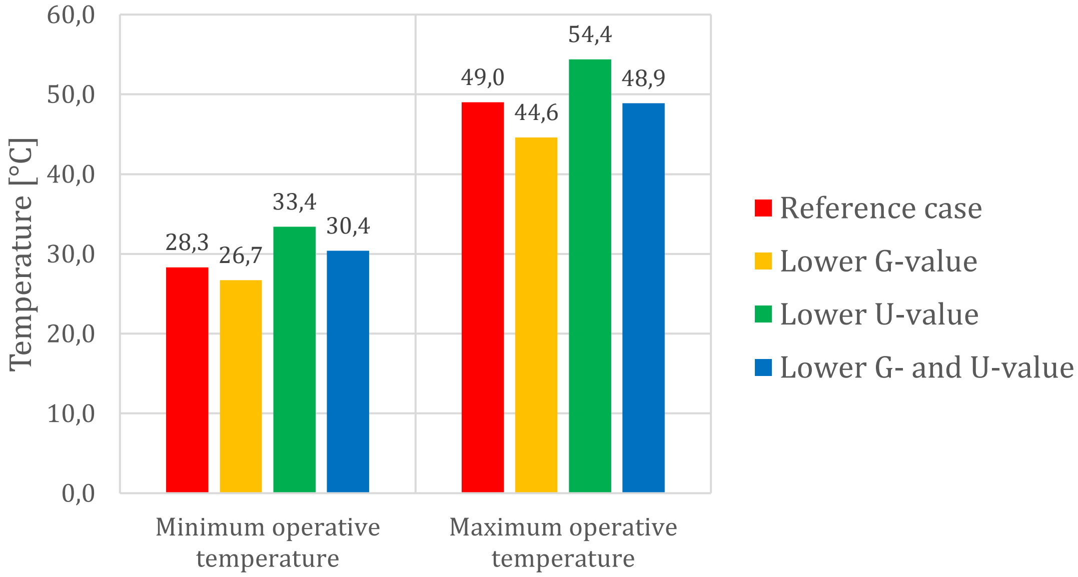

Figure C.11 Minimum and maximum operative temperature in floor 5 during the summer week.

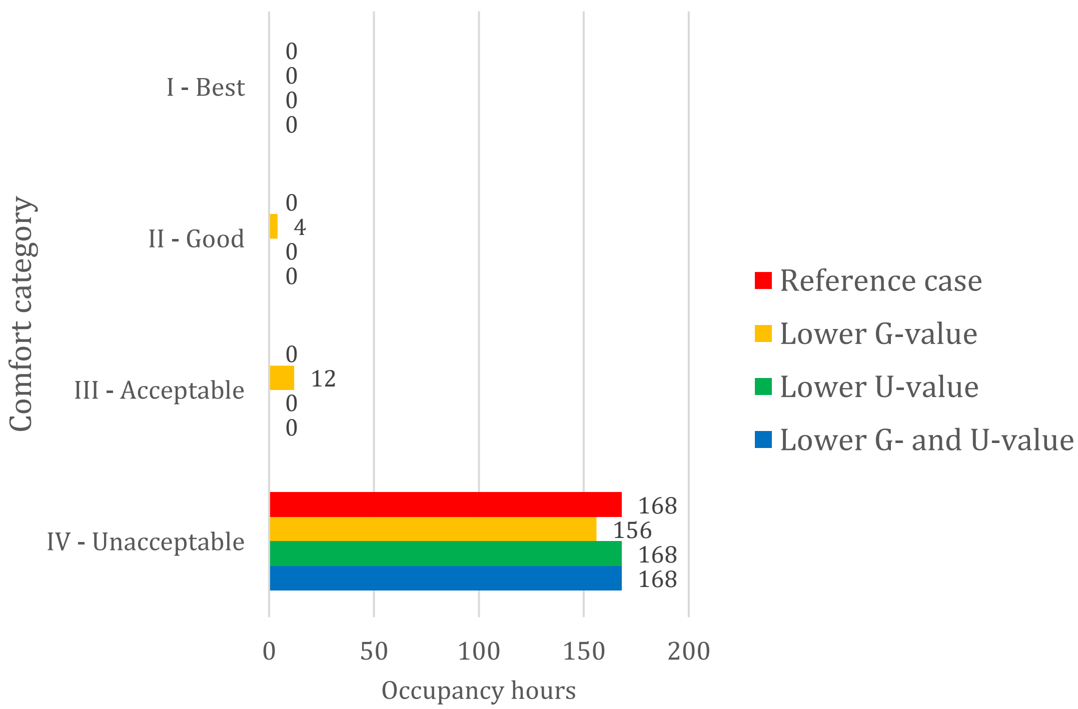

Figure C.12 Occupancy hours of each comfort category in floor 5 during the summer week.

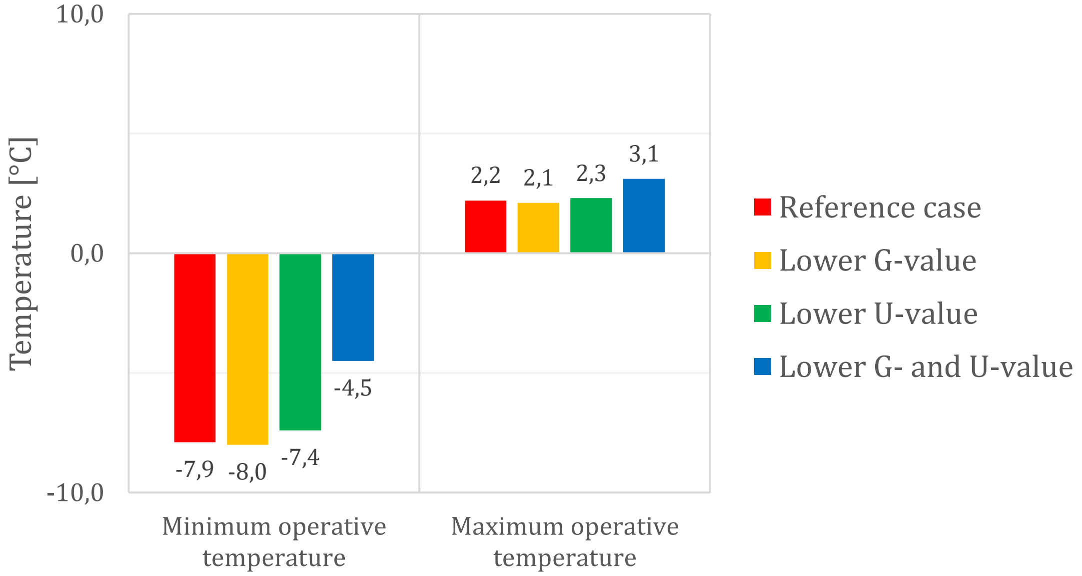

Figure C.13 Minimum and maximum operative temperature in floor 5 during the winter week.

