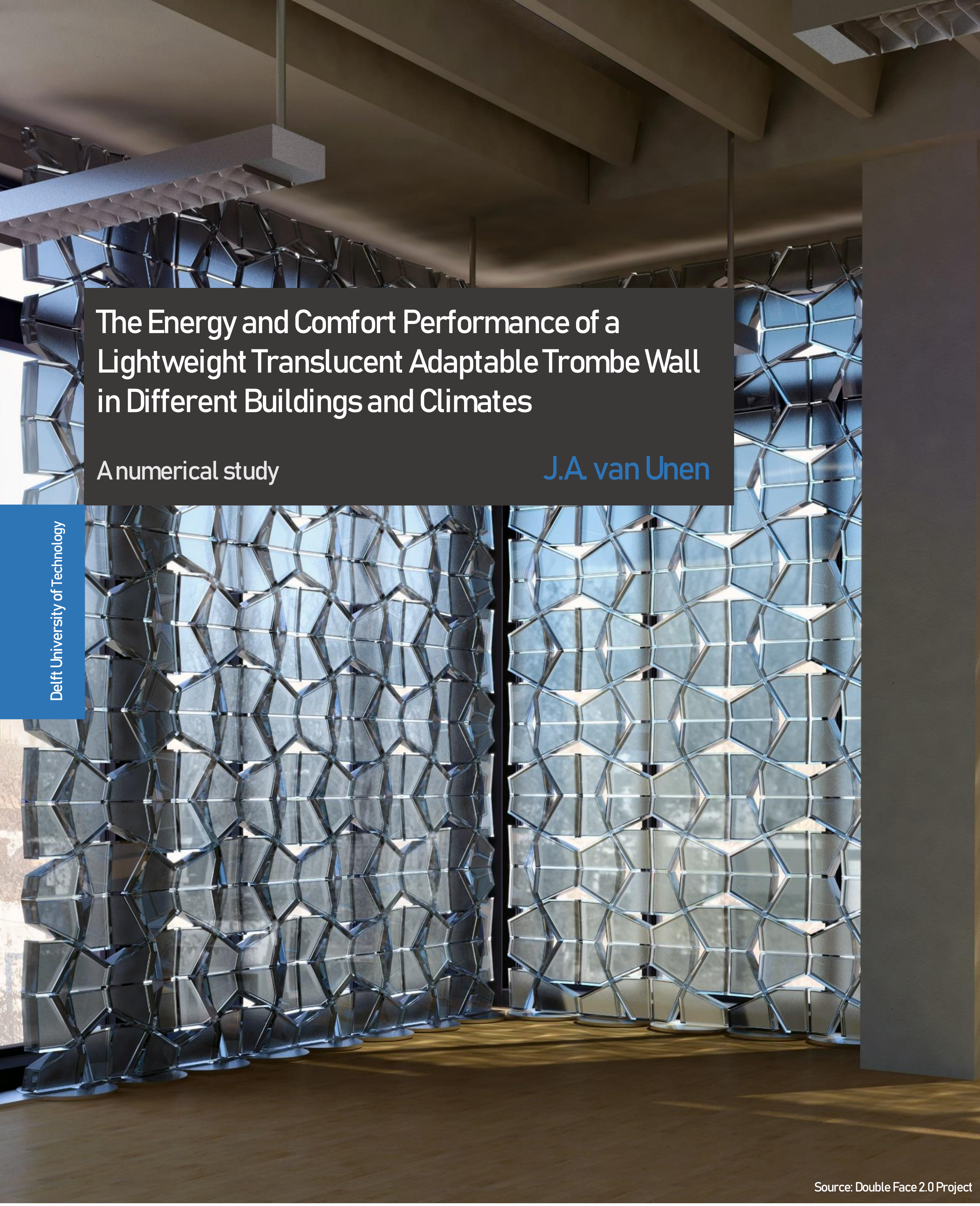
The Energy and Comfort Performance of a Lightweight Translucent Adaptable Trombe Wall in Different Buildings and Climates

A numerical study

J.A. van Unen



Source: Double Face 2.0 Project

Delft University of Technology

Master's thesis
Faculty of Civil Engineering & Geosciences
January 2019

The energy and Comfort Performance of a Lightweight Translucent Adaptable Trombe Wall in Different Buildings and Climates: A numerical study

by

Jeroen van Unen

In partial fulfilment of the requirements for the degree of

Master of Science
In Civil Engineering
At the Delft University of Technology

To be defended publicly on January 15, 2019 at 16:00h

Student number: 4233026

Thesis committee:

Prof. Ir. R. Nijsse (Chair)	Faculty of Civil Engineering
Dr. Ir. M.J. Tenpierik (Daily supervisor)	Faculty of Architecture and the Built Environment
Dr. Ir. W.H. van der Spoel	Faculty of Architecture and the Built Environment
Dr. Ir. H.R. Schipper	Faculty of Civil Engineering

PREFACE

This thesis is the result of the study I conducted at Delft University of Technology and concludes the degree: Master of Science in Civil Engineering (Building Engineering). During my studies, I have learned a lot about all kinds of subjects within the field of civil engineering, and with this thesis, I finish with the subject that interested me most. I am proud of the work presented in this thesis and I could not have done this without the help of many people.

First of all, I would like to express my gratitude to the members of my thesis committee. Thank you Prof. Nijsse for being a clear, critical and kind chairman, making the formal meetings within my graduation project as friendly and helpful as possible. Thank you Mr. Schipper for your critical view during our meetings and your help and teaching throughout my entire Bachelor and Master programme. Thank you very much Mr. van der Spoel for being a very helpful mentor by always being there for me when I encountered difficulties with the development of the simulation model. My initial knowledge of working with a thermal simulation model was often inadequate for solving various issues, but has grown enormously thanks to your help and insights. Whenever I encountered problems, you were always there to help me. Finally, thanks a lot Mr. Tenpierik for being a very helpful, daily mentor, who was always available for answering the many questions I had. For me, you were a listening ear, a person with inspiring ideas and someone who has given me confidence and reassurance.

Besides the people from my thesis committee, I would like to thank the researchers of the Double Face project team. Thanks to them, I have been allowed to be part of the project and I am always provided with useful information. Furthermore, I would like to thank my friends for inspiring me and keeping me motivated to get as much out of this project as possible. Last but not least, I owe many thanks to my family, who supported me both emotionally and financially throughout my studies.

Jeroen van Unen
Delft, January 2019

SUMMARY

A traditional Trombe wall is known as a high thermal-mass wall, situated behind a window of a room and separated by an air cavity. The idea behind using a Trombe wall is that heat, ventilation and comfort can be passively generated by using the 'free' energy of the sun. The surface of the wall absorbs solar radiation when the sun shines, stores the energy and releases the heat at night to the room, when the occupants need it (Saadatian, Lim, Sopian, & Salleh, 2013). In addition, a Trombe wall can be used as natural ventilation system, of which its power is generated by the buoyancy effect in the cavity. Because a traditional Trombe wall is heavy, blocks daylight and cannot be adjusted to changing environmental conditions and seasonal differences, a new and innovative version was devised by the Double Face research team (4TU). The innovative version is called a lightweight translucent adaptable Trombe wall (LTATW) and is about five times lighter than a traditional Trombe wall. In addition, the wall is translucent and can rotate around its axes. The lower weight and translucent character are achieved by applying a phase change material in combination with aerogel, instead of stone or bricks. Phase change materials can store a large amount of (latent) heat during the change from solid to liquid state and thus, increase the thermal inertia of the system. The translucent elements are located in front of a glass façade and act as a thermal buffer in both winter and summer by rotating the elements towards the source of incoming heat or towards the sink for heat release (4TU.Bouw, 2014). In the winter, the layer of PCM is oriented towards the outdoor environment at daytime and is thermally charged by the low winter sun. At night, the system rotates and releases the accumulated heat to the interior. In the summer, the LTATW is oriented towards the interior at daytime to store the interior heat loads and during the night, it rotates again and releases the heat to the outside environment by means of (passive) night ventilation (4TU.Bouw, 2014).

In this thesis, the results of a numerical spin-off study of the Double Face research project are shown, in which the influence of eight parameters (climate, building function, orientation, age, building method, room size, window size and type of glazing) on the energy and comfort performance of the innovative Trombe wall has been studied. First, an initial simulation model was developed in Matlab/Simulink, which was subsequently validated using a cross-comparison with results from DesignBuilder. After validation, the initial model has been extended to a suitable and reliable final version, with which more than 6000 different situations were simulated. The results of the simulations are values for the reduction or increase in energy demand for heating and cooling, expressed in percentages or in kWh. All results are processed in multiple designer tables, which interested designers can consult to assess whether installing the Trombe wall is useful for his or her situation, or not. In addition to the development of designer tables, the influence of each individual parameter on the performance of the Trombe wall was investigated using modeFRONTIER.

It was found that in case of heating only a cold and temperate climate support a proper operation of the Trombe wall, since no heating is required in the other climate types. From the analysis, it was concluded that in relative sense (%), the Trombe wall performs best in a temperate climate, and that in absolute sense (kWh), the Trombe wall performs best in a cold climate. In case of cooling, the system performs best in a temperate climate and in a dry climate. Because the LTATW is designed to be both a passive cooling system in the summer and passive heating system in the winter, it has clearly been proven that only the temperate climate is the most logical choice. The average reduction of the heating energy demand in a temperate climate equals 36.1% (or 181.3 kWh per year) and the average reduction of the cooling energy demand equals 49.9% (or 115.0 kWh per year). Analysis of the second parameter, building function, has shown that in case of heating the function is not of great influence. The system performs well in both an office and a residence. In case of cooling, higher reductions of the energy demand are achieved in residences. Thirdly, the influence of the orientation of the Trombe wall was investigated and it was found that the best performance in case of heating occurs on a southern orientation. In case of cooling, the orientation is of less importance.

The study shows that the age of a building does not have a major influence on the performance of the Trombe wall. Only in case of cooling, a slight preference can be expressed for new buildings. Studying the influence of the construction method on the performance of the wall has shown that this parameter has the least influence of all studied parameters. In both light-weight, medium-weight and heavy-weight buildings, a good performance can be achieved. For the size of the room, it was found that both room sizes

perform equally well. It could be concluded that a Trombe wall can be installed in both small rooms and big rooms, but that when a room is too big, the capacity of the Trombe wall will no longer be useful to reduce a large amount of the initial energy demand. The same applies to cooling. Research has shown that for heating purposes, a room with a smaller window is more often preferred and for cooling purposes, a large window. Because the innovative Trombe wall will have to serve as both a passive heating and cooling device, an average size window will therefore probably be the most suitable. Finally, the influence of type of glazing was studied. It became clear that in relative terms the largest reductions of the heating energy demand are achieved with clear glazing. In case of cooling, the type of glazing is of less influence.

Multiple sensitivity analyses were carried out to study the influence on the results of conditions that are easily affected by building occupants, and finally, a side-study was carried out into the influence of the Trombe wall on the energy demand for artificial lighting. It was found that even under slightly different circumstances the same conclusions can be drawn with regard to the influence of the parameters. The influence of the Trombe wall on the energy demand for artificial lighting is not negligible and should be carefully considered too.

TABLE OF CONTENTS

PART III – CREATION AND DEVELOPMENT OF SIMULATION MODEL

12. Extended simulation model

PART IV – SIMULATION RESULTS AND ANALYSIS

14. Simulation conditions

15. Simulation results and analysis

16. Artificial lighting

Note: page numbers of the pdf version do not match the page numbers of the print version

LIST OF FIGURES

LIST OF TABLES

DESIGNER TABLES

LIST OF SYMBOLS

Symbol	***Unit***	***Description***
Δh	m	Height difference between inlet and outlet opening
Δp	Pa	Pressure drop across Trombe wall opening
ΔT	K	Temperature change
A	h	Amplitude
A	m^2	Surface area
ACH	h^{-1}	Infiltration rate
A_{PCM}	m^2	Surface area of PCM panel
B	h	Bias
b	m	Room width
C_1	-	Flow coefficient
C_d	-	Discharge coefficient
$C_{i,j}$	W/K	Coupling factor between nodes i and j
C_n	-	Flow exponent
c_n	J/kgK	Specific heat capacity of component n
C_p	J/kgK	Sensible specific heat capacity
d	m	Thickness of construction layer
E_l	J	Quantity of absorbed or released latent heat
E_s	J	Quantity of absorbed or released sensible heat
g	m/s^2	Gravitational constant
h	m	Room height
h	W/m^2K	Average heat transmission coefficient between room and wall
h_{rb}	W/m^2K	Black body radiative heat transfer coefficient
h_{sf}	J/kg	Latent heat of fusion
H_{tot}	W/m^2K	Total heat transfer coefficient
L	m	Length
LT	-	Light transmittance
M	J/K	Thermal mass
m	kg	Mass
$\dot{m}_{inf}$	kg/s	Mass flow rate of infiltration air
m_n	kg	Mass of component n
$\dot{m}_{vent}$	kg/s	Mass flow rate of ventilation air
n_{people}	-	Number of people present
O(t)	h	Hour of sunrise or sunset
P	s	Period
P_0	Pa	Atmospheric pressure at sea level
$P_{abs,tot}$	W	Absorbed solar heat
p_{cavity}	Pa	Pressure at cavity side of Trombe wall opening
P_r	W	Transmitted solar radiation
$P_{r,in}$	W	Radiation heat transfer rate from indoor heat sources
p_{room}	Pa	Pressure at room side of Trombe wall opening
Q_{added}	W	Added heating or cooling
$Q_{airflow;room-cavity}$	W	Heat loss or gain due to air exchange between cavity and room
q_{app}	W/m^2	Electrical power of all appliances (lighting excluded)
Q_{bridge}	W	Heat loss or gain due to linear thermal bridge
$Q_{I,j}$	W	Heat transfer between nodes i and j
Q_{inf}	W	Infiltration heat loss or gain
Q_{int}	W	Internal heat gain
q_{light}	W/m^2	Electrical power of lighting devices
Q_M	W	Heat production per person
Q_{pcm}	W	Energy released by PCM wall
Q_{sol}	W	Solar heat gain

$q_{sol,w}$	W/m^2	Incoming solar radiation
Q_{stack}	W	Heat loss or gain resulting from passive stack ventilation
Q_{trans}	W	Transmission heat loss or gain
Q_{vent}	W	Ventilation heat loss or gain
R	J/kgK	Gas constant
R_c	m^2K/W	Façade insulation value
SHGC	-	Solar heat gain coefficient
T_c	ºC	Cavity temperature
$T_{c,set}$	ºC	Cooling thermostat set-point temperature
T_d	ºC	Room temperature at day-time
t_d	s	Charging time (day)
T_e	K	Outdoor temperature
$T_{h,set}$	ºC	Heating thermostat set-point temperature
T_i	K	Indoor temperature
T_n	ºC	Room temperature at night-time
t_n	s	Charging time (night)
$T_{PCM,opt}$	ºC	Optimal phase-change temperature of a PCM
T_r	ºC	Average room temperature
$T_{room,mean(24h)}$	ºC	Average room temperature over the last 24 hours
t_{stor}	s	Diurnal storage cycle
T_{year}	s	Period of one year
U	W/m^2K	Overall heat transfer coefficient of a construction
U_{gl}	W/m^2K	Glazing insulation value
$\dot{V}$	m^3/s	Volume flow rate of air
$\dot{V}_{flow}$	m^3/s	Volume flow rate of air through Trombe wall opening(s)
V_{room}	m^3	Room volume
$\dot{V}_{stack}$	m^3/s	Volume flow rate of stack ventilation air
WWR	-	Window-to-wall ratio
x	m	Distance
α_c	W/m^2K	Convection heat transfer coefficient
α_i	W/m^2K	Heat transfer coefficient for convection and radiation (inside)
α_o	W/m^2K	Heat transfer coefficient for convection and radiation (outside)
β_{floor}	-	Fraction of lit floor surface
ε	-	Emissivity
λ	W/mK	Thermal conductivity
μ	-	Heat recovery efficiency
$\xi_{light,vent}$	-	Fraction of power released to the room
ρ	kg/m^3	Density
τ	s	Time
ϕ	rad	Phase
Ψ	W/mK	Linear thermal transmittance of a thermal bridge
$\psi_{i,j}$	-	Exchange coefficient between nodes i and j
ω	rad/s	Frequency

ACKNOWLEDGEMENTS

The study described in this thesis concerns a spin-off study of the Double Face research project. The Double Face research project is an initiative from the four technical universities in the Netherlands, also known as the 4TU Federation. All information shown in this report and which is related to the research project is obtained thanks to the group of researchers of the project. So far, the Double Face research project consists of two sub-projects: Double Face 1.0 and Double Face 2.0. Double Face 1.0 is financed by the 4TU Federation and the universities involved were Delft University of Technology and Eindhoven University of Technology. The Double Face 1.0 project team consisted of the following people:

DELFT UNIVERSITY OF TECHNOLOGY
Dr. Arch. Michela Turrin
Dr. Ir. Martin Tenpierik
Dr. Ir. Willem van der Spoel
Ir. Winfried Meijer
Carlos Alfredo Chang Lara
Ir. Paul de Ruiter

EINDHOVEN UNVIERSITY OF TECHNOLOGY
Prof. Dr.-Ing. Patrick Teuffel
Dipl.-Ing. Florian Heinzelmann
Ing. Wout van Bommel

The Double Face 2.0 project is part of the research programme: 'Research through Design' (project number 14574) and is (partly) financed by the SIA and NWO (Netherlands Organisation for Scientific Research and Taskforce for Applied Research). The Double Face 2.0 project only consists of people from Delft University of Technology:

Dr. Arch. Michela Turrin
Dr. Ir. Martin Tenpierik
Tudor Cosmatu
Ir. Yvonne Wattez
Stavroula Tsafou

The project is supported by the following partners from industry:

SHAU Architecture and Urbanism
Rubitherm GmbH
GlassX AG
ARUP
Esteco SpA

PART I

INTRODUCTION

1. INTRODUCTION

In this chapter, the main subject of this thesis is introduced and a description of the research is given. Section 1.1 provides a brief introduction to the technology that has been studied in this project and section 1.2 describes the motivation of the author. This motivation describes why the project has been started and with which incentives the project has been completed. The research description, consisting of a problem definition, research questions, objectives, methodology and resources is given in section 1.3. This chapter ends with sections 1.4 and 1.5, which give an overview of the chronology of the steps taken in this project and an overview of the structure of this thesis.

1.1. BACKGROUND INFORMATION

In addition to the transport sector, one of the most energy-consuming sectors in the world are the residential sector and the sector for commercial and public services (on average 32% of the worldwide energy consumption). Therefore, the built environment is responsible for a substantial part of the depletion of national resources and the emission of pollutant emissions (van Bueren, van Bohemen & Visscher, 2012). As can be seen from Figure 1.1 and 1.2, space heating and energy for warm water cover a very high share of the final total energy consumption[1] (almost 70% in the residential sector and about 60% in the commercial/public sector). It is therefore clear that the built environment uses too much energy. By using fossil fuels, this energy consumption causes several environmental impacts and leads to the depletion of abiotic resources.

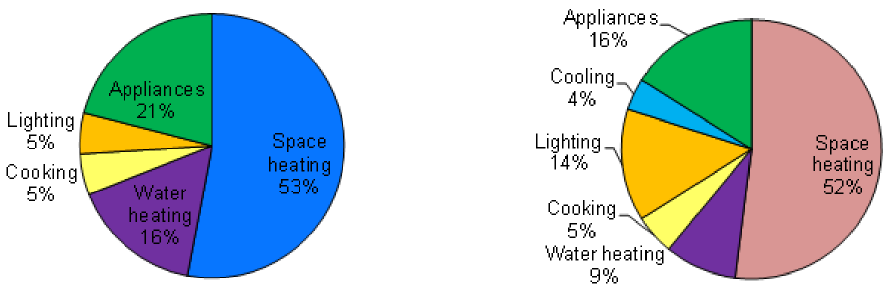


Figure 1.1 and 1.2: Final energy consumption in the residential sector (left) and final energy consumption in the commercial/public sector (right) (van Bueren et al., 2012).

[1] The two diagrams shown in Figure 1.1 and 1.2 show an average and large differences exist between different types of climates.

A group of initiators who want to fight this problem is the Double Face research team. The Double Face research team develops a new, innovative type of Trombe wall that should reduce the energy demand of buildings considerably.

A traditional Trombe wall is known as a high thermal-mass wall situated behind a window of a room, separated by an air cavity. The idea behind using a Trombe wall is that heat, ventilation and comfort can be passively generated by using the 'free' energy of the sun. The surface of the wall absorbs solar radiation when the sun shines, stores the energy and releases the heat at night to the room, when the occupants need it (Saadatian, Lim, Sopian, & Salleh, 2013). In addition, a Trombe wall can be used as natural ventilation system, of which its power is generated by the buoyancy effect in the cavity. Because this wall is heavy, blocks daylight and cannot be adjusted to changing environmental conditions and seasonal differences, a new and innovative version was devised by the Double Face research team (4TU). The innovative version is called a lightweight translucent adaptable Trombe wall (LTATW) and is about five times lighter than a traditional Trombe wall. In addition, the wall is not opaque but translucent and can rotate around its axes. The lower weight and translucent character is achieved by applying a phase change material in combination with aerogel, instead of stone or bricks. Phase change materials can store a large amount of (latent) heat during the change from solid to liquid state and thus, increase the thermal inertia of the system. The translucent elements are located in front of a glass façade and act as a thermal buffer in both winter and summer by rotating the elements towards the source of incoming heat or towards the sink for heat release (4TU.Bouw, 2014). In the winter, the layer of PCM is oriented towards the outdoor environment at daytime and is thermally charged by the low winter sun. At night, the system rotates 180 degrees and releases the accumulated heat to the interior. In the summer, the LTATW is oriented towards the interior at daytime to store the interior heat loads and during the night, the LTATW rotates again and releases the heat to the outside environment by means of (passive) night ventilation (4TU.Bouw, 2014).

This section only provides a brief introduction to the technology addressed in this thesis. A more detailed description about the lightweight translucent adaptable Trombe wall is given in the first chapters of this thesis (part II).

1.2. MOTIVATION

During the Bachelor programme of Civil Engineering at Delft University of Technology, I have learned a lot about all aspects in the field of civil engineering. Subjects in the field of water, geosciences and transport have been treated with great interest, but the most interest was always involved in topics regarding the building sector. A logical choice was therefore to apply for the Master: Building Engineering. Within this Master I was most interested in the field of building physics and facades and therefore, many courses were followed in the field of building technology, climate design, energy and comfort, sustainability, glass and other construction materials. The wish was therefore present to find a subject for my thesis that brings all these topics together.

It seems that I could not have found a more appropriate subject for my thesis than the technology of the lightweight translucent adaptable Trombe wall. With this subject, my knowledge about energy, comfort, glass and building physics could be applied to make a good contribution to a research that is in full swing. Because the Double Face research project is a fairly new project, there were still many aspects of the LTATW to explore and my study would make a major significant contribution to the project.

1.3. RESEARCH DESCRIPTION

The research description provides information about why the study in this Master's thesis project is conducted, what the research questions are, what needs to be achieved, how the study will be carried out and what the resources will be. All this is divided into a problem definition (section 1.3.1), a list of research questions (section 1.3.2), an overview of the aims and objectives (section 1.3.3) and a description of the methodology and resources (section 1.3.4).

1.3.1. PROBLEM DEFINITION

Until now, a lot of research has been carried out by the Double Face research team and several studies have been completed. The objective of one of the first studies in the project was to gain global insight into the energy savings of a room in a winter season as a result of having a lightweight translucent adaptable Trombe wall. This study was performed using a simulation model in Matlab/Simulink, in which a small, basic room (control space) with adiabatic surfaces for the ceiling, floor and inner walls was modelled (see Figure 1.3 and 1.4). The developed Matlab/Simulink model is a full energy performance model and takes into account presence of users, ventilation characteristics, internal heat gains, solar gains, infiltration losses, transmission, heat storage in walls, etc (Cosmatu, Turrin, Wattez, & Tenpierik, 2017).

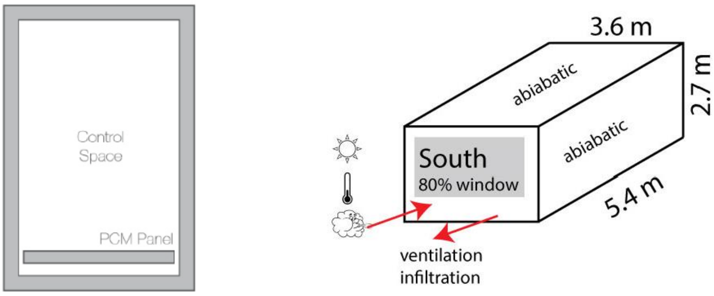


Figure 1.3 and 1.4: Control space with position of PCM panel (left) (Lara, Tenpierik, Turrin, & Van der Spoel, 2015) and 3D scheme and dimensions of control volume (right) (Wattez, 2018).

The results of the energy simulations were promising. It was found that an energy reduction of around 30% could be achieved by using the innovative Trombe wall with 1 cm of phase change material. However, it must be mentioned that this simulation has only been carried out for a 'typical' residential room in the Netherlands. No results were obtained of the energy and comfort performance of the innovative Trombe wall in other building configurations and climates and it is therefore not known how the Trombe wall performs under other (more or less favorable) conditions.

Problem statement (conclusion):
The energy performance simulation in MATLAB/Simulink of the PCM panel has only been carried out for a 'typical' residential room in the Netherlands. It is not known how the innovative Trombe wall performs in other climates and rooms of other type of buildings.

1.3.2. RESEARCH QUESTIONS

The primary objective of this study is to gain knowledge about the influence of various building parameters and climate on the energy and comfort performance of a lightweight, translucent and adaptable Trombe wall. In order to fulfil this objective, one main research question, nine sub-questions and five background questions were formulated:

Main research question:
How do building parameters and climate influence the energy and comfort performance of a lightweight translucent adaptable Trombe wall?

Sub-questions:

1. How does climate influence the performance of a LTATW?
2. How do building parameters influence the performance of a LTATW?
   - 2.1. How does the function of a building influence the performance of a LTATW?
   - 2.2. How does the orientation influence the performance of a LTATW?
   - 2.3. How does the age of a building influence the performance of a LTATW?
   - 2.4. How does the building method influence the performance of a LTATW?
   - 2.5. How does room size influence the performance of a LTATW?
   - 2.6. How does window size influence the performance of a LTATW?
   - 2.7. How does type of glazing influence the performance of a LTATW?

Background questions (relating with sub-question 1):

1.1. What climates need to be studied?
1.2. Does climate influence the selection of a PCM?
1.3. Do climate and building function influence the thermostat set-points of a building?
1.4. What types of PCM are suitable for application in buildings?
1.5. What is the optimal phase change temperature of a PCM in buildings?

1.3.3. OBJECTIVES

The overall objective of this Master's thesis project is to study the influence of different building parameters and climate on the energy and comfort performance of a lightweight translucent adaptable Trombe wall. With the knowledge gained from this study, a well-founded advice can be given to future interested designers about the usefulness of applying the innovative Trombe wall in his/her building. In addition to being able to view this final report with findings, advice is also given by means of multiple 'designer tables', in which colours and values indicate which situations (combination of variables) are favourable and which situations are unfavourable. The designer tables include the most representative climates of the world and different building characteristics of both office buildings and residences. In this way, the designer tables can be used in many buildings all over the world. The studied building parameters are:

- Climate
- Building function
- Orientation
- Age
- Building method
- Room size
- Window size
- Type of glazing

To prevent the tables from becoming too large, only 'typical' and relevant situations are presented. A total of six main tables are developed: two tables indicating the annual reductions of the heating energy demand (both in percentage as in kWh), two tables indicating the annual reductions of the cooling energy demand and two tables indicating the annual increase in energy demand for artificial lighting. There are also eight additional designer tables attached in the appendix, that show for each type of energy demand, the initial energy demand of the room (i.e. without LTATW) and the normalized values of all designer tables.

1.3.4. METHODOLOGY AND RESOURCES

A small part of the study in this project concerns a literature study and the main part concerns running thermal energy simulations. Because the execution of experiments with a prototype is not yet possible, the parameter study is carried out with a computerized simulation model. The software which is used to run the simulations and obtain the data is Simulink. Simulink offers a graphical programming environment, which makes it possible to model and simulate the dynamical system of a LTATW in different room configurations and climates. The Simulink model is assisted and driven by a script written in Matlab, in which all model conditions are specified. Because a 'basic' (and un-validated) simulation model has already been developed in the Double Face 1.0 project, this will also be used in this research. A thorough acquaintance with the model is of importance to see what is missing from the model and thus, what needs to be added, adjusted or removed. To assess the results of the simulation model as reliable (validation and verification), a cross comparison is carried out by comparing results from Matlab/Simulink with results from DesignBuilder. Just like Matlab/Simulink, DesignBuilder is a software package which is capable of simulating a dynamical room system with LTATW. With the knowledge obtained from this validation procedure, the Matlab/Simulink model will be further fine-tuned to a more detailed and advanced simulation model, which is fully capable of obtaining the desired, reliable results for this study.

The extended simulation model will be able to calculate the heating and cooling energy demand over a whole year, for a situation with and without LTATW. In this way, the energy savings can be calculated hereafter. After a data analysis, recommendations can be given about the effectiveness of installing a lightweight translucent adaptable Trombe wall for many different room configurations. With the aid of multiple sensitivity studies, the sensitivity of the results is examined. The sensitivity study will provide insight into the influence of parameters that users can influence themselves, such as applying shading and changing the operative temperature, on the values given in the designer tables. Because the innovative Trombe wall also influences the energy demand for artificial lighting, another side-study is carried out in DesignBuilder with the aim to investigate this influence.

All background questions (1.1 to 1.5) will be answered with a literature study. After having answered the background questions, the main question and sub-questions can be answered by means of numerical simulations.

1.4. PROJECT APPROACH

The approach for this thesis is visualised in Figure 1.5.

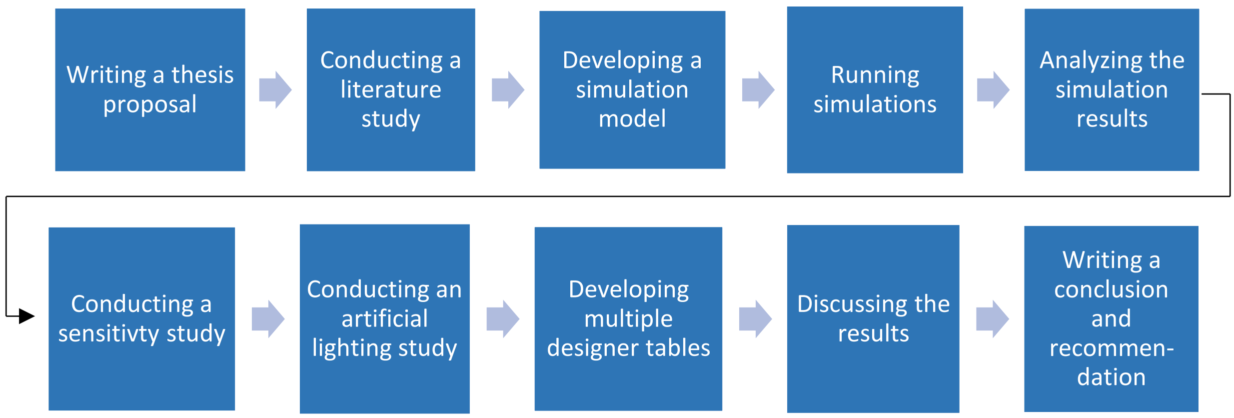


Figure 1.5: Project approach.

1.5. OUTLINE

This thesis contains the following chapters:

Chapter 1:	In which the research subject is introduced and a research description is given
Chapter 2:	In which the principle and literature of passive solar building design are discussed
Chapter 3:	In which the principle and literature of Trombe walls are discussed
Chapter 4:	In which the principle and literature of phase change materials are discussed
Chapter 5:	In which the principle and literature of Trombe walls with PCM are discussed
Chapter 6:	In which the principle and literature of the LTATW are discussed
Chapter 7:	In which the principle of climate classification is described
Chapter 8:	In which a conclusion is given of part II
Chapter 9:	In which the theory of thermal energy balances is explained
Chapter 10:	In which the initial simulation model is described
Chapter 11:	In which is described how the initial simulation model is validated and verified
Chapter 12:	In which the extended simulation model is described
Chapter 13:	In which a conclusion is given of part III
Chapter 14:	In which the simulation conditions are listed
Chapter 15:	In which the simulation results and analysis are shown
Chapter 16:	In which the study into the influence of the LTATW on artificial lighting is described
Chapter 17:	In which the designer tables are shown
Chapter 18:	In which a conclusion is given of part IV
Chapter 19:	In which a discussion is provided
Chapter 20:	in which the final conclusions and recommendations are described

All background questions are answered in chapter 8 and all sub-questions are answered in chapter 18. The Main research question is answered in chapter 20.

PART II

LITERATURE REVIEW

2. PASSIVE SOLAR BUILDING DESIGN

An umbrella term for the main addressed subject in this thesis is 'passive solar building design'. Passive solar building design is a broad subject that is explained in more detail in this chapter by reviewing theory and examples from literature. The first section of this chapter describes the definition of passive solar building design and mentions the advantages of it. Section 2.2 describes the ways in which solar heat is passively managed and section 2.3 lists the most common examples of passive solar design strategies.

2.1. DEFINITION

The main objective in passive solar building design is to reduce the energy consumption in buildings by making optimal use of solar energy. More specifically, a passive solar system aims to establish thermal comfort in buildings, without (a great) need for electrical or mechanical equipment. In the philosophy of passive solar building design, buildings and its components are interpreted as solar systems and the most efficient system is obtained when the most 'optimal' building is designed (Schittich, 2003). In the summer, solar heat needs to be rejected and in the winter, heat needs to be gained as much as possible. The integration of passive solar design strategies are the most successful when they are considered in the conceptual design phase (Stevanović, 2013). At this stage, adapting a design strategy (like for example a building its orientation) results in a reduced energy use against hardly any additional cost (Gupta & Tiwari, 2016).

A list of advantages of passive solar building design is given by the U.S. Department of Energy (2000):

- **Improved energy performance**: passive solar building strategies result in lower energy bills.
- **Attractive living environment:** passive solar building strategies are generally accompanied by large windows and view, open floor plans and sunny interiors.
- **Comfort:** passive solar building strategies create a warmer interior climate in winter and a cooler climate in summer. Passive solar systems are quiet and its construction is solid.
- **Improved value:** Owners of buildings with passive solar strategies are more satisfied and experience high resale value.
- **Low maintenance:** strategies are durable and operation and repair is rarely needed.
- **Investment:** pay-back time of passive solar systems is generally short. Systems are independent from future rise in fuel costs.
- **Environmentally friendly:** passive solar designs don't use any fossil fuels but make use of renewable energy sources.

Passive solar building construction itself is often not experienced as difficult or expensive, but a scientific design requires a thorough study. Lessons can be learned from successful previous passive solar designs, but also from detailed computer simulations (Shingare, Singh, & Sharma, 1986).

2.2. PASSIVE MANAGEMENT OF SOLAR HEAT

'Solar' buildings manage the energy flows from solar radiation through an absorber, a collector (aperture), a distributor, a thermal mass and a control mechanism (Gencoglu & Turkoglu, 2004). These five elements are incorporated in three basic types of passive solar design: direct gain, indirect gain and isolated gain (Figure 2.1).

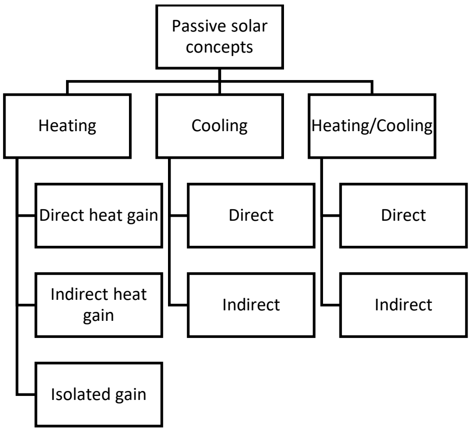


Figure 2.1: Types of passive solar concepts (Gupta & Tiwari, 2016).

Figure 2.2 (left) illustrates a situation where the five elements are shown in a direct gain situation (U.S. Department of Energy (DOE), 2001). In this situation, the absorber is most commonly known as the hard, darkened element like a wall, floor or partition, but can also be an interior element like a piece of furniture. The sunlight is in direct path of the absorber and the energy is stored as heat into the material. At night, when the temperature of the room drops below the temperature of the absorber, the heat is released back into the room by means of convection and radiation. The collector or aperture in this system is the window surface through which sunlight enters the building. The distributor is known as the method by which solar heat is distributed to different areas in a building. In a complete passive design, only the natural heat transfer modes: conduction, convection and radiation arrange these transfers. In many cases however, the distribution of heat through a building is supported by fans, ducts and/or blowers (U.S. Department of Energy (DOE), 2001). The thermal mass represents the materials that store heat, produced by solar radiation. The difference between thermal mass and the absorber is that the absorber represents a surface and the thermal mass represents the material behind that surface. Finally, the control mechanism in this system is the roof overhang, which can be used as a shading system during summer period. Other possible control mechanisms include for example: operable vents, sensing devices, low-emissivity blinds, awnings and dampers (U.S. Department of Energy (DOE), 2001).

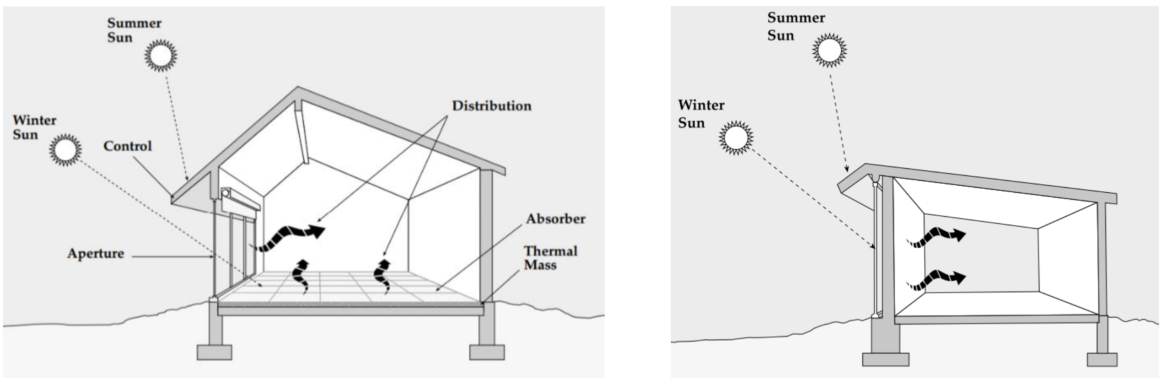


Figure 2.2: Example of direct (left) and indirect (right) solar gain (Gencoglu & Turkoglu, 2004).

An example of a passive solar design with indirect gain is shown on the right in Figure 2.2. Figure 2.2 shows a system where a thermal storage volume between south-facing windows and living spaces is situated. A

Trombe wall is the most common application of such an indirect solar gain system (Gencoglu & Turkoglu, 2004). A Trombe wall system consists of a thick wall (usually masonry or concrete), a cavity and a layer of glass. Solar heat penetrates through the glazing and the cavity, and is absorbed by the wall, which radiates the heat back into the living space when the occupants need it (Saadatian, Sopian, Lim, Asim, & Sulaiman, 2012).

A solarium (or a sunspace) is an example of a solar passive system with isolated solar gain. Sunspaces are made of a large amount of glazed elements without overhead and therefore, experience high heat gains and losses. The resulting temperature variations can be moderated by for example low-emissivity windows and thermal mass. Heat which is captured by the sunspace can be distributed to the main building through vents, doors, windows or fans (U.S. Department of Energy (DOE), 2001).

2.3. DESIGN STRATEGIES

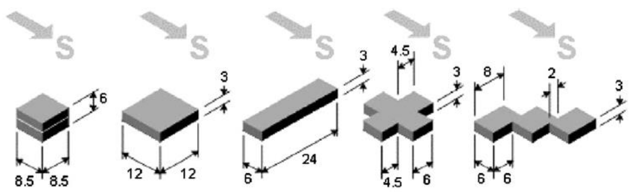
Some of the most common passive solar design strategies that offer a direct, indirect or isolated gain situation are described in section 2.3.1. to 2.3.8.

2.3.1. LOCATION AND MICROCLIMATE

The position of a building on the site has a significant influence on its energy balance. Of course, the global climate plays a major role, but the microclimate has a big influence as well. Each microclimate has its own characteristics determined by topography, surrounding buildings, trees, plants, location near open bodies of water, etc. (Schittich, 2003). Thus, When designing a building, the microclimate must be well considered. For example: constructing a building on a vegetated site with surrounding water bodies enhances the humidity and provision of shade. By embedding a building in the ground, heat losses are diminished because of the insulation of the soil.

2.3.2. SHAPE AND SIZE

An optimized building form takes the microclimate and other environmental concerns into serious consideration. Stevanović (2013) reviewed a study concerning heat flow with respect to the building envelope and revealed that a reduction in heating up to 12% per total building volume can be achieved with an optimized building form. Aldawoud (2013) investigated different geometries of an atrium and discovered that a square-shaped atrium has the best performance in terms of energy savings. Depecker et al. (2001) carried out research into the relation between the shape coefficient and the heating load on buildings. They defined a coefficient as the ratio between the inner volume of a building and the external surface area (Figure 2.3). The thermal performance of 14 different building shapes, positioned in two different climates (cold and temperate Mediterranean) have been investigated and the results show that the heating load in cold climates is almost proportional to the shape coefficient. In temperate climates, no correlation between the shape coefficient and the heating load is found (Stevanović, 2013). In general, traditional building forms perform well in terms of energy performance and have been developed and improved over many centuries (Schittich, 2003). In very cold climates, the envelope surfaces are kept to a minimum and buildings are compact. This is less applied in warmer climates.



$\frac{V}{S} = \frac{432}{348} = 1.24$ $\frac{V}{S} = \frac{432}{432} = 1$ $\frac{V}{S} = \frac{432}{468} = 0.92$ $\frac{V}{S} = \frac{432}{468} = 0.92$ $\frac{V}{S} = \frac{432}{516} = 0.84$

Figure 2.3: ratio between inner volume and external surface area of a building (Gratia & Herde, 2003).

2.3.3. ORIENTATION AND ZONING

It is important to understand the motion of the sun in relation to the block selection and the building design. In the summer, the sun is higher in the sky. By designing a building correctly, it can be made sure that the building is properly shaded in summer by shading devices. Smart positioning of windows also contributes to a better energy performance. For example, by having more windows on the north side of your building, the need for artificial lightning remains low and a building remains cool on summer days (Hollo, 2011). In the winter, the sun is lower in the sky. This means that the sun can penetrate through the glazing to the interior of the home, creating heat gain and reducing the demand for artificial heating. In Central Europe, windows are commonly positioned at the south façade. On the other hand, in hot regions protection from the sun is more important and a southern orientation is not desired. Nowadays, orientation can be quickly evaluated by solar altitude diagrams and advanced computer programs (Schittich, 2003).

Another strategy which is closely related to the orientation of the building is the zoning of rooms inside a building. Zoning is based on the fact that rooms have different thermal requirements regarding their use and indoor climate (especially in residences). Temperature requirements for bedrooms and working spaces are obviously different than those for a living room (Schittich, 2003). Zoning with regard to passive solar design begins by orientating the building to the south (Northern hemisphere). Rooms with the greatest heat requirements are then positioned across the Southern façades and are surrounded by rooms with lower thermal requirements (Hollo, 2011).

2.3.4. SHADING

Once a correct block selection and building orientation has been determined, it is important to shade correctly, so that in winter heat can be gained from the sun and in summer the building is shielded from the sun. A simple way to accomplish this is to ensure that the building has a shading strategy. Shading strategies generally fall into three categories: roof overhangs, landscaping and exterior/interior shading devices (U.S. Department of Energy, 2000). Trees that function as shading are a well-known example of a landscaping strategy. Roof overhangs must be designed in a way that an undesired summer sun is blocked and a desired winter sun is not. When considering exterior and interior shading devices, exterior devices are the most effective, as these devices stop solar gain before the sun is able to hit the building (U.S. Department of Energy, 2000). A wide range of products like canvas, roll-down blinds and louvres are used for this. A disadvantage of strategies like roll-down blinds is that they have to be operated by a building user and thus, are not completely passive.

2.3.5. BUILDING ENVELOPE

The building envelope of a passive solar building should be built tight and should ensure proper ventilation. Infiltration should be minimized with air locks, draught sealing and quality construction of doors and windows (Gupta & Tiwari, 2016). The opaque façade parts should use the appropriate amount and type of insulation and include for example radiant barriers to minimize seasonal excessive heat gains or losses (Shingare et al., 1986). There is little sense in capturing the solar energy if it cannot be effectively stored in the interior (Schittich, 2003). Insulation materials that do not match the desired modes of heat transfer (convective, conductive or radiant) are therefore not a good idea.

As mentioned before, most of the transparent parts of a building are located at the South wall (in colder climates). it is important to not have an oversized amount of windows, so that overheating is prevented. Double or triple glazing with low-e coating is advised to maximize incoming heat while minimizing heat losses (Manual, 2012). On the North wall, windows should be small to reduce heat losses (colder climates).

Another strategy to integrate in the building envelope is the use of transparent or translucent insulating materials (TIM). Glazing systems with translucent material embedded between the glass panes now function as both light-transmitting and insulating material. TIM can also perform as light-scattering glass. In this way, light is evenly transmitted into the interior and is often desired in rooms with great depth (Schittich, 2003). Switchable glazing is another technology that has been developed due to the rapid progress in glass technology. Switchable glass is charged with gases and transformed into different states.

This transformation can cause for example a change from transparent to translucent and might therefore also provide shading (Schittich, 2003).

2.3.6. THERMAL STORAGE

Materials within a building that are able to store heat are referred to as thermal mass. These materials soak up heat when solar energy is transmitted into the material and slowly radiate the heat back at night-time (Manual, 2012). Heat storage materials are present in every building, but in passive solar designs, more thermal mass is required. This thermal mass can be achieved by clever positioning of walls and clever material choices. For direct gain, the thermal mass must be within the rooms that receive sunlight. Common materials are concrete and brick, but also phase change materials can be used to store the energy from the sun (U.S. Department of Energy, 2000). These materials have a thermal storage capacity of around ten times of that of concrete. Another option to increase the thermal storage capacity of a building is to use liquid storage components (like water). However, this requires very large storage volumes and almost always require additional components like pumps (Schittich, 2003). Finally, suspended ceilings and hollow core floor slabs reduce the storage capacity of a building (Schittich, 2003).

2.3.7. GLAZED BUFFER ZONES

A passive solar building strategy which is based on isolated gain is designing glazed buffer zones. Glazed buffer zones like sunspaces are spaces that are not intended for everyday use and are thus, often unheated. A glazed buffer zone consists of large glazed surfaces with preferable single glazing, to collect as much solar heat as possible to distribute it throughout a building by means of gravitational ventilation. In addition to the most obvious choice for designing a glass volume, sliding balcony doors also contribute to the energy-related advantage effect of sunspaces (Schittich, 2003).

2.3.8. LIGHT-DIRECTING ELEMENTS

In addition of making optimal use of solar heat, the use of solar light should also not be forgotten. Light-directing elements can guide daylight into rooms that are positioned deeper in a building and result in a reduction in the need for artificial lighting. Light-directing elements come in the form of light shelves, light-scattering panes or prisms, reflecting louvres and holographic-optical elements. The elements should be designed in such a way that optimal use of the light is achieved, but not too much heat is gained from the incident solar rays (Schittich, 2003).

3. TROMBE WALLS

In this project, a novel type of Trombe wall has been investigated. Therefore, in the continuation of this literature review, the focus is shifted from all passive solar design strategies to the strategy based on indirect gain only: the Trombe wall. Before doing research, knowledge must be gained about the working principle of a Trombe wall and about (recent) developments in the field of Trombe wall technology. The working principle of a Trombe wall is explained in section 3.1 and a look at history is done in section 3.2. Different configurations of Trombe walls are shown in section 3.3. For some configurations, a recent development in the field of research is highlighted as well.

3.1. WORKING PRINCIPLE

A classical Trombe wall is a high thermal-mass wall situated behind an exterior glazing and separated by an air cavity (Figure 3.1). The wall surface, which is often dark-coloured, absorbs direct and diffused solar radiation when the sun shines. By absorbing the solar energy, the temperature of the wall increases and the air in the cavity is heated consequently (Kolaitis, Garay Martinez, & Founti, 2015). To maximise the incident solar radiation, the wall is most often oriented towards the South (Northern hemisphere). One part of the solar energy is released into the indoor room space through the wall by conduction (Chan, Riffat, & Zhu, 2010) and another part is transferred upwards through the cavity due to the buoyancy effect. The lower temperature air enters the cavity between the glazing and the wall via the lower vent and returns to the room through the upper vent of the wall. The idea behind using a Trombe wall is that heat, ventilation and comfort can be passively generated by using the 'free' energy of the sun. A Trombe wall is able to store energy during peak-use periods and can supply it again when building's occupants need it (Saadatian, Lim, Sopian, & Salleh, 2013).

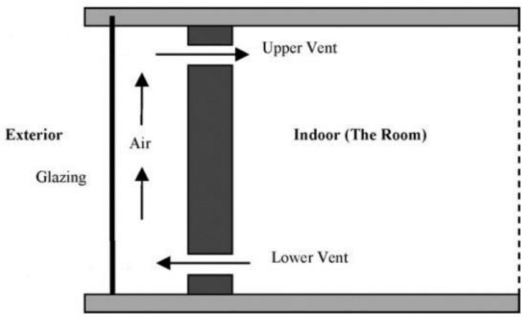


Figure 3.1: Configuration of a classical Trombe wall (Chan et al., 2010).

3.2. HISTORY

Throughout history, mankind has worked to harness energy from the sun in order to save energy and to create comfortable living spaces. Passive solar energy strategies have been used and studied for centuries and have developed over time. This also applies to the Trombe wall.

Since ancient times, massive walls of stone or adobe have been used by people to capture and store the energy of the sun. These walls were intended to store a high amount of thermal energy at daytime, which can be released at night (Torcellini & Pless, 2004). A more improved strategy of thermal energy storage in walls was invented and patented by the American E.L. Morse in 1881. Morse was the first to describe the Trombe wall concept, but it never really got off the ground. It was not until 1972 that the idea of Morse was popularized and re-patented by the French inventor Felix Trombe and the architect Jacques Michel (Ellis, 2003). As a result of their collaboration, the Trombe wall is now also known as the Trombe-Michel wall. The original configuration of a Trombe wall includes vents, but nowadays also unvented variants of Trombe walls are known.

3.3. CONFIGURATIONS

In this section, nine different Trombe walls are discussed: a traditional Trombe wall; a water Trombe wall; a zigzag Trombe wall; a solar trans-wall; a composite Trombe wall; a solar hybrid wall; a fluidised Trombe wall; a photovoltaic Trombe wall and finally a Trombe wall with phase-change material.

3.3.1. TRADITIONAL TROMBE WALL

The principle of a traditional Trombe wall is already explained in section 3.1. A traditional Trombe wall can be divided into three sub-configurations, which are shown in Figure 3.2. In configuration a, no vents are present. A part of the heat from the sunlight passing through the glazing is absorbed by the dark surface, stored as sensible heat in the wall, and conducted slowly inwards through the stone-like material. In the evening and at night this heat is radiated into the space from the back of the wall. In configuration b and c, the Trombe wall is equipped with vents. In this way, the lower temperature air from the room enters the cavity through the lower vent of the wall, heats up by the wall and flows upward due to buoyancy effect (Liu et al., 2017). The heated air then returns to the room space through the upper vent of the wall. This mode is preferred in the winter season. In configuration c, a summer mode of the Trombe wall is shown. By closing the upper vent, the warm air can't air the room and is discharged to the outside environment.

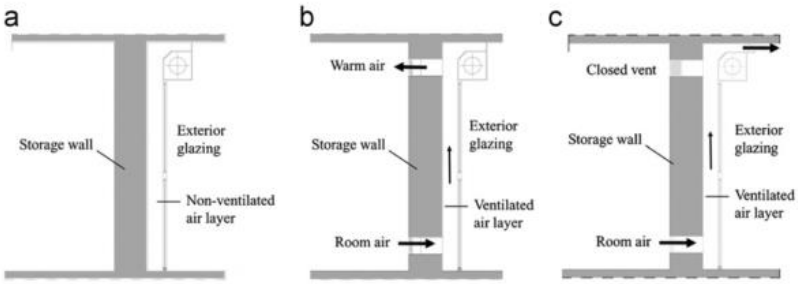


Figure 3.2: Three sub-configurations of a traditional Trombe wall: (a) without ventilation; (b) winter-mode with air circulation; (c) summer-mode with cross ventilation (Stazi, Mastrucci, & di Perna, 2011).

3.3.2. WATER TROMBE WALL

A water Trombe wall works on the same principle as a traditional Trombe wall. However, the difference between the two systems is that a water Trombe wall uses water instead of stone-like materials (Saadatian et al., 2013). In a water Trombe wall, water is stored in containers that are stacked on top of each other (Figure 3.3). Just like a traditional Trombe wall, the high thermal-mass materials are situated behind a glazing to enable the sun's rays to pass through. The water in the containers distribute the heat by convection and releases the heat to the room through radiation (Agrawal & Tiwari, 2011). By replacing masonry/stone with water, a number of advantages arise: one of them is that water performs better in controlling its surface temperature and as a result, less heat is reflected back through the window (Hordeski, 2011). In addition, the specific heat of water is higher than the specific heat of bricks, adobe, concrete and stone and is therefore able to store more heat. Despite these benefits, there are far fewer water walls in use than classical Trombe walls. This has to do with the fact that water containers are less easy to implement, too much space is needed and a high chance of leakages exist (Saadatian et al., 2013). Adams, Becker, Krauss, & Gilman (2010) investigated the effects of the thickness of a solar Trombe wall on its efficiency. The study, which was performed in a controlled environment in Oregon, tested a 3 inch, 6 inch and 9 inch water wall. It was found that a 6 and 9 inch wall were more efficient than a 3 inch wall and that a cooler interior temperature is provided during hot weather. Also, a warmer interior temperature is provided during cold weather.

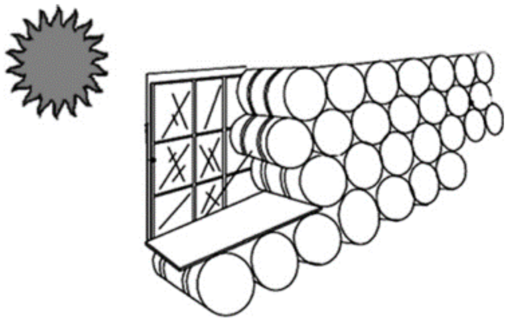


Figure 3.3: Sketch of a water Trombe wall (Saadatian et al., 2013).

3.3.3. ZIGZAG TROMBE WALL

A zigzag Trombe wall is designed to minimize the negative aspects of the sun. A zigzag Trombe wall consists of three sections: one section faces South, while the other two sections are angled inwards, forming a V-shaped wall (Hordeski, 2011). By having this particular shape (see Figure 3.4), a reduction in glare and excessive heat gain during sunny days is accomplished. The South-East facing section has a window that provides light and heat in the morning. The other sections have the same configuration as a traditional Trombe wall and are therefore able to store heat and block undesired incoming light. A zigzag Trombe wall is often incorporated with an exterior overhang to prevent from overheating during hot summer days (Saadatian et al., 2013). A recent prototype (2011) of a zigzag Trombe wall can be observed at the visitors centre of NREL and North Carolina (United States of America) (Sokol, 2008).

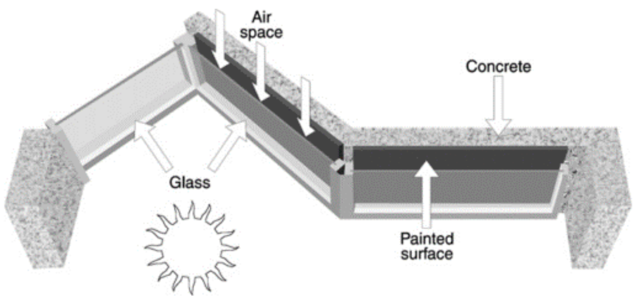


Figure 3.4: A zigzag Trombe wall (Saadatian et al., 2013).

3.3.4. SOLAR TRANS-WALL

A solar trans-wall is a transparent modular water wall that, in addition to providing thermal gain from solar radiation, is still able to provide visual access into a building (Prakash & Garg, 2000). The trans-wall is built on a metal frame that carries a container of water constructed from glass walls and a semi-transparent glass plate (see Figure 3.5). The semi-transparent glass plate absorbs a large part of the solar radiation and transmits the remaining part to the interior. Therefore, both direct and indirect gain systems are combined. Applying the wall in locations where daytime temperatures are relatively high is the most convenient (Saadatian et al., 2013). Due to the convective heat transfer in a trans-wall the efficiency is relatively low, but installing transparent baffles overcomes this. To improve the performance of a solar trans-wall, a high viscosity of water and prevention of microorganisms from growing into the water is desired (Saadatian et al., 2013).

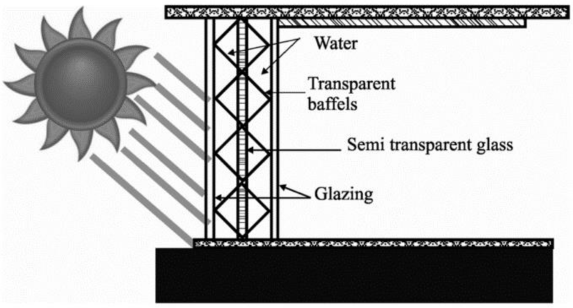


Figure 3.5: Details of a trans-wall (Saadatian et al., 2013)

3.3.5. COMPOSITE TROMBE WALL

A composite Trombe wall is another type of Trombe wall, which comprises several different layers. These layers include a mass heating wall, a transparent cover, a ventilated air cavity, a closed cavity and an insulating panel (see Figure 3.6). The advantage of a composite Trombe wall compared to a traditional Trombe wall is that a composite Trombe wall performs better in reducing the heat loss during cloudy winter days. In addition, it minimizes the undesired heat inputs during hot weather (Zhai, Song, & Wang, 2011). The composite Trombe wall operates as follows: the transparent cover (glazing) distributes the incoming solar beams through the non-ventilated air layer to the storage wall. This storage wall absorbs the solar energy and heats up. The stored heat is partly transmitted into the building’s interior by convection through the ventilated air layer. In addition, a small part of the stored energy is transmitted by conduction into the room (Saadatian et al., 2013).

The advantages of a composite Trombe wall are: (1) an extremely high thermal resistance because of an insulated wall and ventilated channel. (2) Users are able to control the rate of heating by regulating the airflow into the ventilated air layer. A disadvantage of a composite Trombe wall is that a mechanism is required to prevent reverse thermo-circulation, which happens when the temperature of the storage wall drops below the temperature of the ambient air in the room (Zalewski, Joulin, Lassue, Dutil, & Rousse, 2012). One of the many studies on the performance of a composite Trombe wall was carried out by a group of scholars in France. They compared the traditional Trombe wall with the composite wall using experimental testing and the software TRNSYS to analyse the efficiency of the wall. The results demonstrated that a composite Trombe wall performs better than a traditional Trombe wall in cold or cloudy climates (Saadatian et al., 2013).

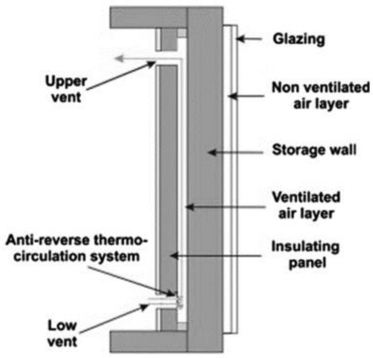


Figure 3.6: A composite Trombe wall (Saadatian et al., 2013)

3.3.6. SOLAR HYBRID WALL

The traditional Trombe wall is designed for cold climates and is known for its positive heating effects during winter. However, some types of Trombe walls are also suitable to serve as cooling device in the summer. One of them is the solar hybrid wall (Figure 3.7), which is presented by Spanish scholars. The solar hybrid wall is also known as a ceramic evaporative cooling wall and functions as a traditional Trombe wall during winter and provides cooling in the summer (Melero, Morgado, Neila, & Acha, 2011).

The solar hybrid wall performs in a similar way as the traditional Trombe wall, but employs an external thermal insulation blind to avoid undesired direct solar gain in the summer (Melero et al., 2011). Also, a high porous type of ceramic is used in the storage wall, which absorbs a large amount of water. In times of hot weather, the ceramic wall is wetted by a water sprinkler installed at the roof, between the glass and the wall. This causes the space to serve as a cooling cell due to the evaporative cooling phenomenon (Melero et al., 2011).

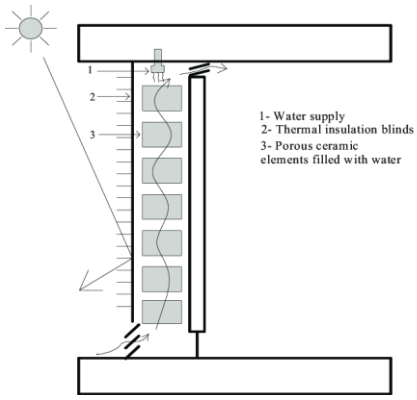


Figure 3.7: A solar hybrid wall (Melero et al., 2011).

3.3.7. FLUIDISED TROMBE WALL

In a fluidised Trombe wall, the gap between the storage wall and the glazing is fluidized by using a low-density, highly absorbent fluid (Tunç & Uysal, 1991). In a fluidization process, a bed of solid particles transforms into a fluid-like state by being brought into contact with air. The air flows slowly upwards by percolating through the voids of a bed of solid particles (see Figure 3.8). A fan at the bottom of the wall transfers the solar energy gained by the fluid into the room. The fluidised particles are prevented from moving into the room by two filters, which are located at the bottom and top of the air channel (Sadineni, Madala, & Boehm, 2011). A group of Turkish scholars, who carried out a study to compare a traditional Trombe wall with a fluidised Trombe wall, claim that a fluidised Trombe wall is far more efficient than a traditional Trombe wall, because the heat-transfer fluid is in direct contact with the solid particles (Tunç & Uysal, 1991).

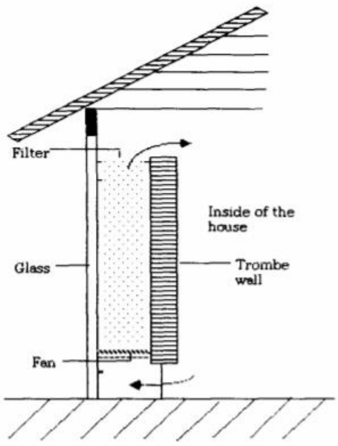


Figure 3.8: A fluidised Trombe wall (Tunç & Uysal, 1991).

3.3.8. PHOTOVOLTAIC TROMBE WALL

In a PV-Trombe wall, the front side of the glazing is composed of photovoltaic panels. The dark blue solar cells cover a large part of the glazed surface and contribute to an aesthetically pleasing design (Sun, Ji, Luo, & He, 2011). In a PV-Trombe wall, the lower temperature air from the room is drawn into the lower vent and absorbs the heat from the PV panels. The air becomes hot and travels to the room through the upper vent. Because the PV panels block the penetration of solar rays into the air gap between the glazing and the walls, the efficiency of the wall is lower than the efficiency of a traditional Trombe wall (in terms of heat gain) (Dehra, 2009). However, this type of Trombe wall is able to generate electricity. To find out how much the difference in efficiency between the two types of walls is, Sun et al. (2011) carried out both a computer simulation and experiment to measure the internal temperature of a building. The building was equipped with a PV panel installed on a Trombe wall and all of the building components where simulated in a dynamic numerical model. The study revealed that the thermal performance of the wall was reduced by 17% due to the obstructed penetration of the solar rays into the storage wall. Another study has been conducted by a group of scholars, who investigated the optimal wall width and area of winter air vents. Additionally, they also studied the influence of insulation and a shading curtain on summer cooling and winter heating. The study revealed that an increased indoor temperature of 2.36 °C in cold weather and decrease of 2.47 °C in hot weather is achieved by adding insulation, and that a decrease of 2.00 °C in hot weather is achieved by a adding a shading curtain (Ji, Yi, He, & Pei, 2007).

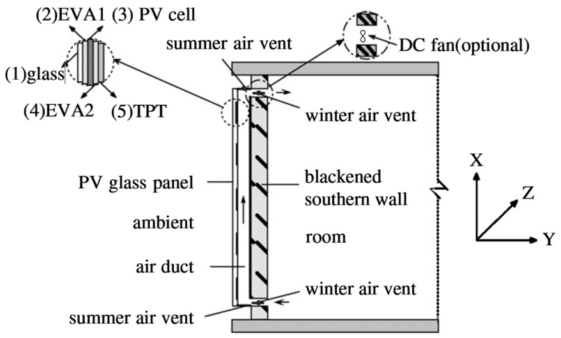


Figure 3.9: A PV Trombe wall with fan (Wei Sun, Ji, Luo, & He, 2011).

3.3.9. TROMBE WALL WITH PHASE CHANGE MATERIAL

One of the most recent configurations of a Trombe wall is the Trombe wall with phase-change material. This type of Trombe wall uses latent heat storage materials instead of sensible heat storage materials to enhance its efficiency. The thick, massive stone-like wall which is often considered a problem by structural engineers is replaced by lightweight storage materials like phase eutectic salts or salt hydrates (Tyagi & Buddhi, 2007). Moreover, The phase-change materials are able to store more energy in a much smaller volume. A more detailed explanation of the functioning of a Trombe wall with phase change material, examples of existing variants and a research review is described in chapter 5.

4. PHASE CHANGE MATERIALS

Before further discussing Trombe walls with phase change material, this chapter discusses one of the most important components of it: the phase change material (PCM). A literature study was carried out to find out how phase change materials work, what the advantages and disadvantages of different types of PCM are and how, when and where they are applied. In section 4.1 an introduction to phase materials and an explanation of two different storage principles is given. In section 4.2 the general working principle of phase change material is explained and a classification based on physical properties, advantages and disadvantages is shown in section 4.3. A literature study into the optimal PCM melting temperature in buildings has been reported in section 4.4 and the chapter ends with a review of a large number of examples of current building applications that incorporate phase change materials.

4.1. INTRODUCTION

An important group of materials known for their large heat capacity are phase change materials (PCM's). Phase change materials are increasingly integrated in buildings and have the ability to stabilize the indoor temperature and shift peak-hour cooling and heating loads. In contrast to usual building storage materials like concrete or brick, PCM's are much lighter and use a lot less space. Phase change materials have the ability to change their phase (most often from solid to liquid and vice versa) at room temperature, whereby chemical bonds are fixed or broken and heat can be absorbed or released, when the material is heated or cooled (Fokaides, Kylili, & Kalogirou, 2015). PCM's that are recommended for thermal storage in buildings have melting temperatures between 20 and 32 degrees Celsius and are typically used for both passive storage and active solar storage for heating and cooling purposes (Tyagi & Buddhi, 2007). The phase change of a phase change material is an endothermic process, which means that heat is absorbed when the ambient temperature is higher than the temperature of the material. As a result, it melts. When the ambient temperature drops again, the PCM returns to a solid state and gives off the absorbed (latent) heat to the environment (Baetens, Jelle, & Gustavsen, 2010).

Phase change materials are not sensible heat storage materials (like conventional building materials) but latent heat storage materials. The difference between both storage principles is explained in sections 4.1.1 and 4.1.2.

4.1.1. SENSIBLE HEAT STORAGE

Sensible energy storage takes place in materials that experience no phase change in the temperature range of the storage process (Fernandez, Martnez, Segarra, Martorell, & Cabeza, 2010). The quantity of energy stored is proportional to the specific heat capacity of the material, the temperature rise and the mass of the material (Ataer, 2006) (Figure 4.1). Sensible storage is the most common method of thermal energy storage and occurs in buildings especially in the form of heavy construction materials such as stone, concrete and bricks. The main advantages of sensible heat storage materials are long working stability and low costs. Indoor temperature swings are suppressed by the heat storage effect of building components as they contribute to the thermal stability of the indoor environment during hot days. However, sensible heat storage is the least effective mode of heat storage, since less energy is involved in increasing the temperature of a substance than in breaking chemical bonds or melting a crystalline composition (Ostry & Charvat, 2013). When a material changes in temperature, the amount of absorbed or released sensible heat is given by equation 4.1.

$$E_s = m\ C_p\ \Delta T \tag{4.1}$$

In which E_s is the quantity of sensible heat (J), m the mass of the substance (kg), C_p the sensible specific heat capacity of the substance (J/kgK) and ΔT the temperature change (K).

4.1.2. LATENT HEAT STORAGE

In latent heat storage, the energy is stored through a reversible change of state (phase change) of a storage medium (Ostry & Charvat, 2013). The advantage of latent heat storage systems is that it uses the sensible heat capacity of a material during the increase of temperature. During the transition of one phase to another, a latent heat storage material absorbs all the energy needed for this purpose, while no increase in temperature or sensible heat occurs (Kienzl, 1999) (Figure 4.1). The energy required or released during the phase change is referred to as latent heat. The latent heat storage capacity of a material is described as enthalpy of vaporization or enthalpy of fusion [kJ/kg] and is unique because of the high amount of energy that can be absorbed (Kienzl, 1999). Because of negligible volume changes of the material, the stored amount of heat during the phase transition from solid to liquid (and vice versa) is equal to the change in enthalpy (equation 4.2).

$$E_l = m\ h_{sf} \tag{4.2}$$

In which E_l is the quantity of stored heat (J), m the mass of the substance (kg) and h_{sf} is the specific enthalpy or latent heat of fusion (J/kg).

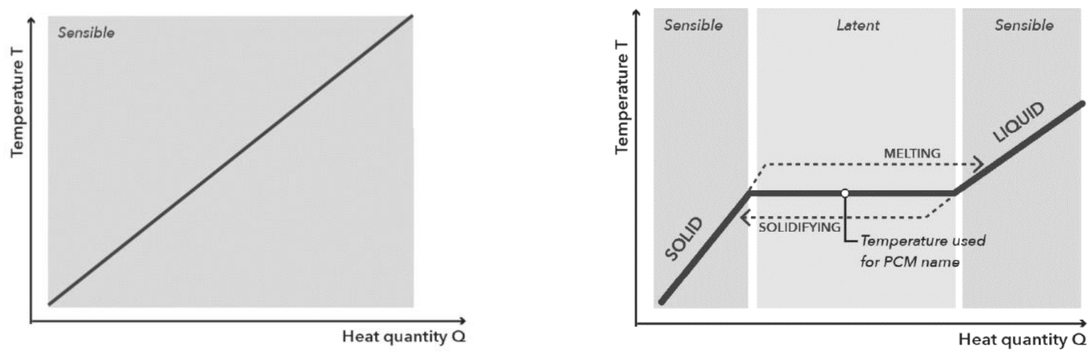


Figure 4.1: Sensible heat storage (left) and latent heat storage (right) (Alexiou, 2017).

4.2. WORKING PRINCIPLE

When a solid piece of PCM is heated, its temperature rises until it starts to melt. During this process, the PCM stores heat in a sensible way. When the melting temperature has been reached, the addition of heat does not longer lead to an increase in temperature (see right graph in Figure 4.1) and the added heat is responsible for the phase change to happen. The added, stored heat is referred to as latent heat. After the whole substance has molten, adding heat leads to a rise in temperature again, at which point the substance again stores heat in a sensible way (Alexiou, 2017). When the PCM solidifies at its freezing temperature again, the absorbed latent heat (energy) is released. This is explained by the fact that the liquid state of a PCM has a higher state of energy than the solid state of a PCM. Therefore, more energy is stored in the liquid that is fully dissipated during the solidification (Alexiou, 2017). When a PCM is integrated in a façade system, the incoming solar radiation is absorbed by the PCM and its temperature starts to rise, until it melts. This melting process lasts a few hours, during which the phase change material remains at melting temperature. When the PCM is in full liquid state, it behaves like a sensible heat storage material and when the temperature decreases up to the freezing temperature in the evening, the PCM begins to crystallise. The energy set free by the freezing process increases the PCM temperature again to melting temperature, after which it takes several hours for the PCM to discharge. During this process, the system not only compensates heat losses, but also helps to reduce the heating demand. Thermal comfort is also improved because of the high surface temperatures of the system (Weinläder, Beck, & Fricke, 2005).

In Figure 4.1 it can be seen that the melting trajectory of a PCM is slightly different from the solidification trajectory of a PCM. This has to do with the hysteresis phenomenon, which means that the melting temperature of a PCM is different from the solidification temperature (Frei, 2016). When a PCM is in solid state and is being heated, the upper trajectory of Figure 4.1 is followed. As the material passes the liquifying temperature, it becomes fully liquid. When the PCM is subsequently cooled in the liquid state, the lower trajectory is followed and the material remains liquid at temperatures below melting temperature. Once the solidification temperature is reached, the PCM becomes completely solid. If the PCM is then heated again, it will follow the upper trajectory, and so on. In the fully molten or fully solid state, the two curves overlap. The latent heat (energy) of phase change is equal to the jump in these curves (Frei, 2016).

One of the phenomena that is experienced as a disadvantage of phase change materials is the effect of supercooling. Supercooling (or subcooling) is the effect that a significant lower temperature than the melting temperature has to be reached, before a PCM solidifies and starts to release heat (Figure 4.2). If this temperature is not reached, the phase change material will not harden at all and will therefore only store sensible heat (Günther, Hiebler, & Mehling, 2015). A common approach to overcome the effect of supercooling is to add special additives (nucleators) to the material to cause heterogeneous nucleation. The additives have been developed for most of the PCM types and are able to reduce supercooling typically to a few kelvin. Most of the nucleators are similar crystal compounds as solid phase change materials to allow the solid state of PCM to grow on the surface of the additives (Alexiou, 2017).

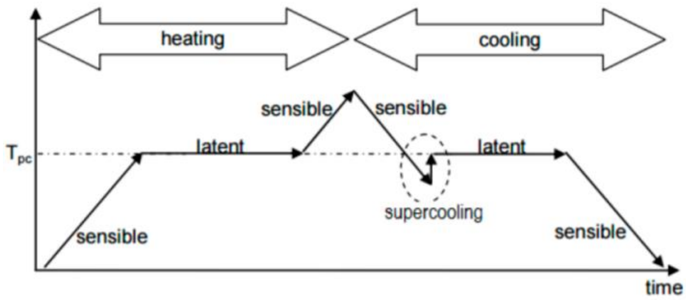


Figure 4.2: Temperature change during heating and cooling of a PCM with supercooling effect (Kolacek, Charvatova, & Sehnalek, 2017).

4.3. CLASSIFICATION

Phase change materials used in thermal energy storage (TES) systems should have a melting and freezing temperature in the range of application and must contain a high thermal conductivity and high latent heat of fusion. Moreover, suitable PCM's should have desirable chemical, thermophysical, economic, kinetic and environmental properties (Soares, Costa, Gaspar, & Santos, 2013). The main criteria for PCM selection are summarized by Soares et al. (2013) in Table 4.1.

Table 4.1: Main selection criteria of PCM's (Soares et al., 2013, p. 86).

Chemical properties	- Completely reversible melting/solidification cycles - Long term chemical stability and no degradation after a large number of melting/solidification cycles - No corrosiveness and capability with construction materials - Non-toxic, non-flammable and non-explosive
Thermal and physical properties	- Suitable phase-change temperature in desired operating temperature range - High thermal conductivity, high specific heat and high density - High latent heat of phase transition per unit mass - Congruent melting and long term thermal stability - Favourable phase change equilibrium and no segregation - Small volume variation of phase-change - Small vapour pressure at operating temperature
Economic properties	- Abundant and available - Cost-effective
Kinetic properties	- High nucleation rate and little or no supercooling of the liquid phase - High rate of crystallization
Environmental properties	- Low embodied energy - Separation facility from the other materials and recycling potential - Low environmental impact and non-polluting

Based on phase-change state, PCM's can be divided into three groups: solid-solid PCM's, liquid-gas PCM's and solid-liquid PCM's. Among these, the solid-liquid PCM's are the most useful ones for thermal energy storage (Zhou, Zhao, & Tian, 2012). The solid-liquid PCM's can again be divided into three other groups: organic compounds, inorganic compounds and eutectics (Figure 4.3).

Organic compounds are non-toxic, non-corrosive, do not suffer from supercooling, have a high latent heat of fusion and are chemically stable in general. Organic compounds are subdivided into two groups: paraffins and non-paraffins (fatty acids). Paraffins, which are simple hydrocarbons, are the most applied PCM's in the building industry, because of their high latent heat of fusion (120-266 kJ/kg), their cost effectiveness and melting temperatures between 20 and 112 °C. Disadvantages however are their low thermal conductivity and their susceptibility to leaking (Baetens et al., 2010). Leaking can occur when significant volume changes happen during the melting and solidification process and when the paraffins are combined with other building materials such as plasterboard. To overcome this problem, paraffins are often encapsulated in small modules with a small buffer space inside. Organic PCM's are often flammable but can be made more fire-save by using fire retardant treatments (Cabeza, Castell, Barreneche, De Gracia, & Fernández, 2011).

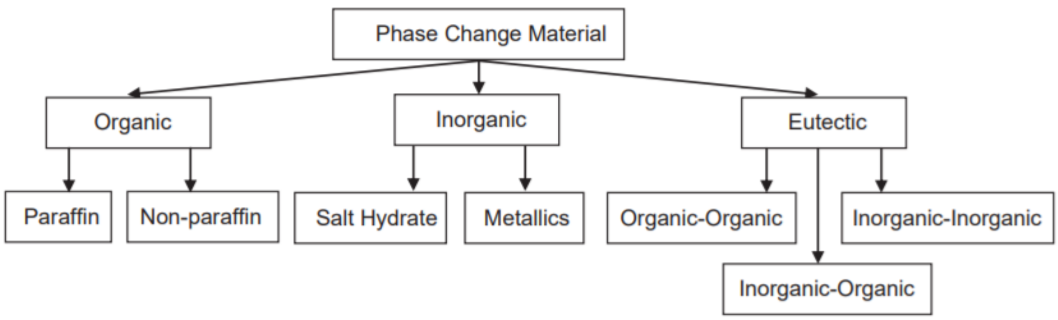


Figure 4.3: Classification of PCM's (Memon, 2014)

Non-paraffins are composed by various organic materials like alcohols, glycols, esters and fatty acids and generally have excellent freezing and melting properties. They are, however, three times more expensive compared to paraffins. The most applied materials in non-paraffins are fatty acids, as they have a high latent heat of fusion, have low-range melting points, undergo small changes in volume during phase change and do not experience the effect of supercooling. Fatty acids have a melting point range between 19 °C and 26 °C and are less prone to leakage (Hasnain, 1998).

Inorganic phase change materials can be subdivided into salt hydrates and metallics. From this subdivision, salt hydrates are the most widely studied. The studies show that salt hydrates lack good thermal stability due to supercooling and phase separation that they undergo after each of the many cycles of heating and cooling. The thermal stability can however be improved by adding thickened or gelled mixtures and suitable nucleating substances. Inorganic compounds are usually more dense than organic compounds and are also more conductive. Their phase change thermal capacity varies between 200 and 400 kJ/kg and the specific heat capacity is in similar range as organic compounds (Alexiou, 2017).

Eutectics are melting compositions of two or more components, each of which freezes and melts congruently, resulting in a mixture of component crystals during crystallization. As a result, none of the phases can sink down due to the difference in densities. Eutectics almost always freeze and melt without segregation because an intimate mixture of crystals is created. This leaves the opportunity for the components to separate. Eutectics have a good storage density and show good melting temperature ranges. Eutectic salt-water solutions have melting temperatures below 0 °C, as the addition of salt reduces the melting temperature. The thermal conductivity of salt-water eutectics is similar to that of water (Alexiou, 2017). An overview of all advantages and disadvantages per type of PCM is shown in Table 4.2.

The phase change enthalpy and melting temperature of existing PCM's are shown in Figure 4.4. As melting temperature is one of the most governing criteria in building applications, it can be seen that for latent heat storage, the potential PCM's are paraffins, fatty acids (non-paraffins), salt hydrates and eutectic mixtures.

In order to investigate the thermal properties of PCM's, a proper measuring method is important. The most commonly used measurement techniques are differential scanning calorimetry (DSC), differential thermal analysis (DTA) and the T-history method (Zhou et al., 2012). In a DSC test, a sample and a reference sample (with known thermal properties) are held at almost the same temperature throughout a measurement process. By measuring the difference between added heat between both samples, many thermal properties can be obtained, such as heat capacity, heat of fusion and solidification/melting temperature. In a differential thermal analysis (DTA), also two samples (with one reference sample) are used. The heat applied to both samples is same and by measuring the temperature difference between both samples the thermal properties can be obtained. The newest method is the method put forward by Yinping, Yi, & Yi (1999), who analysed the limitations of the two previous mentioned methods. They conducted measurements of some PCM's through the T0history method and found a good agreement between experimental data from literature and their test results.

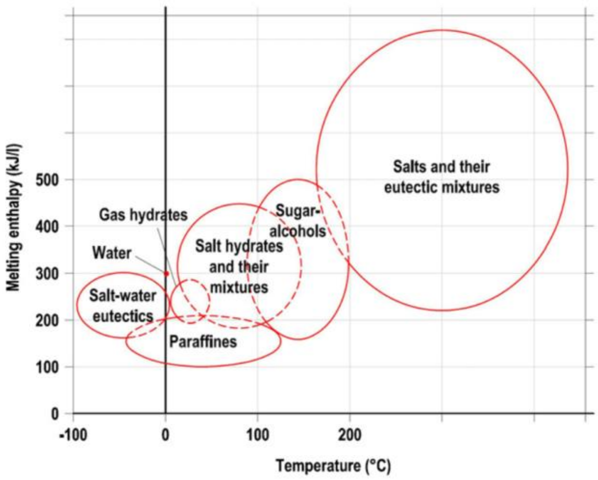


Figure 4.4: Melting temperature and melting enthalpy for different groups of PCM's (Baetens et al., 2010)

Table 4.2: Advantages and disadvantages of different types of PCM (Soares et al., 2013, p. 87).

Classification	Advantages	Disadvantages
Organic compounds	- Availability in a large temperature range - High latent heat of fusion (fatty acids have high heat of fusion values comparable to that of paraffins) - Solidification with little or no subcooling - Congruent phase-change - Self-nucleation properties - No segregation and good nucleation rate - Predictable and thermally and chemically stable, i.e. good stability of material properties during repeated thermal cycles - Low vapour pressure in the melted form - Not dangerous, non-reactive and non-corrosive (fatty acids could be mildly corrosive) - Compatibility with conventional construction materials - Recyclable	- Low thermal conductivity - Lower volumetric latent heat storage capacity, i.e. lower phase-change enthalpy - Lower density - Flammable (possible to use fire-retardant additives) - Non-compatibility with plastic containers - More expensive (commercial paraffins are cheaper and more available than pure paraffins and fatty acids are 2-2.5 times more expensive than technical grade paraffins) - Relatively large volume change (however some fatty acids could undergo small volume changes)
Inorganic compounds	- Higher volumetric latent heat storage capacity, i.e. higher melting enthalpy - Higher latent heat of fusion - Low cost and readily available - Sharper phase-change - Higher thermal conductivity - Non-flammable - Lower volume changes - Compatible with plastics - It is better to use salt-hydrates than paraffins to reduce the manufacturing/disposal environmental impact	- Poor nucleating properties and subcooling problems - Incongruent melting and dehydration in the process of thermal cycling - Phase segregation during transition and thermal stability problems - Their application could require the use of some nucleating and thickening agents - Decomposition and phase separation - Non-compatible with some construction materials - Corrosive to most metals and slightly toxic
Eutectics	- Sharp melting temperature (could be used to deliver the desired melting temperature required) - Volumetric thermal storage density slightly above organic compounds - no segregation and congruent phase-change	- Limited data are available on their thermophysical properties - Some fatty eutectics have quite strong odour and therefore they are not recommended for use in PCM-wallboards

4.4. OPTIMAL PHASE CHANGE TEMPERATURE IN BUILDINGS

For passive application in buildings, phase change materials with a solid-liquid phase-change temperature range between 18 °C and 30 °C are most commonly applied (van der Spoel & Cauberg, 2006). As this temperature range is still quite broad, studies have been carried out into the optimal melting and solidification temperature of phase change materials in different types of buildings. Picking a PCM with a phase change temperature outside the practical and operational storage temperature range may make a PCM integrated building component completely ineffective, as the temperature may never reach the point of melting.

One of the studies was conducted by Drake & Ridge (1987) and Peippo, Kauranen & Lund (1991), who investigated the optimal phase-change temperature of PCM's in wallboards. They developed a formula, based on standard stud walls, with all regular conditions imposed on it. The optimal phase-change temperature $T_{PCM,opt}$ is approximated based on the quantity of flux during the day and the quantity of flux during the night (equation 4.3). A different behaviour can however be expected for different weather conditions, different thermal resistance of the wall and the distinction between internal and external walls (Baetens et al., 2010).

$$T_{PCM,opt} = T_r + \frac{P_{abs,tot}}{ht_{stor}} \qquad \text{where} \qquad T_r = \frac{t_d T_d + t_n T_n}{t_d + t_n} \tag{4.3}$$

In which $T_{PCM,opt}$ is the optimal phase change temperature (°C), $P_{abs,tot}$ is the absorbed (solar) heat (W) by unit area of the room surface, h the average heat transmission coefficient between the room and the wall (W/m^{2}K), T_r the average room temperature (°C), T the temperature (°C) and t the time (s). The subscripts d and n represent day and night-time respectively. The equation shows a strong dependency of $T_{PCM,opt}$ on the quantity of direct solar energy absorbed by the wallboard in case of an exterior wall (Baetens et al., 2010). With equation 4.3, Peippo et al. (1991) calculated the optimal transition temperature for utilization of solar heat for a large space with south-oriented window for the Madison, Wisconsin, USA and Helsinki, Finland weather. They found an optimal transition temperature at 1 °C – 3 °C above the average room temperature (van der Spoel & Cauberg, 2006).

Xu, Zhang, Lin, Di, & Yang (2005) studied the thermal performance of a SSPCM floor and found that the optimal transition temperature was more or less equal to the average room temperature of sunny winter days. Neeper (2000) also found that with an optimal transition temperature equal to the mean room temperature, a maximum diurnal energy storage can be achieved. Van der Spoel & Cauberg (2006) conducted a parametric study that provided insight into the effect of the PCM transition temperature on the seasonal heating and cooling demand. They simulated a room with PCM layer containing walls in a Dutch climate and found that a minimal heating energy demand is achieved when the phase transition temperature is just above thermostat set-point temperature: $T_{PCM,opt} = T_{set,h} + 1.5$ °C. This satisfies the expectations, as in that case, excess heat is most optimally stored in the construction. As the potential energy savings mainly depend on the difference between set-point temperature and PCM transition temperature, it is not desirable that users change the set-point, because the efficiency of the PCM will be sub-optimal in many cases. In case of cooling, a minimum energy demand is achieved when the phase transition temperature is just below the cooling thermostat set-point: $T_{PCM,opt} = T_{set,c} - 1.5$ °C. With this transition temperature, excess coolth is optimally stored in the construction.

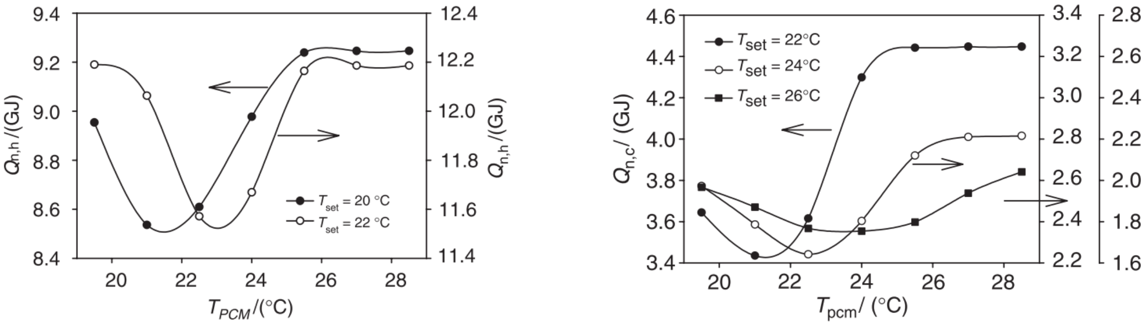


Figure 4.5: Energy demand for heating (left) and cooling (right) as a function of average PCM transition temperature for different thermostat set-points (van der Spoel & Cauberg, 2006).

Just as Peippo et al. (1991), Xiao, Wang, & Zhang (2018) concluded that the optimal transition temperature not only depends on the room temperature, but also on the solar radiation absorbed by the PCM component. The formula they derived slightly differs from equation 4.1 and is shown as equation 4.4.

$$T_{PCM,opt} = T_r + \frac{\int (P_r + P_{r,in})d\tau}{h\ P\ A_{PCM}} \tag{4.4}$$

Where $T_{PCM,opt}$ is the optimal phase change temperature (°C), T_r the average indoor temperature (°C) based on a periodic function, P_r the transmitted solar radiation on the surface (W), $P_{r,in}$ the radiation heat transfer rate from indoor heat sources (W), τ the time (s), h the heat transfer of the interior surface (W/m^{2}K), P the period (s) and A the area of the PCM panel (m^2). Equation 4.2 indicates that when the absorbed solar radiation is zero, the optimal transition temperature equals the average room temperature. This is again consistent with Neeper's (2000) conclusion.

4.5. BUILDING APPLICATIONS AND RESEARCH

Since the introduction of PCM's in the building sector, they have been considered as a promising solution to obtain light weight construction elements with both low mass and high heat capacity. There are many new building installations and building technologies that make use of PCM's and there are also many investigations in possible new PCM building technologies. An overview of the existing applications of PCM's in buildings and some recent investigations that prove the advantage of using PCM in buildings is given below.

PCM WALLBOARDS

Wallboards are often used in buildings and are known for their low costs and variety in use (Tyagi & Buddhi, 2007). Furthermore, wallboards are able to store PCM encapsulations. Shapiro (1989) showed that several PCM's are suitable for introduction into gypsum wallboards (in a Florida climate). Feldman, Banu, Hawes, & Ghanbari (1991) carried out research on the use of PCM's for latent heat storage in wallboards. They found that this application results in a comfortable indoor temperature range in buildings and an increase in thermal storage capacity in the range of 10-130%. Neeper (1986) concluded in his study that PCM wallboards are a good alternative to traditional wallboards. He found that the thermal storage provided by the system would be sufficient to enable a large solar heating portion with direct gain.

PCM WALLS

Evers, Medina, & Fang (2010) investigated the performance of PCM's in frame walls. The frame walls were simulated with a dynamic wall simulator on a typical summer day. The results demonstrated that the PCM enhanced frame walls reduced the average peak heat flux up to 9,2% and reduced the average total daily heat flow up to 1,2%. Medina, King, & Zhang (2008) investigated a new structural insulated panel with PCM's and concluded that the system leads to a significant reduction in wall heat fluxes during peak times. It is also able to produce a rather constant indoor air temperature and wall surface temperature.

PCM SHUTTERS

PCM shutters are movable exterior elements attached to windows in façades. Soares, Samagaio, Vicente, & Costa (2011) investigated a southward PCM shutters system that takes advantage of solar thermal energy for winter night time indoor heating in Coimbra. Weinlaeder, Koerner, & Heidenfelder (2011) investigated an interior sun protection system consisting of vertical slats filled with PCM. The system was monitored from winter 2008 until summer 2010 and showed a significant potential for cooling in summer and some advantages in winter, compared to a traditional shading system.

PCM BUILDING BLOCKS

Various building materials can be impregnated with PCM's. Collier & Grimmer (1979) showed that bricks impregnated with PCM contribute to a significant increase in the energy performance of a room/building. Hadjieva, Stoykov, & Filipova (2000) investigated the structural stability and heat storage capacity of concrete blocks containing PCM. They concluded that certain PCM's improve the its structure stability during thermal cycling and that the heat capacity increases.

AIR-BASED HEATING SYSTEMS WITH PCM

Morrison & Khalik (1978) investigated the performance of an air-based solar heating system. The system uses PCM in a storage unit. Two of their conclusions was that the heating system with PCM requires roughly one-half the storage volume of a water tank and one-fourth the storage volume of a rock bed. Ghonein & Klein (1989) investigated the heat storage system of an air- and water-based solar heating system and found almost the same results as Morrision & Khalik.

PCM FLOORS AND CEILINGS

PCM's can be integrated in floors and ceilings. Athienitis & Chen (2000) investigated the heat transfer in floor heating systems. They concluded that the solar radiation stored in the floor was found to reduce heating energy consumption considerably (30% or more). Bruno & Saman (2002) developed a roof system that stored coolness in PCM and releases it when occupants need it. Kondo & Ibamoto (2003) also proposed a PCM roof system that reduces the peak load of an air conditioning system.

PCM MORTARS

Cabeza et al. (2011) investigated a novel type of concrete with PCM. The goal was to introduce PCM in concrete, but to avoid affecting the mechanical strength of it. They found that the thermal capacity of the concrete was improved and that an adequate strength could be reached.

PCM GLAZING

One of the most recent investigations of PCM in building materials is the investigation of PCM's in transparent envelope components. Grynning, Goia, Rognvik & Time (2013) performed measurements on commercially available windows that integrate PCM by using a large scale climate simulator. The glazing consist of a four-pane glazing with the innermost cavity filled with PCM. It was found that for almost all climates the potential latent heat storage capacity of the PCM was fully activated. Liu et al. (2017) investigated the performance of a PCM-filled double glazing unit. Their results show that the interior surface temperature of the glazing increases by 158.7% and the transmitted solar energy has decreased by 86.1%.