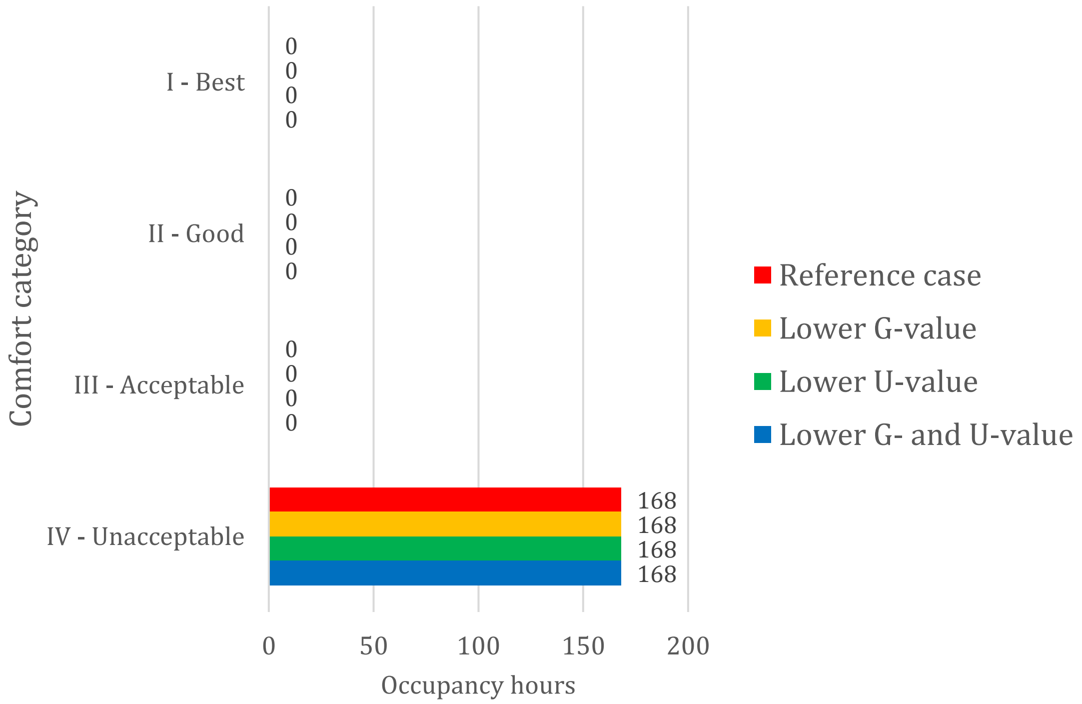

Figure C.14 Occupancy hours of each comfort category in floor 5 during the winter week.

C4 Building orientation

The minimum and maximum operative and the occupancy hours of the evaluation cases with building orientation evaluation is presented during the summer week and winter week.

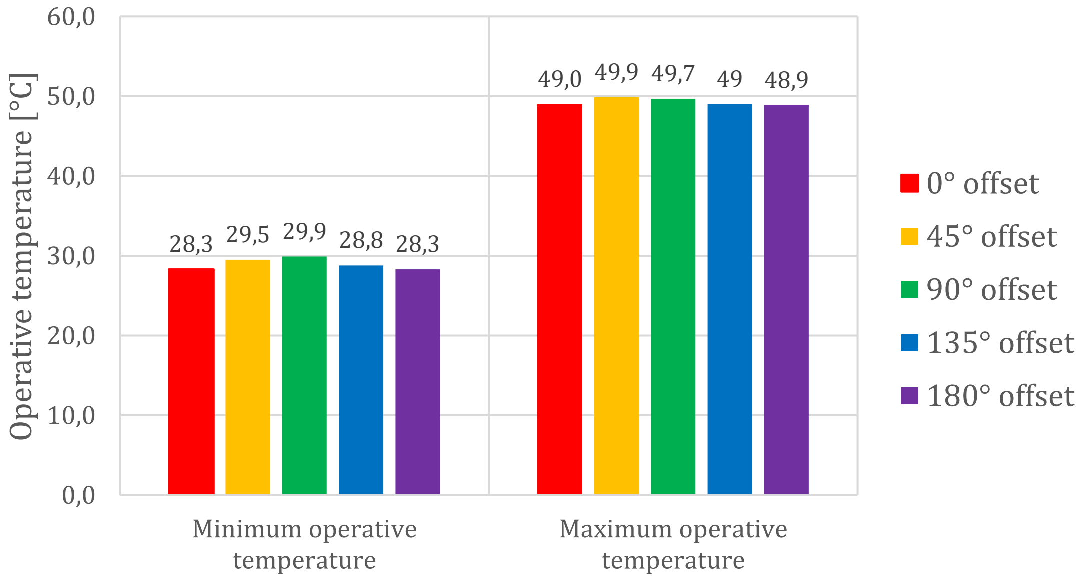

Figure C.15 Minimum and maximum operative temperature in floor 5 during the summer week.