PCM CURTAINS

In some studies, PCM curtains are investigated. The curtain is situated inside a window system. Wang & Zhao (2015) proposed a promising technique which showed that the average heat transfer rate into the room during working hours can be reduced by 30,9% on the hottest summer days in Shanghai. Ismail & Henriquez (2001) also investigated composite glass samples filled with air or PCM. The result of their study was that heat gain and losses are reduced and most of the energy transferred is absorbed during phase change of the PCM.

PCM FACADES

PCM's can also be integrated into a façade. Diarce et al. (2013) investigated and evaluated the thermal performance of a novel type of ventilated active façade that includes PCM in the outer layer. The research, which was carried out in Spain showed that overheating of the façade was better prevented. The simulation showed that the thermal inertia of the façade was improved. Elarga, Goia, Zarrella, Dal, & Benini (2016) investigated the performance of a system that integrated a PV layer and a PCM layer in a double skin façade. The PCM layer in combination with the PV layer leads to a reduction in the monthly cooling energy demand by 20-30% (hot climates).

PCM TROMBE WALLS

The final example of a building application with phase change materials are PCM Trombe walls. As a follow-up to chapter 3 (Trombe walls) and chapter 4 (phase change materials), the following chapter discusses the combination between the two: Trombe walls with phase change material. Examples of different configurations of this type of Trombe wall and associated studies are therefore also described in chapter 5.

5. TROMBE WALLS WITH PHASE CHANGE MATERIAL

This chapter focuses on the combination of the technologies discussed in the two previous chapters: Trombe walls and phase change materials. The final part of the previous chapter already revealed that one of the newest developments in the area of PCM's in buildings is the Trombe wall with phase change material. In order to understand the working principle of a Trombe wall with phase change material, an explanation is given in section 5.1. A literature review of leading researches and their results is described in section 5.2. With the knowledge gained from this chapter, a final step can be made towards the main topic of this thesis: the lightweight, translucent and adaptable Trombe wall.

5.1. WORKING PRINCIPLE

When a traditional Trombe wall is enhanced with phase change material, the thermal mass of the system is increased. Furthermore, by replacing the heavy stony materials with the lower-weight phase change material, the overall volume of the wall can be reduced, resulting in significant advantages in terms of lower dead load (Kolaitis et al., 2015). There are two main configurations of PCM-enhanced Trombe walls: a wall which is partly replaced by PCM, and a wall where all stony materials have been replaced by PCM. In the first case, the two above mentioned benefits (higher thermal mass and lower dead load) are experienced. In the second case, an extra advantage shows up: due to the translucent property of PCM, the wall is no longer a complete obstruction for incoming sunlight and view to the outside environment. In both cases, the system is based on the same working principle as a conventional Trombe wall. When the sun shines, the wall absorbs direct and diffused solar radiation and releases it into the room at evening and at night. Also in this type of Trombe wall, a cavity often exists through which a part of the heat is transferred upwards due to the buoyancy effect.

5.2. RESEARCH REVIEW

One of the first investigations into the effectiveness of a Trombe wall with phase change material was done by Bourdeau (1980). He found that a 15 cm concrete wall can be replaced by a 3.5 cm wall of PCM and perform similarly. Stritih & Novak (1996) presented a solar wall with paraffin wax, that was intended for building ventilation. The solar energy absorbed by the PCM (efficiency of 79%) was used for heating the ventilation air of the house. A simulation showed that a thickness of 50 mm and a melting point a few degrees above room temperature is optimal. Buddhi & Sharma (1999) measured the transmittance of solar radiation through a wall with stearic acid (phase change material) at different thickness and temperatures. Their findings were that the transmittance of the PCM was more than the glass for the same thickness. They suggested phase change materials as a new application in walls/windows as a transparent insulating material.

Another study of Onishi, Soeda, & Mizuno (2001) concluded that the use of phase-change materials in Trombe walls is beneficial for reducing energy consumption in buildings. They undertook many simulations of the thermal performance of a room with PCM Trombe walls. Khalifa & Abbas (2009) found that an 8 cm thick hydrated salt storage wall is more efficient than a thick concrete wall of 20 cm. They carried out a numerical study in Baghdad, Iraq, for a south-facing Trombe wall including different storage materials. They examined concrete, paraffin waxes and encapsulated hydrated salts in copper capsules and found that an 8 cm thick hydrated salt storage wall performs better at maintaining a certain temperature than a 5 cm thick paraffin wax wall.

Zalewski et al. (2012) conducted an experiment with a small-scale Trombe wall in France. A concrete wall was replaced by a wall with both concrete and PCM (hydrated salt) in order to measure the efficiency of the novel system. The results demonstrated that heat can be released with a time lag of two hours and 40 minutes. Fiorito (2012) carried out a research for assessing the thermal performance of Trombe walls with phase change materials in light-weight buildings. He found that the integration of PCM in lightweight buildings is highly beneficial and able to minimize temperature fluctuations. A parametrical assessment was done for five different Australian cities, representative of five different climatic areas. In all climatic areas, the use of PCM's in Trombe walls contributes to restoring the thermal inertia of light-weight constructions.

A simulation study performed by Rabani, Kalantar, Faghih, Rabani & Rabani (2013) showed that a Trombe wall made of paraffin wax could provide more thermal comfort in comparison with other materials. Li & Liu (2014) investigated the solar chimney feature of a PCM Trombe wall. They found that the application of PCM extends the utilization duration of the solar chimney (particularly at night-time). Kolaitis et al. (2015) investigated the thermal behaviour of a solar wall enhanced with PCM by using numerical and experimental simulation techniques. The results of both techniques showed good levels of agreement and indicated that the potential monthly net output of thermal energy of the system may be as high as 4 kWh/m^2. Berthou et al. (2015) investigated a translucent passive solar wall with silica aerogel and glass bricks filled with a eutectic phase change material. Results show that the heat loss through the system is low, while the heat and light gains are high. Guarino, Athienitis, Cellura & Bastien (2017) investigated the use of a thermal storage wall with phase change materials opposing a highly glazed, south oriented, façade. Both experimental an numerical studies show that the storage system is effective in a cold climate during the whole year. The storage system is able to release the absorbed solar radiation after 6-8 hours and therefore has a positive effect on the heating demand and the reduction of daily temperature swings.

Leang, Tittelein, Zalewski, & Lassue (2017) investigated a composite Trombe wall with integrated PCM. They compared a classic Trombe wall (with only concrete) with a Trombe wall incorporating PCM in the mortar. Their results showed that a large capacity of heat is recovered by the Trombe wall with PCM. Furthermore, results show that a 4 cm PCM Trombe wall shows a time delay which is 4 times greater than with a 15 cm storage wall.

During the project 'Double Face', an adjustable and translucent Trombe wall has been developed. The new type of Trombe wall consists of a combination of PCM and insulating aerogel and first simulations of the system showed that the prototype reduces the heating energy demand of a Dutch household by 25-30% (Wattez, Cosmatu, Tenpierik, & Turrin, 2017). Much more information about this 'research through design' project is given in chapter 6.

6. LIGHTWEIGHT TRANSLUCENT ADAPTABLE TROMBE WALL

This chapter continues where the previous chapter ended and describes the lightweight, translucent and adaptable Trombe wall, which is the system that is being studied in this Master's thesis. The LTATW is a technology developed by the 'Double Face' project and has been put into operation by the 4TU Federation (a federation of the four technical universities in the Netherlands) in 2014. The project, which is still in progress, consists of multiple stages, each with their own important findings. In order to understand the working principle of a LTATW, an explanation is given in section 6.1. A literature review of the studies conducted in this project and their results are described in section 6.2. With the knowledge gained from this chapter, the concept is made clear and the findings can be used as input for the research in this Master's thesis project.

6.1. WORKING PRINCIPLE

A lightweight translucent adaptable Trombe wall (Figure 6.1) is based on an innovative approach to the thermal principles of a traditional Trombe wall, but does not entail the three main disadvantages of it. Strictly speaking, the system is not as heavy as a traditional Trombe wall, does not block daylight and can be adapted to the changing environmental conditions and seasonal differences. The lower weight and translucent character are achieved by applying containers made of a layer of phase change material and a layer of aerogel (Figure 6.3), instead of opaque and heavy materials like concrete or brick. The containers are placed on top and next to each other so that a complete wall of PCM and aerogel is created, which is in total five times lighter than a traditional Trombe wall (4TU.Bouw, 2014).

Figure 6.1: Architectural rendering of lightweight translucent adaptable Trombe wall (Turrin et al., 2014)

The LTATW combines the translucent character of PCM and its technical properties to create an aesthetically pleasing interior design, which also improves indoor comfort and reduces the energy use in buildings. By replacing the stony materials with PCM, the thermal inertia of the room is significantly improved as phase change materials provide an improved (latent) heat storage capacity. In case of passive heating, the innovative Trombe wall delays the moment at which the solar heat enters the room to the moment occupants need this (because they are at home in the evening and at night) (Tenpierik, 2017).

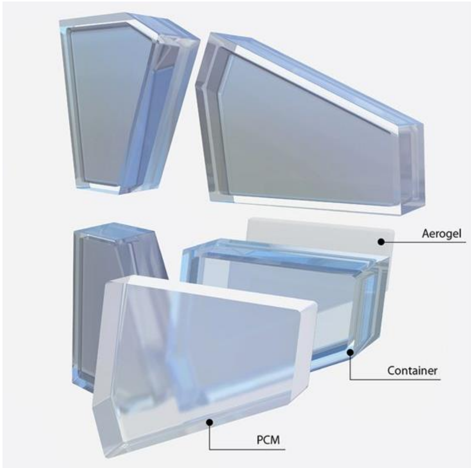


Figure 6.2 and 6.3: Impression of LTATW configuration (left) and their single PCM elements (right) (4TU.Bouw, 2014)

The translucent elements are located in front of a glass façade (Figure 6.2) and act as a thermal buffer in both winter and summer. In each season, this happens by rotating the elements towards the source of incoming heat or towards the sink for heat release (4TU.Bouw, 2014). In the winter, the layer of PCM is oriented towards the outdoor environment at daytime and is thermally charged by the low winter sun. At night, the system rotates 180 degrees and releases the accumulated heat to the interior (Figure 6.4). In the summer, the LTATW is oriented towards the interior at daytime to store the interior heat loads and during the night, the LTATW rotates again and releases the heat to the outside environment by means of (passive) night ventilation (4TU.Bouw, 2014). Within both processes, the insulating layer or aerogel ensures that the heat is transported in the right direction.

The heat transfer to and from the PCM occurs via (short wave) solar radiation, via (long wave) infrared radiation and via convection. This means that the ideal surface of the Trombe wall considers all these three modes of heat transfer (Tenpierik, 2017). When the sun heats up the PCM wall, it slowly changes from solid to liquid, which results in a colour change from whitish opaque to translucent. In the evening, this is reversed and the material changes from translucent to opaque again (Tenpierik, 2017). To prevent the Trombe wall from obstructing the view to outside, openings are realized in the design as well (Wattez et al., 2017).

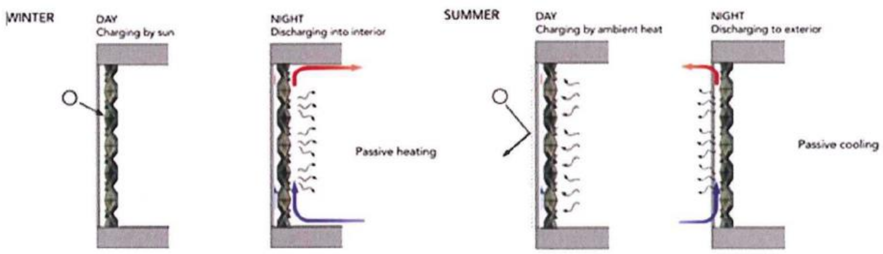


Figure 6.4: Winter and summer mode of the innovative Trombe wall (Tenpierik, 2017).

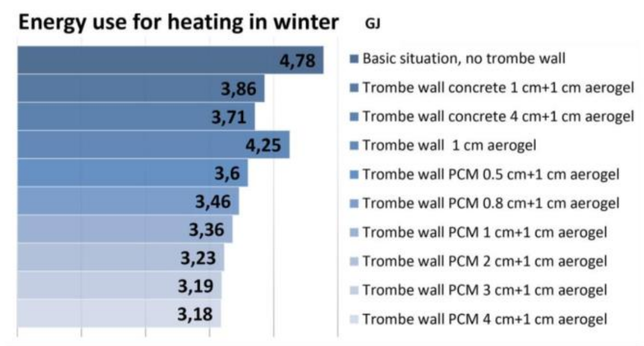
The innovative Trombe wall is shape-optimised to reach optimal energy performance and is created with advanced rapid prototyping techniques like (robotic) FDM printing (Tenpierik, 2017). FDM printing enhances a large freedom in design and allows to design complex patterns and surface textures that are optimised for many different objectives.

6.2. RESEARCH REVIEW

So far, the 'research through design' project has gone through two consecutive stages: the Double Face 1.0 stage and the Double Face 2.0 stage. In the first stage, a preliminary demonstrator has been produced (Wattez et al., 2017). In the second stage a further development and refinement was the main focus. The project has developed a workflow to simulate the cooperation between technical aspects from building physics and integration of the engineering performances into the design of the product. This is done through an iterative form-finding approach. More specifically, the process aims to harmonize hard parameters with soft parameters. Hard parameters are such as technical performances for thermal behaviour and daylight transmittance. Soft parameters are such as overall appearance and aesthetic values. The workflow is being used for different design concepts, some of which will be prototyped and tested (Wattez et al., 2017). In section 6.2.1 the first stage (DF1.0) is discussed further. Section 6.2.2 deals with the second stage (DF2.0) in more detail.

6.2.1. DOUBLE FACE 1.0

The Double Face 1.0 research project started with a wide inventory of existing phase change materials (4TU.Bouw, 2014). In this inventory, an analysis of their properties was done and a short-list of possible materials was set up. For each of the PCM's in this short-list, digital simulations were performed to analyse their thermal behaviour. They were tested in different layer configuration, thickness etc. The samples were made for all the selected PCM products and were tested in Eindhoven for their thermal behaviour and in Delft for their light transmitting behaviour. The analysis of measurements made it possible to narrow down the list of selected PCM's as well as for finetuning the dimensions. As a result, a first adjustable, translucent Trombe wall has been developed with elements of 4 cm PCM type RT25E2 (Wattez et al., 2017). The chosen PCM has a latent heat storage capacity of 180 kJ/kg and a transition temperature for freezing and melting around 25 °C. Besides a layer of PCM, the LTATW in DF1.0 also consists of 1 cm of translucent Lumira aerogel insulation layer. Both the materials are encased in containers as is shown in Figure 6.3 and together form a 3D undulated pentagonal tiling pattern (Wattez et al., 2017). To prevent the innovative Trombe wall from obstructing the view to the exterior, openings in the wall were designed as well. Using the measured and determined properties as input, additional thermal simulations of a standard room with LTATW were run in DesignBuilder (v3.4) to investigate several variations including percentage of holes in the wall, PCM layer thickness, aerogel layer thickness and extra cavities. The simulations showed that the best trade-off between heat storage capacity and unobstructed view would lead to an opening percentage of roughly 10%. An increased opening percentage results in an increased heat transfer between room and cavity, which reduces the time lag advantage of the Trombe wall (Wattez et al., 2017). Because DesignBuilder is not able to include a rotation during a simulation, a Matlab/Simulink model was developed to simulate a flat 2D Trombe wall that revolves twice per day. This simulation model is a full energy performance model for a cubic room with a window including transmission losses, ventilation and infiltration losses, solar gains, internal gains, heat storage in walls, temperature set-points, sun-blinds, etc.



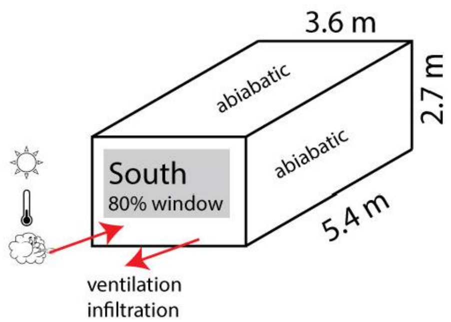


Figure 6.5 and 6.6: Simulated energy demand of a standard residential room with innovative Trombe wall in the Netherlands (left) (Tenpierik, 2017) and 3D scheme and dimensions of cubic room (right) (Wattez, 2018).

The results of the simulations in Matlab/Simulink are shown in Figure 6.5, which gives an overview of the heating energy demand of the room during one winter period with different wall configurations. Without

Trombe wall, the energy demand equals 4.78 GJ and when a Trombe wall with 4 cm PCM is added, the energy demand is reduced to 3.71 GJ. When a lightweight, translucent and adaptable Trombe wall is added, the required energy drops to 3.18 GJ, which is a reduction of 33%. It can also be seen that the optimal PCM thickness lies at 1-2 cm with a decrease of 30-32% (Wattez et al., 2017). With all insights from the Double Face 1.0 project, new design concepts have been developed during the Double Face 2.0 project.

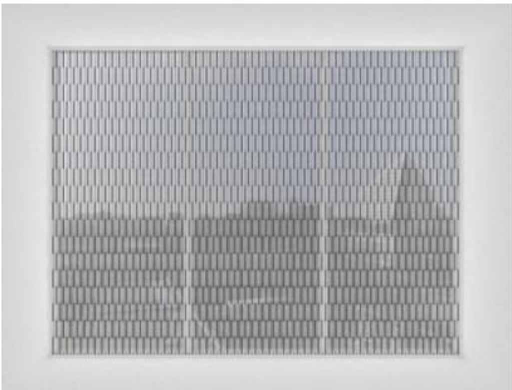
6.2.2. DOUBLE FACE 2.0

In the Double Face 2.0 project, more complex geometries of a lightweight translucent adaptable Trombe wall have been tested and developed. The different design concepts have been studied with advanced computational means and advanced digital manufacturing techniques (Cosmatu et al., 2017) and their thermal performances have been measured. Two of the concepts are the 'Trombe panel' and the 'Jacobs ladder'.

The Trombe panel design integrates optical, structural and thermal properties in one aesthetically designed panel. The design is based on a wall with brain coral pattern, that needs to be rotated an electro-motor or by hand. In the pattern, some parts are filled with PCM (transition temperature of 25 °C) and some parts stay open to allow for view to outside. The thickness of the wall varies at different positions, but the total volume remains the same as for a flat panel with a 2 cm PCM thickness. The annual energy savings resulting from having this Trombe wall is similar to the energy savings calculated with Matlab/Simulink (previous section) (Wattez et al., 2017). An impression of the Trombe wall concept is shown in Figure 6.7.

Figure 6.7: Impression of Trombe wall concept (Wattez et al., 2017).

The Jacobs ladder concept is based on the movement principle of a toy. If the ladder is held at one side, blocks seem to cascade down the strings. This impression is a visual illusion and the result of one block after another flipping over. A composition of intertwined ribbons allows a suggestion that each block is hinged to the next one at one of the two ends. An impression of the Jacobs ladder concept is shown in Figure 6.8. The black vertical lines demonstrate the strings of the ladder (Wattez et al., 2017).



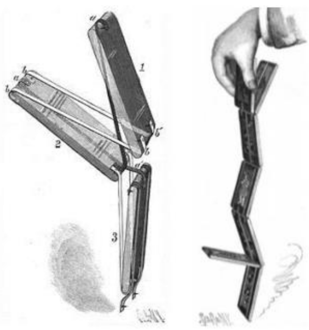


Figure 6.8 and 6.9 Impression of Jacobs ladder concept (left) and principle of Jacobs ladder movement (right) (Wattez et al., 2017).

For different variations of the Jacobs ladder concept, a detailed simulation model in COMSOL (v5.2) was made. COMSOL allows to import geometries, simulate 2D and 3D models over long time periods, simulate moving elements, simulate with real weather data and use the same simulation model for detailed CFD (Computational Fluid Dynamics) simulations as well. The simulation results of the innovative Trombe wall with 2 cm of PCM and 1 cm of insulation aerogel is shown in Figure 6.10. The walls, floor and ceiling (all adiabatic surfaces) are made of concrete and heat transfer takes place through the South façade via conduction and radiation through glazing and Trombe wall. In this model, no heating system is active, no people are present and no sun-shades are used. The LTATW rotates around its centres at fixed times (08:00h and 18:00h).

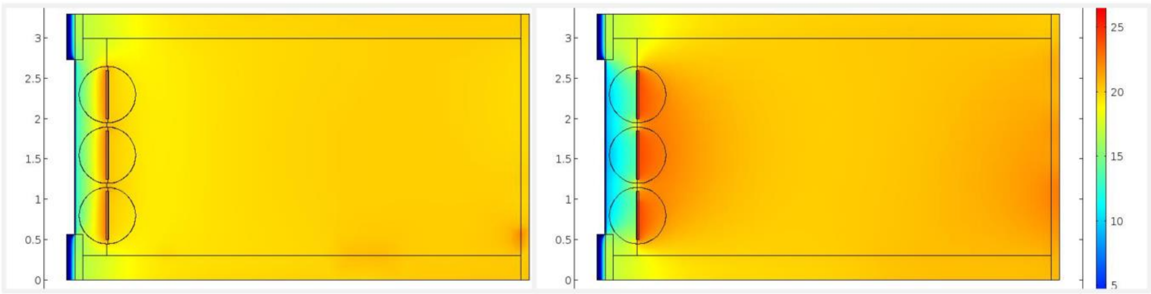


Figure 6.10: Simulation result from COMSOL. Left: January 9, 12:00h – the wall is 'charging'. Right: January 10, 00:00h – the wall releases heat to the room (Tenpierik, 2017).

Figure 6.10 shows the temperatures on 9 January when the PCM layer faces the outdoor environment and the temperatures on 10 January when the PCM layer faces the indoor environment. It can be clearly noticed that the solar radiation heats up the PCM (and the cavity) during the day and that a small part of the heat passes through the openings in the wall (orange dots in the bottom right corner of left figure). At night, when the PCM layer faces the room, it radiates the captured heat into the room. The circles around the wall segments are not part of the design and are only necessary to simulate the rotating mesh (Wattez et al., 2017).

Another set of COMSOL simulations has been performed to understand the effect of material thicknesses and types in the Jacobs ladder concept. In these simulations, different variations (see Table 6.1) of the basic model have been modelled and the results are shown in figure 6.11 and 6.12. Figure 6.11 shows the average room temperature per configuration and Figure 6.12 shows the average temperature of the thermal mass components (concrete or PCM). The effect of solar radiation is clearly visible and the PCM heats up quickly in the configurations with a 2 cm layer of PCM. The heat release takes a long time. A configuration with a 7 cm layer of PCM gives a more stable room temperature and a lower PCM temperature, as can be seen from the purple line. The red line in Figure 6.11 shows the positive effect of a rotating PCM-panel on the room temperature, as it is higher and more stable than when both a configuration without Trombe wall and Trombe-wall with non-rotating panels is applied. The rotating PCM-panel is capable of maintaining a comfortable indoor room temperature for many days after a day of moderate sunshine without requiring an additional heating system (Wattez et al., 2017).

Table 6.1: Different configurations in COMSOL simulations (Wattez et al., 2017).

name	*description*	*material 1*	*material 2*	*rotate*
No_Trombe	no trombe			
Concrete_30	classical 30 cm	concrete 30 cm		no
Concrete_15	classical 15cm	concrete 15 cm		no
1P_7cm	pcm 7cm	pcm 7 cm		no
1P_2cm	pcm 2 cm	pcm 2 cm		no
1P_ins_window	pcm to window, 2 cm, insulated	pcm 2 cm	aerogel 1 cm	no
1P_ins_room	pcm to room, 2 cm, insulated	pcm 2 cm	aerogel 1 cm	no
3P_rotate	3panels pcm rotate	pcm 2 cm	aerogel 1 cm	yes
3P_room	3panels no rotate pcm to room	pcm 2 cm	aerogel 1 cm	no
3P_window	3panels no rotate pcm to window	pcm 2 cm	aerogel 1 cm	no

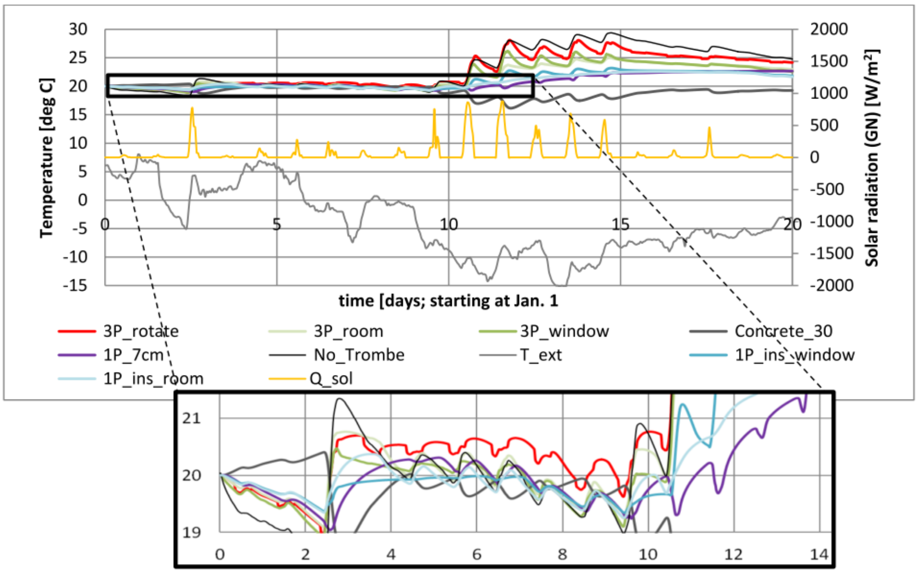


Figure 6.11: Room temperature due to Jacobs ladder concept from Jan 1 – Jan 21; no heating; room unoccupied (Cosmatu et al., 2017).

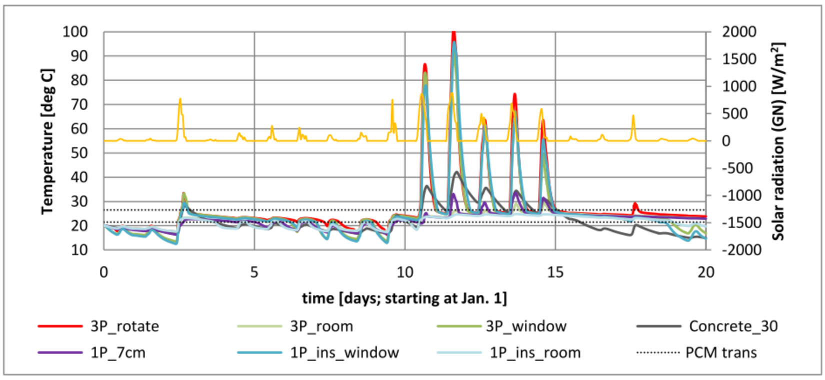


Figure 6.12: PCM or concrete temperature due to Jacobs ladder concept from Jan 1 – Jan 21 (Cosmatu et al., 2017).

From the graphs, it can also be noticed that phase change material is more advantageous than concrete. Where a concrete Trombe wall extracts heat from the room, the PCM-wall uses the radiation of the sun to heat and stabilizes the room temperature. When the PCM temperature is between the transition range of melting and freezing (shown by 'PCM_trans' in Fig. 6.12), the indoor room temperature is stable. This is the case for a Trombe wall with a layer of 2 cm of PCM facing the room and a layer of 1 cm of aerogel facing the cavity (1P_ins_room). The layer of PCM is hardly heated up by the sun because of the insulating layer, so the temperature remains between the transition range. However, this configuration does not use the entering solar radiation for heating the room optimally and therefore, the PCM needs to face the cavity (Wattez et al., 2017).

6.2.3. FUTURE DEVELOPMENT

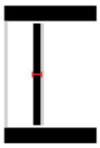
Based on the results of Double Face 2.0, the highest scoring concepts are being analysed again in order to obtain either information which might be useful for other concepts or which will inform the development of the existing concepts (Cosmatu et al., 2017). All individual concepts will be further optimized towards structural performance, visibility, thermal performance and light transmittance. Additional simulations regarding airflow and temperature changes will be investigated with COMSOL and simulations regarding radiation values, sunlight exposure and desired transparency percentages will be carried out with the use of Grasshopper (and relevant plugins such as Honeybee and Ladybug). The obtained simulation data will be examined and visualized within ModeFrontier through a Grasshopper integration node. Finally, more detailed CFD simulations will be performed on the selected designs. The simulation results will be quantified and applied on the Trombe wall designs in an iterative manner (Cosmatu et al., 2017).

6.2.4. SUMMARY OF RESULTS DOUBLE FACE 2.0

In this section, a summary of all important results[2] of the Double Face 2.0 project is given. With the aid of this summary, an improved insight is gained into the performance of the innovative Trombe wall and specific values from results will be used as input for the research in this Master's thesis project.

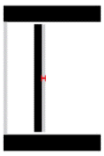
Selection of PCM transition temperature

The transition temperature of a PCM defines at what temperature the PCM starts storing energy. Based on literature research and physical insight, Rubitherm's[3] SP25E was chosen. This type of PCM has a melting temperature of 23-26 degrees Celsius and a freezing temperature of 22-24 degrees Celsius. The particular melting temperature has been selected based on the fact that the PCM is placed in a cavity with direct solar radiation. The particular freezing temperature has been selected based on the fact that cooling mode should be activated when the room temperature varies between 22 and 25 degrees Celsius.



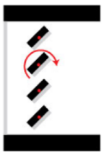
PCM layer thickness

Thermal storage capacity and received solar energy play an important role when optimizing the thickness of the PCM layer. A thicker layer is able to store more energy, but when it is too thick, it does not fully melt and remains partly opaque. In addition, a thicker layer results in a heavier system. Calculations based on solar radiation values and phase change times, the advised layer thickness for best thermal behaviour equals 2.5 cm.



Aerogel layer thickness

The aerogel layer is used to direct heat in the desired direction. To find out what the most optimal layer thickness is, calculations based on two layers of PET (a plastic), one layer of aerogel and the surface resistance are done. A minimum U-value was set and calculations showed that the U-value was reached with an aerogel layer thickness of 1 cm.



Effect of adjustability

In order to understand the effect of adjustability (or rotatability), different configurations of the basic room model were simulated in Comsol. The results show a positive effect of a rotating system on the room temperature because a higher and more stable room temperature are found (red line in figure 6.11). The rotating PCM-panel is capable of maintaining a comfortable indoor room temperature for many days after a day of moderate sunshine without requiring an additional heating system. An adjustable Trombe wall is therefore more effective than a non-adjustable one.

Cavity width

The cavity in front of the LTATW functions like a greenhouse. Due to the incoming solar radiation, it heats up and consequently heats up the LTATW. In summer, the cavity captures the unwanted heat and ventilates it back to the outdoor environment. The effect of the cavity width with a closed LTATW is investigated in Comsol and simulation results show that the effect on cavity temperatures is very small. By keeping the width small, the occupied floor area is made smaller and self-shading draw-backs are minimized. However, the system should be able to rotate around its axes in order to direct the PCM to the cavity or to the room. Therefore, the minimal cavity width is defined by the amount of space needed for adjustability: 4.7 cm.

Internal air movement

The airflow in the cavity is generated by a temperature difference between top and bottom. When air flows over the surface of the LTATW, convective heat transfer increases and a more effective Trombe wall is reached. An experimental set-up at the faculty of Architecture and the Built Environment on the TU Delft was made to measure cavity temperatures, outdoor temperatures and room temperatures over a period of several

[2] All results obtained from research report of Wattez (2018).

[3] Manufacturer of phase change materials.

days. A 3D-printed bone-like structure consisting of several vertical tubes with openings at top and bottom was placed in the cavity and results show that the airflow through these tubes was too small to measure. This means that an increased heat transfer caused by air travelling through the structure was not found and air channels should not be implemented in the Trombe wall design for passive natural air flow.

Effect of shape on room temperature

To study the effect of shape on the room temperature in the winter, different simulation set-ups with different Trombe wall configurations were made (different shape, layer thicknesses, opening percentages, etc.). Some clear findings are that thinner layers of PCM (2-5 cm) tend to overheat after the phase change process has finished and when orienting the elements of the Trombe wall towards the sun, the PCM heats up faster and captures more heat. Self-shading shapes are a good solution to prevent overheating but are able to store less energy. Finally, the less the opening percentage, the better the stabilizing effect of the LTATW.

Physical openings

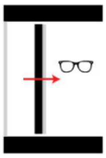
Openings in the LTATW improve the interaction between room and the outside environment but also allow air to move between the room and the cavity, which decreases the performance of the Trombe wall. The effect of the opening percentage is studied in a set of Comsol simulations and in a set of Matlab simulations. It was found that openings up to 5 cm in height are allowed, but smaller heights result in an even better performance. The less the opening percentage, the better, but differences between 8% openings and 20% openings are not too large: maximum of circa 0.7 degrees Celsius over a period of around 6 hours. A system with a low percentage of openings becomes part of the insulating barrier of the façade, which results in lower heating needs. Simulations in Matlab show that a LTATW with 10% physical openings result in the highest energy savings in both winter and summer. 10% is also the minimum value for sufficient see through.

Optimization for heat transfer

It is considered plausible that convective heat transfer between the air in the cavity and the Trombe wall is increased with a certain surface treatment. To validate this, different shaped sample boxes were modelled in Comsol. Although convective heat transfer is a slow process, the simulation results show that shaping of the surface has a positive effect on it. The advice is to design a smooth (corrugated) 3D surface structure with a fineness higher than 10 cm as it performs best in improving the heat transfer via convection.

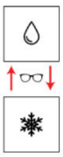
Prevention of PCM overheating

Large volumes of PCM have high internal temperature differences. To prevent from overheating, horizontal subdivisions with a maximum height of 2 cm should be designed. An alternative could be to use a PCM with a higher melting temperature in the top of the system and a lower melting temperature in the bottom of the system or to use automatic rotation.



Translucency

The level of translucency of the LTATW depends on the following aspects: layering, material thickness, production techniques and the phase of the PCM. Different experiments were conducted and results logically show that a smaller thickness results in a better light transmittance. Furthermore, a robotic printing technique (PET-G) instead of FDM printing (PET) is preferred. In a liquid state, a 2.5 cm layer of PCM and 1 cm layer of aerogel transmit 24.2% of the incoming light and 0.2% in a solid state.



PCM phase change

Different types of PCM have different melting and freezing behaviour. During the research project, many samples have been tested on visual properties, light transmitting properties, mixing behaviour, melting behaviour and crystallization behaviour. Important conclusions were that mixing of different PCM’s is not recommended as it breaks the composition and is not able to freeze and melt again. Another conclusion is that dividing the PCM volume into different parts prevents the crystals from dropping to the bottom.

Lightweight vs heavyweight building

An investigation was done to study the effect of the mass of the building on the performance of the LTATW. Measurements and simulations show that an LTATW performs better in a lightweight building with highly fluctuating room temperatures, instead of a heavyweight building.

Validation

In order to investigate the reliability of the digital simulations, the measurement results of the melting of a printed sample box were compared to the measurement results of a comparable setup in Comsol. A 3D printed sample box with solid state PCM (SP25E) is placed in front of a halogen lamp for 1 hour and 15 minutes and the results show comparable PCM and room temperatures during the process of melting.

7. CLIMATE CLASSIFICATION

In the previous chapters of part II, the concepts of passive solar building design, phase change materials and different types of Trombe walls have been explained. With the knowledge obtained from these chapters, three of the five background questions can be answered (see chapter 8). For the remaining two background questions, a literature study into climate classification was required, and is reported in this chapter.

7.1. DEFINITION

Climate is generally defined as ‘’a complete statistical description of weather over a sufficiently long period of time (usually 30 years)’’ (Chen & Chen, 2013, p. 70) and varies at a broad range of time scales. A climate is based on external forcings (solar radiation) and internal dynamics of a climatic system, which are oceanic and atmospheric circulations and earth surface-atmosphere interactions (Chen & Chen, 2013). The internal dynamics are related to the atmospheric modes of circulation with a time scale of up to about two years and the oceanic-atmospheric modes relate with time scales from weeks to several decades (like the El-Nino phenomenon). These modes together produce climate variations in addition to the long term changes which are generally associated with different long term forcings (Chen & Chen, 2013).

7.2. CLASSIFICATION

Climate is measured by assessing the behavior of variation in temperature, precipitation, humidity, atmospheric pressure, radiation, wind and other meteorological variables in a certain region over a long period of time. There are several ways to classify climates into similar systems, and the most commonly used classification scheme in the world is the scheme of Köppen (1900). Other schemes like the classification of ‘Thornthwaite’ and the ‘’Bergeron and Spatial Synoptic Classification system’’ are also consulted , but less quickly. Based on empirical observations, the biologist Vladimir Köppen (1900) developed a climate classification system that used monthly weather data to define boundaries of different climate types around the world (Chen & Chen, 2013). Over the years, the classification scheme of Köppen has been further developed. When the German climatologist Geiger applied a number of refinements, the Köppen-Geiger system was born (Stern, De Hoedt, & Ernst, 2000) and was widely used by climatologists and geographers around the world. The Köppen-Geiger system owes its popularity to its simplicity and the power of linking climate and natural vegetation (Bailey, 2009). Despite the efforts of many German scientists to find alternative ways to classify climates, the system of Koppen remains one of the most widely used systems in the world (Domroes, 2003).

Depending on the data used, mappings of the geographic distribution of the world's climate may have different qualities and details for such a stationary description of the world's climate. Many applications of the classification system of Köppen-Geiger are concerned with mapping with the help of a long term climate dataset (Chen & Chen, 2013). Kottek, Grieser, Beck, Rudolf, & Rubel (2006) developed a well documented and easily accesible update of the climate classifiction in the world, using gridded climate data during 1951 and 2000. The classification is shown in Figure 7.1.

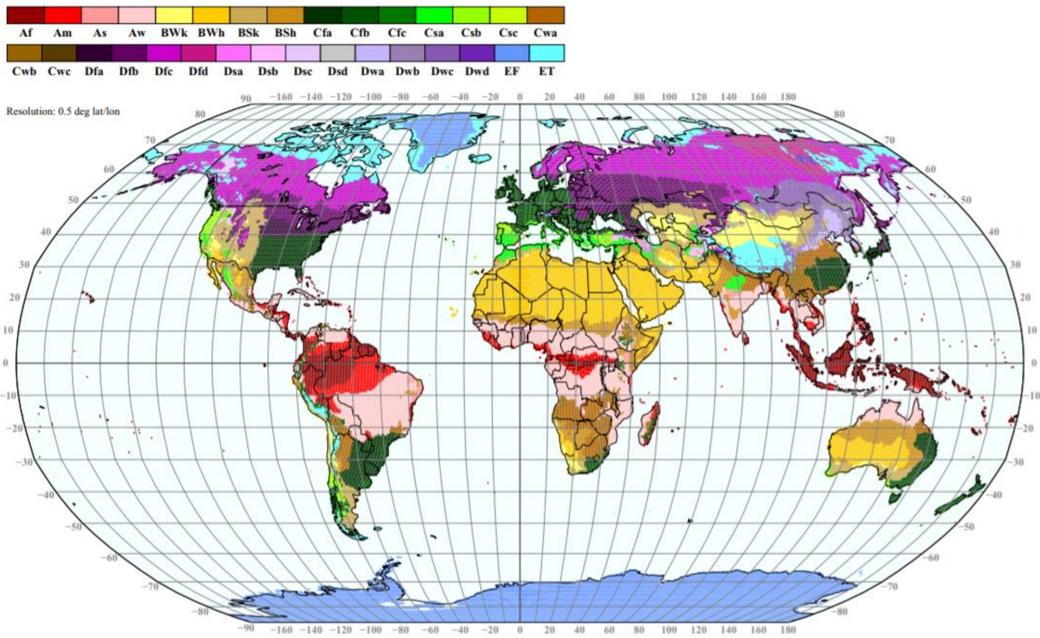


Figure 7.1: World map of the Köppen-Geiger climate classification (Kottek et al., 2006)

The classification system of Köppen-Geiger consists of five major types or climate classes: A (tropical), B (arid), C (temperate), D (cold) and E (polar). Each of these classes have their own sub-classes. Based on a major climate class, a more detailed group is designated by a two- or three-letter combination completely (Sohani, Sayyaadi, & Mohammadhosseini, 2018). An overview of all symbols and their meaning are given in Table 7.1. All the major climate groups except B are determined by temperature only, while the sub-groups (except sub-types under E) are assigned based on the combined criteria relating to seasonal precipitation and temperature (Chen & Chen, 2013).

A tropical climate is a non-arid climate in which all months of the year have average temperatures of at least 18 degree Celsius. Tropical climates, which are usually found along the equator, are frost-free and variations in the solar angle are relatively small. The temperature in tropical climates remains fairly constant throughout the year and the amount of precipitation is high (Linacre & Geerts, 1997). An arid climate is defined by very little precipitation. In this climate, summers are very hot and rainfall is rare. The level of solar radiation is intense and big temperature differences between day and night are observed (Laity, 2009). Temperate climates are those without extreme temperatures or precipitation. Temperate climates are generally positioned in the middle latitudes (between the polar and tropical regions) and are characterized by wider temperature ranges throughout the year (Linacre & Geerts, 1997). Average temperatures in cold climates range from below -3 degree Celsius in cold months to 10 degree Celsius in their warmest months. In cold climates, precipitation is quite moderate and more concentrated in the warmer months. A part of the annual precipitation falls as snowfall and is likely to remain on the ground for more than a month. The summer weather in cold climates is more stable than its winter weather (Buchdahl & Hare, 2010). Lastly, a polar climate is characterized by an average temperature of less than 10 degree Celsius in every month of the year. Regions with a polar climate are usually far from the equator, the sun shines for long hours in the summer and for many fewer hours in the winter (McKnight, 2000).

Table 7.1: Description of symbols which are used in in Köppen-Geiger climate classification (Sohani et al., 2018, p. 332)

Symbol and place in the name			Meaning
1st	2nd	3rd	
A			Tropical
	f		Rainforest
	m		Monsoon
	w		Savannah
B			Arid
	W		Desert
	S		Steppe
		h	Hot
		k	Cold
C			Temperate
	s		Dry summer
	w		Dry winter
	f		Without dry season
		a	Hot summer
		b	Warm summer
		c	Cold summer
D			Cold
	s		Dry summer
	w		Dry winter
	f		Without dry season
		a	Hot summer
		b	Warm summer
		c	Cold summer
		d	Very cold summer
E			Polar
	T		Tundra
	F		Frost

7.3. REPRESENTATIVE CITIES

When studying the influence of different types of climates on a certain system, hourly weather data of representative cities are generally consulted. Of each of the Köppen-Geiger climates, a city can be selected, which is the best representative of its climate. The selection of a representative city for each of the climates can be done with the help of the study of Mansy (2006). Mansy made an initial selection of international cities based on the two major factors that determine local climate, i.e. outdoor temperature and solar radiation. These two factors are the main sources of building facade loads when regarding thermal performance. In the initial location selection phase, the objective was to choose candidate locations that cover a wide range of these factors from all over the world. In his study, Mansy makes a distinction between five climatic regions of the world, which are: tropical, sub-tropical, temperate, sub-polar and polar. These climatic regions fit relatively well with other climate classifications, like the Köppen-Geiger classification (Mansy, 2006).

Initially, three locations per climate zone in the Northern Hemisphere were selected. These locations are selected on 15 degrees spacing in latitude angles, starting from the Equator. A value of 15 degrees has been chosen, so that the intervals coincide with latitudes of climate belts parallel to the equator and that the influence of atmosphere thickness is taken into account as well. The atmosphere thickness gradually decreases from Equator to Pole and has a large influence on the solar intensities at sea level due to the filtrating behavior of the atmosphere (Szokolay & Docherty, 1999). The candidate locations for each climatic region are shown in Table 7.2. Locations close to latitude 15° are excluded since they are still within the tropical belt. The suggested cities represent a gradual drop in solar radiation intensity from the Equator to the North Pole. Besides, the selected locations cover the whole range of the need for heating and cooling. In Singapore, there is generally no need for heating and in Resolute, there is generally no need for cooling.

The translation from the climate classification used in the study of Mansy to the Koppen-Geiger classification is as follows: the representative locations for a tropical and temperate climate are in both classifications the same, and the location for a sub-tropical area is similar to the location in an arid climate. Finally, the cities of a sub-polar climate can be seen as cities of a cold climate, except for Ft. Smith, which lies in a polar climate according to the Köppen-Geiger system.

Table 7.2: Candidate locations that represent the five main climatic regions of the world (Mansy, 2006, p. 2).

Region & Location	Continent	LAT*	ELEV*
Tropical			
Singapore	Asia	1.37	15
Belem	S. America	1.43	24
Nairobi	Africa	1.32	1625
Sub-tropical			
Cairo	Africa	30.13	74
Phoenix	N. America	33.43	339
Tucson	N. America	32.13	788
Temperate			
Burlington	N. America	44.47	101
Milan	Europe	45.43	107
Lyon	Europe	45.73	248
Sub-Polar			
Ft. Smith	N. America	60.02	203
Stockholm	Europe	59.65	16
Oslo	Europe	59.9	61
Polar			
Resolute	N. America	74.72	67

*All latitudes are North latitudes. Elevation is given in meters above sea level.

As a final step, Mansy eliminated all cities that may be affected by the intensity of solar radiation and/or the typical temperature fluctuations. For each main climate, one city remained. The elimination is based on elevation and proximity to large bodies of water or mountains. As can be seen from Table 7.2, some cities are located on a high altitude, and are often accompanied by a unique meso-climate, that is not indigenous to the surrounding region. Based on the altitude criterion, the following cities were eliminated: Nairobi, Phoenix, Tucson and Lyon. A city which lies close to large bodies of water or close to mountainous areas is susceptible to large temperature fluctuations and varying wind patterns. Based on this criterion, the following cities were eliminated: Belem, Burlington, Oslo and Stockholm (Mansy, 2006).

To conclude, the following cities remain: Singapore, Cairo, Milan, Ft. Smith and Resolute.

7.4. CLIMATE VERSUS THERMAL COMFORT STANDARDS IN BUILDINGS

In every building designed for human use, one of the main goals is to create an indoor climate that every individual finds comfortable (HTI, 2005). In accordance with the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standards, the thermal comfort of a person is defined as a certain state of mind, that satisfy with the thermal conditions. The indoor climate of a room is a result of the interaction between the outdoor climate, the thermal state of the room itself and the heating and/or cooling system. The most important factors that influence the thermal comfort of individuals are: the air temperature, the average radiation temperature, the air speed, the humidity, the activity level of a person (metabolism) and the heat resistance of the clothing. For the assessment of thermal comfort, a number of scales, equations and models exist, such as the 'Predicted Mean Vote' (PMV), the 'Predicted percentage of dissatisfied' (PPD) and the adaptive comfort model (HTI, 2005). For mechanically heated and/or cooled buildings, it is recommended to apply the PMV and the PPD indices and for buildings without mechanical cooling (naturally ventilated buildings) it is recommended to use the adaptive comfort model (EN15251, 2007). Because in this thesis, research is done with room models that are not only naturally ventilated, only the PMV and PPD indices are considered here.

The European standard EN15251: ‘Indoor environmental input parameters for design and assessment of energy performance of building addressing indoor air quality, thermal environment, lighting and acoustics’ provides a table of categories for design of mechanical heated and cooled buildings. Assuming different criteria for the PMV-values and PPD-values, different categories of the indoor environment are organized (see Table 7.3). The recommended category (category 2) is indicated with a bold font. Based on a specific category, a recommended design value of the thermostat set-points in buildings is given.

Table 7.3: Categories of design of mechanical heated and cooled buildings (EN15251, 2007).

Category	Thermal state of the body as a whole	
	PPD (%)	PMV
I	<6	-0.2 < PMV < +0.2
II	**< 10**	**-0.5 < PMV < +0.5**
III	< 15	-0.7 < PMV < +0.7
IV	> 15	PMV < -0.7 or +0.7 < PMV

The ‘Hoger technisch instituut’ (HTI) reviewed an experiment with persons from the United States, Denmark and several tropical areas and revealed that no significant differences exist between the three groups that influence comfort in buildings. Possible differences in ambient temperature, which people prefer, are probably only a function of clothing habits. When the clothing-value is chosen in accordance, the comfort equations are valid all over the world (HTI, 2005). This means, that also the category and the corresponding recommended thermostat set-points apply to buildings all over the world. The recommended thermostat set-points for office buildings and residences are shown in Table 7.4.

Table 7.4: Recommended design values of thermostat set-points of buildings and HVAC systems (EN15251, 2007).

Type of building/space	Category	Minimum heating thermostat-setpoint	Maximum cooling thermostat-setpoint
Residential building: living spaces (bed rooms, drawing rooms, kitchen, etc.)	I	21.0	25.5
	II	**20.0**	**26.0**
	III	18.0	27.0
Residential building: other spaces (storages, halls, etc.)	I	18.0	
	II	**16.0**	
	III	14.0	
Single office (cellular office)	I	21.0	25.5
	II	**20.0**	**26.0**
	III	19.0	27.0
Landscaped office (open plan office)	I	21.0	25.5
	II	**20.0**	**26.0**
	III	19.0	27.0

8. CONCLUSION PART II

This chapter is the final chapter of part II and gives an overall conclusion of the knowledge obtained from literature research. In the past five chapters, a literature review has been conducted starting from the overarching subject (passive solar building design), towards the focus on the lightweight, translucent and adaptable Trombe wall. For each topic, a conclusion is described in this chapter, in which all of the background questions are answered as well.

CHAPTER 2: PASSIVE SOLAR BUILDING DESIGN

Chapter 2 has given a global insight into the field of passive solar building design and its common applied strategies. There are three basic types of passive solar design: direct gain, indirect gain and isolated gain, of which the lightweight translucent adaptable Trombe wall can be counted as a system relying on indirect gain. In this system of indirect gain, the absorber is known as the surface area of the Trombe wall, the collector is known as the window through which sunlight enters the building, the distributor is known as the three transfer modes conduction, convection and radiation and the thermal mass is known as the total volume of PCM in the Trombe wall. Finally, the control mechanisms in the system are the external/internal shading devices, the solar heat gain coefficient of the glazing, operable vents and the adaptability of the Trombe wall.

Chapter 2 reveals that by applying a LTATW in a room/building, a number of advantages are experienced. First, when the system performs properly, it results in lower energy bills. Also, the innovative Trombe wall is able to create a warmer interior climate in winter and a cooler interior climate in summer. In addition, the system is silent and owners of buildings with a LTATW will be more satisfied and will experience a higher resale value than without LTATW. Finally, maintenance is most likely less needed for a LTATW than for mechanical equipment and the use of fossil fuels is avoided.

Finally, eight common applied strategies of passive solar building design were mentioned, among which the use of thermal storage materials. Whereas the other strategies often dominated, the strategy with thermal storage has become a much more interesting option since the introduction and development of phase change materials.

CHAPTER 3: TROMBE WALLS

Chapter 3 firstly described the general working principle of a classical Trombe wall. In short, a classical Trombe wall is a massive wall behind a layer of glazing, directed to the South, which improves thermal comfort in building in particularly cold climates. Because the disadvantages of such a Trombe wall still outweigh the advantages, the classical variant is still little applied in buildings and a lot of research has been done with the aim to improve the original concept.

In chapter 3, nine different variations of a traditional Trombe wall are described and developments in the field of new research were given. A water Trombe wall proves to perform at least as well in terms of providing thermal comfort as a traditional Trombe wall, but it also appears that the difficult implementation, the large use of space and the risk of leakage negatively affect the further development of this configuration. A zigzag Trombe wall differs in particular in geometry of a classical Trombe-wall, because two of the three parts together form a V-shaped structure instead of a flat one. Literature describes that the zigzag Trombe-wall would be an improvement of the original variant, but a reason why the system is also not widely used could be that the V-shape is (aesthetically) undesired for many buildings. A solar trans-wall is also a water-based Trombe-wall, and distinguishes itself through its greater transparency compared to a water Trombe-wall. However, this type of wall also entails the disadvantages of water: more use of space, the chance of presence of micro-organisms and the risk of leakage.

A composite Trombe wall appears to be an improvement of a traditional Trombe wall, in particular through the addition of an insulating panel. Research has shown that the composite Trombe wall performs better in terms of providing thermal comfort in cold and cloudy climates. A solar hybrid wall offers an important advantage over the traditional Trombe wall: it is able to provide heat in the winter and cooling in the summer. However, the system cannot be assumed entirely passive, because water sprinklers are incorporated. This also applied to a fluidised Trombe wall, where the transportation of a liquid is driven by a fan at the bottom of the wall. Literature revealed that a photovoltaic Trombe wall is less efficient than a traditional Trombe wall (in terms of heat gain), but is able to generate electricity. Whether generating electrical energy is desirable depends on the type of building.

The Trombe wall with phase change material is a relatively new designed configuration and was originated because the other mentioned configurations often do not offer a suitable or high performance solution for many situations. All configurations with water or another liquid included entail the disadvantages: large use of space, micro-organisms, chance of leakage and in some cases a not entirely passive design. As large use of space and transparency issues also play a role in the other configurations, the more lightweight Trombe wall with phase change material seems to be a good alternative.

CHAPTER 4: PHASE CHANGE MATERIALS

Chapter 4 introduced an important group of materials in this thesis: phase change materials. Phase change materials are known for their large heat capacity and can be used for both passive storage for heating and cooling purposes. As phase change material store energy in a latent way instead of a sensible way, the difference between sensible and latent heat storage was explained. Hereafter, all classification criteria were mentioned. In wanting to integrate phase change material into Trombe walls, the following criteria must be taken into account: the phase change material should have a melting and freezing temperature in the range of application, the material must have high thermal conductivity and the material must have a high latent heat of fusion. In addition, the phase change material should have the desirable chemical, thermophysical, economic, kinetic and environmental properties, as listed in Table 4.1.

Table 4.2 gave an overview of the advantages and disadvantages of different types of PCM. From the table it can be concluded that the most benefits appear with organic PCM's and the least with eutectics. When looking at the disadvantages, it can be seen that organic and inorganic PCMs entail approximately the same amount of disadvantages. A few important disadvantages of organic PCM's however are the higher costs, lower conductivity, flammability and higher volume changes. Literature research revealed that organic solid-liquid paraffins are most applied in building industry, because they are non-corrosive, non-toxic, do not suffer from supercooling, have a high latent heat of fusion, have suitable melting temperatures and are chemically stable in general. Besides organic paraffins, inorganic salt hydrates are also often used. In contrast to organic paraffins, their thermal stability is lower, but can be improved by adding certain mixtures and substances. It can therefore be concluded that both organic paraffins and inorganic salt hydrates are the most suitable for integration in building applications, and that a final choice between both materials has to be made based on the type of application and the effect of local conditions. With this knowledge, background question 1.4 *('What types of PCM are suitable for application in buildings?'*) is answered.

Research has shown that the optimal phase change temperature mainly depends on the absorbed solar heat and the thermostat set-points in buildings. For heating purposes, the phase change temperature should be just above heating set-point temperature and for cooling purposes, the phase-change temperature should be just below the cooling set-point temperature. When a PCM is in contact with solar radiation, a slightly higher melting temperature is desired. With this knowledge, background question 1.5 ('*What is the optimal phase change temperature of a PCM in buildings?*') is answered. When looking at background question 1.2: '*Does climate influence the selection of a PCM?'*, it can now be concluded that not climate, but thermostat set-points are the main influencing variables. Climate, however, also plays an important role, because climate largely determines the amount of incoming solar radiation. In addition, thermostat set-points are often based on climatical conditions (lower heating set-points in cold climates, higher cooling set-points in warm climates). If background question 1.2 has to be answered with only taking the LTATW system in a temperature controlled building in mind, the conclusion is clearer. Namely, when assuming that the thermostat set-points of all buildings equal 20 ºC for heating and 26 ºC cooling, the phase change temperature of a PCM always approaches the average of the heating and cooling thermostat set-points. As solar radiation plays a role too, the transition temperature lies closer to the cooling set-point than the heating set-point.

Chapter 4 ended with a review of common building applications. The review showed that PCM's are widely being studied and used in many building applications, and that in all cases the PCM has a positive influence on the thermal performance of a room or building. Nowadays, still many more buildings without PCM exist than with, but the literature review gives the suspicion that this may be different in the future.

CHAPTER 5: TROMBE WALLS WITH PHASE CHANGE MATERIAL

Chapter 5 discussed the working principle of a PCM Trombe wall and gave a literature review of research that has been done over the years. Every study proves that replacing the solid, stony Trombe wall with PCM or adding PCM to the wall increases the thermal performance of it. By adding phase change material to a stony Trombe wall, the heat capacity is increased and at the same time, weight can be reduced. When the storage material a traditional Trombe wall is fully replaced by phase change material, the wall is no longer a complete obstruction for incoming sunlight and view to the outside environment. As all studies show that integrating PCM into a Trombe wall leads to a better performance in terms of providing thermal comfort, the system is interesting for further research. Future research will have to show whether the reduction in energy demand and the improvement of thermal comfort will outweigh the (investment) costs of adding PCM to the system.

CHAPTER 6: LIGHTWEIGHT TRANSLUCENT ADAPTABLE TROMBE WALL

Chapter 6 introduced the lightweight translucent adaptable Trombe wall. This new type of Trombe wall is not as heavy as a traditional Trombe wall, does not block daylight and can be adapted to the changing environmental conditions and seasonal differences throughout the year. It therefore seems to avoid all the major drawbacks of a traditional Trombe wall. Literature review has shown the progress of the Double Face research project and its most important results. Compared to all other Trombe-wall configurations discussed in chapter 3, this type of Trombe wall can be used in both summer and winter, is translucent and does not involve space-consuming materials like water and thick pieces of stony materials.

Research has proven that the specific new features such as rotation really pay-off and that a significant reduction in energy demand can be achieved. It also showed that the PCM-panel is capable of maintaining a more stable and comfortable indoor room temperature for many days after a day of moderate sunshine without requiring an additional heating system.

In the end, an overview of the most optimal characteristics of a LTATW was given. A PCM with a melting temperature of 23-26 °C and a freezing temperature of 22-24 °C was chosen, which corresponds well with the knowledge obtained from literature research about most optimal phase change temperature. The melting temperature of the PCM is higher than the heating set-point temperature and the solidification temperature of the PCM is slightly lower than the cooling set-point temperature. Because the PCM-wall is in direct contact with solar radiation, the average of the melting and solidification temperatures lies closer to the cooling set-point than to the heating set-point. The selected PCM (SP25E2) is an inorganic salt hydrate that has been preferred over an organic PCM, especially because of lower costs, compatibility with plastic containers, non-flammability, lower volume changes and higher latent heat of fusion. Most optimal material layer thicknesses and other specifications like cavity width were determined and will also be used in this Master's thesis project.

CHAPTER 7: CLIMATE CLASSIFICATION

In chapter 7, a climate classification according to the Köppen-Geiger system was described. It was revealed that the five major climate types are: a tropical climate, a dry climate, a temperate climate, a cold climate and a polar climate. Three representative cities were selected for each of these climates, after which one best representative city remained after a final elimination step. With this knowledge, background question 1.1 ('*What climates need to be studied'*) can be answered. To limit the scope of the research, it was intended to study only the major climate types. Now that we know that there are five major climate types, the answer should be: a tropical climate, a dry climate, a temperate climate, a cold climate and a polar climate. However, because the polar climate is almost uninhibited, there is no point in researching when knowing that the gained knowledge from this research will not or hardly be applied. Therefore, the polar climate will be disregarded and the four remaining climate types were further investigated during this project.

The second part of chapter 7 described which cities best represent the major climates. It was concluded that the selected cities were: Singapore, Cairo, Milan, Ft. Smith and Resolute. Unfortunately, however, the latter two cities are located in a polar climate according to the Köppen-Geiger classification system. Therefore, another representative city must be chosen for a cold climate. It has been decided to choose Stockholm, because according to the classification system of Mansy, it represents the cold climate as second best. To conclude, the climate data used in this study are from to the cities: Singapore, Cairo, Milan and Stockholm.

The final part of chapter 7 described the influence of climate on the thermal comfort standards in buildings. This literature study was done to answer background question 1.5 ('*Do climate and building function influence the thermostat set-points of a building?*'). From the literature study, it was found that thermal comfort can be measured with comfort indexes such as the PMV and the PPD and that the study of HTI showed that the value of these indices is not necessarily dependant on the location on the world. Therefore, for further research, it can be assumed that the recommended thermostat-setpoints in buildings are approximately the same at every location in the world. In this research project, two buildings functions are studied: offices and residences. From Table 7.4 can be seen that the recommended minimal heating thermostat-setpoint in residences equals 20 °C and the recommended maximum cooling thermostat set-point equals 26 °C. For offices, this is the same.

PART III
CREATION AND DEVELOPMENT OF SIMULATION MODEL

9. THEORY OF THERMAL ENERGY BALANCES

To determine how much energy a room or building demands to maintain a required level of health and comfort, it is necessary to make an inventory of all building-related flows of energy. If the sum of these energy flows is negative, too little heat is received by the building and heating is needed. When the sum of the energy flows is positive, cooling is required. The process of making an inventory of all energy flows is called an energy balance and is based on a thermodynamical law: the amount of energy entering an isolated system, kept at constant temperature, is equal to the amount of energy leaving the system (van der Spoel, 2016). There are different ways to draw up an energy balance for a building, and one is more detailed than the other. In this chapter, the basic principles of different approaches of heat balances are explained. First, all main parameters that appear in the balance are highlighted one by one. Then, the principle of a simple (stationary) heat balance is explained. The chapter ends with the most advanced version of a heat balance: the non-stationary multi-node heat balance, which is used in the numerical simulations in this project.

9.1. FLOWS OF ENERGY

Heat transfer mainly takes place as a result of conduction, convection or radiation. In a building, these heat transfer mechanisms are combined into four main energy flows (Van Bueren, van Bohemen & Visscher, 2012):

- Transmission
- Ventilation and infiltration
- Solar gains
- Internal heat gains

9.1.1. TRANSMISSION

As a result of the temperature difference between the indoor and outdoor air, heat will flow through the building envelope. A heat flow can take place through walls, glazing, roofs and floors and is a combination of conduction, convection and radiation (see Figure 9.1).

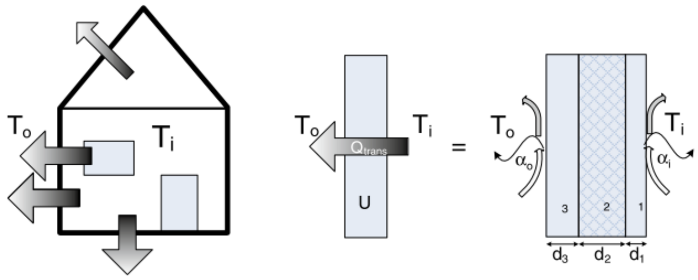


Figure 9.1: transmission losses through walls, window, floor and roof (left) and their relationship with convection, conduction and radiation (right) (Van Bueren et al., 2012).

The transmission through a construction can be calculated using equation 9.1 and 9.2:

$$Q_{trans,s} = U\ A\ (T_e - T_i) \tag{9.1}$$

$$\text{where} \quad U = \frac{1}{\frac{1}{\alpha_i} + R_c + \frac{1}{\alpha_o}} \tag{9.2}$$

In the above equations, $Q_{trans,s}$ represents the transmission heat loss (or gain) in W, T_e represents the outdoor temperature (K), T_i the indoor temperature (K), U the overall heat transfer coefficient of the construction in W/m^{2}K and A the surface area (m^2) of the construction wall. The U-value is calculated with the R_c-value (m^{2}K/W) and the combined heat transfer coefficients for convection and radiation (α_o and α_i). For α_i a value of 7.8 is often assumed (when the air speed in buildings is relatively low) and for α_o the value strongly depends on the wind speed, but a yearly average value of 25 W/m^{2}K is often applied (Van Bueren et al., 2012). If a construction wall is composed of multiple layers (three shown in equation 9.3), the thermal resistance is calculated as follows:

$$R_{c,tot} = R_{c,1} + R_{c,2} + R_{c,3} = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} \tag{9.3}$$

In equation 9.3, d represents the thickness of the construction layer (m) and λ the thermal conductivity of the material (W/mK). To find out how much energy is being transported due to transmission, the transmission through windows, walls, roofs and ground should be added together. When the outdoor temperature is lower than the indoor temperature, heat is transferred from inside to the outside environment. When the outdoor temperature is higher than the indoor temperature, this is the opposite. For windows, the U-value of the total window construction is generally used and for the ground, the transmission medium is the soil instead of the ambient air. In addition to transmission through the envelope, there is also a possibility of transmission due to the presence of thermal bridges. Cold bridges (heat leakages) occur when insulation is not positioned in an optimal way or arise on the spot of a balcony or column/beam that runs from the outdoor climate to the indoor climate. Heat loss due to a linear thermal bridge (W) is calculated with equation 9.4:

$$Q_{bridge} = \Psi\ L\ (T_e - T_i) \tag{9.4}$$

In this equation, L is the length of the thermal bridge (m) and Ψ linear thermal transmittance of the thermal bridge in W/mK. The total heat transfer as result of transmission (W) can now be calculated using equation 9.5:

$$Q_{trans} = Q_{trans,s} + Q_{bridge} \tag{9.5}$$

In the continuation of this study, heat losses due to thermal bridges are ignored, as a cubic room in the middle of a building, without the presence of many junctions and balconies is studied.

9.1.2. VENTILATION AND INFILTRATION

Air from outside ('fresh' air) flows into and out of a building through openings in the façade (windows, grilles, pipes, etc.). This flow of air can be experienced as desired (ventilation) or as undesired (infiltration).

Infiltration takes place uncontrollably, depends on the technical quality of a building and mainly takes place through cracks and seams in the construction (especially when connecting window frames against walls and roofs against walls). Infiltration is difficult to model in detail and is often calculated using practical rules of thumb (Van Bueren et al., 2012). Ventilation is of great importance to ensure health and comfort in a building, as fresh air is necessary for the supply of oxygen, the removal of waste materials, odors and moisture, keeping the building at a desired temperature and, for example, to provide certain rooms with an overpressure in case of fire. The amount of ventilation air that a person requires depends on his or her metabolism and therefore his or her level of physical activity. In smaller buildings with lower occupancy rates (such as residences), the amount of air entering the building through infiltration and opening windows is often enough to ensure a healthy amount of fresh air (not always found enough by building regulations, however). In general, an airtight envelope is found in new buildings and extra measures for ventilation are needed as result (Van Bueren et al., 2012).

Heat losses (or gains) due to infiltration (W) are approximated with equation 9.6:

$$Q_{inf} = \dot{m}_{inf} \, C_{p,air} \, (T_e - T_i) \tag{9.6}$$

Here, $\dot{m}_{inf}$ is the mass flow rate of air (kg/s) and $C_{p,air}$ is the heat capacity of dry air in J/kgK. The heat capacity is equal to 1000 J/kgK (at ambient temperature) and stands for the amount of heat that one kilogram of air can absorb at a temperature change of 1 K. To convert a volume flow rate in a mass flow rate of air (kg/s), one can use the following equation:

$$\dot{m}_{inf} = \frac{\rho_{air} \, \dot{V}_{hour}}{3600} = \frac{\rho_{air} V_{room} ACH}{3600} \tag{9.7}$$

The density of air varies with temperature, but an average value of 1.2 kg/m^3 is often assumed. $\dot{V}_{hour}$ represents the volume flow rate of air in m^3/h. Due to the dependence on the size of cracks, seams and openings in the façades and local pressure differences around the structural parts, the determination of the mass flow rate is not easy. In general, the mass flow rate is based on the infiltration rate (ACH), which indicates how often the building volume is changed per hour. A ventilation rate between 0.1 and 0.2 applies for large, air-tight new buildings and a value between 0.2 and 0.3 for small new buildings. For old buildings, an infiltration rate between 0.5 and 1 generally applies (Van Bueren et al., 2012). The three basic types for ventilation are shown in Figure 9.2.

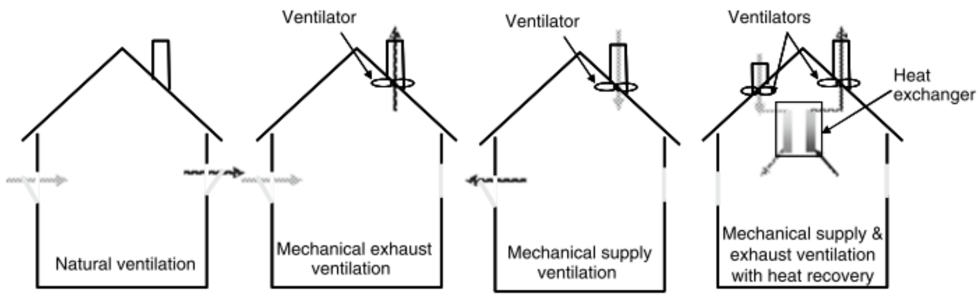


Figure 9.2: The main types of ventilation systems in buildings (Van Bueren et al., 2012).

- Natural ventilation through windows and grilles. No fan required.
- Ventilation via mechanical supply or discharge. One fan required.
- Balanced ventilation with heat recovery. Two fans (and a heat recovery system) required.

In case of balanced ventilation, a heat recovery system is almost always added. In the cooling season, warm outside air is freely cooled by using the colder inside air. In the heating season the cold outside air is heated with the relatively warm indoor air. The heat loss (W) due to ventilation (for all three systems) can be calculated with equation 9.8:

$$Q_{vent} = (1-\mu) \, \dot{m}_{vent} \, C_{p,air} \, (T_e - T_i) \tag{9.8}$$

In case of natural ventilation or ventilation with mechanical supply or discharge, the value of μ equals 0. In case of balanced ventilation with heat recovery, the value of μ varies between 0.60 and 0.95 (Van Bueren et al., 2012).

9.1.3. SOLAR GAINS

Solar radiation penetrates a building through the windows and is largely absorbed by the surface of walls, floors and roofs, which experience an increase in temperature. When the surface temperature exceeds the indoor temperature, the absorbed heat will flow back into the room via conduction and convection (see Figure 9.3).

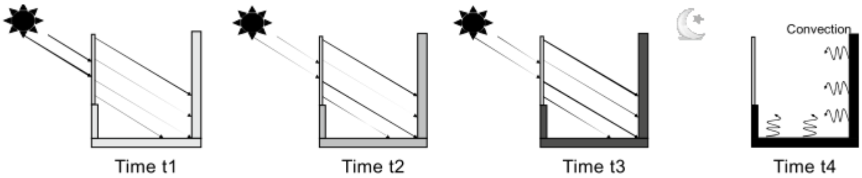


Figure 9.3: Process of absorption of solar radiation into parts of the construction (Van Bueren et al., 2012).

In buildings with a high thermal mass, this process is slower than in a building with low thermal mass. The accumulated quantity of heat is therefore determined by the total thermal mass of a building and the heat capacity of the materials used. A concrete floor, for example, absorbs heat much better than a wooden floor and a floor covered with furniture absorbs much less heat than an uncovered floor. In addition to the thermal mass of a building, the incoming heat due to solar irradiation is highly dependent on the orientation, surface and physical properties of windows (Van Bueren et al., 2012). The percentage of total solar radiation transmitted through a glazed surface is translated into the SHGC value. In addition to the SHGC value of the glazing, the SHGC value of external shading is important to consider as well. A rough estimate of the incoming energy due to solar radiation (W) can be made with equation 9.9:

$$Q_{sol} = \sum_i SHGC^i_{glass} \cdot A^i_{window} \cdot SHGC^i_{shade} \cdot q^i_{sol,w} \tag{9.9}$$

In this case, for each facade with orientation i the $SHGC_{glass}$ value (-) is equal to the combined SHGC value for both the glass and the window frame. $q_{sol,w}$ is the total solar radiation in W/m^2 and A is the surface area of the window in m^2. As mentioned, the use of equation 9.9 leads to a rough estimate of reality. A more detailed calculation requires advanced software (Van Bueren et al., 2012).

9.1.4. INTERNAL HEAT GAINS

Internal heat gains are the result of the energy produced by people and by electrical appliances such as computers, refrigerators, washing machines, printers and lighting. The human body produces heat that is transferred to the environment to maintain a normal body temperature. Heat is propagated through exhaled air, sweat and convection at the closer area of the skin. The amount of heat released depends on the level of activity, the amount of clothes that are worn and the temperature and moisture content of the surrounding air (Höppe, 1993). The internal heat production (W) due to the presence of people is calculated with equation 9.10:

$$Q_{int,people} = n_{people} \cdot Q_M \tag{9.10}$$

Here, n is equal to the number of people present and Q_M equals the heat production per person in W. Only a very small part of the energy needed to make lighting possible is converted into light. The largest part comes as free heat in a room through radiation and convection. The light itself is absorbed by walls, floors and furniture and is finally converted into heat and released to the room. As a result, it can be assumed that all installed lighting power is finally released as heat. The internal heat gains coming from artificial lighting (W) can be calculated using equation 9.11:

$$Q_{int,lighting} = \xi_{light,vent} \cdot \beta_{floor} \cdot A_{floor} \cdot q_{light} \tag{9.11}$$

Herein, A is the relevant floor area in m^2, q_{light} the electrical power of the lighting in W/m^2 and $\xi_{light, vent}$ the fraction of the power that is released to the room. $\xi_{light, vent}$ is equal to 1 (-) when the luminaires are not ventilated and $\xi_{light, vent}$ is 0.2-0.6 if they are ventilated. β_{floor} is equal to the percentage of the floor surface that is lit at the relevant time. For estimates, a value of 1 is generally assumed (Van Bueren et al., 2012). For electrical devices such as printers, televisions, computers, servers, refrigerators and freezers, a large part of the power is converted into heat. This heat (W) is transferred to the room and can be calculated with equation 9.12:

$$Q_{int,app} = A_{floor} \cdot q_{app} \tag{9.12}$$

Here, q_{app} is the total heat production of all appliances (excluding lighting) in W/m^2. The total internal heat production in W can be calculated with equation 9.13:

$$Q_{int} = Q_{int,people} + Q_{int,lighting} + Q_{int,app} \tag{9.13}$$

9.2. STATIONARY HEAT BALANCES

The first type of heat balance that is discussed in this chapter is the stationary heat balance. When considering problems of stationary heat transfer, temperatures and heat fluxes are constant in time. In a stationary system, the energy conservation law is the starting point and states that the sum of heat flows coming from the interior and exterior must add to zero (van der Spoel, 2016). The conservation law can be applied to a one-dimensional system (line), a two-dimensional system (surface) and a three-dimensional system. When regarding a room or a complete building (three-dimensional), the interior is generally called the 'control volume'. In a stationary heat balance, thermal energy storage is not taken into account.

In all types of heat balances, the incoming heat flows obtain a positive sign in the balance and outgoing heat flows obtain a negative sign. The stationary heat balance is shown in equation 9.15:

$$\Sigma Q = 0 \qquad Q_{trans} + Q_{inf} + Q_{vent} + Q_{sol} + Q_{int} + Q_{added} = 0 \tag{9.15}$$

In this balance, all quantities are shown as positive, but energy flows leaving the control volume must enter the balance with a negative sign. Before setting up a stationary heat balance, it is important to properly define the boundaries of the control volume. Only then, the heat flow through the boundaries can be easily determined (van der Spoel, 2016). If the sum of these energy flows is negative, too little heat is received by the building and heating is needed. When the sum of the energy flows is positive, cooling is required:

If $Q_{added} < 0$: $Q_{added} = Q_{cooling}$
If $Q_{added} = 0$: no heating or cooling required.
If $Q_{added} > 0$: $Q_{added} = Q_{heating}$

9.3. NON-STATIONARY HEAT BALANCES

A more realistic calculation of the energy demand of (rooms in) buildings is not based on a stationary heat balance, but on a non-stationary heat balance. Non-stationary means that heat fluxes and temperatures vary with time (van der Spoel, 2016). A non-stationary heat balance therefore, represents a much more realistic outcome than a stationary heat balance as temperatures and heat fluxes in and around buildings regularly change and thermal storage should not be neglected. Because of the complex nature of non-stationary heat balance calculations, computer models are often used. In this section, the numerical principle of these computer calculations is explained. The principles of the modelling approach will first be clarified based on a simplified one-node model for a room. After that, also an example of a multi-node room is shown.

9.3.1. PRINCIPLE

The principle of a non-stationary heat balance is first explained based on a simplified one-node room model with schematization shown in Figure 9.4. The model consists of a basic, rectangular room with one thermal node, which represents the heat storage in the room air, ceilings, walls, floors and furniture. The temperature of the thermal node is assumed to be the same as the operative room temperature and only incoming solar radiation and transmission through the exterior wall are considered.

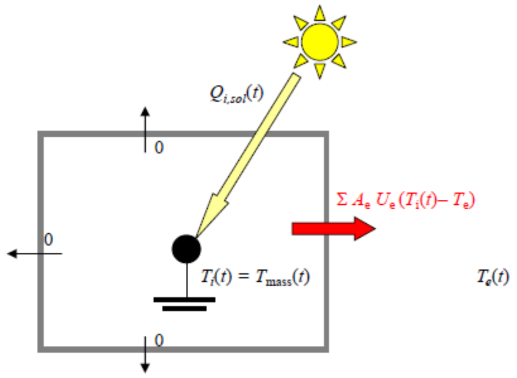


Figure 9.4: one-node room model (van der Spoel, 2016).

The heat balance for this room at time t is shown in equation 9.16:

$$+Q_{sol}(t) + Q_{trans}(t) - M \frac{dT_i(t)}{dt} = 0 \qquad [J/s = W] \qquad (9.16)$$

$$\text{Where } Q_{trans}(t) = H_e(T_e(t) - T_i(t)) \quad \text{and} \quad H_e = \sum U_e A_e$$

In which M represents the total thermal mass (J/K) being the sum of component n with specific heat capacity c_n and mass m_n:

$$M = \sum_n (m_n c_n) \qquad (9.17)$$

By assuming that both heat flows are stationary during the time-step from t to t+Δt, the temperature change $\Delta T_i(t)$ can be calculated with equation 9.18:

$$M \frac{\Delta T_i(t)}{\Delta t} = Q_{sol}(t) + Q_{trans}(t) \qquad (9.18)$$

Since $\Delta T_i(t) = T_i(t+\Delta t) - T_i(t)$, the temperature at time t+Δt can be calculated with equation 9.19:

$$M \frac{T_i(t+\Delta t) - T_i(t)}{\Delta t} = Q_{sol}(t) + Q_{trans}(t) \quad \leftrightarrow \quad T_i(t+\Delta t) = T_i(t) + \frac{\Delta t}{M}(Q_{sol}(t) + Q_{trans}(t)) \qquad (9.19)$$

Equation 9.19 is a so-called fully explicit expression for the time differentiation, which means that the temperature at t+Δt is written as a function of the heat flows and temperature that occurred before time t+Δt (van der Spoel, 2016). Equation 9.19 can also be written in an implicit scheme (temperature change is written in terms of the unknown heat flows at time t+Δt), in an intermediate scheme (combination of explicit and implicit) and in a semi-analytical scheme (based on an analytical expression). Every scheme has its own advantages and disadvantages regarding accuracy and instability issues. By using the Matlab/Simulink software (with even more advanced numerical methods) in this research project, accuracy is provided and instability issues are relatively easy to avoid. Therefore, in this chapter, the heat balances are only shown in an explicit way and stability and accuracy criteria are not discussed.

Because climatic data files are generally used to obtain $Q_{sol}(t)$, equation 9.19 should be written in a slight different way. A given solar load $Q_{sol}(t)$ at time t may refer to the average load occurring between time t-Δt and time t. Since the interval Δt is usually not less than one hour and we want to calculate ΔT_i from time t to t+Δt, it is better to use $Q_{sol}(t+\Delta t)$ (van der Spoel, 2016). The temperature at time t+Δt is then calculated with equation 9.20:

$$T_i(t+\Delta t) = T_i(t) + \frac{\Delta t}{M}(Q_{sol}(t+\Delta t) + Q_{trans}(t)) \qquad (9.20)$$

9.3.2. ONE-NODE ROOM MODEL

To better understand the working principle of a non-stationary heat balance, an example with one thermal node with more heat flows is discussed in this section. In this rectangular room (shown in Figure 9.5), thermal mass, incoming solar radiation, ventilation and transmission through an exterior wall are considered. The situation is simplified by excluding the energy flows from infiltration.

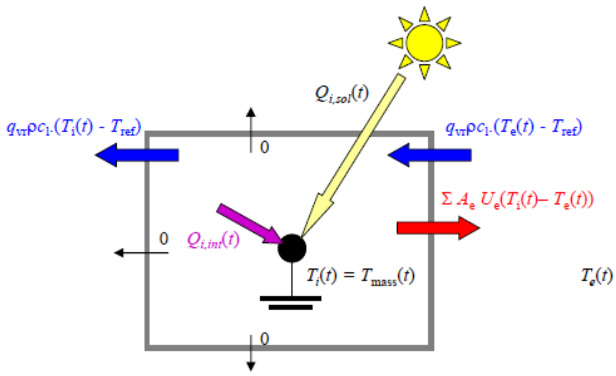


Figure 9.5: one-node room model (van der Spoel, 2016).

The heat balance for this room at time t is shown in equation 9.21. Note that some parameters shown in Fig. 9.5 have been translated into the same, but differently formulated parameters, as used in this thesis ($q_{vr}\rho = \dot{m}_{vent}$).

$$SHGC_{glass}A_{window}q_{sol,w}(t) + Q_{int}(t) + \sum A_e U_e \cdot (T_e(t) - T_i(t)) + \dot{m}_{vent}C_p(T_e(t) - T_i(t)) - M\frac{dT_i(t)}{dt} = 0 \qquad (9.21)$$

Or more concisely:

$$Q_{int,tot}(t) + Q_{trans}(t) - M\frac{dT_i(t)}{dt} = 0 \qquad (9.22)$$

where $Q_{int,tot}(t) = Q_{sol}(t) + Q_{int}(t)$

$$Q_{trans+vent}(t) = H_{tot}(T_e(t) - T_i(t))$$

$$H_{tot} = \sum A_e U_e + \dot{m}_{vent}C_p$$

Following Eq. (9.20), the explicit expression for the temperature reads:

$$T_i(t+\Delta t) = T_i(t) + \frac{\Delta t}{M}(Q_{int,tot}(t+\Delta t) + Q_{trans}(t)) \qquad (9.23)$$

To calculate the indoor room temperature as a function of time, an Excel spreadsheet can be used.

9.3.3. TWO-NODE ROOM MODEL

Now, two one-node room models are combined into a two-node room model by simply placing them next to each other. A schematization of the two-node model can be seen in Figure 9.6. Note that in addition to the energy flows by solar radiation, ventilation and transmission, the internal air flows are included as well. For each of the rooms, subscripts '1' and '2' are used to indicate the position of the flows. With t' as a continuous time variable and heat gains, losses and storage as constants, the heat balance for room 1 is shown in equation 9.24:

$$Q_{1,sol} + Q_{1,int} - \sum A_{1,e}U_{1,e} \cdot (T_1(t') - T_e(t')) - \sum A_{1,2}U_{1,2} \cdot (T_1(t') - T_2(t')) -$$

$$(\dot{m}_{vent,1\rightarrow e} + \dot{m}_{vent,1\rightarrow 2})C_pT_1(t') + \dot{m}_{vent,e\rightarrow 1}C_pT_e(t') + \dot{m}_{vent,2\rightarrow 1}C_pT_2(t') - M_1\frac{dT_1(t')}{dt'} = 0 \qquad (9.24)$$

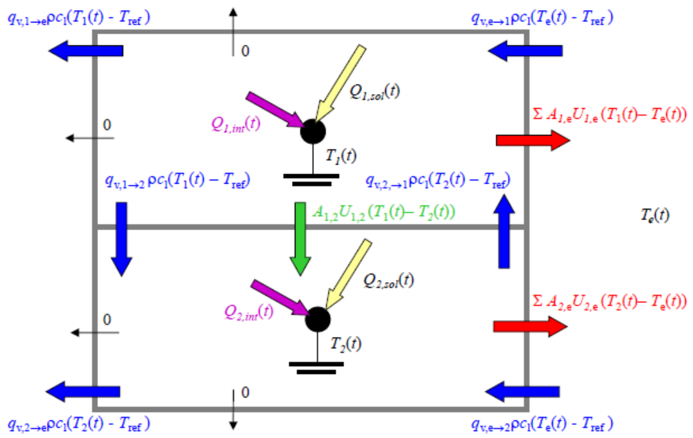


Figure 9.6: two-node model of two adjacent rooms (van der Spoel, 2016).

The heat balance for room 2 is shown in equation 9.25:

$$Q_{2,sol} + Q_{2,int} - \sum A_{2,e}U_{2,e}\cdot (T_2(t')-T_e(t')) + \sum A_{1,2}U_{1,2}\cdot (T_1(t')-T_2(t')) -$$

$$(\dot{m}_{vent,2\to e} + \dot{m}_{vent,2\to 1})C_pT_2(t') + \dot{m}_{vent,e\to 2}C_pT_e(t') + \dot{m}_{vent,1\to 2}C_pT_1(t') - M_2\,\frac{dT_2(t')}{dt'} = 0 \tag{9.25}$$

Equation 9.24 and 9.25 may also be written as:

$$Q_{1,tot} - S_{1,e}T_e(t') - S_{1,1}T_1(t') - S_{1,2}T_2(t') - M_1\,\frac{dT_1(t')}{dt'} = 0 \tag{9.26}$$

$$Q_{2,tot} - S_{2,e}T_e(t') - S_{2,1}T_1(t') - S_{2,2}T_2(t') - M_2\,\frac{dT_2(t')}{dt'} = 0 \tag{9.27}$$

Following equation 9.23, the explicit expressions for the temperature read:

$$T_1(t+\Delta t) = T_1(t) + \frac{\Delta t}{M_1}\,(Q_{int,tot}(t+\Delta t) - S_{1,e}T_e(t) - S_{1,1}T_1(t) - S_{1,2}T_2(t)) \tag{9.28}$$

$$T_2(t+\Delta t) = T_2(t) + \frac{\Delta t}{M_2}\,(Q_{int,tot}(t+\Delta t) - S_{2,e}T_e(t) - S_{2,2}T_2(t) - S_{2,1}T_1(t)) \tag{9.29}$$

9.4. NON-STATIONARY MULTI-NODE HEAT CONDUCTION

Before being able to explain the principle of a non-stationary multi-node heat balance, this section first clarifies the principles of non-stationary multi-node heat conduction. The multi-node time-dependant approach of one-dimensional heat conduction is a mathematical approach which is identical to the approach of convection and radiation, but only has different input values (van der Spoel, 2016). When the principle of multi-node heat conduction is understood, the final step can be made towards a non-stationary multi-node heat balance, in which all forms of heat transfer are included.

As mentioned before, heat flows through a control volume in a non-stationary heat balance need not necessarily add up to zero. When the sum of energy flows result in a negative outcome, a temperature decrease will be the result. Vice versa, a temperature increase will happen when the sum of energy flows result in a positive outcome (equation 9.30). The rate of change of this temperature depends on the thermal capacity M of the control volume, which is calculated by multiplying the control volume, the material's mass density (assumed to be homogenous) and its specific heat capacity (equation 9.31). In equation 9.30, the partial derivative is taken, because the temperature is in fact a function of position and time (more than one variable).

$$\sum Q = M\,\frac{\partial T}{\partial t} \tag{9.30}$$

$$M = \rho c V \tag{9.31}$$

The principle of multi-node heat conduction is explained by considering a problem of one-dimensional heat conduction in a (homogeneous) material with thickness d (see Figure 9.7).

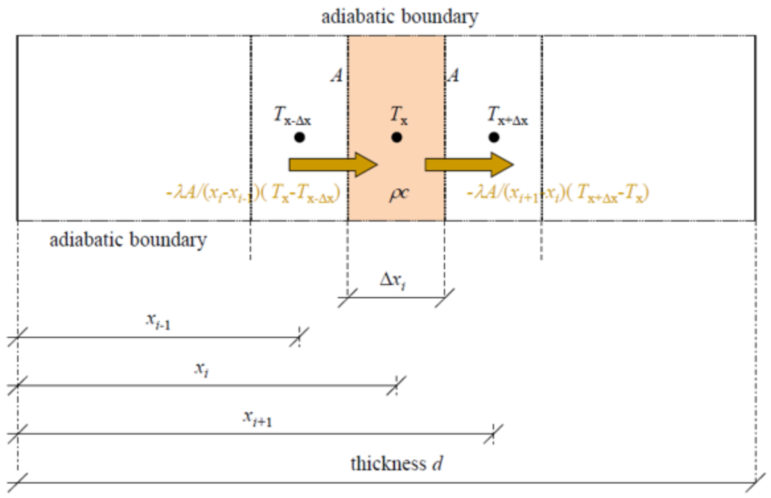


Figure 9.7: Schematization of one-dimensional heat conduction in a solid (van der Spoel, 2016).

The distance from the left boundary to the middle of the material is indicated as x_i and a surface area A represents a surface in perpendicular direction of the figure. For setting up a heat balance equation, the problem domain is subdivided into multiple control volumes which are numbered using index i. So, the first control volume has a subscript '1' and the second volume a subscript '2'. There are N control volumes in total. Each control volume has a certain thickness $d_{x,i}$ and the temperature in the control volume is denoted as $T_{x,i}$. The time-dependent heat balance for heat conduction of the orange control volume is shown in equation 9.32.

$$\frac{-\lambda A}{x_i-x_{i-1}}\left(T_{x_i}-T_{x_{i-1}}\right)-\frac{-\lambda A}{x_{i+1}-x_i}\left(T_{x_{i+1}}-T_{x_i}\right)=\rho c A \Delta x_i \frac{\partial T_{x_i}}{\partial t} \tag{9.32}$$

When materials with different properties are considered, extra care must be taken to model the correct heat flux between the adjoining control volumes (van der Spoel, 2016). Figure 9.8 shows a schematization of two adjoining control volumes and the heat flux between both volumes can be written as:

$$\frac{-A(T_{x_{i+1}}-T_{x_i})}{\frac{\Delta x_i}{2\lambda_i}+\frac{\Delta x_{i+1}}{2\lambda_{i+1}}}$$

The nodal points are situated in the centre of the control volumes, so that the distance between the interface and the nodal point equals half the control volume width (van der Spoel, 2016).

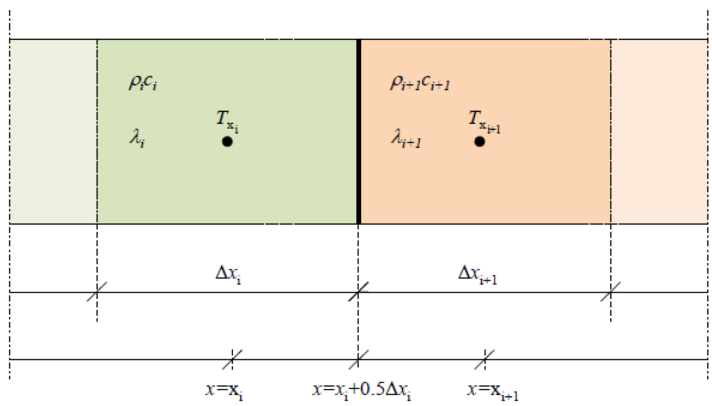


Figure 9.8: Schematization of 1-D heat conduction at a transition between two different materials (van der Spoel, 2016).

The heat balance of one control volume now reads:

$$\frac{-A(T_{x_i}-T_{x_{i-1}})}{\frac{\Delta x_i}{2\lambda_i}+\frac{\Delta x_{i-1}}{2\lambda_{i-1}}}-\frac{-A(T_{x_{i+1}}-T_{x_i})}{\frac{\Delta x_i}{2\lambda_i}+\frac{\Delta x_{i+1}}{2\lambda_{i+1}}}=\rho_i c_i A\Delta x_i\frac{\partial T_{x_i}}{\partial t} \tag{9.33}$$

9.5. NON-STATIONARY MULTI-NODE HEAT BALANCES

Where the non-stationary multi-node heat conduction problem shown in the previous chapter could still be solved with a spreadsheet, most problems in practice involve more than just one-dimensional heat conduction (van der Spoel, 2016). To solve these more advanced problems, a non-stationary multi-node heat balance should be drawn up, that can be solved with more advanced software, such as Matlab/Simulink. One example of a multi-node heat balance has already been treated in the previous section, namely: a two-node heat balance. Two heat balance equations were derived:

$$Q_{1,tot} - S_{1,e}T_e(t) - S_{1,1}T_1(t) - S_{1,2}T_2(t) - M_1\frac{dT_1(t)}{dt'}=0 \tag{9.26}$$

$$Q_{2,tot} - S_{2,e}T_e(t) - S_{2,1}T_1(t) - S_{2,2}T_2(t) - M_2\frac{dT_2(t)}{dt'}=0 \tag{9.27}$$

By using a matrix notation, the equations can be written down in a more concise manner:

$$\begin{pmatrix}Q_{1,tot}\\Q_{2,tot}\end{pmatrix}-\begin{pmatrix}S_{1,e}\\S_{2,e}\end{pmatrix}T_e(t)-\begin{pmatrix}S_{1,1} & S_{1,2}\\S_{2,1} & S_{2,2}\end{pmatrix}\begin{pmatrix}T_1(t)\\T_2(t)\end{pmatrix}-\begin{pmatrix}M_1 & 0\\0 & M_2\end{pmatrix}\begin{pmatrix}\dot{T}_1(t)\\\dot{T}_2(t)\end{pmatrix}=0 \tag{9.34}$$

An even shorter notation is:

$$\mathbf{M}\underline{\dot{T}}+\mathbf{S}\underline{T}=\underline{Q} \tag{9.35}$$

Where **M** is the so-called mass matrix, **S** the stiffness matrix, $\underline{\mathbf{Q}}$ the load vector and $\underline{\mathbf{T}}$ the vector with the time-dependent variables. When considering a problem with N nodes, N equations will arise and the following matrices can be formed:

$$\begin{pmatrix}M_1 & & & & & & 0\\ & M_2 & & & & & \\ & & M_3 & & & & \\ & & & \ddots & & & \\ & & & & M_{N-2} & & \\ & 0 & & & & M_{N-1} & \\ & & & & & & M_N\end{pmatrix}\begin{pmatrix}\dot{T}_1\\\dot{T}_2\\\dot{T}_3\\\vdots\\\dot{T}_{N-2}\\\dot{T}_{N-1}\\\dot{T}_N\end{pmatrix}+$$

$$+\begin{pmatrix}S_{1,1} & S_{1,2} & & & & & \\ S_{2,1} & S_{2,2} & S_{2,3} & & & 0 & \\ & S_{3,2} & S_{3,3} & S_{3,4} & & & \\ & \ddots & \ddots & \ddots & & & \\ & & & & S_{N-2,N-2} & S_{N-2,N-1} & \\ & 0 & & & S_{N-1,N-2} & S_{N-1,N-1} & S_{N-1,N}\\ & & & & & S_{N,N-1} & S_{N,N}\end{pmatrix}\begin{pmatrix}T_1\\T_2\\T_3\\\vdots\\T_{N-2}\\T_{N-1}\\T_N\end{pmatrix}=\begin{pmatrix}Q_1\\Q_2\\Q_3\\\vdots\\Q_{N-2}\\Q_{N-1}\\Q_N\end{pmatrix} \tag{9.36}$$

According to the modelling approach in this thesis, the mass matrix only contains positive values at the diagonal. The number of control volumes does not influence the solution T(t), but does only yield different matrices. Once the user has defined the matrices **M**, **S** and $\underline{\mathbf{Q}}$, Matlab/Simulink is able to solve equation 9.35 with by using in-built functions and calculates the temperatures as a function of time (van der Spoel, 2016).

In order to create a simulation model of a room, a clear schematization of the heat transfer problem needs to be made. The schematization includes the following steps, described by van der Spoel (2016):

1. Determine the position of the control volumes and thermal nodes. Figure 9.7 and 9.8 already gave some insight how to do this.
2. Assign a node (or multiple nodes) to a known or bound temperature, such as the outside air temperature.
3. Number each node. From a programming point of view, it is convenient to number the nodes with a bound/known temperature as the last ones.
4. Determine which process(es) of heat transfer occur between each pair of nodes.
5. Determine where the heat loads occur.
6. Populate the mass matrix by assigning the specific thermal mass to each node, except for the bound nodes.
7. Populate the stiffness matrix by formulating each heat transfer process between nodes.
8. Populate the load vector.
9. Separate the free nodes from the **M** and **S** matrix from the bound nodes of the matrices.
10. Transfer the terms of the **S** matrix with bound nodes to the right-hand side of the equation system.

9.5.1. SETTING UP THE MASS MATRIX

The mass matrix **M** is formed based on the size and location of the control volumes, the position of the thermal nodes and the mass properties of the material. In the method used in this thesis, only the diagonal of the mass matrix contains values and each value on the diagonal represents the thermal capacity (J/K) of the corresponding control volume. The thermal capacity is calculated as shown in equation 9.37:

$$M_i = \rho_i c_i A \Delta x_i \tag{9.37}$$

9.5.2. SETTING UP THE STIFFNESS MATRIX

Heat transfers from one node to another, generated by conduction, radiation or convection. Each of these heat transfer processes are characterized by its own, typical coupling factor. In case of conduction, the heat transfer rate between two nodes is governed by the distance Δx between the nodes, the heat conduction coefficient λ of the material in between and the surface area A through which the transfer takes place. The coupling factor, which denotes the heat transfer rate (W) between node i and j at temperature difference of 1 kelvin, is defined as follows:

$$C_{i,j} = \frac{\lambda A}{\Delta x} \tag{9.38}$$

In case of radiation, the (linearized) heat transfer rate between two nodes is governed by the surface emissivity ε, the surface area A, the exchange coefficient ψ and the black-body radiative heat transfer coefficient h_{rb}. The heat transfer due to radiation can be calculated with equation 9.39:

$$Q_{ij} = \varepsilon_i \varepsilon_j A_i \psi_{ij} h_{rb}(T_i - T_j) \tag{9.39}$$

Therefore, the coupling factor is written as shown in equation 9.40:

$$C_{i,j} = \varepsilon_i \varepsilon_j A_i \psi_{ij} h_{rb} \tag{9.40}$$

In case of convection, the heat transfer rate between two nodes is governed by a convection coefficient α_c and the surface area A. The heat transfer due to convection can be calculated with equation 9.41:

$$Q_{ij} = \alpha_{c,i,j} A(T_i - T_j) \tag{9.41}$$

The coupling factor is written as shown in equation 9.42:

$$C_{i,j} = \alpha_{c,i,j}A \tag{9.42}$$

9.5.3. SETTING UP THE LOAD VECTOR

The components of load vector **Q** contains all heat loads (W) occurring on the thermal nodes. A positive value is called a heat source, which means that heat is being added. A negative value is called a heat sink, which means that heat is being removed (van der Spoel, 2016).

9.5.4. SOLUTION PROCEDURE IN SIMULINK

By following steps 9 and 10 of the schematization procedure described in section 9.5, equation 9.35 should be re-written as follows:

$$\mathbf{M\dot{\underline{T}} + S\underline{T} = \underline{Q} - S_{bound}\underline{T}_{bound}} \tag{9.43}$$

By multiplying both sides of the equation with $\mathbf{M}^{-1}$, the following expression is obtained:

$$\mathbf{\dot{\underline{T}} = M^{-1}(\underline{Q} - S\underline{T} - S_{bound}\underline{T}_{bound})} \tag{9.44}$$

Or by time-integration:

$$\mathbf{\underline{T}(t) = \int_0^t M^{-1}\,(\underline{Q} - S\underline{T} - S_{bound}\underline{T}_{bound})dt} \tag{9.45}$$

Equation 9.45 is basically the equation being solved in Simulink. How the equations and matrices shown in this chapter are implemented in Matlab/Simulink is shown in the next chapter.

10. INITIAL SIMULATION MODEL

Now that the theory behind thermal energy balances has been made clear, the next step towards the implementation of a dynamic room system with a lightweight translucent adaptable Trombe wall in Matlab/Simulink can be made. As stated in the previous chapter, the room model with which the study is conducted is entirely based on a non-stationary multi-node heat balance. For each problem or system, the schematization with geometries, control volumes, thermal nodes and simulation conditions is different, but every system is based on the same mathematical principle. In this chapter, all features of the initial simulation model, which was developed in the Double Face 1.0 project, are extensively described. The model schematization is described in section 10.1, all model components and capabilities are described in section 10.2 and the most important Simulink components are described in section 10.3.

10.1. MODEL SCHEMATIZATION

As mentioned before, a simulation model was developed in DF1.0, and was used to get a first idea of the energy savings that could be achieved in a 'basic' residential room. In this section, the schematization of the room and the LTATW is described, node definitions are shown, modes of heat transfer are elucidated and the corresponding mass matrix and stiffness matrix are presented.

10.1.1. SCHEMATIZATION OF ROOM AND LTATW

The initial simulation model consists of a cubic room, which walls are named: orien1, orien2, orien3 and orien4. The LTATW is set to always be behind the orien1 wall (with glazing) (see Figure 10.1) (Lara et al., 2015). In Matlab, the orientation of the LTATW is determined by the following command:

```
orientation =  180;
```

In DF1.0, all simulations were carried out for a situation with a south-facing LTATW and therefore, the orientation was set at 180. To select another orientation, the following overview can be used:

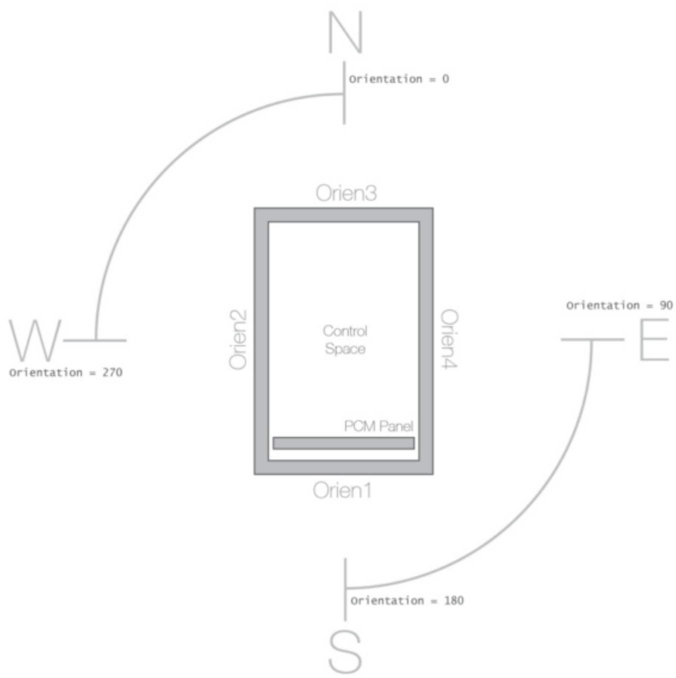


Figure 10.1: Schematization of room/control space with position of PCM panel/LTATW and defined walls and orientations (Lara et al., 2015).

Orientation = 0:	LTATW faces north
Orientation = 90:	LTATW faces east
Orientation = 180:	LTATW faces south
Orientation = 270:	LTATW faces west.

The room dimensions are determined with the following commands:

```
room.depth  = 5.4; % in this case in orien1-orien3 direction
room.width  = 3.6; % in this case in orien2-orien4 direction
room.height = 2.7;
room.volume = room.depth*room.width*room.height; % air volume room [m3]
room.area   = room.depth*room.width;
```

The position and size of windows are determined with the following commands:

```
A_gl_orien1 = 0.8*room.width*room.height; % surface area glass orien1 (m^2)
A_gl_orien2 = 0;                          % surface area glass orien2 (m^2)
A_gl_orien3 = 0;                          % surface area glass orien3 (m^2)
A_gl_orien4 = 0;                          % surface area glass orien4 (m^2)
```

The (total) surface area of the external constructions is determined with the following commands:

```
e1_constr_A  = room.width*room.height-A_gl_orien1;
e2_constr_A  = room.depth*room.height-A_gl_orien2;
e3_constr_A  = room.depth*room.height-A_gl_orien3;
e4_constr_A  = room.depth*room.height-A_gl_orien4;
e5_constr_A  = room.width*room.depth;               % roof
e6_constr_A  = room.width*room.depth;               % floor

A_total =
e1_constr_A+e2_constr_A+e3_constr_A+e4_constr_A+e5_constr_A+e6_constr_A;
```

The presence of the LTATW and the cavity width are determined with the following commands:

```
panel_present = 1;         % 1 = yes, 0 = no
d_cavity      = 0.2;       % width of cavity between panel and wall orien1 (m)
```

10.1.2. NODE DEFINITIONS

The nodes in the model are distributed across the construction envelopes and the LTATW. The first 25 nodes are bound/fixed nodes and are part of the control space interior air and the construction envelope. Each construction wall is set to be made up of three different layers, so: a node is placed at the interior and exterior surface, and at each layer interface, making a total of four nodes per wall (see Figure 10.2). The node numbering starts from the interior to the exterior layer, and moves from wall orien1 to wall orien2, then from wall orien3 to wall orien4 and finally from roof to floor surface (see Figure 10.3). In total, 24 nodes (six walls with four nodes each) are placed in the envelopes and one node (node 25) was set to be the node of the interior air (Lara et al., 2015).

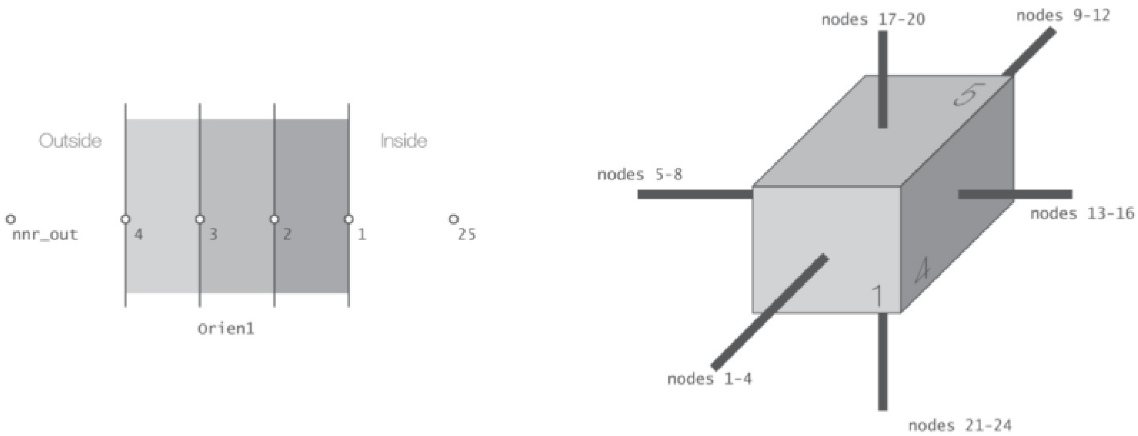


Figure 10.2 and 10.3: Position and definition of room model nodes (Lara et al., 2015).

The number of nodes in the LTATW is determined by the number of control volume layers of the PCM and the number of control volume layers of the insulation. Just like in the construction envelopes, one node was placed at each interface between the control volume layers of the LTATW (see Figure 10.4).

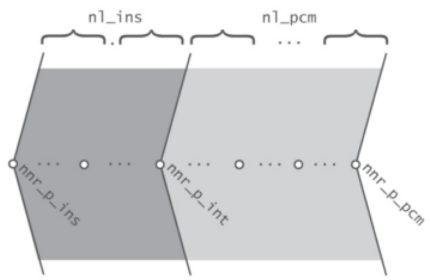


Figure 10.4: Position and definition of nodes in the LTATW (Lara et al., 2015).

The amount of PCM volume control layers and insulation volume control layers is determined by the following commands:

```
nl_pcm       = 3;
nl_ins       = 1;
```

For all simulations carried out during DF1.0, nl_pcm was set at three and nl_ins was set at one. Therefore, the LTATW has a total of five nodes. After defining nodes for the room envelopes, interior air and LTATW, a node was defined to represent the volume in the air cavity. Finally, a last node was defined to represent the outside air (Lara et al., 2015). In the continuation of this report, a further explanation is based on the above set-up for simplicity purposes. However, it must be kept on mind that the node numbering after node 25 changes when the number of control volumes is set differently. Since the behaviour of the LTATW is not isotropic, nodes were set for two possible scenarios: one scenario where the PCM layer faces the interior (Figure 10.5) and one scenario where the PCM layer faces the exterior (Figure 10.6).

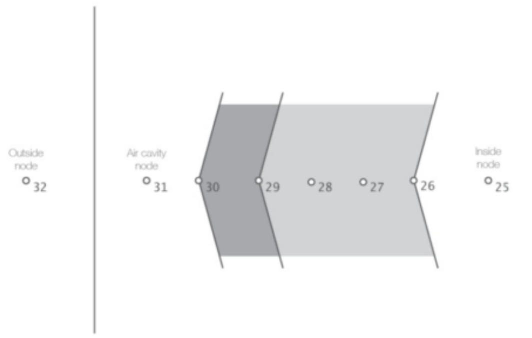


Figure 10.5: Scenario 1: LTATW faces interior (Lara et al., 2015).

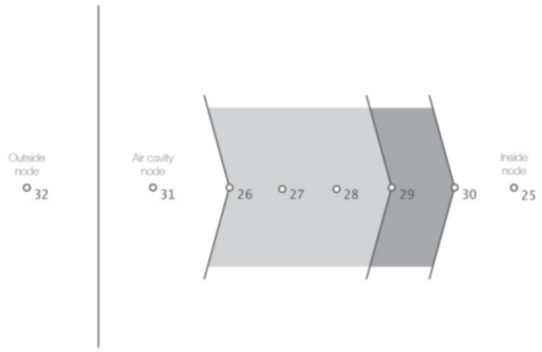


Figure 10.6: Scenario 2: LTATW faces exterior (Lara et al., 2015).

10.1.3. MODES OF HEAT TRANSFER

In this section, the interaction between each node is shown in a graphical manner. The interaction is shown as a coloured line, which represents a transfer of heat due to conduction, convection or radiation. The modes of heat transfer occurring in and at nodes of wall orien2 are shown in Figure 10.7. Note that the modes of transfer are similar for each of the other six room surfaces.

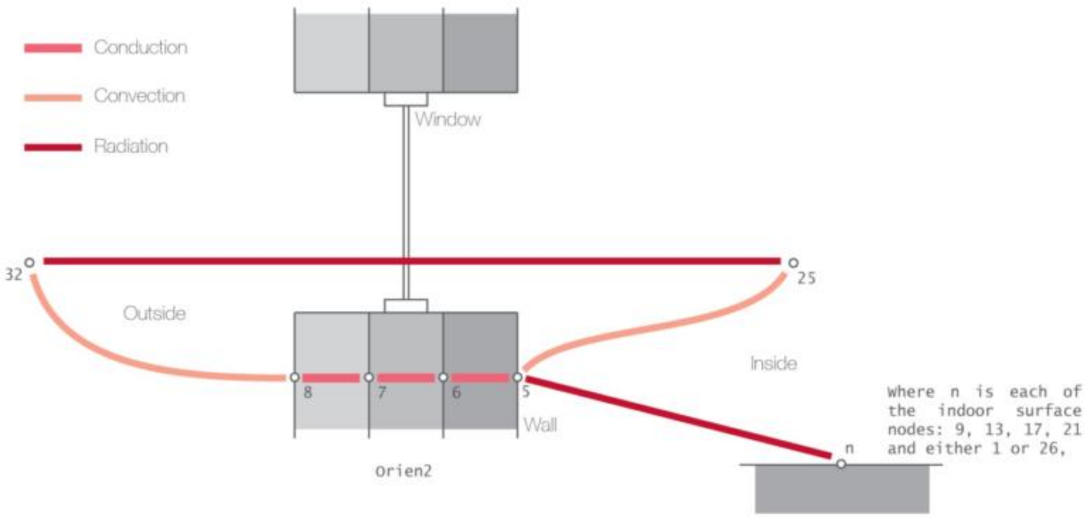


Figure 10.7: Modes of heat transfer for nodes in/at wall at orien2 (Lara et al., 2015).

The modes of heat transfer occurring in and at nodes of the LTATW are shown in Figure 10.8.

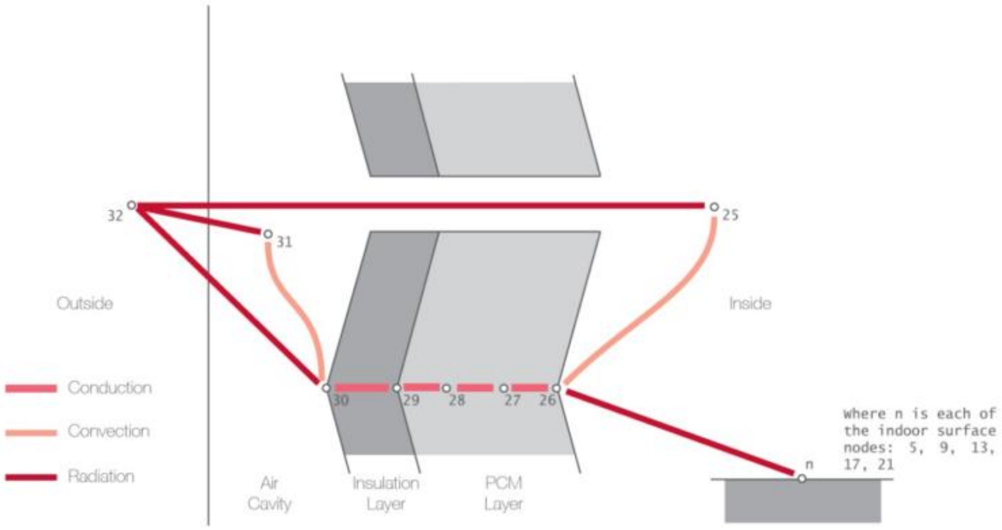


Figure 10.8: Modes of heat transfer for nodes in/at LTATW (Lara et al., 2015).

10.1.4. MASS MATRIX

In this dynamic system, two mass matrices exist: one matrix containing the mass properties of the sensible heat storage materials, and one matrix containing the mass properties of the latent heat storage materials (PCM). The sensible part is shown in section 10.1.4.1. and the latent part is shown in section 10.1.4.2.

10.1.4.1. SENSIBLE PART

The mass matrix for the sensible heat storing part of the room is shown below. As the definition is too long in a number of cases, it is written on the next line. This is obviously not the case in the Matlab script itself.

```
M_r_s(1,1)=   0.5* e1_constr(1).d*e1_constr(1).rho*e1_constr(1).c*e1_constr_A;
M_r_s(2,2)=   0.5*(e1_constr(1).d*e1_constr(1).rho*e1_constr(1).c*e1_constr_A +
              e1_constr(2).d*e1_constr(2).rho*e1_constr(2).c*e1_constr_A);
M_r_s(3,3)=   0.5*(e1_constr(2).d*e1_constr(2).rho*e1_constr(2).c*e1_constr_A +
              e1_constr(3).d*e1_constr(3).rho*e1_constr(3).c*e1_constr_A);
M_r_s(4,4)=   0.5* e1_constr(3).d*e1_constr(3).rho*e1_constr(3).c*e1_constr_A;
M_r_s(5,5)=   0.5* e2_constr(1).d*e2_constr(1).rho*e2_constr(1).c*e2_constr_A;
M_r_s(6,6)=   0.5*(e2_constr(1).d*e2_constr(1).rho*e2_constr(1).c*e2_constr_A +
              e2_constr(2).d*e2_constr(2).rho*e2_constr(2).c*e2_constr_A);
M_r_s(7,7)=   0.5*(e2_constr(2).d*e2_constr(2).rho*e2_constr(2).c*e2_constr_A +
              e2_constr(3).d*e2_constr(3).rho*e2_constr(3).c*e2_constr_A);
M_r_s(8,8)=   0.5* e2_constr(3).d*e2_constr(3).rho*e2_constr(3).c*e2_constr_A;
M_r_s(9,9)=   0.5* e3_constr(1).d*e3_constr(1).rho*e3_constr(1).c*e3_constr_A;
M_r_s(10,10)=0.5*(e3_constr(1).d*e3_constr(1).rho*e3_constr(1).c*e3_constr_A +
              e3_constr(2).d*e3_constr(2).rho*e3_constr(2).c*e3_constr_A);
M_r_s(11,11)=0.5*(e3_constr(2).d*e3_constr(2).rho*e3_constr(2).c*e3_constr_A +
              e3_constr(3).d*e3_constr(3).rho*e3_constr(3).c*e3_constr_A);
M_r_s(12,12)=0.5* e3_constr(3).d*e3_constr(3).rho*e3_constr(3).c*e3_constr_A;
M_r_s(13,13)=0.5* e4_constr(1).d*e4_constr(1).rho*e4_constr(1).c*e4_constr_A;
M_r_s(14,14)=0.5*(e4_constr(1).d*e4_constr(1).rho*e4_constr(1).c*e4_constr_A +
              e4_constr(2).d*e4_constr(2).rho*e4_constr(2).c*e4_constr_A);
M_r_s(15,15)=0.5*(e4_constr(2).d*e4_constr(2).rho*e4_constr(2).c*e4_constr_A +
              e4_constr(3).d*e4_constr(3).rho*e4_constr(3).c*e4_constr_A);
M_r_s(16,16)=0.5* e4_constr(3).d*e4_constr(3).rho*e4_constr(3).c*e4_constr_A;
M_r_s(17,17)=0.5* e5_constr(1).d*e5_constr(1).rho*e5_constr(1).c*e5_constr_A;
M_r_s(18,18)=0.5*(e5_constr(1).d*e5_constr(1).rho*e5_constr(1).c*e5_constr_A +
              e5_constr(2).d*e5_constr(2).rho*e5_constr(2).c*e5_constr_A);
M_r_s(19,19)=0.5*(e5_constr(2).d*e5_constr(2).rho*e5_constr(2).c*e5_constr_A +
              e5_constr(3).d*e5_constr(3).rho*e5_constr(3).c*e5_constr_A);
```

```
M_r_s(20,20)=0.5* e5_constr(3).d*e5_constr(3).rho*e5_constr(3).c*e5_constr_A;
M_r_s(21,21)=0.5* e6_constr(1).d*e6_constr(1).rho*e6_constr(1).c*e6_constr_A;
M_r_s(22,22)=0.5*(e6_constr(1).d*e6_constr(1).rho*e6_constr(1).c*e6_constr_A +
             e6_constr(2).d*e6_constr(2).rho*e6_constr(2).c*e6_constr_A);
M_r_s(23,23)=0.5*(e6_constr(2).d*e6_constr(2).rho*e6_constr(2).c*e6_constr_A +
             e6_constr(3).d*e6_constr(3).rho*e6_constr(3).c*e6_constr_A);
M_r_s(24,24)=0.5* e6_constr(3).d*e6_constr(3).rho*e6_constr(3).c*e6_constr_A;
M_r_s(25,25)=1200*room.volume*4; %rho*c*air_volume times 4 to include furniture
```

The left hand part of the equations defines the matrix positions to be filled and as explained in chapter 9, values only appear on the diagonal of the matrix. The right hand part of the equations equals the outcome of equation 9.37. In this matrix, the thickness of the (first) material layer is defined as `e1_constr(1).d`, the density as `e1_constr(1).rho`, the heat capacity as `e1_constr(1).c` and the surface area as `e1_constr_A`. Node number 25 represents the air volume of the room and is defined by the same heat storage equation, shown in a different form and multiplied by four, to include furniture. The last node number (31) represents the air volume of the cavity:

```
M_r_s(31,31) = d_cavity*room.width*room.height*1200;
```

10.1.4.2. LATENT PART

The mass matrix for the latent heat storing part of the room is shown below. Based on the choice of amount of control volumes, some altered definitions for thicknesses and surface area appear. These are based on logical functions and are not shown here. Again, some of the definitions are too long to fit on this page and are therefore set on the next line. To view the complete script, reference is made to the Matlab-file.

```
if nl_pcm == 1
    M_r_l(nnr_r+1,nnr_r+1)=       0.5*panel_pcm.dx*panel_pcm.rho*
                                  panel_A*panel_pcm.h/(Tl_pcm-Ts_pcm);
    M_r_l(nnr_r+2,nnr_r+2)=       0.5*panel_pcm.dx*panel_pcm.rho*
                                  panel_A*panel_pcm.h/(Tl_pcm-Ts_pcm);
else
    M_r_l(nnr_r+1,nnr_r+1)=       0.5*panel_pcm.dx*panel_pcm.rho*
                                  panel_A*panel_pcm.h/(Tl_pcm-Ts_pcm);
    for i = 2:nl_pcm
        M_r_l(nnr_r+i,nnr_r+i)=   panel_pcm.dx*panel_pcm.rho*
                                  panel_A*panel_pcm.h/(Tl_pcm-Ts_pcm);
    end
    M_r_l(nnr_r+nl_pcm+1,nnr_r+nl_pcm+1)= 0.5*panel_pcm.dx*panel_pcm.rho*
                                          panel_A*panel_pcm.h/(Tl_pcm-Ts_pcm);
end
```

Now, the right hand part of the equations are derived from equation 4.2 and again, the left hand part of the equations defines the matrix positions to be filled. For latent heat storage, the same principle of equation 9.37 holds, but c is replaced by the specific enthalpy, dived by the difference in melting and solidification temperature of the phase change material.

10.1.5. STIFFNESS MATRIX

The simulation model contains three stiffness matrices: a matrix that determines that the Trombe wall faces the room, a matrix that describes that the Trombe wall faces the cavity and a matrix that assumes a situation without Trombe wall. For convenience, only the first matrix is shown below. To view the other matrices, reference is made to Matlab-file.

```
Y_r1(1,2)    = e1_constr(1).la*e1_constr_A/e1_constr(1).d;      % conduction
Y_r1(2,3)    = e1_constr(2).la*e1_constr_A/e1_constr(2).d;      % conduction
Y_r1(3,4)    = e1_constr(3).la*e1_constr_A/e1_constr(3).d;      % conduction
Y_r1(5,6)    = e2_constr(1).la*e2_constr_A/e2_constr(1).d;      % conduction
Y_r1(6,7)    = e2_constr(2).la*e2_constr_A/e2_constr(2).d;      % conduction
Y_r1(7,8)    = e2_constr(3).la*e2_constr_A/e2_constr(3).d;      % conduction
Y_r1(9,10)   = e3_constr(1).la*e3_constr_A/e3_constr(1).d;      % conduction
Y_r1(10,11)  = e3_constr(2).la*e3_constr_A/e3_constr(2).d;      % conduction
```

```
Y_r1(11,12)  = e3_constr(3).la*e3_constr_A/e3_constr(3).d;      % conduction
Y_r1(13,14)  = e4_constr(1).la*e4_constr_A/e4_constr(1).d;      % conduction
Y_r1(14,15)  = e4_constr(2).la*e4_constr_A/e4_constr(2).d;      % conduction
Y_r1(15,16)  = e4_constr(3).la*e4_constr_A/e4_constr(3).d;      % conduction
Y_r1(17,18)  = e5_constr(1).la*e5_constr_A/e5_constr(1).d;      % conduction
Y_r1(18,19)  = e5_constr(2).la*e5_constr_A/e5_constr(2).d;      % conduction
Y_r1(19,20)  = e5_constr(3).la*e5_constr_A/e5_constr(3).d;      % conduction
Y_r1(21,22)  = e6_constr(1).la*e6_constr_A/e6_constr(1).d;      % conduction
Y_r1(22,23)  = e6_constr(2).la*e6_constr_A/e6_constr(2).d;      % conduction
Y_r1(23,24)  = e6_constr(3).la*e6_constr_A/e6_constr(3).d;      % conduction
Y_r1(4,nnr_out)   = e1_alpha_e*e1_constr_A; % convection air-outer surf constr 1
Y_r1(8,nnr_out)   = e2_alpha_e*e2_constr_A; % convection air-outer surf constr 2
Y_r1(12,nnr_out)  = e3_alpha_e*e3_constr_A; % convection air-outer surf constr 3
Y_r1(16,nnr_out)  = e4_alpha_e*e4_constr_A; % convection air-outer surf constr 4
Y_r1(20,nnr_out)  = e5_alpha_e*e5_constr_A; % convection air-outer surf constr 5
Y_r1(24,nnr_out)  = e6_alpha_e*e6_constr_A; % convection air-outer surf constr 6
Y_r1(5,25)   = e2_alpha_i*e2_constr_A; % convection air-inner surface constr 2
Y_r1(9,25)   = e3_alpha_i*e3_constr_A; % convection air-inner surface constr 3
Y_r1(13,25)  = e4_alpha_i*e4_constr_A; % convection air-inner surface constr 4
Y_r1(17,25)  = e5_alpha_i*e5_constr_A; % convection air-inner surface constr 5
Y_r1(21,25)  = e6_alpha_i*e6_constr_A; % convection air-inner surface constr 6
Y_r1(5,9) = 5*e3_constr_A/(A_total-e2_constr_A)*e2_constr_A; %radiation exchange
Y_r1(5,13)= 5*e4_constr_A/(A_total-e2_constr_A)*e2_constr_A; %radiation exchange
Y_r1(5,17)= 5*e5_constr_A/(A_total-e2_constr_A)*e2_constr_A; %radiation exchange
Y_r1(5,21)= 5*e6_constr_A/(A_total-e2_constr_A)*e2_constr_A; %radiation exchange
Y_r1(9,13)= 5*e4_constr_A/(A_total-e3_constr_A)*e3_constr_A; %radiation exchange
Y_r1(9,17)= 5*e5_constr_A/(A_total-e3_constr_A)*e3_constr_A; %radiation exchange
Y_r1(9,21)= 5*e6_constr_A/(A_total-e3_constr_A)*e3_constr_A; %radiation exchange
Y_r1(13,17)=5*e5_constr_A/(A_total-e4_constr_A)*e4_constr_A; %radiation exchange
Y_r1(13,21)=5*e6_constr_A/(A_total-e4_constr_A)*e4_constr_A; %radiation exchange
Y_r1(17,21)=5*e6_constr_A/(A_total-e5_constr_A)*e5_constr_A; %radiation exchange
 Y_r1(25,nnr_p_pcm) = p_alpha_i*panel_A; % convection between room air and inner
                                            surface PCM side of panel
Y_r1(5,nnr_p_pcm) = 5*e2_constr_A/(A_total-panel_A)*panel_A; %radiation exchange
Y_r1(9,nnr_p_pcm) = 5*e3_constr_A/(A_total-panel_A)*panel_A; %radiation exchange
Y_r1(13,nnr_p_pcm)= 5*e4_constr_A/(A_total-panel_A)*panel_A; %radiation exchange
Y_r1(17,nnr_p_pcm)= 5*e5_constr_A/(A_total-panel_A)*panel_A; %radiation exchange
Y_r1(21,nnr_p_pcm)= 5*e6_constr_A/(A_total-panel_A)*panel_A; %radiation exchange
for i = nnr_p_pcm:nnr_p_pcm+nl_pcm-1
    Y_r1(i,i+1)     = panel_pcm.la*panel_A/panel_pcm.dx;         % conduction
end
for i = nnr_p_pcm+nl_pcm:nnr_p_pcm+nl_pcm+nl_ins-1
    Y_r1(i,i+1)     = panel_ins.la*panel_A/panel_ins.dx;         % conduction
end

Y_r1(nnr_p_ins,nnr_cav)= p_alpha_cav*panel_A; %convection between cavity air and
                                               surface insulation side of panel
```

The left hand part of the equations defines between which two nodes the heat transfer occurs. The right hand side of the equations define the coupling factors, which are different for conduction, convection and radiation. It can be seen that for conduction, equation 9.38 has been applied. For convection, equation 9.42 has been applied and for radiation, equation 9.40 has been applied. After populating the stiffness matrices, a script was developed to distinguish fixed/bound node matrix values from free node matrix values.

10.2. MODEL COMPONENTS AND CAPABILITIES

The simulation model developed in DF1.0 is a realistic room model which takes into account multiple components/mechanisms such as shading, ventilation and presence of people. By having these components, the simulation model is capable of estimating the energy demand of different room configurations that represent realistic situations. In this section, a description of all model capabilities and its implementation in Matlab is given. Later in this chapter, the implementation of the most important components in Simulink is described.

10.2.1. SIMULATION TIME

To determine the simulation time, the following two commands were defined:

```
start_time = 0*86400;
stop_time  = 365*86400;
```

The values are expressed in seconds. When the start time equals zero, the simulation starts at 1 January. When the first term of the stop time equals 365, the simulation stops at the end of 31 December.

10.2.2. INITIAL NODE TEMPERATURE

The initial temperature condition is set by the following command:

```
TinIC = 23;
```

The initial temperature is set at 23 °C by default and is the average temperature of the heating and cooling thermostat set-point temperatures. When simulating long periods (like a season or a year), the influence of the initial node temperature on the resulting energy demand becomes negligible. When simulating short periods (like a day or a week), the initial conditions of the room must be better studied beforehand.

10.2.3. OCCUPATION

The occupation conditions for an office room are defined with the commands shown below. With the commands, the amount of working days (i.e. days when people are present), the times on a day when people are present and the total sensible heat production (W/m^2) can be defined:

```
working_days = 5;   % number of 'working days' in a week, must be >=0 and <=7

p_i = 25;           % total sensible internal heat production in W/m2, only
                    applies when people are present.
hour_people_present =  [8,18];    % between these hours of a 'working day' (0 <=
                                  hour <= 24), people are present. First number
                                  may be larger than second.
```

10.2.4. VENTILATION

The simulation model considers two types of ventilation: natural ventilation and balanced mechanical (night) ventilation with heat recovery. Natural ventilation takes place when the room air temperature is higher than 24 °C, causing the windows to be opened.

```
ThresholdWindowOpen    = 24;  % Room air temp above which the windows are opened
ThresholdWindowClosed  = 22;  % Room air temp below which the windows are closed
                              (a relay applies between both threshold setpoints)
VentRateOpenWindow     = 2/3600;  % Additional ventilation rate with windows
                                  open[per hour]. Simple type of modelling.
```

Mechanical ventilation constantly takes place when people are present. In the script shown here, the heat recovery efficiency of the mechanical ventilation air equals 0.9. The heat recovery system is bypassed when the operative room air temperature is both higher than 24 °C and higher than the outside air temperature. Mechanical night ventilation only takes place at night when the operative room air temperature is both higher than 24 °C and higher than the outside air temperature.

```
ventilation_rate   = 0.5/3600;   % mechanical ventilation rate of the room (s-1)
hour_vent_flow     = [0,24];     % between these hours of a 'working day' (0 <=
                                   hour <= 24), mechanical ventilation is on.
WTW_efficiency     = 0.9;

Threshold_Toper_night_ventilation_on  = 24; % Threshold oper. Room temperature
                                            above which mech. night ventilation
                                            is on, provided Toper > Te
Threshold_Toper_night_ventilation_off = 22; % Threshold oper. room temperature
                                            below which mech. night ventilation
                                            is off
```

```
Threshold_Toper_bypass_on = 24; % Threshold oper. room temperature above which
                                 heat recovery is bypassed, provided Toper > Te0
Threshold_Toper_bypass_off = 22;% Threshold oper. room temperature below which
                                 heat recovery is in use (bypass is off)
```

10.2.5. THERMOSTAT SET-POINTS AND HEATING CONTROL

In the Matlab-file, the heating and cooling thermostat set-points are defined as shown below. The other commands provide an adequate response from the heating and cooling system. With the input shown below (also used in DF1.0), no fluctuations and oversupply occur, and desired temperature levels are reached relatively fast.

```
heating_setpoint        = 20;      % only applies when people are present (°C)
heating_proportional    = 2000;    % proportional part of PI-controller (W/K)
heating_integral        = 0.1;     % integral part of PI-controller (W/Ks)
heating_max_power       = 10000;   % maximum power heating (W)
cooling_setpoint        = 26;      % only applies when people are present (°C)
cooling_proportional    = 2000;    % proportional part of PI-controller (W/K)
cooling_integral        = 0.1;     % integral part of PI-controller (W/Ks)
cooling_max_power       = 10000;   % maximum power heating (W)
```

10.2.6. CONSTRUCTION PROPERTIES

In the Matlab-file, many commands are written that specify the material properties of walls, floor, ceiling and glazing. The U-value and SHGC-value of the glazing are defined as follows:

```
U_gl_orien1 = 1.65;
U_gl_orien2 = 1.65;
U_gl_orien3 = 1.65;
U_gl_orien4 = 1.65;

SHGC_orien1 = 0.6;
SHGC_orien2 = 0.6;
SHGC_orien3 = 0.6;
SHGC_orien4 = 0.6;
```

The material properties of walls, floor and ceiling are defined as shown below. The same principle holds for walls of orien2, orien3, orien4 and for the floor and ceiling.

```
% orien1, external construction 1 layer 1
% Rc=3 m2K/W, virtually no mass
e1_constr(1).d   = 0.01;        % thickness, inside layer
e1_constr(1).rho = 10;          % density
e1_constr(1).c   = 840;         % spec. heat capacity
e1_constr(1).la  = 0.01;        % heat conduction coefficient
% external construction 1 layer 2
e1_constr(2).d   = 0.01;        % thickness, middle layer
e1_constr(2).rho = 10;          % density
e1_constr(2).c   = 840;         % spec. heat capacity
e1_constr(2).la  = 0.01;        % heat conduction coefficient
% external construction 1 layer 3
e1_constr(3).d   = 0.01;        % thickness, outside layer
e1_constr(3).rho = 10;          % density
e1_constr(3).c   = 840;         % spec. heat capacity
e1_constr(3).la  = 0.01;        % heat conduction coefficient
```

Because thermal simulations are carried out in this study, a lot of heat transfer and absorption coefficients exist. The first coefficient relates to the convection factor of solar radiation entering the room. The fraction shown below is given off to the room air node, while the remainder is given off to the floor surface.

```
CFsol  = 0.2;
```

The surface heat transfer coefficients are defined as shown below. A total surface heat transfer coefficient of zero means that the surface is modelled as adiabatic surface.

```
e1_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 1
                       (also applies in cavity where PCM_panel is present)
e2_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 2
e3_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 3
e4_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 4
e5_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 5
e6_alpha_i    = 2.7; % convective surface heat transfer coeff. inside constr. 6

e1_alpha_e        = 25;    % total surface heat transfer coeff. outside constr. 1
e2_alpha_e        = 0;     % total surface heat transfer coeff. outside constr. 2
e3_alpha_e        = 0;     % total surface heat transfer coeff. outside constr. 3
e4_alpha_e        = 0;     % total surface heat transfer coeff. outside constr. 4
e5_alpha_e        = 0;     % total surface heat transfer coeff. outside constr. 5
e6_alpha_e        = 0;     % total surface heat transfer coeff. outside constr. 6
```

The solar absorption coefficients are defined as shown below. A solar absorption coefficient of zero means that the surface is modelled as adiabatic surface (so, no solar influence).

```
e1_sol_abs    = 0.5;    % solar absorption coeff. outside surface construction 1
e2_sol_abs    = 0;      % solar absorption coeff. outside surface construction 2
e3_sol_abs    = 0;      % solar absorption coeff. outside surface construction 3
e4_sol_abs    = 0;      % solar absorption coeff. outside surface construction 4
e5_sol_abs    = 0;      % solar absorption coeff. outside surface construction 5
```

10.2.7. SHADING

The initial simulation model is equipped with a shading mechanism, which is activated after certain threshold-values are exceeded. The shading mechanism is a relatively 'simple' component and nothing more than a reduction of the SHGC-coefficient of the glazing:

```
% Solar heat gain coefficient glass with sunblinds
SHGC_orien1_SB = SHGC_orien1*0.25;
SHGC_orien2_SB = SHGC_orien2*0.25;
SHGC_orien3_SB = SHGC_orien4*0.25;
SHGC_orien4_SB = SHGC_orien4*0.25;
```

In the script below, the shading mechanism is turned on when the operative room temperature exceeds 24 °C and when simultaneously the incoming solar radiative power exceeds a value of 100 W.

```
ThresholdSBoff  = 22; % Oper. room temp below which the sunblinds are never used
ThresholdSBon   = 24; % Oper. room temp above which the sunblinds are in use,
                        provided that Isol > ThresholdSBIsol
ThresholdSBIsol= 100; % Incoming solar radiative power below which the sunblinds
                        are never used (per orientation)
```

10.2.8. LTATW CHARACTERISTICS

The liquifying temperature and the solidification temperature of the phase change material are defined in Matlab as follows:

```
Ts_pcm      = 23;          % temperature below which PCM is solid  [°C]
Tl_pcm      = 26;          % temperature above which PCM is liquid [°C]
```

When a Trombe wall is present, solar energy is absorbed by the panel. Different absorption factors apply for different orientation and material state (solid or liquid). The values are determined in DF1.0 and are different for each type of PCM and insulation material. In this project, one specific type of PCM and aerogel is investigated, which means that the values shown below are dealt with as constants.

```
a_sol1_pcm_s  = 0.91*0.97; % part of incident solar energy on panel absorbed by
                             the PCM layer, solid  state, when PCM faces room
```

```
a_sol1_pcm_l  = 0.91*0.63; % part of incident solar energy on panel absorbed by
                            the PCM layer, liquid state, when PCM faces room
a_sol1_ins_s  = 0.09;       % part of incident solar energy on panel absorbed by
                            the insulation layer, solid state,when PCM faces room
a_sol1_ins_l  = 0.09;     % part of incident solar energy on panel absorbed by
                          the insulation layer, liquid state, when PCM faces room
                          % linear interpolation between solid and liquid state
                          based on volume-averaged PCM temperature
 a_sol2_pcm_s  = 0.97;    % part of incident solar energy on panel absorbed by
                          the PCM layer, solid  state, when PCM faces cavity
a_sol2_pcm_l  = 0.63;       % part of incident solar energy on panel absorbed by
                            the PCM layer, liquid state, when PCM faces cavity
a_sol2_ins_s  = 0.03*0.09; % part of incident solar energy on panel absorbed by
                            the insulation layer, solid state,when PCM faces room
a_sol2_ins_l  = 0.37*0.09; % part of incident solar energy on panel absorbed by
                            the insulation layer,liquid state,when PCM faces room
                            % linear interpolation between solid and liquid state
                            based on volume-averaged PCM temperature
```

The percentage of openings in the LTATW is defined as follows:

```
panel_A_fac = 0.9;  % fraction of the panel surface area not consisting of
                    holes. So when panel_A_fac = 1, the panel is closed and
                    completely covers the orien1 façade
```

The material properties of the PCM and insulation layer are defined as follows:

```
panel_pcm.d = 0.025;        % thickness of PCM layer
panel_ins.d = 0.01;         % thickness of insulation layer
panel_pcm.c   = 2000;       % sensible specific heat capacity of PCM [J/(kg K)],
                            assumed equal for solid and liquid state
panel_pcm.rho = 1450;       % mass density of PCM [kg/m3]
panel_pcm.la  = 0.6;        % heat conduction coefficient of PCM [W/(m K)],
                            assumed equal for solid and liquid state
panel_pcm.h   = 1.8e5;      % latent heat of PCM (J/kg)
panel_ins.c   = 1440;       % sensible specific heat capacity of insulation
                            [J/(kgK)]
panel_ins.rho = 75;         % mass density of nsulation [kg/m3]
panel_ins.la  = 0.012;      % heat conduction coefficient of insulation [W/(m K)]

p_alpha_i     = 2.7; % conv. surface heat transfer coeff. room side of panel
p_alpha_cav   = 2.7; % conv. surface heat transfer coeff. cavity side of panel
```

Due to the existence of openings in the LTATW and a temperature difference between cavity and room, air flows from cavity to the room, or vice versa. In the initial simulation model, this air flow is assumed to be constant:

```
Q_room_cavity  =  0.01;    % air flow rate between cavity and room air in m3/s.
```

10.2.9. WEATHER DATA

The weather data used for simulation contains two variables: the outside temperature over time $T_e(t)$ and the solar irradiance values over time $q_{sol}(t)$. The solar data file 'qsol_NEN5060B2_1p_double' shown below contains the hourly global (direct and diffuse) incoming solar radiation in W/m^2 on the horizontal plane and on each of the four orientations. The temperature data file contains the hourly outside temperature in °C. The weather files are loaded into the Matlab-file and are defined as shown below. In the example below, a weather file of the Netherlands is used.

```
load('Te_NEN5060B2_1p_double');
load('qsol_NEN5060B2_1p_double');

Te        = Te_NEN5060B2_1p_double;
qtemp     = qsol_NEN5060B2_1p_double;
```

10.3. IMPORTANT SIMULINK COMPONENTS

As mentioned before, the simulation environment of the simulation model consists of a textual programming part in Matlab and a graphical programming part in Simulink. With the textual programming part from Matlab (with definitions of parameters, matrices, etc.) a graphical model is developed to simulate and analyse the behaviour of the dynamic system. The Simulink model is built up of many components with block diagrams which are connected in such a way, that the right mathematical solving procedure is enhanced. Of course, each individual component or mechanism in Simulink is important to obtain the desired and reliable results. However, to keep the size of this thesis in limitation, only the most important components are shown in this section. It is important to mention that the Simulink components shown in this section are obtained from the initial simulation model (from DF1.0). During this Master's thesis project, components have been slightly modified in some cases. However, the principles remain the same.

The Simulink component that incorporates all heat loads is shown in section 10.3.1. The component with the shading and internal solar load mechanism is shown in section 10.3.2, the ventilation component is shown in section 10.3.3 and the rotation schedule mechanism is shown in section 10.3.4. Finally, the solution procedure is shown in section 10.3.5 and the mechanism for calculation of heating and cooling energy demand is shown in section 10.3.6 and 10.3.7, respectively.

10.3.1. HEAT LOADS

The initial simulation model contains heat loads resulting from incoming solar radiation, ventilation losses, internal heat production and added heating or cooling. From Figure 10.9 can be seen that multiple solar energy flows are taken into account: radiation absorbed by the outer surfaces (north, east, south, west and horizontal), incoming solar radiation falling directly on the inner floor surface (Psol_rad) and solar energy given off as heat to the room air (Psol_con). All heat loads together are assigned in the heat load factor 'Qroom'.

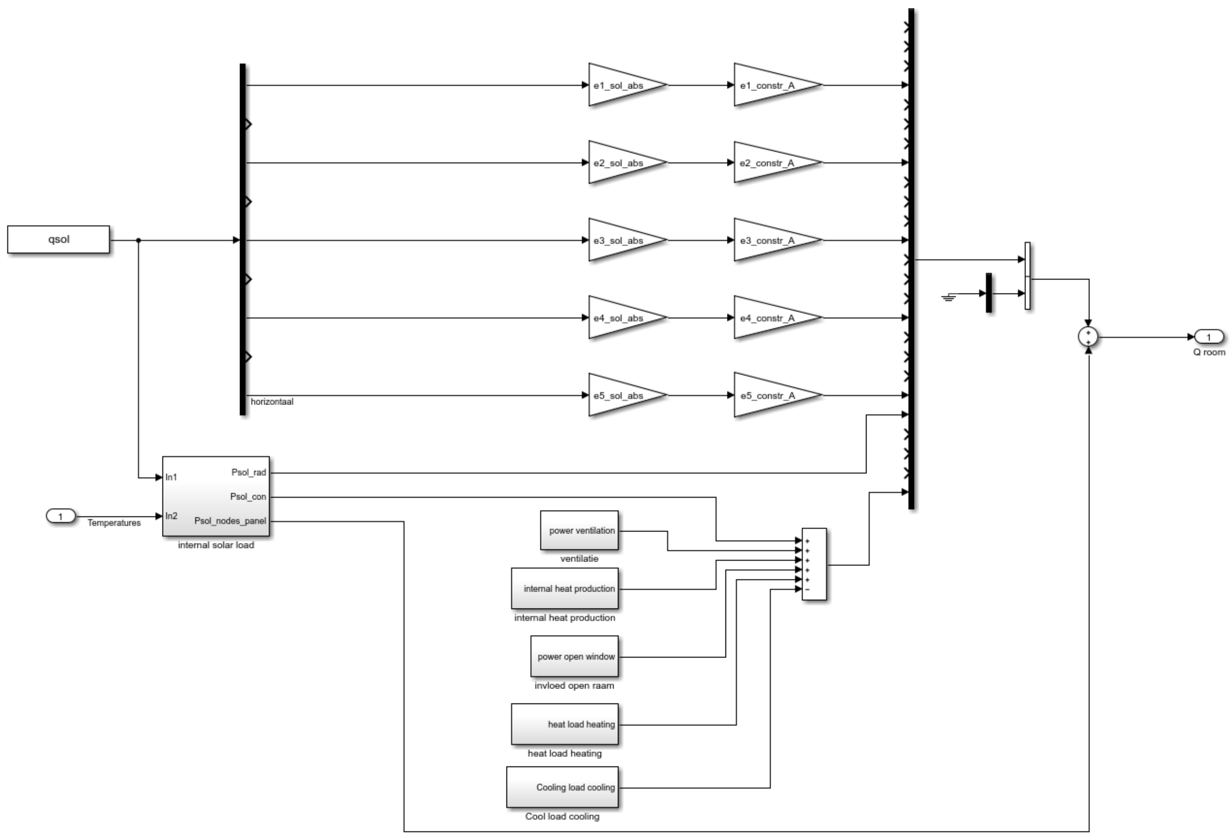


Figure 10.9: Simulink component of all heat loads on room.

10.3.2. SHADING AND INTERNAL SOLAR LOADS

The incoming solar radiation falling directly on the inner floor surface (Psol_rad) and the solar energy given off as heat to the room air (Psol_con) are calculated according to the subsystem 'internal solar load' (see Figure 10.9). When opening this subsystem, the mechanism shown in Figure 10.10 is displayed. From Figure 10.10 can be seen that the solar radiation is multiplied (triangular block with denotation '-K-') by one of the two different SHGC-coefficients, depending on the conditions mentioned in section 10.2.7 (shading principle). After multiplication of the remainder by the surface area of the glazing, the intensities are enumerated and multiplied by a utilization factor and by CFsol.

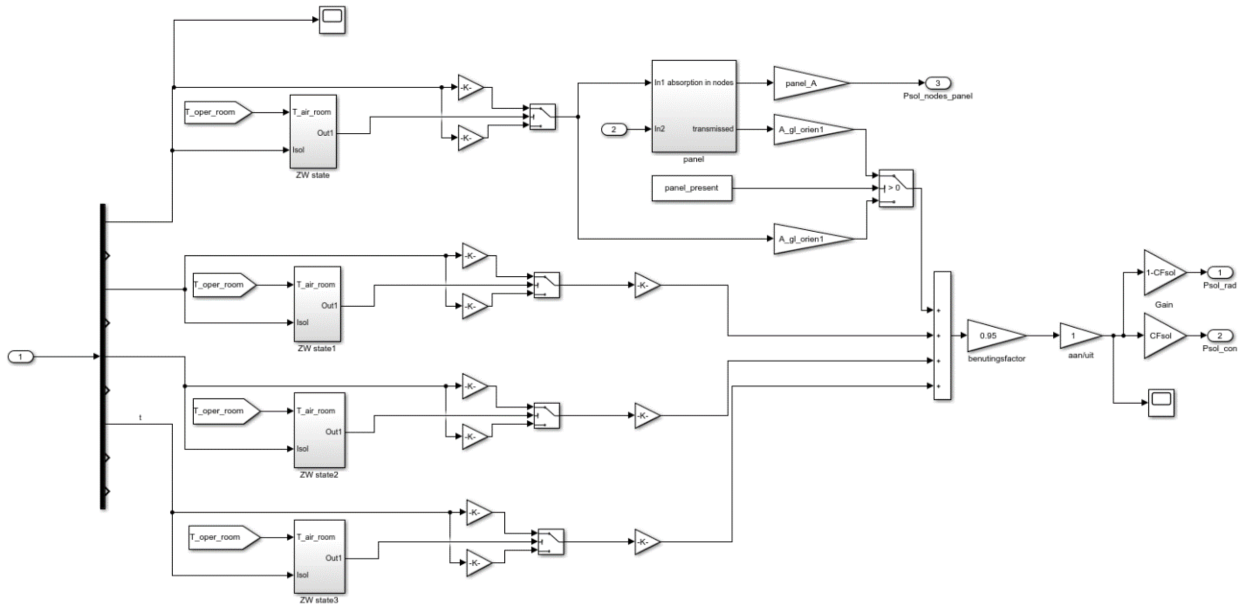


Figure 10.10: Simulink component of subsystem of shading and calculation of internal solar loads.

10.3.3. VENTILATION

The initial simulation model takes into account two types of ventilation: natural ventilation and mechanical ventilation. From Figure 10.9 can be seen that the heat loss due to natural ventilation is called 'power open window' and is calculated as shown in Figure 10.11. Only when the Boolean condition 'vw_open_windows' is met (return value of 1), a heat flow is generated. The size of the heat flow (W) is calculated by multiplying the temperature difference with the ventilation flow, the density of air and the heat capacity of the air (see also equation 9.6 and 9.7). In Figure 10.11, the ventilation flow is defined as 'Q_vent_direct' (V_{room} x ACH/3600) and the product of the density and heat capacity of air is shown as a block containing a value of 1.2 x 1000 =1200 J/m^{3}K.

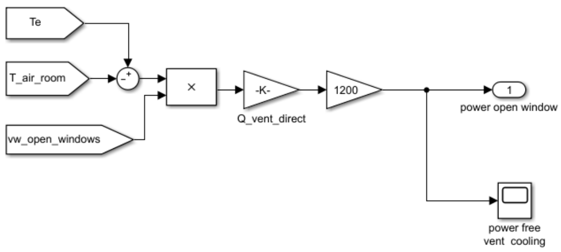


Figure 10.11: Simulink component of subsystem 'power open window'

From Figure 10.9 can be seen that the heat loss due to mechanical ventilation is called 'power ventilation' and is calculated as shown in Figure 10.12. When one of the conditions 'vw_day_operation_vent' and/or vw_night_ventilation' is met (return value > 0), a heat flow is generated, calculated according to the same principle as shown in Figure 10.11. When the condition 'vw_bypass' is met (see section 10.2.4), the heat recovery is bypassed (return value of 1) and when the condition is not met, the heat recovery is not bypassed, and a reduction of the heat loss of (1-μ) is taken into account (see equation 9.8).

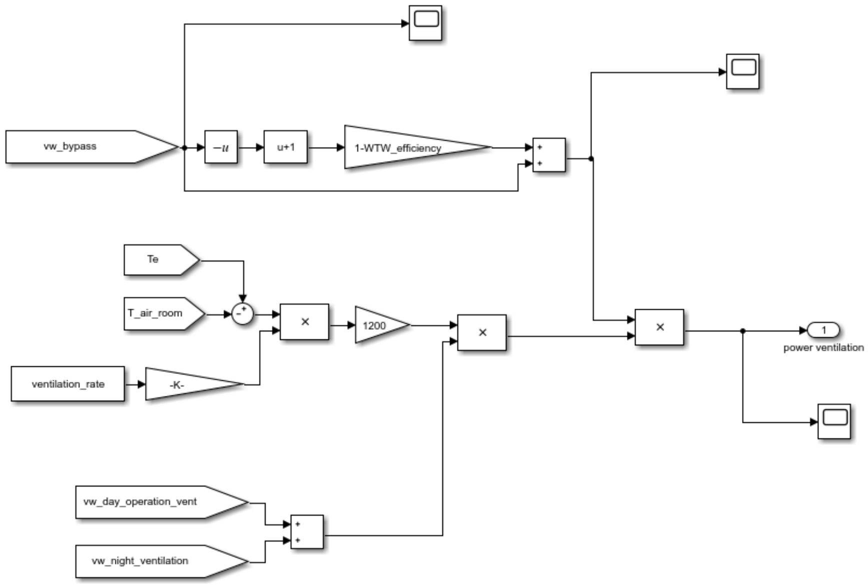


Figure 10.12: Simulink component of subsystem 'power ventilation'.

10.3.4. ROTATION SCHEDULE

One of the capabilities of the simulation model is simulating the adaptability of the LTATW. The orientation of the LTATW (oriented towards the interior or towards the cavity/exterior) is determined, depending on the most favourable situation with regard to energy and comfort performance. The initial simulation model was only used for a winter period simulation and therefore, the LTATW always faced the outdoor environment at daytime (heat is absorbed by the LTATW) and always faced the room interior at night-time (heat is released to the room). The control mechanism that determines the orientation of the LTATW is shown in Figure 10.13. The two blocks with a sine-icon represent the times of sunrise (upper block) and sunset (lower block). When the simulation time is between these two times, the LTATW faces the exterior (a 'NOT' block is included). When the simulation time is outside these two times, the LTATW faces the indoor environment.

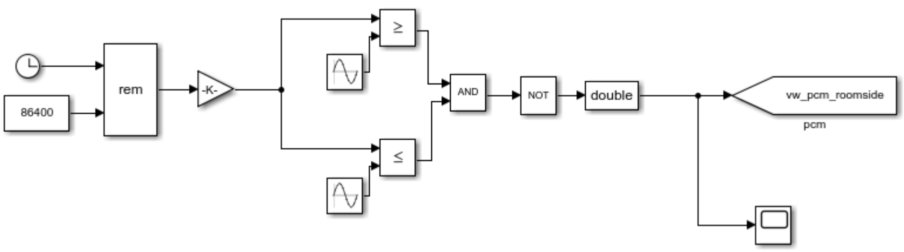


Figure 10.13: Simulink component of control mechanism of LTATW orientation.

10.3.5. SOLUTION PROCEDURE

In chapter 9, the mathematical solution procedure of a room model with thermal nodes was explained. The room balance equations were showed and a final expression to calculate the unknown variable $\underline{\dot{T}}$ was given:

$$\underline{\mathbf{T}}(t) = \int_0^t \mathbf{M}^{-1} (\underline{\mathbf{Q}} - \mathbf{S}\underline{\mathbf{T}} - \mathbf{S}_{bound}\underline{\mathbf{T}}_{bound})dt \tag{9.45}$$

In Simulink, equation 9.45 is solved as shown in Figure 10.14.

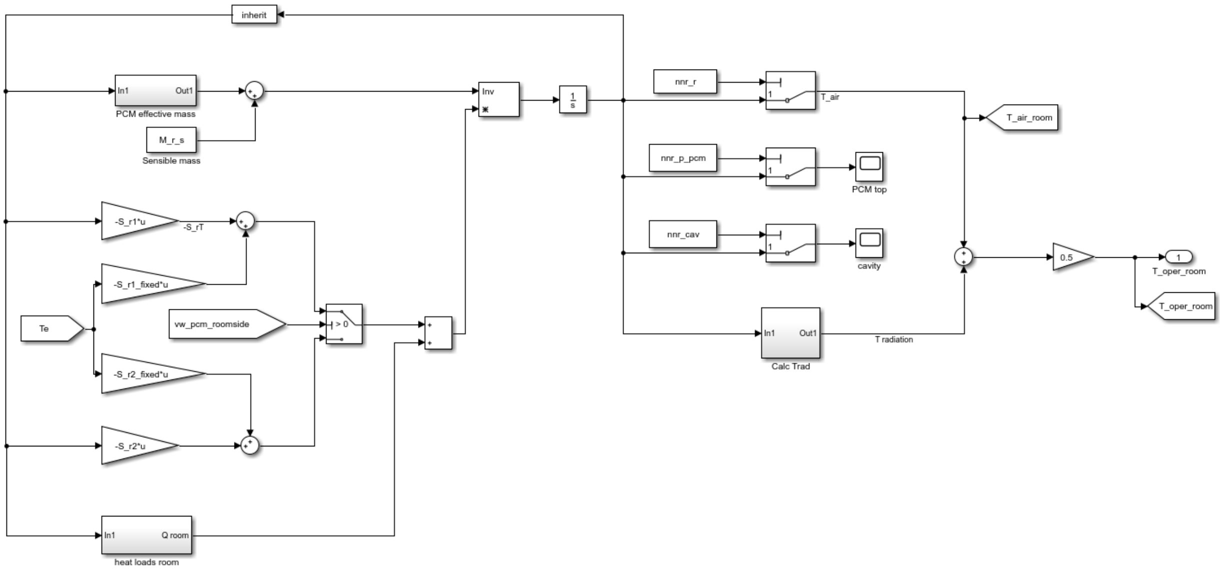


Figure 10.14: Simulink component of solution procedure.

From the left bottom part of Figure 10.14 can be seen that the stiffness matrix with free nodes **-S** is multiplied by the room temperature $\underline{\mathbf{T}}$ and that the stiffness matrix with fixed nodes $\mathbf{-S_{bound}}$ is multiplied by the outside temperature $\underline{\mathbf{T}}_{\mathbf{bound}}$. The result of both multiplications are added together. Depending on whether the LTATW is directed towards the room or towards the outside environment, the 'bound' and 'free' temperatures are multiplied by a different stiffness matrix: $\mathbf{-S_{r1,bound}}$ or $\mathbf{-S_{r2,bound}}$. Then, the heat load vector $\underline{\mathbf{Q}}$ is added to the result and multiplied by $\mathbf{M^{-1}}$. To calculate the room air temperature at time t, an integrator block is placed after it. From the right hand part of Figure 10.14 can be seen that the operative room temperature is calculated by taking the average of the air temperature and the radiant temperature.

From Figure 10.13 can be seen that $\mathbf{M^{-1}}$ is the sum of the sensible mass matrix and the latent mass matrix (called 'PCM effective mass'). In the subsystem 'PCM effective mass', a control mechanism is implemented that determines between which temperatures the heat capacity of the PCM is increased. A more detailed description of how this subsystem works can be seen in section 12.2.

10.3.6. HEATING LOAD

The Simulink mechanism that calculates the heating load is shown in Figure 10.15.

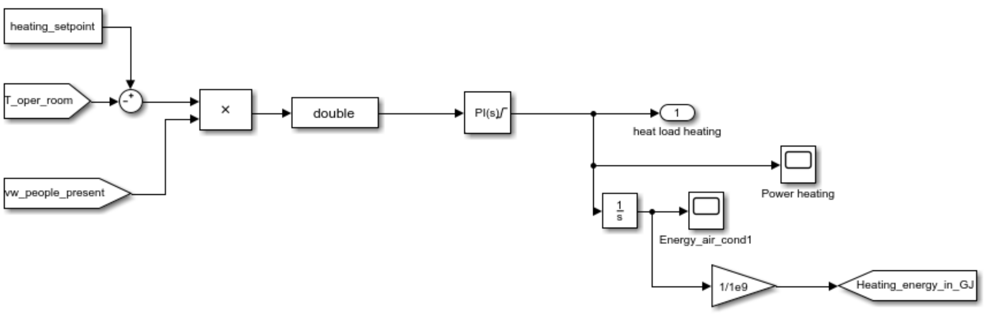


Figure 10.15: Simulink component of heating load.

First, the operative room temperature is subtracted from the heating thermostat set-point temperature. When the signal outcome is higher than zero, heating is required. The block called 'PI(s)' is a PID-controller, which determines the heating power characteristics of the heating system. After the PID-controller, the signal passes some 'scope' blocks to view the heating power over time, and an integrator, which integrates the value of power to energy.

10.3.7. COOLING LOAD

The Simulink mechanism that calculates the cooling load is shown in Figure 10.16.

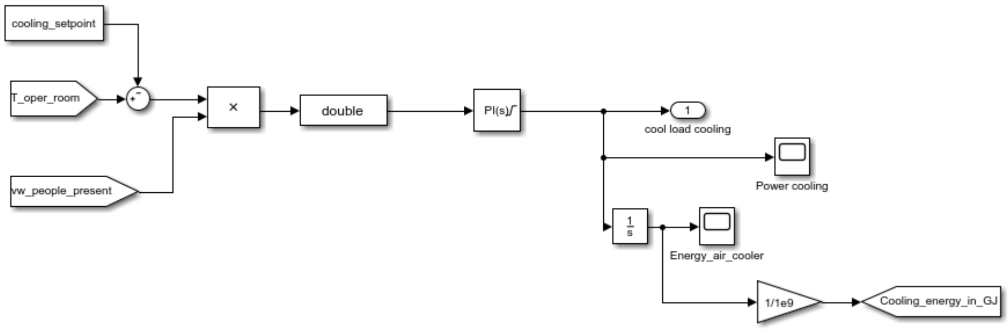


Figure 10.16: Simulink component of cooling load.

First, the cooling thermostat set-point temperature is subtracted from the operative room temperature. When the signal outcome is higher than zero, cooling is required. The PID-controller again determines the cooling power characteristics of the cooling system and an integrator integrates the value of power to energy.

11. VALIDATION AND VERIFICATION

Performance measures extracted from a computer simulation model can only be correctly interpreted and used if the model is a good representation of the real system. Whether or not a model is judged as 'good' is subjective, but from a performance modelling point of view there are certain criteria for judging the goodness of models (Hillston, 2003). This chapter is all about: How accurately do the measures extracted from the initial simulation model correspond to the measures which would be obtained from the representative real system? Or more concisely: how reliable and accurate is the simulation model that was developed in the Double Face 1.0 project? The chapter starts with an introduction in which the terms validation and verification are explained. After this, a framework is provided to contribute to a good understanding of the terminology used. In section 11.3 and 11.4, the validation and verification procedure and its simulation conditions is described and in section 11.5, the results are shown. After the first validation and verification steps, various modifications to the simulation model were made. The modifications and final results are described in sections 11.6 and 11.7.

11.1. INTRODUCTION

Simulation models in general are more abstract than the system it represents. When building a simulation model, assumptions are made to eliminate unnecessary details and to create a better focus on the elements within the system which are the most important (Hillston, 2003). As a result, inaccuracy is introduced. This inaccuracy may be necessary to make the simulation model more manageable and efficient, but effort needs to be made to find out if the model is (still) a good, representative simulation model. There are two steps to assess how good a model is with regard to the system. It has to be checked whether the model correctly implements the assumptions (model verification) and whether the assumptions made are reasonable in relation to the real system (model validation) (Hillston, 2003).

11.1.1. MODEL VERIFICATION

Verification of a simulation model is intended to ensure that the model does what it is made for. It is the process of confirming that implementation is correctly done with respect to the conceptual model and that it matches the assumptions and specifications agreed-upon (Carson, 2002). As simulation models are often large computer programs, the chance of (small) emerging modelling flaws is high. Verification is like debugging: tracing the errors. There are many techniques to verify a simulation model. The technique used in this study is described later in this chapter.

11.1.2. MODEL VALIDATION

Validation is the task of proving that the simulation model is a reasonable representation of the actual system and that it reproduces the system behavior with sufficient reliability to satisfy analysis objectives (Hillston, 2003). Validation is an iterative process and a test to establish the validity of a simulation model of a system that sometimes does not yet exist. Hillston (2003) and Van der Spoel (2016) together mention the following validation techniques:

- **Theoretical results/analytical validation**: The model may be compared to analytical solutions that are well-known. This method is generally used for relatively simple cases for which analytical solutions are known.
- **Empirical validation**: Also known as real system measurements. The model is being compared to obtained data from measurements in real buildings, a laboratory or controlled test cells. This method often brings relatively high complexity and costs due to the need for high-quality data sets.
- **Expert intuition:** The examination of the model is led by an 'expert' who has great knowledge about the system under investigation. This expert is responsible of a careful inspection of the model behavior and its output.
- **Comparative testing**: The simulation model is compared to other, more complex and validated models. These comparisons can be done at many levels of complexity and are relatively inexpensive. A disadvantage of this technique is that, partly due to difficulties in equivalencing both model inputs, it can be more time-consuming.

11.2. TERMINOLOGY FRAMEWORK

Verification does not imply validation, nor validation imply verification. However, in practice, verification is often combined with validation, especially when measurement data is already available for the system being modelled. If in this case, the comparison of the model results and the results from system measurements show proper similarities, then the simulation model is assumed to be both a valid representation of the system and a verified implementation of the assumptions (Hillston, 2003).

To facilitate a more efficient communication between the builder of a simulation model and its potential user about validation and verification, a framework can be helpful. In this framework (Figure 11.1) a standard set of terminology is used. The framework shown divides the simulation environment into three basic elements: reality, conceptual model and computerized model (Schlesinger, 1979).

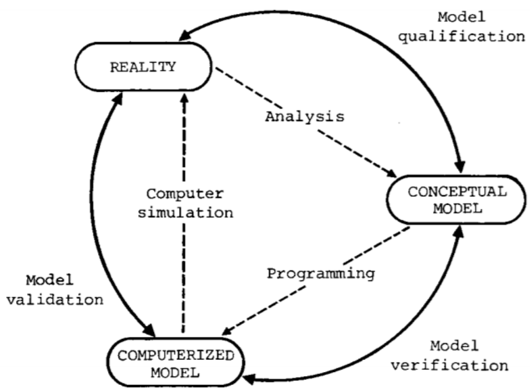


Figure 11.1: Framework with set of terminology regarding model validation and verification (Schlesinger, 1979).

The 'reality' element represents a system which has been selected for analysis (in this project, the system presented in chapter 6). The conceptual model is a set of verbal descriptions, equations, relationships or natural laws that aim to describe this reality (in this project, the equations in chapter 9). Lastly, the computerized model is an operational computer program that has implemented the conceptual model (as was done in chapter 10). The inner arrows between the three basic elements correspond to the processes that occur between them and the outer arrows refer to the procedures that evaluate the credibility of these processes (Schlesinger, 1979).

11.3. VALIDATION AND VERIFICATION PROCEDURE

In this study, the energy and comfort performance of a lightweight, translucent, adaptable Trombe wall has been investigated. This type of Trombe wall does not exist yet and therefore, fewer options were available to validate the model. Now, for example, it was not possible to validate the simulation model by real system measurements. In addition, consulting an expert was not an obvious choice, as we are dealing with a new, advanced and unknown technology to many. Two options remained: comparing the simulation results to analytical solutions and validation by means of comparative testing. As mentioned earlier in this chapter, the idea of theoretical/analytical validation is to compare the results of model to analytical solutions that are well known and that this method is used for simple cases in general. In case of this study, where a LTATW in a certain, specified room is being investigated, we're dealing with a very complex system. The behavior of such a complex system is highly difficult to model due to the many relationships, dependencies and other types of interactions between their elements. Therefore, the decision was made to study the credibility of the Matlab/Simulink model through comparative testing.

In the process of comparative testing, the output of two of the same models, which are modelled in two different types of software is compared. The computerized model made in Matlab/Simulink, was created by means of (textual and graphical) programming. This means that all instructions needed for the program/model to work are written (or composed) by the modeler itself. The instructions are given in the programming language of Matlab (writing lines of codes) and by using the graphical programming options offered by Simulink (Figure 11.2). The advantage of creating a computerized model in the Matlab/Simulink environment is that the created models allow for a high degree of flexibility and features can be easily removed, changed or added, so that the model functions as desired. The major disadvantages of this type of modelling, however, are that writing the code can be very time-consuming and mistakes are made quickly. In addition, a lot of knowledge is required about the working principles and algorithms behind the system modelled.

The software that is used to compare the simulation results of Matlab/Simulink is DesignBuilder. In DesignBuilder, the same specified model is not created by programming, but by graphical modelling. DesignBuilder uses a graphical user interface that allows users to specify a system via visual indicators and graphical icons (Figure 11.3). Unlike a command line operation system such as the Matlab/Simulink environment, DesignBuilder is much easier to learn due to the user-friendly interface and as less knowledge behind the calculations is needed (DesignBuilder, 2018).

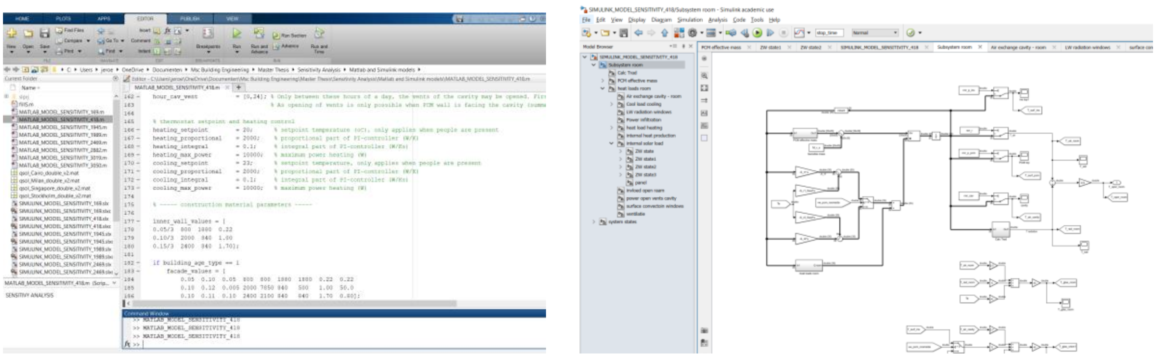


Figure 11.2: Programming based modelling (Matlab/Simulink)

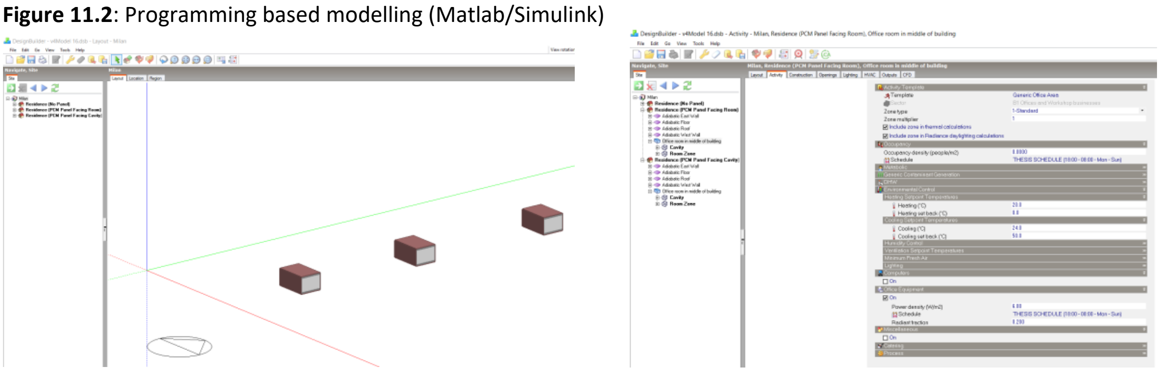


Figure 11.3: Modelling with a graphical user interface (DesignBuilder)

Table 11.1: Overview of tested situations.

Function	Age	Building method	Room characteristics	Type of glazing	Orientation North				Orientation East				Orientation South				Orientation West			
					Tropical	Arid	Temperate	Cold	Tropical	Arid	Temperate	Cold	Tropical	Arid	Temperate	Cold	Tropical	Arid	Temperate	Cold
Office	Old	Light-weight	Small Room	Single, Clear	1															
				Double, Coated															2	
			Big Room	Single, Clear																
				Double, Coated																
		Heavy-weight	Small Room	Single, Clear											3					
				Double, Coated			4													5
			Big Room	Single, Clear																
				Double, Coated																
	New	Light-weight	Small Room	Single, Clear								6								
				Double, Coated																
			Big Room	Single, Clear												7				
				Double, Coated									8							
		Heavy-weight	Small Room	Single, Clear														9		
				Double, Coated																
			Big Room	Single, Clear						10										
				Double, Coated																
Residence	Old	Light-weight	Small Room	Single, Clear																
				Double, Coated																
			Big Room	Single, Clear				11												
				Double, Coated									12					13		
		Heavy-weight	Small Room	Single, Clear																
				Double, Coated																
			Big Room	Single, Clear		14			15											
				Double, Coated																
	New	Light-weight	Small Room	Single, Clear																
				Double, Coated							16									
			Big Room	Single, Clear																
				Double, Coated																17
		Heavy-weight	Small Room	Single, Clear											18					
				Double, Coated	19															
			Big Room	Single, Clear																
				Double, Coated						20										

In this study, the Matlab/Simulink model is used to calculate the energy and comfort performance of the LTATW in a large number of different 'situations'. These situations arise by combining all sorts of subdivisions within the following parameters:

- Climate
- Building function
- Orientation
- Age
- Building method
- Room size
- Window size
- Type of glazing

As it is almost impossible (within an accepted amount of time) and unnecessary to validate and verify all possible different situations, only a small percentage of it will be tested. This smaller part has been selected in a thoughtful way, to make sure that every component of the simulation model is tested. In the comparative study, all functions, climates, ages, room sizes and orientations have been tested. Within the parameters: building method and type of glazing, only the two outer subdivisions have been evaluated. When only evaluating these parameters, a size-reduced table (Table 11.1) remained. In this matrix, 20 situations are randomly picked in such a way, that in the end, every parameter is tested equally. This means that ten configurations with a new building, ten configurations with an old building, five configurations in a tropical climate, five configurations in an arid climate, etc. are being evaluated. As a result, a detailed insight was gained about the accuracy and reliability of all components and capabilities of the Matlab/Simulink simulation model.

By using two types of software that obtain data in a fairly short period of time, validation and verification of the Matlab/Simulink simulation model have been combined in one technique. 20 different simulation models were implemented in both Matlab/Simulink and DesignBuilder, and were simulated hereafter. It is assumed that when the comparison of the results of both types of software show proper similarities in all 20 models, implementation of every aspect of the conceptual model was done correctly. It could now also be assumed that the computerized model does what it is made for and that it is fully debugged. Besides the fact that the model is therefore verified, the model has also been validated. When two models made in two different types of software predict approximately the same energy demand in all 20 models, it is not plausible that this outcome does not approximate reality.

11.4. SIMULATION CONDITIONS

Because in DesignBuilder it is not possible to simulate the time-dependent rotation of the Trombe wall, three simulations were run per situation: a simulation without Trombe wall, a simulation in which the PCM layer of the Trombe wall is constantly directed to the outside environment, and a simulation in which the PCM layer of the Trombe wall is constantly directed towards the room (see Figure 11.4).

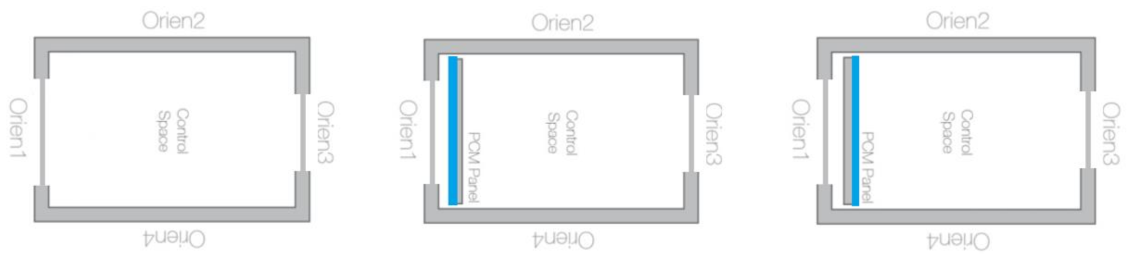


Figure 11.4: The three situations tested. Left: without panel, middle: panel towards outside, right: panel towards room.

For all situations, seven winter weeks and seven summer weeks were simulated. The most complicated task was to set all properties and conditions of the model of Matlab/Simulink exactly the same as the model of DesignBuilder. In both cases, all simulation conditions must be exactly the same, in order to be able to detect errors.

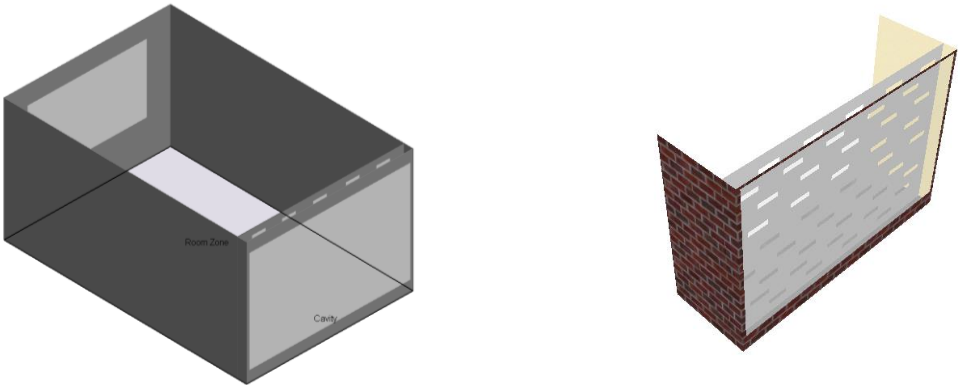


Figure 11.5: 3D schematization of room model with LTATW in DesignBuilder (small room).

A 3D schematization of a (small) room model modelled in DesignBuilder can be seen in Figure 11.5. The cubic room consists of a small window at orien3 and a large window at orien1, behind which is the Trombe wall. The LTATW is modelled as a vertical plate with openings homogeneously distributed over the total surface area. During comparative testing, the sidewalls (orien2 and orien4), floor and ceiling were assumed to be adiabatic in both the Matlab models and the DesignBuilder models. All other simulation conditions are listed in Table 11.2 (constants) and Table 11.3 (variables).

Table 11.2: Overview of constant simulation conditions.

Parameter	Simulation condition(s)
Simulation time	Winter weeks: November 22^{nd} until January 9^{th} Summer weeks: July 3^{rd} until August 20^{th}
Window size	Orien1: WWR = 80% Orien3: WWR = 40%
Shading	No shading
Thermostat set-points	Heating: 20 °C Cooling: 24 °C
LTATW characteristics	Cavity width: 0.2 m PCM layer thickness: 2.5 cm Aerogel layer thickness: 1 cm
Type of PCM	Rubitherm SP25E2
Percentage of openings in LTATW	10%
Heat transfer coefficients	α_i = 2.7 W/m^{2}K ; α_e = 25.0 W/m^{2}K
Airflow through LTATW	$Q_{r\text{-}c}$ = 0.1 m^3/s

Table 11.3: Overview of variable simulation conditions.

Parameter	Simulation condition(s)
Climate / weather data[4]	Cold: SWE_Stockholm.Arlanda.024600_IWEC Temperate climate: ITA_Milano-Linate.160800_IGDG Arid: EGY_Cairo.Intl.Airport.623660_ETMY Tropical: SGP_Singapore.486980_IWEC
Orientation	North, east, south and west
Internal gains	Offices: 25 W/m^2 Residences: 6 W/m^2
Occupancy	Offices: people present from 08:00-18:00 (Monday-Friday) Residences: people present from 18:00 – 08:00 (Monday-Sunday)
Infiltration	New buildings: ACH = 0.2 Old buildings: ACH = 0.8

[4] Obtained from: https://energyplus.net/weather.

Natural ventilation	No natural ventilation
Mechanical ventilation	Offices: ventilation rate = 2.0 h^{-1} (only when people present) Residences: ventilation rate = 1.0 h^{-1} (only when people present) Heat recovery efficiency: 0.9 (no bypass)
Construction material/composition	Light-weight: Non-adiabatic walls: hardboard-insulation-metal cladding Adiabatic walls: timber (5 cm) Heavy-weight: Non-adiabatic walls: concrete-insulation-brickwork Adiabatic walls: concrete (15 cm)
Insulation value of façades	Old buildings: R_c = 2.0 m^2K/W New buildings: R_c = 3.0 m^2K/W (does not represent reality)
Glazing properties	Single clear glazing: U = 3.0 W/m^2K; SHGC=0.17 Triple coated glazing: U = 0.8 W/m^2K; SHGC=0.80
Room size	Small room: width x depth x height = 3.6 m x 5.4 m x 2.7 m Big room: width x depth x height = 7.2 m x 10.8 m x 3.0 m

11.5. COMPARISON OF RESULTS

In this section, an overall impression of the results from the first phase of the comparative study are shown. The results include ten graphs per model: six graphs showing the total energy demand (kWh) per week for a situation without Trombe wall, a situation with a Trombe wall facing the interior and a situation with a Trombe wall facing the exterior. Three of the six graphs show the results for a winter season simulation (left) and the other three graphs show the results for a summer season simulation (right). Finally, the last four graphs show the relative change (%) between the energy demand in a situation without Trombe wall and a situation with Trombe wall. The appearance of a red line means that heating is required and the appearance of a blue line means that cooling is required. Finally, a dashed line represents the results from DesignBuilder and a continuous line represents the results from Matlab/Simulink.

The results giving the best impression of all first-phase results come from model seven and are shown in Figure 11.6 and 11.7. Model seven represents a big office room, with southern orientation and single clear glazing. It has a new, lightweight structure and is located in a cold climate (Stockholm).

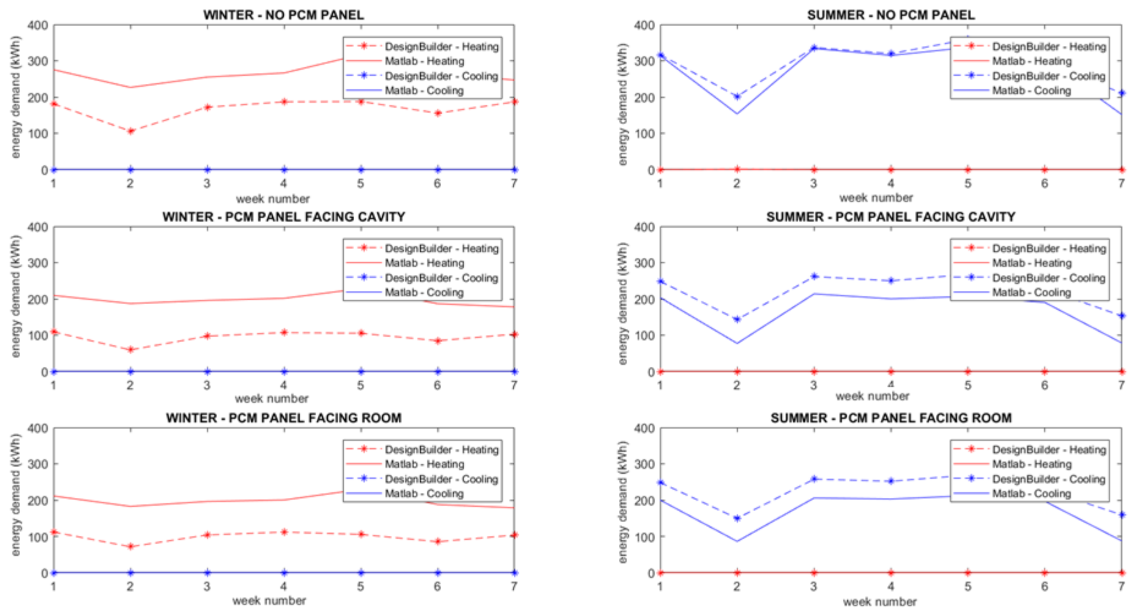


Figure 11.6: Total energy demand (kWh) per winter week (left) and summer week (right) of model 7, calculated by Matlab/Simulink and DesignBuilder in first phase.

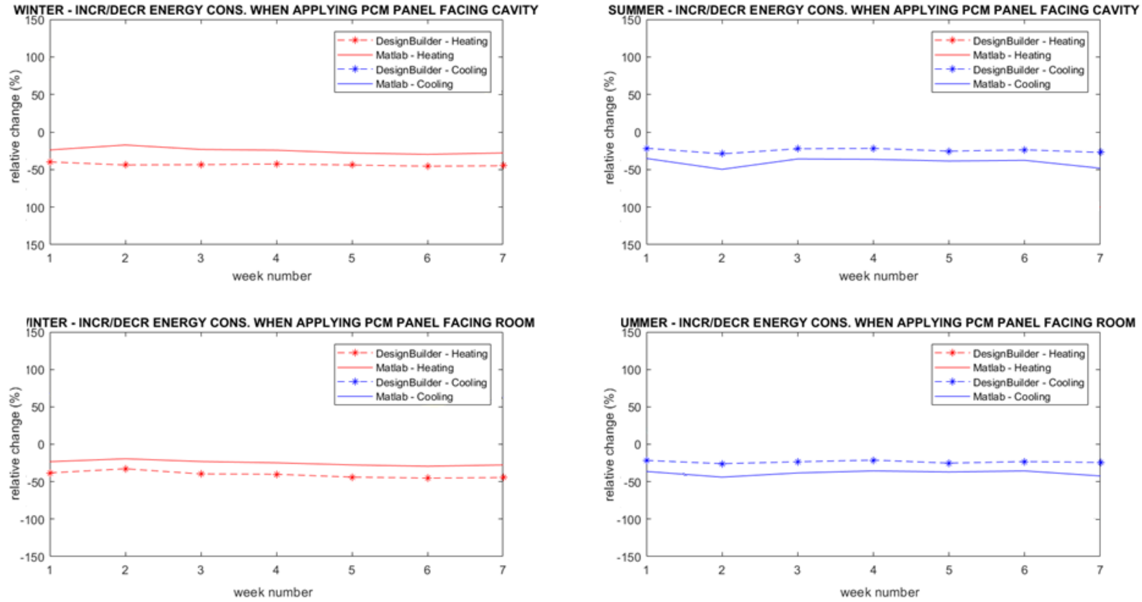


Figure 11.7: Increase or decrease in energy demand per week (%) of model 7 when applying a LTATW (facing cavity or room) (first phase).

From figures 11.6 and 11.7 it can be seen that significant differences exist between the first-phase results from Matlab/Simulink and the first-phase results from DesignBuilder. In the winter, Matlab/Simulink estimates an energy demand which is, in many weeks, twice as high as the energy demand calculated by DesignBuilder. In summer, this is the other way around: the energy demand calculated by DesignBuilder is significantly higher than the energy demand calculated by Matlab/Simulink. When looking at Figure 11.7, it can be seen that for the winter weeks, DesignBuilder calculates a higher reduction in energy demand due to the presence of a LTATW. In the summer, this is the other way around. The same ratio between calculated values of both software is not always the same in the results of the other 19 models, but differences in absolute values are often in the order of magnitude as shown in Figure 11.6 and 11.7.

11.6. MODIFICATIONS OF SIMULATION MODEL

Because the results of the first phase(s) of the comparison study were poor, research was conducted into the origin of these differences. When the results from the previous section were analyzed, it could be concluded that there were not only errors in the Matlab models, but also in the DesignBuilder models.

Based on logical reasoning and trial-and-error, modifications were made in both simulation models, until the similarities between Matlab/Simulink and DesignBuilder were assessed as 'good' (iterative process). The results of the comparison in the first phase(s) of the research were moderate to poor, but the procedure with an adapted, reliable model, showed good similarities (shown in the next section) between Matlab/Simulink and DesignBuilder. The most important modifications of the Matlab/Simulink simulation model are listed below:

- Adjusting simulation settings in Simulink: running a simulation file that was created in an older version of Simulink (with other simulation settings) caused errors. Simulation settings have been adjusted so that the correct and reliable results can be obtained.
- Adjusting PID-controller settings: Simulation settings have been adjusted so that the correct and reliable results can be obtained.
- Clearing programming errors: small programming errors were found in expressions regarding occupant behavior, orientation of windows and calculation of long-wave radiation through windows.
- Adding a Simulink component to reduce the influence of the initial room temperature (TinIC): when a certain period in DesignBuilder is simulated, a realistic start value of TinIC is taken into account (a small simulation of the model precedes the period). In contrast to DesignBuilder,

Matlab/Simulink calculated with an estimated (often wrong) starting value, which turned out to be of great influence. The influence of this has been reduced by adding a smarter module.

- Adding a Simulink component that incorporates the angle-dependent transmission of incoming solar radiation: calculations in DesignBuilder take into account the angle-dependent transmission of the incoming solar radiation. Less solar energy is transmitted through the glazing when the angle with the sun is small. When the incoming solar radiation is perpendicular to the façade (angle of 180°) the transmittance is at its highest. The same principle is added to the Matlab/Simulink model.
- Modifying the heat transmission through windows: In cases where the radiative room temperature deviated considerably from the room air temperature and when the U-value of the glazing is high, heat transmission through the glazing was not correctly calculated.