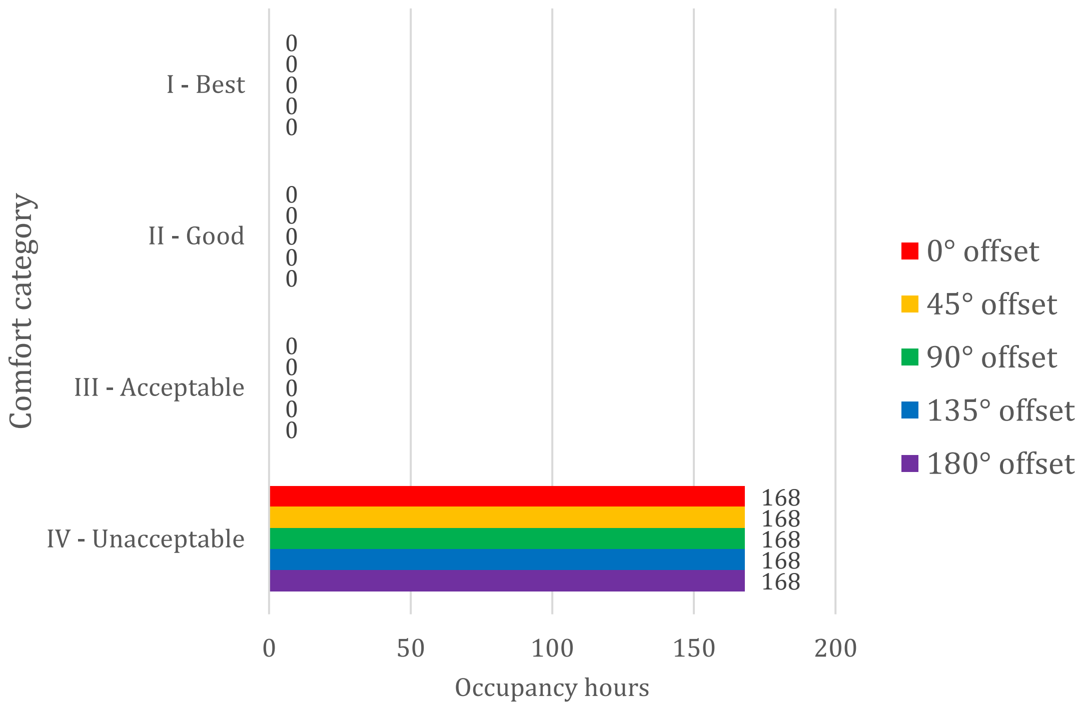

Figure C.16 Occupancy hours of each comfort category in floor 5 during the summer week.

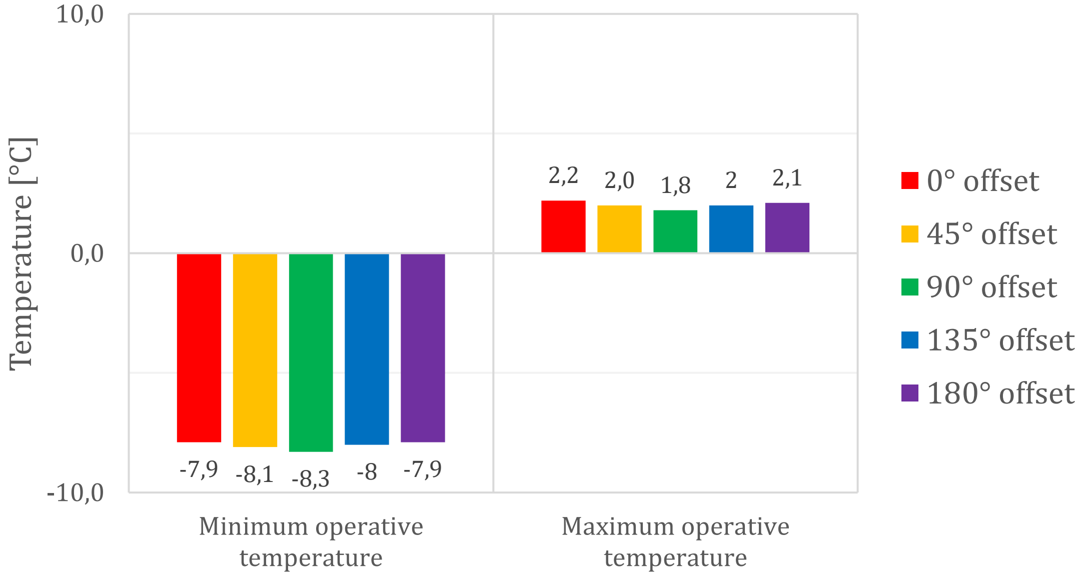

Figure C.17 Minimum and maximum operative temperature in floor 5 during the winter week.

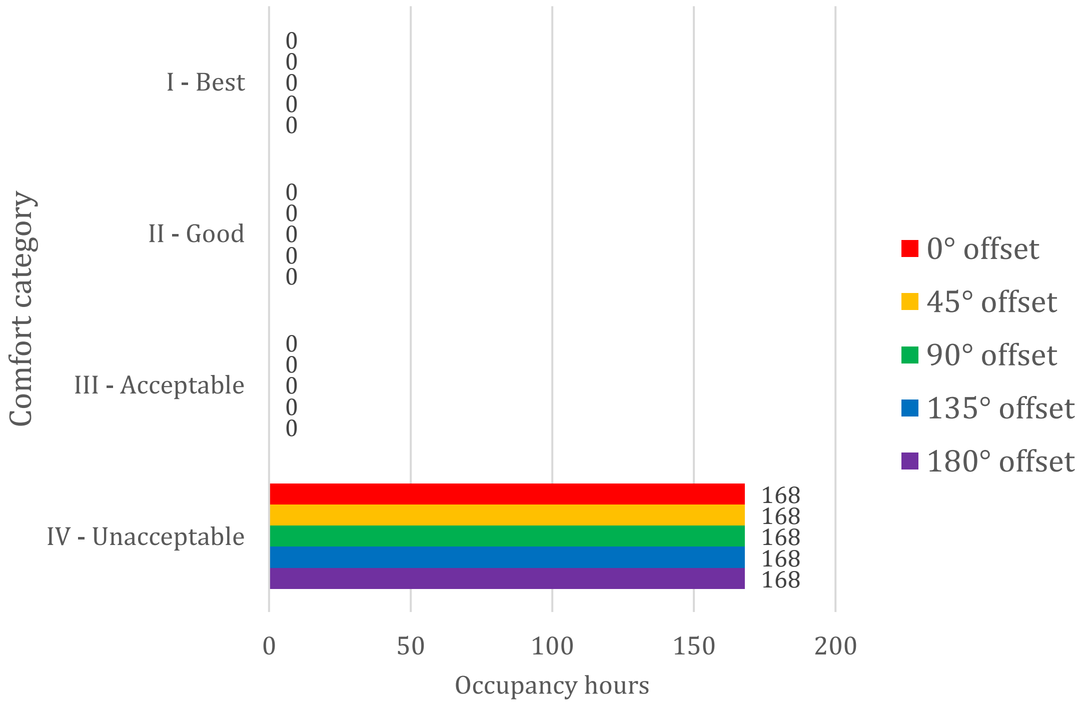

Figure C.18 Occupancy hours of each comfort category in floor 5 during the winter week.

C5 Atrium type

The minimum and maximum operative and the occupancy hours of the evaluation cases with atrium type evaluation is presented during the summer week and winter week.