11.7. FINAL RESULTS

After making all the adjustments mentioned in the previous section, all 20 models have been simulated again. In this section, again, the final results of model seven are shown in Figure 11.8 and 11.9.

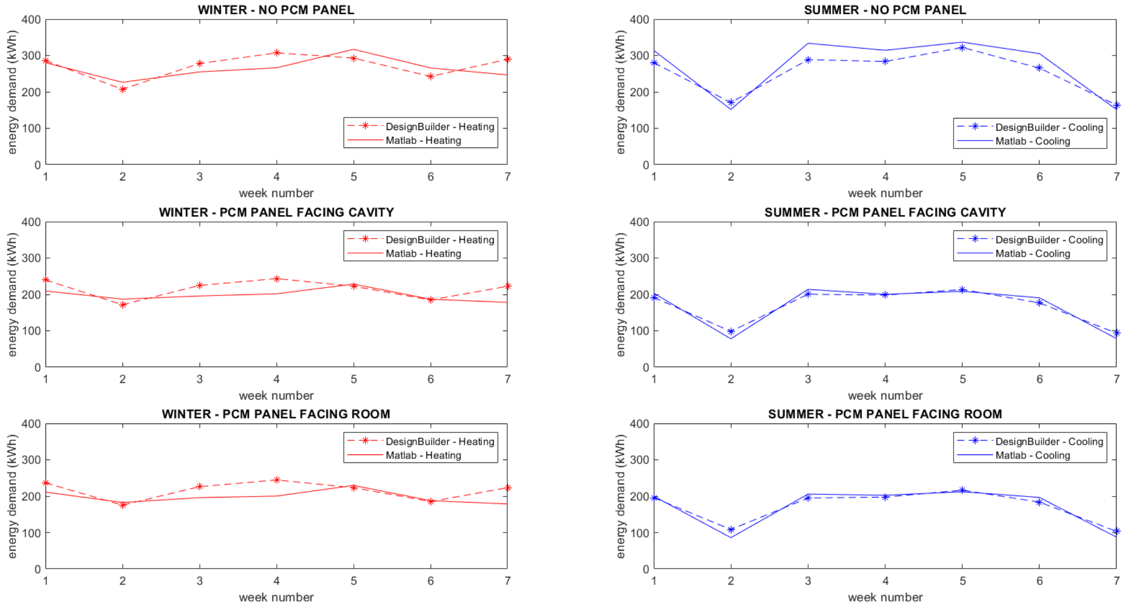


Figure 11.8: Total energy demand (kWh) per winter week (left) and summer week (right) of model 7, calculated by Matlab/Simulink and DesignBuilder in final phase.

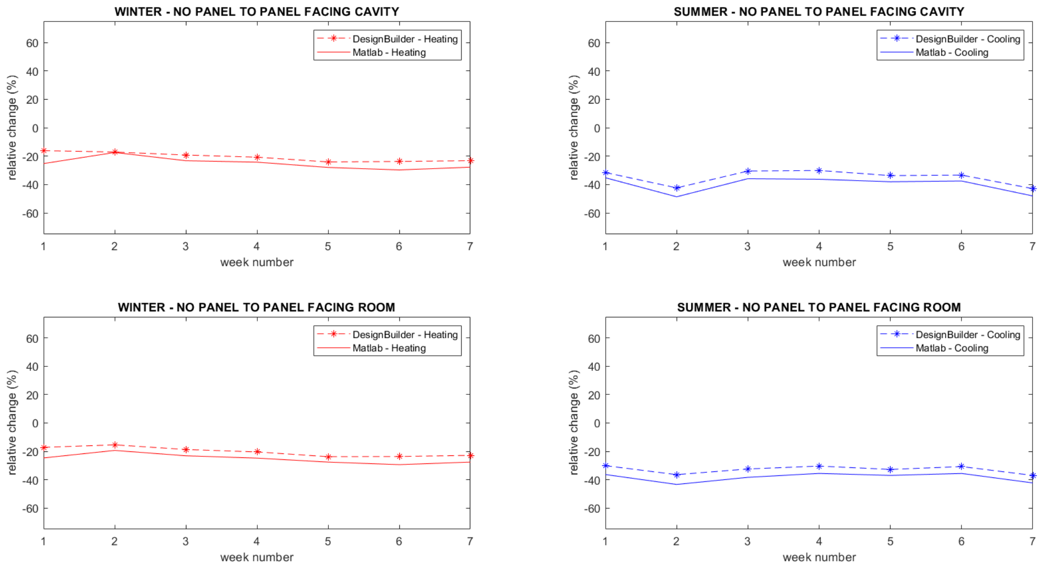


Figure 11.9: Increase or decrease in energy demand per week (%) of model 7 when applying a LTATW (facing cavity or room) (final phase).

The final results of all 20 models can be found in Appendix A. The results are assessed as ‘good’ in 17 out of 20 cases (models 1 to 8 and 12 to 20) and in 3 out of 20 cases the results are ‘moderate’ to ‘good’ (models 9 to 11). Based on the results obtained, it was decided to continue with the (now validated) simulation model in the further course of the project.

12. EXTENDED SIMULATION MODEL

After successfully testing the reliability of the modified, initial simulation model, the next step was to expand the model to a model that can meet the objectives of this research. To be able to meet the objectives, the following components had to be added: a component that calculates the energy losses due to infiltration, a component that takes into account the hysteresis phenomenon of the PCM, a component that determines the orientation of the LTATW throughout the whole year instead of just one season, a component that models a more realistic behavior of the air flow through the LTATW and a component that supports simulating a room with a night ventilation system. In this chapter, the description, implementation and validation of the added components is explained in detail in section 12.1 until 12.6.

12.1. INFILTRATION

To investigate the influence of the age of a building, infiltration had to be included. The difference between a new and existing construction is determined, among other things, by the amount of infiltration in a building and therefore needs to be implemented as a variable in the simulation model. The thermal losses (or gains) due to infiltration (W) can be calculated using equation 9.6:

$$Q_{inf} = \dot{m}_{inf}\, C_p\, (T_e\text{-}T_i) = \frac{\rho V_{room} ACH}{3600}\, C_p\, (T_e\text{-}T_i) \tag{9.6}$$

The simulation mechanism for infiltration is modeled in Simulink as shown in Figure 12.1:

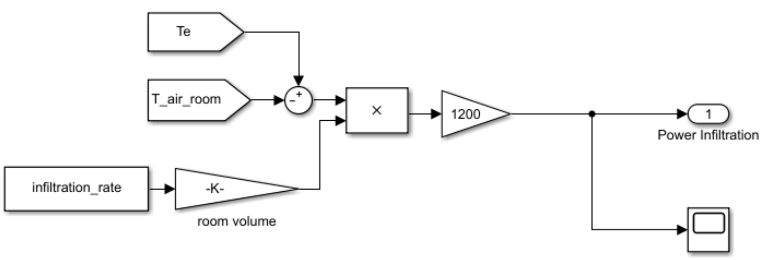


Figure 12.1: Simulink component of infiltration heat losses/gains.

The 'infiltration_rate' is defined in Matlab as follows:

```
infiltration_rate = 0.2/3600;
```

The heat load from infiltration has been added to other heat loads as shown in Figure 12.2:

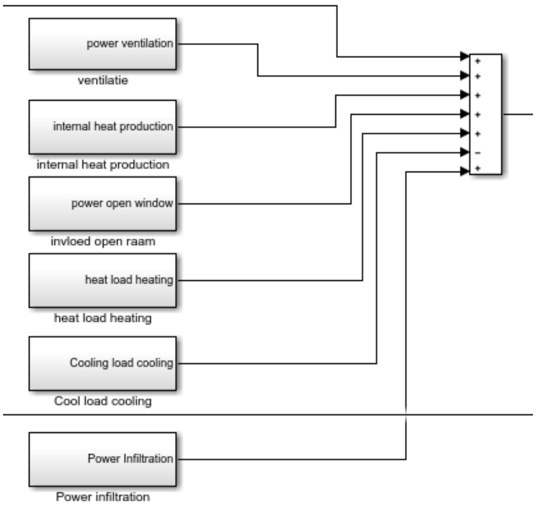


Figure 12.2: Heat load from infiltration added to other heat loads.

12.2. PCM HYSTERESIS

An aspect that has not been tested in the comparative study with DesignBuilder is the modeling of the hysteresis behavior of the PCM. A material with thermal hysteresis exhibits a melting temperature that is different from the solidification temperature (Frei, 2016). When the enthalpy of the PCM (SP25E2) is plotted against the temperature, two curves as shown in Figure 12.3 can be seen. When the PCM is in solid state and is being heated, the enthalpy is determined by the bottom (red) curve or path. As the PCM passes the melting temperature, it completely liquifies. When the liquid PCM is subsequently cooled, it will follow the upper curve, thus the material remains liquid at temperatures below the melting temperature. Once the solidification temperature is reached, the PCM becomes completely solid. If the PCM is then heated back up, the bottom curve will be followed, and so on (Frei, 2016).

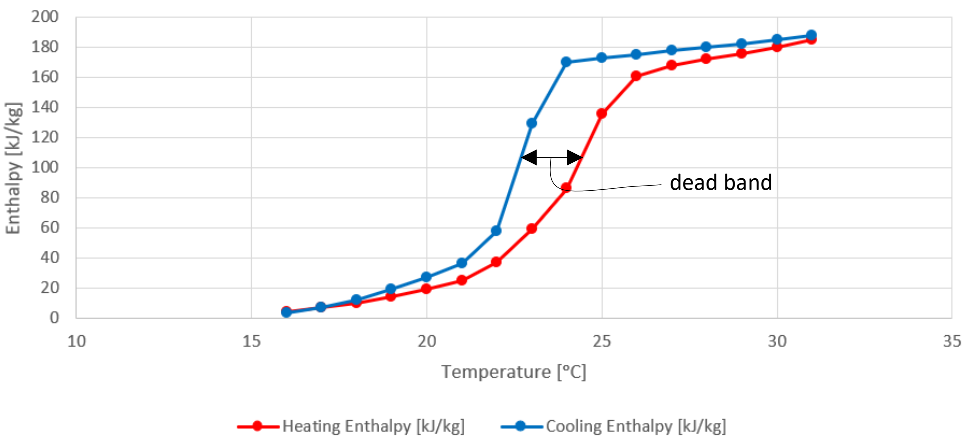


Figure 12.3: Enthalpy curve of Rubitherm's SP25E2 (made by the author).

One of the first versions of the simulation model already contained a component that takes into account this hysteresis effect, but it has been changed after several analyses. The final module is modeled in Simulink as shown in Figure 12.4 and determines that when the temperature of the PCM is between the melting and solidification temperature, an extra heat capacity is added to the PCM.

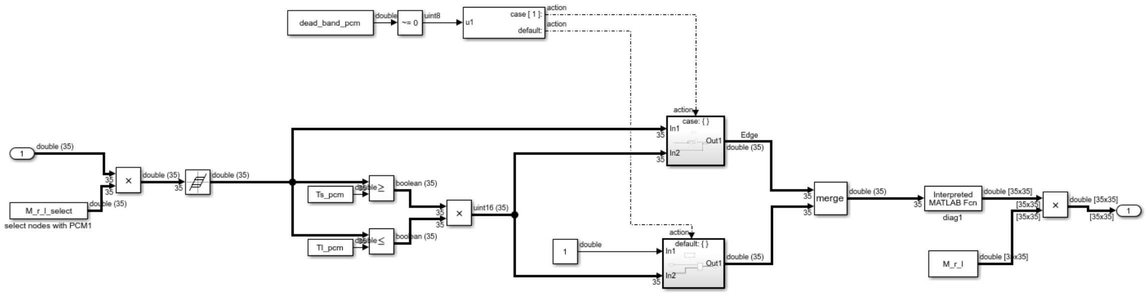


Figure 12.4: Subsystem 'PCM effective mass' (see Figure 10.14).

For the PCM product 'SP25E2', the value for 'dead_band_pcm' equals 2.0 °C and is defined in the Matlab-file as follows:

```
dead_band_pcm = 2.0;          % PCM dead band due to hysteresis [K]
```

The principle of increasing the heat capacity between the solidification and melting temperature is shown in figure 12.5, in which a PCM with a melting temperature of 18.5 °C and a solidification temperature of 21.5 °C is considered. In Figure 12.5, h_{sf} represents the specific enthalpy (or latent heat of fusion) and ΔT_{pc} represents the difference between melting temperature and solidification temperature.

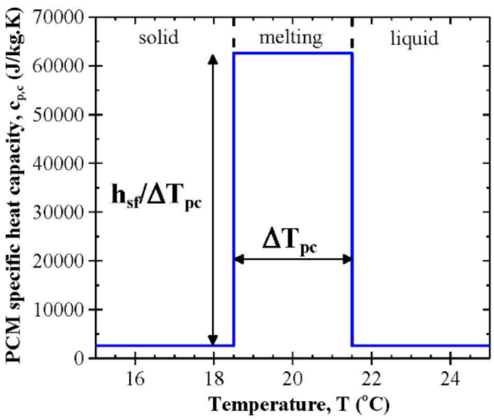


Figure 12.5: specific heat capacity of a PCM as a function of its temperature (Thiele, Sant, & Pilon, 2015).

12.3. ROTATION SCHEDULE

One of the main advantages of a lightweight translucent adaptable Trombe wall, is that it possesses a rotation mechanism. This mechanism makes it possible to adjust its orientation to the most favorable one, in terms of comfort and energy savings. In climate areas where there is clearly a difference in temperature between winter and summer (such as in a cold or temperate climate), the system is thermally charged by facing the outdoor environment in the winter, at daytime. At night, the system rotates 180 degrees and releases the accumulated heat to the interior. In summer, the LTATW faces the interior at daytime to store the heat loads from within the building and at night, the system reverses again and releases the heat to the outside environment by means of night ventilation.

In climate areas where the average summer temperatures do not differ much from the average winter temperatures (such as in a tropical or arid climate), the system does not always work as in the above-mentioned schedule. Since the rotation characteristics differ per climate and season, a rotation mechanism was developed in Simulink. This rotation mechanism generates the right rotation schedule for each climate, based on times of sunrise and sunset, and conditions that determine whether the system should be active in 'winter mode' or in 'summer mode'. The difference between winter mode and summer mode is explained in section 12.3.1. The influence of varying times for sunrise and sunset of the different climates is explained in section 12.3.2. Finally, the implementation of all modes and times in Simulink is explained in section 12.3.3.

12.3.1. WINTER MODE AND SUMMER MODE

There are two possible modes on which the LTATW bases its orientation: winter mode and summer mode. In a winter mode, the PCM layer of the innovative Trombe wall faces the outdoor environment at daytime and must capture the energy from the sun. Winter mode is activated when the average room temperature over the last 24 hours is lower than the average of the two (heating and cooling) thermostat set-points. In a summer mode, the PCM layer of the innovative Trombe wall faces the indoor environment at daytime and must capture the energy from internal sources. Summer mode is activated when the average room temperature of the last 24 hours is higher than the average of the two setpoint temperatures:

Winter mode: $T_{room,mean(24h)} \leq T_{h,set} + \frac{T_{c,set}-T_{h,set}}{2}$

Summer mode: $T_{room,mean(24h)} \geq T_{h,set} + \frac{T_{c,set}-T_{h,set}}{2}$

As the setpoint temperatures for heating and cooling (20 °C and 26 °C) are assumed to be the same in all climates, winter mode and summer mode are described as follows:

Winter mode: $T_{room,mean(24h)} \leq 23$ °C

Summer mode: $T_{room,mean(24h)} \geq 23$ °C

12.3.2. DAY-TIME AND NIGHT-TIME

In both a winter mode and a summer mode, the LTATW rotates twice a day: once when the sun comes up and once when the sun goes down. The LTATW faces the outdoor environment at daytime in a winter mode, and faces the indoor environment at daytime in a summer mode. There are different times for sunrise and sunset for each climate, and vary throughout the year as well.

In this Master thesis, a city has been chosen for each climate that is representative of the weather conditions of the climate in question. In order to determine the rotation times per climate, also the times of sunrise and sunset of the representative cities were chosen as the starting point. As all representative cities (all located on the Northern hemisphere) were selected on 15 degrees increments in latitude angles (which determine times of sunset and sunrise), a proper subdivision was also made for this issue. The four cities used in this study (Stockholm, Milan, Cairo and Singapore) are all located on the Northern hemisphere. In the Northern hemisphere, the longest day happens in summer and the shortest day in winter. The longest period of daylight occurs at summer solstice (also known as June solstice), when the sun has a maximum tilt towards the Earth's poles and when it reaches its highest position in the sky (Browning, 1961). Around this moment of time there is continuous daylight at the pole. For all locations on the Northern hemisphere, the summer solstice occurs around 21 June and the winter solstice occurs around 21 December, depending on the shift of the calendar. As the earth orbits the sun in an ellipse, the dates of the longest day and shortest day vary by a few days from the dates of the earliest sunrise and latest sunsets (Browning, 1961). The exact times[5] of the earliest sunrise and sunset and the latest sunrise and sunset for each city are as listed in Table 12.1 and 12.2. The times shown are times according to the 'standard' time system (winter time).

From Table 12.1 and 12.2 can be deduced that the biggest difference between earliest and latest sunset/sunrise time occurs at the location closest to the pole (Stockholm). The smallest differences occur in Singapore, which is almost exactly located on the Equator. For that reason, the dates of the earliest and latest sunset/sunrise are the least similar to the dates of the summer and winter solstices (21 Dec and 21 June). Locations with latitudes similar to Singapore show no clear summer and winter solstices and the times of earliest and latest sunset/sunrise hardly differ from each other.

[5] Retrieved from: www.timeanddate.com

Table 12.1: Times of earliest and latest sunrise for each of the four representative cities

	Earliest sunrise		**Latest sunrise**	
	Time	Date	Time	Date
Stockholm	2:30	19-Jun	8:45	27-Dec
Milan	4:34	16-Jun	8:03	2-Jan
Cairo	4:53	12-Jun	6:52	10-Jan
Singapore	6:46	2-Nov	7:16	1-Feb

Table 12.2: Times of earliest and latest sunset for each of the four representative cities

	Earliest sunset		**Latest sunset**	
	Time	Date	Time	Date
Stockholm	14:46	16-Dec	21:08	23-Jun
Milan	16:39	10-Dec	20:15	26-Jun
Cairo	16:54	2-Dec	19:00	30-Jun
Singapore	18:50	4-Nov	19:20	13-Feb

12.3.3. IMPLEMENTATION IN MATLAB/SIMULINK

Using the data from section 12.3.1 and 12.3.2, multiple mechanisms have been developed that describe whether the LTATW orientates itself to the outdoor or indoor environment. The first mechanism is shown in Figure 12.6 and determines whether the LTATW is in winter mode or in summer mode:

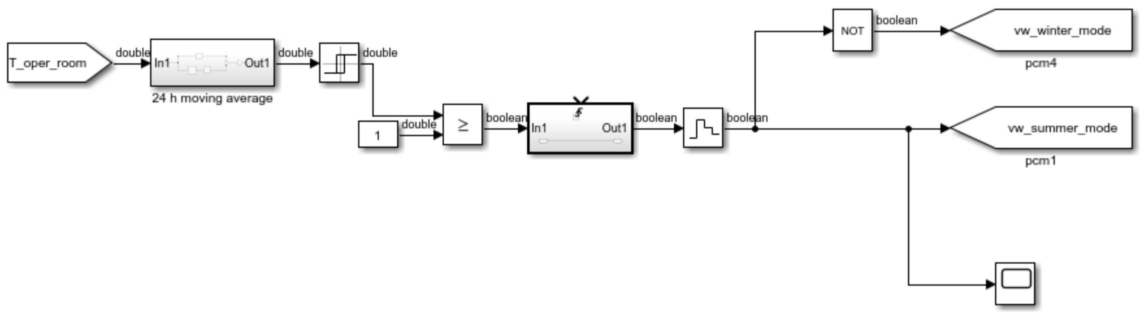


Figure 12.6: Simulink component that determines whether the LTATW is in winter mode or in summer mode.

In section 12.3.1 is stated that the LTATW operates in summer mode when the average room temperature of the last 24 hours is higher than 23 °C and that the system operates in winter mode when average room temperature of the last 24 hours is lower than 23 °C. To prevent the system from rotating too often, a relay of 0.5 °C has been modelled. This relay generates a positive outcome when the 24 hour moving average of the room temperature exceeds 23.5 °C (summer mode is turned on) and remains in summer mode, even when the temperature drops between 23.5 and 22.5 °C again. When the average temperature drops below 22.5 °C, winter mode is turned on and stays on, until the threshold value of 23.5 °C is reached again.

The second mechanism, which determines whether the LTATW should operate in day-time or night-time mode, is shown in figure 12.7. In this mechanism, the times of sunrise and sunset are described using two sine waves. The first sine wave (upper block) describes the times of sunrise throughout the year (for a specific climate) and the second sine wave (bottom block) describes the times of sunset throughout the year. When the time in a simulation is between the times of sunrise and sunset, the system operates in daytime mode. Although the dates of the solstices are not exactly the same as the dates of the earliest and

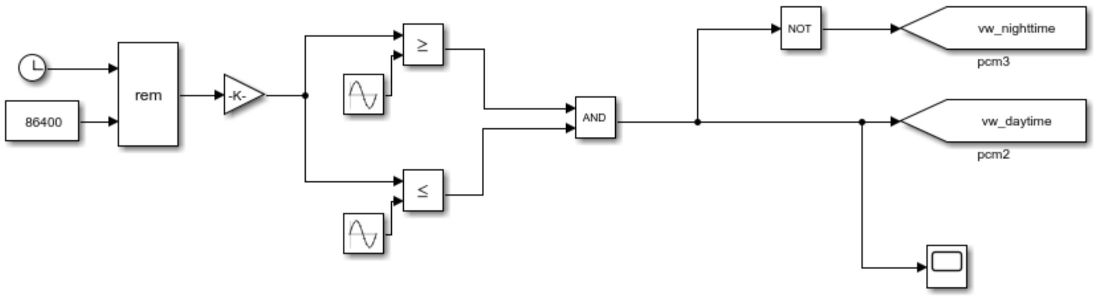


Figure 12.7: Simulink component that determines whether the LTATW is in day-time mode or in night-time mode.

latest sunsets/sunrises, they are being programmed like that. From this point of view it means that the maximum and minimum points of the sine function represent the two solstices of the year and that the corresponding times for sunrise and sunset on these maximums are equal to the times shown in table 12.1 and 12.2.

The sine waves are specified by equation 12.1.

$$O(t) = B + A \cdot \sin(\omega t + \phi) \tag{12.1}$$

In this formula, O(t) represents the outcome and B represents the bias. The bias is the equilibrium position around which the sine function moves. This bias is therefore the average between the earliest and latest time of sunrise or sunset. The amplitude A represents the height of the peaks and valleys in this function, the frequency ω (rad/s) is the number of cycles that occur each second of time and the phase shift φ (rad) specifies where in its cycle the oscillation is at t = 0. For both the sine functions of sunset time and sunrise time, ω is the same:

$$\omega = \frac{2\pi}{T_{year}} = \frac{2\pi}{365 \cdot 86400} \tag{12.2}$$

The value of φ does not differ per climate, but does differ per sine wave. In case of sunrise, the graph its minimum should be exactly located at t = 21 June (day 172) and the graph its maximum should be exactly located at t = 21 December (day 355). In case of sunset this is exactly the opposite (see Figure 12.8). For the sine wave of sunrise this means that φ = 1.75 rad and for the sine wave of sunset this means that φ = 4.9 rad (= 1.75 + π).

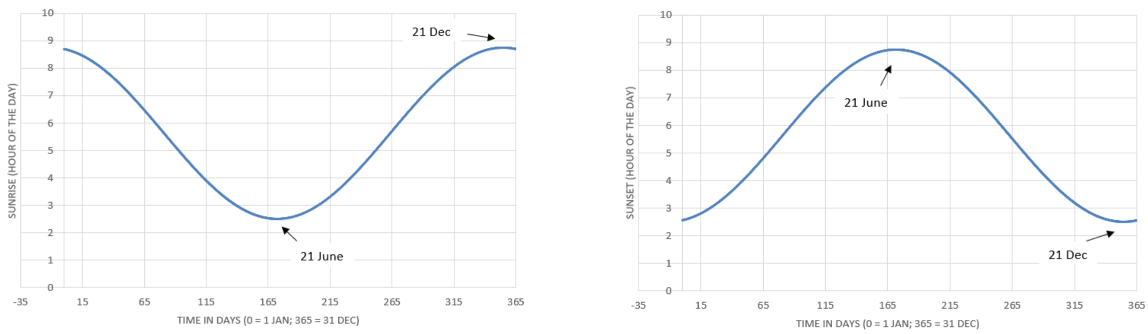


Figure 12.8: times of sunrise (left) and sunset (right) throughout the year, idealised by a sine wave.

The values of A and B differ per climate, as different times of sunrise and sunset apply. An overview of the values are shown in Table 12.3 and 12.4.

A third mechanism in Simulink finally determines whether the LTATW faces the outdoor environment or the indoor (room) environment. The condition is based on conditions of summer mode, winter mode, daytime and night time (see Figure 12.9). The LTATW faces the room environment if two combinations occur: it is

Table 12.3: Values of A, B and ϕ per location of sunrise sine wave

	Amplitude	Bias	Phase
Stockholm	3.2	5.625	1.75
Milan	1.8	6.31	1.75
Cairo	1	5.88	1.75
Singapore	0.25	7.02	1.75

Table 12.4: Values of A, B and ϕ per location of sunset sine wave

	Amplitude	Bias	Phase
Stockholm	3.2	17.95	4.9
Milan	1.8	18.45	4.9
Cairo	1	17.95	4.9
Singapore	0.25	19.08	4.9

daytime and the system is in summer mode (capturing heat from internal gains), and when it's night time and the system is in winter mode (releasing the captured heat from the sun to the room at night-time). In all other (opposite) cases, the system faces the cavity.

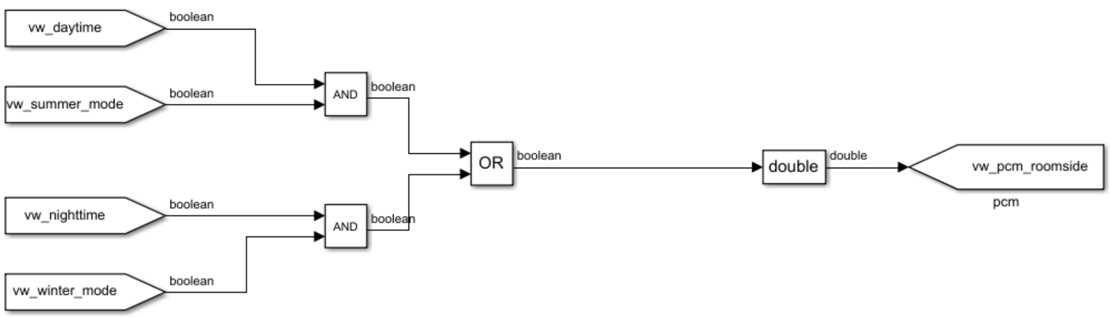


Figure 12.9: Simulink component that determines whether the LTATW faces the interior or the exterior.

12.4. AIR EXCHANGE BETWEEN CAVITY AND EXTERIOR

The fourth component that was not present in the initial simulation model was the modeling of the air exchange between the cavity and the outdoor environment (night ventilation). This air exchange only takes place at night and in summer mode (when the captured heat at day-time has to be released to the outside air at night). How the night ventilation process is added to the Matlab and Simulink model is explained in this section. The principle of the natural night ventilation system is explained in section 12.4.1 and in section 12.4.2 a parameter has been investigated that has a major influence on the performance of the system: the size of openings in the façade. The implementation of the system in Matlab and Simulink is described in section 12.4.3.

12.4.1. PRINCIPLE

There are multiple types of night ventilation, such as mechanical night ventilation, passive cross ventilation and passive stack ventilation (Blondeau & Spe, 1997). In the initial simulation model, only mechanical night ventilation was modelled. In the extended simulation model, also passive stack ventilation was added. In passive stack ventilation, the extraction is imposed by the stack effect. It relies on the buoyancy of warm air that rises in the cavity space and leaves through openings in the façade at ceiling height. The air in the cavity is replaced by cooler outside air that enters the cavity through inlets located near the floor (see Figure 12.10).

When the resistance to airflow in the cavity is neglected and the airflow through inlets and outlets is assumed to be non-viscous, the flow rate produced by the stack effect can be calculated with equation 12.3 and 12.4. (van der Spoel, 2018).

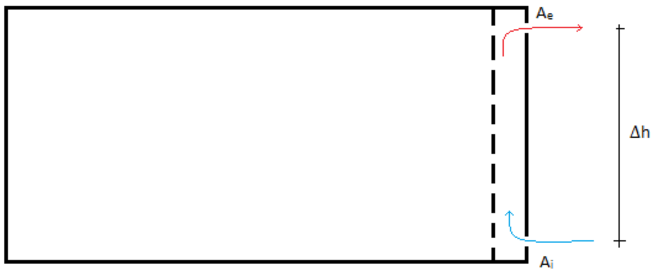


Figure 12.10: Principle of passive stack ventilation (made by the author).

$$\dot{V}_{stack} = C_d \cdot A_{eff} \cdot \sqrt{\frac{2g\Delta h P_0}{R}\left(\frac{1}{T_e} - \frac{1}{T_c}\right)} \tag{12.3}$$

$$\frac{1}{A_{eff}^2} = \frac{1}{A_i^2} + \frac{1}{A_e^2} \tag{12.4}$$

In which $\dot{V}_{stack}$ is the air flow rate in m^3/s, C_d a discharge coefficient (-), A_{eff} the effective surface area of the openings in the façade in m^2, A_i the surface area of the inlet opening in m^2, A_e the surface area of the outlet opening in m^2, g the gravitational constant (m/s^2), Δh the height difference between both openings (m), P_0 the atmospheric pressure at sea level (=101325 Pa), R the gas constant (=287 J/kgK) and T_e and T_c the temperature (°C) of outside and cavity, respectively.

12.4.2. IDEAL SIZE OF FAÇADE INLET AND OUTLET

A key parameter that has a major influence on the airflow rate in the cavity are the sizes of the inlets and outlets of the façade. When the façade openings are large, the air flow induced by the stack effect will also be large. When the openings in the façade are relatively small, a much smaller rate is induced. When night ventilation is to be applied, an 'ideal' amount of heat removal is desired. Openings must not be too small, so that not enough heat can be dissipated. Too large openings, on the other hand, are also not desirable, as not too much energy may be lost. In the simulation model made in this Master thesis project, one single value for the opening size in the façade that fits the innovative Trombe wall system, was assumed (allowed by the findings in this section). This is done so that the amount of variables is reduced and clear conclusions can be drawn from a system with the same specific configuration, tested under different conditions (different climates, different types of glazing, window sizes, etc.).

In order to find the most ideal size of the inlet and outlet, a study was carried out. In this study, a balance equation has been drawn up in which all the relevant heat flows are included. A schematization of the problem is shown in Figure 12.11. in Figure 12.11 a vertical cross section of a room with LTATW is sketched. When the side walls of the room are assumed adiabatic, the problem can be simplified to a situation with

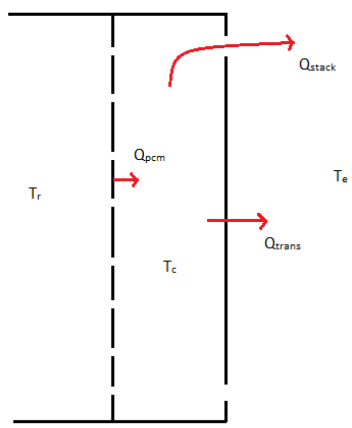


Figure 12.11: Heat flows to and from cavity space (made by the author).

three different spaces: room, cavity and outside environment. Each room has its own average temperature and the heat exchange is determined by three energy flows: heat generated by the Trombe wall, an air flow from the outside environment through the cavity and a transmission loss through the glazing. The energy balance in which the three energy flows are included is as follows:

$$Q_{stack} - Q_{trans} + Q_{pcm} = 0 \tag{12.5}$$

Q_{stack} is the energy flow in W resulting from natural ventilation in the cavity, generated by the chimney effect. Q_{trans} is the energy flow in W through the glazing and Q_{pcm} is the energy flow in W from the LTATW. All heat flows can be calculated with the following equations:

$$Q_{stack} = \rho c \cdot \dot{V}_{stack} \cdot (T_e - T_c) \tag{12.6}$$

$$Q_{trans} = bh \cdot U_{gl} \cdot (T_c - T_e) \tag{12.7}$$

$$Q_{pcm} = bh \cdot h_c \cdot \left(T_{pcm} - T_c\right) \tag{12.8}$$

In which ρc is the product of the density and the heat capacity of dry air (=1200 J/m^{3}K), b the width of the room in m, h the height of the room in m, U_{gl} the insulation value of the glazing (W/m^{2}K), h_c the convective heat transfer coefficient (W/m^{2}K) and T_{pcm} the temperature of the PCM in the LTATW (°C).

During night ventilation, the warm air in the cavity is replaced by fresh, cooler outside air and always applies that $T_e < T_c$, so that:

$$Q_{pcm} = Q_{stack} + Q_{trans} \tag{12.9}$$

By solving equation 12.9, the ideal opening size of the openings in the facade can be found. A disadvantage is that all variables in the equation contain the variable T_c, which makes it an implicit expression that must be solved with an iterative method.

The study has been carried out taking into account all possible circumstances that are dealt with in the main research of this project. This study made it possible to determine whether simulations can be performed with one specific opening size, or whether the size must be a variable, depending on the configuration. The conditions that influence the energy balance are: climate (determines the average value of T_e), type of glazing (determines U-value of the glazing) and window size (determines vertical distance between inlet and outlet, Δh).

The annual values of the average night temperatures per location/climate[6] are shown in Table 12.5 to 12.8.

Table 12.5: Stockholm monthly temperatures 2015-2018.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Day-time temperature	0 °C	1 °C	4 °C	8 °C	16 °C	19 °C	21 °C	21 °C	17 °C	10 °C	6 °C	4 °C
Night-time temperature	-5 °C	-5 °C	-3 °C	0 °C	6 °C	10 °C	13 °C	12 °C	10 °C	5 °C	1 °C	-1 °C

Table 12.6: Milan monthly temperatures 2015-2018.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Day-time temperature	9 °C	8 °C	14 °C	19 °C	22 °C	28 °C	31 °C	29 °C	24 °C	18 °C	12 °C	9 °C
Night-time temperature	-1 °C	2 °C	4 °C	9 °C	11 °C	17 °C	20 °C	19 °C	14 °C	9 °C	3 °C	0 °C

[6] Retrieved from: www.climate-data.org

Table 12.7: Cairo monthly temperatures 2015-2018.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Day-time temperature	22°C	25 °C	28°C	33°C	36 °C	38 °C	37 °C	37 °C	35 °C	31 °C	26 °C	24 °C
Night-time temperature	7 °C	7 °C	11°C	13°C	16 °C	20 °C	21 °C	22 °C	20 °C	17 °C	12 °C	9 °C

Table 12.8: Singapore monthly temperatures 2015-2018.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Day-time temperature	31°C	30°C	32°C	32°C	32 °C	31 °C	31 °C	31 °C	31 °C	31°C	31 °C	31 °C
Night-time temperature	25°C	25 °C	25°C	26°C	27 °C	27 °C	26 °C	26 °C	26 °C	26°C	26 °C	25 °C

Based on the average day temperatures, the following cooling periods with corresponding average night temperature are defined:

Table 12.9: Cooling period per location and corresponding mean night temperatures.

	Cooling period	Mean night temperature (°C)
Stockholm	May - Sept	10
Milan	Apr - Oct	14
Cairo	Jan - Dec	15
Singapore	Jan - Dec	26

In addition to climate, the influence of the different types of glazing and window size is also taken into account. In this project, four glazing types with two different insulation values (double glazing and triple glazing) are studied: U = 1.6 W/m^{2}K and U = 0.7 W/m^{2}K. Two window sizes are studied: A window with a window-to-wall ratio of 0.25 (small window) and a window with a window-to-wall ratio 0.75 (big window). These ratios result in a value for Δh of 0.8 and 2.2 respectively (where a window is assumed in which the distance between the bottom of the window frame and the floor is equal to the distance between the side of the window frame and the side wall. The center points of the openings are each 5 cm from the bottom and top).

All combinations were studied using an iterative calculation in Excel. In this calculation, the following values were assumed:

C_d = 0.8
ρc = 1200 J/m^{3}K
g = 9.81 m/s^2
h_c = 5 W/m^{2}K
T_{pcm} = 298 K (25°C)

In Excel, the values for the opening percentage in the façade were plotted against the values of Q_{pcm}. To calculate the value of Q_{pcm}, an estimate was made for the value of T_c. When the estimation results in a difference between Q_{pcm} and Q_{stack} + Q_{trans} (according to energy balance they should be equal to each other), a new estimate was made for the value of T_c by means of the difference (divided by a factor of 1000) until the difference was minimal. This principle has been done for a large number of opening percentages and the results for Q_{pcm} show, under each circumstance, a type of curve as shown in Figure 12.12. When T_c is plotted against the opening percentage, a type of curve as shown in Figure 12.13 can be seen.

Both graphs show a trend towards to a horizontal asymptote. When it is stated that on average at least 75% of the maximum heat flow must be transported, the opening percentages per circumstance as shown in Table 12.10 apply.

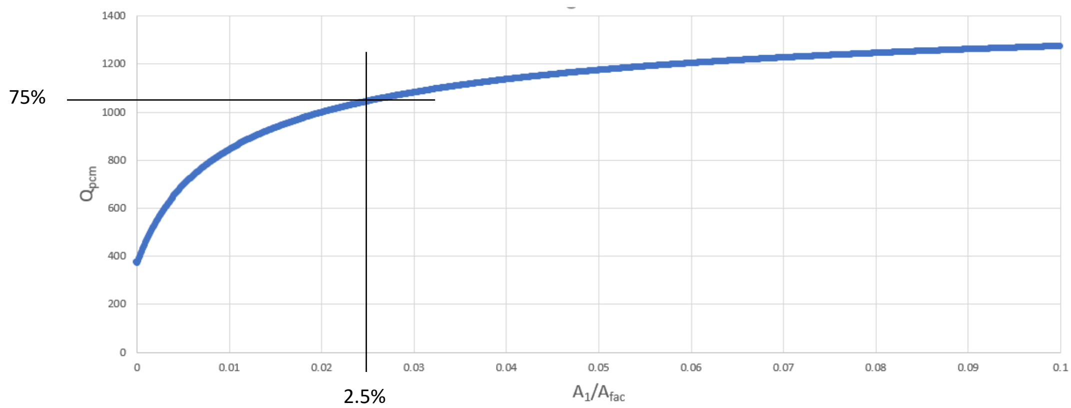


Figure 12.12: Q_{pcm} versus opening percentage of inlet or outlet.

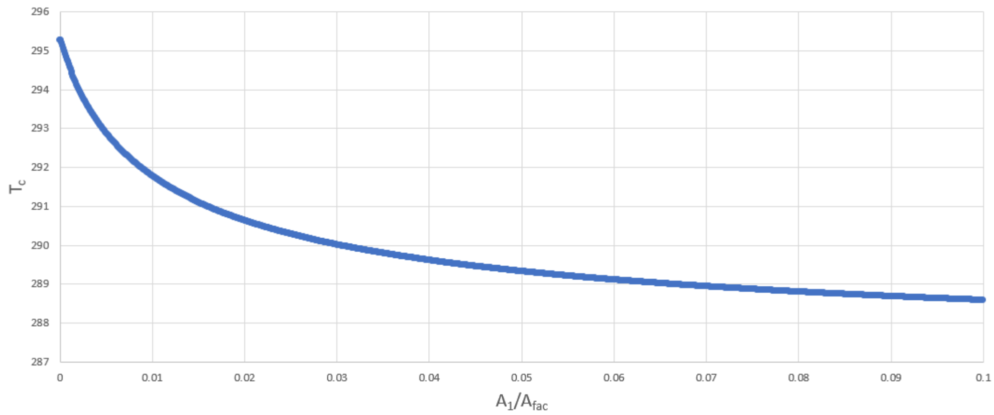


Figure 12.13: T_c versus opening percentage of inlet or outlet.

Table 12.10: Ideal opening percentage of inlet or outlet in façade for different circumstances.

Location	Mean night temperature in cooling period	U-value of glazing (W/m²K)	Δh = 0.8 m	Δh = 2.2 m
Stockholm	10 °C	1.6	2.70%	1.40%
		0.7	2.90%	1.60%
Milan	14 °C	1.6	3.10%	2.20%
		0.7	3.40%	2.40%
Cairo	15 °C	1.6	3.20%	2.20%
		0.7	3.40%	2.40%
Singapore	26 °C	1.6		
		0.7		

The percentages found represent the size of one opening: the inlet or the outlet. Both openings have the same size. Because the average night temperature in Singapore is equal to 26 °C, night cooling is not applicable as it is not effective.

From Table 12.10 can be seen that ideal opening size differs from 1.40% to 3.40% and that the average of all outcomes equals 2.5%. The results show expected patterns: in situations with a higher outside temperature, larger openings are required. This also applies in situations where the glazing is better insulated (heat can escape less well). Varying the distance between the openings has a practically same effect as varying the climate.

If in a case where 3.4% of opening is desired (Cairo, U = 0.7, dh = 0.8), the value of 2.5% is applied, Q_{pcm} will be equal to 844.8 W instead of 911.9 W. This means that 7.4% less energy is removed than desired. If the same calculation is made for all situations, results are obtained as shown in Table 12.11. Table 12.11 shows that the influence of assuming the average value for the opening percentage does not have an impact higher

Table 12.11: Increase or decrease of Q_{pcm} when applying average opening percentage from table 12.10

Location	Mean night temperature in cooling period	U-value of glazing (W/m^2K)	Δh = 0.8 m	Δh = 2.2 m
Stockholm	10 °C	1.6	-1.6%	+10.7%
		0.7	-3.4%	+8.3%
Milan	14 °C	1.6	-4.6%	+2.4%
		0.7	-7.2%	+0.8%
Cairo	15 °C	1.6	-5.3%	+2.4%
		0.7	-7.4%	+0.9%
Singapore	26 °C	1.6		
		0.7		

than 10.7%. Given the fact that the objective of this project is to investigate the influence of certain variables, it is desired to reduce the number of additional variables as much as possible. A maximum difference of 10.7% is therefore considered 'OK' and therefore, the size of the openings in the outer wall is fixed at 2.5%.

12.4.3. IMPLEMENTATION IN MATLAB/SIMULINK

Before implementation in Matlab and Simulink, equation 12.3 has been defined in a different from:

$$\dot{V}_{stack} = C_1 \cdot \sqrt{\left(\frac{1}{T_e} - \frac{1}{T_c}\right)} \tag{12.10}$$

$$C_1 = C_d \cdot \sqrt{\frac{2g\Delta h P_0/R}{\frac{1}{A_i^2}+\frac{1}{A_e^2}}} \tag{12.11}$$

In which C_1 represents the 'flow coefficient'. The heat loss (W) due to night ventilation are calculated with equation 12.12:

$$Q_{stack} = \rho c \cdot \dot{V}_{stack} \cdot (T_e - T_c) \tag{12.12}$$

The simulink component that calculates the heat loss is shown in Figure 12.14. The implementation of equation 12.10 can easily be seen in the figure. It can also be seen that only when the Boolean conditions: 'vw_cav_vents_open', 'vw_nighttime' and 'vw_summer_mode' are met, a heat loss is put in operation.

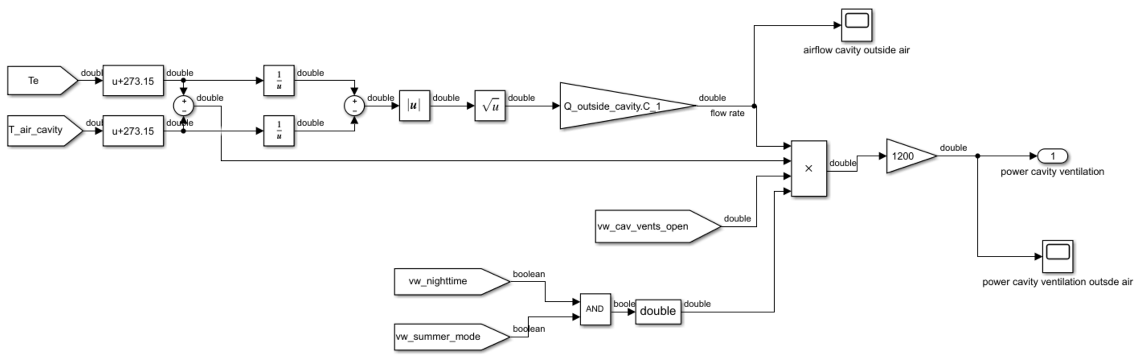


Figure 12.14: Simulink component of night ventilation system.

In the Matlab-file, the following commands are defined:

```
Q_oc.A1    = 0.025*room.width*room.height;    %surface area of inlet (m2)
Q_oc.A2    = 0.025*room.width*room.height;    %surface area of outlet (m2)
```

```
Q_oc.dH     = 2.2;              %height difference of the two vent openings (m).
Q_oc.Cd     = 0.8;              %discharge coefficient (-)

% definition of the flow coefficient C_1:
Q_outside_cavity.C_1 = Q_oc.Cd*( 2*
1/(1/Q_oc.A1^2+1/Q_oc.A2^2)*9.8*Q_oc.dH*101325/287)^0.5;

%control settings for opening/closing of the cavity vents:
ThresholdCavVentOpen    = 24; % Operative temp above which the vents are opened
ThresholdCavVentClosed  = 22; % Operative temp below which the vents are closed
                             (a relay applies between the threshold setpoints)
```

12.5. AIR EXCHANGE BETWEEN CAVITY AND ROOM

The fifth and final component that was not present in the initial simulation model was the modelling of the air exchange between the cavity and the room. In the initial model, a constant airflow was modelled, but in reality, this air exchange varies over time. The airflow is generated by a temperature difference between the room and the cavity, which consequently causes a difference in air density between both spaces.

In this section, the influence of the configuration of the openings in the innovative Trombe wall on the behavior of the airflow between room and cavity is described. Section 12.5.1 explains the working principle of the air exchange between both spaces. Section 12.5.2 explains how and why a certain number of openings exist and the working principle and details of the study are described in section 12.5.3. The implementation of the results of the study in the simulation model of Matlab/Simulink is described in section 12.5.4.

12.5.1. PRINCIPLE

In a traditional Trombe wall, openings only exist at the top and bottom of the wall, where in a lightweight, translucent adaptable Trombe wall, numerous openings are spread homogeneously over the entire surface of the wall. Heat flows through these openings, of which the size depends on the temperature difference between cavity and room. When the temperature in the cavity is lower than the temperature in the room, heat flows from room to cavity (heat loss), but when the temperature in the cavity is higher than the temperature in the room (by, for example, a high amount of incoming solar radiation) heat flows from cavity to room (as indicated in Figure 12.15).

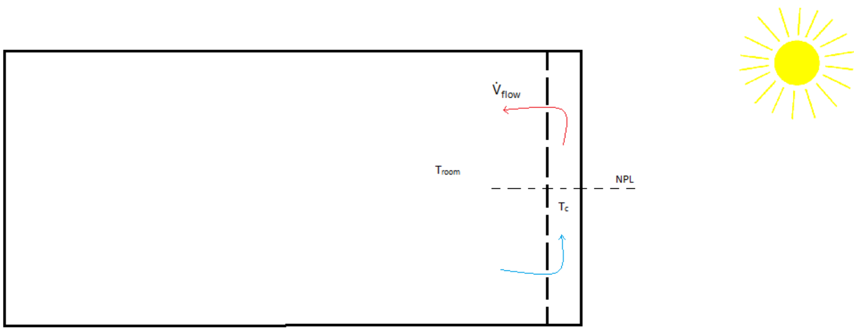


Figure 12.15: Principle of air exchange between room and cavity (made by the author).

The volume flow rate of air (m^3/s) through each opening can be calculated with equation 12.13:

$$\dot{V}_{flow,hole} = c_1 \cdot (\Delta p)^{c_n} \tag{12.13}$$

In which c_1 is the flow coefficient (-), c_n the flow exponent (-) and Δp the pressure drop across the opening. The flow coefficient c_1 and the flow exponent c_n are related to the size of the opening and the type of flow (laminar or turbulent). As it is desirable to rewrite this formula in an expression in which the relationship between flow and temperature is described, the law of Gay-Lussac is applied. Gay-Lussac's law states that if the volume of a certain amount of gas is held constant as the temperature increases, the pressure also increases (Benedict, 1984). The relation is presented in equation 12.14:

$$\frac{p_{room}}{T_{room}} = \frac{p_{cavity}}{T_{cavity}} \tag{12.14}$$

In which p_{room} represents the pressure at room side of the opening (Pa), p_{cavity} the pressure at cavity side of the opening (Pa), T_{room} the temperature at room side of the opening (°C) and T_{cavity} the temperature at cavity side of the opening (°C).

If one wants to calculate the total airflow through all the openings together, the average temperature of the room and the average temperature of the cavity should be used. Under the assumptions that the air is a perfect gas under the entrance and exit conditions of the opening and that the flow is adiabatic, the equation can now be rewritten in the form shown in equation 12.15:

$$\dot{V}_{flow,total} = c_1 \cdot (T_{cavity} - T_{room})^{c_n} \tag{12.15}$$

12.5.2. AMOUNT OF OPENINGS IN THE LTATW

One of the most important starting points at the start of the Double Face project was to design an innovative Trombe wall, which is partly translucent and partly transparent. The wall had to be partially transparent, so that the view towards outdoors would be preserved. The disadvantage of designing too many openings in the innovative Trombe wall, however, is that this is accompanied by a reduced performance of the wall, in terms of energy savings. In one of the early stages of the Double Face project, research has been done into the effect of the amount of openings in the innovative Trombe wall on the energy savings of the system. A total of three studies have been conducted: one with simulations in Matlab, one with simulations in Comsol and one with more detailed simulations in Comsol CFD. Based on the findings from these studies (see section 6.2.4), it was indicated that the ideal opening percentage in the innovative Trombe wall is equal to 10%. This value is therefore also adopted in this Master thesis study.

12.5.3. INFLUENCE OF AMOUNT OF OPENINGS ON AIR EXCHANGE

To investigate how the configuration of openings in the wall affects the air flow between room and cavity, or in other words: what the values of c_1 and c_n are, different models were analyzed in DesignBuilder. The models all represent a 'basic' room with the same dimensions. To ensure that the findings are valid for each climate and each period of the year, different times (both in summer and in winter) and all four different climates and orientations have been studied. The LTATW is modeled in DesignBuilder as shown in Figure 12.16.

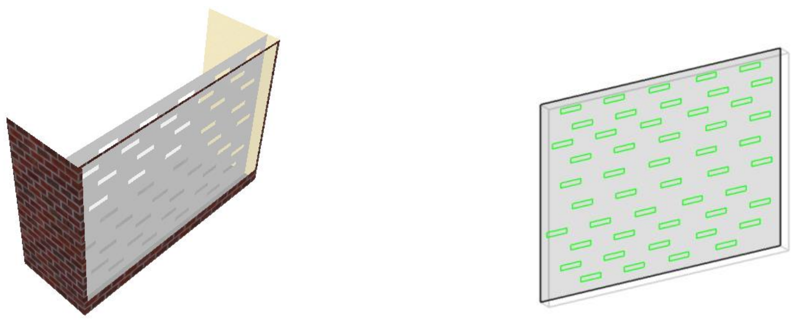


Figure 12.16: Configuration of openings in DesignBuilder simulation model.

The holes in the wall are homogeneously distributed over the surface and the opening percentage equals 10%. In total there are ten layers with five openings in each layer, except in the bottom layer, which consist of four openings.

With the help of all input data, DesignBuilder is able to measure the amount of natural ventilation through a construction. There are two types of infiltration and natural ventilation modelling options in DesignBuilder: scheduled and calculated. In a scheduled type of simulation, the natural ventilation change rate and infiltration air change rate is explicitly defined beforehand. In a calculated type of simulation, infiltration and natural ventilation are calculated based on crack dimensions, window openings, buoyancy, etc. The latter type of modelling results in slower simulations, but also in more accurate results (DesignBuilder, 2018). As the complexity of the basic model is not high, the calculated type of simulation was not too time-consuming. The results of one room, with western orientation and located in Stockholm (on a summer day) are shown in Figure 12.17 to 12.26. In these results, the amount of air (m^3/s) through a single hole of a specific layer is shown. In all cases, the airflow through openings of the same layer is the same.

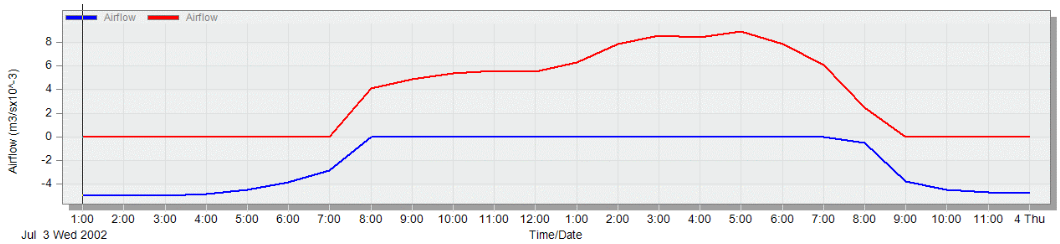


Figure 12.17: Airflow through one of the five holes of layer 1 (top layer) on Wednesday 3 July 2002.

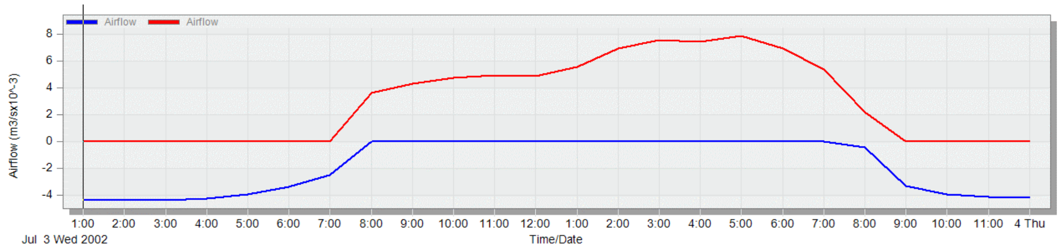


Figure 12.18: Airflow through one of the five holes of layer 2 on Wednesday 3 July 2002.

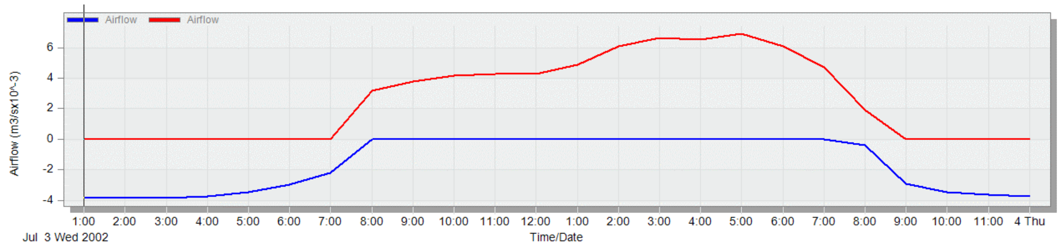


Figure 12.19: Airflow through one of the five holes of layer 3 on Wednesday 3 July 2002.

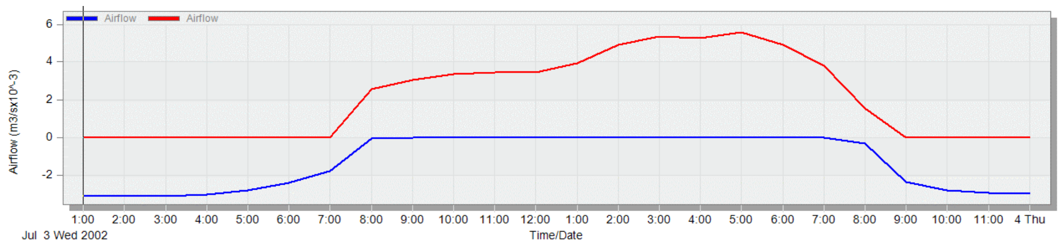


Figure 12.20: Airflow through one of the five holes of layer 4 on Wednesday 3 July 2002.

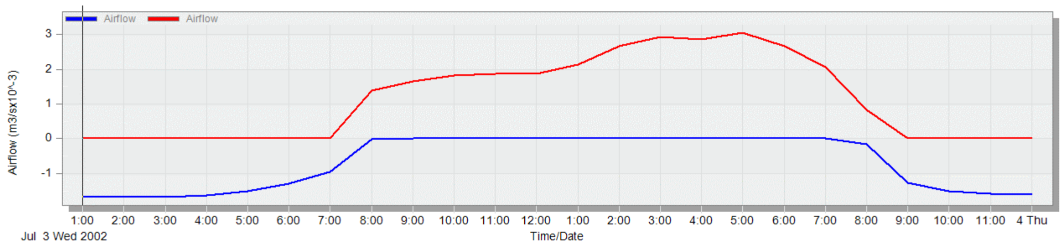


Figure 12.21: Airflow through one of the five holes of layer 5 on Wednesday 3 July 2002.

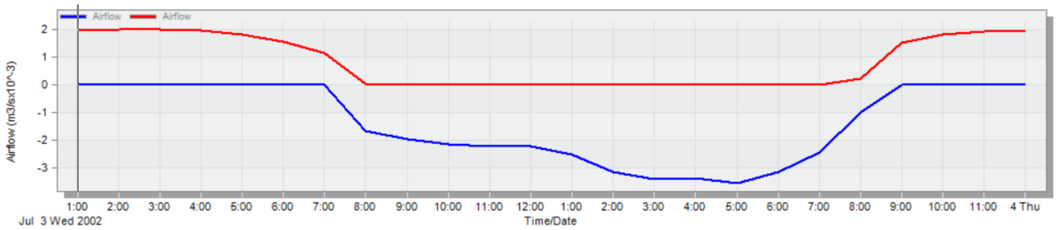


Figure 12.22: Airflow through one of the five holes of layer 6 on Wednesday 3 July 2002.

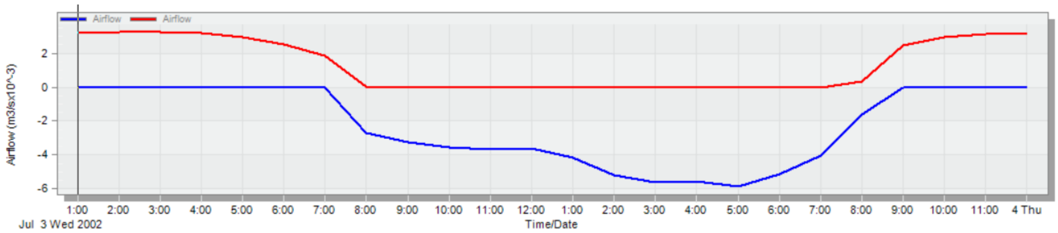


Figure 12.23: Airflow through one of the five holes of layer 7 on Wednesday 3 July 2002.

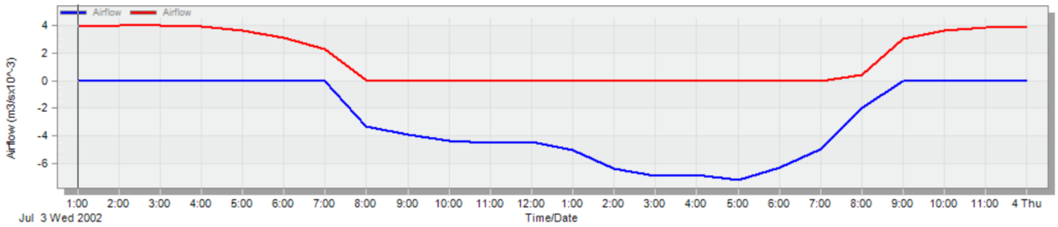


Figure 12.24: Airflow through one of the five holes of layer 8 on Wednesday 3 July 2002.

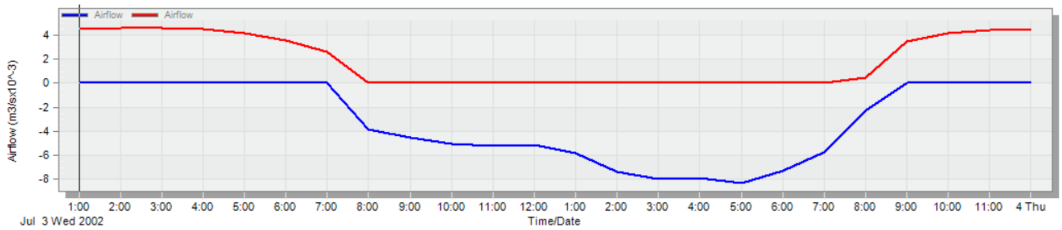


Figure 12.25: Airflow through one of the five holes of layer 9 on Wednesday 3 July 2002.

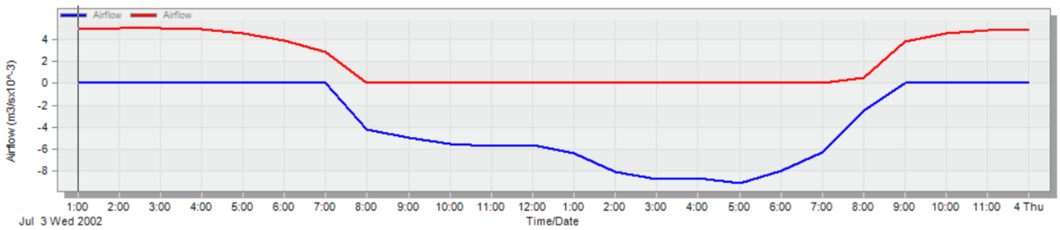


Figure 12.26: Airflow through one of the four holes of layer 10 (bottom layer) on Wednesday 3 July 2002.

The red curve shows the size of air flow from cavity to room and the blue curve shows the size of air flow from room to cavity. From all results (also the results of other climates, orientations and seasons), it can be seen that the neutral pressure line is located between layer five and six (exactly in the middle of the height of the wall). Above this line, the air flows in an opposite direction of the air below this level (see Figure 12.15). When the air temperature in the cavity is higher than the air temperature in the room, the air in the cavity flows upwards and warm air enters at the top of the room. When the temperature in the cavity is lower than that of the room, air flows in the opposite direction. The total air flow between the room and cavity is the air flow through all holes in the layers above the neutral line or below the neutral line added together.

Now that many different models have been simulated in DesignBuilder, the relation between the airflow and the temperature difference between cavity and room could be determined. For all models, $\dot{V}_{flow,total}$ and the corresponding temperature difference between room and cavity was obtained (T_{cavity} - T_{room}). Total airflow values were selected at the following times: 06:00 AM, 12:00 PM and 06:00 PM (see Figure 12.27). The values of these times are added for each layer and listed against the corresponding average room and cavity temperature.

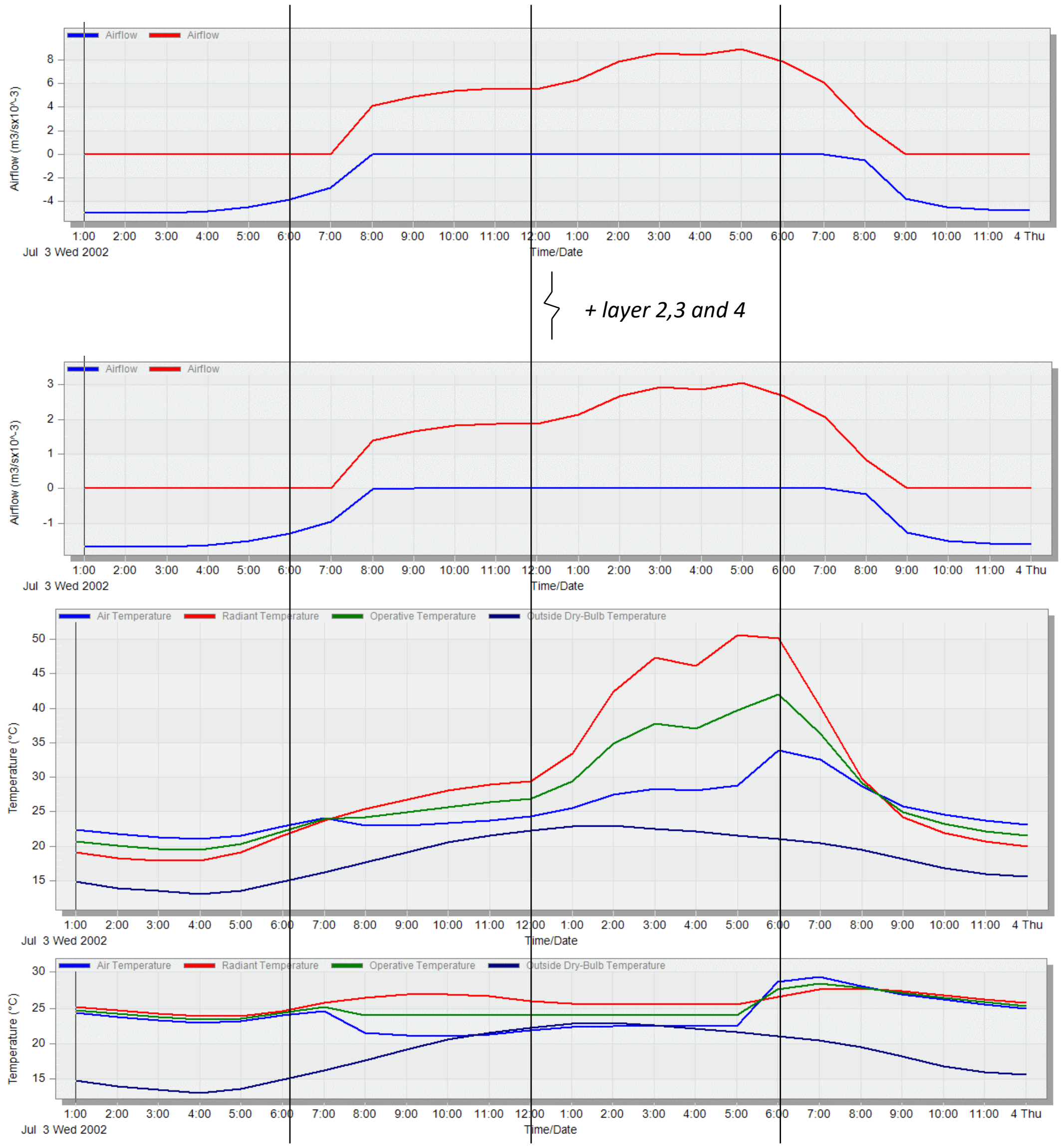


Figure 12.27: Analysis of values for $\dot{V}_{flow,total}$ (only layer 1 and layer 5 showed), T_c and T_{room} (bottom graph) at 06:00 AM, 12:00 PM and 06:00 PM.

The relation between $\dot{V}_{flow,total}$ and (T_c-T_r)is shown in Figure 12.28.

With the aid of a curve fitting tool, the values of c_1 and c_n were determined:

c_1 = 0.061
c_n = 0.5

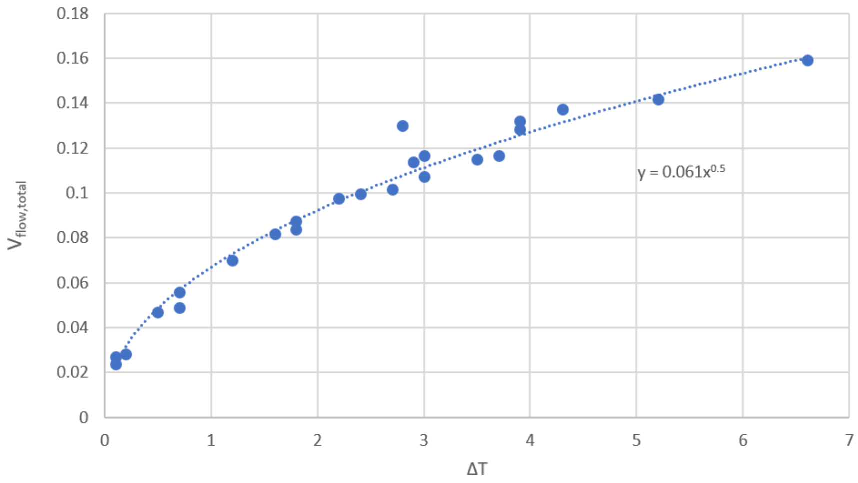


Figure 12.28: relation between total airflow rate and temperature difference between cavity and room.

12.5.4. IMPLEMENTATION IN MATLAB/SIMULINK

The heat load (W) due to the airflow between cavity and room can be calculated using equation 12.16:

$$Q_{\text{airflow room-cavity}} = \rho c \cdot \dot{V}_{\text{flow,total}} \cdot \left(T_{\text{cavity}} - T_{\text{room}}\right) \qquad (12.16)$$

In which ρc represents the product of the density of air (=1.2 kg/m^3) and the heat capacity of air (=1000 J/kgK). The simulation component in Simulink is shown in Figure 12.29.

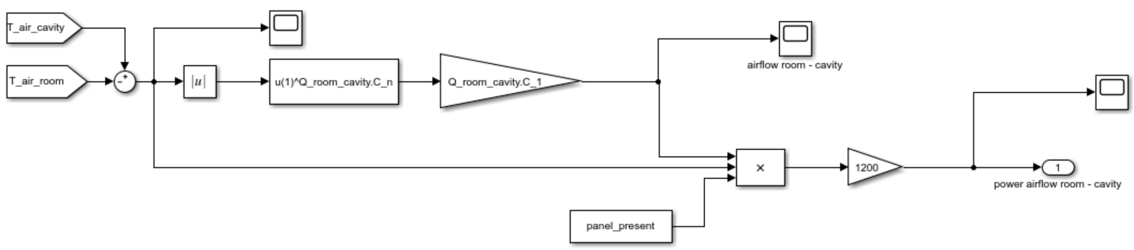


Figure 12.29: Simulink component of air exchange between cavity and room.

In Matlab, the flow coefficient c_1 and the exponent coefficient c_n are defined as follows:

```
Q_room_cavity.C_1 = 0.061;
Q_room_cavity.C_n = 0.5;
```

12.6. VALIDATION OF COMPONENTS

In chapter 11 was described how the initial simulation model was validated. The results of this validation procedure were sufficient and it was concluded that the initial (modified) simulation model is a good representation of the real system, with accurate and reliable outcomes. However, by adding the five simulation components mentioned in this chapter to the initial simulation model, the validation is no longer fully valid. Therefore, all simulation components need to be tested on their reliability and correctness of implementation. When it can be concluded that all components have been implemented correctly, and the (partial) simulation results are as expected, it can also be concluded that the extended simulation model is validated.

In chapter 11, four validation techniques were listed: analytical validation, empirical validation, expert intuition and comparative testing. Because, in case of the five simulation components, it is dealt with just one aspect instead of a whole dynamic system, they are validated with the analytical validation technique. Of each of the components, the analytical solution is known and results can more easily be compared to knowledge from theory. In this section, the analysis of the simulation results of each component is described. Section 12.6. starts with the validation of the infiltration component and ends with the validation of the component of the air exchange between room and cavity.

12.6.1. INFILTRATION

In order to assess whether the mechanism of infiltration was correctly implemented, the results for the energy flow due to infiltration during one year (Jan-Dec) for each climate were analyzed. The results of an old and a new building in a cold climate (Stockholm) and an old building in a tropical climate (Singapore) are shown in Figure 12.30, 12.31 and 12.32, respectively. The results are as expected: the infiltration losses in Stockholm are high in the winter (temperature difference between inside and outside is high) and low in the summer (temperature difference between inside and outside is low). In case of an 'old' building (ACH = 0.8), the heat losses are much higher compared to the heat losses of a 'new' building (ACH = 0.2). For an old building, the heat losses in the winter are around 300 to 400 W and around 0 W in the middle of the summer. In case of a new building, these heat losses are four times as low. In Singapore, heat gains from infiltration occur instead of heat losses. As the outside temperature is almost always consistently higher than the room temperature, a fairly horizontal graph is seen.

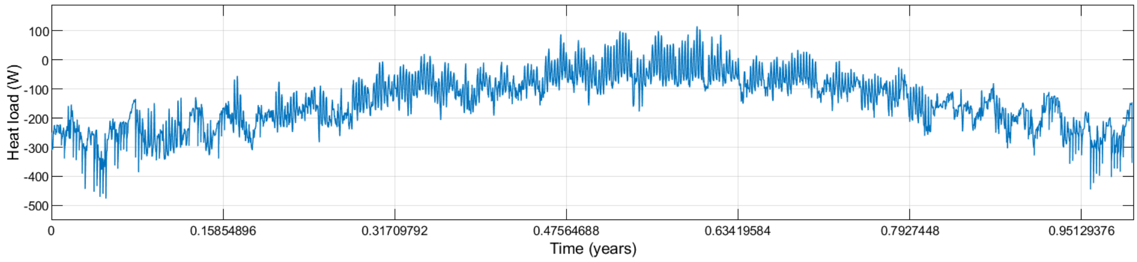


Figure 12.30: Heat load due to infiltration on old building in Stockholm.

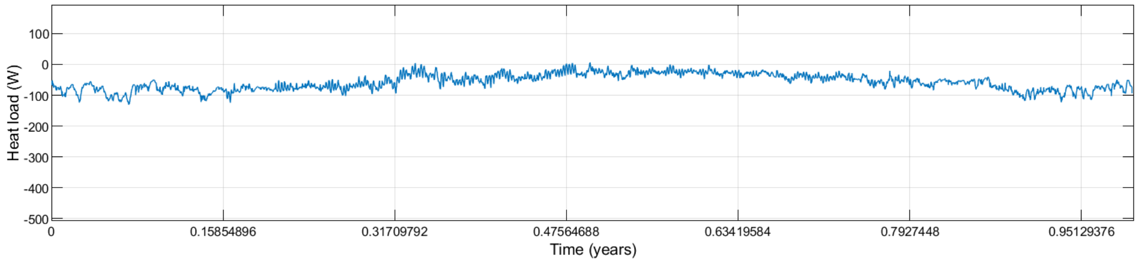


Figure 12.31: Heat load due to infiltration on new building in Stockholm.

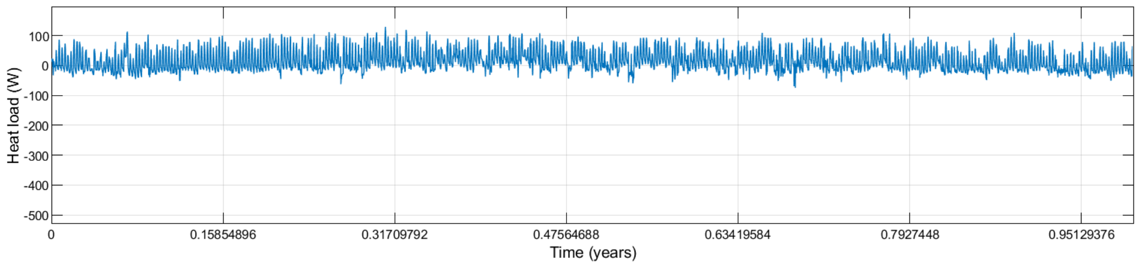


Figure 12.32: Heat load due to infiltration on old building in Singapore.

12.6.2. PCM HYSTERESIS

To assess whether the PCM hysteresis mechanism works correctly, a test-case was performed. In this test-case a PCM was modeled in a simple situation. The test case consisted of a one-dimensional homogeneous PCM plate with an adiabatic boundary condition on one side and heat transfer to an air cavity on the other side. In the test-case, multiple variant calculations have been done in Matlab, in which the following parameters were set as constants:

```
Ts_pcm      = 23;
Tl_pcm      = 26;
panel_pcm.d = 0.025;
panel_pcm.c   = 2000;
panel_pcm.rho = 1450;
panel_pcm.la  = 0.6;
p_alpha_cav   = 7.7;
```

The following parameters were set as variables:

```
panel_pcm.h
dead_band_pcm
nl_pcm
```

The temperature in the cavity concerns a square wave with a period of 24 hours. The temperature is 19.5 C for 12 hours and 29.5 C for the next 12 hours, etc. The average of 24.5 C corresponds to the average of the phase-change melting and solidification temperature. This signal is not further varied in this study. An overview of the variables and their values is shown in Table 12.12.

Table 12.12: Value of variable for each variant.

Variant nr.	nl_pcm	enthalpy (kJ/kg)	dead_band (°C)
1	1	0	0
2	5	0	0
3	1	180	0
4	5	180	0
5	1	180	2
6	5	180	2
7	1	180	5
8	5	180	5

Ten days were calculated for each variant. The results during the last two days are shown in each graph as follows (axes not labelled in figures):

Upper plot:
- Cavity temperature (red if nl_pcm = 1, purple if nl_pcm = 5).
- Temperature at PCM surface (blue).
- Other temperatures in the PCM if nl_pcm = 5 (various colours).

Middle plot:
- Heat flow density from the PCM to the cavity in W/m^2K

Lower plot:
- Stored heat in the PCM in 10^6 J

Comments on the results of the calculations are given below. The graphs are shown in Figure 12.33 to 12.40.

Variant 1

Without latent energy, the temperature of the plate approaches the cavity temperature after every 12 hours. At a delta T=10 °C, layer thickness d=0.025 m, density ρ=1450 kg/m^3 and heat capacity c=2000 J/kgK, the expected heat exchange is 0.73 MJ. This corresponds very well to the amplitude of the stored heat in the calculation (bottom plot).

Variant 2 (as variant 1 but with multiple control volumes in the PCM)

With the plate divided into multiple control volumes, it can be seen that the heat resistance in the plate plays a role. The plate undergoes a ΔT averaging about 7.5 °C and corresponding to a heat exchange of 0.55 MJ. The amplitude of the stored heat in the calculation is also approximately 0.55 MJ.

Variant 3 (as variant 1 but with latent energy)
With latent energy the temperature of the PCM remains in the phase-change area and varies approximately with 0.8 °C. The corresponding latent heat storage is 0.8/3*180*1450*0.025=1.74 MJ. This corresponds well with the amplitude of the stored heat in the calculation.

Variant 4 (as variant 3 but with multiple control volumes in the PCM)
With the plate divided into multiple control volumes, it can be seen that the surface temperature of the PCM 'goes through' the melting temperature of 26 °C. The temperature deeper in the PCM, at a depth of 2.5 cm, hardly varies. The heat exchange is considerably lower with 1.25 MJ than with variant 3. This can be explained by the larger amplitude of the temperature at the PCM surface.

Variant 5 (as variant 3 but with hysteresis of 2 °C)
The effect of hysteresis is clearly reflected in the temperature trend of the PCM. The heat exchange is approximately 1.35 MJ.

Variant 6 (as variant 5 but with multiple control volumes in the PCM)
With the plate divided into multiple control volumes, it can be seen that the surface temperature of the PCM 'goes through' the melting temperature of 26 °C. Because of the hysteresis of 2 °C, this now takes place at 27 °C. The hysteresis is still clearly visible in the temperature curve in the PCM at 2.5 cm depth. The heat exchange is approximately 1.05 MJ.

Variant 7 (as variant 3 but with hysteresis of 5 ° C)
The hysteresis of 5 °C is clearly reflected in the temperature curve of the PCM. The heat exchange is approximately 1.05 MJ.

Variant 8 (as variant 7 but with multiple control volumes in the PCM)
With the plate divided into multiple control volumes, it was seen in the previous variants that the surface temperature of the PCM 'went through' the melting temperature of 26 °C. That is no longer the case now, which can be explained by the hysteresis. The heat exchange is approximately 0.90 MJ.

Conclusions
The results of the PCM Simulink component are consistent with the expected outcomes based on physical insight for the tested cases. The method of modeling the phase change and the associated latent energy can be characterized as 'realistic' on the basis of this comparison.

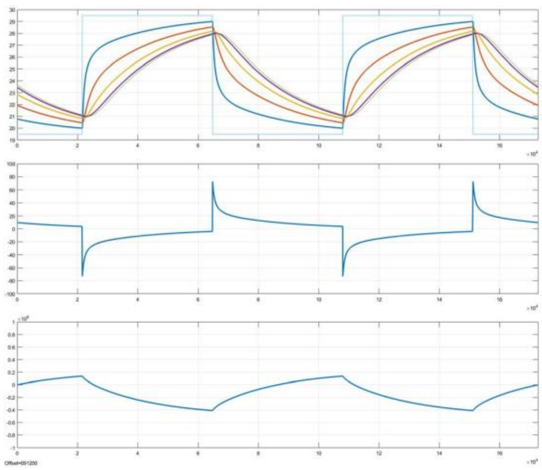


Figure 12.33: Results variant 1.

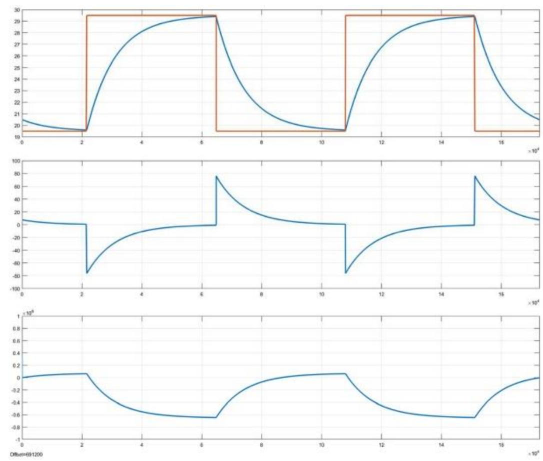


Figure 12.34: Results variant 2.

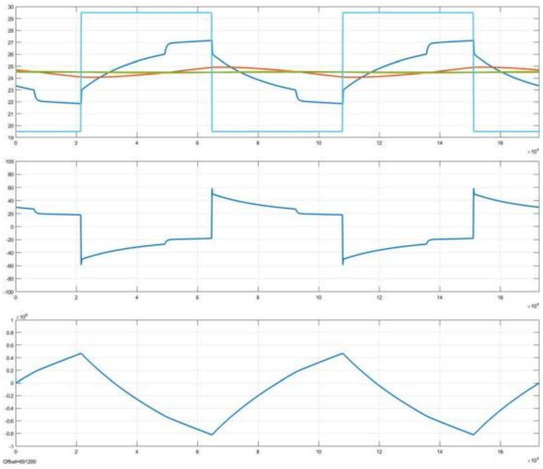


Figure 12.35: Results variant 3.

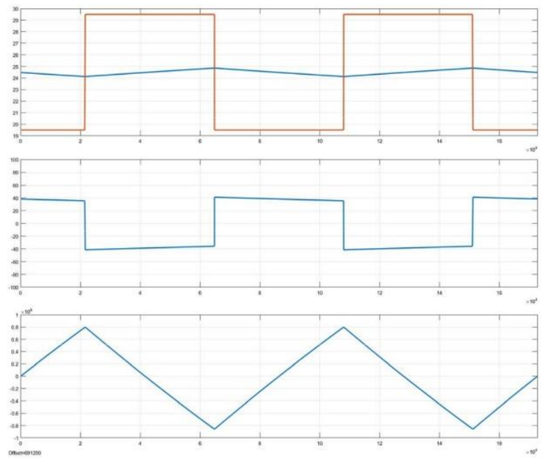


Figure 12.36: Results variant 4.

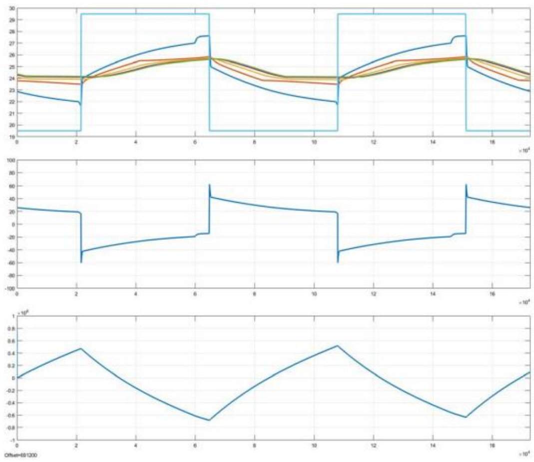


Figure 12.37: Results variant 5.

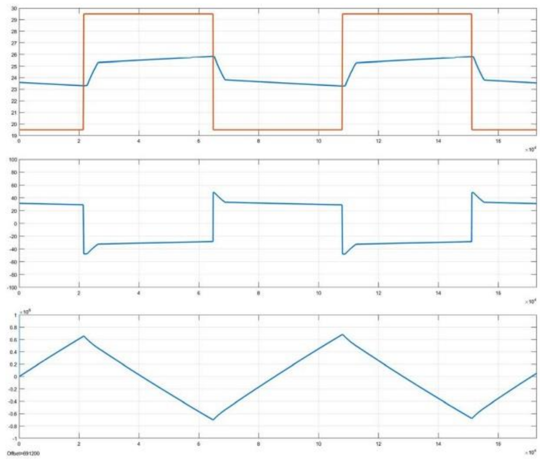


Figure 12.38: Results variant 6.

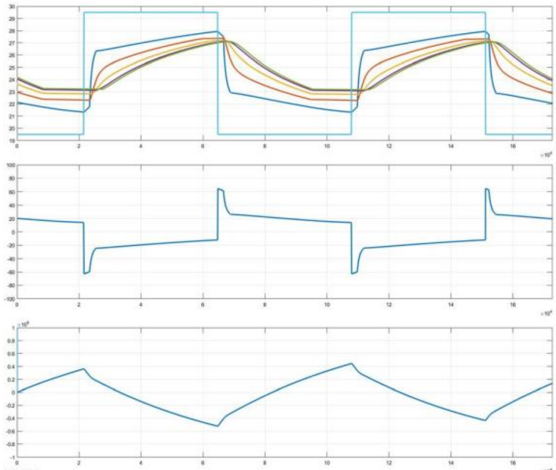


Figure 12.39: Results variant 7.

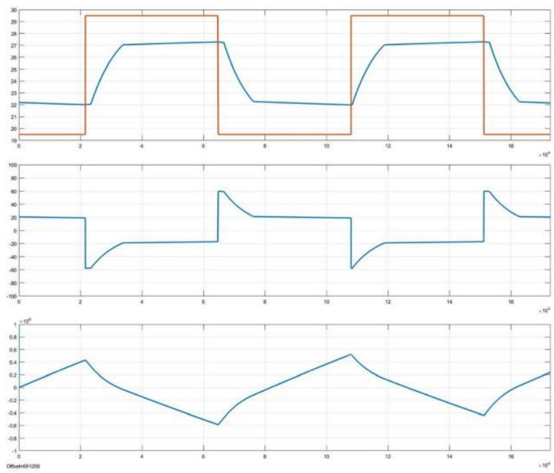


Figure 12.40: Results variant 8.

12.6.3. ROTATION SCHEDULE

To assess whether the rotation schedule component has been implemented correctly, multiple simulations of one year in all four climates were run. The results of the 'summer mode' condition of the same room (but in different climates) are shown in Figure 12.41 to 12.44.

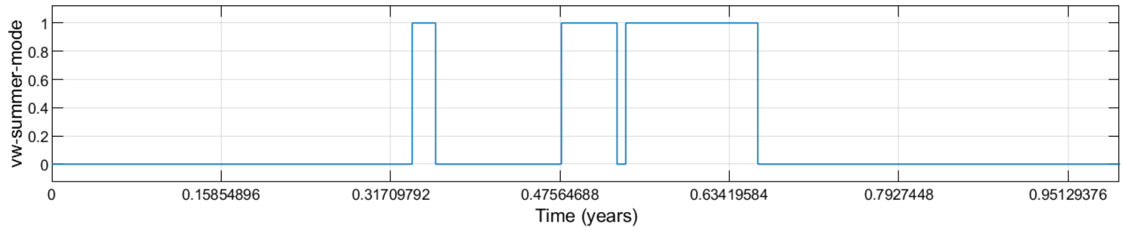


Figure 12.41: vw_summer_mode in an annual simulation of a room in a cold climate (Stockholm).

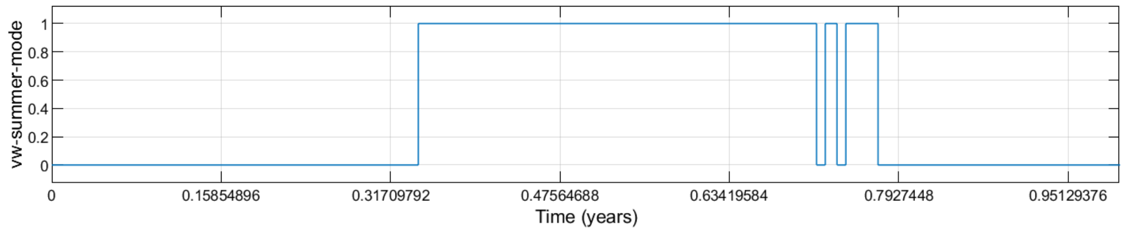


Figure 12.42: vw_summer_mode in an annual simulation of a room in a mild climate (Milan).

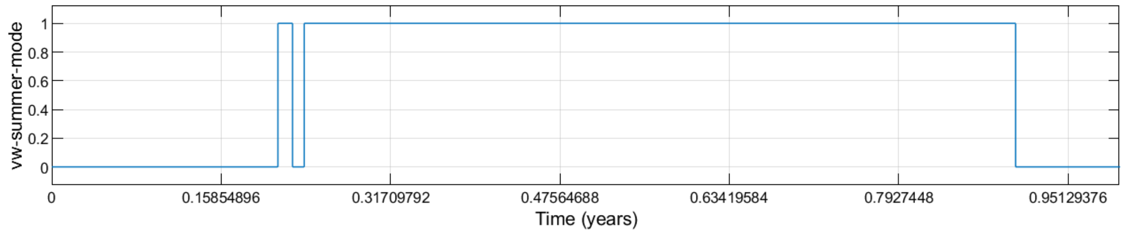


Figure 12.43: vw_summer_mode in an annual simulation of a room in a dry climate (Cairo).

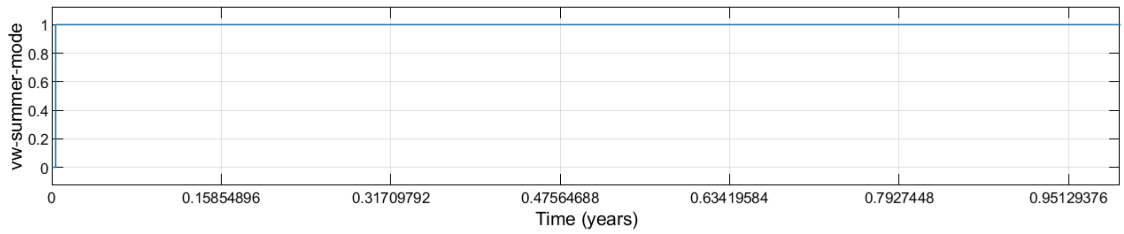


Figure 12.44: vw_summer_mode in an annual simulation of a room in a tropical climate (Singapore).

The above graphs show an expected behavior: in Stockholm, the summer mode condition is short (only in the middle of summer) and in Singapore, summer mode is always activated. In addition to the summer and winter mode condition, also the conditions of day-time and night-time were analysed. The results of the last days of December of the simulation of a room in a cold climate and in a tropical climate are shown in Figure 12.45 and 12.46.

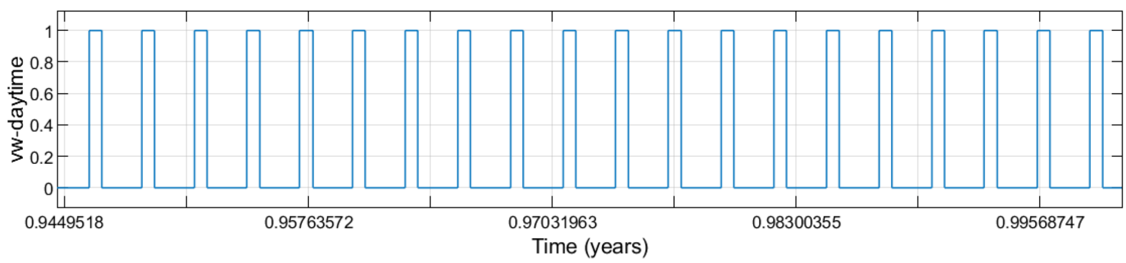


Figure 12.45: vw_daytime on the last days in December of a room in a cold climate (Stockholm).

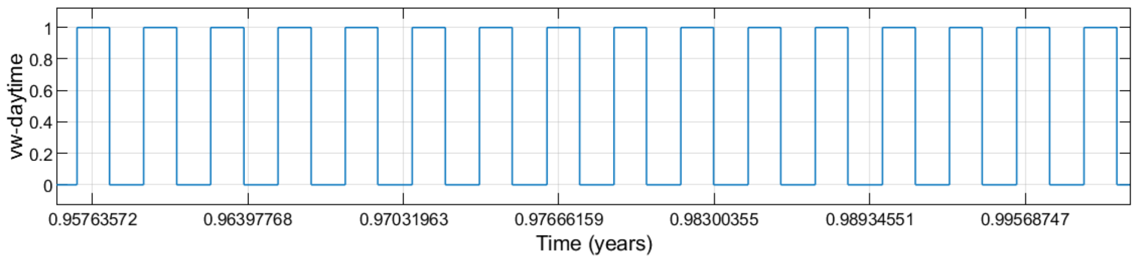


Figure 12.46: vw_daytime on the last days in December of a room in a tropical climate (Singapore).

It is clear to see that the winter days in a cold climate are relatively short and the winter days in a tropical climate are about as long as the winter nights. Finally, the conditions determining the orientation of the LTATW were analysed. The results of the last days of December of the simulation of a room in a cold climate and in a tropical climate are shown in Figure 12.47 and 12.48.