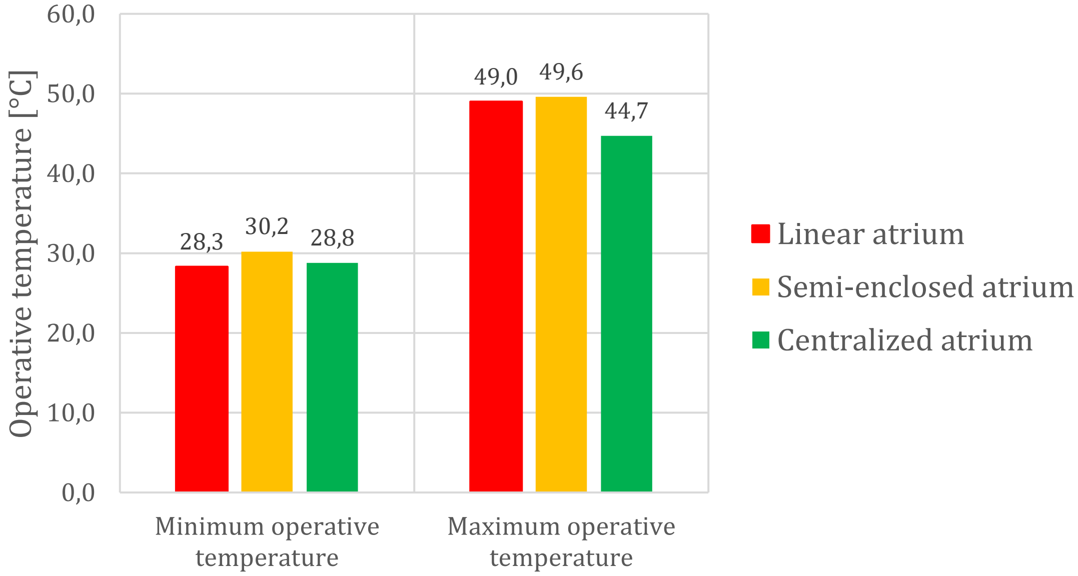

Figure C.19 Minimum and maximum operative temperature in floor 5 during the summer week.

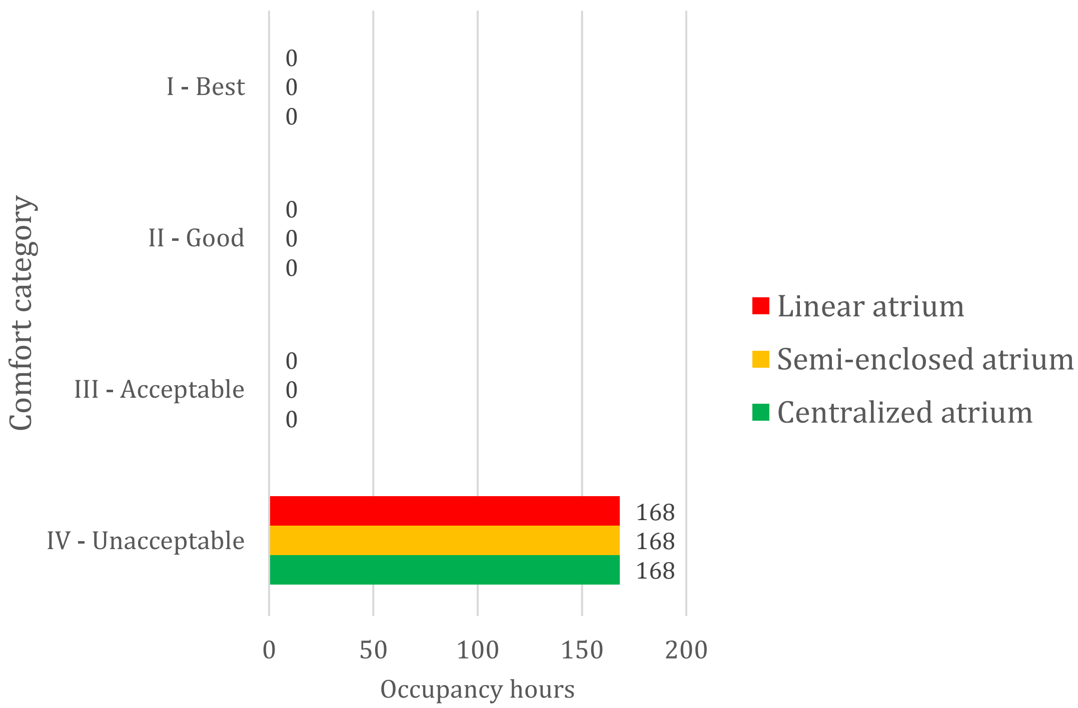

Figure C.20 Occupancy hours of each comfort category in floor 5 during the summer week.

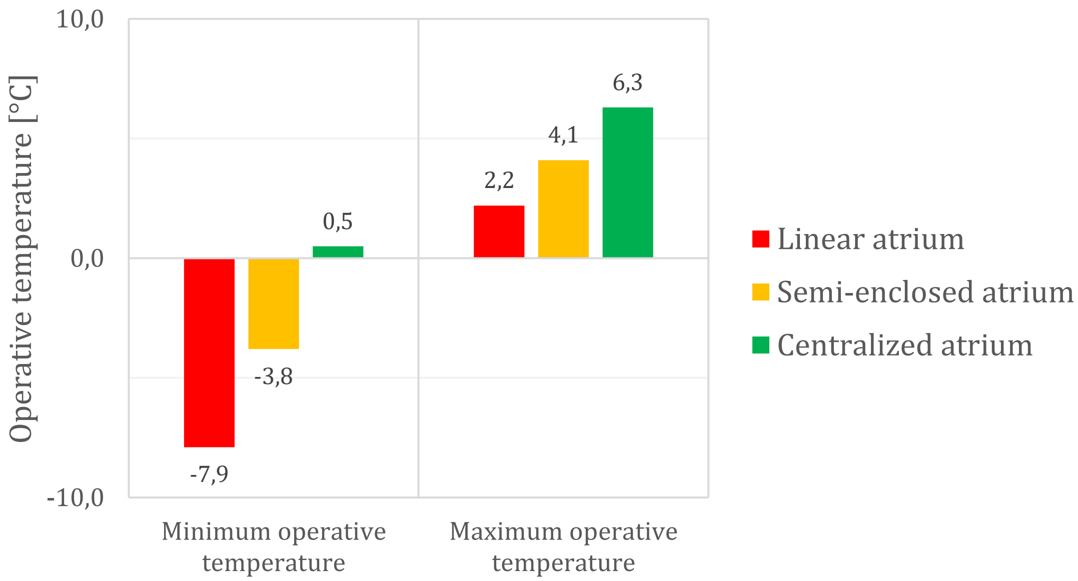

Figure C.21 Minimum and maximum operative temperature in floor 5 during the winter week.

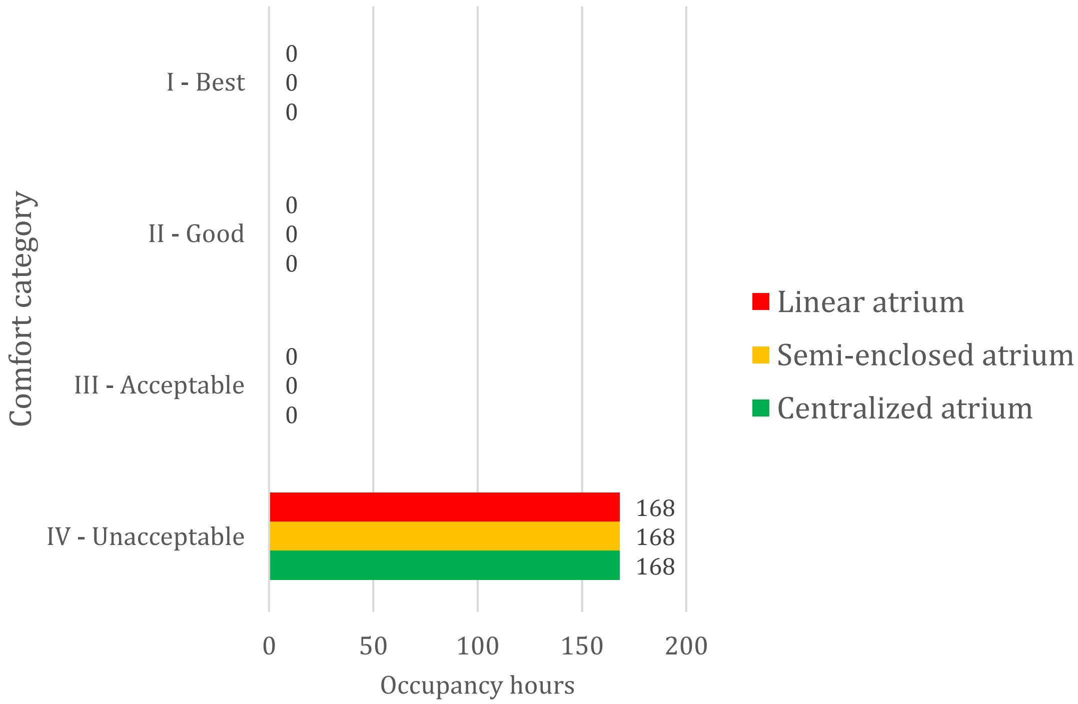

Figure C.22 Occupancy hours of each comfort category in floor 5 during the winter week.

C6 Atrium dimension

The minimum and maximum operative and the occupancy hours of the evaluation cases with atrium dimension evaluation is presented during the summer week and winter week.

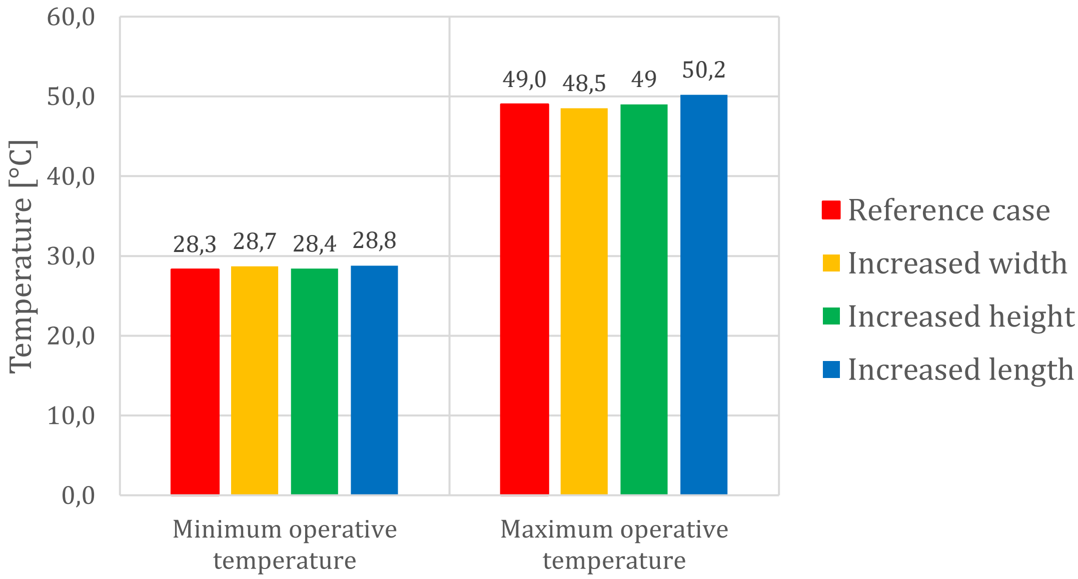

Figure C.23 Minimum and maximum operative temperature in floor 5 during the summer week.

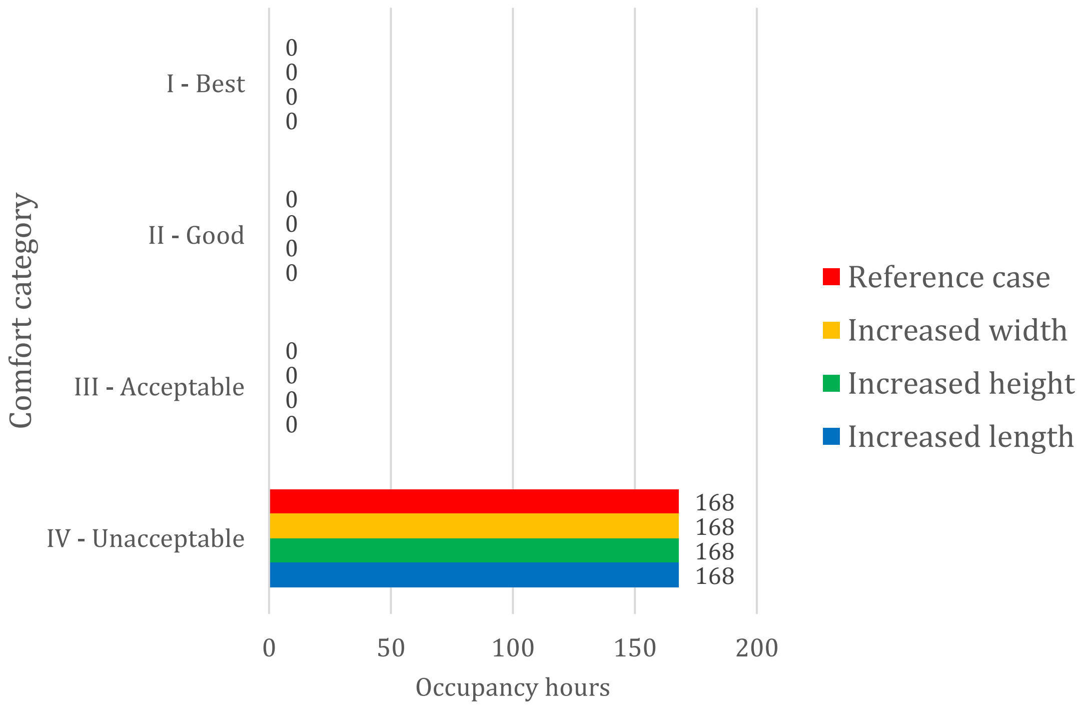

Figure C.24 Occupancy hours of each comfort category in floor 5 during the summer week.