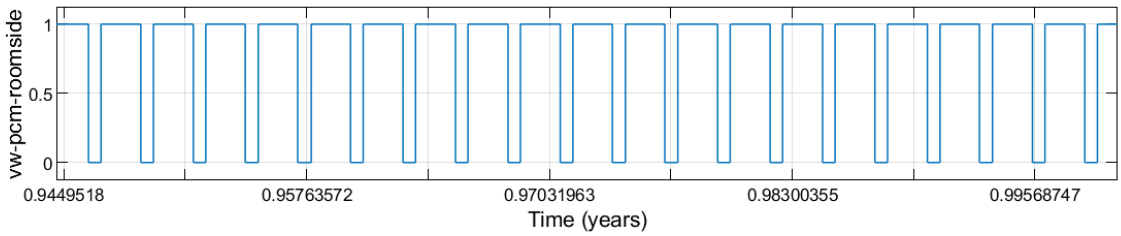


Figure 12.47: vw_pcm_roomside on the last days in December of a room in a cold climate (Stockholm).

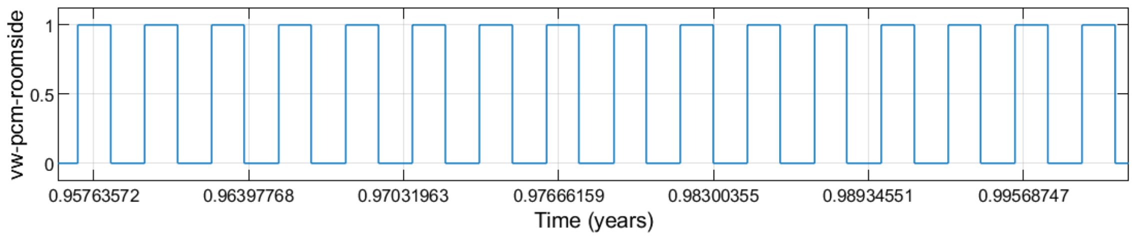


Figure 12.48: vw_pcm_roomside on the last days in December of a room in a tropical climate (Singapore).

The results for 'vw_pcm_roomside' are as expected. It is clear to see that in a cold climate the LTATW is oriented towards the interior at night and that in a tropical climate the LTATW is oriented towards the exterior at night.

12.6.4. AIR EXCHANGE BETWEEN CAVITY AND EXTERIOR

To assess whether the night ventilation mechanism has been implemented correctly, the results for each climate have been analyzed. The results of an annual simulation of a room in a cold climate and a room in a temperate climate are shown in Figure 12.49 and 12.50.

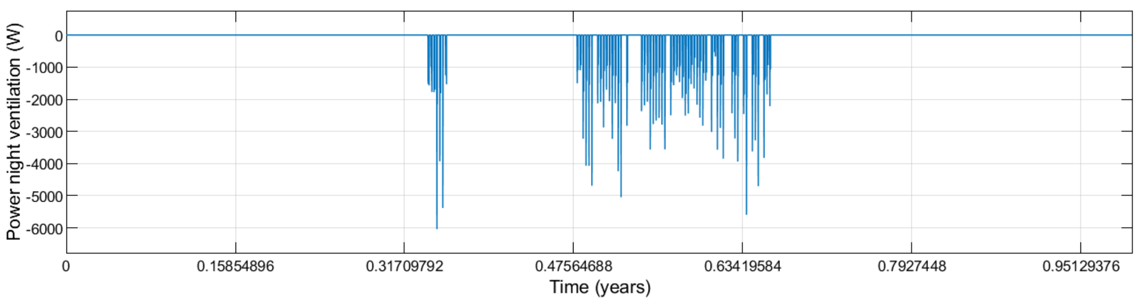


Figure 12.49: Power of night ventilation system in annual simulation of a room in a cold climate (Stockholm).

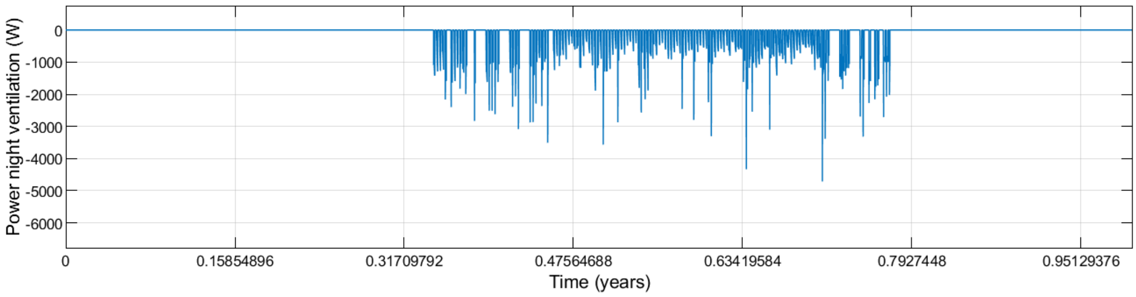


Figure 12.50: Power of night ventilation system in annual simulation of a room in a temperate climate (Milan).

The results are as expected. Night cooling occurs only in summer mode and is on average at its highest in the periods when the difference between cavity temperature and exterior night temperature is at its greatest: just before mid-summer and just after mid-summer.

12.6.5. AIR EXCHANGE BETWEEN CAVITY AND ROOM

In order to assess whether the mechanism of air exchange between cavity and room has been implemented correctly, the results have been analyzed under different conditions. The results of a room (southern orientation of LTATW, triple clear glazing) in a cold climate and the results of a room (southern orientation of LTATW, triple clear glazing) in a temperate climate are shown in Figure 12.51 and 12.52.

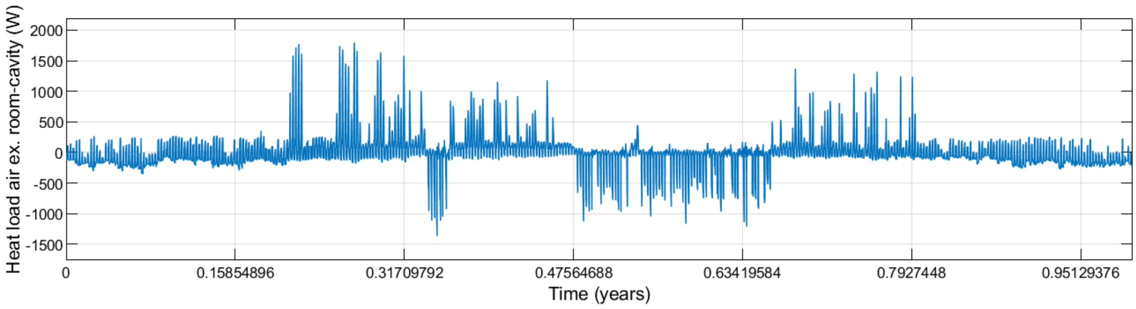


Figure 12.51: Heat loads from air exchange room-cavity in annual simulation of a room in a cold climate (Stockholm).

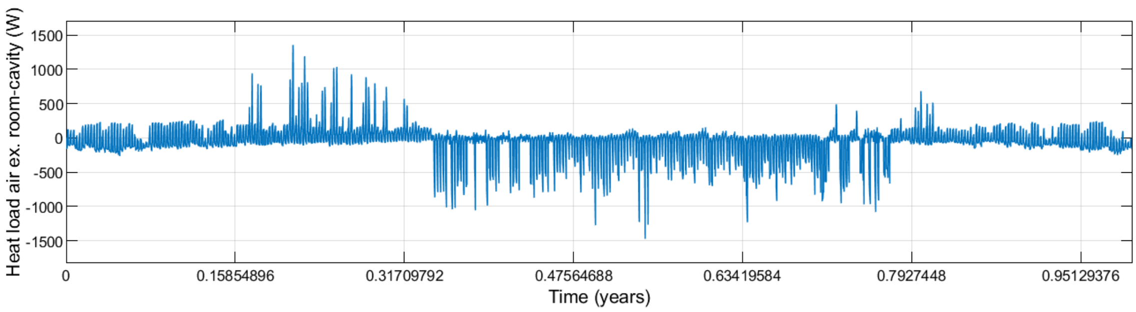


Figure 12.52: Heat loads from air exchange room-cavity in annual simulation of a room in a temperate climate (Milan).

The results are as expected. The equilibrium position of both graphs is just below zero in the winter and just above zero in the summer. Therefore, the cavity generally functions as heat sink in the winter and as heat source in the summer. However, the cavity behaves every day for a small period of time also as heat source, due to the incoming solar radiation (see Figure 12.53). During this period, the cavity is heated up and heat flows from cavity to room. On some days the intensity of the sun is high, as can be seen from the high peaks that occasionally occur. From Figure 12.51 and 12.52 can also be seen that only in summer mode, the heat losses are much greater. These heat losses only occur at night, when night ventilation is activated. During night ventilation, heat is removed from the cavity, causing the temperature to drop and heat losses through openings in the LTATW are greatly increased (see Figure 12.53).

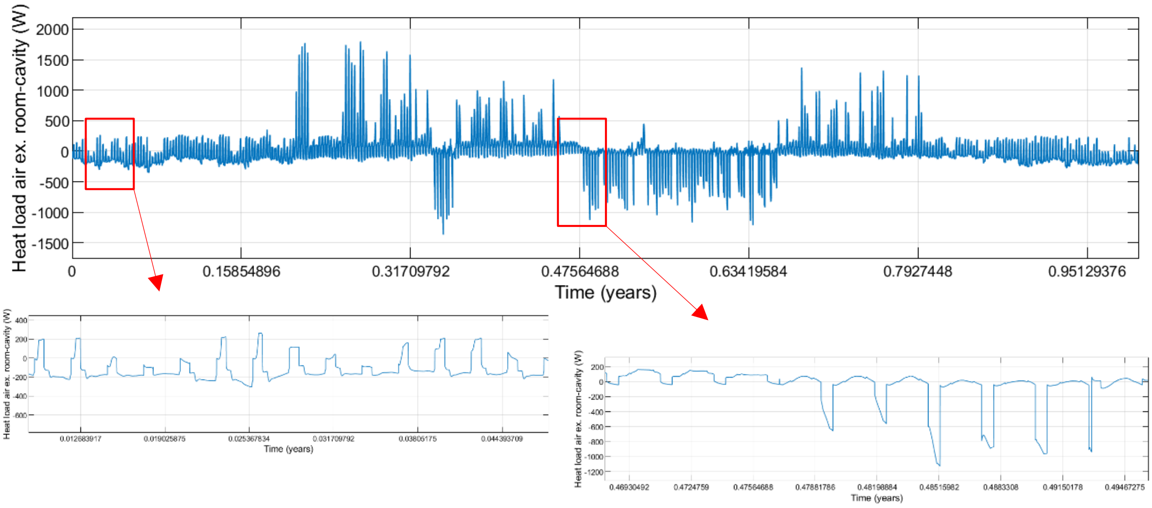


Figure 12.53: Heat loads from air exchange room-cavity in annual simulation of a room in a cold climate (Stockholm). Two zoom-ins to show: heat flow from cavity to room due to solar radiation (left) and heat flow from room to cavity due to night ventilation (right).

13. CONCLUSION PART III

This chapter is the final chapter of part III and gives an overall conclusion of the findings made during the synthesis and development of the simulation model. In the past four chapters, the theory behind thermal energy simulations was explained, the features of the initial simulation model were described and the validation and verification procedure of this model was explained. Finally, the simulation model has been extended with addition of new components, which were all tested and analyzed, and a reliable model has been obtained that is ready for the parameter study of this Master's thesis project. Of each topic in part III, a conclusion is described in this chapter.

CHAPTER 9: THEORY OF THERMAL ENERGY BALANCES

Chapter 9 has given insight into the working principle behind thermal energy balances. A thermal energy balance considers four main flows of energy: transmission, ventilation and infiltration, solar gains and internal gains, which are all taken into account into the simulation model developed in this project. All these flows of energy are implemented in the simulation model by using the equations shown in section 9.1. The simulation model developed in this project is not based on a stationary heat balance, but on a non-stationary heat balance. In a stationary heat balance, temperatures and heat fluxes are constant in time and energy storage is not taken into account. Because in reality, heat fluxes and temperatures do vary with time, and heat storage should not be neglected, a stationary heat balance is not suitable for the research in this thesis. In section 9.3, the numerical principle of a non-stationary heat balance was explained by showing examples of two one-node room models and one two-node room model. With the knowledge gained from the examples and the numerical principle of non-stationary multi-node heat conduction, the final step towards the non-stationary multi-node heat balance could be made. In section 9.5, all important equations were described, on which the simulation model in Matlab/Simulink is based. With this information, the Matlab script and the corresponding Simulink components can be more easily understood.

CHAPTER 10: INITIAL SIMULATION MODEL

In chapter 10, all aspects of the initial simulation model were described one-by-one. A schematization of the room and the LTATW was shown, the node definitions were described and the modes of heat transfer were explained graphically. As it is not convenient to include the entire Matlab-file in this thesis, only the most important parts are shown, of which are the definition of a lot of parameters and conditions, the mass matrix and the stiffness matrix. Finally, in section 10.3, the most important Simulink components were shown.

CHAPTER 11: VALIDATION AND VERIFICATION

Chapter 11 started with a literature review on the principle of computerized simulation model validation and verification. Verification of a computerized model is intended to ensure that the model does where it is made for. It is the process of confirming that implementation is correctly done with respect to the conceptual model and that it matches the assumptions and the specifications agreed-upon. Model validation is the task of proving that the simulation model is a reasonable representation of the actual system. In this project, the simulation model is validated an verified in one step, and with one technique: comparative testing. The main reason for choosing this technique is because a technology is studied of which a prototype does not yet exist and therefore, real system measurements are not possible. In the validation procedure, simulation results of 20 different room configurations in Matlab/Simulink and DesignBuilder are compared, and after various modifications, the results were similar enough. Because of similarity in results, it is consequently assumed that implementation of every aspect of the conceptual model is done correctly and that the computerized model does where it is made for. In other words; the simulation model is both validated and verified, and can be used for further research.

CHAPTER 12: EXTENDED SIMULATION MODEL

In chapter 12, the procedure of improving the initial simulation model was described. In order to meet the objectives of this research, the initial simulation model needed to be improved by the addition of five missing components: modelling of infiltration, modelling of PCM hysteresis, modelling a certain rotation schedule, modelling of night ventilation and modelling of the air exchange between cavity and room. The first component, infiltration, was developed based on the analytical relation between air tightness of a building and the temperature difference between the indoor and outdoor environment. The simulation results for various room configurations were analysed and assessed as expected. The second component, PCM hysteresis, was already implemented in the initial simulation model, but was not tested in the validation procedure. After discovering the malfunctioning of the mechanism, a new mechanism has been developed that has been tested in a variant study. The study revealed that the modelling of the thermal behaviour of the PCM was assessed as realistic. The third component was developed based on three conditions: winter/summer mode, daytime/night-time mode and roomside/cavityside mode. The implementation of the conditions was tested by performing multiple simulations of different room configurations in all four climates and the results showed expected behaviour. The fourth component, the night ventilation mechanism, was just like infiltration, based on equations from theory. Based on a sub-study, one ideal opening size of inlet and outlet was determined. The implementation was analysed in Simulink by annual simulations and the results showed expected behaviour. The final component of the air exchange between cavity and room was also based on an analytical relation between air flow rate and temperature difference between room and cavity. The exact relation was determined with the help of simulation results from DesignBuilder, and the Simulink component was validated by performing annual simulations of various rooms in different climates. In this case again, the results were as expected.

In part III the simulation model has been explained, validated and improved/extended. After a validation of the extended version, the final result of part III is an accurate, reliable and useful simulation model with which the parameter study in this Master's thesis project can be performed.

PART IV
SIMULATION RESULTS AND ANALYSIS

14. SIMULATION CONDITIONS

After studying literature, gaining knowledge and implementing this knowledge into a reliable and effective simulation model, part IV of this thesis is about the simulation of it. The first chapters of part IV describe the simulation conditions, the results and the analysis of these results. Hereafter, a sensitivity analysis is reported and a side-study is carried out into the influence on the energy demand for artificial lighting. Before going into all these topics, the purpose of this chapter is to explain what the simulation conditions, assumptions and starting points were, before the simulation was started. An overview of the variables, with their classification and values of their chosen subdivisions are described in section 14.1. All parameters and associated values that have been kept constant in the study is given in section 14.2. Finally, section 14.3 and 14.4 briefly describe the simulation settings and simulation procedure.

14.1. VARIABLE PARAMETERS

The variable parameters of the simulation model are the parameters of which their influence is studied in this project. The variables are:

- Climate
- Building function
- Orientation
- Age
- Building method
- Room size
- Window size
- Type of glazing

The eight variables above are treated as discrete variables, which means that only a certain number of 'intermediate' values is studied. In this thesis, these intermediate values have also been called 'subdivisions', and their number differs per variable. The objective of this research is to be able to study the influence of the variable parameters on the energy and comfort performance of the LTATW as well as possible, provided that the size of the project does not become too large. Therefore, only most 'typical' or most relevant subdivisions have been selected. An overview of the subdivisions of all variable parameters and their values is given in Table 14.1 and Table 14.2 (building method properties). The sources of these values are given in Table 14.4.

Table: 14.1: Variable parameters, their subdivisions and values.

Parameter	Subdivisions	Value(s)
Climate	Cold	**Weather data:** T_e = Te_Stockholm_double (obtained from weatherfile: SWE_Stockholm.Arlanda.024600_IWEC) q_{sol} = qsol_Stockholm_double (obtained from weatherfile: SWE_Stockholm.Arlanda.024600_IWEC) **Rotation schedule:** $A_{sunrise}$ = 3.2; A_{sunset} = 3.2 $B_{sunrise}$ = 5.625; B_{sunset} = 17.95
	Temperate	**Weather data:** T_e = Te_Milan_double (obtained from weatherfile: ITA_Milano-Linate.160800_IGDG) q_{sol} = qsol_Milan_double (obtained from weatherfile: ITA_Milano-Linate.160800_IGDG) **Rotation schedule:** $A_{sunrise}$ = 1.8; A_{sunset} = 1.8 $B_{sunrise}$ = 6.31; B_{sunset} = 18.45
	Dry	**Weather data:** T_e = Te_Cairo_double (obtained from weatherfile: EGY_Cairo.Intl.Airport.623660_ETMY) q_{sol} = qsol_Cairo_double (obtained from weatherfile: EGY_Cairo.Intl.Airport.623660_ETMY) **Rotation schedule:** $A_{sunrise}$ = 1.0; A_{sunset} = 1.0 $B_{sunrise}$ = 5.88; B_{sunset} = 17.95
	Tropical	**Weather data:** T_e = Te_Singapore_double (obtained from weatherfile: SGP_Singapore.486980_IWEC) q_{sol} = qsol_Singapore_double (obtained from weatherfile: SGP_Singapore.486980_IWEC) **Rotation schedule:** $A_{sunrise}$ = 0.25; A_{sunset} = 0.25 $B_{sunrise}$ = 7.02; B_{sunset} = 19.08
Building function	Office	Total internal heat gains: 25 W/m^2 people present: 08:00 - 18:00 (Mon-Fri) Mechanical ventilation rate: 2.0/3600 (s^{-1}) Mechanical ventilation flow: 08:00 - 18:00 (Mon-Fri)
	Residence	Total internal heat gains: 6 W/m^2 people present: 18:00 - 08:00 (Mon-Fri) and 00:00 - 24:00 (Sat-Sun) Mechanical ventilation rate: 0.7/3600 (s^{-1}) Mechanical ventilation flow: 18:00 - 08:00 (Mon-Fri) 00:00 - 24:00 (Sat-Sun)
Orientation	North	Different values of q_{sol}
	East	Different values of q_{sol}
	South	Different values of q_{sol}
	West	Different values of q_{sol}

Age	New	Infiltration rate = 0.2/3600 (s^{-1}) R_c = 4.5 m^2K/W (façade)
	Old	Infiltration rate: 0.8/3600 (s^{-1}) R_c = 2.0 m^2K/W (façade)
Room size	Small room	A = 20 m^2 (square surface)
	Big room	A = 100 m^2 (square surface)
Window size	Small window	WWR = 25% Δh = 0.8 m (difference in height inlet/outlet)
	Large window	WWR = 75% Δh = 2.2 m (difference in height inlet/outlet)
Type of glazing	Double, clear glazing	U_{gl} = 1.6 W/m^2K SHGC = 0.7
	Double, coated glazing	U_{gl} = 1.6 W/m^2K SHGC = 0.2
	Triple, clear glazing	U_{gl} = 0.7 W/m^2K SHGC = 0.5
	Triple, coated glazing	U_{gl} = 0.7 W/m^2K SHGC = 0.1

Table: 14.2: Variable parameter 'building method' and its subdivisions and values.

Building method	Inner walls (all adiabatic)	Outer wall (orien1 façade cavity wall with glazing, not adiabatic)	thickness	
			new building	old building
Light-weight	5 cm timber	inner leaf: timber wall	5.0 cm	5.0 cm
		insulation: polystyrene	10.0 cm	4.0 cm
		outer leaf: timber cladding	5.0 cm	5.0 cm
Medium-weight	10 cm sand-lime stone	inner leaf: sand-lime stone	10.0 cm	10.0 cm
		insulation: polystyrene	12.0 cm	5.0 cm
		outer leaf: metal cladding	0.5 cm	0.5 cm
Heavy-weight	15 cm heavy concrete	inner leaf: heavy concrete	10.0 cm	10.0 cm
		insulation: polystyrene	11.0 cm	4.0 cm
		outer leaf: brickwork	10.0 cm	10.0 cm

Table: 14.3: Material properties.

Material	Density (kg/m^3)	specific heat capacity (J/kgK)	Conductivity (W/mK)
Sand-lime stone	2000	840	1
Polystyrene (extruded)	35	1470	0.027
Timber	800	1880	0.22
Metal cladding	7850	500	50
Heavy concrete	2400	840	1.7
Brickwork	2100	840	0.8

Table: 14.4: Source of parameter values.

Parameter	Source
Weather file values	https://energyplus.net/weather
Rotation schedule values	https://timeanddate.com
Internal heat gains	Itard (2018)
Mechanical ventilation rates	Itard (2018)
Infiltration rates	Van Bueren et al. (2012)
Façade insulation values	https://.bouwbesluitonline.nl
Glazing properties	Van Bueren et al. (2012)
Material properties	van der Linden, Erdtsieck, Kuijpers-van Gaalen, & Zeegers (2011)

From the tables it can be seen that only the four main climates of the world, determined with the aid of chapter 7, have been investigated. In the simulation model, the difference in climate is expressed by differences in values for outdoor temperature, solar radiation and times for sunrise and sunset. Two building functions have been investigated: offices and residences, of which the difference between the two is expressed in differences between occupation times, internal heat gains and ventilation rates. Of the third parameter, orientation, the four main orientations were studied: north, east, south and west. The difference between orientations is expressed in different values for incoming solar radiation.

In this study, two buildings ages have been investigated: 'old' buildings and 'new' buildings. An old building is characterized by a building with outdated building envelope, which has a relatively low insulation value and a low airtightness. The two parameters that determine the layout of the room construction are the floor surface area and the window-to-wall ratio. When combining the subdivisions of both parameters, four possible constructions arise: a small room with a small window, a small room with a large window, a big room with a small window, and a big room with a large window. In all cases, it is assumed that the surface/size of the LTATW is equal to the area of the window (it is placed right behind the window, with a small distance between). In case of a large room with large window there is therefore a larger LTATW than in case of a small room with large window.

Four glazing types have been studied: double clear glazing, double coated glazing, triple clear glazing and triple coated glazing. Because single glazing is hardly, if at all, applied in new buildings (which are eligible for this innovative system), this type of glazing was not selected in the study. The coated glazing versions were also examined, just to gain insight into the performance of the LTATW in for example, a glazed skyscraper with coated/reflective glazing. Of the last variable, the construction method, three typical subdivisions were made: a light-weight, medium-weight and heavy-weight load-bearing structure. A light-weight building is defined here as a building with timber frame construction, a medium-weight building is defined as a building with a steel construction and sand-lime walls, and a heavy-weight building is defined as a building that is only made up of thick walls of concrete.

14.2. CONSTANT PARAMETERS

The constant parameters in this study are all other parameters of the simulation model, except the variable parameters mentioned in section 14.1. An overview of all constant parameters and their values is given in Table 14.5.

Table 14.5: Values of constant parameters

Parameter	Simulation condition(s)
Simulation time	1 January – 31 December
Initial node temperature	23 °C
Room height	2.7 m
Shading	When $T_{room,oper}$ > 24 °C and $P_{sol,in}$ > 100 W
	$SHGC_{shading}$ = 0.25 (25% unshaded)
Natural ventilation	When $T_{room,air}$ > 24 °C
	Rate = 2.0/3600 (s^{-1})

Heat recovery	Efficiency = 0.9
	Bypassed when $T_{room,oper}$ > 24 °C and $T_{room,oper} > T_e$
Mechanical night ventilation	When $T_{room,oper}$ > 24 °C and $T_{room,oper} > T_e$
Natural night ventilation	$A_{inlet} = A_{outlet} = 0.025*A_{facade}$
	$C_d = 0.8$
	When $T_{room,oper}$ > 24 °C and $T_{room,oper} > T_e$
Thermostat set-points	Heating: 20 °C Cooling: 26 °C
LTATW characteristics	Cavity width: 0.2 m PCM layer thickness: 2.5 cm Aerogel layer thickness: 1 cm
Type of PCM	Rubitherm SP25E2 (T_s = 23 °C; T_l = 26 °C; hysteresis = 2.0 °C)
Percentage of openings in LTATW	10%
Heat transfer coefficients (convection)	α_i = 2.7 W/m²K; α_e = 25.0 W/m²K
	adiabatic walls: α_e = 0 W/m²K
nl_pcm	5
nl_ins	3
Airflow through LTATW	$C_1 = 0.0669$
	$C_n = 0.4627$
Rotation schedule	$\phi_{sunrise} = 1.75$
	$\phi_{sunset} = 4.9$

The simulations in this study assume that a room is located in the middle of a building (see Figure 14.1). This means, that all walls, except the outer wall are schematized as adiabatic surfaces. Only in the outer wall (façade of the building), a window exists. The other five walls are made up of a closed, solid construction.

14.3. SIMULATION SETTINGS

The solver configuration settings of the simulation model are shown in Appendix B. From appendix B it can be seen that the start time and stop time of the simulation are defined by two parameters from the Matlab-file. The type of solver used is 'ode23tb (stiff/TR-BDF2)' (a variable-step solver). All solver details and zero-crossing options are set up on the advice of the supervisors/mentors of this project.

14.4. PROCEDURE

When all intermediate values (or subdivisions) of the variable parameters are combined, a total of 3072 different situations arise. For each situation, the system is simulated with and without LTATW, resulting in a total of 6144 simulations. Because each simulation requires about 3 to 8 minutes, the simulation procedure was conducted with multiple computers.

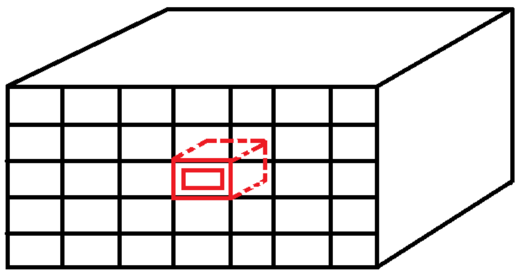


Figure 14.1: Schematization of room in building (made by the author).

15. SIMULATION RESULTS AND ANALYSIS

In this chapter, the simulation results of all room configurations are shown and analyzed. First, the overall results of the energy performance of the Trombe wall are shown in section 15.1. These results include scatter plots in which the values for energy reduction (both relative and absolute) are shown per configuration, distribution charts that show the probability density of values for energy reduction and finally, correlation charts, which give insight into the influence of each individual variable parameter. In section 15.2, the influence of these variables is analyzed in more detail and in section 15.3, the results of a sensitivity study are shown.

15.1. SIMULATION RESULTS

Section 15.1.1 shows the distribution charts, section 15.1.2 shows the configurations charts and section 15.1.3 shows the correlation charts. The analysis and generation of charts was done with modeFRONTIER.

15.1.1. DISTRIBUTION CHARTS

Figure 15.1 and 15.2 show the probability density distribution (histograms) of the outcomes for relative change in heating energy demand (change in %) and absolute change in heating energy demand (difference in kWh), as a result of installing a LTATW. The probability density distributions provide insight into the occurrence of the different outcomes of all 3072 room configurations.

It can be seen that a large amount of the outcomes are represented by the bar above zero (most right bar in Figure 15.1 and most left bar in Figure 15.2). This bar is in both cases that high, because this result occurs in many of the room configurations located in a dry or tropical climate, since no heating is required. Also at a 100% reduction (Figure 15.1) there is a higher bar, because in a considerable amount of situations, the initial energy demand is reduced to zero. It can be demonstrated with modeFRONTIER that the average reduction in heating energy demand equals 21.3% of the initial energy demand or 127.7 kWh in absolute sense. The standard deviation of the reduction in percentage is equal to 28.2% and the standard deviation of the reduction in absolute terms is equal to 197.5 kWh.

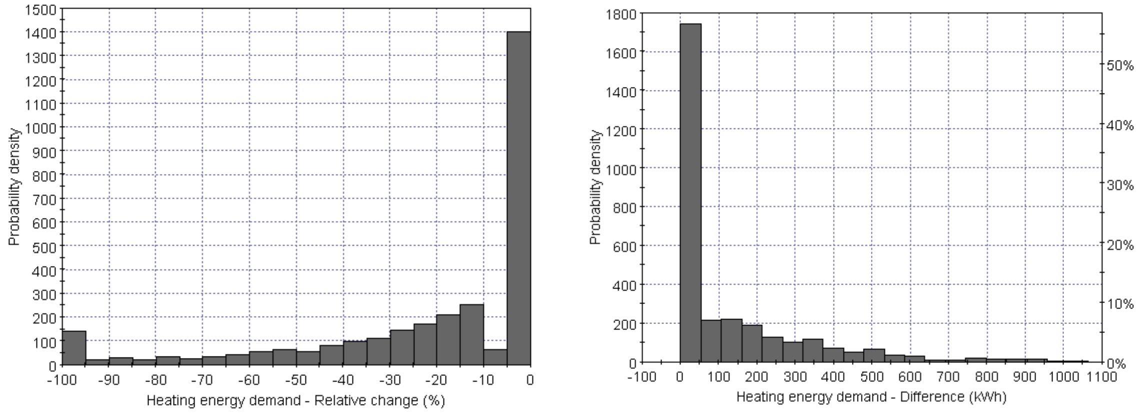


Figure 15.1 and 15.2: Probability density distribution of values of relative change and difference in heating energy demand.

Figure 15.3 and 15.4 show the probability density distribution of the outcomes for relative change and absolute change in cooling energy demand. Again, extremes can be seen around 0%, 100% and 0 kWh. This can be explained by the fact that cooling is often not required in cold and temperate climates, and that again, the energy demand is fully reduced in a some of the room configurations. modeFRONTIER demonstrates that the average reduction in cooling energy demand equals 23.1% of the initial energy demand or 126.6 kWh in absolute sense. The standard deviation equals 29.5% in relative sense and 121.5 kWh in absolute sense.

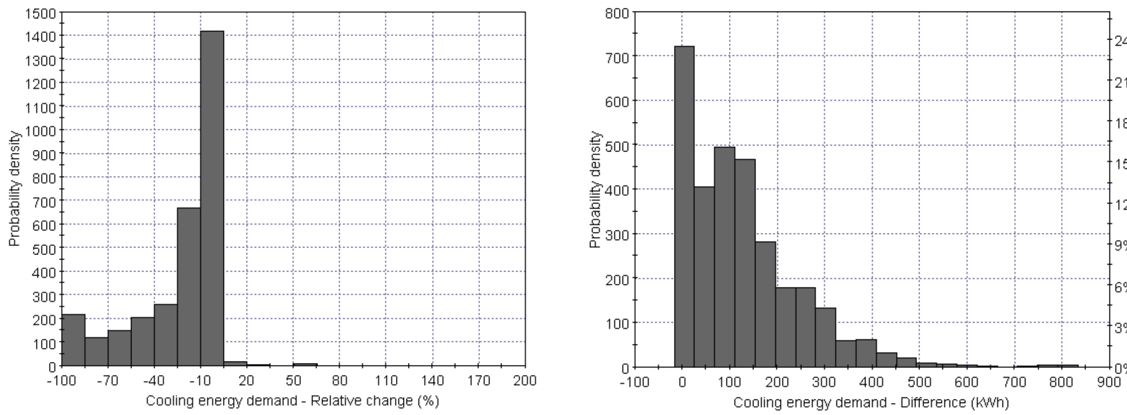


Figure 15.3 and 15.4: Probability density of values for relative change and difference in cooling energy demand.

Because all climates have been included in the analysis of the distribution charts, the values for the average results are not very representative. It is true that in case of heating much higher reductions (more than 21.3%) occur in the cold and mild climates, and that in the case of cooling higher reductions (more than 23.1%) occur in the hot climates. Therefore, to obtain representative values for the average reduction of the heating and cooling energy demand, the distribution charts per climate are shown in section 15.1.1.1 to 15.1.1.4.

15.1.1.1. DISTRIBUTION IN A COLD CLIMATE

Figure 15.5 and 15.6 show the probability density distribution of the outcomes for relative change in heating energy demand (change in %) and absolute change in heating energy demand (difference in kWh), as a result of installing a LTATW in a cold climate. The total number of configurations is equal to a quarter of the total number of configurations in this study (768 rooms). Now, a smoother trend can be seen, without a high bar above zero. It can be demonstrated with the software that the average reduction in heating energy demand in a cold climate equals **32.4%** of the initial energy demand or **326.3 kWh** in absolute sense. The standard deviation of the reduction in percentage is equal to 23.9% and the standard deviation of the reduction in absolute terms is equal to 242.7 kWh.

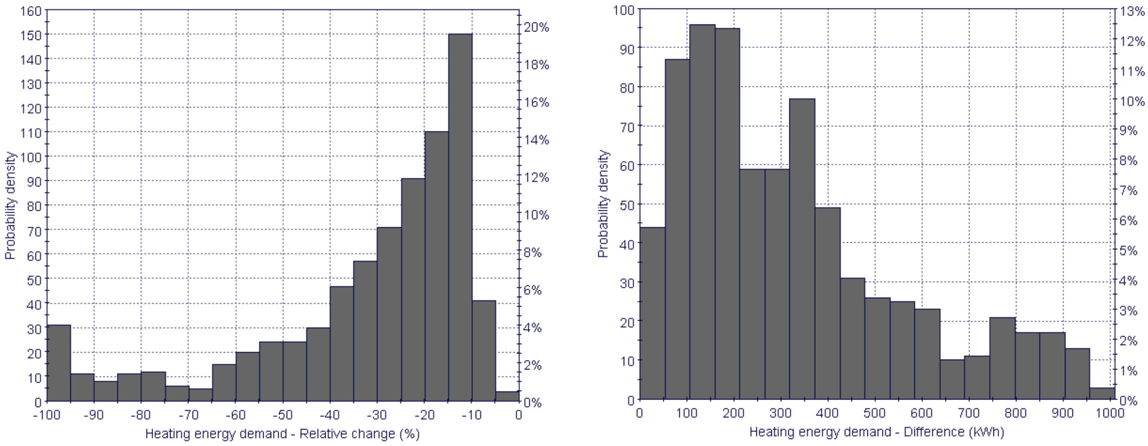


Figure 15.5 and 15.6: Probability density distribution of values of relative change and difference in heating energy demand in a cold climate.

Figure 15.7 and 15.8 show the probability density distribution of the outcomes for relative change and absolute change in cooling energy demand. Because cooling is not required in many cases in a cold climate, as expected, a high bar can be noticed above zero (both charts). In some cases the reduction in percentage of the cooling energy demand is very high (see Figure 15.7), but it can be seen from Figure 15.8 that the corresponding reduction in kWh is relatively low. With the charts it can be demonstrated that the average reduction in cooling energy demand in a cold climate equals **22.4%** of the initial energy demand or **8.3 kWh** in absolute sense. The standard deviation equals 39.9% in relative sense and 22.7 kWh in absolute sense.

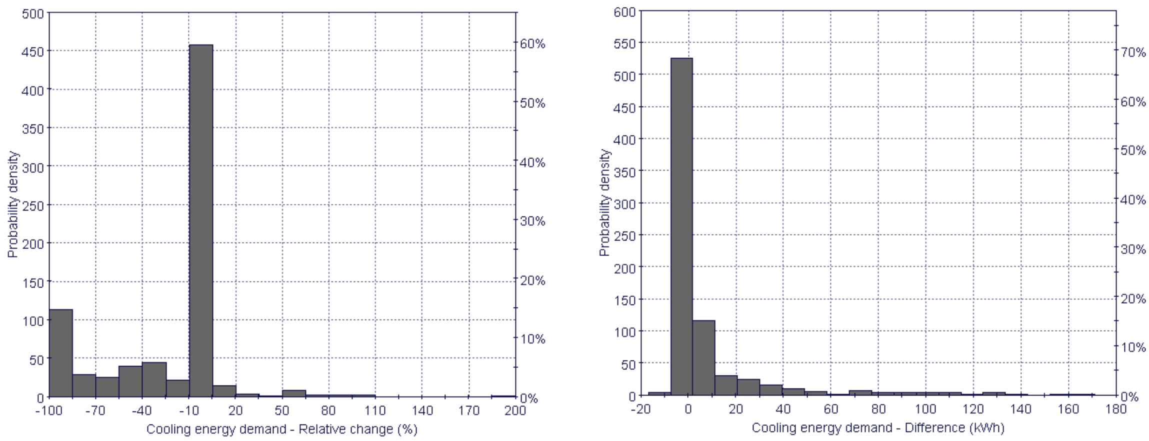


Figure 15.7 and 15.8: Probability density of values for relative change and difference in cooling energy demand in a cold climate.

15.1.1.2. DISTRIBUTION IN A TEMPERATE CLIMATE

Figure 15.9 and 15.10 show the probability density distribution of the outcomes for relative change in heating energy demand and absolute change in heating energy demand, as a result of installing a LTATW in a temperate climate. With the charts it can be demonstrated that the average reduction in heating energy demand in a temperate climate equals **36.1%** of the initial energy demand (which is more than in a cold climate) or **181.3 kWh** in absolute sense (which is less than in a cold climate). The standard deviation of the reduction in percentage is equal to 27.5% and the standard deviation of the reduction in absolute terms is equal to 151.7 kWh.

Figure 15.11 and 15.12 show the probability density distribution of the outcomes for relative change and absolute change in cooling energy demand. With the charts it can be demonstrated that the average reduction in cooling energy demand in a temperate climate equals **49.9%** of the initial energy demand or **115.0 kWh** in absolute sense. The standard deviation equals 26.4% in relative sense and 87.3 kWh in absolute sense.

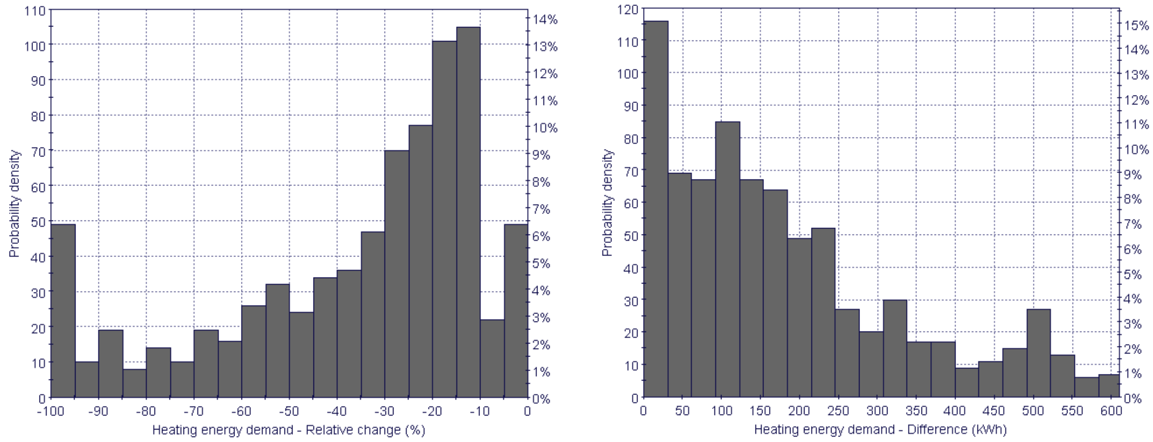


Figure 15.9 and 15.10: Probability density distribution of values of relative change and difference in heating energy demand in a temperate climate.

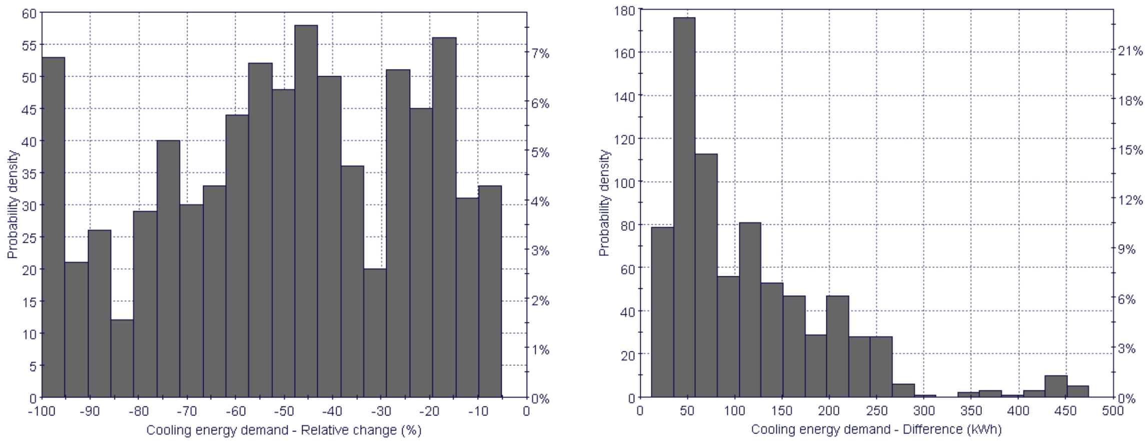


Figure 15.11 and 15.12: Probability density of values for relative change and difference in cooling energy demand in a temperate climate.

15.1.1.3. DISTRIBUTION IN A DRY CLIMATE

Figure 15.13 and 15.14 show the probability density distribution of the outcomes for relative change in heating energy demand and absolute change in heating energy demand, as a result of installing a LTATW in a dry climate. Because heating is not required in many cases in a dry climate, as expected, a high bar can be noticed above zero (both charts). In a small number of cases the reduction in percentage of the heating energy demand is very high (see Figure 15.13), but it can be seen from Figure 15.14 that the corresponding reduction in kWh is relatively low. With the charts it can be demonstrated that the average reduction in heating energy demand in a dry climate equals **16.8%** of the initial energy demand or **3.1 kWh** in absolute sense. The standard deviation equals 32.3% in relative sense and 7.7 kWh in absolute sense.

Figure 15.15 and 15.16 show the probability density distribution of the outcomes for relative change and absolute change in cooling energy demand. With the charts it can be demonstrated that the average reduction in cooling energy demand in a dry climate equals **15.2%** of the initial energy demand (which is less than in a temperate climate) or **233.1 kWh** in absolute sense (which is more than in a temperate climate). The standard deviation equals 7.6% in relative sense and 137.3 kWh in absolute sense.

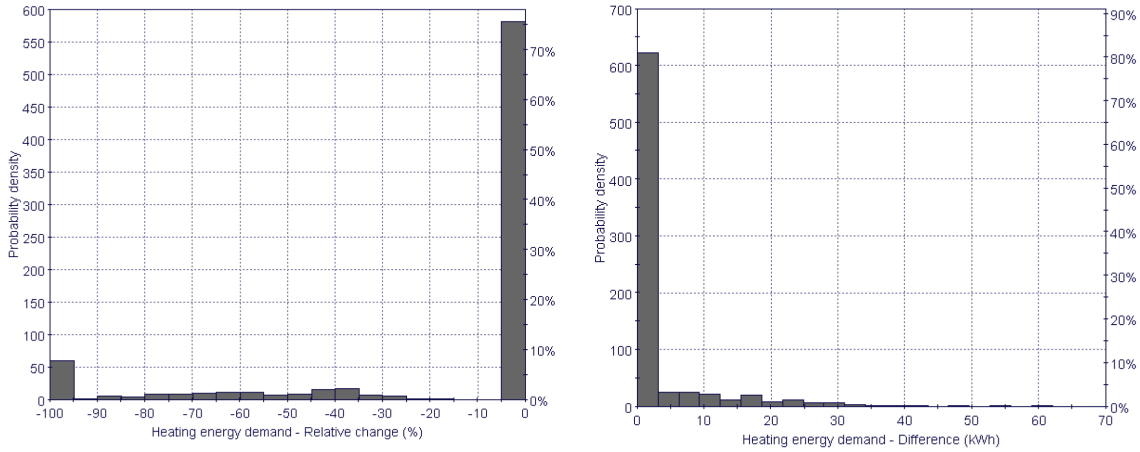


Figure 15.13 and 15.14: Probability density distribution of values of relative change and difference in heating energy demand in a dry climate.

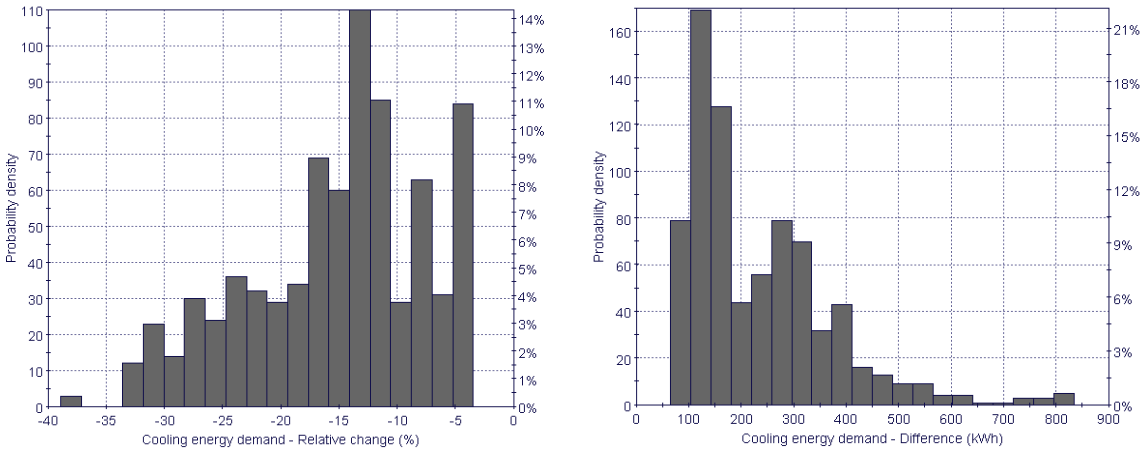


Figure 15.15 and 15.16: Probability density of values for relative change and difference in cooling energy demand in a dry climate.

15.1.1.4. DISTRIBUTION IN A TROPICAL CLIMATE

Figure 15.17 and 15.18 show the probability density distribution of the outcomes for relative change in heating energy demand and absolute change in heating energy demand, as a result of installing a LTATW in a tropical climate. Because heating is not required in all cases in a tropical climate only one bar can be noticed above zero (both charts). Therefore, the average reduction in heating energy demand in a tropical climate equals **0.0%** of the initial energy demand or **0.0 kWh** in absolute sense.

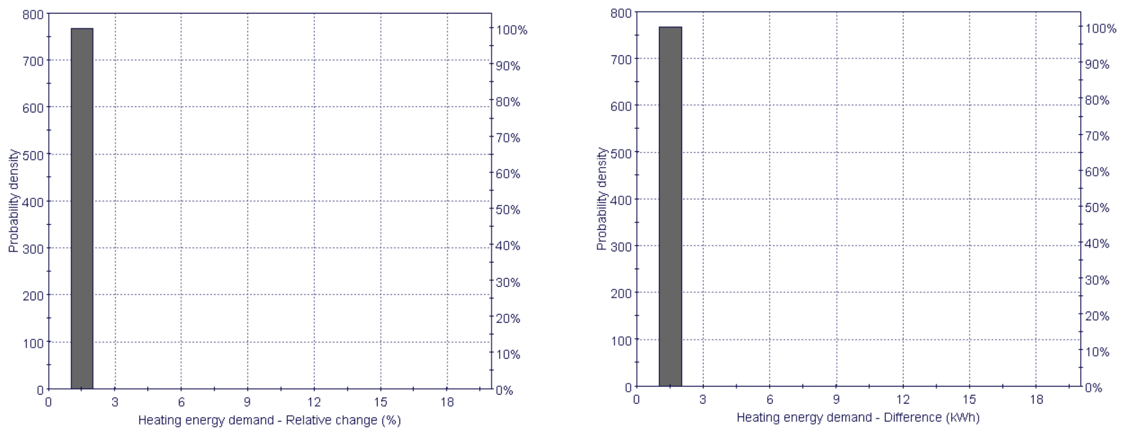


Figure 15.17 and 15.18: Probability density distribution of values of relative change and difference in heating energy demand in a tropical climate.

Figure 15.19 and 15.20 show the probability density distribution of the outcomes for relative change and absolute change in cooling energy demand. With the charts it can be demonstrated that the average reduction in cooling energy demand in a tropical climate equals **4.7%** of the initial energy demand (which is less than in dry climate) or **149.9 kWh** in absolute sense (which is also less than in a dry climate). The standard deviation equals 2.5% in relative sense and 78.1 kWh in absolute sense.

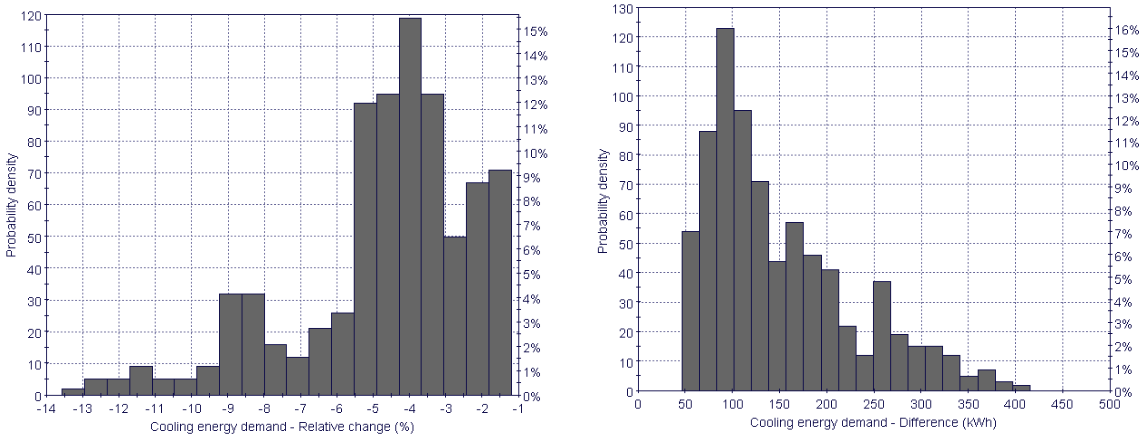


Figure 15.19 and 15.20: Probability density of values for relative change and difference in cooling energy demand in a dry climate.

15.1.2. CONFIGURATIONS CHARTS

Figure 15.21 shows a scatter chart with the heating energy simulation results of all 3072 room configurations. The results in the chart include two values, which are plotted against each other: the energy reduction in relative sense (change in %) and the energy reduction in absolute sense (difference in kWh). From the figure, it can be seen that a rather exponential distribution describes the relation between the two. When the relative change in energy demand is high, a relatively lower difference in energy demand is seen. On the other hand, a lower relative change is generally accompanied by a higher difference between the energy demand before and after.

With the inclusion of lines representing the average reductions found in the previous section, the chart of Figure 15.21 can be divided into four different areas: A, B, C and D (see Figure 15.22). Area A represents an area filled with room configurations that show great potential for installing the innovative Trombe wall, as both a relatively high energy reduction in percentage and energy reduction in absolute sense is experienced (both above average). In this area, installing a LTATW leads to a considerable reduction in energy demand, while the investment costs will also be paid-back faster than average (pay-back time is shorter with a higher difference in energy demand (kWh)).

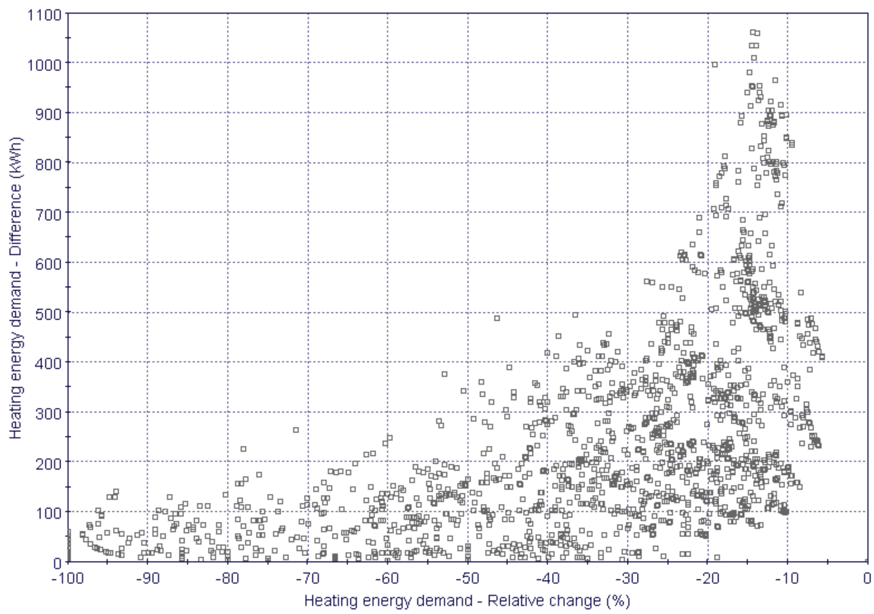


Figure 15.21: Absolute versus relative reduction in heating energy demand after installing a LTATW.

Because detailed information about the investment costs of the LTATW is still unknown, it is also unknown if the average reduction in absolute sense corresponds to a common, average and not too long pay-back time. However, for now, it is assumed that this is the case. (This chart could be used to determine the maximum investment costs in future research).

Area B represents an area with room configurations that experience a relatively high reduction in energy demand in absolute sense, but low reduction in relative sense. In this region, a lot of energy is reduced (and therefore the system will be paid-back much faster), but the reduction is small compared to the initial energy demand. In this area, therefore, the advice applies that it may be better to look for other energy-saving alternatives that are capable of reducing a larger part of the energy demand of the room (or in the end: the building). When a designer or building owner agrees with a relatively a low percentage decrease than average, this area is still an area with high potential.

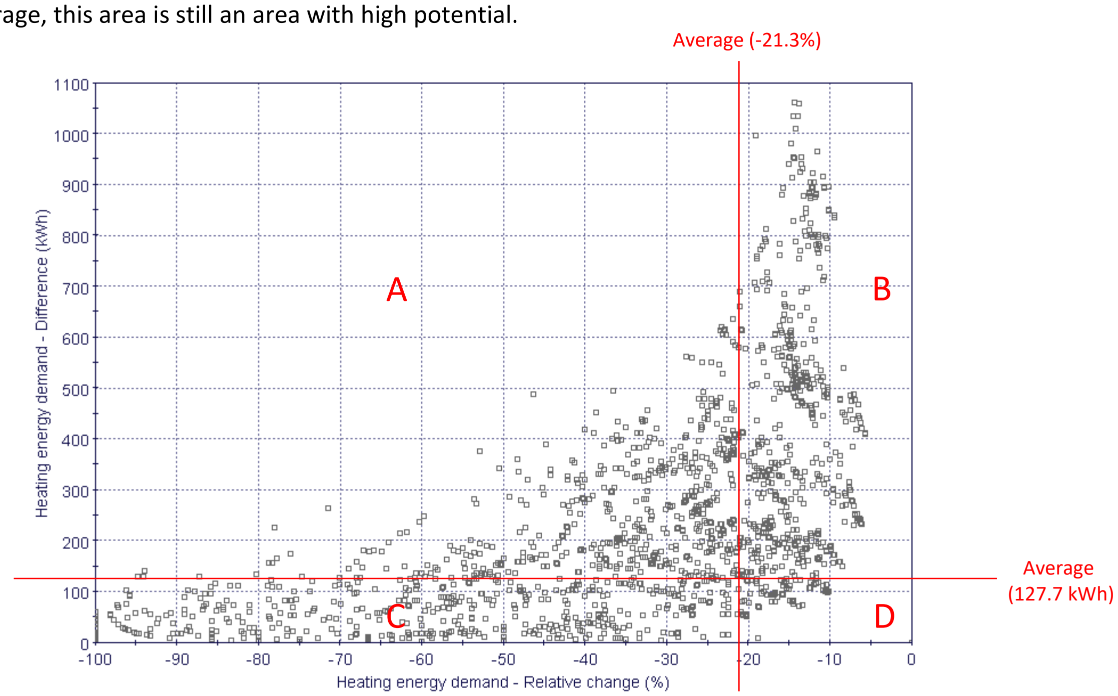
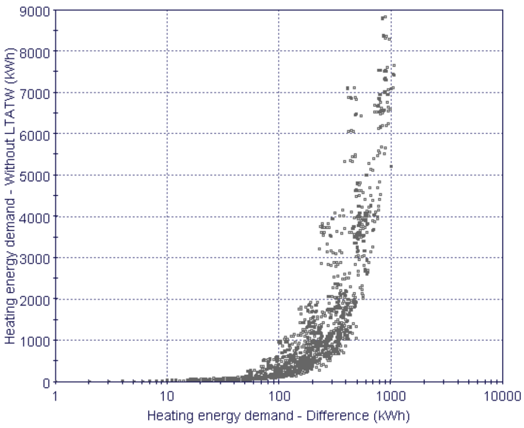


Figure 15.22: Absolute and relative reduction in heating energy demand after installing a LTATW – four different chart areas.

Area C represents an area with rooms that experience a percentage reduction of the energy demand which is average to high (even up to 100%), but where the absolute differences are relatively small. For these room configurations, the system therefore seems to be an ideal energy reducer in the first case, but the disadvantage is that the investment costs can probably not be repaid within a reasonable amount of time. The system is therefore probably too expensive in this area, and only when money does not play a significant role, this area has some potential.

Finally, area D represents an area in which both the relative change and the absolute difference in energy demand is low. Room configurations in this area do not offer any potential for installing a LTATW.



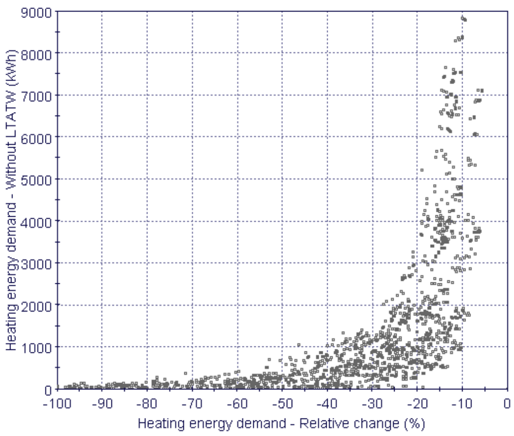


Figure 15.23 and 15.24: Heating energy demand without LTATW versus absolute energy reduction with LTATW (left) and versus relative energy reduction with LTATW (right).

In Figure 15.23, the absolute energy reduction is plotted against the initial energy demand. From the figure it can be seen that the higher the initial energy demand, the higher the reduction, until a maximum reduction is reached. This means that the Trombe wall can reduce a certain maximum amount of energy, and thus has a certain maximum capacity. In this study, it was assumed that a larger room with a larger window results in a larger Trombe wall. A hypothesis might therefore have been that there would be a more linear relationship., but apparently, a larger room (with accompanying larger energy demand) cannot be proportionally 'maintained' by the larger Trombe wall. Also from Figure 15.21 and 15.24, the presence of a maximum capacity can be noticed, as a relatively higher initial energy demand never results in a very high reduction in percentage.

Figure 15.25 shows a scatter chart with the cooling energy simulation results of all 3072 room configurations. Again, the same two values are plotted against each other: the energy reduction in relative sense and the energy reduction in an absolute sense.

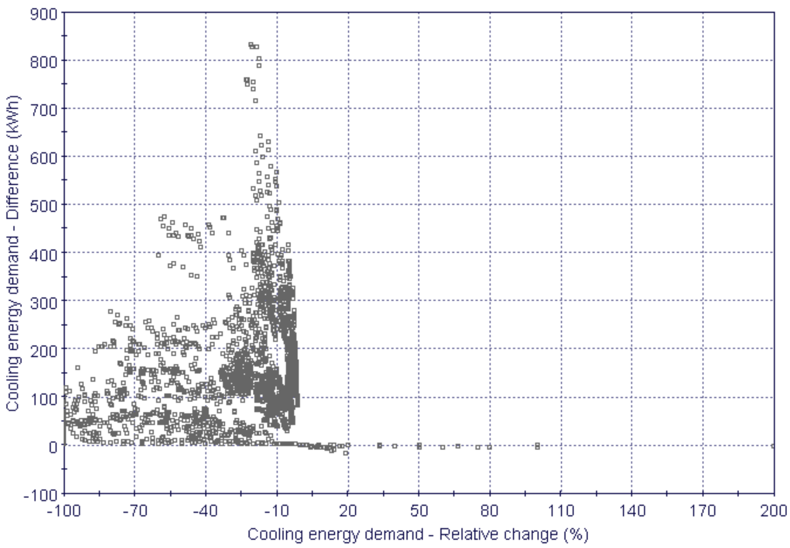


Figure 15.25: Absolute and relative reduction in cooling energy demand after installing a LTATW.

It can be seen from the figure that in case of cooling, not all rooms experience an energy reduction, but that there are also rooms in which an increase in energy demand takes place. However, it is reassuring that all these configurations are on the same line around an absolute reduction of 0 kWh, which means that in all these cases the energy demand changes in one way or another from a small value to a slightly larger, small value (such as a change of for example 0.1 to 0.5 = 50%). When a large part of these configurations is ignored, the chart shown in Figure 15.26 arises.

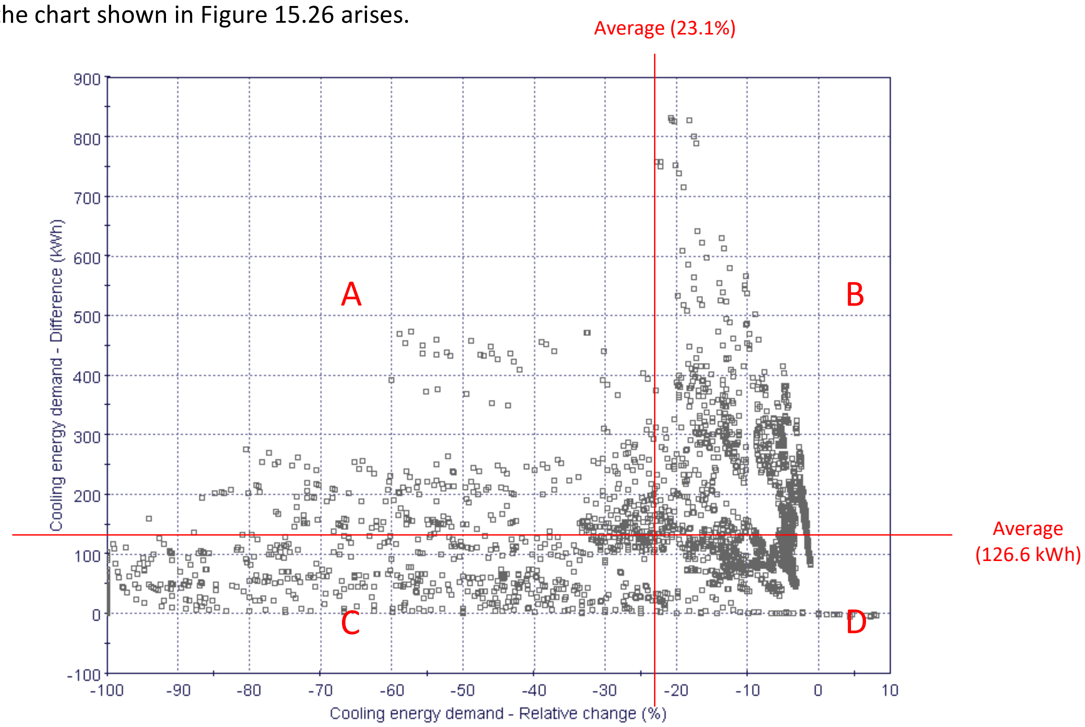


Figure 15.26: Absolute and relative reduction in cooling energy demand after installing a LTATW – four different chart areas.

Remarkable is that there is again a concentration of most room configurations above the horizontal axis and the vertical axis, but now, no clear exponential relation can be seen (which was the case in the heating chart). The distribution in this chart seems to be deflecting to the left, and shows that in some cases, relatively high absolute reductions can be achieved with at the same time a relatively large reduction in percentage. Again, the chart in Figure 15.26 is divided into four different areas: A, B, C and D. Area A represents an area filled with room configurations that show great potential for installing a LTATW, as both a relatively high energy reduction in percentage and energy reduction in absolute sense is experienced. Area B again represents an area with high absolute reductions, but in which only a small part of the initial energy demand is reduced, Area C again represents a relatively less profitable part and area D is again an area without any potential.

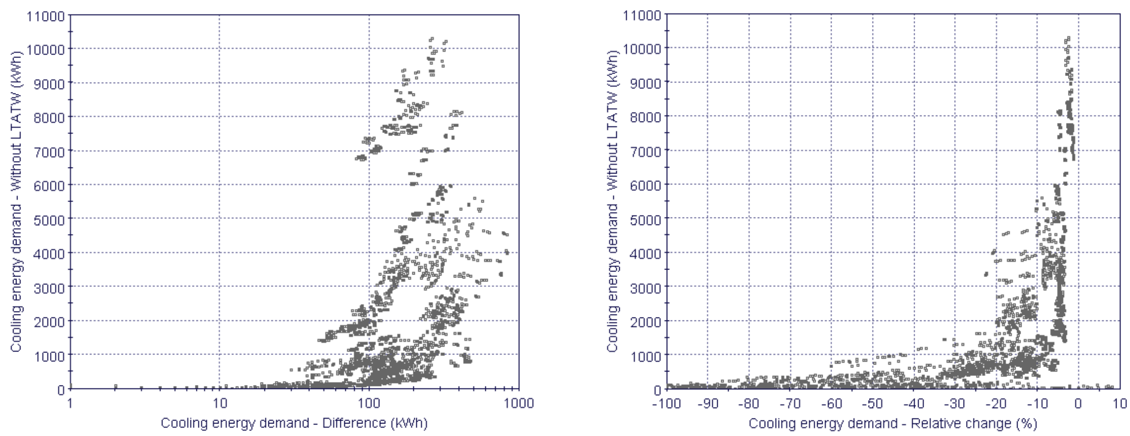


Figure 15.27 and 15.28: Cooling energy demand without LTATW versus absolute energy reduction with LTATW (left) and versus relative energy reduction with LTATW (right).

In Figure 15.27, the absolute energy reduction (kWh) is plotted against the initial energy demand. It can be seen that also in case of cooling, a maximum capacity of the LTATW exists. However, a less obvious asymptote can be seen here, in contrast to the graph of heating. It seems that even at higher initial energy demands, a larger part can still be reduced (also seen in Figure 15.28), and explains the distribution in Figure 15.26.

15.1.3. CORRELATION CHARTS

Figure 15.29 shows a correlation matrix with six of the eight variable parameters on the vertical axis and six outcomes regarding energy demand on the horizontal axis. For each combination of variable parameter and outcome, the correlation matrix shows the relevant correlation coefficient. This correlation coefficient is based on the principle of Pearson (Pearson correlation) and is a number between -1 and 1. The Pearson correlation coefficient indicates the extent to which two parameters are linearly related: a correlation coefficient of -1 indicates that the data points in a scatter chart lie exactly on a straight, descending line, which means that the two parameters are perfectly, but negatively linearly related. A correlation of 0 means that the two parameters don't have any linear relation and a correlation of 1 means that the two parameters are perfectly positively linearly related (Cohen, Cohen, West, & Aiken, 1983). The variables 'type of glazing' and 'orientation' are not included, as their subdivisions are randomly arranged 'values' and a possible optimum might exist at one of the middle values (like a southern orientation). The influence of these two variables is clarified with others charts and tables in the remainder of part IV.

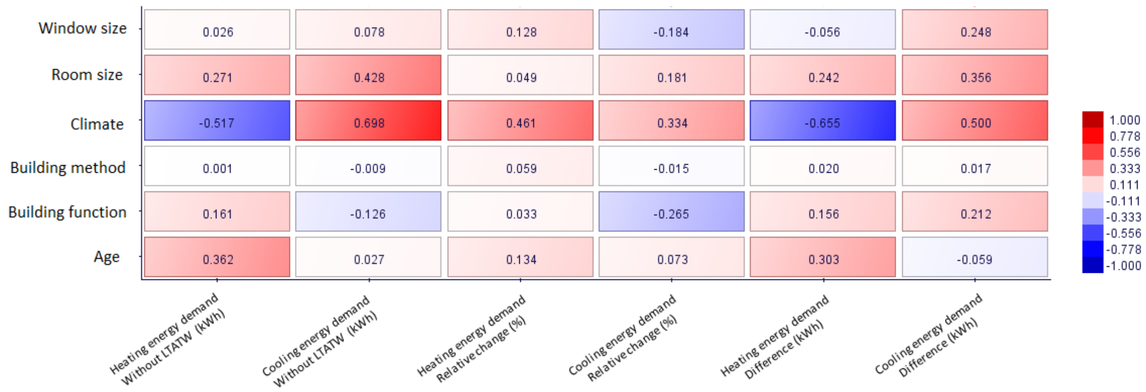


Figure 15.29: Correlation matrix.

In the matrix, six outcomes regarding energy demand are taken into account: the initial heating and cooling energy demand, the relative change in heating and cooling energy demand and the absolute difference in heating and cooling energy demand. For each type of energy demand, the results of the correlation matrix are presented in a clearer, graphical way in Figure 15.30 to 15.35.

Before discussing the results of the correlation matrix, the following must be explained: as mentioned before and above, the variables studied in this thesis are discrete variables instead of continuous variables. Before simulation, these discrete variables were arranged from 'low' to 'high' using the numbers 1 to 4. Showing this order (Table 15.1) is important to understand what a negative and a positive correlation coefficient exactly means.

Table 15.1: Classification of variables.

Variable	low → high			
	1	**2**	**3**	**4**
Climate	Cold	Temperate	Dry	Tropical
Building function	Office	Residence		
Age	New	Old		
Building method	Light-weight	Medium-weight	Heavy-weight	
Room size	Small	Big		
Window size	Small	Large		

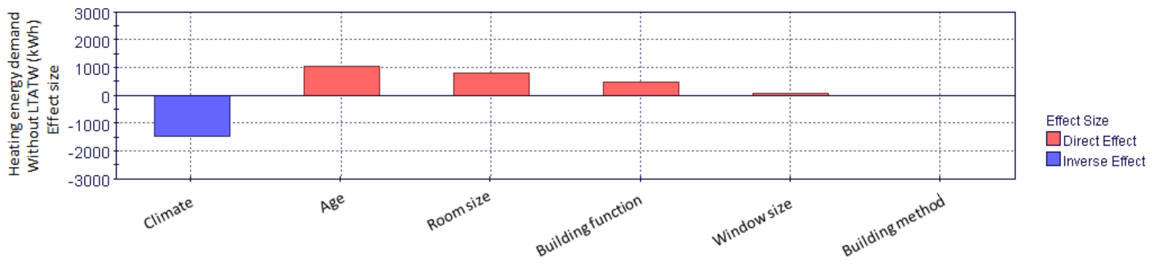


Figure 15.30: Effect size of variable parameters on heating energy demand without LTATW.

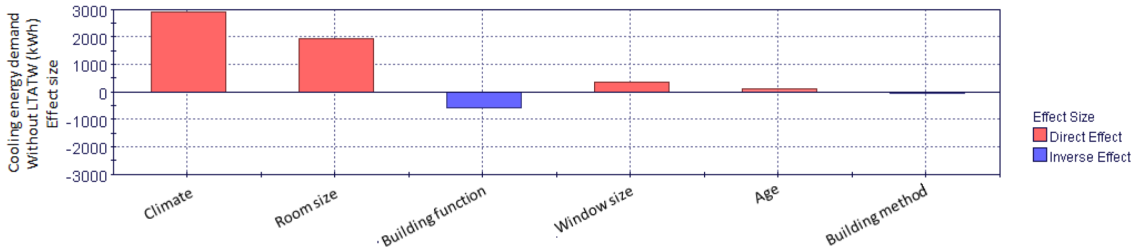


Figure 15.31: Effect size of variable parameters on cooling energy demand without LTATW.

From the correlation matrix and the charts of Figure 15.30 and 15.31 it quickly becomes clear that climate has the highest influence on the outcomes for the initial energy demand. As expected: the warmer the climate, the lower the heating energy demand (negative relation, indicated with a blue color) and the higher the cooling energy demand (positive relation, indicated with a red color). Of course, a bigger room results in a higher energy demand and a lower air tightness and insulation value of the façade results in more need for heating. Also, the heating energy demand of offices is much lower than the heating energy demand of residences. What is striking, however, is that the construction method has a relatively very small influence on the initial heating and cooling energy demand.

The influence of the variables on the heating energy reduction in relative and absolute sense is shown in Figure 15.32 and 15.33. From Figure 15.32 can be seen that on average, all parameters have a positive effect on the relative change in heating energy demand. It appears to be that in a warmer climate and in an older and heavier residential building, a higher reduction in relative sense can be achieved. Furthermore, a bigger room with a larger window also result in a better performance in relative sense.

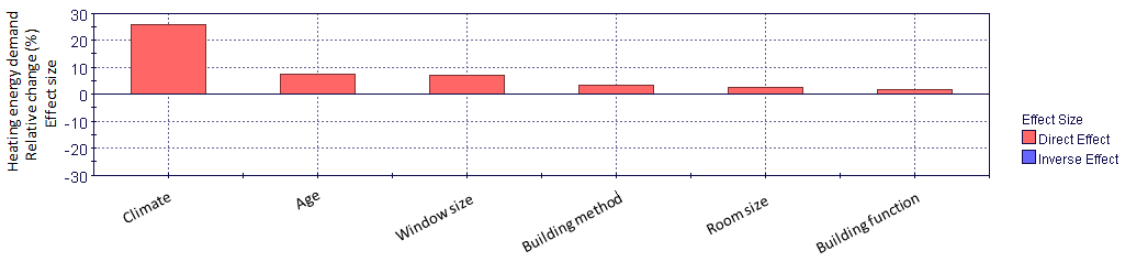


Figure 15.32: Effect size of variable parameters on relative change in heating energy demand.

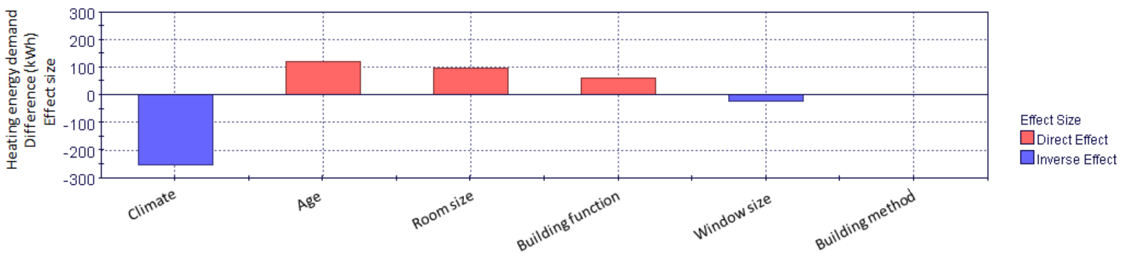


Figure 15.33: Effect size of variable parameters on difference in heating energy demand.

However, when looking at Figure 15.33, it can be seen that a warmer climate does not lead to a higher reduction of the heating energy demand in absolute sense. In this case, in fact, it appears to be that the colder the climate, the higher the total energy reduction in kWh. It is true again, that a Trombe wall in a big room of an old residential building provides the highest reductions.

The influence of the variables on the cooling energy reduction in relative and absolute sense is shown in Figure 15.34 and 15.35. From Figure 15.34 can be seen that a warmer climate results in a higher energy reduction in relative sense. Furthermore, a 'higher' building function (residence) is accompanied with a lower percentage reduction, just like a room with smaller window (and also a smaller LTATW). From Figure 15.35 can be seen that, on average, a warmer climate results in the highest reduction in absolute sense, just like a bigger room with larger window. In a residence, the absolute reductions are also slightly larger.

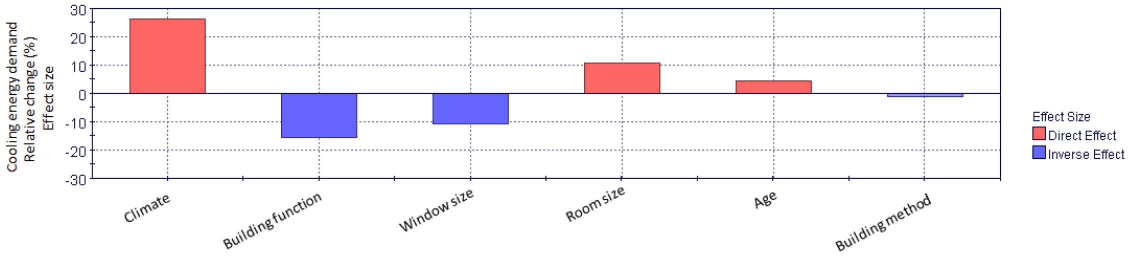


Figure 15.34: Effect size of variable parameters on relative change in cooling energy demand.

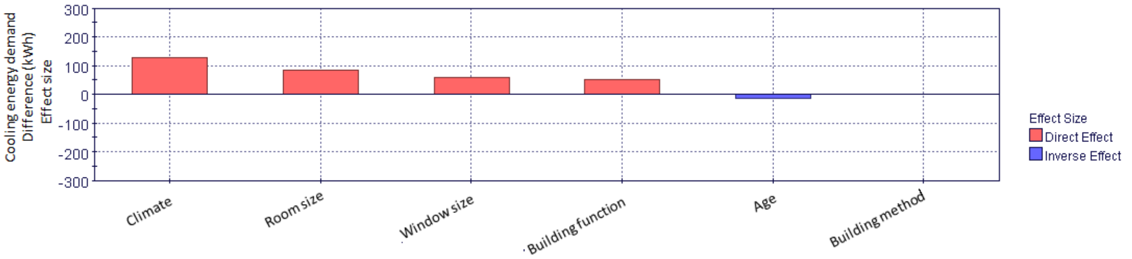


Figure 15.35: Effect size of variable parameters on difference in cooling energy demand.

Finally, the results of the correlation analysis are also shown using pie charts (Figure 15.36). In these pie charts, only the ratio between the effect sizes of the variables is shown and not the direction (negative or positive) of the correlation. Therefore, the variables 'type of glazing' and 'orientation' are included as well. From the pie charts can be seen that the type of glazing and orientation have a greater influence on the initial heating energy demand than the initial cooling energy demand. Apparently, in rooms that require heating, receiving solar gains and not losing lots of heat through the glazing is of greater influence than in cooling cases. When looking at the pie charts of relative difference in energy demand, it can be seen that orientation and type of glazing do not have a major influence. In case of absolute energy reduction, however, the influence is greater. What the order size of this influence is and which orientation and type of glazing is the most favourable, is explained in the next section and can also be determined from the designer tables in chapter 17.

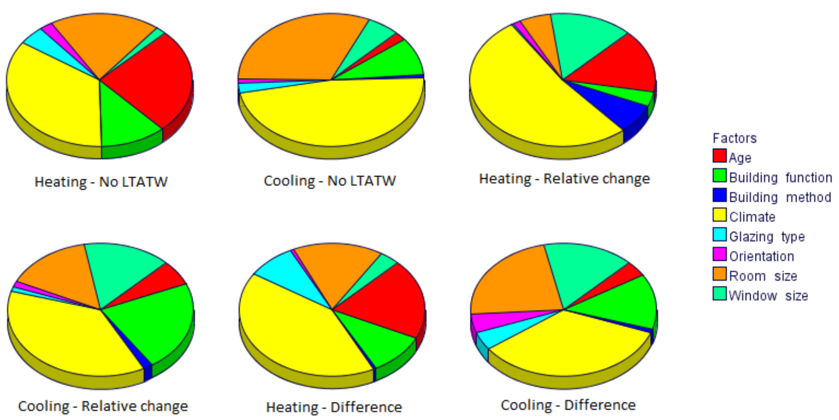


Figure 15.36: Pie charts of effect sizes of variable parameters.

15.2. ANALYSIS OF INDIVIDUAL PARAMETER INFLUENCE

In the previous section, it was made clear which variables have the most influence on the energy and comfort performance of the LTATW, and what the direction of the correlation between variable and energy performance is. With this knowledge an idea has been obtained of the effect size of the variables, but because this analysis is based on a correlation calculated over an enormous number of different situations, the results are difficult to interpret. In this section, insight into the performance of the Trombe wall under different circumstances is improved by using the scatter charts from the previous section. With these scatter charts, more knowledge can be gained about the most potential circumstances and the performance of each individual variable and its subdivision values. All eight variables are discussed in section 15.2.1 to 15.2.8.

15.2.1. INFLUENCE OF CLIMATE

Figure 15.37 shows the relation between relative change in heating energy demand and absolute difference in heating energy demand. Now, however, the type of climate is indicated with a color for each of the 3072 room configurations. It is immediately noticeable that for heating reduction purposes, only the cold and mild climates are of major relevance. Configurations of a dry climate can also be seen, but their absolute reduction in energy demand is relatively low. Room configurations from a tropical climate cannot be seen in the graph, because obviously, no heating is required in these cases. With the division of the chart in different areas (previous section) in mind, it can be concluded that the LTATW performs best in a cold climate and temperate climate (heating). In relative terms, the LTATW performs slightly better in a temperate climate, but the highest reductions in absolute terms are achieved in a cold climate. This supports the findings from Figure 15.32 and 15.33 and tells again that the findings from the previous chapter can be misleading and do not directly reveal the most optimal situation.

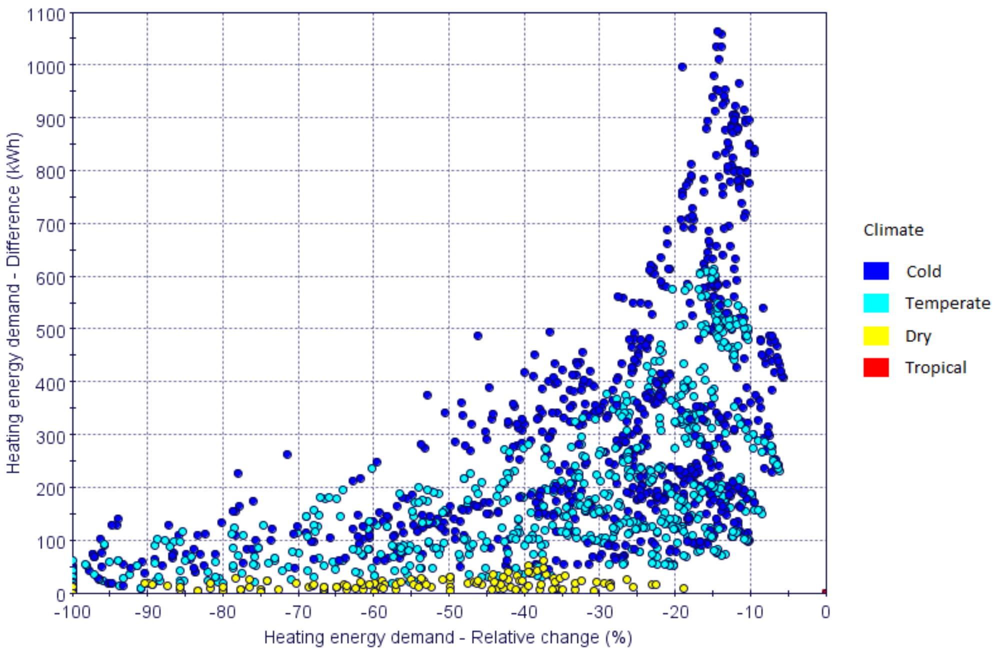


Figure 15.37: Relative change versus difference in heating energy demand with indication of climate types.

Figure 15.38 shows the relation between relative change in cooling energy demand and absolute difference in cooling energy demand. Again, the type of climate is indicated with a color. It is immediately noticeable that for cooling reduction purposes, the tropical, dry and temperate climates are of relevance. Configurations of a cold climate can also be seen, but their absolute reduction in energy demand is low. With the division of the chart in different areas in mind, it can be concluded that the LTATW performs best in a temperate or dry climate (cooling), but that also in a tropical climate, the performance is fine. The highest absolute reductions are achieved in a dry climate, and the highest percentage reductions can be achieved in temperate climates. For this, it is true that shorter pay-back times occur in the rooms located in a dry climate. An increase in energy demand only occurs in room configurations of cold climates, but they are not of major importance as absolute differences here are around 0 kWh.

Again, the chart of Figure 15.38 shows that the results shown in the previous section can be misleading. Figure 15.34 and 15.35 revealed that on average, a warmer climate both results in a higher cooling energy reduction in relative and absolute sense. From Figure 15.38 can be seen that this is indeed true, until the tropical climate has been 'reached'. In this climate both the reduction in absolute sense and in relative sense is again smaller than in a dry climate. Finally, it can again be seen from Figure 15.38 that the innovative Trombe wall has a maximum reducing capacity, because in a dry climate with higher cooling energy demands, it is not able anymore to reduce more than about 30% of the initial energy demand.

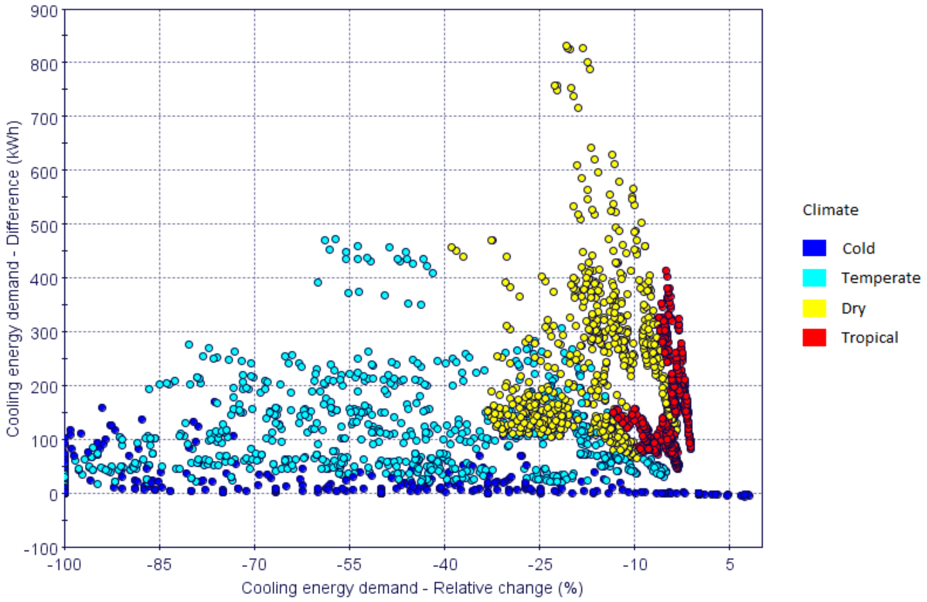


Figure 15.38: Relative change versus difference in cooling energy demand with indication of climate types.

In conclusion of this section, Figure 15.39 shows the relation between absolute reduction in heating energy demand and absolute reduction in cooling energy demand. The chart shows that the multi-seasonal operation capability of the LTATW is best utilized in a temperate climate. In this climate, the LTATW can be used both in summer as passive cooling mechanism and in winter as passive heating mechanism.

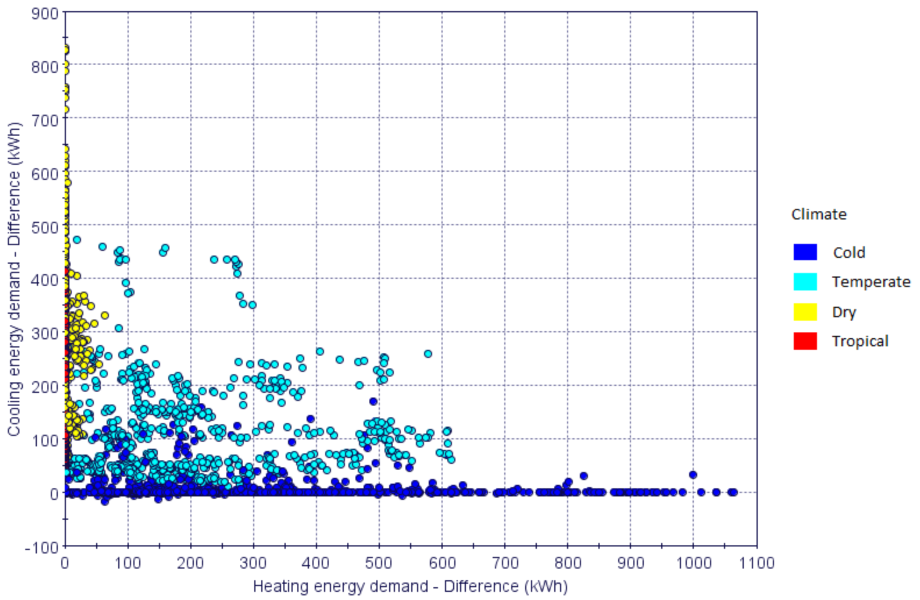


Figure 15.39: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of climate types.

15.2.2. INFLUENCE OF BUILDING FUNCTION

The influence of the function of a building is studied with the same type of chart. From Figure 15.40 can be seen that in case of reduction of heating demand purposes, the function of a building is not of great importance. The same, good performances can be achieved in both offices and residences. However, slightly higher reductions in percentages are achieved in offices and slightly higher absolute reductions are achieved in residences. This can be explained by the fact that the heating demand is slightly higher in rooms of residences.

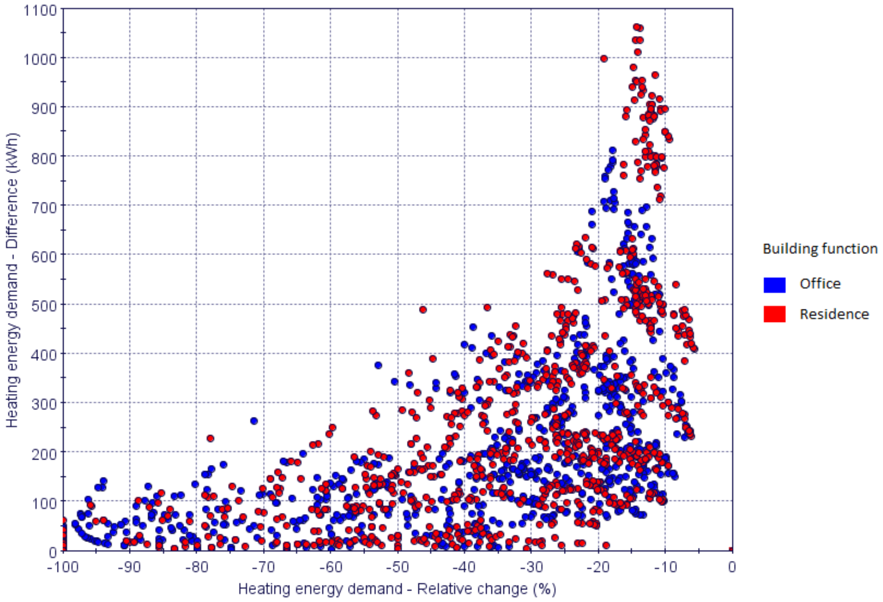


Figure 15.40: Relative change versus difference in heating energy demand with indication of building functions.

From Figure 15.41 can be seen that in case of reduction of cooling demand purposes, the function of a building is of much greater importance than in case of heating. Better performances are seen in the rooms of residences, as both a higher absolute reduction and a higher relative reduction is achieved. In Figure 15.42, the relation between absolute reduction in heating energy demand and absolute reduction in cooling energy demand is shown. The chart also reveals that higher reductions of cooling energy demand occur in rooms of residences. However, both building functions do not form an obstacle to being able to make use of the multi-seasonal operation capability of the LTATW.

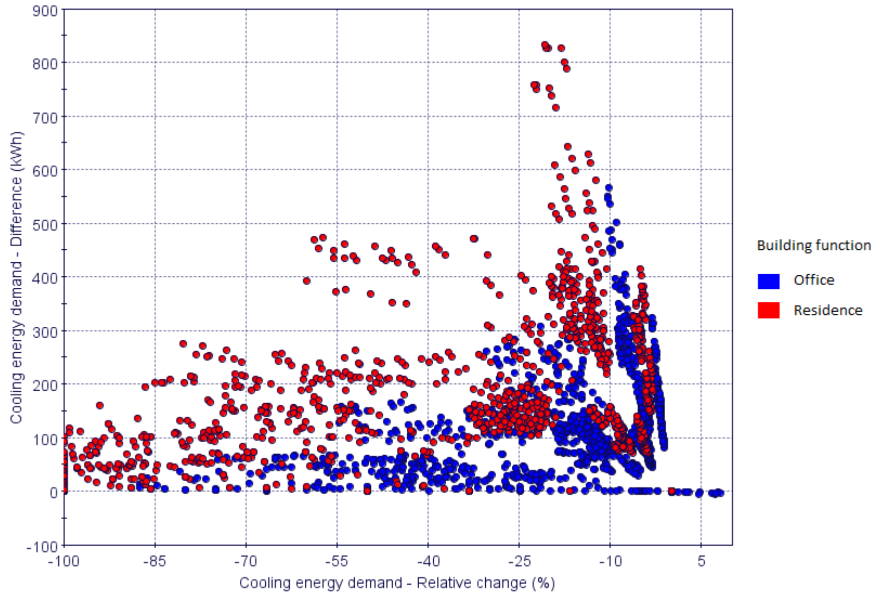


Figure 15.41: Relative change versus difference in cooling energy demand, with indication of building functions.