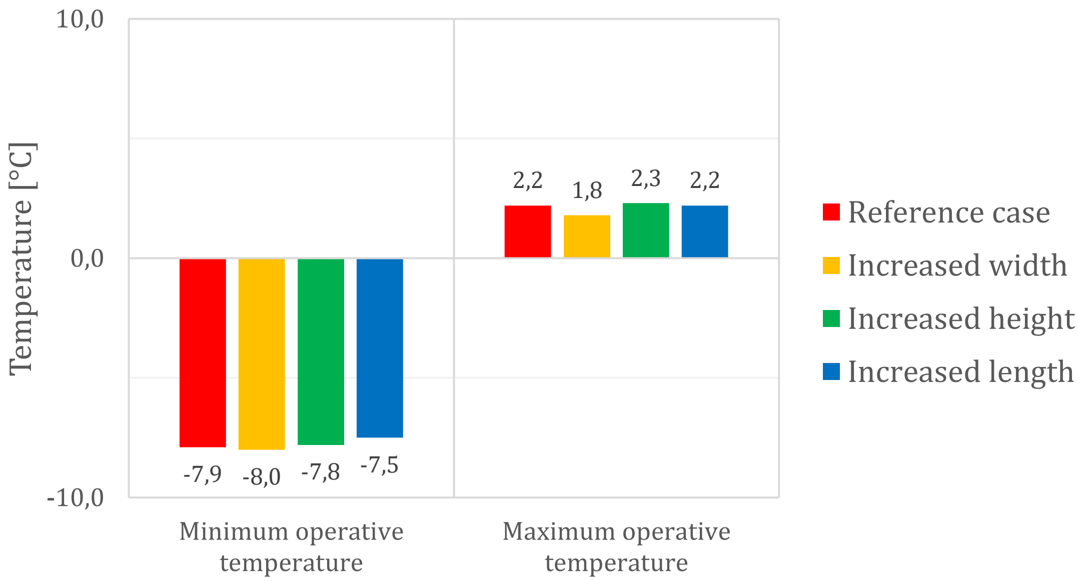

Figure C.25 Minimum and maximum operative temperature in floor 5 during the winter week.

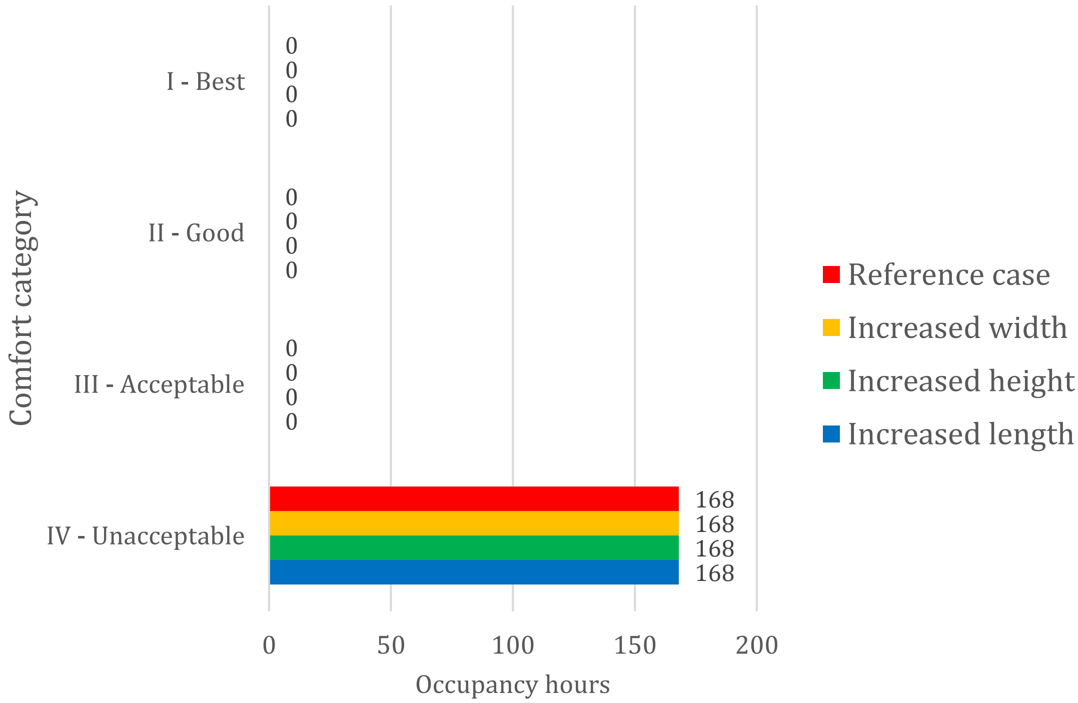

Figure C.26 Occupancy hours of each comfort category in floor 5 during the winter week.

C7 Solar shading

The minimum and maximum operative and the occupancy hours of the evaluation cases with solar shading evaluation is presented during the summer week and winter week.

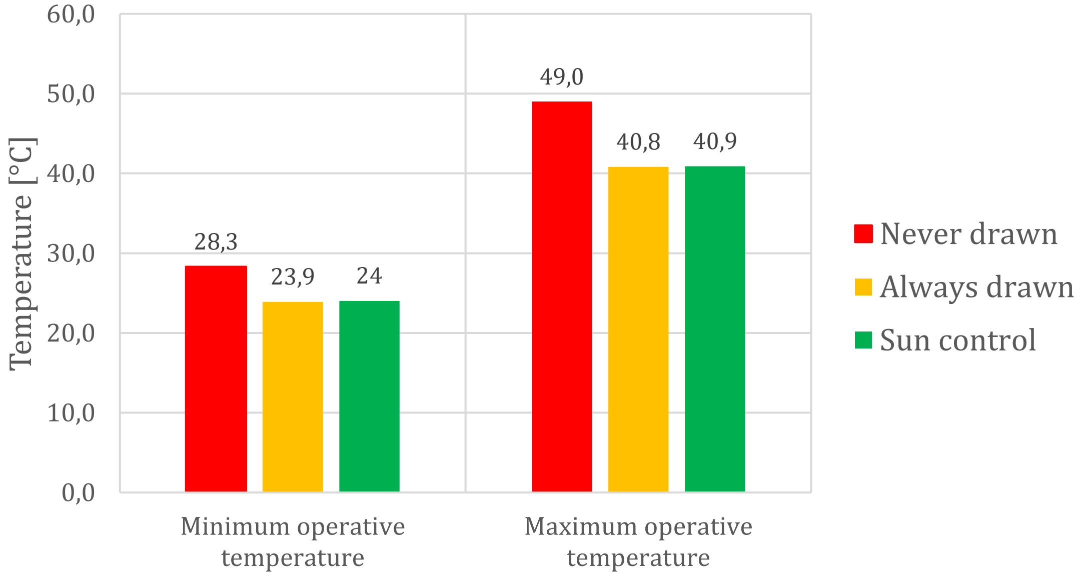

Figure C.27 Minimum and maximum operative temperature in floor 5 during the summer week.

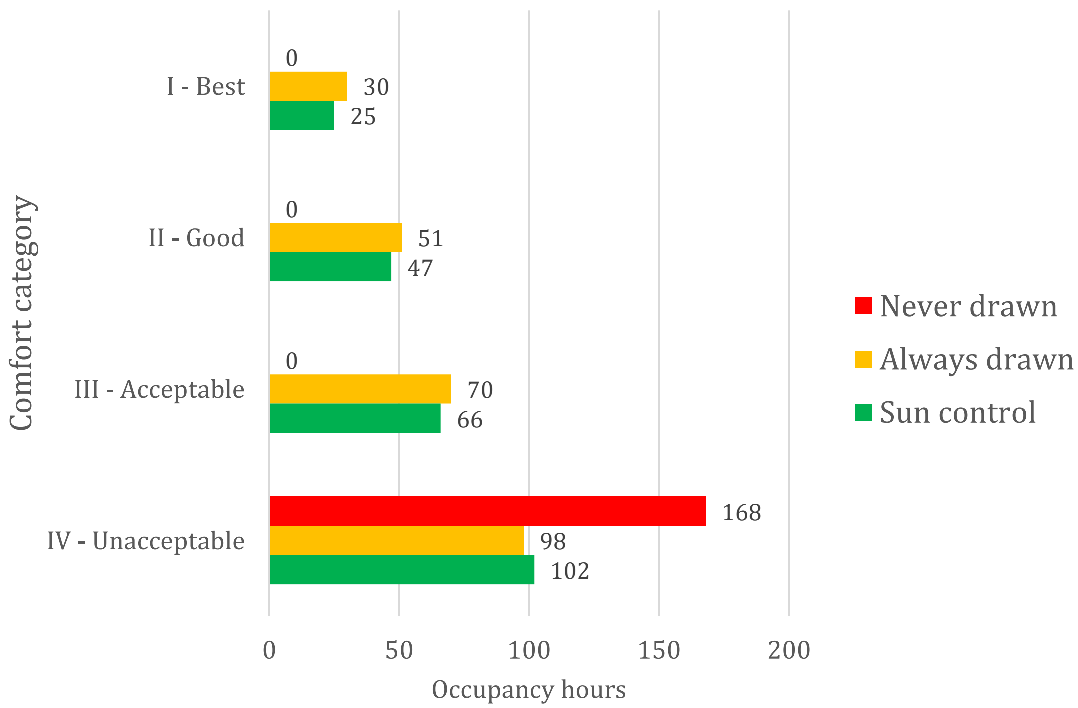

Figure C.28 Occupancy hours of each comfort category in floor 5 during the summer week.

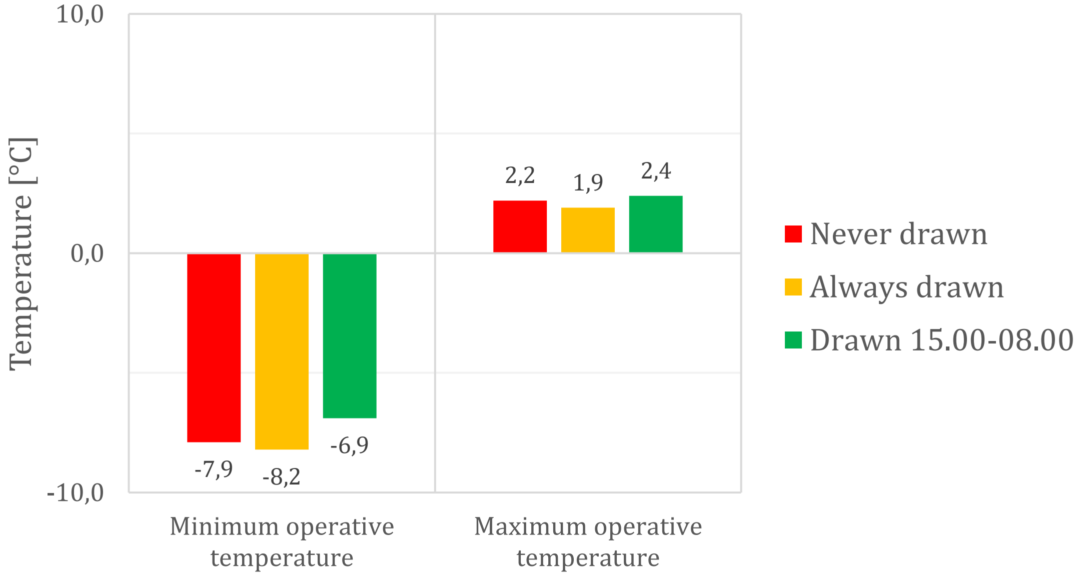

Figure C.29 Minimum and maximum operative temperature in floor 5 during the winter week.