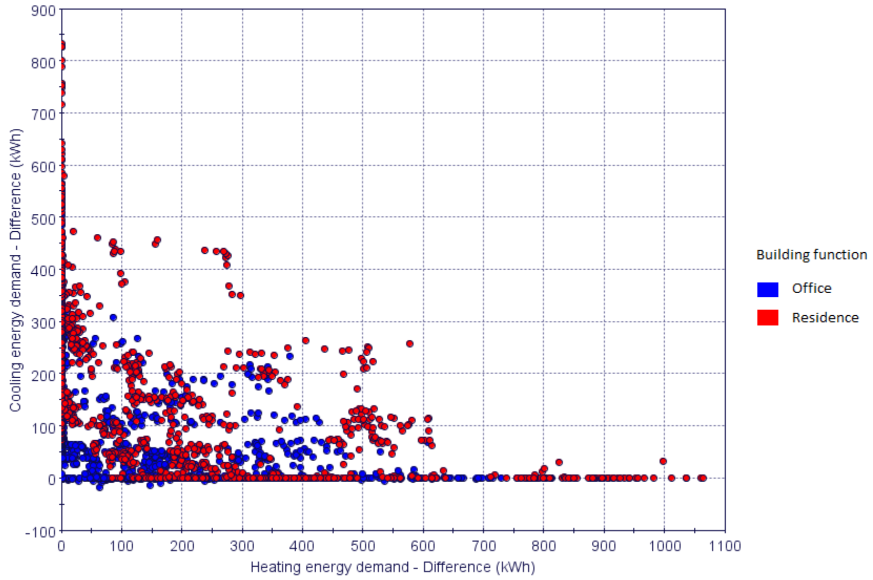


Figure 15.42: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of building functions.

15.2.3. INFLUENCE OF ORIENTATION

From both Figure 15.43 and 15.44 it can be seen that the effect size of orientation is low, as there are both good and bad performances of rooms with a LTATW on each orientation. This is logical, because the Trombe wall with its energy storing phase change material performs well, even without a rotation mechanism and a position behind the window. However, when the graphs (and also the designer tables in chapter 17) are better studied, it can be seen that per situation, certain orientations result in a better performance than other orientations. As the innovative part of the Double Face project is based on adaptability and positioning behind a window, it is important to find the best orientation here, even though the results can be good for all orientations.

When studying Figure 15.43, it can be seen that data-points/rooms with a southern orientation of the LTATW are more often concentrated at the upper boundary of the distribution. This would suggest that a southern orientation leads more often to both a higher reduction in relative sense, and higher reduction in absolute sense. Because it is interesting to know here, per situation, what the influence of the orientation is, four data-points of three of the same rooms (but with varying orientation) are highlighted and a green arrow is drawn to indicate the 'path' from north, east and west to south. In all three cases, it can be seen that the data-points of north, east and west are concentrated around the same value of energy reduction (both absolute and relative) and that a southern orientation, however, leads to a significant shift. In all three cases, it can be seen that when a room is oriented towards the south, the data-point also moves to the upper boundary of the chart. In one case, both a higher relative reduction and absolute reduction is achieved (data-point 2377), but in the other two cases a higher reduction in relative sense occurs and a lower reduction in absolute sense. Apparently it is true that a southern orientation provides the best reduction in relative terms, but because the initial heating energy is lower due to the solar gains, the absolute reduction is also less in the end. It is made clear here that a southern orientation, as expected, results in the best performance (because the LTATW can now absorb more energy from the sun), but it must be checked with the aid of the designer tables, whether the reduction in absolute terms will still be above average.

From Figure 15.44 it can be seen that there is a weaker correlation between (cooling) energy performance and orientation. Also here, four data-points of three of the same room configurations and circled with a green line. Now, however, no direct preference can be expressed for optimal orientation, and to see what is the best for each situation, the designer table should be consulted. In two of the three highlighted room cases, the following behavior is seen: a northern orientation provides a slightly larger reduction in relative terms, but a slightly lower reduction in absolute terms. This can be explained by the fact that the initial cooling demand for a northern orientation is already lower, so that the absolute reduction will also be lower in the end (same principle as for heating, but vice versa). The results for cooling are as expected, because the working principle of passive cooling of the Trombe wall does not rely on direct contact with the energy of the sun, but with the energy from sources within the building.

Figure 15.45 shows that for all orientations, the LTATW can function both as a passive heating and passive cooling system.

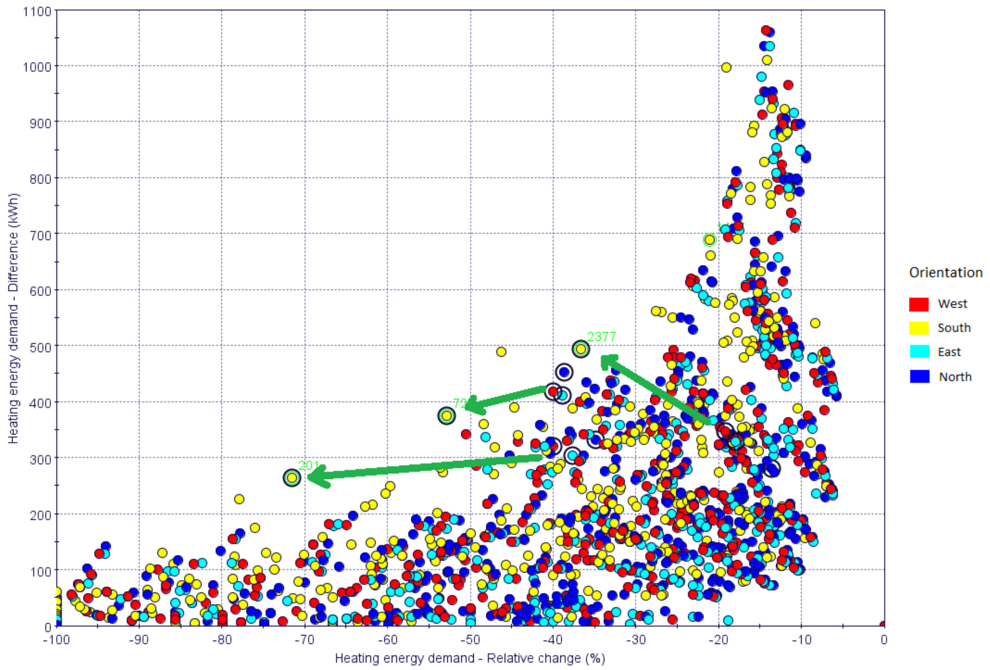


Figure 15.43: Relative change versus difference in heating energy demand with indication of LTATW orientations. Green arrows indicate the path of a data-point of the same situation, moving from a north/east/west data-point to a data-point with southern orientation.

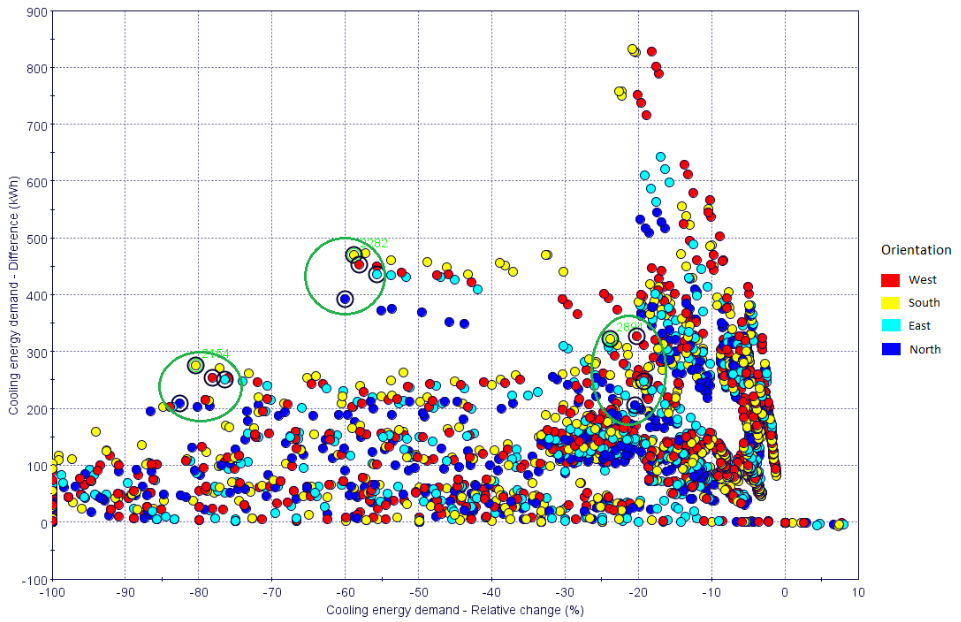


Figure 15.44: Relative change versus difference in cooling energy demand with indication of LTATW orientations. Green circles indicate the location on the chart of four of the same room configurations with varying orientation.

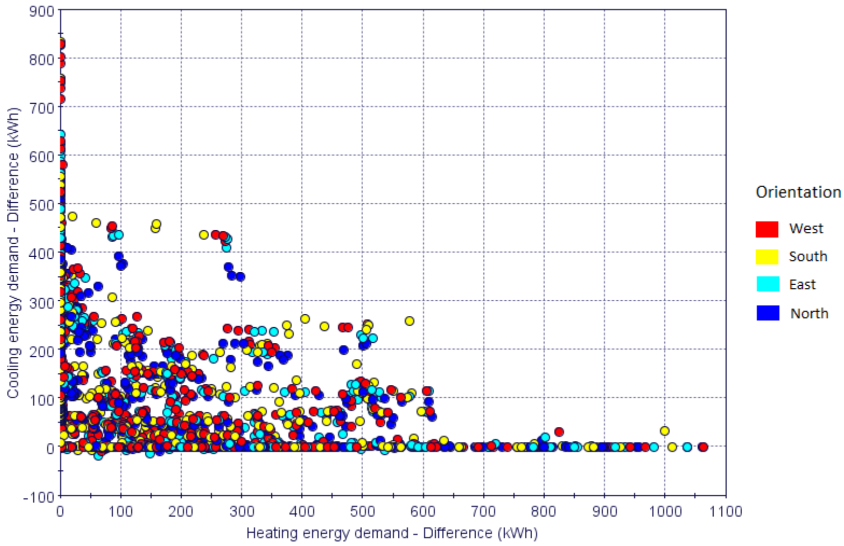


Figure 15.45: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of LTATW orientations.

15.2.4. INFLUENCE OF AGE

Figure 15.46 shows the distribution of room configurations in old buildings and in new buildings. What can be seen is a clear distribution, in which the data points of rooms in new buildings are concentrated more around the bottom left part of the figure, while data points of rooms in old buildings are concentrated more to the right. With the division of the chart in the four areas A, B, C and D in mind, it can be concluded that the situations that are most suitable for a considerable reduction of the initial energy demand of the room are rooms of a new building. However, a LTATW installed in an old building is capable of reducing much more energy in absolute sense, because the initial heating energy demand in these cases is much higher, due to the higher infiltration rate and poorer façade insulation properties.

From Figure 15.47 it can be seen that the correlation in case of cooling is slightly weaker than in case of heating. Nevertheless, a clear distribution pattern can still be seen, in which the innovative Trombe wall in rooms of a new building perform slightly better. It is noted in fact that the data-points of rooms in old buildings concentrate more to the bottom the right, and that the data-points of rooms in new buildings often have both a higher relative reduction as well as an absolute reduction.

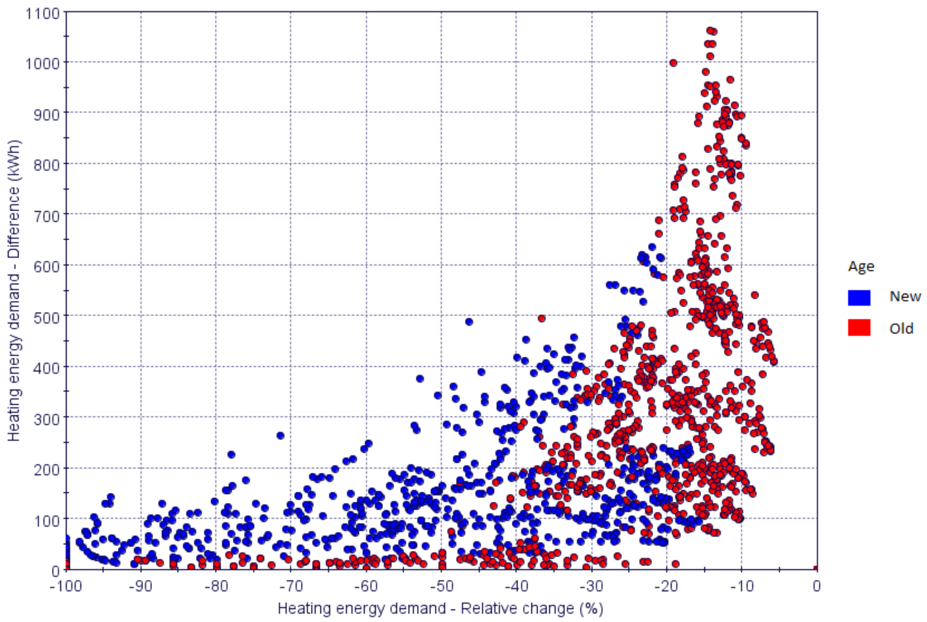


Figure 15.46: Relative change versus difference in heating energy demand with indication of building ages.

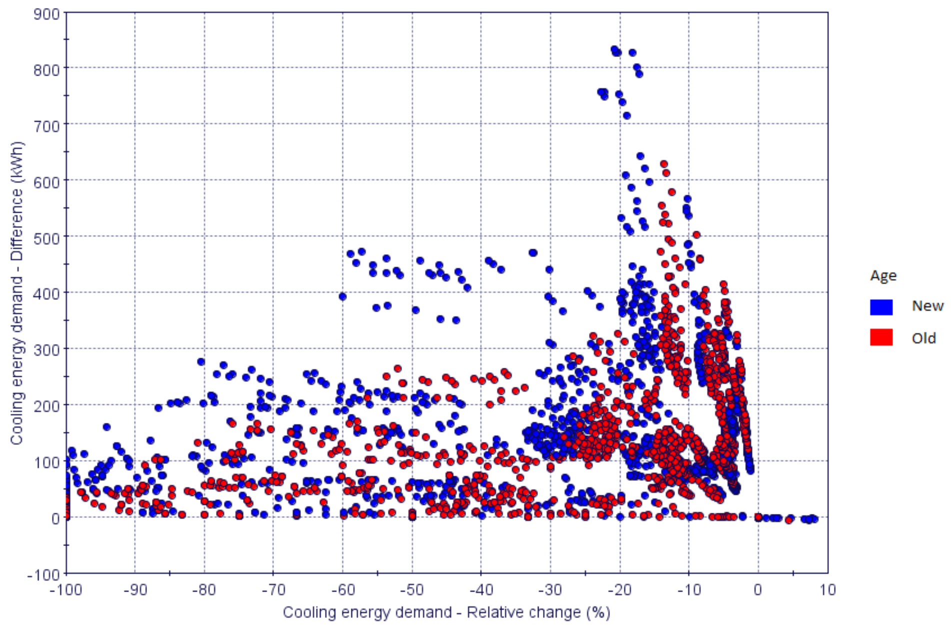


Figure 15.47: Relative change versus difference in heating energy demand with indication of building ages.

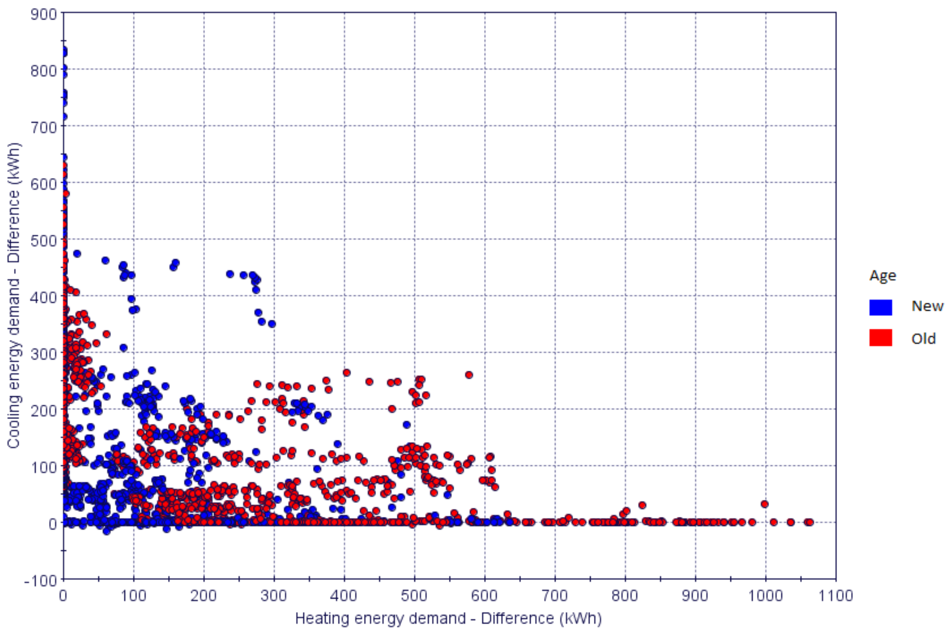


Figure 15.48: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of building ages.

From Figure 15.48 can be seen that no preference can be expressed regarding best option to benefit from the multi-seasonal operation capability of the LTATW, since both ages perform well. A LTATW in a new building, however, perform slightly better for cooling purposes and a LTATW in an old building slightly better for heating (which matches the findings above).

15.2.5. INFLUENCE OF BUILDING METHOD

Figure 15.49 shows that the influence of type of building method on the performance of the LTATW is low. Good performances are achieved in both light-weight buildings, medium-weight buildings and heavy-weight buildings. To find out which construction method is best for a specific situation, reference is made to the designer tables. In these tables, a slightly better performance is found for heavy-weight buildings (also confirmed by Figure 15.32 and 15.33).

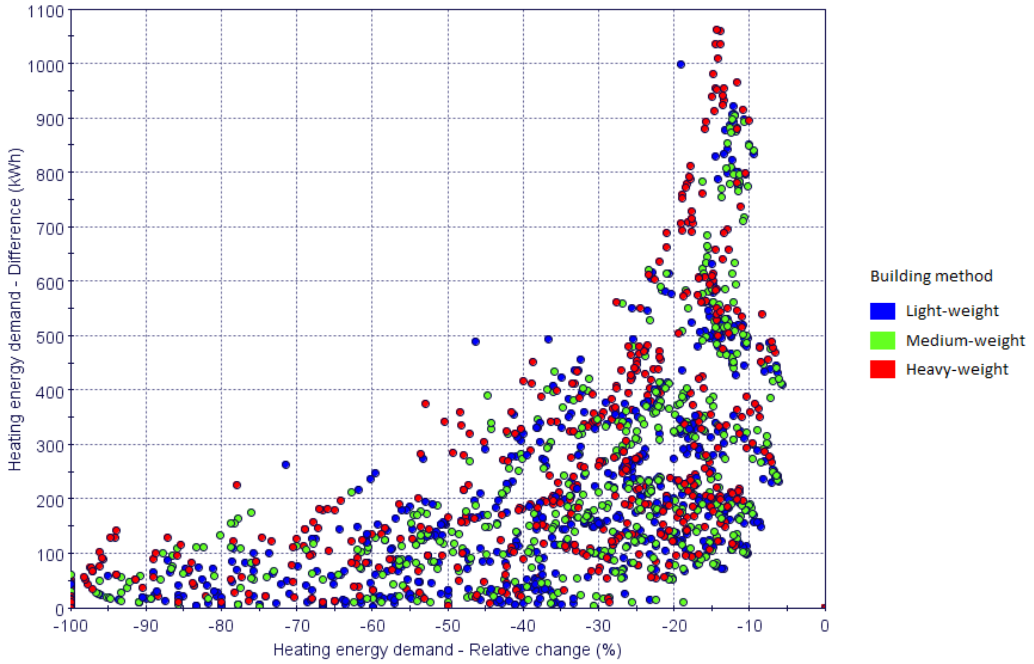


Figure 15.49: Relative change versus difference in heating energy demand with indication of building methods.

In case of cooling, the same, low correlation applies. Therefore, the designer tables should again be consulted per situation. Both absolute reductions in cooling and heating energy demand can be achieved in all building methods (Figure 15.51).

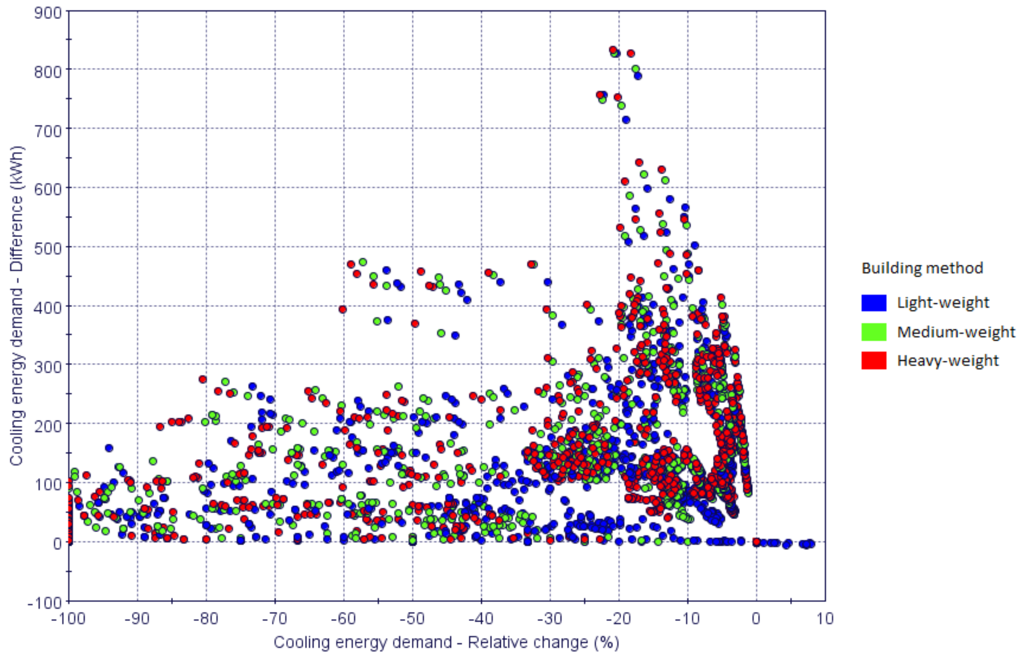


Figure 15.50: Relative change versus difference in cooling energy demand with indication of building methods

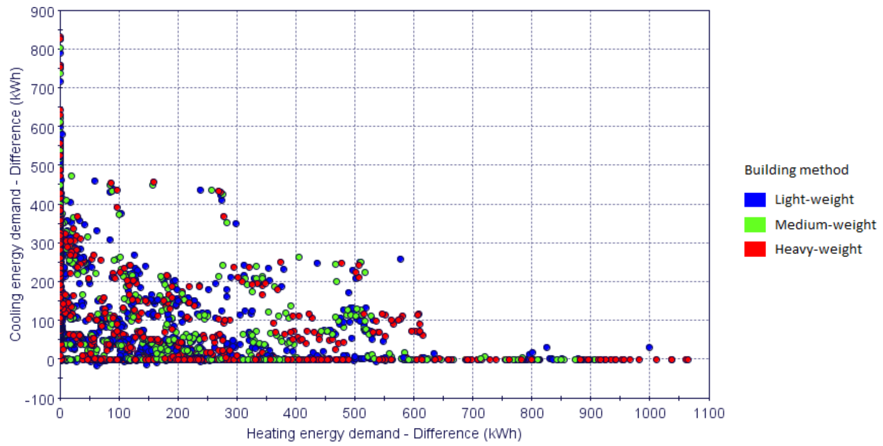


Figure 15.51: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of building methods.

15.2.6. INFLUENCE OF ROOM SIZE

Figure 15.52 shows a distribution which is quite similar to the distribution shown in Figure 15.46. Again, a clear difference in distribution can be seen, in which the data points of small rooms are concentrated more around the bottom left part of the figure, while data points of big rooms in are concentrated more to the right. With the division of the chart into the four areas A, B, C and D in mind, it can be concluded that the situations that are most suitable for reducing the heating energy demand of the room are situations with big rooms (data-points positioned more in both area A and B). This can be explained by the fact that the energy demand for heating of bigger rooms is much higher, due to the higher room volume, and more energy is available to reduce. In relative sense, however, it seems to be that the LTATW performs slightly better in smaller rooms.

Because the energy demand of a small room differs considerably from the energy demand of a big room, the normalized results are also analyzed for this variable. These normalized results represent the energy consumption per square meter and are shown in Figure 15.53. From Figure 15.53 it can be seen that the best performance of the LTATW is achieved in small rooms. In these rooms, it seems to be that the Trombe wall reduces the most energy per square meter. In bigger rooms, the wall according to Figure 15.52 also performs well, because the reduction in kWh is high, but it seems that the larger wall (because of a bigger room) is not used to its full potential. With this knowledge, it can be concluded that a Trombe wall can be installed in both small rooms and big rooms. Yet, when a room is too big, the capacity of the LTATW will no longer be sufficient and only a small part of the energy will be reduced.

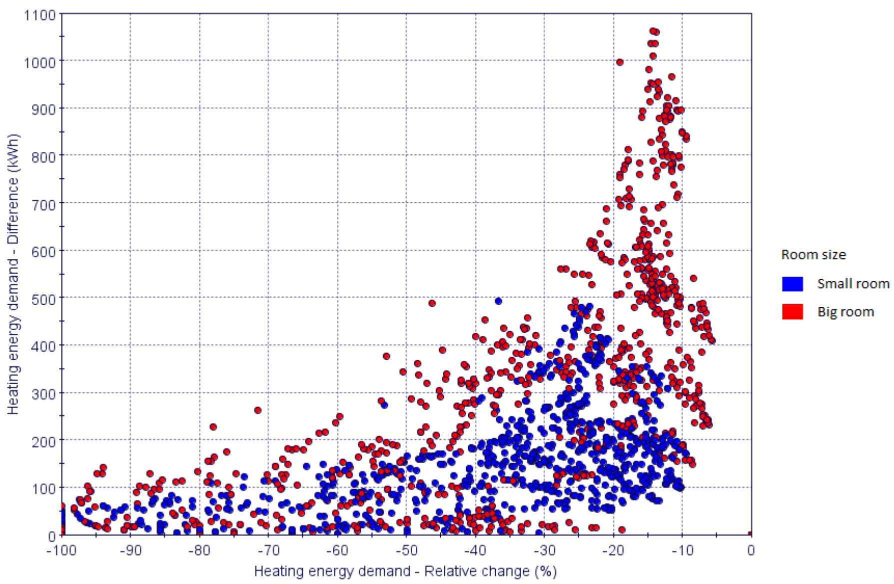


Figure 15.52: Relative change versus difference in heating energy demand with indication of room sizes.

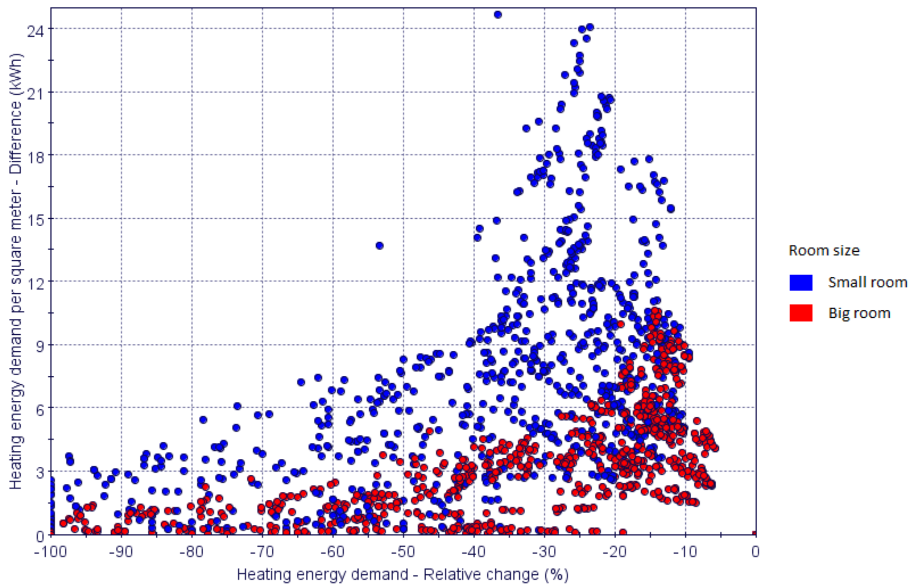


Figure 15.53: Relative change versus difference in heating energy demand with indication of room sizes (per square meter).

In the case of cooling, the same two charts were analyzed: the chart with the exact values (Figure 15.54) and the chart with the normalized values (Figure 15.55). From Figure 15.54, the same type of behavior can be noticed as was seen in Figure 15.52. In relative sense, the LTATW performs slightly better in smaller rooms, but higher reductions in absolute sense are achieved in bigger rooms. From Figure 15.55 it can be seen that the best cooling performance of the LTATW is achieved in small rooms. In these rooms, it also seems to be that the Trombe wall reduces the most energy per square meter. In bigger rooms, the wall according to Figure 15.54 also performs well, because the reduction in kWh is high, but it seems that the larger wall (because of a bigger room) is not used to its full potential. With this knowledge, it can be concluded that a Trombe wall can be installed in both small rooms and big rooms. Yet, when a room is too big, the capacity of the LTATW will no longer be sufficient and only a small part of the energy will be reduced. In order to know whether enough energy will be reduced to repay the system, the designer tables will have to be consulted.

As expected, Figure 15.56 shows that room size does not affect the multi-seasonal operation capability of the LTATW.

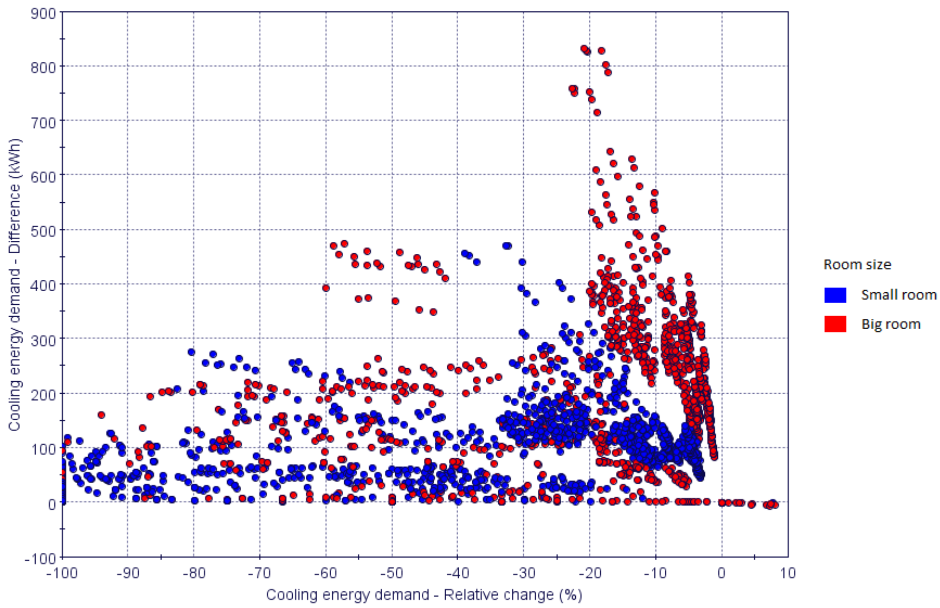


Figure 15.54: Relative change versus difference in cooling energy demand with indication of room sizes.

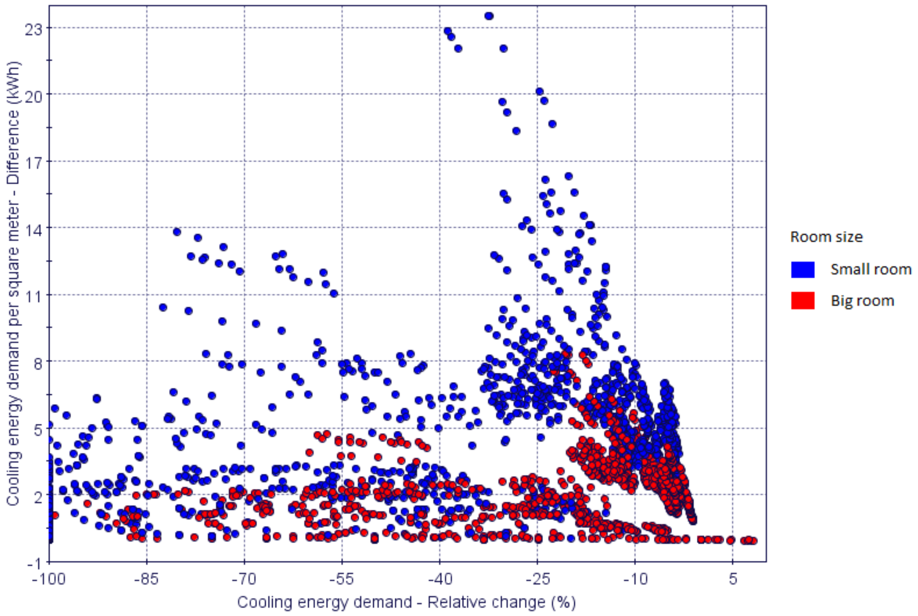


Figure 15.55: Relative change versus difference in cooling energy demand with indication of room sizes (per square meter).

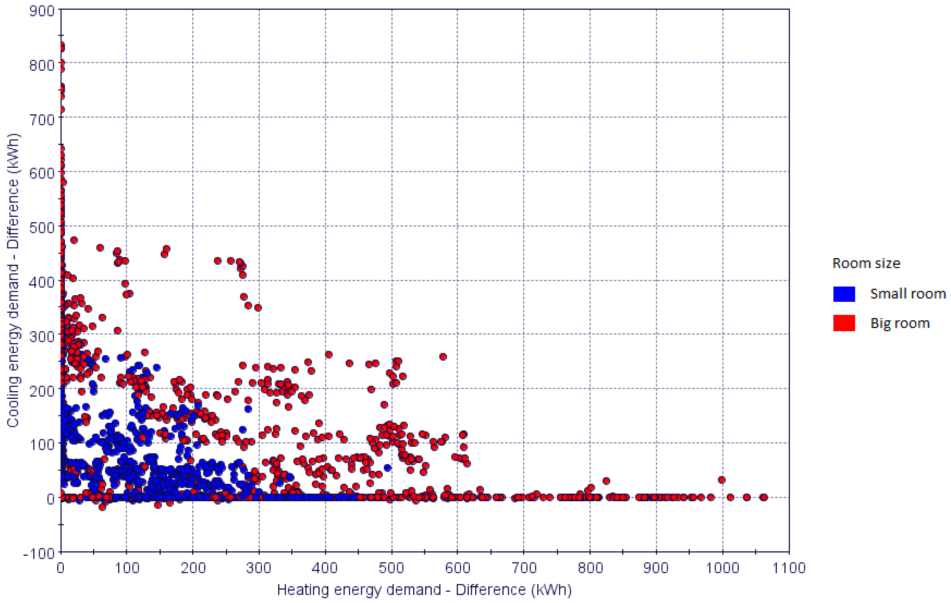


Figure 15.56: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of room sizes.

15.2.7. INFLUENCE OF WINDOW SIZE

Figure 15.57 shows a clear distribution between the reduction of the heating energy demand and the window size. Data-points of rooms with small windows are most positioned above the yellow line, while data points of rooms with large windows are most positioned below the yellow line. It can therefore be concluded that the Trombe wall can better be placed in a room with a smaller window, than in a room with a larger window, as it is apparently the case that the combination of an almost fully glazed façade (with more heat losses through the glazing) and a Trombe wall results in a poorer performance. To support this conclusion, the same chart has been created in which the two possible U-values of the four types of glazing are indicated (see Figure 15.58). It can indeed be deduced from this chart that a same, clear separation in the distribution exist for U-values of the glazing and that the U-value might indeed be the explanation why a Trombe wall performs better behind a smaller window. Apparently, a combination of a small window with double glazing gives the best results because the least transmission losses occur and at the same time, most of the solar energy is transmitted to enhance the working principle of the LTATW. As mentioned before, this study assumed that the size of the Trombe wall is the same as the size of the window. A small window therefore means a smaller Trombe wall, and therefore also, less storage materials/capacity. Figure 15.57, however, reveals that the size of the Trombe wall has no major influence on the performance and that even a smaller version provides enough 'capacity'.

From Figure 15.59, a clear difference in distribution can be seen as well. However, in this case, the Trombe wall performs slightly better behind a large window, as data points of rooms with small windows are located more near the right bottom corner. This could be explained by the fact that rooms with large windows have a larger Trombe wall and experience higher solar loads, so more cooling energy can be reduced. As expected, Figure 15.60 shows that the size of the window does not significantly affect the multi-seasonal operation capability of the LTATW. Smaller windows are preferred for heating purposes and larger windows are preferred for cooling purposes.

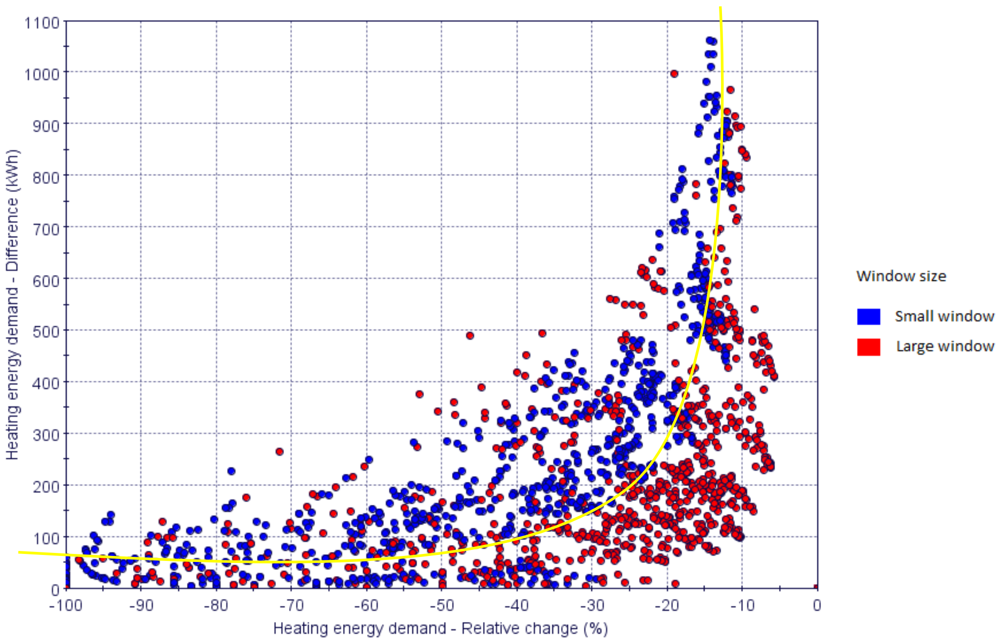


Figure 15.57: Relative change versus difference in heating energy demand with indication of window sizes.

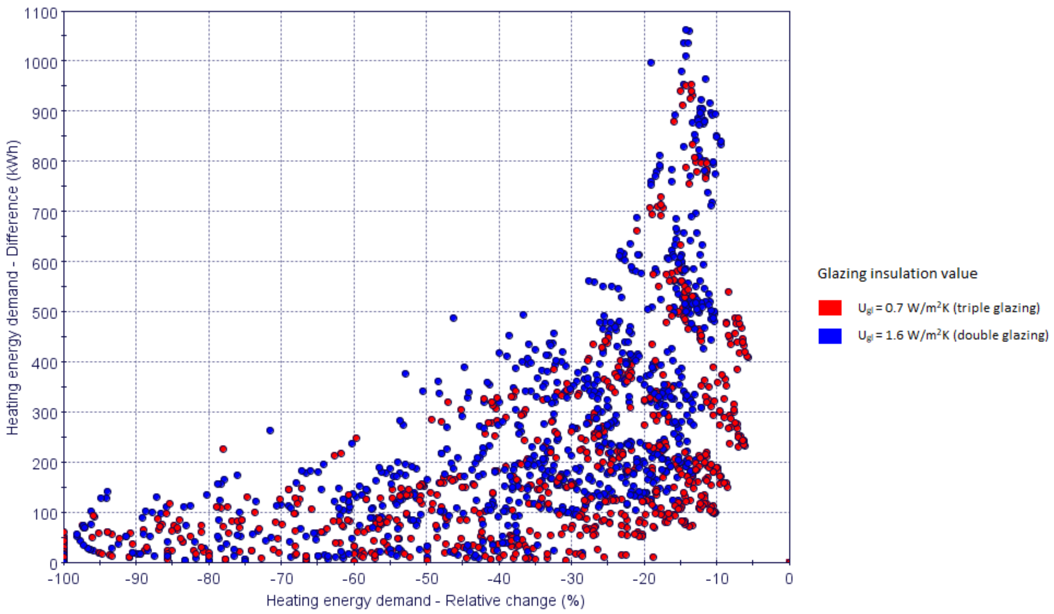


Figure 15.58: Relative change versus difference in heating energy demand with indication of the two possible U-values of all four glazing types.

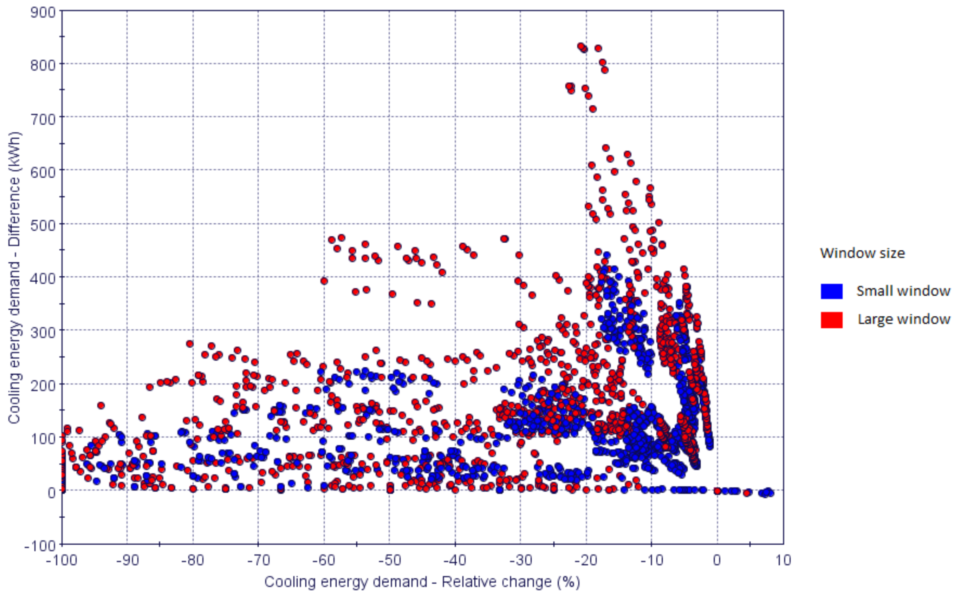


Figure 15.59: Relative change versus difference in cooling energy demand with indication of window sizes.

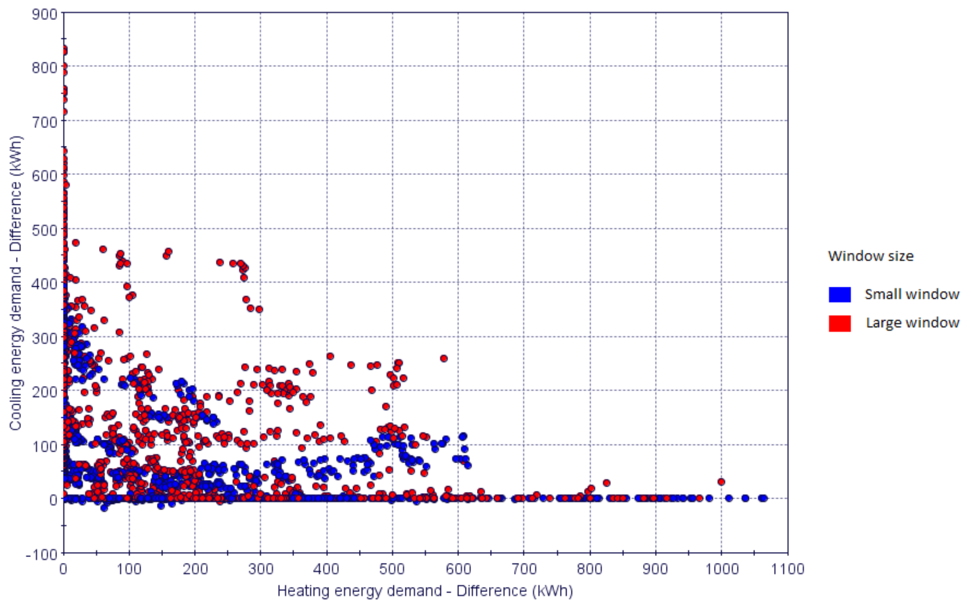


Figure 15.60: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of window sizes.

15.2.8. INFLUENCE OF TYPE OF GLAZING

The last parameter that has been analyzed is the type of glazing. From Figure 15.61 it can be seen that the correlation between heating energy reduction and type of glazing is not that high and just as in case of orientation, good performances can be achieved with all four types of glazing. However, these good performances are not due to the position and adaptability capacity of the Trombe wall, but are the result of the energy storage capacity of the wall, which is utilized anyway. In order to be a better building application with PCM than for example, ordinary technologies like a PCM/concrete wall, the type of glazing is certainly of importance. Just as in case of the charts with varying orientation, when the chart with varying glazing types (and also the designer tables in chapter 17) are studied more locally, it can be seen that per situation, certain types of glazing result in a better performance than other types of glazing.

When studying Figure 15.61, it can be seen that rooms with triple coated glazing are more often concentrated near the origin of the chart. This suggests that with this type of glazing, an often lower reduction in absolute sense and relative sense is experienced. For the other types of glazing, it is more difficult to form a substantiated conclusion. Therefore, reference is made to the designer tables in chapter 17. From these tables, it becomes clear that in most of the situations, a better performance in relative sense is achieved with a clear type of glazing (both double and triple). However, more energy is often reduced in absolute sense with the coated types of glazing. This can be explained by the fact that with a coated type of glazing, the heating energy demand is higher, and so, the Trombe wall reduces more energy in total. It is made clear here that a clear type of glazing, as expected, results in the best performance (because the LTATW can now absorb more energy from the sun), but it must be checked with the aid of the designer tables, whether the reduction in absolute sense will still be above average.

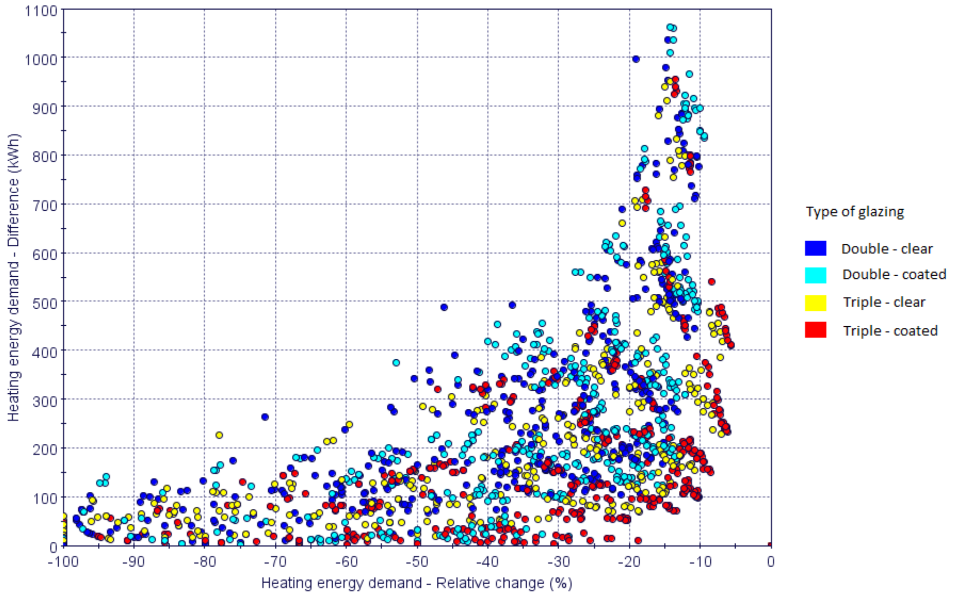


Figure 15.61: Relative change versus difference in heating energy demand with indication of glazing types.

In case of cooling (Figure 15.62), a same kind of distribution can be noticed. In this case, however, it is more clear that the uncoated types of glazing (both double and triple) result in the highest reduction of the cooling energy demand. Double coated glazing performs just a bit better than triple coated glazing, but their reductions are lower compared to the uncoated glazing types. Because the results differ greatly depending on the situation though, it is better to consult the designer tables again.

Finally, Figure 15.63 shows that type of glazing does not significantly affect the multi-seasonal operation capability of the LTATW. With double clear glazing however, the highest reductions are achieved.

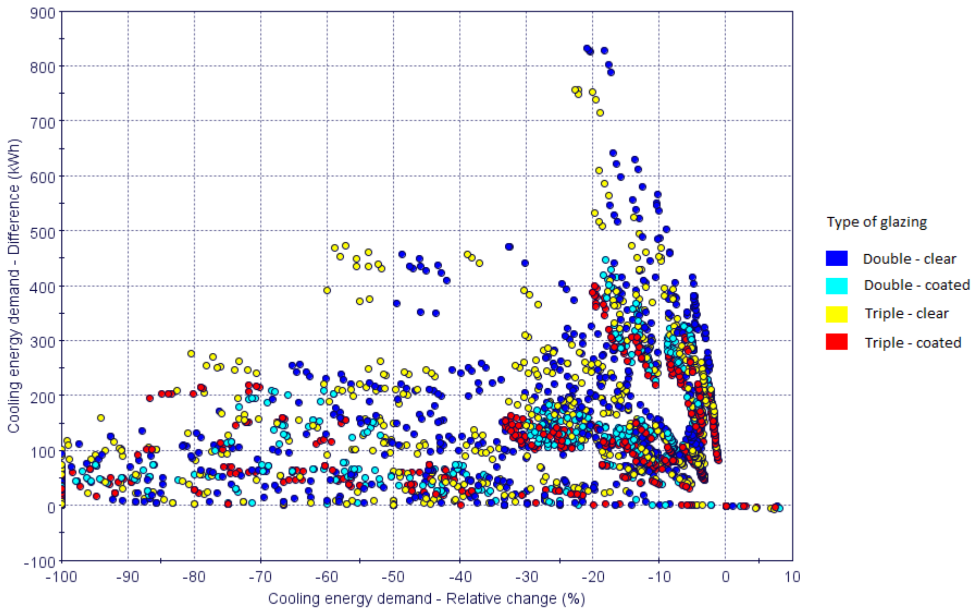


Figure 15.62: Relative change versus difference in cooling energy demand with indication of glazing types.

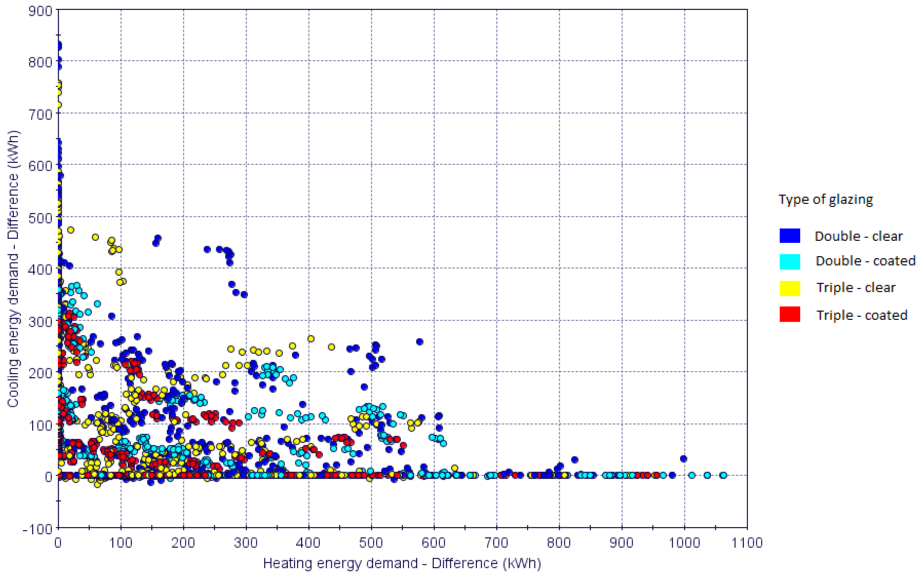


Figure 15.63: Absolute change in cooling energy demand versus absolute change in heating energy demand, with indication of glazing types.

15.3. SENSITIVITY ANALYSIS

In this study, eight parameters were treated as variables and a many other parameters were assumed to be constants. The values of these constant parameters were determined based on customary, most common or most relevant values (the starting points and assumptions can be found in Table 14.5). In this section, the influence of changing these parameters is studied. The study in the section is also called the sensitivity analysis, as it is studied how representative the results of the simulations are when other values of these constant parameters are chosen. Are the findings from this study also valid for other starting assumptions, and if not, how sensitive are the results for a change in these assumptions?

In this sensitivity study, four constant parameters were analysed: the heating thermostat set-point, the cooling thermostat-setpoint, shading and the type of PCM. The first three parameters have been chosen because they can easily be influenced by people. In offices, for example, it can be assumed that the heating thermostat set-point is held fairly constant throughout the year, but in residences it is more common that people change this value now and then. The same applies to the cooling thermostat set-point. Besides thermostat set-points, shading is also a parameter that can often be influenced by users themselves. Some people prefer much incoming sunlight, but other people prefer to shield themselves from the sun as much as possible. A parameter that will not be influenced by users, but was interesting to study, is the type of phase change material. In the Double Face 1.0 project a particular type of PCM was chosen and this sensitivity analysis will show whether a good choice was made.

For each of the four studied parameters, four room configurations were analysed for a heating energy demand case, and four room configurations were analysed for a cooling energy demand case: one room configuration with both a high percentage reduction and a high absolute reduction (in area A), one room configuration with mainly a high absolute reduction (in area B), one room configuration with only a high percentage reduction (in area C) and one room configuration with both a low percentage and absolute reduction (area D). The four configurations regarding heating energy demand are highlighted in Figure 15.64 and the four configurations regarding cooling energy demand are highlighted in Figure 15.65.

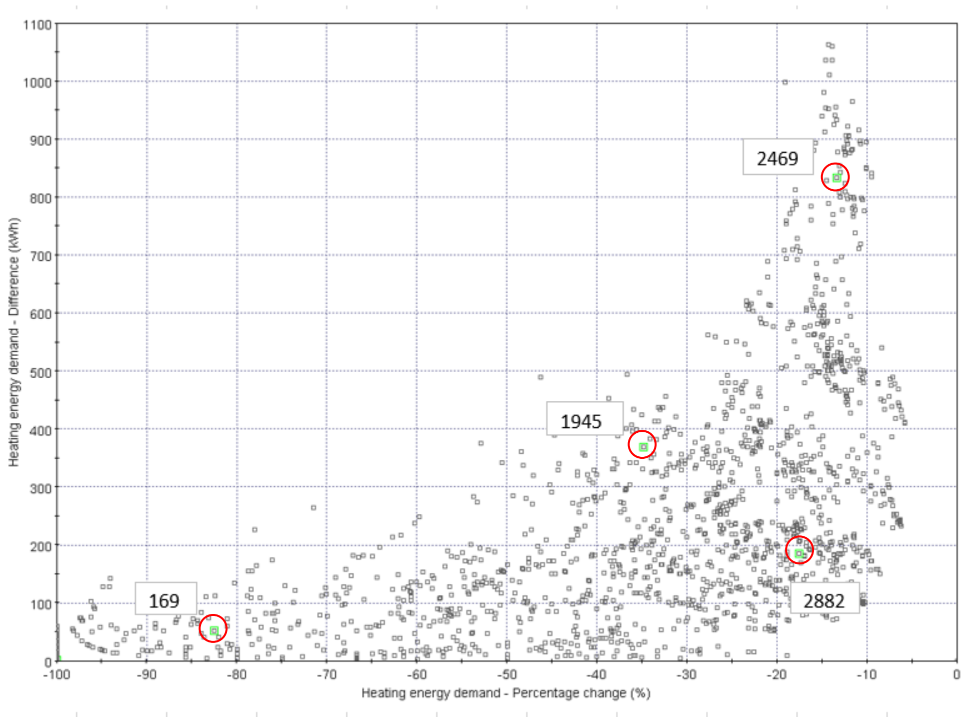


Figure 15.64: Analyzed room configurations and their configuration number (heating energy demand).

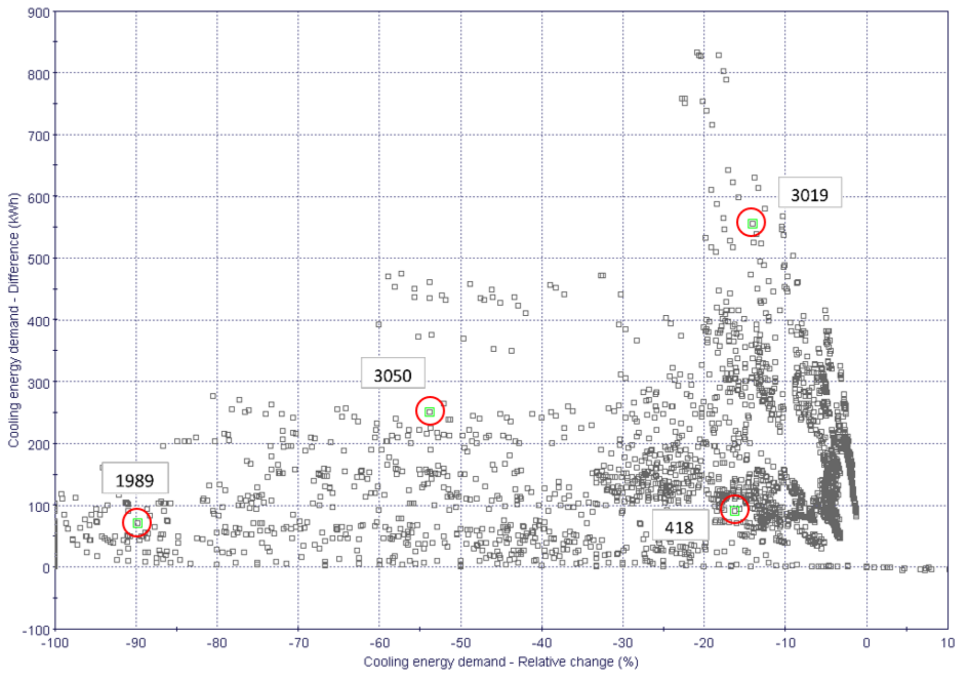


Figure 15.65: Analyzed room configurations and their configuration number (cooling energy demand).

15.3.1. HEATING THERMOSTAT SET-POINT

The influence of the heating thermostat set-point on the absolute reduction of the heating energy demand of all four rooms is shown in Figure 15.66. It can be seen that a lower set-point temperature results in a lower reduction of the heating energy demand, and can be explained by the fact that a lower set-point temperature results in a reduction of the initial energy demand. From Figure 15.23 can then be seen that a lower initial energy demand results in a lower reduction by the LTATW. What can also be seen is that the ratio between the points remains fairly the same, so that the findings from the main study (influence of parameters) of this thesis also apply to rooms with a slightly lower heating set-point temperature. However, something striking is what happens when the heating set-point temperature is increased. Up to 22 °C the same trend still applies, but when the set-point temperature is set at 23 °C, a sudden maximum appears. The same applies to a set-point temperature of 26 °C. This of course has everything to do with the melting and solidification temperature of the PCM. In part II (literature review) was revealed that the best storage performance of a PCM is achieved when the melting temperature of the PCM was set just above the heating set-point temperature.

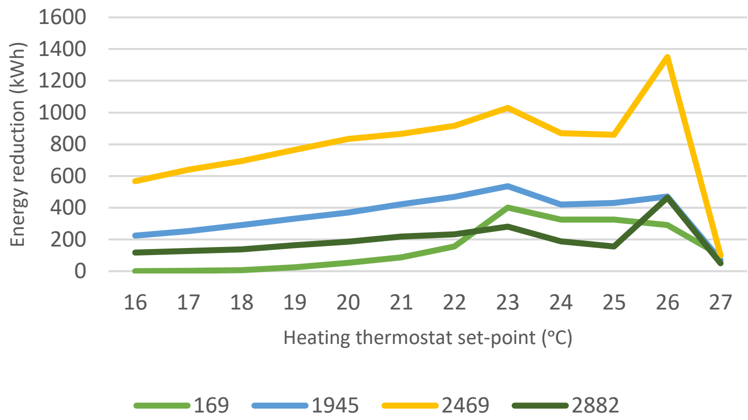


Figure 15.66: Effect of heating thermostat set-point temperature on reduction of heating energy demand by the LTATW.

Figure 15.67 shows the results of relative change and absolute change in heating energy demand for all four rooms, with indication of the path that is followed when a different set-point is chosen. The data points with the default thermostat set-point (20 °C) are highlighted with a small circle. From the graph it can be seen that a higher thermostat set-point results in a higher absolute energy reduction and that multiple maximums exist.

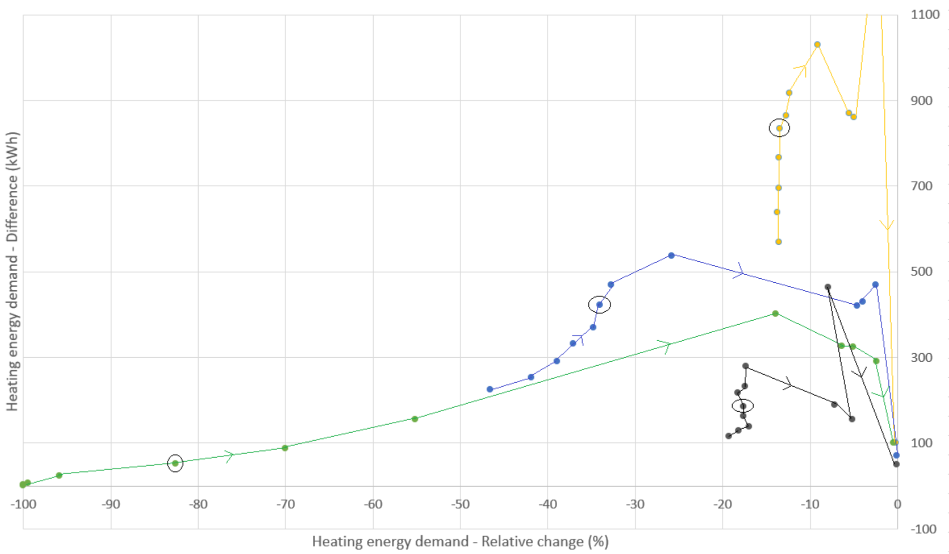


Figure 15.67: Effect of changing the heating thermostat set-point temperature from 16 °C to 27 °C and path of the four data points.

When the set-point temperature is increased too much (higher than 26 °C), the reduction drops to almost zero. As a lot of temperatures have been studied here, the sensitivity seems reasonably large. However, it must be noted that if people change the set-point temperature, this is often only by a few degrees. Therefore, the sensitivity is in fact moderate.

15.3.2. COOLING THERMOSTAT SET-POINT

The influence of the cooling thermostat set-point on the absolute reduction of the cooling energy demand of all four rooms is shown in Figure 15.68. It can be seen that a lower set-point temperature results in a higher reduction of the cooling energy demand, and can be explained by the fact that a lower set-point temperature results in an increase of the initial energy demand. From Figure 15.27 can then be seen that a higher initial energy demand generally results in a higher reduction by the LTATW. The ratio between the results of the rooms is fairly the same, except of room 418. It is again striking that a minimum appears at a thermostat set-point of 23 °C. This can be explained by the fact that when the temperature in the room never exceeds 23 °C, the LTATW becomes useless.

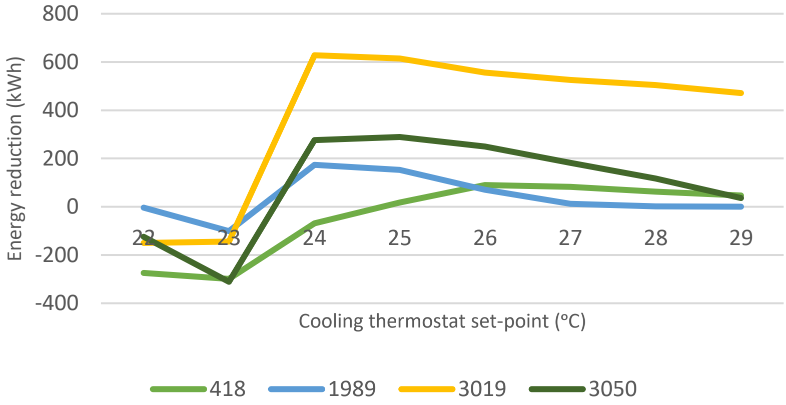


Figure 15.68: Effect of cooling thermostat set-point temperature on reduction of cooling energy demand by the LTATW.

Figure 15.69 shows the results of relative change and absolute change in cooling energy demand for all four rooms, with indication of the path that is followed when a different cooling set-point is chosen. The data points with the default thermostat set-point (26 °C) are highlighted with a small circle. From the graph can be seen that a higher thermostat set-point results in a lower absolute energy reduction and that a maximum exist at 23 °C, which is always located around lower reductions.

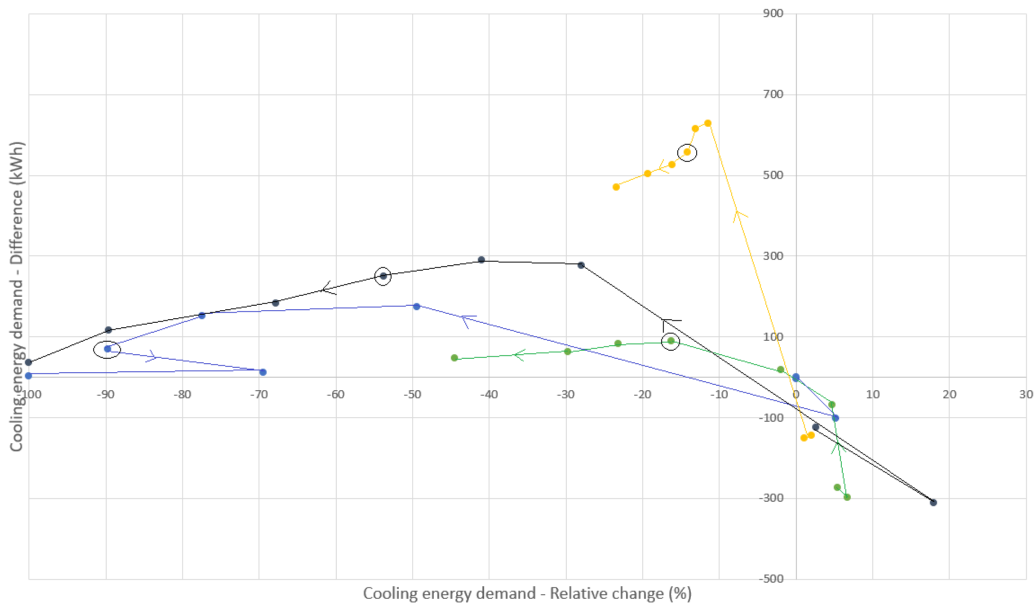


Figure 15.69: Effect of changing the cooling thermostat set-point temperature from 22 °C to 29 °C and path of the four data points.

In contrast to the results from the sensitivity analysis of the heating set-point, the sensitivity seems to be somewhat higher in case of cooling set-point temperature.

15.3.3. SHADING

In all room models, the shading device is activated by default when the sun is shining (with a solar radiative power higher than 100 W) and when the operative temperature of the room exceeds 24 °C. In this sensitivity analysis, it is studied what the influence of the results is, when the preferences of occupants regarding shading are different. Or, in other words: how sensitive are the results when shading is already activated by users at a lower operative room temperature? Or even at a higher temperature than 24 °C?

The influence of the minimum 'shading temperature' on the absolute reduction of the cooling energy demand of all four rooms is shown in Figure 15.70. From the figure can directly be seen that the influence is minimal. Only when the shading device is used after 26 °C, the energy reduction decreases slightly for rooms 3019 and 3050.

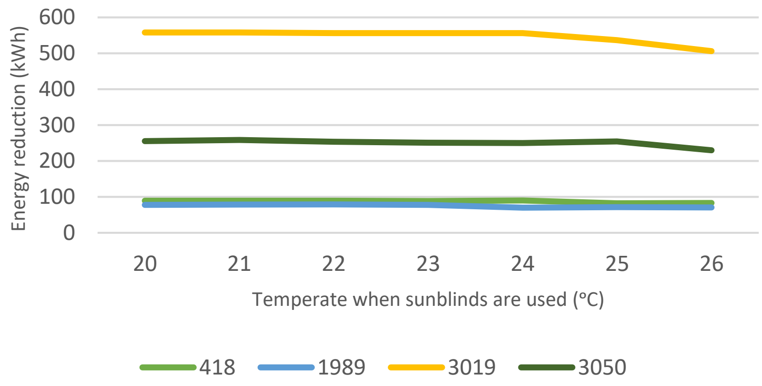


Figure 15.70: Effect of 'minimal shading temperature' on reduction of cooling energy demand by the LTATW.

Figure 15.71 shows the results of relative change and absolute change in cooling energy demand for all four rooms, with indication of the path that is followed when a different shading schedule is chosen. The data points with the default minimal temperature (24 °C) are highlighted with a small circle. From the graph can be seen that when the sun blinds are used at a higher temperature, lower reduction of cooling energy are achieved, as all paths move to the origin. However, the sensitivity is very low. Therefore, it can be concluded that whatever the shading schedule is, the results of the main study of this thesis are still valid.

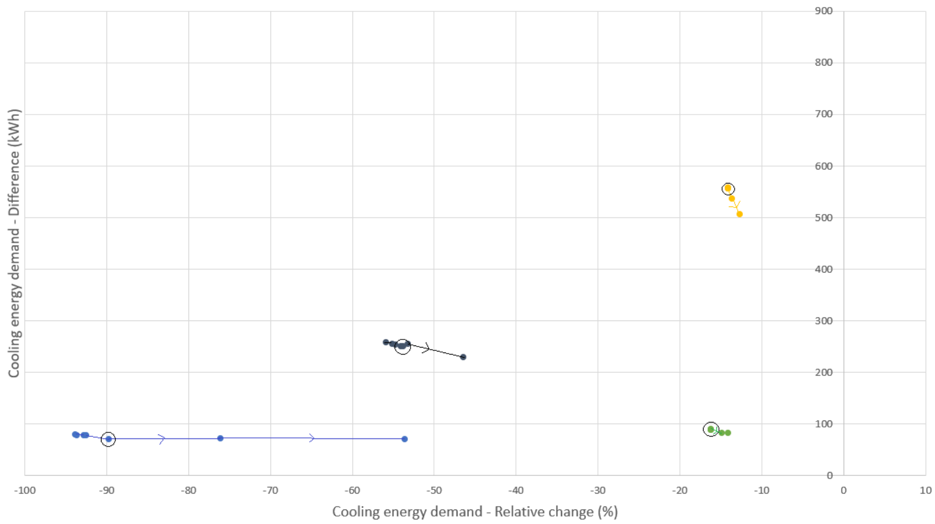


Figure 15.71: Effect of 'minimal shading temperature' and path of the four data points.

15.3.4. TYPE OF PCM

Finally, the influence of type of PCM on the validity of the results was investigated. Because this parameter affects both the heating and the cooling demand, both cases are analyzed.

15.3.4.1. HEATING

The influence of the type of PCM on the absolute reduction of the heating energy demand of all four rooms is shown in Figure 15.72. From the figure, a fairly constant behaviour can be seen, with an optimum for the PCM product SP24E (room 169, 1945 and 2882) and SP25E2 (room 2469). The presence of the maxima is as expected: a PCM used for heating purposes performs at its best when the solidification temperature is just above heating thermostat set-point temperature and the solidification temperature of SP24E is at 22 °C. These results give the suspicion that a 'lower' PCM should have been chosen, but it should be noted that the LTATW is also used for cooling purposes and that therefore, a melting temperature just below the cooling set-point temperature is required. Furthermore, the influence of direct solar radiation causes a PCM type to be chosen that has an even higher transition temperature (demonstrated by room 2469).

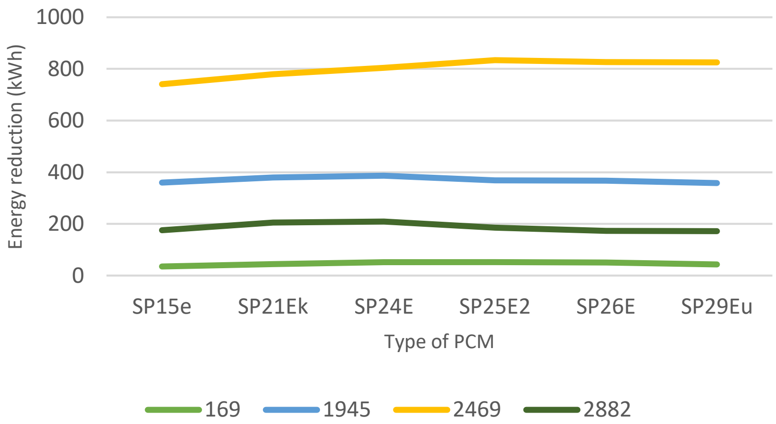


Figure 15.72: Effect of PCM type on reduction of heating energy demand by the LTATW.

Figure 15.73 shows the results of relative change and absolute change in heating energy demand for all four rooms, with indication of the path that is followed when a different type of PCM is chosen. The data points with the default PCM type are highlighted with a small circle. From the graph can be seen that the path is limited and an optimum occurs at a certain spot on the path. It can also be seen that the sensitivity is relatively low.

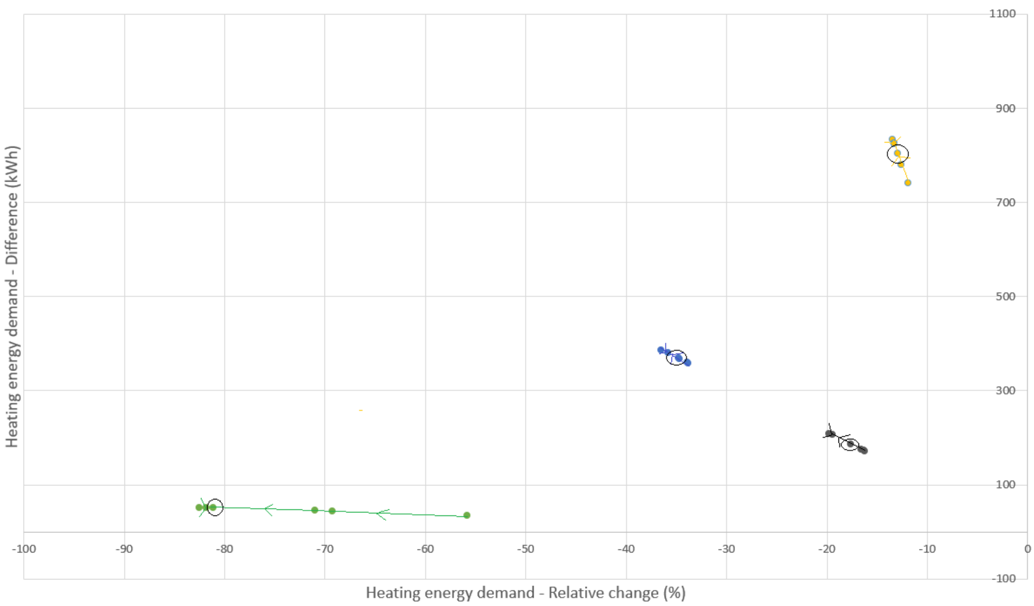


Figure 15.73: Effect of PCM type and path of the four data points.

It has thus been proven above that an optimum reduction exist with a PCM with a transition temperature just above the heating thermostat set-point temperature. What is against the expectations, however, is that even with PCM's with a transition temperature lower and much higher than the heating set-point, the results are still good. A less horizontal trend of the lines was expected here in advance. It therefore seems that the system also functions well without the presence of latent heat storage materials. To investigate whether this is true, three new simulations were done for each of the four room configurations: a simulation including a Trombe wall without latent energy (PCM is seen as a sensible heat storage material), a simulation including a Trombe wall in which the PCM is replaced by water and a simulation in which the Trombe wall has no thickness (and is just modelled as a flat vertical plane). The results are shown in Table 15.2.

Table 15.2: Reduction of heating energy demand with different Trombe wall layer characteristics.

	Reduction of heating energy demand (kWh)			
	169	**1945**	**2469**	**2882**
PCM layer = SP25E2 (h_{sf} = 1.8e10^5 J/kg)	52	369	834	186
PCM layer = SP25E2 (h_{sf} = 0 J/kg)	35	355	738	164
PCM layer = Water[7]	40	356	746	169
No thickness of PCM layer and insulation layer	32	307	733	121

It can indeed be seen from Table 15.2 that the installation of the Trombe wall system also results in substantial energy savings without integration of a latent storage material. Nevertheless, it can be seen that when a material with latent storage capacity (PCM) is chosen, an even higher reduction will take place. If only the results of the above four room configurations are considered, it can be calculated that of the total reduction, on average 15% is achieved by the latent heat storage principle of the PCM and 85% by the Trombe wall construction itself. Replacing the PCM layer with (the much cheaper material) water or only applying a flat plate without thickness will also lead to substantial reductions in energy demand, according to this numerical study.

15.3.4.2. COOLING

The influence of the type of PCM on the absolute reduction of the cooling energy demand of all four rooms is shown in Figure 15.74. From the figure, a fairly constant behaviour can be seen, with an optimum for the PCM product SP26E. The presence of the maxima is reasonably as expected: a PCM used for cooling purposes performs at its best when the melting temperature is just below cooling thermostat set-point temperature and the melting temperature of SP26E is at 26 °C. Therefore, the PCM type looks a bit too 'high'. However, it can be concluded that the choice for SP25E2 is the right choice, as it represents the average of the ideal temperatures found for heating and cooling.

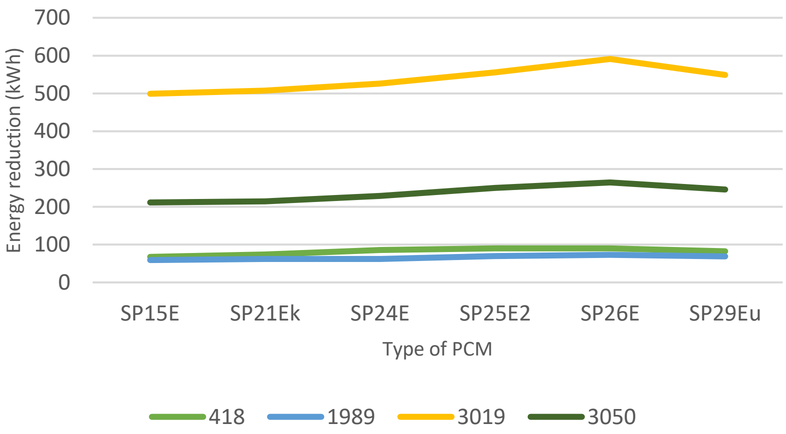


Figure 15.74: Effect of PCM type on reduction of cooling energy demand by the LTATW.

[7] Material characteristics of water: C_p = 4200 J/kgK; ρ = 1000 kg/m^3; λ = 0.6 W/mK; h_{sf} = 0 J/kg

Figure 15.75 shows the results of relative change and absolute change in cooling energy demand for all four rooms, with indication of the path that is followed when a different type of PCM is chosen. The data points with the default PCM type are highlighted with a small circle. From the graph can be seen that again, the path is limited and an optimum occurs at a certain spot on the path. Again, the sensitivity is relatively low.

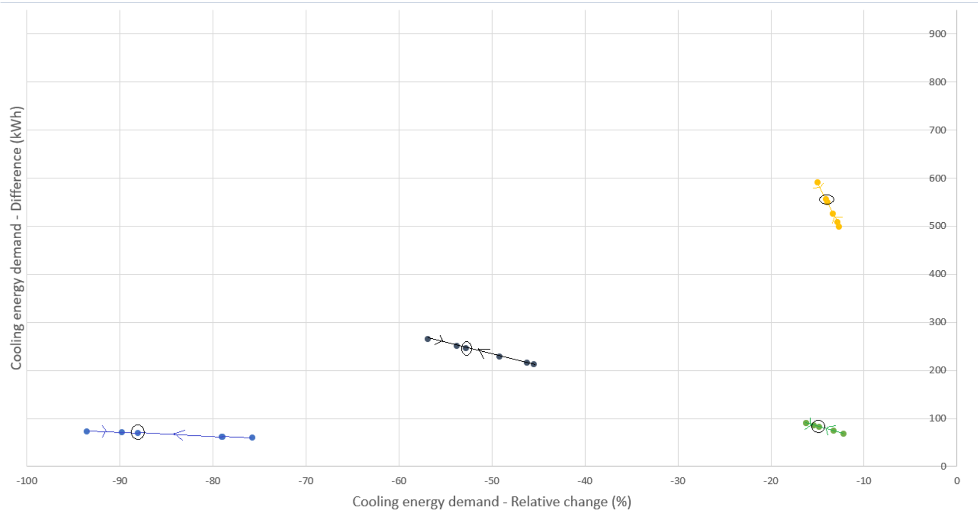


Figure 15.75: Effect of PCM type and path of the four data points.

Because also in case of cooling, a less horizontal trend of the lines in Figure 15.74 was expected, three new simulations were done for each of the four room configurations as well. The results are shown in Table 15.3.

Table 15.3: Reduction of cooling energy demand with different Trombe wall layer characteristics.

	Reduction of cooling energy demand (kWh)			
	418	**1989**	**3019**	**3050**
PCM layer = SP25E2 (h_{sf} = 1.8e10^5 J/kg)	90	70	556	250
PCM layer = SP25E2 (h_{sf} = 0 J/kg)	68	59	504	213
PCM layer = Water	78	61	554	223
No thickness of PCM layer and insulation layer	66	61	435	196

From Table 15.3 it can also be seen that the installation of the Trombe wall system results in substantial energy savings even without integration of a latent storage material. Nevertheless, it can be seen that when a material with latent storage capacity (PCM) is chosen, the highest reduction will take place. If only the results of the above four room configurations are considered, it can be calculated that of the total reduction, on average 16% is achieved by the latent heat storage principle of the PCM and 84% by the Trombe wall construction itself. Replacing the PCM layer with (the much cheaper material) water or only applying a flat plate without thickness will also lead to substantial reductions in energy demand.

16. ARTIFICIAL LIGHTING

In this Master thesis study, the main goal was to predict the thermal energy savings that result from installing an innovative Trombe wall in a room. A type of energy demand that is not explicitly included in the main study is the (electrical) energy demand for artificial lighting. Nevertheless, given the purpose of this study (providing recommendations to designers based on the energy savings), it is important to study these as well. It is often the case that the innovative Trombe wall comes with significant thermal energy savings, but by blocking the incoming sunlight, the electrical energy demand for artificial lighting is obviously higher. As a result, some favorable situations are therefore not as favorable as they may seem in advance. This chapter shows the results of this particular study, focused only on the energy consumption for artificial lighting. In section 16.1 the simulation models with their specific configuration, materials and dimensions are explained. In section 16.2 the lighting schedules are described and in section 16.3 the type of artificial lighting used and their corresponding lighting control mechanism is explained. The chapter ends with sections 16.4 and 16.5, in which the results of the simulations are shown and the conclusions are described.

16.1. SIMULATION MODELS

The energy demand for artificial lighting is calculated using DesignBuilder, in which 256 different situations have been modelled. In comparison with the main study of this Master thesis project, the amount of situations investigated is much less. In the main study, eight different aspects are examined: building function, age, building method, room size, window size, type of glazing, orientation and climate. The combinations of all these parameters with their corresponding subdivisions result in a total of 3072 possible situations. The parameters that have an influence on the energy demand for artificial lighting are: building function, room size, window size, type of glazing, orientation and climate. Because the parameters age and building method have no influence, and when it is assumed that the difference in light transmission through double glazing and triple glazing is negligible (so two types of glazing are studied instead of four), 256 situations remain.

For every single situation, two models have been made: one without LTATW and one with LTATW. The differences between both models can be seen in Figure 16.1 and Figure 16.2 (a large window is shown in the example).

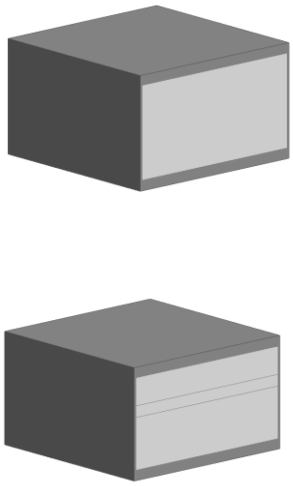


Figure 16.1: Small room with and without LTATW.

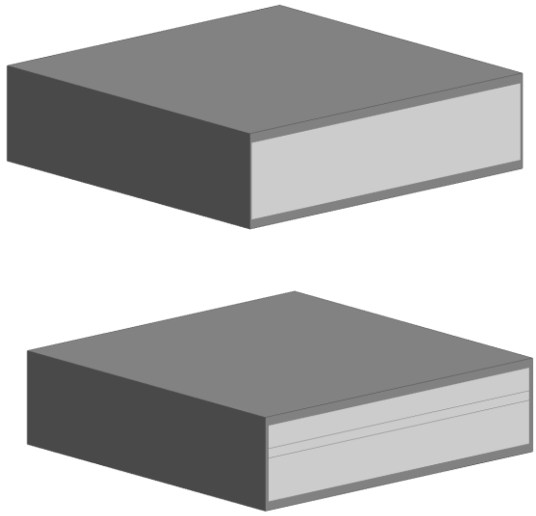


Figure 16.2: Big room with and without LTATW.

Both models represent the same rectangular space, consisting of four walls, a roof and a floor. The only difference between the two models is the layout of the glazing: in the model without LTATW, the glass has the same properties over the entire surface. In the model with LTATW, the glazed surface consists of three layers, in which the middle layer represents the concentration of openings in the Trombe wall. This layout is a simplification of reality, but it does approach the final design of the LTATW, where the openings are no longer homogeneously distributed over the surface, but are concentrated around eye level. The total surface area of the middle layer is equal to 10% of the total glazed area. The walls, roof and floor of the room all have a reflection factor of 0.

As mentioned above, two types of glazing have been investigated: clear and coated. The clear glazing has a light transmittance of 80% and the coated glazing has a light transmittance of 20%[8]. The two different phases of the PCM (solid and liquid) are also taken into account. A PCM in solid state transmits less daylight compared to a PCM in liquid state. The LT-value of a solid piece of PCM is equal to 0.2% and the LT-value of a liquid piece of PCM equals 24.2% (Wattez, 2018). Eventually, the net light transmission into the room is equal to the product of the LT-value of the glazing and the LT-value of the innovative Trombe wall. An overview of all possible glazing layer characteristics is given in Table 16.1.

In DesignBuilder, the minimum allowed value of the light transmission through a glazed surface equals 0.01. As a consequence, in the cases with the presence of a LTATW in solid state in combination with a layer of clear or coated glazing in front, a configuration shown in Figure 16.3 is used. In this model, the low light transmittance through the top and bottom layer is neglected, and only one layer is modelled.

Table 16.1: LT-values of all layers in DesignBuilder model

	LT - Clear	**LT - Coated**
No Panel:	0.8	0.2
With LTATW – Liquid state:		
Layer representing openings (middle layer)	0.8	0.2
Layer representing LTATW (top and bottom layer)	0.1936	0.0484
With LTATW – Solid state:		
Layer representing openings (middle layer)	0.8	0.2
Layer representing LTATW (top and bottom layer)	0.0016	0.0004

[8] Values for light transmittance obtained from: https://kennisbank.isso.nl

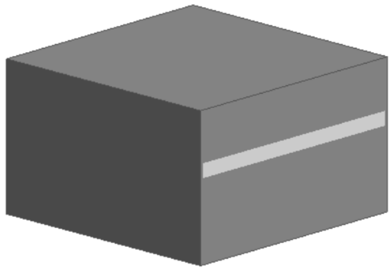


Figure 16.3: Small room of a residence with the LTATW in solid state.

16.2. LIGHTING SCHEDULES

This study assumes that the PCM-containers in the PCM wall are in complete fluid state in the office cases. In these cases, the occupation times are from 08:00 – 18:00 (Monday to Friday), so during the day. During this period, it is assumed that the sun shines uninterrupted. In case of a residence, it is assumed that the LTATW is completely solid within the lighting schedule of week days and partly liquid or solid during the weekend. For the residences, a lighting schedule of 07:00 – 08:00 and 18:00 – 23:00 (Monday to Friday) is used. On Saturday and Sunday, the occupation time is assumed to be from 09:00 – 00:00. Within the latter, the PCM is assumed to be in liquid state from 09:00 – 18:00 and in solid state from 18:00 – 00:00 (see Table 16.2). In DesignBuilder, an on-off simulation including different phases of PCM over time is not possible. Therefore, in case of the residences, two different simulations had to be run (one with using a liquid PCM and one with using a solid PCM) and the results were added together. Within the occupation time of the office rooms, no phase transition of the PCM occurs, and a single simulation was enough.

Table 16.2: Lighting schedule of offices and residences and associated state of PCM.

	Lighting schedule	State of PCM
Offices		
Monday – Friday	08:00 – 18:00	liquid
Saturday, Sunday	-	-
Residences		
Monday – Friday	07:00 – 08:00	solid
	18:00 – 23:00	solid
Saturday, Sunday	09:00 – 18:00	liquid
	18:00 – 00:00	solid

16.3. LUMINAIRE TYPE AND LIGHTING CONTROL

In DesignBuilder, calculations have been done assuming a suspended luminaire type (see Figure 16.4), with a normalised power density of 2.0 W/m^2 per 100 lux. The lighting control mechanism includes a target illuminance[9] of 500 lux (at 0.80 m height) for offices and a target illuminance of 200 lux for residences.

The electric lights are controlled according to the availability of natural daylight. In DesignBuilder, a simulation is done where the illuminance levels are calculated at each time step. After this, it is determined how much the artificial lighting can be reduced. The illuminance level resulting from the incoming sunlight depends on many factors, including sun position, sensor positions, location, glass transmittance of windows, room size, shading and reflectance of interior surfaces. In DesignBuilder, the reduction of the electrical energy can be calculated in several ways. In this study, a linear control type is used (Figure 16.5). With linear control, the luminaires dim and light up in a continuously and linearly way from maximum light output to minimum light output, and vice versa (DesignBuilder, 2018).

[9] Target illuminance values obtained from: NEN-EN 12464-1 (2011) and BIM (2010).

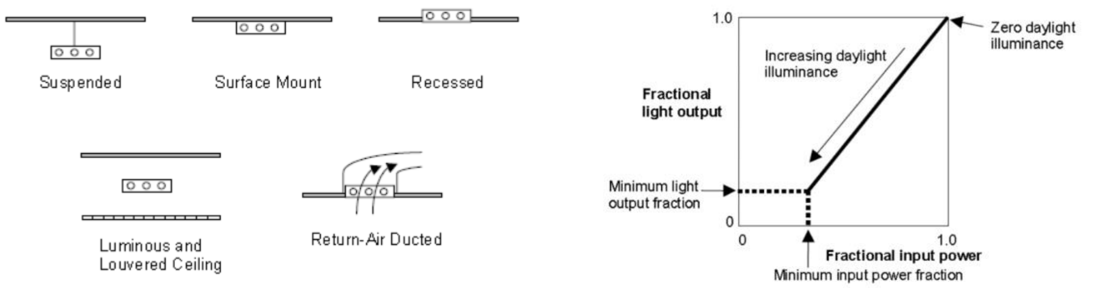


Figure 16.4 and 16.5: Luminaire types (left) and linear lighting control (right) (DesignBuilder, 2018).

16.4. SIMULATION RESULTS

Just like the models in the main study, all 256 situations have been simulated over a period of one year (1 Jan – 31 Dec). For each situation, two simulations were carried out: one without LTATW and one with LTATW. For both cases, the annual electrical energy demand in kWh was calculated, as was the absolute difference and the increase in percentage. The results regarding energy increase are shown in the designer tables (Table 5 and 6) in chapter 17.

For all situations investigated in the main study, this study also reveals the energy and comfort performance related to artificial lighting. Multiple tables have been developed in this thesis (see chapter 17), and to obtain a total picture for a given situation, several tables have to be consulted one after the other. What is important to mention here is that the values in Table 1 to 4 (related to thermal energy) represent the *energy demand*. The final *energy consumption* depends on the type of heating or cooling generation system used (the energy demand has to be multiplied by a conversion factor, which differs per generation system). The values in Table 5 and 6 already represent the electrical energy *consumption* for artificial lighting.

Also for this side-study, a short data-analysis was carried out with modeFRONTIER. For findings regarding the influence of the variable parameters, the results for initial electrical energy demand are as expected. The size of the room has the biggest influence on the energy demand, followed by the type of glazing (Figure 16.6). A bigger room means a higher energy demand, just like a coated type of glazing. The energy demand for artificial lighting in small office rooms is in most cases lower than the energy demand of small rooms of residences. This can be explained by the fact that in office cases, the occupation times are during the day when the sun is shining. For residences, the occupation times are mainly in the evening when its dark, and therefore, more lighting is needed. Only in a cold climate there are cases where the energy demand of offices is higher, which is logical, because days in cold climates are relatively shorter. It can also be seen that when the room gets bigger, the influence of the higher target illuminance in offices becomes more influential, as a result of which the energy demand is often larger. From the designer tables (Table 5 and 6) can be seen that the influence of orientation is relatively small.