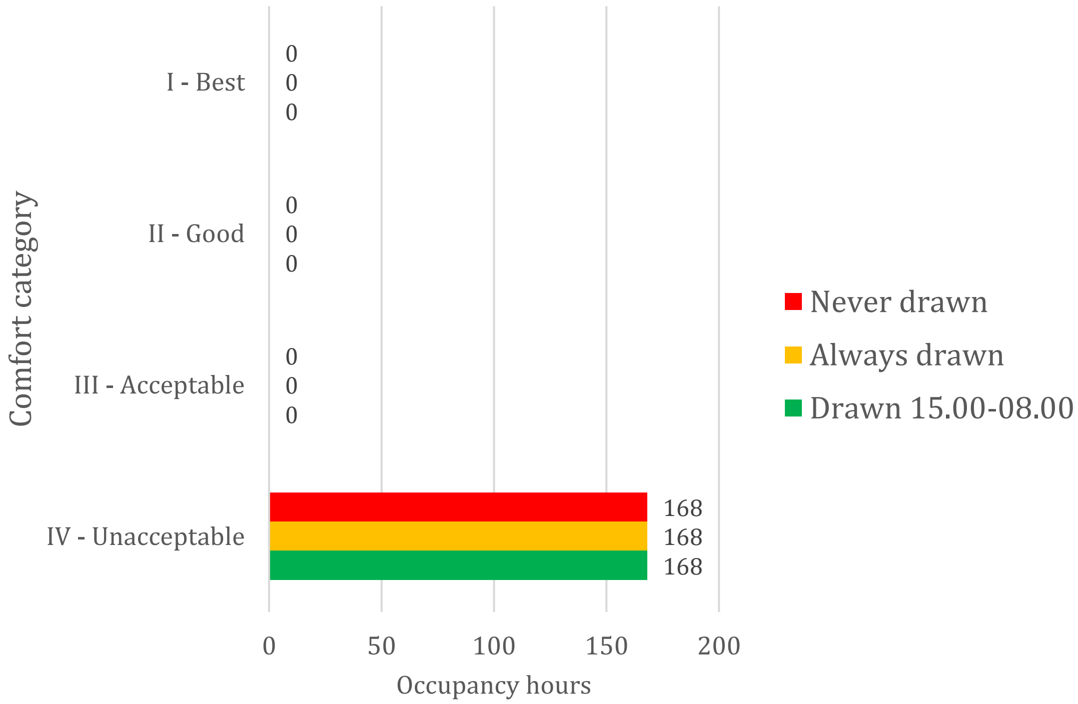

Figure C.30 Occupancy hours of each comfort category in floor 5 during the winter week.

C8 Natural ventilation

The minimum and maximum operative and the occupancy hours of the evaluation cases with natural ventilation evaluation is presented during the summer week.

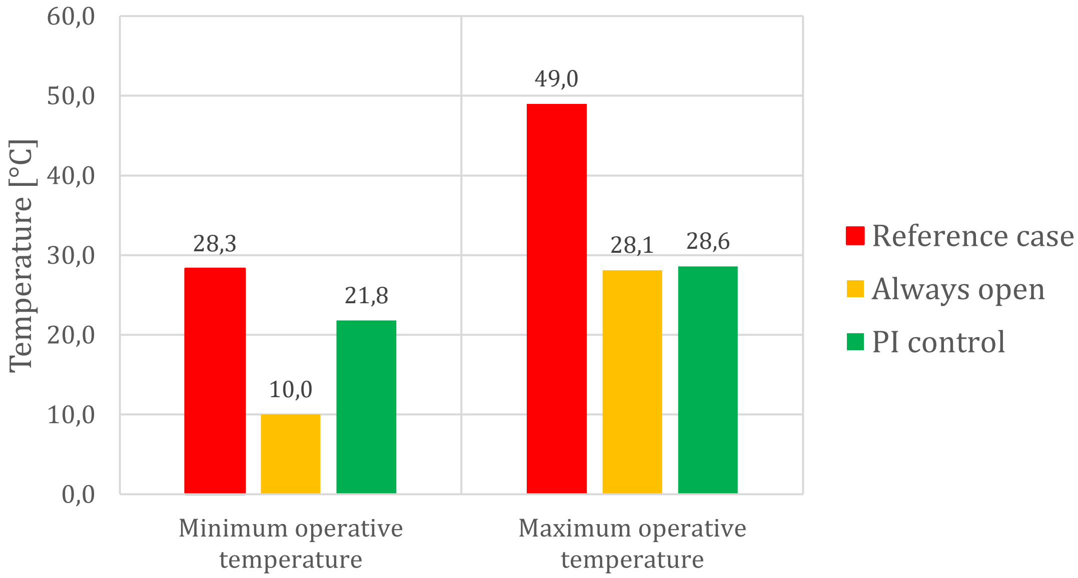

Figure C.31 Minimum and maximum operative temperature in floor 5 during the summer week.

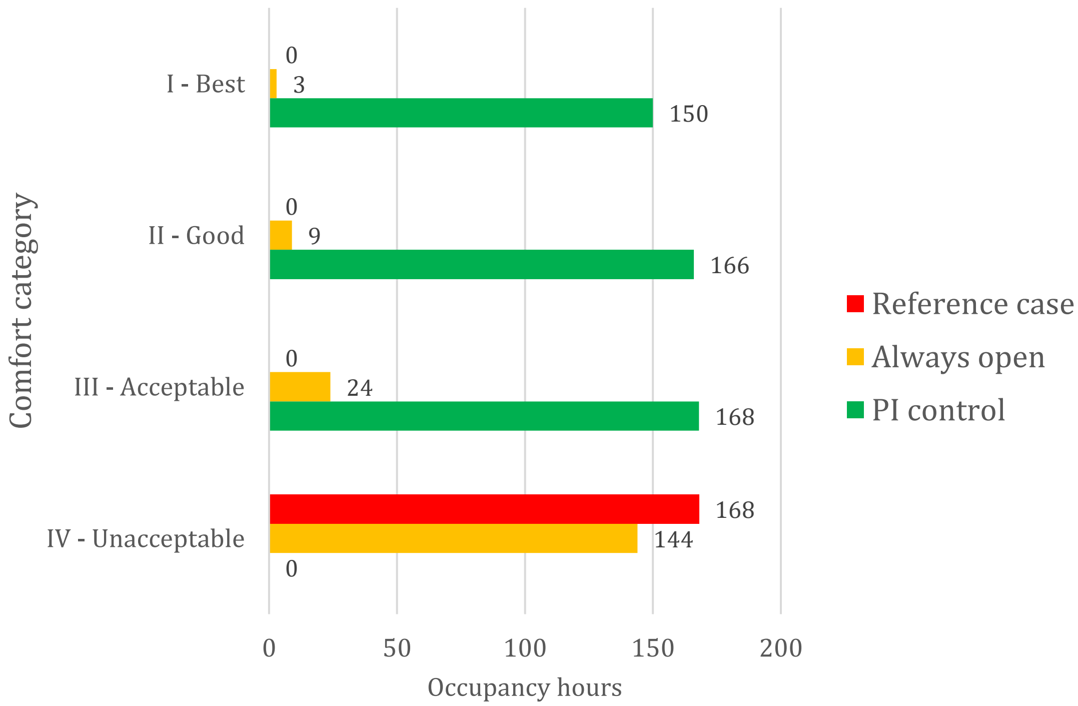

Figure C.32 Occupancy hours of each comfort category in floor 5 during the summer week.

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