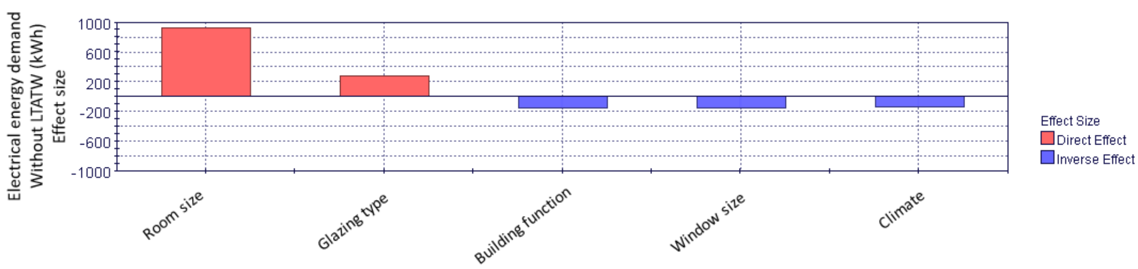


Figure 16.6: Effect size of variable parameters on electrical energy demand for artificial lighting, without LTATW.

From Figure 16.7 and Table 5 and 6 in chapter 17 can be seen that the highest increase in electrical energy demand is found in office cases. This makes sense, because suddenly the amount of natural light is greatly reduced. In residences, the sun does not always shine during occupation times, as a result of which the LTATW has less influence on the energy demand. After building function, the size of the room and climate are of greatest influence. Logically, the biggest change occurs for small rooms, as in the warmest climates (with the longest days).

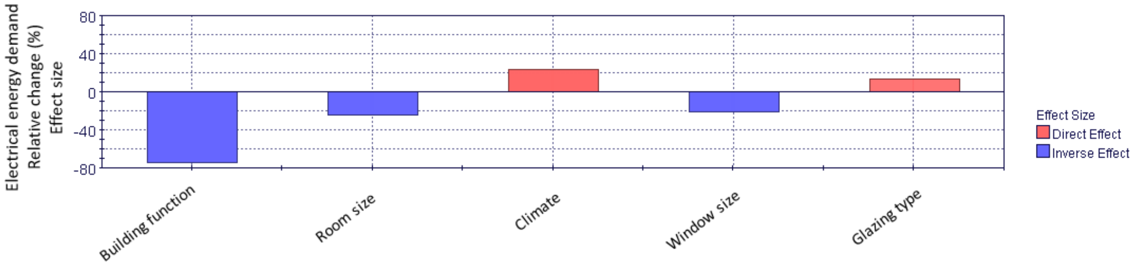


Figure 16.7: Effect size of variable parameters on the percentage increase in electrical energy demand for artificial lighting.

From Figure 16.7 and Table 5 and 6 in chapter 17 can be seen that also the highest increase in absolute sense occurs in office rooms. A bigger room means a higher energy demand and therefore, also a bigger increase and a smaller window means less natural light, so a higher increase in energy demand.

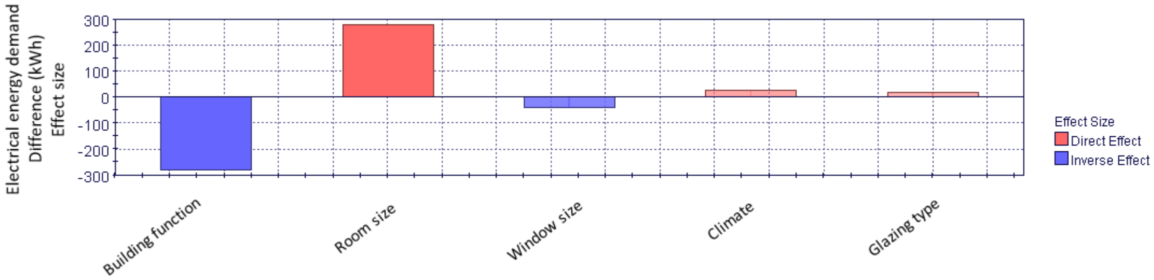


Figure 16.8: Effect size of variable parameters on the difference in electrical energy demand for artificial lighting.

Finally, Figure 16.9 and 16.10 reveal that the average increase in energy demand equals 52.4% in relative sense and 222.9 kWh in absolute sense. However, the standard deviation is in both cases too high to assume this average value for all situations. That is why it is better to consult the designer table for each individual situation.

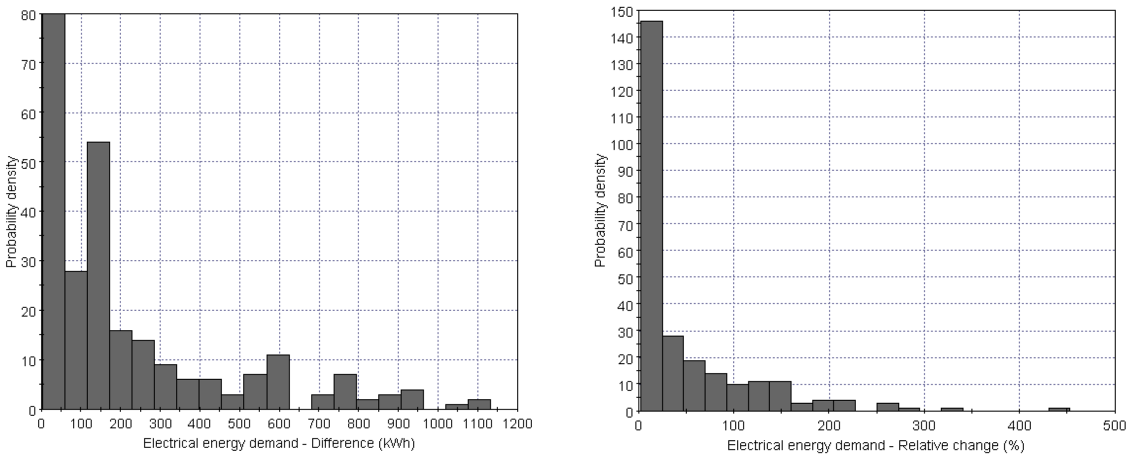


Figure 16.9 and 16.10: Probability density of values for relative change and difference in energy demand for artificial lighting.

16.5. SENSITIVITY ANALYSIS

One of the assumptions in this study was that the phase change material in the LTATW is in liquid state every day and in every climate between 08:00 AM and 18:00 PM. In practice, however, the times for sunrise and sunset vary by climate and season. In climates and seasons where the sun starts to shine before 08:00 AM, the results with this assumption will approach reality, but in climates and season where the sun starts to shine later (and also goes down earlier) the LTATW is in a liquid state for a much shorter amount of time.

In this section, a sensitivity analysis is conducted into the influence of the start and end time of the liquid state of the PCM on the findings of the study. Also in this sensitivity analysis, not all 256 situations are re-simulated, but only four: two situations (one office room and one residence room) where the energy demand increases the least (in absolute sense) and two situations (one office room and one residence room) where the energy demand increases the most (in absolute sense). From Table 6 in chapter 17 can be seen that these are the following room configurations:

1. Lowest increase in residence: small room – dry climate – large window with clear glazing, facing east (3.26 kWh).
2. Lowest increase in office: small room – dry climate – large window with clear glazing, facing south (2.14 kWh).
3. Highest increase in residence: big room – temperate climate – small window with clear glazing, facing north (236.8 kWh).
4. Highest increase in office: big room – tropical climate – small window with clear glazing, facing north (1131.76 kWh).

For each of the four configurations, a new simulation has been carried out in which the time span (of 10 hours) of the liquid state of the PCM has been moved to earlier in the day and later in the day. The results are shown in Figure 16.11.

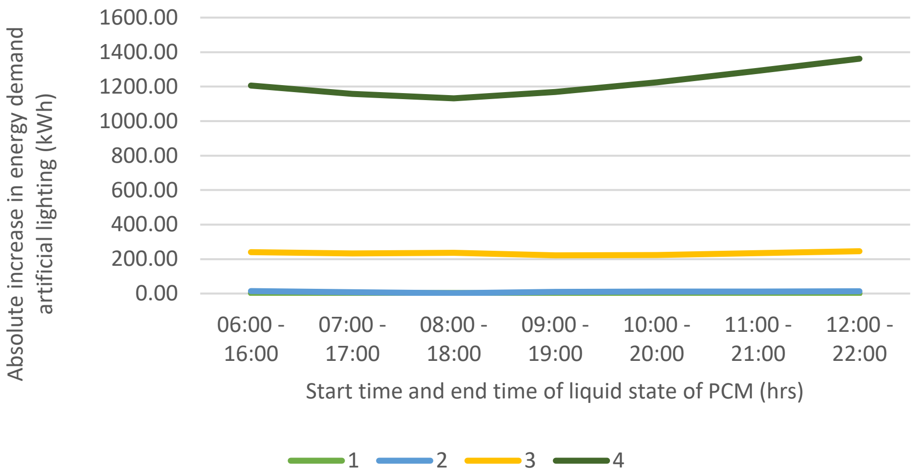


Figure 16.11: Effect of times of liquid state of PCM on increase in electrical energy demand for artificial lighting.

From Figure 16.11 can be seen that the time span on which the PCM is in liquid state has a small to moderate influence on the increase in energy demand. Only in case of room 4 it appears that an optimal result has been achieved with the assumption made. In the other three room cases, the energy increase is almost constant. For rooms 2 and 4 (both office rooms), a minimum can be seen, which can be explained by the fact that at this time span the office always receives sunlight through a Trombe wall in liquid state. For all other time spans, there is always at least one hour where the wall is in solid state (during the occupation time). For room cases 1 and 3 (both rooms in residences), slight optimums can also be seen at later time spans, which makes sense, because then the room will also experience a part of daylight that passes through a liquid wall.

17. DESIGNER TABLES

In addition of studying the influence of different parameters on the energy and comfort performance of the lightweight, translucent adaptable Trombe wall, another objective was to develop several designer tables. With these tables, an interested designer or owner of a building can instantly get an idea of the performance of the system in his or her situation in a few glances. In addition, it can also be derived from the tables, how a better performance may be achieved, if certain values or configurations in the design are adjusted. In total, six main tables were developed: two with regard to the heating energy demand, two with regard to the cooling energy demand and two with regard to the energy demand for artificial lighting.

17.1. EXPLANATORY NOTES

As mentioned above, two tables have been developed for each type of energy demand: one table has been set up with values for the energy reduction or increase in absolute terms and one with values of the energy reduction of increase expressed in percentages. In this way, the designer receives a complete picture of his or her situation, and knows whether installing a LTATW is effective or useful, or not. Two tables for each type of energy demand have been developed, in order to prevent a distorted picture from being given. Namely, when only a table with values for the increase or decrease in percentages is given, one does not know for sure whether a large reduction in absolute sense also takes place. Also the other way around, when a large reduction in absolute sense is achieved, it is also desirable to know how many percent this is of the initial energy demand. By being able to consult both tables, the designer can now know both.

In addition to being able to read the exact values from the tables, it is also indicated with a colour which situations are favourable and which are not. A green cell means a favourable result and a red cell means a poor result. Everything in between is indicated with a lighter green colour, a lighter red colour or a yellow colour. In order to still be able to see in only one table whether a value is favourable in both absolute and relative terms, some values are bolded and some are not. In the tables with absolute values (in kWh), a bolded value means that in this situation, also an above average reduction is achieved in relative sense (%) (located in area A and C). In the table with percentage changes, a bolded value means that in that situation, also an above average reduction occurs in absolute sense (located in area A and B). The values in the tables of heating and cooling represent the decrease in energy *demand* per year. The values in the tables of artificial lighting represent the increase in energy *consumption* (final energy) per year.

The vertical and horizontal arrangement of the variable parameters and their subdivisions is based on their influence. The parameters with the greatest influence are most left or most at the top in the tables and the parameters with the smallest influence are located at the most right or at the bottom part of the axes. Therefore, note that the arrangement differs per table.

17.2. TABLE 1: RELATIVE CHANGE IN HEATING ENERGY DEMAND

TABLE 1: RELATIVE CHANGE IN HEATING ENERGY DEMAND (%)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Age ↓	Window size ↓	Building method ↓	Room size ↓	Orientation / Type of glazing	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
New building	Small window (wwr=0.25)	Light-weight	Small room (A=20m²)	Double glazing (clear)	-54.3	-57.4	-83.1	-57.5	-37.9	-37.4	-52.8	-38.3	-78.7	-85.7	-96.0	-82.0	-47.7	-52.7	-67.3	-52.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-51.7	-51.4	-60.7	-52.8	-33.7	-34.5	-39.2	-35.8	-64.2	-65.2	-71.4	-65.6	-40.9	-40.7	-45.8	-41.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-81.1	-84.4	-100.0	-86.8	-50.3	-50.8	-73.7	-52.3	-100.0	-100.0	-100.0	-100.0	-70.0	-78.0	-100.0	-75.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-75.4	-75.9	-84.9	-76.9	-45.4	-46.1	-50.5	-46.8	-85.7	-85.2	-90.5	-88.9	-55.2	-56.7	-60.6	-56.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-56.9	-58.3	-75.8	-58.1	-35.0	-33.7	-45.0	-34.0	-65.2	-72.1	-80.6	-68.9	-46.6	-52.0	-60.8	-53.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-55.0	-55.6	-59.3	-56.2	-32.4	-32.7	-36.1	-33.2	-55.3	-53.8	-60.3	-53.8	-41.4	-42.1	-45.7	-42.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-56.7	-59.6	-82.5	-63.8	-40.4	-41.0	-59.7	-41.6	-75.9	-80.8	-93.8	-80.0	-60.7	-67.6	-87.1	-68.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-55.9	-56.2	-58.1	-56.9	-37.8	-38.1	-40.9	-38.4	-55.3	-56.8	-57.6	-56.8	-50.6	-51.0	-54.7	-51.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Medium-weight	Small room (A=20m²)	Double glazing (clear)	-56.2	-60.7	-88.1	-61.5	-35.8	-36.1	-54.2	-36.2	-92.5	-96.4	-100.0	-96.4	-47.0	-52.1	-66.7	-51.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-53.3	-53.4	-62.1	-53.6	-32.5	-33.2	-38.5	-34.2	-74.0	-75.7	-83.7	-76.1	-39.1	-39.1	-45.0	-39.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-90.8	-92.3	-100.0	-96.2	-48.6	-49.2	-76.1	-50.6	-100.0	0.0	0.0	0.0	-73.1	-85.1	-100.0	-81.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-86.5	-86.7	-93.3	-86.7	-43.5	-44.6	-49.5	-45.0	-100.0	-100.0	-100.0	-100.0	-55.5	-56.4	-61.7	-56.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-80.2	-82.5	-96.7	-83.5	-33.4	-32.3	-47.2	-32.8	-100.0	-100.0	0.0	-100.0	-47.6	-54.6	-68.8	-54.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-77.8	-78.4	-85.9	-78.8	-31.3	-31.5	-34.8	-32.1	-100.0	-100.0	-100.0	-100.0	-42.2	-42.7	-46.3	-42.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-93.3	-100.0	-100.0	-100.0	-40.2	-40.7	-62.8	-42.0	0.0	0.0	0.0	0.0	-67.8	-78.9	-100.0	-77.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-95.2	-95.0	-90.9	-94.7	-36.4	-36.7	-40.3	-36.9	0.0	0.0	0.0	0.0	-52.7	-53.6	-58.3	-53.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Heavy-weight	Small room (A=20m²)	Double glazing (clear)	-62.8	-69.1	-97.8	-70.6	-38.1	-37.5	-61.5	-38.2	-100.0	-100.0	0.0	-100.0	-50.8	-57.4	-78.8	-57.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-58.3	-58.9	-73.5	-60.1	-33.9	-35.1	-40.7	-36.1	-89.1	-91.4	-97.2	-91.4	-41.5	-41.7	-48.1	-41.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-100.0	-100.0	-100.0	-100.0	-52.5	-54.7	-84.0	-56.4	0.0	0.0	0.0	0.0	-84.3	-93.9	-100.0	-93.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-97.4	-97.2	-100.0	-97.2	-46.5	-47.6	-53.6	-48.2	-100.0	-100.0	0.0	-100.0	-60.9	-62.1	-70.8	-62.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-96.3	-96.2	-100.0	-97.4	-35.7	-35.7	-53.7	-36.3	0.0	0.0	0.0	0.0	-56.5	-65.9	-88.7	-65.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-94.0	-94.2	-97.2	-94.9	-33.0	-33.2	-37.7	-33.6	0.0	0.0	0.0	0.0	-47.3	-48.0	-54.0	-48.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-100.0	0.0	0.0	0.0	-45.3	-47.9	-78.0	-49.3	0.0	0.0	0.0	0.0	-85.4	-95.8	-100.0	-95.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-100.0	-100.0	-100.0	-100.0	-40.4	-41.1	-47.1	-42.2	0.0	0.0	0.0	0.0	-67.3	-69.0	-74.7	-69.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Large window (wwr=0.75)	Light-weight	Small room (A=20m²)	Double glazing (clear)	-24.5	-27.8	-62.1	-30.8	-20.1	-22.4	-53.3	-24.5	-37.7	-47.4	-73.3	-51.2	-26.2	-34.4	-64.4	-36.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-22.4	-22.6	-31.1	-25.1	-17.3	-18.1	-25.4	-19.8	-29.9	-29.8	-37.3	-30.8	-19.8	-20.9	-26.5	-21.8	-100.0	0.0	0.0	0.0	-100.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-31.5	-38.5	-100.0	-38.4	-20.5	-26.7	-78.4	-28.7	-74.2	-85.7	-100.0	-85.7	-38.2	-53.9	-88.6	-52.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-26.8	-27.5	-35.8	-28.2	-15.9	-17.0	-23.2	-18.2	-36.6	-37.6	-50.0	-38.4	-20.9	-20.3	-26.8	-21.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-34.9	-37.7	-71.5	-40.1	-23.6	-23.8	-46.3	-25.5	-51.7	-61.0	-78.7	-58.3	-32.4	-37.4	-60.3	-37.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-32.3	-32.0	-41.3	-34.1	-20.8	-21.3	-25.6	-22.9	-43.3	-42.3	-48.3	-43.7	-26.6	-26.0	-30.6	-26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-42.0	-42.4	-89.0	-44.5	-18.9	-21.4	-61.8	-24.4	-68.1	-81.1	-89.5	-71.1	-38.2	-45.5	-95.2	-47.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-33.4	-35.7	-43.5	-35.9	-17.1	-17.4	-21.8	-18.1	-39.4	-40.2	-47.4	-40.9	-23.1	-23.9	-28.1	-24.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Medium-weight	Small room (A=20m²)	Double glazing (clear)	-25.0	-28.2	-60.7	-31.8	-20.0	-21.5	-44.8	-22.4	-38.9	-48.6	-77.6	-51.4	-26.4	-31.2	-56.2	-35.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-22.6	-23.2	-31.2	-24.9	-17.3	-17.5	-23.4	-19.2	-29.3	-29.5	-37.9	-30.5	-20.2	-20.5	-26.2	-21.3	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-32.9	-36.8	-100.0	-42.6	-19.9	-25.5	-68.1	-28.0	-100.0	-100.0	-100.0	-100.0	-41.2	-57.3	-100.0	-56.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-26.9	-27.1	-34.8	-27.9	-15.8	-16.5	-22.7	-17.4	-43.6	-44.9	-54.8	-45.7	-20.4	-20.3	-27.0	-20.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-38.1	-42.2	-76.1	-44.3	-23.2	-23.9	-44.8	-25.5	-70.1	-86.6	-93.3	-87.8	-32.6	-40.1	-54.9	-37.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-36.0	-36.0	-44.3	-36.8	-21.0	-21.9	-26.9	-23.4	-51.4	-52.9	-59.6	-53.6	-26.5	-26.3	-32.3	-26.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-53.6	-58.7	-100.0	-64.6	-18.9	-22.2	-51.0	-24.7	0.0	0.0	0.0	0.0	-42.7	-56.5	-100.0	-54.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-48.0	-48.1	-61.5	-49.3	-17.0	-17.6	-21.1	-18.2	-85.7	-90.9	-100.0	-90.9	-24.3	-25.2	-28.3	-25.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Heavy-weight	Small room (A=20m²)	Double glazing (clear)	-26.2	-29.4	-62.0	-34.2	-21.0	-21.5	-50.0	-23.9	-42.2	-57.4	-88.5	-59.2	-28.1	-34.3	-54.0	-37.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-23.4	-24.4	-33.7	-26.0	-17.4	-18.2	-24.6	-20.5	-31.3	-32.1	-40.1	-33.1	-20.8	-21.4	-27.0	-21.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-37.7	-42.2	-100.0	-48.6	-20.8	-29.0	-70.6	-31.7	-100.0	0.0	0.0	0.0	-45.3	-61.9	-100.0	-62.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-29.9	-30.1	-42.4	-30.9	-16.7	-17.8	-24.7	-18.5	-55.6	-60.0	-82.1	-60.0	-21.4	-22.4	-28.9	-23.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-41.6	-48.2	-87.2	-50.5	-24.6	-24.6	-48.4	-26.1	-89.1	-98.1	-100.0	-98.2	-33.8	-42.7	-67.9	-42.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-38.7	-38.9	-53.0	-40.0	-21.9	-22.7	-27.7	-23.4	-64.2	-66.5	-78.5	-67.2	-27.8	-27.2	-33.4	-28.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-77.3	-83.7	0.0	-90.5	-21.0	-25.7	-70.2	-27.8	0.0	0.0	0.0	0.0	-52.7	-85.8	0.0	-75.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-65.8	-68.1	-83.9	-68.3	-17.9	-18.7	-23.8	-19.4	-100.0	0.0	0.0	0.0	-27.4	-27.9	-34.5	-28.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Old building	Small window (wwr=0.25)	Light-weight	Small room (A=20m²)	Double glazing (clear)	-24.7	-25.6	-32.0	-26.3	-22.4	-23.5	-27.8	-23.3	-30.1	-32.0	-38.2	-31.9	-24.7	-26.3	-30.5	-26.3	-100.0	0.0	0.0	0.0	-81.8	-100.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-23.9	-23.8	-25.3	-24.3	-20.8	-21.3	-22.6	-21.6	-27.4	-27.3	-29.0	-27.7	-21.9	-22.2	-23.4	-22.3	-75.0	-80.0	-100.0	-75.0	-55.1	-59.4	-83.3	-63.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-26.9	-28.1	-33.7	-28.8	-24.0	-25.2	-29.0	-24.8	-33.6	-34.8	-40.8	-34.4	-26.4	-28.6	-32.9	-28.0	-100.0	0.0	0.0	0.0	-77.8	-100.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-25.8	-25.6	-26.7	-26.1	-22.0	-22.0	-22.7	-22.2	-29.7	-30.0	-30.7	-30.1	-23.2	-23.1	-23.5	-23.1	-60.0	-75.0	-100.0	-66.7	-59.0	-58.6	-66.7	-59.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-14.9	-15.3	-17.8	-15.6	-12.6	-13.3	-14.6	-13.0	-18.2	-19.1	-22.0	-19.2	-13.6	-14.8	-16.0	-14.0	-68.8	-75.0	0.0	-80.0	-50.9	-61.5	-100.0	-66.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-14.8	-14.8	-15.1	-14.9	-12.0	-12.2	-12.5	-12.4	-17.4	-17.2	-17.9	-17.5	-13.0	-12.9	-13.7	-13.0	-35.7	-43.5	-63.6	-42.9	-39.6	-39.0	-45.7	-44.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-14.7	-15.3	-16.9	-15.3	-12.2	-13.4	-14.2	-13.0	-18.1	-18.4	-20.0	-18.8	-13.5	-14.6	-16.6	-14.3	-66.7	-77.8	0.0	-66.7	-50.0	-57.1	-100.0	-65.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-14.4	-14.2	-14.4	-14.3	-11.5	-11.4	-11.6	-11.5	-16.8	-16.6	-16.7	-16.8	-12.4	-12.3	-12.3	-12.3	-33.3	-38.1	-57.1	-35.0	-38.4	-37.2	-37.8	-36.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Medium-weight	Small room (A=20m²)	Double glazing (clear)	-25.8	-27.3	-31.9	-27.7	-22.4	-22.7	-26.4	-22.7	-31.5	-32.9	-39.2	-32.7	-24.6	-26.0	-30.0	-26.0	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-25.0	-24.9	-26.5	-25.2	-20.7	-21.2	-22.5	-21.9	-28.9	-29.0	-30.7	-29.5	-21.8	-22.0	-23.3	-22.2	-100.0	0.0	0.0	0.0	-56.4	-54.2	-100.0	-62.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-27.8	-29.3	-34.7	-29.7	-23.8	-24.4	-29.1	-24.1	-34.5	-35.7	-40.9	-35.7	-26.2	-28.8	-32.2	-28.0	0.0	0.0	0.0	0.0	-100.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-26.9	-26.7	-27.6	-26.9	-21.8	-21.8	-22.4	-22.1	-31.5	-31.5	-32.0	-31.7	-23.0	-23.0	-23.5	-23.0	0.0	0.0	0.0	0.0	-60.0	-52.4	-85.7	-58.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-15.7	-16.2	-18.5	-16.1	-12.6	-13.0	-13.7	-12.5	-19.7	-20.7	-22.1	-19.9	-13.7	-14.7	-15.9	-14.3	0.0	0.0	0.0	0.0	-53.5	-89.5	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-15.7	-15.5	-15.7	-15.6	-12.0	-11.9	-12.4	-12.3	-18.9	-18.8	-19.3	-18.9	-12.8	-12.8	-13.4	-12.9	-100.0	-100.0	0.0	0.0	-39.6	-32.4	-60.7	-36.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-15.5	-16.3	-18.1	-15.9	-12.2	-13.1	-13.8	-12.7	-19.3	-20.0	-21.9	-20.0	-13.4	-14.4	-16.3	-13.9	0.0	0.0	0.0	0.0	-47.5	-81.8	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-15.2	-14.9	-14.9	-15.0	-11.5	-11.4	-11.5	-11.5	-18.4	-18.3	-18.4	-18.3	-12.3	-12.1	-12.2	-12.2	0.0	0.0	0.0	0.0	-35.4	-30.4	-39.5	-29.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Heavy-weight	Small room (A=20m²)	Double glazing (clear)	-29.4	-30.9	-36.7	-31.0	-25.0	-25.7	-30.8	-25.8	-35.5	-36.1	-42.9	-37.3	-27.9	-29.6	-33.3	-29.9	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-28.3	-27.8	-29.8	-28.2	-23.5	-24.0	-25.8	-24.6	-32.9	-33.1	-35.3	-33.3	-24.7	-25.1	-26.3	-25.2	0.0	0.0	0.0	0.0	-61.8	-65.0	0.0	-85.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-32.0	-33.6	-39.1	-33.9	-27.1	-27.7	-32.5	-27.7	-39.0	-40.3	-47.6	-40.5	-30.1	-32.4	-36.6	-32.0	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-30.7	-30.2	-31.5	-30.6	-24.9	-25.1	-25.8	-25.4	-36.1	-35.9	-37.1	-36.2	-26.3	-26.3	-26.9	-26.4	0.0	0.0	0.0	0.0	-68.0	-66.7	-100.0	-80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-18.3	-19.0	-21.1	-19.1	-14.6	-14.8	-15.8	-14.6	-22.7	-23.8	-26.2	-23.1	-15.9	-16.8	-18.3	-16.7	0.0	0.0	0.0	0.0	-76.5	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-17.9	-17.8	-18.5	-18.0	-13.9	-13.9	-14.2	-14.3	-22.0	-21.8	-22.2	-22.1	-14.8	-14.8	-15.3	-15.0	0.0	0.0	0.0	0.0	-41.0	-42.2	-100.0	-53.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-18.3	-19.2	-21.0	-19.0	-14.3	-15.1	-15.9	-14.7	-23.3	-23.1	-25.6	-23.6	-15.9	-16.9	-18.8	-16.5	0.0	0.0	0.0	0.0	-74.2	-100.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-17.8	-17.5	-17.8	-17.7	-13.5	-13.4	-13.7	-13.5	-21.9	-21.7	-21.8	-21.8	-14.4	-14.3	-14.4	-14.4	0.0	0.0	0.0	0.0	-42.9	-40.7	-70.4	-46.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Large window (wwr=0.75)	Light-weight	Small room (A=20m²)	Double glazing (clear)	-13.4	-15.4	-37.0	-18.9	-13.6	-18.0	-36.6	-19.2	-18.5	-21.2	-43.6	-22.4	-17.0	-20.7	-39.5	-21.1	-100.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-13.0	-12.8	-16.8	-14.1	-12.1	-13.7	-17.2	-14.5	-15.4	-15.6	-19.0	-16.1	-13.0	-13.4	-16.7	-14.3	-61.5	-83.3	0.0	-100.0	-44.4	-54.8	-100.0	-87.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-12.5	-14.9	-38.1	-18.3	-11.6	-15.7	-32.8	-15.3	-18.6	-22.4	-47.8	-25.9	-15.8	-19.2	-37.6	-19.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-10.5	-10.9	-13.7	-11.4	-9.5	-10.5	-12.9	-11.4	-13.4	-13.8	-17.2	-14.5	-10.2	-10.4	-12.4	-10.6	-60.0	-66.7	0.0	-100.0	-41.9	-41.2	-100.0	-72.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-10.8	-11.9	-23.2	-14.4	-10.5	-11.8	-19.1	-12.4	-14.8	-15.1	-29.1	-18.2	-12.6	-13.8	-20.5	-14.0	-100.0	-100.0	0.0	0.0	-90.0	-100.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-10.9	-10.8	-12.5	-11.5	-9.5	-10.2	-12.1	-10.8	-13.6	-13.4	-15.2	-14.2	-10.3	-10.4	-12.1	-10.7	-43.2	-64.0	-100.0	-65.0	-37.6	-42.3	-90.5	-50.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-7.1	-8.3	-18.5	-11.3	-7.2	-8.7	-15.0	-8.1	-10.8	-12.7	-26.5	-13.4	-9.1	-12.2	-19.0	-10.8	-100.0	-100.0	0.0	0.0	-100.0	-100.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-6.8	-6.7	-8.1	-7.0	-5.8	-6.3	-7.5	-6.5	-8.8	-8.6	-9.6	-9.0	-6.3	-6.2	-7.0	-6.4	-36.0	-40.0	-100.0	-41.2	-26.5	-23.2	-68.2	-33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Medium-weight	Small room (A=20m²)	Double glazing (clear)	-15.3	-16.4	-34.0	-18.9	-13.3	-15.6	-30.2	-16.1	-19.2	-22.5	-38.6	-24.1	-17.0	-19.0	-33.9	-19.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-14.2	-14.1	-17.5	-15.2	-12.2	-13.4	-16.2	-14.3	-16.7	-17.0	-19.7	-17.9	-13.1	-13.7	-16.3	-14.3	-75.0	-100.0	0.0	0.0	-44.0	-50.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-14.4	-15.3	-33.3	-18.5	-11.4	-14.1	-24.6	-13.8	-18.8	-23.1	-47.2	-24.8	-15.1	-19.0	-34.1	-17.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-11.8	-11.7	-14.6	-12.2	-9.6	-10.5	-12.5	-11.1	-14.5	-14.6	-16.8	-14.9	-10.4	-10.5	-12.4	-10.9	0.0	0.0	0.0	0.0	-36.4	-30.8	0.0	-77.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-12.3	-13.0	-21.7	-14.0	-10.3	-10.7	-16.2	-10.9	-15.9	-17.6	-27.5	-17.2	-11.8	-14.5	-19.0	-13.1	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-12.0	-11.9	-13.3	-12.3	-9.5	-10.1	-11.7	-10.7	-14.9	-14.9	-15.9	-15.3	-10.4	-10.5	-12.0	-10.8	-75.0	-100.0	0.0	-100.0	-37.6	-28.6	-100.0	-46.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-8.3	-9.6	-16.3	-10.4	-6.9	-8.2	-13.3	-7.2	-11.3	-13.7	-25.2	-14.5	-8.5	-11.7	-18.4	-9.7	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-7.7	-7.6	-9.0	-7.7	-5.8	-6.1	-7.4	-6.4	-9.9	-9.9	-10.5	-10.1	-6.4	-6.3	-7.0	-6.5	-100.0	0.0	0.0	0.0	-22.5	-18.9	-100.0	-25.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Heavy-weight	Small room (A=20m²)	Double glazing (clear)	-17.3	-17.9	-35.4	-19.4	-14.2	-15.8	-26.7	-17.4	-20.8	-25.2	-43.1	-25.6	-17.6	-19.3	-32.7	-20.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-15.3	-15.3	-18.0	-16.0	-13.1	-14.1	-16.4	-15.2	-18.4	-18.9	-21.5	-19.6	-14.0	-15.0	-17.6	-15.3	-100.0	0.0	0.0	0.0	-46.3	-76.5	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-16.0	-18.3	-37.1	-18.3	-13.0	-15.2	-26.5	-14.9	-22.5	-24.8	-48.7	-28.6	-15.3	-20.1	-33.2	-20.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-13.4	-13.3	-17.4	-14.0	-10.8	-11.7	-14.5	-12.4	-16.7	-16.8	-19.8	-17.2	-11.8	-12.0	-14.3	-12.4	0.0	0.0	0.0	0.0	-44.4	-50.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Big room (A=100m²)	Double glazing (clear)	-13.7	-14.4	-23.0	-14.5	-10.6	-11.7	-16.2	-11.3	-16.7	-19.1	-26.5	-18.7	-12.8	-14.3	-19.5	-13.5	0.0	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Double glazing (coated)	-12.9	-12.8	-14.6	-13.5	-10.2	-11.0	-11.7	-11.6	-16.3	-16.1	-17.8	-16.8	-11.1	-11.1	-13.0	-11.8	0.0	0.0	0.0	0.0	-34.7	-40.4	0.0	-78.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (clear)	-10.0	-11.1	-16.8	-11.7	-7.5	-8.8	-14.0	-8.5	-13.9	-15.8	-25.0	-17.8	-9.6	-11.4	-17.5	-10.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Triple glazing (coated)	-8.8	-8.7	-10.5	-9.3	-6.6	-6.9	-8.4	-7.1	-11.4	-11.4	-12.5	-11.5	-7.2	-7.2	-8.1	-7.5	0.0	0.0	0.0	0.0	-28.8	-28.6	0.0	-53.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 2: ABSOLUTE REDUCTION OF HEATING ENERGY DEMAND (KWH/YEAR)

Age ↓	Room size ↓	Type of glazing ↓	Window size ↓	Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
				Building method / Orientation	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
New building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	119	109	74	107	194	164	132	163	48	42	24	41	103	96	68	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	114	105	52	104	174	150	116	145	37	27	5	27	93	85	52	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	123	114	44	113	185	153	126	151	27	15	0	15	96	89	52	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	142	136	149	150	202	193	274	206	75	73	63	83	115	123	145	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	149	141	111	155	198	179	172	181	75	67	38	73	112	104	91	117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	156	146	93	164	206	177	166	190	76	70	23	74	116	109	68	119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	140	129	119	132	207	199	186	204	61	58	50	59	122	114	109	115	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	137	126	108	125	193	184	173	187	57	53	41	54	109	102	99	103	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	147	136	122	137	200	194	181	197	57	53	35	53	113	105	102	104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	174	158	165	176	229	218	239	234	106	96	93	100	139	135	140	141	1	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0
				Medium-weight	184	170	165	180	226	208	212	225	105	96	91	100	140	130	133	135	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	192	179	174	188	226	215	219	239	110	102	91	106	142	132	133	136	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	73	65	28	66	153	133	101	134	14	10	5	11	77	71	43	69	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	59	48	8	50	136	118	83	118	1	0	0	0	68	63	30	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	52	39	2	38	145	128	84	128	0	0	0	0	70	62	21	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	56	55	44	53	84	92	109	95	23	18	11	18	50	48	31	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	54	46	18	52	79	84	64	88	14	5	1	5	49	43	15	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	57	46	5	51	80	92	48	96	3	0	0	0	48	39	1	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	86	82	73	83	172	166	155	167	24	23	19	24	90	89	83	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	77	72	56	72	154	150	140	150	10	8	4	8	81	79	74	79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	75	70	47	69	164	159	149	159	2	1	0	1	84	82	80	83	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	72	68	63	69	96	95	99	100	34	32	32	33	60	54	57	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	70	64	55	65	94	90	93	93	34	31	23	32	56	52	54	53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	75	68	61	69	98	95	98	97	35	33	23	33	56	55	54	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	164	147	100	143	424	357	291	351	45	44	29	42	198	191	121	195	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	165	156	110	156	421	400	369	403	11	9	4	10	217	209	188	210	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	142	129	69	129	434	413	388	413	0	0	0	0	227	218	201	218	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	395	359	355	384	614	581	550	617	198	176	160	185	375	342	329	354	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	435	397	340	401	615	591	560	621	188	174	130	178	363	335	332	343	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	453	412	376	418	636	604	562	613	197	179	124	182	369	334	326	348	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	187	179	153	181	457	437	408	438	52	49	47	49	233	227	210	228	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	165	156	110	156	421	400	369	403	11	9	4	10	217	209	188	210	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	142	129	69	129	434	413	388	413	0	0	0	0	227	218	201	218	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	395	359	355	384	614	581	550	617	198	176	160	185	375	342	329	354	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	435	397	340	401	615	591	560	621	188	174	130	178	363	335	332	343	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	453	412	376	418	636	604	562	613	197	179	124	182	369	334	326	348	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	68	62	52	67	308	279	249	278	22	21	15	20	136	127	88	128	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	14	11	2	10	282	253	214	256	0	0	0	0	118	112	61	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1	0	0	0	305	280	227	286	0	0	0	0	117	91	18	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	102	84	65	85	189	185	217	204	32	30	17	27	104	85	59	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	74	61	3	62	182	183	124	196	0	0	0	0	99	87	19	84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	58	41	0	38	193	200	127	207	0	0	0	0	97	97	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	81	77	68	78	341	332	313	331	21	21	19	21	157	153	145	153	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	20	19	10	18	305	296	284	295	0	0	0	0	136	133	126	133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1	1	1	1	329	321	320	326	0	0	0	0	148	145	130	145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	116	117	104	117	239	227	225	232	39	37	36	38	127	124	116	127	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	110	102	72	104	230	223	207	226	12	10	4	10	125	121	106	122	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	106	98	47	97	234	229	223	234	1	0	0	0	129	122	114	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Old building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	271	253	243	260	399	380	356	369	161	155	146	157	238	234	224	234	2	0	0	0	9	4	0	2	0	0	0	0	0	0	0	0
				Medium-weight	301	288	248	289	396	363	326	358	176	167	152	167	236	229	214	229	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	361	343	298	339	455	424	392	419	207	191	171	198	276	267	242	270	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	171	169	262	209	282	330	494	347	108	105	156	115	182	197	282	200	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	212	194	229	220	274	277	346	279	120	118	124	129	180	175	207	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	246	215	231	228	295	280	288	299	132	133	125	137	186	176	184	189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	293	279	270	284	415	407	401	411	171	164	161	167	241	236	234	238	6	4	1	3	27	19	5	14	0	0	0	0	0	0	0	0
				Medium-weight	325	309	299	312	412	404	397	416	190	184	179	188	239	234	232	236	1	0	0	0	22	13	3	10	0	0	0	0	0	0	0	0
				Heavy-weight	385	362	352	366	482	471	466	480	226	219	214	221	278	274	269	275	0	0	0	0	21	13	0	12	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	204	185	204	205	309	325	354	341	125	119	126	124	184	179	198	191	8	5	0	4	28	17	5	14	0	0	0	0	0	0	0	0
				Medium-weight	242	222	229	238	310	318	327	335	148	141	139	149	186	184	192	192	3	1	0	0	22	11	0	11	0	0	0	0	0	0	0	0
				Heavy-weight	267	248	240	257	336	333	330	356	166	159	153	166	199	201	206	205	1	0	0	0	19	13	0	8	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	256	244	232	249	376	362	338	351	153	145	138	145	223	226	219	221	2	0	0	0	7	4	0	2	0	0	0	0	0	0	0	0
				Medium-weight	278	269	244	269	371	348	333	339	162	154	140	155	220	225	209	219	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	339	326	290	325	436	408	386	404	192	182	169	184	262	261	244	258	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	108	111	173	136	165	196	282	187	69	70	100	83	113	121	166	124	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	132	120	140	142	163	172	183	164	72	73	85	80	106	116	128	109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	150	146	149	142	186	186	191	177	86	78	75	91	107	122	117	123	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	272	262	258	267	383	373	367	376	156	154	150	155	222	216	211	216	3	3	1	2	23	17	6	13	0	0	0	0	0	0	0	0
				Medium-weight	298	287	279	289	379	369	361	372	173	169	162	170	219	215	210	215	0	0	0	0	18	11	6	10	0	0	0	0	0	0	0	0
				Heavy-weight	357	341	334	345	449	438	429	442	207	201	196	203	258	253	248	254	0	0	0	0	17	12	3	12	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	114	112	124	118	172	180	199	194	73	72	80	76	101	99	108	101	3	2	0	3	13	7	3	8	0	0	0	0	0	0	0	0
				Medium-weight	136	128	140	133	173	180	191	189	83	80	81	82	103	100	107	104	0	0	0	0	8	4	0	7	0	0	0	0	0	0	0	0
				Heavy-weight	158	149	170	156	197	200	221	210	97	93	96	95	117	114	123	118	0	0	0	0	8	5	0	6	0	0	0	0	0	0	0	0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	562	536	525	546	886	878	829	844	326	320	320	326	514	530	509	502	11	6	0	4	27	16	6	12	0	0	0	0	0	0	0	0
				Medium-weight	645	623	585	614	883	854	770	810	373	367	332	356	516	527	499	511	0	0	0	0	23	17	0	7	0	0	0	0	0	0	0	0
				Heavy-weight	780	760	689	754	1036	981	894	954	439	431	396	419	609	608	580	606	0	0	0	0	26	8	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	445	428	607	528	796	801	998	824	282	252	378	312	501	496	577	507	8	1	0	0	18	4	0	4	0	0	0	0	0	0	0	0
				Medium-weight	561	521	584	557	776	719	784	712	326	316	342	313	468	516	509	466	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	642	587	613	583	799	782	761	738	343	342	308	338	506	501	506	476	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	596	579	559	584	906	893	878	906	341	330	327	338	531	516	527	522	10	10	7	9	53	39	16	35	0	0	0	0	0	0	0	0
				Medium-weight	686	661	634	666	905	876	873	897	396	385	375	389	524	514	517	519	1	1	0	0	40	24	17	22	0	0	0	0	0	0	0	0
				Heavy-weight	813	788	772	792	1060	1036	1011	1063	471	457	439	462	614	602	596	610	0	0	0	0	34	27	15	28	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	521	485	499	521	835	851	923	897	324	304	313	326	497	481	518	496	16	16	3	13	62	41	19	32	0	0	0	0	0	0	0	0
				Medium-weight	634	594	587	615	841	849	883	893	388	370	353	382	501	488	509	503	3	1	0	1	47	20	4	22	0	0	0	0	0	0	0	0
				Heavy-weight	697	658	658	690	896	916	881	966	427	404	395	421	535	515	550	546	0	0	0	0	34	23	0	29	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	508	497	480	500	803	834	789	800	294	284	275	293	473	491	508	481	10	7	0	4	25	16	6	13	0	0	0	0	0	0	0	0
				Medium-weight	581	578	551	562	798	809	755	779	329	323	309	325	471	485	492	467	0	0	0	0	19	18	0	11	0	0	0	0	0	0	0	0
				Heavy-weight	710	708	662	694	952	940	881	913	403	380	365	390	564	576	574	562	0	0	0	0	23	11	0	1	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	230	237	389	326	439	480	633	435	155	162	263	175	289	353	436	312	5	1	0	0	12	1	0	1	0	0	0	0	0	0	0	0
				Medium-weight	293	301	349	323	418	448	532	386	169	183	235	195	268	332	404	275	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	360	351	355	364	457	478	545	452	206	207	218	236	302	320	374	294	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	526	511	501	514	801	784	772	785	296	289	282	292	467	456	447	458	8	8	8	7	43	35	17	29	0	0	0	0	0	0	0	0
				Medium-weight	602	583	563	587	798	779	767	784	343	336	327	337	461	451	442	452	0	0	0	0	29	21	15	18	0	0	0	0	0	0	0	0
				Heavy-weight	729	707	692	715	955	933	925	941	416	407	395	409	550	539	530	541	0	0	0	0	30	24	19	24	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	253	240	271	254	410	433	487	446	158	150	157	158	242	233	250	241	9	8	7	7	26	16	15	18	0	0	0	0	0	0	0	0
				Medium-weight	316	300	327	304	412	421	476	441	190	184	182	189	244	236	250	244	1	0	0	0	16	10	11	11	0	0	0	0	0	0	0	0
				Heavy-weight	367	352	389	375	469	478	541	489	219	212	214	215	277	268	288	279	0	0	0	0	17	12	0	17	0	0	0	0	0	0	0	0

17.4. TABLE 3: RELATIVE CHANGE IN COOLING ENERGY DEMAND

TABLE 3: RELATIVE CHANGE IN COOLING ENERGY DEMAND (%)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Window size ↓	Room size ↓	Age ↓	Building method ↓	Orientation / Type of glazing	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small window (wwr=0.25)	Small room (A=20 m^2)	New building	Light-weight	Double glazing (clear)	80.0	50.0	17.6	7.7	-100.0	-88.9	-86.7	-88.9	-24.1	-19.8	-24.4	-24.2	-70.6	-65.8	-68.2	-67.3	-10.9	-9.9	-11.2	-12.1	-24.8	-24.0	-27.1	-24.8	-3.7	-3.7	-3.8	-4.1	-7.0	-6.8	-6.9	-7.1
				Double glazing (coated)	0.0	66.7	33.3	50.0	0.0	0.0	0.0	0.0	-25.9	-23.9	-26.3	-25.2	-88.7	-86.7	-86.9	-86.7	-10.5	-10.6	-10.8	-11.6	-26.8	-26.9	-28.0	-27.1	-3.5	-3.6	-3.5	-3.6	-8.7	-8.9	-8.6	-9.0
				Triple glazing (clear)	100.0	75.0	60.0	50.0	-100.0	-100.0	-100.0	-100.0	-25.5	-21.6	-25.6	-27.4	-79.8	-76.0	-77.3	-75.2	-11.2	-10.7	-11.8	-12.1	-27.7	-26.9	-29.8	-27.2	-3.3	-3.3	-3.3	-3.5	-7.0	-6.9	-6.9	-7.1
				Triple glazing (coated)	0.0	33.3	50.0	50.0	0.0	0.0	0.0	0.0	-25.7	-25.0	-25.2	-27.1	-93.9	-92.6	-90.9	-90.7	-10.7	-11.0	-11.2	-11.0	-29.3	-30.1	-30.5	-30.2	-3.4	-3.5	-3.2	-3.5	-9.2	-9.4	-9.0	-9.4
			Medium-weight	Double glazing (clear)	0.0	-50.0	-33.3	-50.0	0.0	-100.0	-100.0	-100.0	-41.2	-39.7	-40.9	-39.6	-80.5	-74.3	-77.1	-76.4	-11.9	-11.4	-12.5	-13.1	-26.2	-25.7	-28.8	-26.8	-3.6	-3.6	-3.6	-3.9	-6.7	-6.3	-6.6	-6.7
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-45.7	-42.7	-44.3	-44.3	-97.8	-94.2	-96.1	-96.2	-12.2	-12.1	-12.5	-12.3	-27.9	-27.7	-28.8	-28.2	-3.5	-3.6	-3.5	-3.7	-8.4	-8.5	-8.3	-8.5
				Triple glazing (clear)	0.0	-100.0	-100.0	-100.0	0.0	0.0	0.0	0.0	-42.9	-41.0	-44.2	-44.4	-90.9	-85.7	-86.9	-85.7	-12.3	-11.6	-12.7	-13.1	-29.4	-28.3	-31.4	-29.4	-3.2	-3.2	-3.2	-3.4	-6.7	-6.5	-6.4	-6.6
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-48.0	-46.9	-47.5	-47.5	-100.0	-100.0	-100.0	-100.0	-12.5	-12.6	-12.9	-12.9	-30.7	-31.0	-31.9	-31.3	-3.3	-3.5	-3.3	-3.4	-8.8	-8.9	-8.6	-8.9
			Heavy-weight	Double glazing (clear)	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	-45.1	-44.1	-44.5	-44.8	-86.5	-81.2	-81.6	-81.8	-12.6	-12.0	-13.3	-13.9	-27.3	-27.3	-30.3	-28.1	-3.7	-3.6	-3.7	-4.0	-6.9	-6.7	-6.7	-7.0
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-54.4	-49.3	-52.0	-52.0	-100.0	-100.0	-100.0	-100.0	-12.3	-12.4	-13.0	-13.0	-28.3	-28.1	-29.5	-28.7	-3.7	-3.8	-3.7	-3.9	-8.7	-8.7	-8.5	-8.9
				Triple glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-49.1	-48.0	-50.0	-49.2	-95.5	-91.1	-91.3	-91.0	-13.2	-12.5	-13.3	-13.9	-30.1	-29.3	-32.6	-30.4	-3.3	-3.3	-3.3	-3.5	-6.9	-6.7	-6.8	-7.0
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-56.5	-55.2	-56.7	-56.7	-100.0	-100.0	-100.0	-100.0	-12.8	-13.1	-13.4	-13.5	-30.8	-31.0	-32.0	-31.8	-3.6	-3.7	-3.5	-3.7	-9.1	-9.3	-8.9	-9.2
		Old building	Light-weight	Double glazing (clear)	0.0	50.0	12.5	-16.7	0.0	-50.0	-33.3	-50.0	-19.9	-14.5	-19.9	-21.3	-59.5	-56.0	-58.8	-56.4	-9.7	-9.4	-10.3	-11.7	-19.7	-19.0	-20.9	-20.4	-4.8	-4.9	-4.7	-5.1	-8.9	-8.8	-8.8	-9.1
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-22.1	-22.4	-21.9	-24.0	-73.5	-73.8	-73.8	-73.8	-9.6	-10.2	-10.7	-11.1	-21.9	-22.6	-23.5	-23.2	-4.8	-5.1	-4.8	-5.0	-11.0	-11.4	-10.9	-11.4
				Triple glazing (clear)	0.0	40.0	0.0	0.0	0.0	0.0	0.0	0.0	-20.8	-17.5	-22.9	-22.3	-70.8	-64.2	-67.1	-67.1	-9.6	-9.5	-10.7	-11.5	-21.3	-20.7	-22.2	-21.3	-4.5	-4.7	-4.5	-4.8	-9.3	-9.3	-9.0	-9.5
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-21.6	-22.9	-22.3	-23.4	-79.3	-80.0	-80.0	-80.0	-9.7	-10.6	-11.0	-11.3	-23.2	-24.5	-25.3	-25.0	-4.8	-5.1	-4.7	-5.0	-11.5	-12.0	-11.3	-12.0
			Medium-weight	Double glazing (clear)	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	-34.5	-32.6	-34.3	-33.6	-75.7	-69.2	-71.4	-70.3	-10.9	-10.7	-11.9	-12.5	-20.7	-20.5	-22.4	-21.7	-4.9	-5.1	-5.0	-5.3	-8.9	-8.9	-8.8	-9.1
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-35.8	-35.5	-36.8	-37.3	-87.0	-87.1	-87.1	-87.1	-11.2	-11.9	-12.4	-12.8	-21.9	-23.0	-23.8	-23.8	-5.3	-5.5	-5.2	-5.6	-11.1	-11.4	-10.9	-11.5
				Triple glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-34.0	-36.0	-36.8	-36.6	-81.8	-77.5	-78.9	-79.2	-11.1	-11.4	-12.0	-12.5	-21.7	-21.9	-24.1	-23.1	-4.8	-5.0	-4.8	-5.1	-9.2	-9.3	-9.0	-9.4
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-38.7	-38.2	-38.2	-39.7	-94.7	-92.0	-92.0	-92.0	-11.5	-12.4	-12.8	-13.2	-23.2	-24.5	-25.4	-25.3	-5.4	-5.7	-5.2	-5.6	-11.5	-12.1	-11.3	-12.0
			Heavy-weight	Double glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-37.4	-38.5	-38.8	-38.5	-84.7	-77.8	-77.2	-79.0	-11.6	-11.7	-12.4	-13.6	-21.5	-22.1	-24.3	-23.7	-5.6	-5.7	-5.6	-6.0	-10.1	-10.0	-9.9	-10.2
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-42.6	-42.9	-43.5	-43.5	-100.0	-100.0	-100.0	-100.0	-12.1	-13.0	-13.5	-14.2	-23.9	-24.7	-25.6	-25.9	-6.2	-6.4	-6.0	-6.5	-12.4	-12.9	-12.3	-12.8
				Triple glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-40.5	-42.2	-44.1	-41.0	-93.5	-88.9	-88.5	-88.9	-11.8	-12.1	-12.7	-13.8	-23.2	-23.5	-25.9	-25.3	-5.6	-5.7	-5.5	-5.9	-10.5	-10.6	-10.2	-10.6
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-43.8	-45.5	-47.3	-47.3	-100.0	-100.0	-100.0	-100.0	-12.5	-13.7	-14.0	-14.8	-24.9	-26.6	-27.5	-28.1	-6.3	-6.6	-6.1	-6.6	-12.9	-13.6	-12.8	-13.5
	Big room (A=20 m^2)	New building	Light-weight	Double glazing (clear)	14.3	13.4	1.0	-2.3	-100.0	-66.7	-65.0	-60.0	-5.2	-5.7	-7.5	-6.4	-43.9	-42.8	-44.0	-43.3	-4.2	-4.4	-4.7	-5.4	-14.1	-14.0	-15.7	-15.1	-1.7	-1.7	-1.7	-1.9	-4.0	-4.0	-4.0	-4.2
				Double glazing (coated)	0.0	8.0	2.1	-2.3	-100.0	0.0	0.0	0.0	-7.1	-5.9	-6.4	-7.6	-53.6	-52.8	-53.8	-53.2	-3.9	-3.8	-4.1	-4.1	-14.1	-14.3	-15.0	-15.0	-1.5	-1.5	-1.5	-1.6	-4.2	-4.3	-4.1	-4.3
				Triple glazing (clear)	6.7	19.3	7.2	11.4	-100.0	-85.7	-72.7	-62.5	-5.2	-5.6	-6.3	-6.6	-49.2	-48.0	-49.8	-48.6	-3.8	-4.0	-4.3	-4.8	-14.8	-14.9	-16.3	-15.5	-1.3	-1.3	-1.3	-1.5	-3.5	-3.6	-3.5	-3.7
				Triple glazing (coated)	2.9	4.7	7.3	2.6	0.0	0.0	0.0	0.0	-6.8	-6.3	-6.8	-6.8	-57.9	-57.2	-57.7	-57.2	-3.7	-3.8	-3.8	-3.8	-14.9	-15.3	-15.4	-15.8	-1.3	-1.3	-1.2	-1.3	-3.9	-4.1	-3.9	-4.1
			Medium-weight	Double glazing (clear)	-25.0	16.7	-10.0	14.3	0.0	0.0	0.0	0.0	-15.6	-17.3	-17.5	-17.2	-49.5	-46.9	-48.9	-48.1	-4.9	-4.6	-5.2	-5.6	-15.0	-15.0	-16.2	-15.8	-1.7	-1.6	-1.6	-1.8	-3.8	-3.8	-3.7	-4.0
				Double glazing (coated)	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	-13.7	-12.6	-13.0	-13.3	-62.8	-61.2	-62.2	-62.2	-4.9	-4.8	-5.0	-4.9	-15.7	-15.8	-16.1	-16.0	-1.5	-1.5	-1.5	-1.5	-4.0	-4.1	-3.9	-4.1
				Triple glazing (clear)	-33.3	80.0	33.3	20.0	0.0	0.0	0.0	0.0	-16.2	-17.8	-19.5	-18.2	-56.2	-52.8	-55.1	-54.2	-4.7	-4.5	-4.9	-4.9	-16.1	-16.1	-17.0	-16.5	-1.3	-1.3	-1.3	-1.4	-3.3	-3.3	-3.3	-3.5
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-14.5	-13.6	-14.1	-14.1	-67.6	-66.4	-66.8	-66.8	-4.7	-4.7	-4.7	-4.8	-16.6	-16.9	-17.0	-17.1	-1.3	-1.3	-1.2	-1.3	-3.7	-3.8	-3.6	-3.8
			Heavy-weight	Double glazing (clear)	0.0	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	-17.8	-19.1	-17.8	-18.9	-53.7	-52.1	-53.7	-52.9	-4.9	-4.7	-5.3	-6.0	-15.8	-15.9	-17.2	-16.8	-1.7	-1.7	-1.7	-1.9	-4.0	-4.0	-4.0	-4.2
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-17.8	-16.9	-17.5	-18.0	-68.1	-66.5	-67.3	-66.8	-4.7	-4.7	-4.8	-5.0	-15.9	-16.2	-16.6	-16.8	-1.6	-1.6	-1.5	-1.7	-4.2	-4.2	-4.1	-4.3
				Triple glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-18.4	-18.2	-17.5	-18.7	-59.7	-58.4	-60.5	-57.7	-4.7	-4.6	-4.7	-5.3	-16.8	-16.9	-17.8	-17.4	-1.4	-1.3	-1.3	-1.4	-3.5	-3.5	-3.4	-3.6
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-18.6	-18.0	-18.6	-18.6	-73.7	-71.9	-72.4	-72.2	-4.6	-4.7	-4.7	-4.8	-16.8	-17.2	-17.4	-17.7	-1.3	-1.4	-1.3	-1.4	-3.8	-3.9	-3.8	-4.0
		Old building	Light-weight	Double glazing (clear)	-4.3	12.0	-4.7	-8.6	0.0	-50.0	-33.3	0.0	-7.6	-6.6	-8.6	-8.0	-33.7	-33.1	-32.1	-33.4	-3.8	-3.7	-4.2	-5.1	-10.2	-10.3	-11.2	-11.2	-2.1	-2.2	-2.1	-2.4	-4.9	-5.0	-4.9	-5.2
				Double glazing (coated)	0.0	-9.1	-5.0	-11.1	0.0	0.0	0.0	0.0	-6.1	-6.4	-6.9	-7.2	-40.4	-39.7	-40.2	-40.8	-3.7	-3.8	-4.1	-4.4	-10.8	-11.6	-11.8	-12.0	-2.0	-2.1	-2.0	-2.1	-5.2	-5.5	-5.2	-5.5
				Triple glazing (clear)	-4.3	10.3	0.0	-3.6	0.0	-100.0	0.0	0.0	-6.6	-5.9	-8.2	-7.1	-39.2	-36.7	-37.7	-36.1	-3.5	-3.5	-4.1	-4.5	-10.3	-10.3	-11.4	-11.2	-1.9	-2.0	-1.8	-2.0	-4.6	-4.8	-4.6	-4.8
				Triple glazing (coated)	-6.7	-5.3	-5.6	-5.9	0.0	0.0	0.0	0.0	-5.5	-6.0	-6.5	-6.1	-42.2	-44.6	-44.6	-44.6	-3.5	-3.9	-4.0	-4.1	-10.9	-12.0	-12.2	-12.6	-1.9	-2.0	-1.8	-1.9	-5.0	-5.4	-5.0	-5.3
			Medium-weight	Double glazing (clear)	0.0	-14.3	-25.0	50.0	0.0	0.0	0.0	0.0	-10.9	-11.6	-13.0	-12.4	-44.5	-42.6	-42.5	-43.0	-4.4	-4.5	-4.8	-5.5	-10.6	-11.2	-12.0	-12.1	-2.3	-2.3	-2.3	-2.5	-4.9	-5.0	-4.9	-5.2
				Double glazing (coated)	0.0	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	-9.7	-10.2	-11.1	-10.7	-55.9	-57.7	-57.4	-57.7	-4.4	-4.7	-5.0	-5.1	-10.6	-11.4	-11.8	-12.3	-2.3	-2.4	-2.2	-2.4	-5.3	-5.5	-5.2	-5.5
				Triple glazing (clear)	0.0	-33.3	200.0	0.0	0.0	0.0	0.0	0.0	-10.7	-13.0	-12.6	-12.7	-53.2	-51.1	-51.6	-48.9	-4.2	-4.3	-4.7	-5.2	-10.8	-11.6	-12.2	-12.4	-2.0	-2.1	-2.0	-2.2	-4.6	-4.7	-4.5	-4.8
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-10.1	-10.4	-11.2	-10.7	-59.3	-60.3	-60.3	-60.3	-4.3	-4.7	-4.8	-5.0	-10.7	-11.7	-12.1	-12.7	-2.1	-2.2	-2.0	-2.2	-5.0	-5.3	-5.0	-5.3
			Heavy-weight	Double glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-14.0	-14.3	-15.0	-15.2	-51.4	-50.4	-49.3	-50.2	-4.8	-4.8	-5.4	-6.0	-11.7	-12.3	-13.1	-13.6	-2.7	-2.7	-2.6	-2.9	-5.6	-5.8	-5.6	-5.9
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-12.7	-14.1	-14.7	-15.1	-69.7	-68.9	-69.8	-68.9	-4.8	-5.2	-5.4	-5.8	-11.6	-12.8	-13.2	-13.8	-2.7	-2.8	-2.6	-2.8	-6.0	-6.3	-5.9	-6.3
				Triple glazing (clear)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-13.9	-14.7	-16.0	-16.0	-60.1	-56.3	-56.0	-55.7	-4.7	-4.7	-5.1	-5.8	-11.9	-12.5	-13.3	-13.7	-2.4	-2.5	-2.4	-2.6	-5.3	-5.5	-5.3	-5.6
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-12.9	-14.9	-15.5	-15.3	-73.8	-74.7	-75.5	-74.5	-4.6	-5.2	-5.2	-5.7	-11.8	-12.8	-13.3	-14.2	-2.5	-2.7	-2.4	-2.7	-5.8	-6.2	-5.7	-6.1
Large window (wwr=0.25)	Small room (A=20 m^2)	New building	Light-weight	Double glazing (clear)	-38.5	-29.9	-37.1	-45.3	-95.6	-80.4	-79.0	-79.3	-34.5	-30.6	-33.7	-33.3	-58.8	-56.4	-58.0	-57.5	-14.8	-13.0	-16.8	-16.8	-23.8	-21.7	-30.3	-22.9	-4.8	-4.5	-4.9	-5.5	-5.0	-4.4	-5.0	-5.0
				Double glazing (coated)	-75.0	-22.2	-55.6	-71.4	0.0	-100.0	-100.0	-100.0	-44.3	-36.5	-42.3	-43.8	-87.7	-86.0	-86.2	-86.2	-15.8	-14.5	-16.1	-15.4	-27.4	-24.8	-26.8	-24.6	-4.1	-4.1	-4.2	-4.4	-8.1	-7.6	-8.1	-8.0
				Triple glazing (clear)	-43.3	-42.9	-39.4	-47.9	-100.0	-94.9	-92.7	-93.5	-39.1	-36.7	-37.9	-37.9	-73.4	-70.7	-73.3	-72.0	-16.6	-14.7	-19.0	-17.4	-29.7	-27.4	-37.2	-28.3	-4.2	-4.1	-4.3	-4.8	-4.6	-3.9	-4.4	-4.5
				Triple glazing (coated)	-75.0	-20.0	-40.0	-75.0	0.0	0.0	0.0	0.0	-48.8	-44.3	-46.2	-47.3	-98.4	-95.7	-95.7	-95.7	-16.3	-16.0	-16.7	-16.4	-31.7	-30.9	-32.6	-30.5	-3.4	-3.4	-3.4	-3.5	-8.1	-7.6	-7.9	-8.0
			Medium-weight	Double glazing (clear)	-72.7	-67.4	-62.5	-69.4	-100.0	-94.4	-92.6	-93.9	-43.3	-42.5	-44.5	-43.0	-64.4	-60.3	-64.1	-63.1	-15.7	-14.4	-18.5	-17.0	-25.0	-23.6	-32.5	-24.1	-4.3	-4.1	-4.5	-5.0	-5.0	-4.5	-5.1	-5.0
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-57.4	-52.9	-55.4	-56.3	-96.9	-94.8	-94.7	-94.9	-16.5	-15.6	-16.5	-16.2	-27.2	-25.9	-27.7	-26.0	-4.3	-4.2	-4.4	-4.5	-8.1	-7.6	-8.0	-7.9
				Triple glazing (clear)	-85.7	-78.6	-80.9	-78.1	-100.0	-98.8	-99.2	-100.0	-51.4	-50.0	-52.1	-52.0	-78.5	-74.0	-77.2	-76.0	-17.5	-16.5	-20.3	-18.7	-31.1	-29.7	-38.3	-29.7	-3.7	-3.6	-3.9	-4.2	-4.3	-3.9	-4.4	-4.2
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-65.2	-63.6	-64.6	-65.3	-100.0	-100.0	-100.0	-100.0	-17.8	-17.3	-18.0	-17.5	-32.7	-31.3	-33.2	-31.5	-3.6	-3.5	-3.6	-3.6	-7.9	-7.7	-7.9	-7.9
			Heavy-weight	Double glazing (clear)	-100.0	-69.6	-74.5	-76.7	-100.0	-98.6	-97.4	-96.3	-46.9	-43.4	-46.1	-45.8	-68.3	-62.6	-65.2	-64.6	-16.2	-15.0	-18.7	-17.0	-25.8	-24.2	-32.7	-24.7	-4.2	-3.8	-4.3	-4.8	-5.1	-4.5	-5.1	-5.1
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-65.3	-60.6	-62.0	-62.3	-100.0	-100.0	-100.0	-100.0	-16.3	-15.1	-16.5	-16.1	-27.7	-26.5	-28.5	-26.7	-4.4	-4.3	-4.5	-4.6	-8.2	-7.8	-8.1	-8.1
				Triple glazing (clear)	-100.0	-84.6	-86.2	-87.5	-100.0	-100.0	-100.0	-100.0	-54.7	-51.6	-54.3	-53.5	-82.6	-76.5	-80.5	-78.2	-17.8	-16.9	-20.3	-19.2	-31.8	-30.3	-38.9	-30.5	-3.6	-3.3	-3.7	-4.0	-4.3	-3.9	-4.3	-4.2
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-74.7	-70.9	-73.3	-71.8	-100.0	-100.0	-100.0	-100.0	-17.5	-17.2	-17.8	-17.2	-32.4	-32.2	-33.3	-32.4	-3.7	-3.5	-3.7	-3.7	-8.0	-7.7	-8.0	-8.0
		Old building	Light-weight	Double glazing (clear)	-47.6	-12.1	-33.0	-42.2	-92.3	-62.8	-73.0	-67.9	-30.1	-24.6	-31.4	-29.8	-51.3	-48.1	-52.8	-49.5	-12.8	-10.6	-14.8	-14.6	-18.4	-16.4	-21.5	-18.0	-4.5	-4.3	-4.7	-5.1	-5.1	-4.6	-5.2	-5.2
				Double glazing (coated)	-100.0	-50.0	-60.0	-75.0	0.0	0.0	-100.0	-100.0	-41.9	-36.1	-39.0	-41.1	-82.5	-76.5	-77.9	-80.0	-13.3	-12.5	-13.5	-13.7	-22.1	-20.5	-22.3	-20.8	-4.2	-4.1	-4.2	-4.5	-8.1	-7.9	-8.0	-8.2
				Triple glazing (clear)	-35.7	-27.0	-33.3	-46.3	-100.0	-88.9	-91.1	-90.9	-35.1	-30.0	-34.2	-35.5	-65.7	-61.5	-64.3	-62.1	-13.6	-11.9	-15.7	-15.1	-21.1	-19.8	-23.8	-20.3	-4.0	-3.9	-4.2	-4.6	-4.8	-4.3	-4.7	-4.8
				Triple glazing (coated)	-100.0	-75.0	-66.7	-100.0	0.0	0.0	0.0	0.0	-44.4	-42.0	-42.4	-40.9	-92.9	-89.6	-91.5	-89.6	-13.4	-13.6	-14.3	-13.8	-24.6	-24.3	-25.2	-23.4	-3.6	-3.6	-3.6	-3.7	-8.2	-8.1	-8.1	-8.3
			Medium-weight	Double glazing (clear)	-80.0	-30.0	-45.9	-58.3	-100.0	-86.4	-84.8	-85.2	-40.3	-36.6	-39.7	-38.4	-60.2	-54.1	-58.0	-55.1	-13.3	-11.5	-15.0	-14.5	-19.7	-18.2	-23.0	-19.4	-4.2	-4.0	-4.4	-4.9	-5.4	-5.0	-5.5	-5.4
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-52.1	-47.7	-50.5	-50.5	-93.2	-89.3	-89.1	-91.1	-14.2	-13.6	-14.6	-14.5	-22.0	-21.4	-22.8	-21.6	-4.5	-4.4	-4.6	-4.6	-8.4	-8.1	-8.2	-8.3
				Triple glazing (clear)	-100.0	-45.5	-52.9	-66.7	-100.0	-100.0	-96.0	-100.0	-46.5	-43.0	-45.5	-45.3	-75.0	-67.6	-72.5	-70.4	-14.5	-13.2	-16.2	-15.7	-22.9	-21.8	-26.0	-22.1	-3.8	-3.6	-3.9	-4.3	-4.8	-4.5	-4.8	-4.7
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-58.4	-56.5	-58.3	-57.6	-100.0	-100.0	-97.2	-100.0	-15.0	-15.0	-15.4	-15.1	-24.2	-24.3	-25.7	-24.3	-3.9	-3.9	-3.9	-4.0	-8.2	-8.2	-8.3	-8.3
			Heavy-weight	Double glazing (clear)	-100.0	-30.0	-35.3	-54.5	0.0	-85.7	-88.5	-90.9	-43.0	-37.2	-41.8	-41.3	-63.1	-54.9	-59.1	-58.0	-13.3	-12.1	-14.9	-14.6	-20.5	-19.3	-23.9	-20.3	-4.2	-3.9	-4.4	-4.8	-5.6	-5.1	-5.7	-5.6
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-58.8	-54.3	-57.0	-56.5	-100.0	-95.7	-97.8	-97.8	-14.4	-13.9	-14.8	-14.6	-22.5	-21.6	-23.8	-22.1	-4.8	-4.7	-4.8	-5.0	-8.8	-8.5	-8.7	-8.8
				Triple glazing (clear)	0.0	-83.3	-57.1	-80.0	0.0	-100.0	-100.0	-100.0	-50.5	-46.2	-50.4	-48.1	-81.0	-73.4	-75.9	-72.4	-14.5	-13.4	-15.9	-16.1	-23.6	-22.8	-26.8	-23.2	-3.7	-3.7	-3.9	-4.2	-5.0	-4.7	-5.1	-5.0
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-66.7	-63.9	-65.7	-64.8	-100.0	-100.0	-100.0	-100.0	-14.9	-14.9	-15.5	-15.2	-24.6	-25.2	-26.0	-25.5	-4.3	-4.2	-4.2	-4.4	-8.7	-8.6	-8.7	-8.8
	Big room (A=20 m^2)	New building	Light-weight	Double glazing (clear)	-22.6	-16.5	-30.8	-27.8	-87.0	-73.3	-76.3	-79.6	-18.9	-16.9	-21.6	-20.0	-43.8	-42.0	-43.4	-42.9	-8.6	-7.7	-10.4	-10.3	-16.4	-15.8	-20.4	-17.3	-2.8	-2.7	-2.9	-3.3	-4.6	-4.4	-4.7	-4.9
				Double glazing (coated)	-42.9	-13.6	-30.6	-38.7	-100.0	-100.0	-100.0	-100.0	-20.9	-18.1	-18.2	-19.2	-61.0	-59.0	-60.6	-59.1	-8.2	-7.8	-8.3	-8.5	-17.0	-16.4	-17.0	-16.5	-2.4	-2.3	-2.4	-2.5	-5.1	-5.0	-5.1	-5.2
				Triple glazing (clear)	-18.4	-15.0	-28.0	-27.1	-100.0	-91.2	-94.1	-92.1	-18.6	-18.6	-21.3	-21.1	-53.6	-51.8	-53.8	-52.3	-8.6	-7.5	-9.8	-9.8	-18.6	-17.6	-22.3	-19.0	-1.9	-1.9	-2.0	-2.3	-3.3	-3.1	-3.4	-3.5
				Triple glazing (coated)	-42.6	-21.7	-30.8	-27.3	0.0	-100.0	-100.0	-100.0	-21.1	-19.5	-20.3	-19.3	-71.9	-70.3	-71.9	-70.7	-7.7	-7.6	-8.0	-7.8	-18.3	-18.1	-18.5	-18.3	-1.6	-1.5	-1.6	-1.6	-3.8	-3.8	-3.9	-3.9
			Medium-weight	Double glazing (clear)	-62.5	-31.8	-42.3	-53.4	-100.0	-89.7	-87.8	-88.3	-23.6	-24.0	-25.9	-24.8	-45.9	-45.1	-46.2	-46.0	-8.4	-8.0	-10.0	-10.2	-16.8	-16.4	-20.6	-17.6	-2.8	-2.6	-2.8	-3.2	-4.6	-4.4	-4.7	-4.9
				Double glazing (coated)	-100.0	-75.0	-57.1	-83.3	0.0	0.0	0.0	0.0	-27.4	-25.9	-26.5	-27.3	-69.1	-66.0	-68.4	-68.0	-8.8	-8.7	-8.8	-8.6	-18.0	-17.4	-17.9	-17.3	-2.4	-2.4	-2.5	-2.6	-5.1	-4.9	-5.0	-5.1
				Triple glazing (clear)	-58.8	-39.5	-48.3	-55.6	-100.0	-100.0	-99.1	-100.0	-28.3	-26.1	-28.7	-27.1	-55.2	-53.8	-57.3	-55.7	-8.4	-7.9	-9.3	-9.8	-19.1	-18.4	-22.3	-19.7	-1.8	-1.7	-1.9	-2.1	-3.2	-3.0	-3.2	-3.3
				Triple glazing (coated)	-100.0	0.0	-66.7	-50.0	0.0	0.0	0.0	0.0	-28.5	-28.0	-27.5	-29.6	-80.2	-79.1	-78.7	-79.1	-8.6	-8.3	-8.7	-8.6	-19.6	-19.4	-19.7	-19.4	-1.6	-1.6	-1.6	-1.6	-3.7	-3.7	-3.7	-3.8
			Heavy-weight	Double glazing (clear)	-87.5	-27.3	-33.3	-58.1	0.0	-100.0	-100.0	-100.0	-25.9	-26.0	-26.8	-27.1	-49.6	-47.1	-48.8	-47.5	-8.6	-8.4	-10.2	-10.5	-17.5	-17.0	-20.9	-18.2	-2.7	-2.5	-2.8	-3.2	-4.6	-4.3	-4.7	-4.9
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-29.4	-26.9	-29.9	-28.9	-73.4	-70.9	-71.9	-71.3	-8.8	-8.3	-8.8	-8.7	-18.0	-17.7	-18.4	-18.2	-2.5	-2.5	-2.5	-2.6	-5.2	-5.0	-5.1	-5.2
				Triple glazing (clear)	-75.0	-50.0	-40.9	-56.3	0.0	-100.0	-100.0	-100.0	-28.2	-28.9	-30.5	-28.5	-60.1	-55.7	-58.9	-58.1	-8.5	-7.8	-9.2	-10.1	-19.8	-19.2	-22.7	-20.2	-1.8	-1.7	-1.9	-2.1	-3.3	-2.9	-3.2	-3.4
				Triple glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-33.3	-31.9	-32.5	-33.0	-86.7	-83.5	-84.9	-84.0	-8.1	-8.0	-8.3	-8.3	-19.6	-19.8	-20.1	-19.7	-1.6	-1.6	-1.6	-1.7	-3.8	-3.7	-3.8	-3.9
		Old building	Light-weight	Double glazing (clear)	-27.4	-12.4	-34.5	-35.7	-86.7	-45.2	-51.6	-54.5	-17.7	-14.8	-19.0	-18.7	-37.2	-33.8	-36.8	-36.2	-7.1	-6.2	-7.7	-9.0	-12.1	-10.6	-13.0	-12.5	-2.7	-2.5	-2.8	-3.2	-4.5	-4.3	-4.6	-4.7
				Double glazing (coated)	-26.3	-25.0	-26.7	-34.6	0.0	-100.0	0.0	0.0	-18.0	-16.1	-17.8	-18.3	-56.4	-52.0	-54.5	-54.0	-6.9	-6.4	-7.1	-7.1	-13.3	-13.2	-13.4	-12.7	-2.3	-2.3	-2.3	-2.5	-5.0	-4.9	-5.0	-5.1
				Triple glazing (clear)	-32.2	4.4	-34.0	-29.5	-100.0	-40.9	-45.2	-40.7	-18.5	-14.4	-18.8	-20.0	-46.5	-43.8	-45.2	-44.3	-6.5	-5.6	-7.3	-8.0	-12.2	-11.2	-12.7	-12.1	-1.9	-1.8	-2.0	-2.3	-3.3	-3.2	-3.4	-3.5
				Triple glazing (coated)	-30.0	-16.0	-18.2	-28.6	0.0	0.0	0.0	0.0	-18.2	-18.5	-18.2	-18.4	-61.7	-59.4	-61.0	-60.6	-6.2	-6.2	-6.6	-6.5	-13.0	-13.1	-13.5	-13.2	-1.6	-1.6	-1.6	-1.7	-3.9	-4.0	-3.9	-4.0
			Medium-weight	Double glazing (clear)	-58.3	-21.6	-37.8	-46.9	0.0	-77.8	-37.5	-16.7	-22.1	-20.8	-22.8	-23.0	-38.8	-35.2	-38.9	-38.2	-7.3	-6.1	-7.6	-8.5	-12.3	-11.4	-13.5	-13.3	-2.7	-2.5	-2.7	-3.1	-4.7	-4.5	-4.8	-5.0
				Double glazing (coated)	0.0	0.0	-33.3	-50.0	0.0	0.0	0.0	0.0	-23.2	-22.2	-24.4	-24.1	-67.3	-66.2	-66.1	-66.7	-7.4	-7.1	-7.6	-7.7	-13.0	-12.8	-13.5	-13.2	-2.5	-2.5	-2.5	-2.6	-5.0	-5.0	-5.0	-5.2
				Triple glazing (clear)	-33.3	-31.8	-44.0	-50.0	0.0	-100.0	-50.0	0.0	-23.8	-23.2	-24.1	-24.5	-51.3	-47.7	-52.1	-48.5	-7.1	-6.1	-7.1	-8.0	-13.1	-12.1	-13.5	-13.0	-1.9	-1.8	-1.9	-2.2	-3.4	-3.3	-3.4	-3.6
				Triple glazing (coated)	0.0	-50.0	-100.0	-100.0	0.0	0.0	0.0	0.0	-24.8	-24.2	-25.3	-24.3	-75.7	-74.8	-75.7	-76.2	-6.8	-6.8	-7.1	-6.9	-12.6	-12.8	-13.3	-13.0	-1.7	-1.8	-1.7	-1.8	-3.9	-4.0	-3.9	-4.0
			Heavy-weight	Double glazing (clear)	-100.0	-25.0	-22.7	-42.9	0.0	0.0	0.0	0.0	-22.8	-22.2	-23.3	-23.5	-44.7	-37.3	-40.0	-41.2	-7.3	-6.5	-7.5	-8.5	-13.0	-12.6	-14.1	-13.8	-2.7	-2.5	-2.8	-3.2	-4.9	-4.7	-4.9	-5.1
				Double glazing (coated)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-26.9	-25.9	-25.8	-26.9	-76.9	-74.5	-75.2	-74.5	-7.4	-7.1	-7.6	-8.0	-13.1	-13.2	-14.1	-13.5	-2.6	-2.6	-2.6	-2.8	-5.3	-5.3	-5.3	-5.5
				Triple glazing (clear)	0.0	-50.0	-44.4	-66.7	0.0	0.0	0.0	0.0	-25.4	-24.7	-26.4	-26.6	-56.5	-51.3	-53.8	-51.5	-7.1	-5.7	-6.7	-8.0	-13.5	-13.1	-14.2	-13.9	-1.9	-1.8	-2.0	-2.3	-3.6	-3.4	-3.5	-3.7
				Triple glazing (coated)	0.0	-100.0	0.0	0.0	0.0	0.0	0.0	0.0	-28.9	-28.3	-28.8	-28.9	-88.6	-86.6	-87.2	-86.4	-6.8	-6.9	-7.1	-7.2	-12.7	-13.2	-13.6	-13.4	-1.9	-1.9	-1.9	-2.0	-4.2	-4.2	-4.2	-4.3

17.5. TABLE 4: ABSOLUTE REDUCTION OF COOLING ENERGY DEMAND

TABLE 4: ABSOLUTE REDUCTION OF COOLING ENERGY DEMAND (KWH/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Room size ↓	Window size ↓	Type of glazing ↓	Age ↓	Orientation / Building method	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=$20m^2$)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	-4	-6	-3	-1	2	8	13	8	40	38	47	45	84	96	103	99	85	86	100	116	139	159	187	194	65	68	66	73	90	91	88	95
				Medium-weight	0	1	1	1	0	1	2	2	56	62	65	61	91	104	111	107	89	95	106	121	145	169	197	208	64	65	64	70	85	85	84	89
				Heavy-weight	0	0	1	0	0	0	0	0	55	64	65	64	90	108	111	108	92	99	111	128	150	178	206	217	65	66	65	72	88	90	85	93
			Old building	Light-weight	0	-4	-1	1	0	1	1	1	28	24	33	34	47	56	60	57	81	87	97	119	124	138	154	171	90	95	89	99	130	135	129	139
				Medium-weight	0	0	1	0	0	0	0	0	39	43	46	44	53	63	65	64	89	97	109	125	128	147	163	180	95	101	96	105	131	137	130	140
				Heavy-weight	0	0	0	0	0	0	0	0	37	47	47	45	50	63	61	64	93	105	113	135	132	159	177	198	109	115	108	120	149	156	146	158
		Double glazing (coated)	New building	Light-weight	0	-2	-2	-1	0	0	0	0	28	28	31	29	47	52	53	52	68	72	74	82	112	121	127	131	53	54	52	55	86	90	85	90
				Medium-weight	0	0	0	0	0	0	0	0	37	38	39	39	44	49	49	50	75	78	81	83	114	122	128	134	53	54	53	56	82	85	81	85
				Heavy-weight	0	0	0	0	0	0	0	0	37	37	39	39	38	46	46	46	74	78	82	86	114	122	129	135	56	58	55	59	85	87	83	88
			Old building	Light-weight	0	0	0	0	0	0	0	0	21	24	23	25	25	31	31	31	69	77	81	87	110	122	128	135	80	85	79	84	129	136	127	136
				Medium-weight	0	0	0	0	0	0	0	0	24	27	28	28	20	27	27	27	78	87	91	98	107	121	126	135	89	94	87	94	130	137	128	137
				Heavy-weight	0	0	0	0	0	0	0	0	23	27	27	27	16	24	24	24	83	94	98	108	116	130	135	147	104	110	101	111	147	156	145	155
		Triple glazing (clear)	New building	Light-weight	-4	-6	-6	-4	1	5	9	6	38	36	43	45	83	95	99	94	81	84	95	103	137	154	177	180	53	56	54	59	79	82	78	83
				Medium-weight	0	1	1	1	0	0	0	0	51	55	61	59	90	102	106	102	84	87	96	107	144	160	184	192	52	54	52	56	75	76	72	77
				Heavy-weight	0	0	0	0	0	0	0	0	52	59	62	60	85	102	105	101	88	92	99	112	146	165	190	198	54	55	53	58	77	79	76	81
			Old building	Light-weight	0	-2	0	0	0	0	0	0	26	25	33	31	46	52	55	55	75	81	92	105	120	132	143	154	80	86	80	87	122	128	119	129
				Medium-weight	0	0	0	0	0	0	0	0	33	41	42	41	45	55	56	57	84	94	100	112	120	138	153	165	87	92	86	94	121	128	118	129
				Heavy-weight	0	0	0	0	0	0	0	0	34	43	45	41	43	56	54	56	88	99	105	123	127	148	165	182	101	107	99	109	139	147	136	146
		Triple glazing (coated)	New building	Light-weight	0	-1	-1	-1	0	0	0	0	26	27	27	29	46	50	50	49	65	69	71	71	111	120	122	127	48	50	46	50	82	85	80	85
				Medium-weight	0	0	0	0	0	0	0	0	36	38	38	38	42	47	47	47	72	75	77	79	114	121	125	129	47	50	46	49	78	80	76	80
				Heavy-weight	0	0	0	0	0	0	0	0	35	37	38	38	35	40	40	40	72	76	78	81	112	119	124	129	50	53	49	52	80	83	78	82
			Old building	Light-weight	0	0	0	0	0	0	0	0	19	22	21	22	23	28	28	28	66	75	78	82	107	120	124	129	76	82	74	80	124	132	122	132
				Medium-weight	0	0	0	0	0	0	0	0	24	26	26	27	18	23	23	23	76	85	88	93	104	116	121	127	85	91	83	89	124	133	122	132
				Heavy-weight	0	0	0	0	0	0	0	0	21	25	26	26	12	19	19	19	81	93	95	104	111	126	131	142	100	107	98	106	141	151	139	150
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	15	26	53	43	43	86	124	96	116	130	151	136	177	221	240	229	173	184	268	283	236	276	441	374	117	119	121	141	107	102	108	115
				Medium-weight	8	29	45	34	26	84	126	92	125	156	167	154	188	232	257	243	178	200	275	283	247	302	471	394	110	110	115	133	109	105	111	117
				Heavy-weight	4	16	38	23	14	70	112	77	130	152	165	158	194	236	255	243	182	207	274	283	254	309	471	403	106	104	111	128	110	105	111	118
			Old building	Light-weight	10	7	32	27	12	27	54	36	87	92	122	106	117	142	163	150	152	151	231	245	187	208	295	291	114	116	120	137	117	113	119	127
				Medium-weight	4	6	17	14	2	19	39	23	100	115	127	118	130	153	170	157	156	162	222	242	199	233	312	312	112	112	117	134	125	124	127	135
				Heavy-weight	2	3	6	6	0	6	23	10	101	111	127	121	130	150	166	159	155	171	219	245	206	248	323	327	111	110	118	135	131	129	132	140
		Double glazing (coated)	New building	Light-weight	3	2	5	5	0	1	2	2	62	57	66	67	64	74	75	75	124	123	139	141	152	154	168	173	72	74	74	78	104	102	105	107
				Medium-weight	0	0	0	0	0	0	0	0	62	64	67	67	63	73	72	74	124	128	136	143	148	159	171	181	76	76	78	81	104	102	103	106
				Heavy-weight	0	0	0	0	0	0	0	0	62	66	67	66	57	70	67	70	120	121	133	140	148	161	174	184	79	78	80	84	106	105	104	108
			Old building	Light-weight	2	3	3	3	0	0	1	1	54	53	57	58	47	52	53	56	111	113	123	132	138	142	155	160	78	79	79	85	116	117	115	121
				Medium-weight	0	0	0	0	0	0	0	0	49	51	54	53	41	50	49	51	116	120	129	137	134	145	155	164	85	86	87	90	121	121	119	124
				Heavy-weight	0	0	0	0	0	0	0	0	47	51	53	52	34	44	44	45	116	121	129	137	135	145	160	166	91	92	92	97	127	128	125	132
		Triple glazing (clear)	New building	Light-weight	13	27	39	34	46	93	127	100	111	128	138	128	196	241	263	247	166	175	248	241	242	282	441	367	89	92	93	107	79	73	76	83
				Medium-weight	6	22	38	25	33	84	118	90	125	150	159	153	205	248	271	254	169	190	247	253	252	306	452	384	81	82	85	96	74	73	77	77
				Heavy-weight	2	11	25	14	23	66	103	74	128	147	158	151	209	251	276	255	169	193	243	260	256	311	457	393	78	77	81	91	75	72	74	77
			Old building	Light-weight	5	10	20	19	7	24	41	30	84	90	105	102	119	142	155	146	140	143	202	209	174	202	259	257	89	92	93	107	89	86	89	96
				Medium-weight	3	5	9	8	1	11	24	15	94	107	115	110	129	150	166	157	145	156	199	215	188	223	279	279	86	88	90	103	91	91	91	94
				Heavy-weight	0	5	4	4	0	2	8	3	96	108	120	111	132	157	167	155	144	157	192	220	193	233	287	293	86	89	90	102	95	96	96	101
		Triple glazing (coated)	New building	Light-weight	3	1	2	3	0	0	0	0	60	58	60	61	61	67	67	67	110	114	119	122	139	146	154	157	52	53	52	55	83	80	81	84
				Medium-weight	0	0	0	0	0	0	0	0	60	63	64	64	54	62	60	62	114	117	122	124	141	146	155	160	55	55	55	56	81	81	81	82
				Heavy-weight	0	0	0	0	0	0	0	0	59	61	63	61	46	55	53	55	109	113	117	119	137	148	153	163	56	55	56	58	81	80	81	83
			Old building	Light-weight	2	3	2	2	0	0	0	0	48	50	50	47	39	43	43	43	98	104	110	110	124	131	136	136	59	61	59	62	96	97	95	99
				Medium-weight	0	0	0	0	0	0	0	0	45	48	49	49	31	37	35	37	106	111	114	117	119	128	135	138	65	67	65	68	96	99	97	99
				Heavy-weight	0	0	0	0	0	0	0	0	42	46	46	46	24	29	28	30	103	108	113	116	119	131	135	143	72	72	70	74	102	103	102	106
Big room (A=$100m^2$)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	-9	-13	-1	2	5	8	13	9	41	49	64	53	181	200	210	203	145	161	174	207	307	338	386	402	127	129	127	142	201	206	198	216
				Medium-weight	1	-2	1		0	0	0	0	93	112	115	110	193	209	221	214	159	159	181	203	322	356	393	416	125	126	124	137	190	193	186	202
				Heavy-weight	0	0	0	1	0	0	0	0	95	111	103	109	189	214	224	217	154	159	180	215	338	377	415	442	129	130	129	143	198	204	197	213
			Old building	Light-weight	1	-6	2	3	0	1	1	0	52	50	64	58	89	101	99	103	141	147	165	209	255	279	306	332	175	183	174	195	284	297	282	307
				Medium-weight	0	1	1	-1	0	0	0	0	54	63	72	67	98	113	111	114	157	171	184	219	258	299	321	353	189	197	187	209	286	299	282	309
				Heavy-weight	0	0	0	0	0	0	0	0	61	70	73	73	92	116	111	114	168	179	201	235	283	324	347	393	221	229	217	243	327	347	323	353
		Double glazing (coated)	New building	Light-weight	0	-4	-1	1	1	0	0	0	46	40	43	51	142	150	154	151	123	124	134	135	262	275	290	301	105	108	102	110	182	188	179	190
				Medium-weight	0	-1	0	0	0	0	0	0	63	61	63	64	145	153	156	155	146	145	150	152	287	300	306	316	104	107	102	108	171	177	169	178
				Heavy-weight	0	0	0	0	0	0	0	0	72	72	74	76	139	147	148	147	136	139	142	150	286	304	313	329	111	113	107	116	178	183	175	186
			Old building	Light-weight	0	2	1	2	0	0	0	0	34	38	41	42	67	73	74	75	126	134	144	157	239	265	272	286	155	165	151	163	267	284	264	284
				Medium-weight	-1	0	3	0	0	0	0	0	38	42	46	44	66	79	78	79	146	158	168	177	228	255	265	285	173	184	169	183	268	284	266	285
				Heavy-weight	0	0	0	0	0	0	0	0	42	50	52	53	62	73	74	73	155	171	178	197	246	282	293	318	206	219	201	219	307	328	303	327
		Triple glazing (clear)	New building	Light-weight	-4	-17	-6	-8	5	6	8	5	39	45	51	52	186	201	212	204	125	140	151	172	301	328	365	372	97	99	96	107	165	172	164	175
				Medium-weight	1	-4	-2	-1	0	0	0	0	90	106	118	108	200	210	222	215	146	146	160	165	322	349	374	390	94	94	91	102	155	159	151	164
				Heavy-weight	0	-1	-1	0	0	0	0	0	91	96	92	98	190	212	222	209	142	145	151	175	333	365	390	409	99	98	96	106	161	166	159	171
			Old building	Light-weight	1	-4	0	1	0	2	0	0	42	41	57	48	91	97	100	96	126	131	154	175	241	259	288	301	148	157	146	162	249	264	248	268
				Medium-weight	0	1	-2	-1	0	0	0	0	49	66	64	63	100	114	114	109	145	153	168	193	247	284	302	329	161	170	159	176	251	264	247	267
				Heavy-weight	0	0	0	0	0	0	0	0	56	66	71	71	92	103	102	102	159	165	180	213	270	306	326	360	193	203	188	210	290	308	287	311
		Triple glazing (coated)	New building	Light-weight	-1	-2	-3	-1	0	0	0	0	43	41	44	44	150	155	157	155	113	117	119	120	263	277	280	293	88	91	84	90	161	169	159	169
				Medium-weight	0	0	0	-1	0	0	0	0	65	63	65	65	152	158	159	159	135	137	137	140	288	302	304	313	85	89	82	88	150	156	148	157
				Heavy-weight	0	0	0	0	0	0	0	0	73	73	75	75	146	151	152	151	127	131	132	138	288	303	306	321	91	94	88	94	156	162	153	164
			Old building	Light-weight	1	1	1	1	0	0	0	0	30	34	37	34	65	75	75	75	117	132	137	140	231	260	265	281	140	150	136	146	247	265	244	262
				Medium-weight	0	-1	0	0	0	0	0	0	38	41	44	42	64	73	73	73	138	153	156	165	219	248	256	276	157	168	151	165	247	264	244	262
				Heavy-weight	0	0	0	0	0	0	0	0	41	50	52	51	59	71	71	70	145	166	168	185	238	268	278	306	190	203	183	201	285	306	281	303
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	33	39	108	69	47	107	171	133	222	234	308	268	350	410	437	423	376	381	551	567	518	598	827	789	258	257	265	310	322	325	332	360
				Medium-weight	15	21	44	39	12	70	137	83	218	259	283	263	353	427	449	436	347	376	488	537	528	622	828	802	257	251	264	304	324	327	333	360
				Heavy-weight	7	9	14	18	0	26	94	43	222	259	271	269	369	432	458	435	351	388	486	546	546	643	833	828	256	247	265	305	326	320	331	363
			Old building	Light-weight	20	19	70	51	13	19	32	30	180	181	233	217	209	230	259	252	320	313	406	503	405	415	524	580	262	256	268	315	345	349	356	381
				Medium-weight	7	8	17	15	0	7	6	2	176	194	213	210	200	224	251	245	318	300	378	461	410	446	539	613	264	256	270	314	364	367	372	403
				Heavy-weight	1	4	5	6	0	0	0	0	167	190	200	198	212	224	242	247	314	314	367	460	428	489	556	630	270	262	279	325	376	382	382	415
		Double glazing (coated)	New building	Light-weight	21	11	22	24	3	5	4	6	156	145	143	148	189	203	209	204	287	284	306	322	366	379	397	415	180	179	182	191	256	256	255	268
				Medium-weight	2	6	4	5	0	0	0	0	146	148	152	154	188	202	210	208	288	299	304	308	383	398	412	429	185	185	188	197	254	254	250	264
				Heavy-weight	0	0	0	0	0	0	0	0	139	136	152	145	179	195	194	196	281	278	295	304	379	402	420	448	190	191	192	202	258	257	258	268
			Old building	Light-weight	5	9	8	9	0	1	0	0	117	114	125	126	124	128	133	134	256	250	277	285	331	348	354	357	187	187	190	202	283	286	285	298
				Medium-weight	0	0	1	1	0	0	0	0	107	112	122	119	113	129	127	130	264	264	282	298	316	330	349	366	202	205	204	216	289	292	287	303
				Heavy-weight	0	0	0	0	0	0	0	0	107	113	111	116	100	117	115	117	259	261	277	305	311	336	359	368	216	218	217	229	305	311	302	320
		Triple glazing (clear)	New building	Light-weight	23	27	70	52	43	104	160	117	196	224	261	247	376	432	461	439	343	329	451	470	509	564	758	716	163	161	170	198	200	197	206	219
				Medium-weight	10	17	29	25	7	53	110	69	235	241	266	246	373	435	474	450	313	326	396	445	518	587	750	739	156	152	162	187	191	187	192	210
				Heavy-weight	3	9	9	9	0	11	56	29	211	247	261	240	393	436	470	454	310	317	382	454	533	610	758	753	154	149	160	185	196	186	191	211
			Old building	Light-weight	19	-5	48	31	6	9	14	11	167	150	196	200	212	236	248	242	271	252	340	394	357	371	430	462	170	169	176	207	222	222	229	244
				Medium-weight	2	7	11	9	0	3	2	0	165	182	190	189	213	240	264	244	283	265	314	378	376	399	451	495	170	166	174	204	228	230	228	250
				Heavy-weight	0	4	4	4	0	0	0	0	160	176	189	188	212	238	250	239	277	243	290	377	385	430	473	525	177	172	182	211	240	240	236	261
		Triple glazing (coated)	New building	Light-weight	20	15	20	15	0	1	1	1	147	143	148	138	207	215	220	217	248	250	265	264	347	358	367	379	111	110	111	114	170	171	171	176
				Medium-weight	1	0	2	1	0	0	0	0	140	145	141	152	203	216	214	216	258	258	269	274	368	380	385	397	113	111	114	117	164	166	164	169
				Heavy-weight	0	0	0	0	0	0	0	0	144	145	146	149	195	203	203	204	238	241	249	257	363	382	388	400	116	114	112	119	167	165	166	171
			Old building	Light-weight	6	4	4	6	0	0	0	0	109	118	115	116	113	117	119	120	215	222	236	237	288	300	310	314	122	124	121	129	201	204	198	207
				Medium-weight	0	1	1	1	0	0	0	0	105	107	112	107	103	113	112	115	227	231	241	239	271	286	297	303	133	136	133	140	201	205	198	209
				Heavy-weight	0	1	0	0	0	0	0	0	103	107	108	109	93	103	102	102	221	230	236	246	269	289	298	307	146	147	144	153	213	217	212	222

17.6. TABLE 5: RELATIVE CHANGE IN ENERGY DEMAND FOR ARTIFICIAL LIGHTING

TABLE 5: RELATIVE CHANGE IN ENERGY DEMAND FOR ARTIFICIAL LIGHTING (%)			Climate →	Cold climate				Temperate climate				Dry climate				Tropical climate			
Building function ↓	Room size ↓	Window size ↓	Orientation / Type of glazing	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Office	Small room (A=20m²)	Small window (wwr=0.25)	Clear	77.4	61.0	36.1	58.4	122.3	93.6	64.9	98.3	153.3	102.3	43.1	95.9	131.1	133.7	140.5	141.6
			Coated	130.1	147.2	186.7	151.2	139.7	170.8	215.2	167.0	177.3	220.5	338.3	452.7	263.1	251.4	278.3	271.7
		Large window (wwr=0.75)	Clear	44.6	35.6	21.4	34.2	64.6	44.9	32.0	52.0	13.0	6.7	2.5	6.8	12.7	20.0	12.3	22.9
			Coated	57.6	49.9	45.4	54.0	84.4	73.6	75.4	78.7	151.2	118.2	102.5	105.0	223.7	149.7	223.0	188.2
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	37.6	41.9	48.7	44.1	51.5	62.0	79.4	61.9	116.0	120.7	134.3	94.2	198.6	138.5	192.3	159.0
			Coated	6.4	12.3	26.1	14.1	7.9	15.1	21.0	14.9	12.8	22.1	36.9	36.1	20.9	28.2	21.3	26.7
		Large window (wwr=0.75)	Clear	71.7	54.9	35.8	57.8	108.6	81.8	64.5	90.9	123.1	65.0	30.6	76.9	123.8	112.7	128.5	145.0
			Coated	16.8	26.4	46.9	30.6	21.4	38.3	62.2	39.6	38.9	62.8	97.9	63.0	80.3	79.7	78.3	87.6
Residence	Small room (A=20m²)	Small window (wwr=0.25)	Clear	20.3	17.4	16.5	16.2	22.1	18.8	19.2	16.6	11.5	8.4	11.2	9.2	14.9	12.7	14.6	15.6
			Coated	21.4	16.6	15.9	19.4	24.8	19.7	17.1	23.5	26.6	22.6	16.5	16.3	18.9	19.1	18.9	17.3
		Large window (wwr=0.75)	Clear	10.1	11.8	9.9	9.0	9.8	12.2	10.8	8.8	2.8	2.0	2.6	3.1	12.3	12.7	12.5	11.1
			Coated	21.0	17.3	16.0	16.0	24.6	18.9	17.4	16.8	15.4	11.2	11.8	8.9	11.7	12.3	11.7	10.8
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	24.3	18.7	17.0	19.8	28.0	21.0	18.8	22.0	20.8	16.9	13.5	12.1	14.3	14.7	14.3	13.8
			Coated	7.8	10.5	12.4	13.1	9.1	12.8	15.0	16.7	12.7	17.5	17.5	15.3	16.0	16.2	15.7	16.5
		Large window (wwr=0.75)	Clear	18.3	16.3	15.6	13.5	20.6	17.4	18.0	13.3	9.3	7.6	10.1	6.2	13.3	12.2	13.0	12.8
			Coated	19.0	14.9	12.7	15.7	22.0	17.3	15.4	19.8	24.3	20.1	14.0	13.6	17.5	17.1	16.6	15.9

17.7. TABLE 6: ABSOLUTE INCREASE IN ENERGY DEMAND FOR ARTIFICIAL LIGHTING

TABLE 6: ABSOLUTE INCREASE IN ENERGY DEMAND FOR ARTIFICIAL LIGHTING (KWH/YEAR)			Climate →	Cold climate				Temperate climate				Dry climate				Tropical climate			
Building function ↓	Room size ↓	Window size ↓	Orientation / Type of glazing	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Office	Small room (A=20m²)	Small window (wwr=0.25)	Clear	159.55	117.44	60.49	108.57	181.45	124.99	77.02	129.33	151.04	100.72	39.56	87.99	75.77	84.57	80.34	81.78
			Coated	276.41	269.35	257.59	264.45	279.81	273.75	275.12	272.78	293.4	284.12	289.69	518.3	298.78	267.63	301.49	278.35
		Large window (wwr=0.75)	Clear	66.57	51.39	29.38	48.43	63.32	43.3	29.51	49.04	11.39	6.01	2.14	5.84	6.73	10.61	6.53	12.09
			Coated	156.98	121.33	85.5	124.37	187.24	137.26	111.21	147.32	216.22	147.89	102.97	127.01	172.42	135.8	173.08	152.02
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	622.87	602.7	530.8	600.62	751.64	734.3	757.2	737.75	1070.8	914.76	762.47	686.32	1131.76	886.99	1112.29	951.85
			Coated	152.64	270.77	484.14	301.52	184.11	320.27	414.43	317.47	279.11	429.97	614.38	598.19	413.84	513.81	419.68	494.29
		Large window (wwr=0.75)	Clear	742.71	522.53	294.4	530.86	835.23	560.58	389.22	614.41	602.71	319.59	139.13	348.65	367.03	372.27	380.79	429.38
			Coated	345.77	466.7	615.16	515.35	414.46	597.19	785.22	622.37	622.4	774.61	868.96	681.08	914.36	844.48	899.11	911.74
Residence	Small room (A=20m²)	Small window (wwr=0.25)	Clear	33.11	28.52	26.77	26.21	34.11	29.37	29.63	25.24	18.87	13.74	18.23	15.14	23.31	20.12	22.9	24.18
			Coated	41.61	32.3	29.3	36.08	46.23	36.45	30.71	41.22	47.61	39.56	28.95	28.66	33.46	33.75	33.35	30.28
		Large window (wwr=0.75)	Clear	15.74	18.38	15.43	13.93	14.48	18.14	15.95	12.98	4.51	3.26	4.29	5	18.37	19	18.58	16.51
			Coated	36.5	30.3	27.35	27.35	40.05	31.36	28.36	26.91	25.63	18.68	19.54	14.77	19.26	20.36	19.28	17.6
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	217.53	167.95	148.2	171.42	236.8	179.07	157.2	179.71	174.43	141.04	112.08	101.97	120.27	123.63	120.05	115.6
			Coated	88.34	113.7	126.38	136.27	101.33	134.58	151.02	166.85	133.91	174.05	167.78	146.25	161.41	160.67	158.56	162.4
		Large window (wwr=0.75)	Clear	150.53	134.39	127.65	110.06	158.99	135.67	139.28	101.33	75.43	61.5	81.85	50.6	103.93	96.83	101.88	99.31
			Coated	186.22	145.87	118.98	147.63	206.76	161.31	140.12	174.89	215.29	173.71	121.75	118.66	154.94	150.04	147.22	139.06

18. CONCLUSION PART IV

This chapter gives an overall conclusion of the knowledge obtained from part IV. In the past four chapters, the simulation conditions were listed, the simulation results were shown and the analysis was reported. Part IV ended with a side-study into the influence of the LTATW on the energy demand for artificial lighting and with the final chapter showing the six most important designer tables. For chapter 15, 16 and 17, a conclusion is described in this chapter, in which all of the sub-questions stated in chapter 1 are answered as well.

CHAPTER 15: SIMULATION RESULTS AND ANALYSIS

In chapter 15, the simulation results were shown using the modeFRONTIER data analysis tools. Various results have been obtained from the analysis, including results relating to the distribution of the results of all 3072 room configurations, the results per room configuration and results related to correlation between building parameter and energy performance. Of the first-mentioned results, the most important findings were that in case of heating, the LTATW ensures an average reduction of 21.3% of the initial energy demand (or 127.7 kWh per year) and in case of cooling, it has been revealed that the LTATW provides an average reduction of 23.1% (or 126.6 kWh per year). Because in both situations, the standard deviation is high (in the order of magnitude of the value itself) and all climate types have been included, this average does not immediately give a good idea of the energy results that will be experienced in the specific situation of the interested designer. Therefore, the average reductions per climate type have also been analysed. It was found that in a cold climate the average reduction of the heating energy demand is 32.4% (or 326.3 kWh per year) and for cooling 22.4% (or 8.3 kWh per year). In a temperate climate, the average reduction of the heating energy demand equals 36.1% (or 181.3 kWh per year) and the average reduction of the cooling energy demand equals 49.9% (or 115.0 kWh per year). The reduction of the heating energy demand in a dry climate equals 16.8% (or 3.1 kWh per year) and the reduction of the cooling energy demand equals 15.2% (or 233.1 kWh per year). Finally, there is no reduction of the heating energy demand in a tropical climate and the reduction of the cooling energy demand equals 4.7% (or 149.9 kWh per year).

The configurations charts of heating and cooling have shown the distribution when the energy reduction in relative terms (%) is plotted against the energy reduction in absolute terms (kWh). With the aid of this graph and the average values found in the distribution charts, four graph parts could been drawn up: A, B, C and D. Using this graph, it can directly be seen under which circumstances the purchase of a LTATW will be the most profitable. Parts A and B of the chart represent a part in which room configurations experience an above-average reduction in absolute sense, and in which the pay-back time will therefore be shorter. In the more right parts of the chart, there is a high energy reduction in absolute sense, but the energy demand will still be relatively high. In the best case scenario, a room is therefore located in part A, where a large part of the energy demand is reduced, and at the same time, a lot of costs.

Besides being able to see the most potential situations from the graph, it is often also possible to deduce what the best performing values of the variables are. In fact, the best performing values/subdivisions of the variables are often located at the upper boundary of the graph (area A) and the least performing variables are slightly more concentrated towards the origin. This is so, because under the best circumstance, often both a higher reduction in absolute sense and higher reduction in relative sense is experienced. Because in the chart it is not indicated which rooms have the same configurations (except for the variable studied), one can better consult the designer tables for this purpose.

The correlation charts in section 15.1.3 give a good idea of the magnitude of the influence of each variable, but do not give a representative result about which value of this parameter results in the best performance. In fact, there is often an optimum performance found for one of the 'middle' subdivisions (such as for a dry climate and temperate climate in case of cooling). They therefore only give information about the average trend, determined over all situations.

In order to answer all sub-questions of this research, the influence of each individual parameter was analysed. The first variable that was analysed was climate. It was revealed that in case of heating only a cold and temperate climate are of relevance, since no heating is required in the other types of climates. From the analysis it could be concluded that in relative sense, the Trombe wall performs best in a temperate climate, and that in absolute sense, the Trombe wall performs best in a cold climate. In case of cooling, the system performs best in a temperate climate and a dry climate. Because the LTATW is designed to be both a passive cooling system in the summer and passive heating system in the winter, it has clearly been proven that only the temperate climate is the most logical choice. With this knowledge gained, sub-question 1 (*How does climate influence the performance of a LTATW?)* is answered.

Analysis of the second variable, building function, has shown that in case of heating the function is not of great influence. The system performs well in both an office and a residence. In case of cooling, higher reductions of the energy demand are achieved in residences. This answers sub-question 2.1 (*How does the function of a building influence the performance of a LTATW?)*

Thirdly, the influence of the orientation of the Trombe wall was investigated. The study shows that the Trombe wall always delivers a considerable reduction in energy demand, as it provides the room with an additional amount of storage capacity. Nevertheless, even greater performance can be achieved when the wall is positioned at a southern orientation (as expected), because now, the wall is able to absorb the most solar energy. In many cases of heating, however, it is true that a southern orientation is also accompanied with a lower initial energy demand, so it must be checked in the designer table whether the reduction in kWh is still enough as well. In case of cooling, it was revealed that orientation is of a much lesser influence. This result is also as expected, since the passive cooling principle of the Trombe wall is not based on direct contact with the sun, but with the internal heat loads. A northern orientation seems to be providing the best results in relative terms, but in absolute sense it is sometimes the case that less energy is reduced in kWh in total (same principle as for relation heating-southern orientation). This answers sub-question 2.2 (*How does the orientation influence the performance of a LTATW?).*

The study shows that the age of a building does not have a major influence on the performance of the Trombe wall. In old buildings, the initial energy demand for heating is often higher, so that a lot more energy can be reduced in absolute sense. In new buildings, the energy demand is lower on average, so that the LTATW can ensure a substantial reduction on the energy demand in percentage. Therefore, in both cases, the Trombe wall performs well. In case of cooling, the same is experienced, although a slight preference can be expressed for new buildings. This answers sub-question 2.3 (*How does the age of a building influence the performance of a LTATW?).*

Studying the influence of the construction method on the performance of the wall has shown that this parameter has the least influence of all studied parameters. In both light-weight, medium-weight and heavy-weight buildings, a good performance can be achieved. Of course, there is a slightly more suitable building method for each situation, and this can therefore be determined from the designer tables. This answers sub-question 2.4 (*How does the building method influence the performance of a LTATW?).*

For the size of the room, the same findings regarding heating apply as for the age of a building: both room sizes perform equally well. It could be concluded that a Trombe wall can be installed in both small rooms and big rooms, but that when a room is too big, the capacity of the Trombe wall will no longer be useful to reduce a large amount of the initial energy demand. The same applies to cooling. Clearer results of the study have come from the analysis of the influence of the size of the window. Research has shown that for heating purposes, a room with a smaller window is more often preferred and for cooling purposes, a large window. Because the innovative Trombe wall will have to serve as both a passive heating and cooling device, an average size window (with for example WWR=0.5) will therefore probably be the most suitable. This answers sub-question 2.5 and 2.6 (*How does room size influence the performance of a LTATW?; How does window size influence the performance of a LTATW?).*

Finally, the influence of type of glazing was studied. When studying the graphs it was difficult to distinguish between which type of glazing results in a better performance of the Trombe wall than the other. With the aid of the designer tables, however, it became clear that in relative terms the largest reductions of the heating energy demand (as expected) were achieved with clear glazing. With clear glazing, more energy can be absorbed from the sun. Just like with the orientation, the reduction in absolute terms with the best performing variable seems to be less in much cases, and for each situation, the designer tables should be consulted as well. In case of cooling, it is a bit more clear that the uncoated types of glazing results in the highest reductions of the cooling energy demand. This answers sub-question 2.7 (*How does type of glazing influence the performance of a LTATW?).*

In the final section of chapter 15, the sensitivity of the results of the study to adjusting four of the assumptions was tested. These assumptions included four parameters that were set as constants: the heating and cooling thermostat set-point, the shading schedule and the type of PCM. The sensitivity analysis showed that when changing the heating thermostat-setpoint temperature, almost the same conclusions can be derived from the result of the study, since the ratio between the changes remains the same. The actual values in the designer tables, however, do change considerably. In addition, if the temperature is increased to above 23 °C, the results change enormously (caused by the hysteresis of the PCM). When it is assumed that people do not adjust the thermostat set-point to a temperature below 18 degrees or above 23 degrees, it can be concluded that the sensitivity is not too high. Secondly, rooms with different values for cooling set-points were simulated in order to study the sensitivity to changing this aspect. The same order of magnitude sensitivity was found as with the heating set-point and also here, only major changes in results in ratio between results happen below a set-point of 23 °C.

The third constant parameter that has been analysed was the shading schedule. In the simulations, it was assumed that shading is only switched on when the operative room temperature rises above 24 °C. In the sensitivity study it was investigated whether a change of this temperature has an influence on the final findings of the study and it was found that changing this temperature hardly influences the results. The results are therefore also valid for buildings with a varying or slightly other shading strategy.

Finally, the influence of type of PCM on the energy performance of the LTATW was investigated. In case of heating, an optimum was found with a PCM with a transition temperature just above the heating set-point temperature. In case of cooling, this optimum was found on and just below the cooling set-point temperature (findings correspond with the findings from literature study). The choice for SP25E2 therefore seems to be a good middle way, with which the wall can function well in both seasons. Finally, it should be mentioned that the influence of the type of PCM is less than expected. Additional research indicated that the Trombe wall construction also provides a substantial reduction in energy demand even without latent heat storage materials (approximately 15% of the total reduction is caused by the PCM and 85% by the construction itself).

CHAPTER 16: ARTIFICIAL LIGHTING

Chapter 16 investigated the influence of the Trombe wall on the electrical energy demand for artificial lighting. For all possible situations, models were simulated in DesignBuilder and results were shown using correlation charts, distribution charts and the designer tables.

The correlation charts have shown that room size and building function have the greatest influence on the increase in energy demand. As expected, the increase in energy demand is the highest in rooms of office buildings. Here, the positive influence of sunlight during the day is reduced the most. for the same reason, the increases are the highest in the two warmest climates (climates with the longest days). When the LTATW is placed behind a larger window, the increase in energy consumption will be the least on average. The distribution graphs have shown that the average increase in energy demand for artificial lighting is 52.4%. Because the standard deviation here is also relatively high, it is better to assess each situation using the designer tables.

Finally, a sensitivity analysis was performed, to investigate how decisive the assumption was that the PCM is in liquid state from 08:00 to 18:00 hrs. It was found that in case of office rooms, this assumption leads to the most favorable results. When times of liquid state of the PCM varies, the energy demand will increase, but remains within limitation. In case of the residential rooms, the sensitivity is low, and it can therefore be assumed that the results of the side-study are also valid enough for deviating times of sunrise and sunset.

CHAPTER 17: DESIGNER TABLES

The influence of the variables on the performance of the LTATW can roughly be determined with the help of the correlation matrices in chapter 15 (option 1). A much better and more reliable picture, however, can be obtained by studying the configurations charts with indications of the different values of the variables (option 2). However, because the performance is often very dependent on each situation, most information can be obtained from the designer tables. For each situation, the exact values of energy savings can be read and also with the help of the colour indications in the tables it can be quickly determined which situations result in the best performance, and which situations result in worse performances. To conclude: green cells with a bolded value represent the most favourable situations.

PART V

WRAP-UP

19. DISCUSSION

In this chapter, the value of the findings from this Master's thesis project are discussed. How can the findings be best interpreted? And what were important limitations in this study? The answer to these two questions has been answered in sections 19.1 and 19.2. Finally, a number of important issues are mentioned that can be investigated in the future in order to confirm or contradict the results of this research. There are also additional things mentioned that are interesting to be investigated in the future (section 19.3).

19.1. INTERPRETATION OF FINDINGS

In chapter 15 and 16, all results of the study were shown using correlation charts, distribution charts and scatter charts. The best picture of the results is obtained with the aid of the scatter charts, in which the values of the studied variable parameters are indicated. With the correlation charts, clear conclusions can be derived, but because such a large number of room configurations are examined in the study, this result does not often apply to the actual situation. It is simply an average, calculated over a large number of situations. An even better picture for every single situation can be obtained with the designer tables. These tables show the result with regard to energy savings for each specific situation. The advantage of the designer tables is that the influence of a variable parameter can be viewed much more clearly per situation, while the scatter chart does not indicate which data-points are of the same room configuration.

Because climate has such a large influence on the results, it seems in the correlation charts that parameters such as orientation and building method have a very low influence. This is relatively the case, but it can be seen in the designer tables that with a correct choice for orientation and construction method, even higher reductions can be achieved. Furthermore, it was interesting in this project to also study the influence of the glazing types. Because coated glazing was therefore also included in the study (which will be less the case in buildings with a LTATW), the final average reductions achieved with the wall will be higher.

An assumption that has made it difficult to investigate the influence of the variable parameters room size and window size is the assumption that the Trombe wall has the same size (surface area) as the size of the window. This assumption has been made to make the situations in the designer tables as realistic as possible: when an interested designer has a room with a small window, he or she wants to know what the energy savings are with a LTATW of the same size (and not with a too large LTATW, which is also much more expensive). In addition, it is also assumed that behind a large window in a larger room there is a much larger version of the Trombe wall. This assumption therefore makes the use of the designer tables more appropriate, but makes investigating the influence of room size and window size more difficult. For example, if the results show that a Trombe wall performs better in a big room, it is not directly clear whether this is due to the room size or to the larger version of the Trombe wall (as it has more storage capacity). In case of these two variables, therefore, a good overall conclusion about the influence on the performance of the LTATW cannot be formulated with the results of this study.

One thing that has also complicated the analysis of the influence of the variables is that changing the value of a variable affects both the initial energy demand and the energy demand after installing a LTATW. The clearest example of this occurs in the analysis of the variable orientation. When the Trombe wall is placed on a southern orientation instead of a northern one, the reduction of the heating energy demand is expected to increase in percentage. This is indeed true, but the reduction in absolute sense often goes down here. This is because the initial heating energy demand at a southern orientation is now lower (due to more incoming solar radiation), and thus also the total reduction in kWh will also be lower. That is why it was of great importance in this study to not only show the reductions in percentages, but also the reductions in kWh. Only if both values of reductions are high, purchasing a LTATW is recommended.

In the artificial lighting side-study, the increase in energy demand for all possible situations was calculated. These results give an interested designer even more information about the future energy demands, but should only be consulted when the room has only one window (behind which the Trombe wall stands). When the room has multiple windows, behind which there is no Trombe wall, in most cases enough daylight will come in, so that the influence of installing one wall has a minor influence on the energy demand for artificial lighting.

Finally, it is important to mention that the findings in this thesis are obtained with a numerical study. The exact values of the results (in the designer tables) may therefore differ slightly in reality. However, the relation between outcomes for different situations will probably remain the same and the conclusions about the global influence of the variable parameters will therefore continue to apply. However, this must be confirmed with a validation by means of experimental research in the future.

19.2. LIMITATIONS

An important limitation in this study is of course the amount of variable parameters and their number of subdivisions included. In this study, the influence of eight variable parameters has been investigated, each with a certain amount of subdivisions. With the chosen quantities a total of 3072 different situations arise, and 6144 simulations were therefore required. With every addition of a new variable or subdivision, there is also a considerable increase in the number of required simulations. If, for example, another building age is examined (a third one), the number of required simulations already increases from 6144 to 9216. Because the research in this Master's thesis project has to be completed within a certain time, this number of simulations is too great. Only when there are a lot more computers available, or when the speed of the simulations increases, more variables can be examined, within the same amount of time. Because the number of variables/subdivisions had to remain limited, only the most typical and most common situations were examined in this study.

Another important limitation in this study was the inability to validate the numerically obtained results with the results from experimental research. Now, the results have been validated using a cross comparison between two different types of software, but the most formal way of validation is by comparing with the results of experimental research. In fact, it is not certain that the results from the other type of software (DesignBuilder) do represent reality.

19.3. FUTURE DIRECTIONS

In this section, a number of suggestions are made for interesting follow-up steps/studies in the future. The simulation model developed in this project can be used for this purpose. The suggestions are listed below:

- When more time and/or resources will be available in the future, it is interesting to study more parameters. In order to arrive at more detailed findings, it is also interesting to study the same eight parameters again, but to include many more subdivisions. Because it is now known that the LTATW is hardly needed for heating purposes in a dry or tropical climate and is hardly needed for cooling purposes in a cold climate, these climates do not have to be studied in a future study. It would then be much better to focus only on the temperate climate, in which all kinds of sub-climates also exist (see Table 7.1). In addition to other climates, there are of course also a lot of other building functions, window sizes, room sizes and more specific building ages than just 'new' and 'old' that could be studied.
- Another suggestion is not to work in a future study with different results for reduction of heating energy demand, reduction of cooling energy demand and values in kWh and percentages, but to come up with just one result for each situation: the pay-back period. With this value, a good picture is immediately given of in which situations the innovative Trombe wall is recommended and in which situations it is not. In the pay-back period both the reductions for heating and cooling energy demand are included, just like the investment costs, and therefore, it does not have to be checked in the designer tables (chapter 17) or scatter charts (chapter 15) whether the situations are in area A or B (above the average reduction in kWh line). Because detailed information about the costs of the LTATW is fairly unknown so far, this has not been possible to apply in this study.
- In this study, the energy savings were calculated, resulting from the installation of a LTATW in a specific room. With the sensitivity study in chapter 15 it was discovered that these savings are partly due to the position of the Trombe wall in front of the window, and partly due to the storage principle of the PCM. A future interesting study would be to investigate how different aspects of the LTATW exactly contribute to the total energy savings. Are there mainly energy savings because a kind of extra insulation layer is created in front of the window? Or does the principle of a double skin façade with its natural ventilation features already provide a lot of energy savings? And what exactly is the size of the influence on the energy savings of applying phase change material in the wall? If this influence is small, would it not be more sensible to use another (more transparent and less expensive) fluid in the Trombe wall?
- To obtain even more reliable findings, the model should be validated in the future with the results from experimental research.
- The simulation model could be extended with a mechanism that calculates the energy demand for artificial lighting. In this study, these simulations were done with DesignBuilder, but a more advanced simulation model would be able to obtain all results in one.

20. FINAL CONCLUSION AND RECOMMENDATION

This thesis started with a literature study within the global topic of passive solar building design. from this main topic, more and more was zoomed in on the main subject: the lightweight translucent and adaptable Trombe wall. With the literature study it was revealed that a passive solar building design strategy often leads to lower energy bills, a more comfortable indoor climate in summer and winter, more satisfaction of the user and the avoidance of the use of fossil fuels. One passive solar building strategy is the Trombe wall concept (system based on indirect gain), which never really got off the ground in the past. However, by applying phase change materials in the Trombe wall, a new, innovative idea seems to have been devised, which increases the storage capacity of the wall, reduces the weight, allows sunlight to pass through and ensures the preservation of the view to the outside environment. With the choice of SP25E2 as PCM product, the most suitable type of PCM (based on desirable chemical, thermophysical, economic, kinetic and environmental properties) with the right phase-transition temperature has been chosen.

The second part of this thesis described the creation and development of the simulation model used in the main research of this thesis. The creation of an initial simulation model (made in DF1.0) has been studied and described and was subsequently extended to a suitable simulation model. The calculation of the simulation model is based on a non-stationary multi-node heat balance, in which all relevant flows of energy and all simulation conditions are taken into account. The simulation model has been validated using a cross-comparison with DesignBuilder and with the help of a test-case and multiple analyses. After validation of the extended model, an accurate, reliable and useful simulation model was obtained with which the parameter study in this Master's thesis project could be carried out.

With more than 6000 simulations, it was found that by installing a LTATW in a room, the average reduction of the heating energy demand equals 21.3% and the average reduction of the cooling energy demand equals 23.1%. Because high differences exist between the four studied climates, the average reductions per climate were also determined: it was found that in a cold climate the average reduction of the heating energy demand is 32.4% (or 326.3 kWh per year) and for cooling 22.4% (or 8.3 kWh per year). In a temperate climate, the average reduction of the heating energy demand equals 36.1% (or 181.3 kWh per year) and the average reduction of the cooling energy demand equals 49.9% (or 115.0 kWh per year). The reduction of the heating energy demand in a dry climate equals 16.8% (or 3.1 kWh per year) and the reduction of the cooling energy demand equals 15.2% (or 233.1 kWh per year). Finally, there is no reduction of the heating energy demand in a tropical climate and the reduction of the cooling energy demand equals 4.7% (or 149.9 kWh per year).

After simulations, the influence of the following eight parameters on the energy and comfort performance of the lightweight translucent and adaptable Trombe wall was studied: climate, building function, orientation, age, building method, room size, window size and type of glazing. It was revealed that in case of heating, only a cold and temperate climate are of relevance, since no or very little heating is required in a dry and tropical climate. It could be concluded that in relative sense (reduction in percentage), the Trombe wall performs best in a temperate climate, and that in absolute sense (reduction in kWh), the Trombe wall performs best in a cold climate. In case of cooling, the system performs best in a temperate climate and in a dry climate. Because the LTATW is designed to be both a passive cooling system in the summer and passive heating system in the winter, it has clearly been proven that only the temperate climate is the most logical choice.

Analysis of the second variable, building function, has shown that in case of heating the function is not of great influence. The system performs well in both offices and residences. In case of cooling, higher reductions are achieved in residences. Thirdly, the influence of the orientation of the Trombe wall was investigated. It was found that on all orientations, the Trombe wall delivers a considerable reduction in energy demand, but the greatest performance can be achieved when the wall is positioned at a southern orientation (in case of reduction of the heating energy demand). In many cases of heating, however, it is true that a southern orientation is also accompanied with a lower initial energy demand, so it must be checked in the designer tables whether the reduction in kWh is still enough as well. In case of cooling, it was revealed that orientation is of a much lesser influence.

The study shows that the age of a building does not have a major influence on the performance of the Trombe wall. In old buildings, the initial energy demand for heating is often higher, so that a lot more energy can be reduced in absolute sense. In new buildings, the energy demand is lower on average, so that the LTATW can ensure a substantial reduction on the energy demand in percentage. In case of cooling, the same is experienced, although a slight preference can be expressed for new buildings.

Studying the influence of the construction method on the performance of the wall has shown that this parameter has the least influence of all studied parameters. In both light-weight, medium-weight and heavy-weight buildings, a good performance can be achieved. Of course, there is a slightly more suitable building method for each situation, and this can therefore be determined from the designer tables.

For the size of the room, the same findings regarding heating apply as for the age of a building: both room sizes perform equally well. It can be concluded that a Trombe wall can be installed in both small rooms and big rooms, but that when a room is too big, the capacity of the Trombe wall will no longer be useful to reduce a large amount of the initial energy demand. The same applies to cooling. Clearer results of the study have come from the analysis of the influence of the size of the window. Research has shown that for heating purposes, a room with a smaller window is more often preferred and for cooling purposes, a large window. Because the innovative Trombe wall will have to serve as both a passive heating and cooling device, an average size window (with for example WWR=0.5) will therefore probably be the most suitable.

Finally, the influence of type of glazing was studied. When studying the graphs it was difficult to distinguish between which type of glazing results in a better performance of the Trombe wall than the other. With the aid of the designer tables, however, it became clear that in relative terms the largest reductions of the heating energy demand (as expected) were achieved with clear glazing. With clear glazing, more energy can be absorbed from the sun. Just like with the orientation, the reduction in absolute terms with the best performing variable seems to be less in much cases, and for each situation, the designer tables should be consulted as well. In case of cooling, it is a bit more clear that the uncoated types of glazing results in the highest reductions of the cooling energy demand. With the information above, the main research question can be answered (*How do building parameters and climate influence the energy and comfort performance of a lightweight translucent adaptable Trombe wall?*).

With the sensitivity studies it was found that changing the heating thermostat set-point temperature (up to 23°C) and cooling thermostat set-point temperature (up to a minimum of 23°C) has little or no influence on the way in which the variables influence the performance of the Trombe wall. However, it is true that the numerical results for reduction of heating and cooling (as shown in the designer tables) change considerably. The designer tables are therefore only valid with the set-point temperatures that are assumed in this thesis. With the sensitivity study it was also found that shading has little influence on the results.

Finally, the influence of the type of PCM on the energy performance of the LTATW was investigated. In case of heating, an optimum was found with a PCM with a transition temperature just above the heating set-point temperature. In case of cooling, this optimum was found on and just below the cooling set-point temperature. Finally, it should be mentioned that the influence of the type of PCM is less than expected. Additional research indicated that the Trombe wall construction also provides a substantial reduction in energy demand even without latent heat storage materials (approximately 15% of the total reduction is caused by the PCM and 85% by the Trombe-wall construction itself).

In addition to the main study, a side-study was carried out into the influence of the innovative Trombe wall on the energy demand for artificial lighting. It was shown that room size and building function have the greatest influence on the increase in energy demand and that the increase in energy demand is the highest in rooms of office buildings and rooms located in the two warmest climates. It was shown that the average increase in energy demand for artificial lighting is 52.4%. Because the standard deviation here is relatively high, it is better to assess each situation using the designer tables.

If only the results from rooms in a temperate climate are considered, and it is thought of the fact that the Trombe wall must serve as a heating and cooling device in all seasons, it is most recommended to install the Trombe wall in a new-built residence with heavy-weight structure. The Trombe wall can best be placed behind a south-facing, medium-sized window (WWR ≈ 0.5) with clear triple glazing, in a room not much larger than 100 m^2. To prevent the energy demand for artificial lighting from becoming too high, it is recommended to place the wall in a room with more than just one window.

REFERENCES

4TU.Bouw. (2014). Double Face: A System for Adjustable Translucent Thermal mass; Delft University of Technology & Eindhoven University of Technology. Retrieved from https://www.4tu.nl/bouw/en/LHP2014/doubleface/

Adams, S., Becker, M., Krauss, D., & Gilman, C. (2010). Not a dry subject: optimizing water Trombe wall. In *Proceedings of the Solar Energy Society Annual Conference 2010*.

Agrawal, B., & Tiwari, G. N. (2010). *Building integrated photovoltaic thermal systems: for sustainable developments*. Royal Society of Chemistry.

Aldawoud, A. (2013). The influence of the atrium geometry on the building energy performance. *Energy and Buildings*, *57*, 1-5.

Alexiou, M. (2017). *Adaptive façade system based on phase change materials* (Master's thesis, Delft University of Technology, The Netherlands). Retrieved from: https://repository.tudelft.nl/

Ataer, O. E. (2006). Storage of Thermal Energy. Encyclopedia of Life Support Systems (EOLSS) UNESCO.

Athienitis, A. K., & Chen, Y. (2000). The effect of solar radiation on dynamic thermal performance of floor heating systems. *Solar Energy*, *69*(3), 229-237.

Baetens, R., Jelle, B. P., & Gustavsen, A. (2010). Phase change materials for building applications: a state-of-the-art review. *Energy and buildings*, *42*(9), 1361-1368.

Bailey, R. G. (2009). *Ecosystem geography: from ecoregions to sites*. Springer Science & Business Media.

Benedict, R. P., & Xvi, B. (1984). *Fundamentals of temperature, pressure, and flow measurements*. John Wiley & Sons.

Berthou, Y., Biwole, P. H., Achard, P., Sallée, H., Tantot-Neirac, M., & Jay, F. (2015). Full scale experimentation on a new translucent passive solar wall combining silica aerogels and phase change materials. *Solar Energy*, *115*, 733-742.

BIM. (2010). Fiche 2.2: Het ontwerp van kunstmatige verlichting in woningen en kantoren.

Blondeau, P., Spérandio, M., & Allard, F. (1997). Night ventilation for building cooling in summer. *Solar energy*, *61*(5), 327-335.

Bourdeau, L. E. (1980). Study of two passive solar systems containing phase change materials for thermal storage. In *Presented at the 5th Natl. Passive Solar Conf., Amherst, Mass., 19-26 Oct. 1980*.

Browning, R. (1961). The Seasons.

Bruno, F., & Saman, W. Y. (2002). Testing of a PCM energy storage system for space heating.

Buchdahl, J. (2010). Atmosphere, Climate & Environment Information Programme. *Ace. mmu. ac. uk. Archived from the original on*, 07-01.

Buddhi, D., & Sharma, S. D. (1999). Measurements of transmittance of solar radiation through stearic acid: a latent heat storage material. *Energy conversion and management*, *40*(18), 1979-1984.

Cabeza, L. F., Castell, A., Barreneche, C. D., De Gracia, A., & Fernández, A. I. (2011). Materials used as PCM in thermal energy storage in buildings: a review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1675-1695.

Carson, I. I., & John, S. (2002, December). Verification validation: model verification and validation. In *Proceedings of the 34th conference on Winter simulation: exploring new frontiers* (pp. 52-58). Winter Simulation Conference.

Chan, H. Y., Riffat, S. B., & Zhu, J. (2010). Review of passive solar heating and cooling technologies. *Renewable and Sustainable Energy Reviews*, *14*(2), 781-789.

Chen, D., & Chen, H. W. (2013). Using the Köppen classification to quantify climate variation and change: an example for 1901–2010. *Environmental Development*, *6*, 69-79.

Cohen, P., West, S. G., & Aiken, L. S. (2014). *Applied multiple regression/correlation analysis for the behavioral sciences*. Psychology Press.

Collier, R. K., & Grimmer, D. P. (1979). *Experimental evaluation of phase change material building walls using small passive test boxes* (No. LA-UR-79-175; CONF-790106-4). Los Alamos Scientific Lab., NM (USA).

Cosmatu, T., Wattez, Y., Turrin, M., & Tenpierik, M. (2017). Integrating technical performances within design exploration. The case of an innovative Trombe wall. In *Symposium on Simulation for Architecture and Urban Design* (p. 101). Simulation Councils.

Dehra, H. (2009). A two dimensional thermal network model for a photovoltaic solar wall. *Solar Energy*, *83*(11), 1933-1942.

Depecker, P., Menezo, C., Virgone, J., & Lepers, S. (2001). Design of buildings shape and energetic consumption. *Building and Environment*, *36*(5), 627-635.

DesignBuilder. (2018). Simulation made easy. Retrieved from https://www.designbuilder.co.uk/

Diarce, G., Urresti, A., García-Romero, A., Delgado, A., Erkoreka, A., Escudero, C., & Campos-Celador, Á. (2013). Ventilated active façades with PCM. *Applied energy*, *109*, 530-537.

Domroes, M. (2003). Climatological characteristics of the tropics in China: climate classification schemes between German scientists and Huang Bingwei. *Journal of Geographical Sciences*, *13*(3), 271-285.

Drake, J. B. (1987). *A study of the optimal transition temperature of PCM (phase change material) wallboard for solar energy storage* (No. ORNL/TM-10210). Oak Ridge National Lab., TN (USA).

Elarga, H., Goia, F., Zarrella, A., Dal Monte, A., & Benini, E. (2016). Thermal and electrical performance of an integrated PV-PCM system in double skin façades: A numerical study. *Solar Energy*, *136*, 112-124.

Ellis, P. G. (2003). *Development and validation of the unvented Trombe wall model in EnergyPlus* (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Evers, A. C., Medina, M. A., & Fang, Y. (2010). Evaluation of the thermal performance of frame walls enhanced with paraffin and hydrated salt phase change materials using a dynamic wall simulator. *Building and Environment*, *45*(8), 1762-1768.

Feldman, D., Banu, D., Hawes, D., & Ghanbari, E. (1991). Obtaining an energy storing building material by direct incorporation of an organic phase change material in gypsum wallboard. *Solar energy materials*, *22*(2-3), 231-242.

Fernandez, A. I., Martínez, M., Segarra, M., Martorell, I., & Cabeza, L. F. (2010). Selection of materials with potential in sensible thermal energy storage. *Solar Energy Materials and Solar Cells*, *94*(10), 1723-1729.

Fiorito, F. (2012). Trombe walls for lightweight buildings in temperate and hot climates. Exploring the use of phase-change materials for performances improvement. *Energy Procedia*, *30*, 1110-1119.

Fokaides, P. A., Kylili, A., & Kalogirou, S. A. (2015). Phase change materials (PCMs) integrated into transparent building elements: a review. *Materials for Renewable and Sustainable Energy*, *4*(2), 6.

Frei, W. (2016). Thermal Modelling of Phase-Change Materials with Hysteresis. Retrieved from: https://www.comsol.com/blogs/thermal-modeling-of-phase-change-materials-with-hysteresis/

Gencoglu, M. T., & Turkoglu. (2004). Passive Solar Building Design.

Ghoneim, A. A., & Klein, S. A. (1989). The effect of phase-change material properties on the performance of solar air-based heating systems. *Solar Energy*, *42*, 441-447.

Gratia, E., & De Herde, A. (2003). Design of low energy office buildings. *Energy and Buildings*, *35*(5), 473-491.

Grynning, S., Goia, F., Rognvik, E., & Time, B. (2013). Possibilities for characterization of a PCM window system using large scale measurements. *International Journal of Sustainable Built Environment*, *2*(1), 56-64.

Guarino, F., Athienitis, A., Cellura, M., & Bastien, D. (2017). PCM thermal storage design in buildings: Experimental studies and applications to solaria in cold climates. *Applied energy*, *185*, 95-106.

Günther, E., Hiebler, S., Mehling, H., & Redlich, R. (2015). Enthalpy of phase change materials as a function of temperature: required accuracy and suitable measurement methods. *International Journal of Thermophysics*, *30*(4), 1257-1269.

Gupta, N., & Tiwari, G. N. (2016). Review of passive heating/cooling systems of buildings. *Energy Science & Engineering*, *4*(5), 305-333.

Hadjieva, M., Stoykov, R., & Filipova, T. Z. (2000). Composite salt-hydrate concrete system for building energy storage. *Renewable Energy*, *19*(1-2), 111-115.

Hasnain, S. M. (1998). Review on sustainable thermal energy storage technologies, Part I: heat storage materials and techniques. *Energy conversion and management*, *39*(11), 1127-1138.

Hillston, J. (2003). Model validation and verification. *Edinburgh: University of Edinburgh*.

Hollo, N. (2011). Warm house cool house—Inspirational designs for low-energy housing. In *Fuel and Energy Abstracts*(Vol. 37, No. 3, p. 203). Elsevier.

Höppe, P. R. (1993). Heat balance modelling. *Experientia*, *49*(9), 741-746.

Hordeski, M. F. (2011). *Megatrends for energy efficiency and renewable energy*. The Fairmont Press, Inc..

HTI. (2005). Thermische behaaglijkheid. *Dictaat Technische installaties.* 1-20.

Ismail, K. A. R., & Henríquez, J. R. (2001). Thermally effective windows with moving phase change material curtains. *Applied Thermal Engineering*, *21*(18), 1909-1923.

Itard, L. (2018). Towards zero-energy buildings [Powerpoint lecture slides]. Retrieved from: https://brightspace.tudelft.nl/

Ji, J., Yi, H., He, W., & Pei, G. (2007). PV-Trombe wall design for buildings in composite climates. *Journal of Solar Energy Engineering*, *129*(4), 431-437.

Khalifa, A. J. N., & Abbas, E. F. (2009). A comparative performance study of some thermal storage materials used for solar space heating. *Energy and Buildings*, *41*(4), 407-415.

Kienzl, N. (1999). *Advanced building skins: translucent thermal storage elements* (Doctoral dissertation, Massachusetts Institute of Technology).

Koláček, M., Charvátová, H., & Sehnálek, S. (2017). Experimental and numerical research of the thermal properties of a PCM window panel. *Sustainability*, *9*(7), 1222.

Kolaitis, D. I., Garay Martinez, R., & Founti, M. A. (2015). An experimental and numerical simulation study of an active solar wall enhanced with phase change materials. *Journal of Facade Design and Engineering*, *3*(1), 71-80.

Kondo, T., & Ibamoto, T. (2003). Research on using the PCM for ceiling board. In *Proceedings of the 9th International Conference on Thermal Energy Storage–Futurestock*.

Köppen, W. (1900). Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. *Geographische Zeitschrift*, *6*(11. H), 593-611.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., & Rubel, F. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift*, *15*(3), 259-263.

Laity, J. J. (2009). *Deserts and desert environments* (Vol. 3). John Wiley & Sons.

Lara, C. C., Tenpierik, M., Turrin, M., & Van der Spoel, W. (2015). Thermal simulations. Double Face Project, 1-18.

Leang, E., Tittelein, P., Zalewski, L., & Lassue, S. (2017). Numerical study of a composite Trombe solar wall integrating microencapsulated PCM. *Energy Procedia*, *122*, 1009-1014.

Li, Y., & Liu, S. (2014). Experimental study on thermal performance of a solar chimney combined with PCM. *Applied Energy*, *114*, 172-178.

Linacre, E., & Geerts, B. (1997). *Climates and weather explained: an introduction from a southern perspective*. Routledge.

Liu, C., Wu, Y., Li, D., Zhou, Y., Wang, Z., & Liu, X. (2017). Effect of PCM thickness and melting temperature on thermal performance of double glazing units. *Journal of Building Engineering*, *11*, 87-95.

Mansy, K. (2006). Five locations to represent world climates. *Europe*, *45*, 107.

Manual, R. (2012). Green & Sustainable Remediation Manual.

McKnight, T. L. (2000). Climate zones and types. *Physical geography: a landscape appreciation*.

Medina, M. A., King, J. B., & Zhang, M. (2008). On the heat transfer rate reduction of structural insulated panels (SIPs) outfitted with phase change materials (PCMs). *Energy*, *33*(4), 667-678.

Melero, S., Morgado, I., Neila, F. J., & Acha, C. (2011). Passive evaporative cooling by porous ceramic elements integrated in a Trombe wall. *Architecture & sustainable development*, *2*, 267.

Memon, S. A. (2014). Phase change materials integrated in building walls: A state of the art review. *Renewable and sustainable energy reviews*, *31*, 870-906.

Morrison, D. J., & Abdel-Khalik, S. I. (1978). Effects of phase-change energy storage on the performance of air-based and liquid-based solar heating systems. *Solar Energy*, *20*(1), 57-67.

Neeper, D. A. (2000). Thermal dynamics of wallboard with latent heat storage. *Solar energy*, *68*(5), 393-403.

Neeper, D. A. (1986). Solar buildings research: what are the best directions. *Passive Sol J*, *3*, 213-219.

NEN-EN 12464-1. (2011). Light and lighting – Lighting of work places – Part 1: Indoor work places. *Nederlands Normalisatie Instituut.*

NEN-EN 15251. (2007). Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. *Nederlands Normalisatie Instituut.*

Onishi, J., Soeda, H., & Mizuno, M. (2001). Numerical study on a low energy architecture based upon distributed heat storage system. *Renewable energy*, *22*(1-3), 61-66.

Ostry, M., & Charvat, P. (2013). Materials for advanced heat storage in buildings. *Procedia Engineering*, *57*, 837-843.

Peippo, K., Kauranen, P., & Lund, P. D. (1991). A multicomponent PCM wall optimized for passive solar heating. *Energy and buildings*, *17*(4), 259-270.

Prakash, G., & Garg, H. P. (2000). Solar energy: fundamentals and applications.

Rabani, M., Kalantar, V., Faghih, A. K., Rabani, M., & Rabani, R. (2013). Numerical simulation of a Trombe wall to predict the energy storage rate and time duration of room heating during the non-sunny periods. *Heat and Mass Transfer*, *49*(10), 1395-1404.

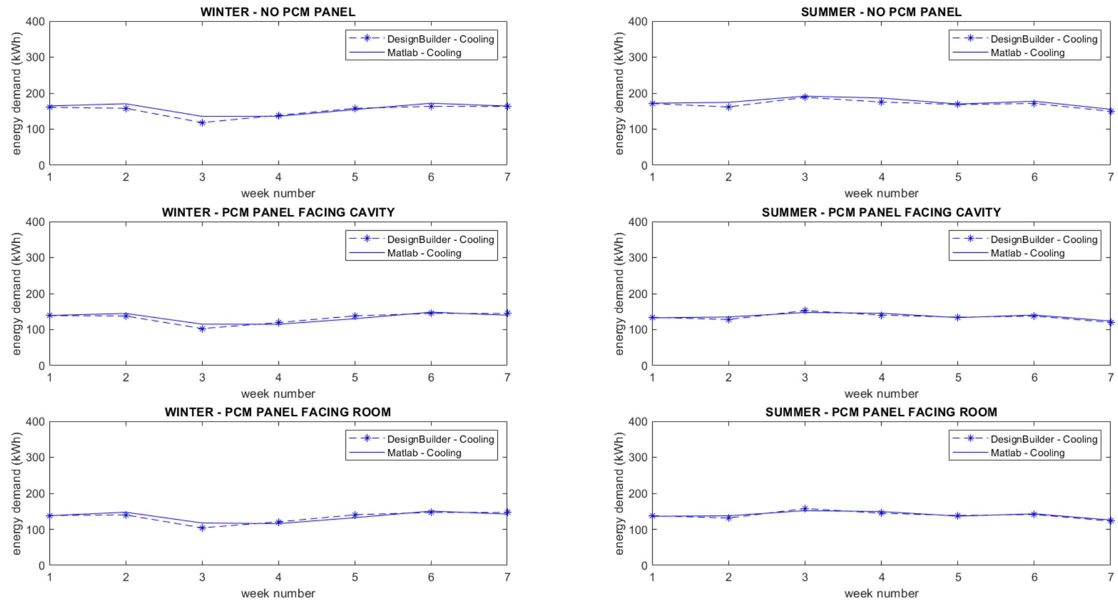
Saadatian, O., Lim, C. H., Sopian, K., & Salleh, E. (2013). A state of the art review of solar walls: Concepts and

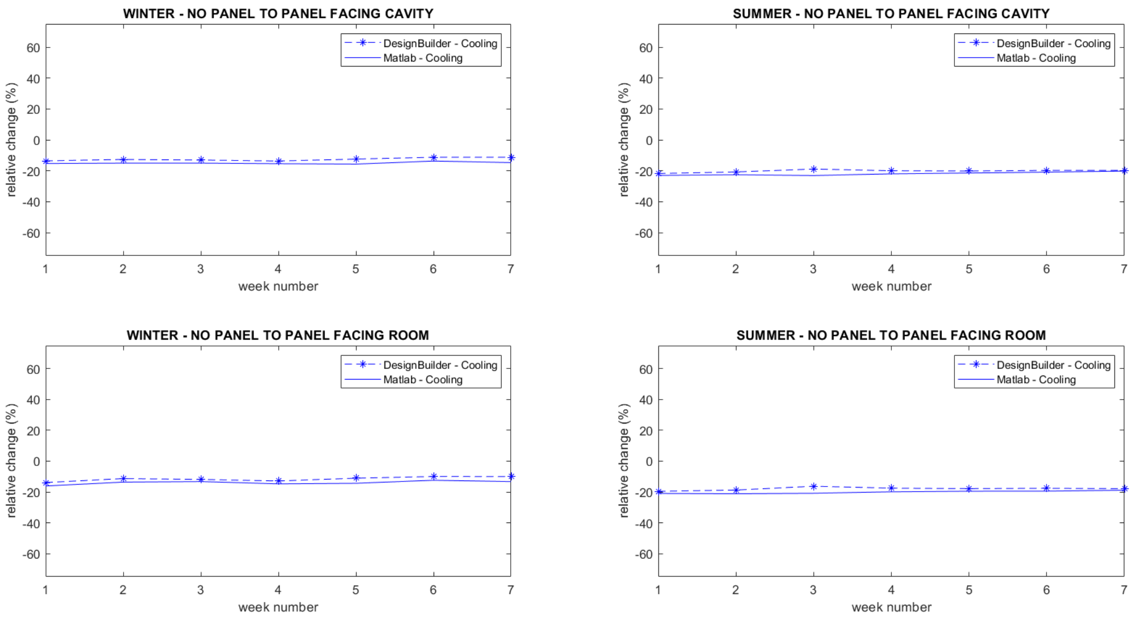
applications. *Journal of Building Physics*, *37*(1), 55-79.
Saadatian, O., Sopian, K., Lim, C. H., Asim, N., & Sulaiman, M. Y. (2012). Trombe walls: A review of opportunities and challenges in research and development. *Renewable and Sustainable Energy Reviews*, *16*(8), 6340-6351.
Sadineni, S. B., Madala, S., & Boehm, R. F. (2011). Passive building energy savings: A review of building envelope components. *Renewable and sustainable energy reviews*, *15*(8), 3617-3631.
Schittich, C. (Ed.). (2003). *Solar architecture: strategies, visions, concepts*. Walter de Gruyter.
Schlesinger, S. (1979). Terminology for model credibility. *Simulation*, *32*(3), 103-104.
Shapiro, M. (1989). Development of the enthalpy storage materials, mixture of methyl stearate and methyl palmitate. *Subcontract report to Florida Solar Energy Center.*
Shingare, A., Singh, H., & Sharma, M. (1986). Design of Passive Solar Building. *International Journal For Engineering Applications and Technology, 1*(C), 1-6.
Soares, N., Costa, J. J., Gaspar, A. R., & Santos, P. (2013). Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency. *Energy and buildings*, *59*, 82-103.
Soares, N., Samagaio, A., Vicente, R., & Costa, J. (2011, November). Numerical simulation of a PCM shutter for buildings space heating during the winter. In *World Renewable Energy Congress-Sweden; 8-13 May; 2011; Linköping; Sweden* (No. 057, pp. 1797-1804). Linköping University Electronic Press.
Sohani, A., Sayyaadi, H., & Mohammadhosseini, N. (2018). Comparative study of the conventional types of heat and mass exchangers to achieve the best design of dew point evaporative coolers at diverse climatic conditions. *Energy Conversion and Management*, *158*, 327-345.
Sokol, D. (2008). Off the wall: Trombe walls at a visitor's center bask in the sunshine. *Green Source, the magazine of sustainable design*.
Stazi, F., Mastrucci, A., & di Perna, C. (2012). The behaviour of solar walls in residential buildings with different insulation levels: an experimental and numerical study. *Energy and Buildings*, *47*, 217-229.
Stern, H., De Hoedt, G., & Ernst, J. (2000). Objective classification of Australian climates. *Australian Meteorological Magazine*, *49*(2), 87-96.
Stevanović, S. (2013). Optimization of passive solar design strategies: A review. *Renewable and Sustainable Energy Reviews*, *25*, 177-196.
Stritih, U., & Novak, P. (1996). Solar heat storage wall for building ventilation. *Renewable Energy*, *8*(1-4), 268-271.
Sun, W., Ji, J., Luo, C., & He, W. (2011). Performance of PV-Trombe wall in winter correlated with south façade design. *Applied Energy*, *88*(1), 224-231.
Szokolay, S., & Docherty, M. J. (1999). Climate Analysis (PLEA Note 5).
Tenpierik, M. (2017). Double Face 2.0. A lightweight translucent adaptable Trombe wall. *RuMoer, 66. Adaptation,* 6-11.
Thiele, A. M., Sant, G., & Pilon, L. (2015). Diurnal thermal analysis of microencapsulated PCM-concrete composite walls. *Energy Conversion and Management*, *93*, 215-227.
Torcellini, P., & Pless, S. (2004). Trombe walls in low-energy buildings: practical experiences. *National Renewable Energy Laboratory*, *1617*, 80401-3393.
Tunç, M., & Uysal, M. (1991). Passive solar heating of buildings using a fluidized bed plus Trombe wall system. *Applied energy*, *38*(3), 199-213.
Turrin, M., Tenpierik, M., de Ruiter, P., van der Spoel, W., Lara, C. C., Heinzelmann, F., ... & van Bommel, W. (2014). DoubleFace: Adjustable translucent system to improve thermal comfort. *SPOOL*, *1*(2), 5-9.
Tyagi, V. V., & Buddhi, D. (2007). PCM thermal storage in buildings: a state of art. *Renewable and Sustainable Energy Reviews*, *11*(6), 1146-1166.
U.S. Department of Energy. (2000). Passive Solar Design Strategies: Guidelines for Home Building Passive Solar Design Strategies. *Guidelines for BODle Builders,* 97.
U.S. Department of Energy (DOE). (2001). Passive Solar Design for the Home. *Energy Efficiency and Renewable Energy,* 1-8.
Van Bueren, E., van Bohemen, H., & Visscher, H. (2012). Sustainable urban environments. *An Ecosystems Approach*.
Van der Linden, A. C., Erdtsieck, P., Kuijpers-van Gaalen, I. M., & Zeegers, A. (2011). *Bouwfysica*. ThiemeMeulenhoff.
Van der Spoel, W. H. (2016). Playing with heat balances: An introduction to numerical modelling of heat transfer problems (lecture reader).
Van der Spoel, W. H. (2018). CIE4225: Advanced and applied building physics. Air flow [Powerpoint lecture slides]. Retrieved from: https://brightspace.tudelft.nl/

Van der Spoel, W. H., & Cauberg, J. J. M. (2006). Optimization of passive application of phase-change materials in building walls. 433-440.
Wang, Q., & Zhao, C. Y. (2015). Parametric investigations of using a PCM curtain for energy efficient buildings. *Energy and Buildings*, *94*, 33-42.
Wattez, Y. (2018). Double Face 2.0 – Final report thermal aspects, measurements and simulations.
Wattez, Y., Cosmatu, T., Tenpierik, M., Turrin, M., Heinzelmann, F., Brotas, L., & Nicol, F. (2017). Renewed Trombe wall passively reduces energy consumption.
Weinläder, H., Beck, A., & Fricke, J. (2005). PCM-facade-panel for daylighting and room heating. *Solar Energy*, *78*(2), 177-186.
Weinlaeder, H., Koerner, W., & Heidenfelder, M. (2011). Monitoring results of an interior sun protection system with integrated latent heat storage. *Energy and Buildings*, *43*(9), 2468-2475.
Xiao, W., Wang, X., & Zhang, Y. (2009). Analytical optimization of interior PCM for energy storage in a lightweight passive solar room. *Applied Energy*, *86*(10), 2013-2018.
Xu, X., Zhang, Y., Lin, K., Di, H., & Yang, R. (2005). Modeling and simulation on the thermal performance of shape-stabilized phase change material floor used in passive solar buildings. *Energy and Buildings*, *37*(10), 1084-1091.
Yinping, Z., & Yi, J. (1999). A simple method, the-history method, of determining the heat of fusion, specific heat and thermal conductivity of phase-change materials. *Measurement Science and Technology*, *10*(3), 201.
Zalewski, L., Joulin, A., Lassue, S., Dutil, Y., & Rousse, D. (2012). Experimental study of small-scale solar wall integrating phase change material. *Solar Energy*, *86*(1), 208-219.
Zhai, X. Q., Song, Z. P., & Wang, R. Z. (2011). A review for the applications of solar chimneys in buildings. *Renewable and Sustainable Energy Reviews*, *15*(8), 3757-3767.
Zhou, D., Zhao, C. Y., & Tian, Y. (2012). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied energy*, *92*, 593-605.

Room model 1:

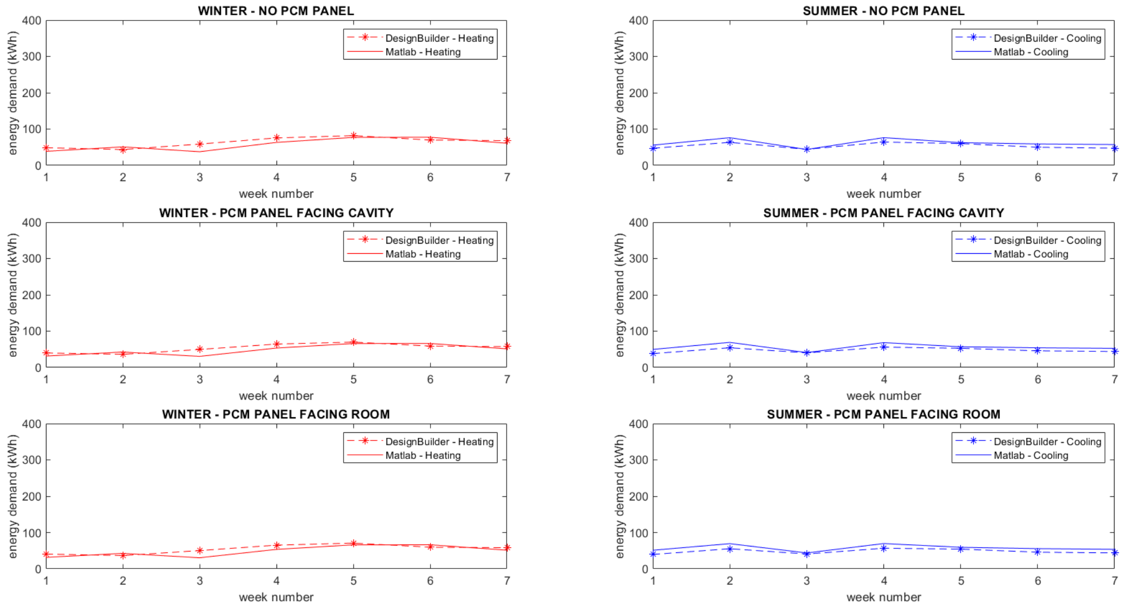
Office – Tropical climate – Northern orientation – Single clear glazing – Small room – Lightweight structure – Old building

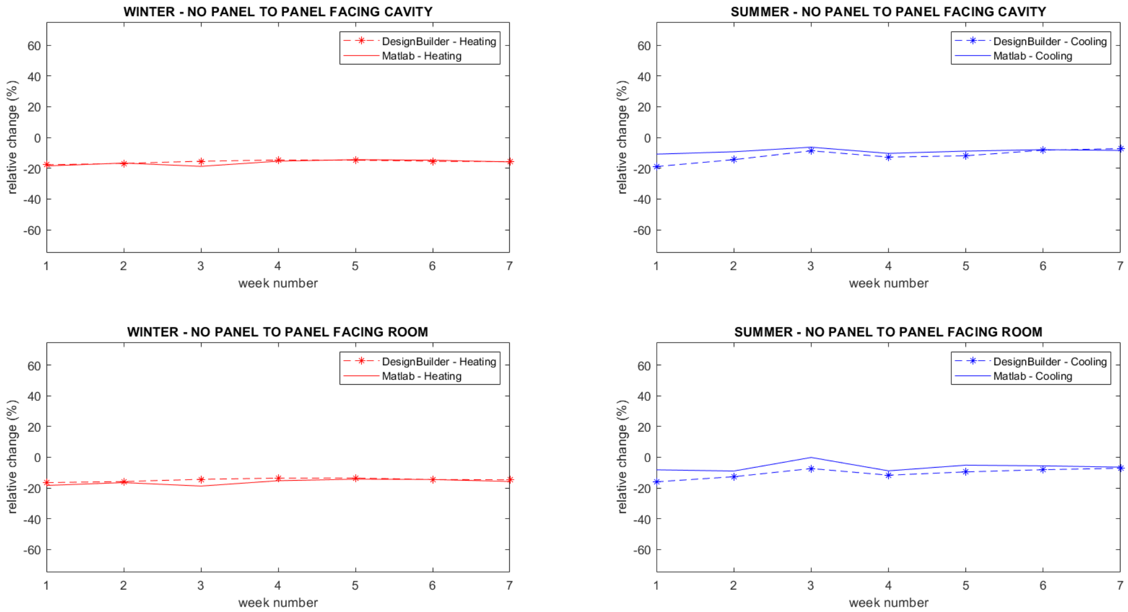




Room model 2:

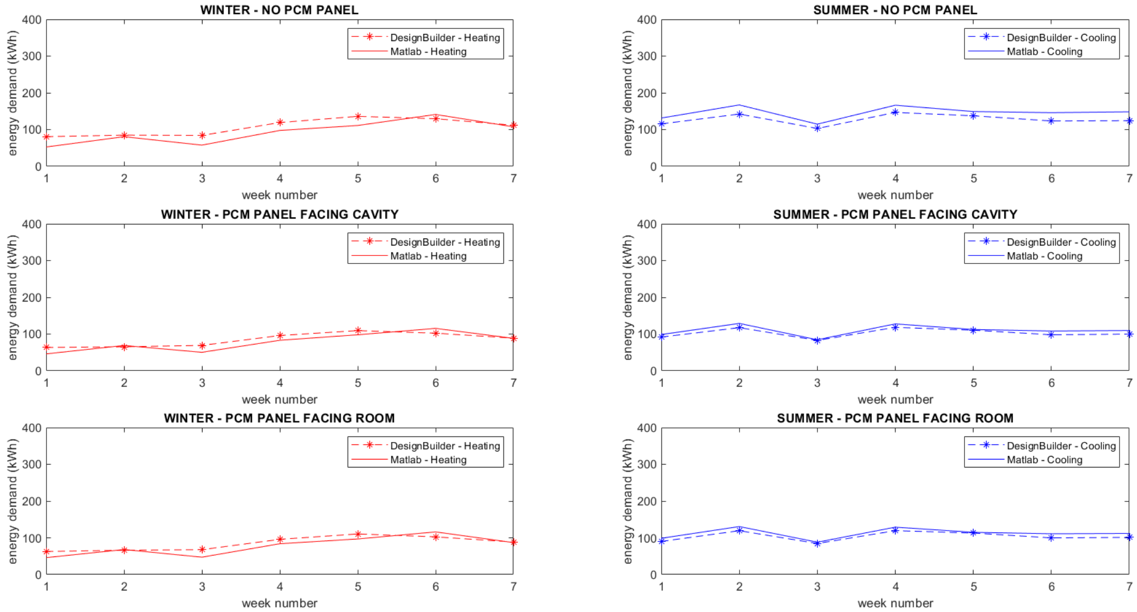
Office – Temperate climate – Western orientation – Triple coated glazing – Small room – Lightweight structure – Old building

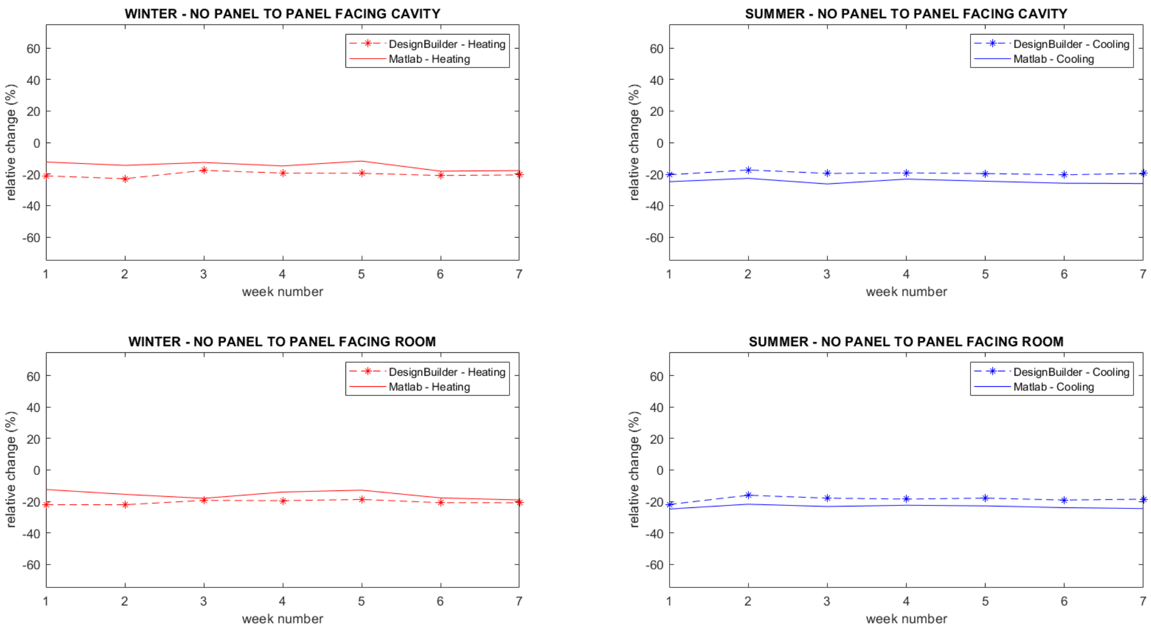




Room model 3:

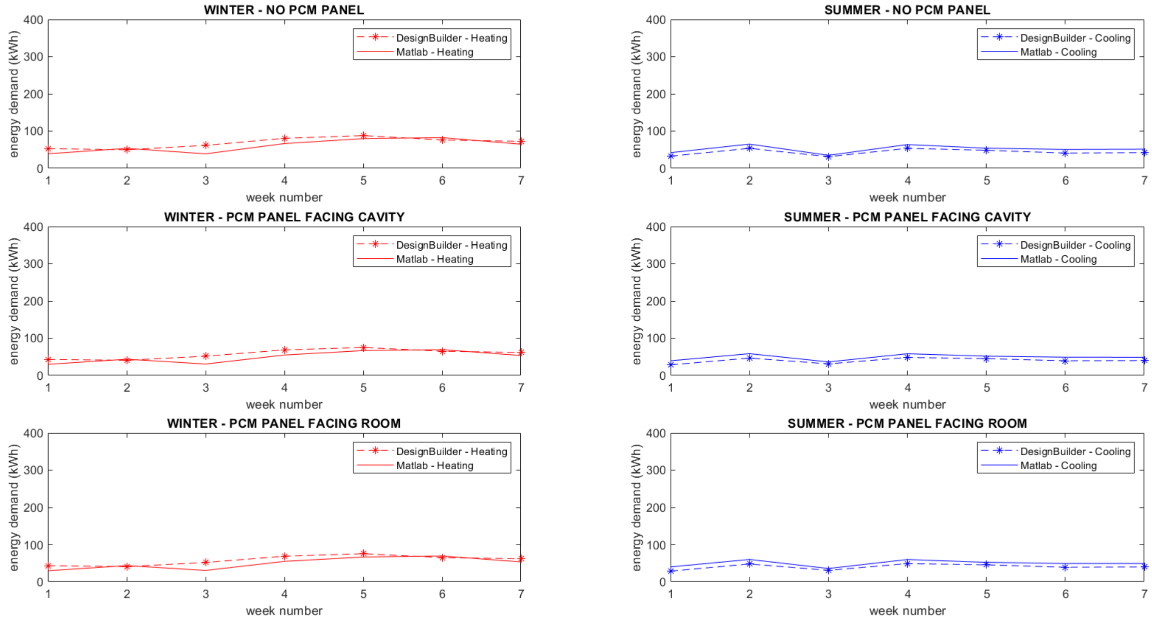
Office – Temperate climate – Southern orientation – Single clear glazing – Small room – Heavyweight structure – Old building

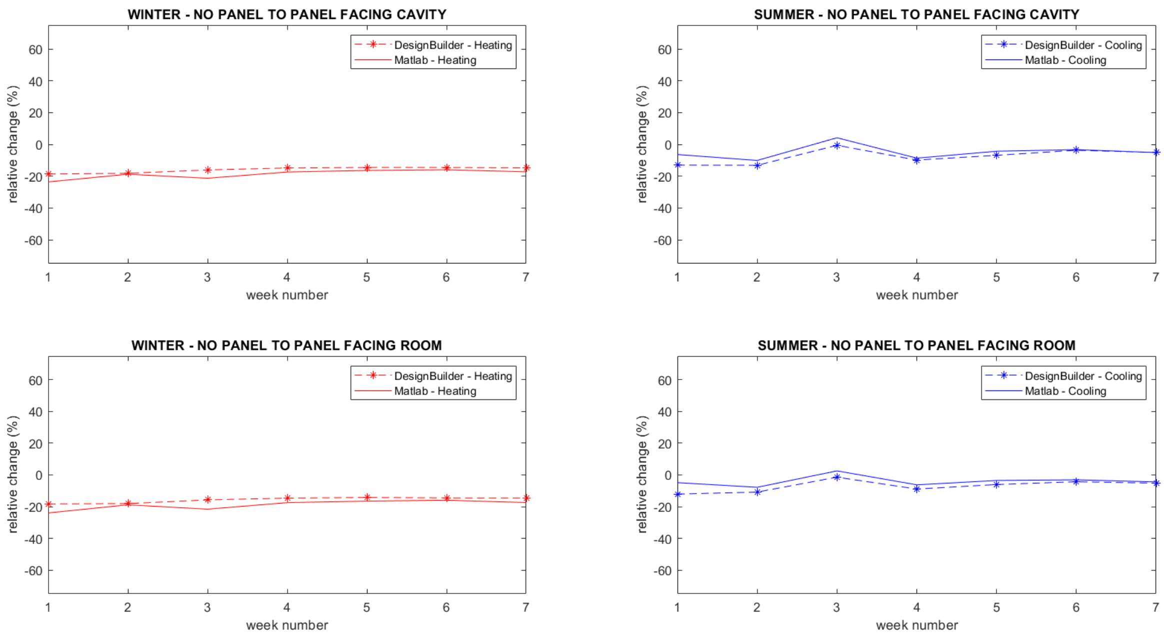




Room model 4:

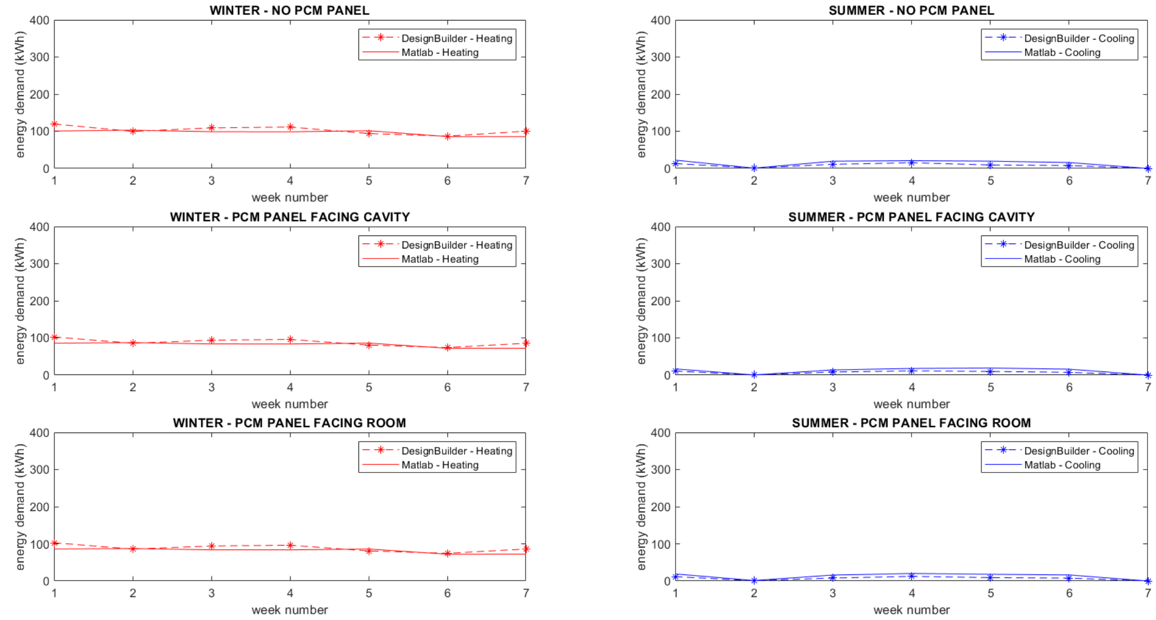
Office – Temperate climate – Northern orientation – Triple coated glazing – Small room – Heavyweight structure – Old building

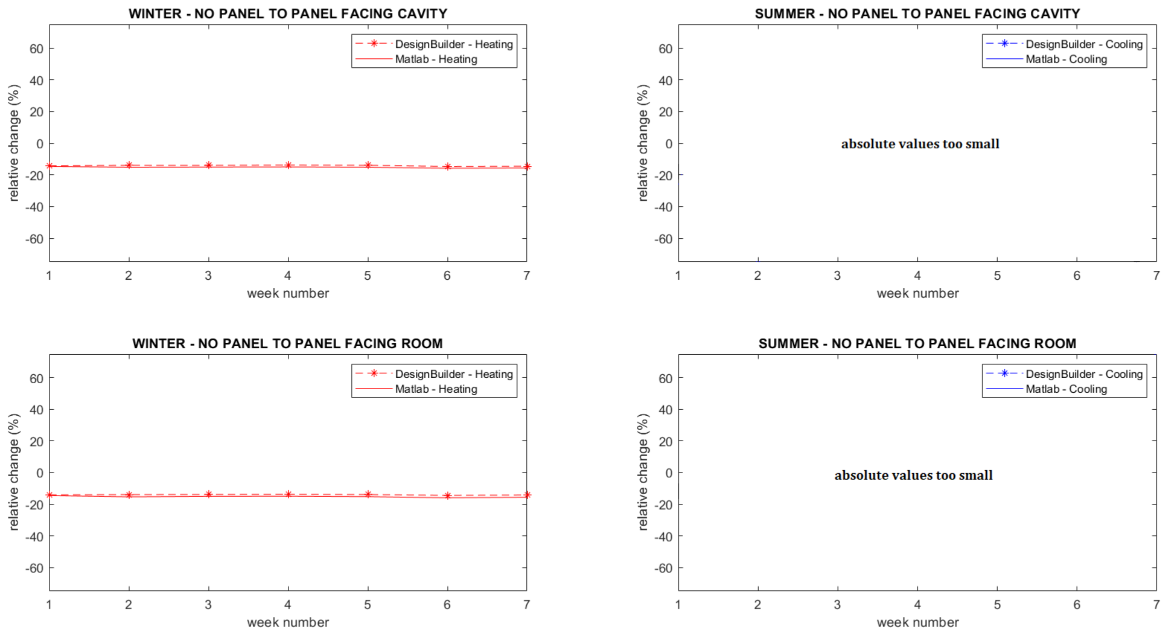




Room model 5:

Office – Cold climate – Western orientation – Triple coated glazing – Small room – Heavyweight structure – Old building

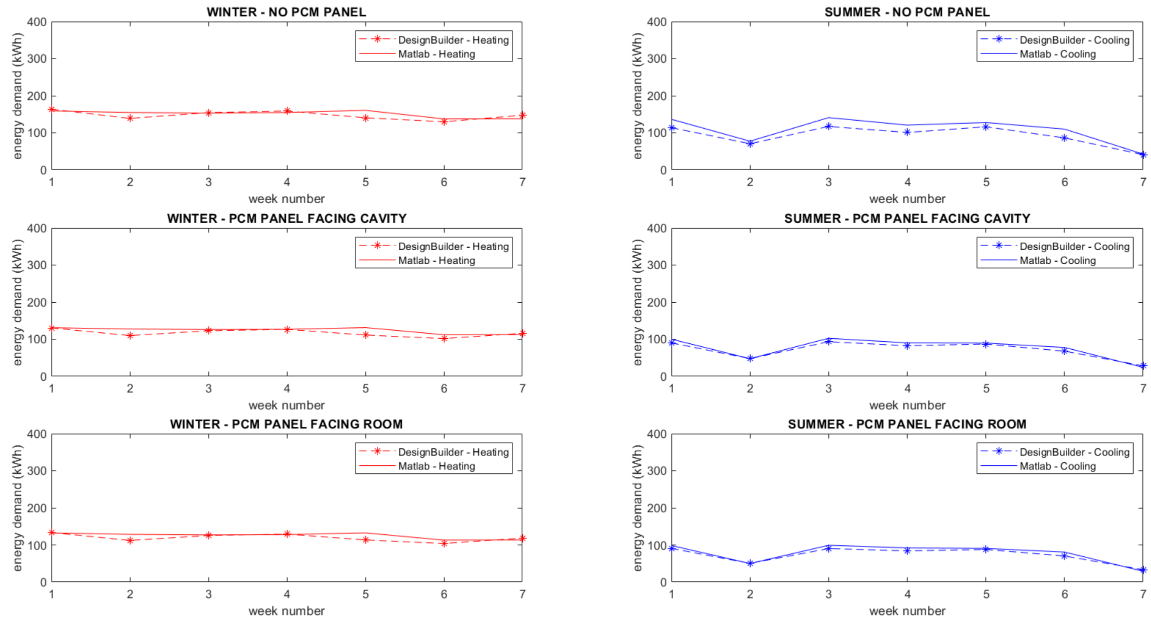


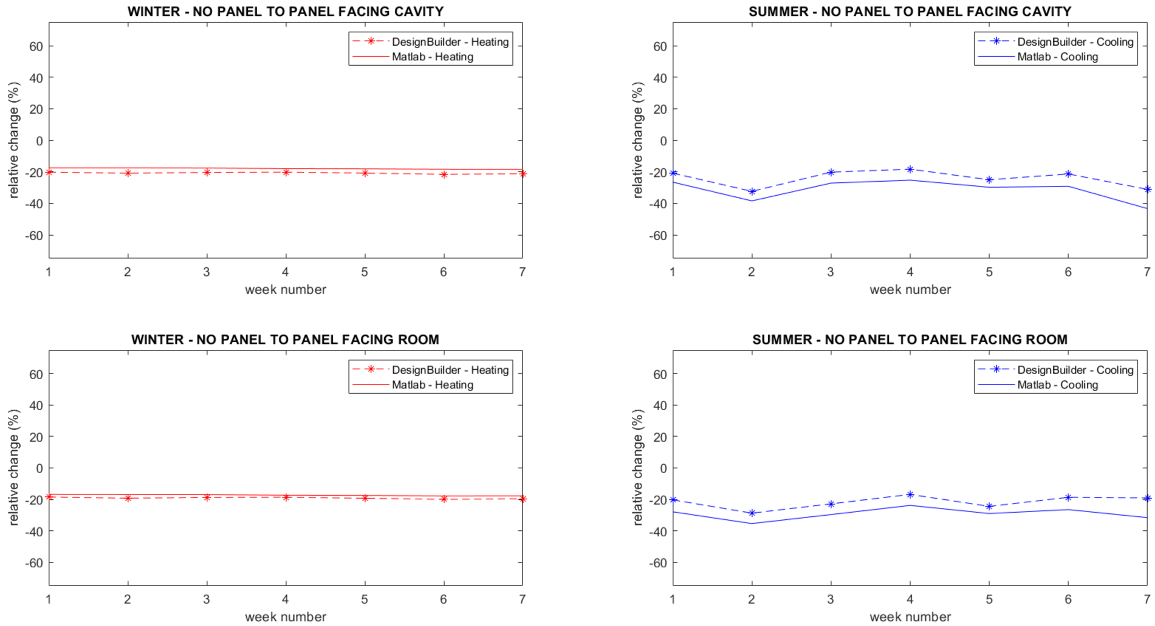


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 6:

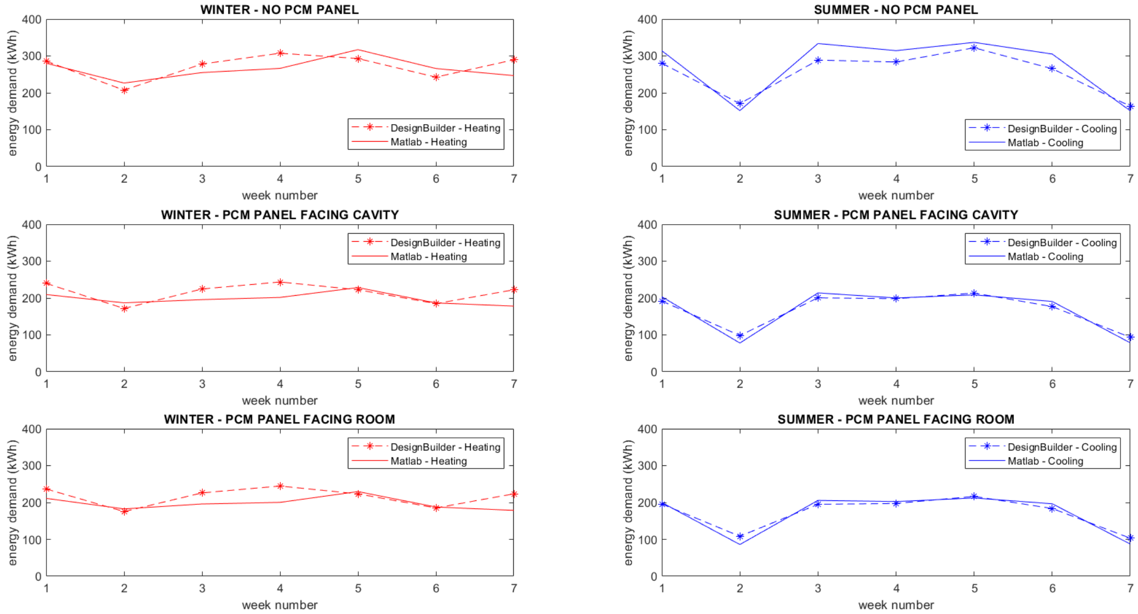
Office – Cold climate – Eastern orientation – Single clear glazing – Small room – Lightweight structure – New building

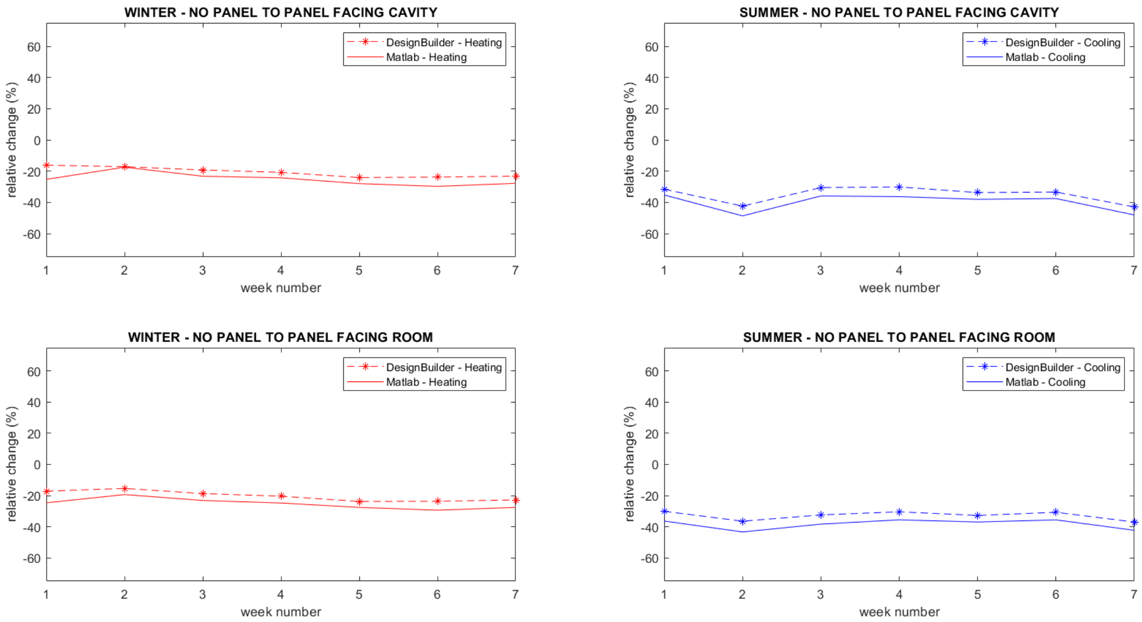




Room model 7:

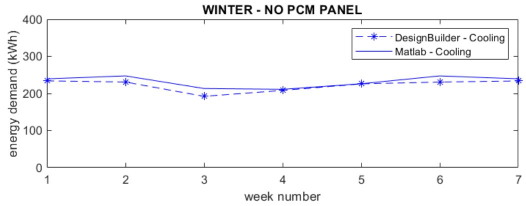
Office – Cold climate – Southern orientation – Single clear glazing – Big room – Lightweight structure – New building

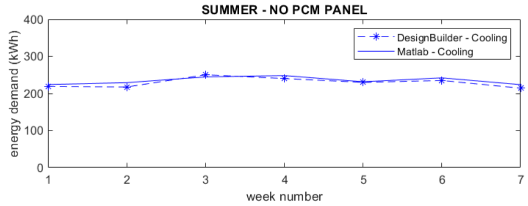


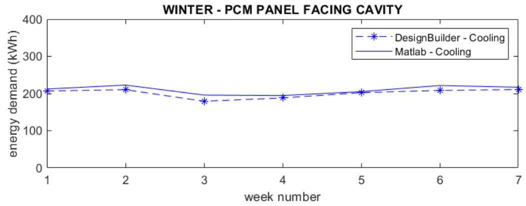


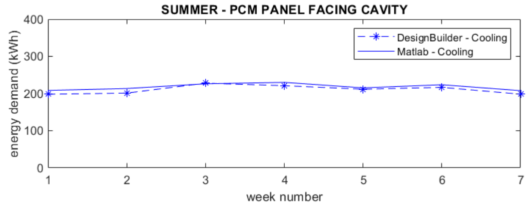
Room model 8:

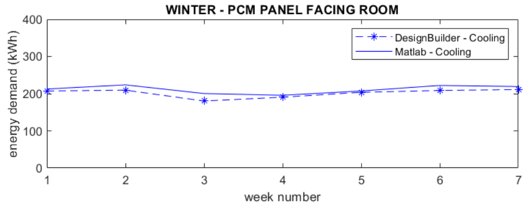
Office – Tropical climate – Southern orientation – Triple coated glazing – Big room – Lightweight structure – New building

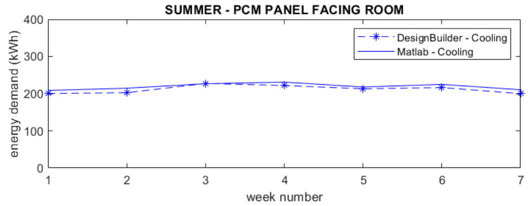


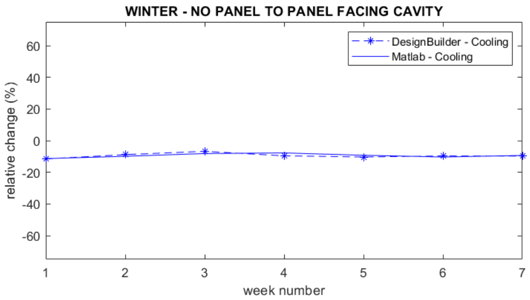


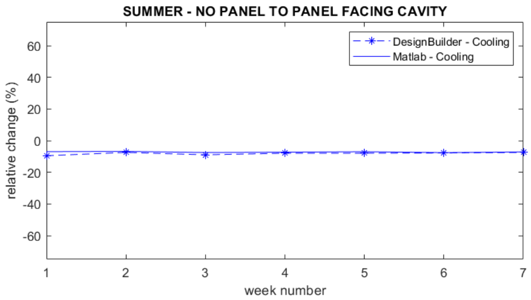


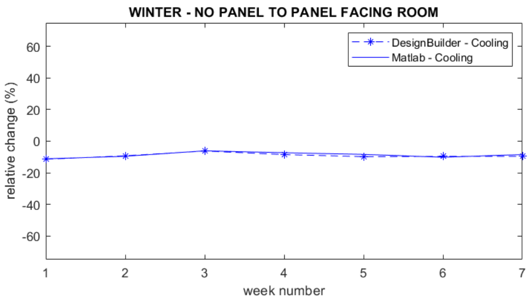


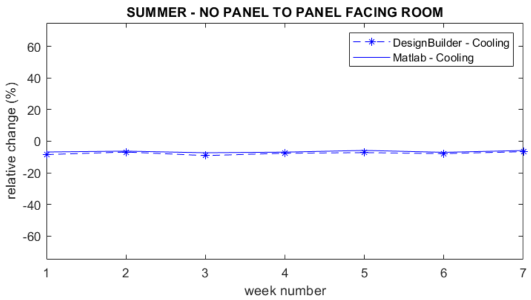






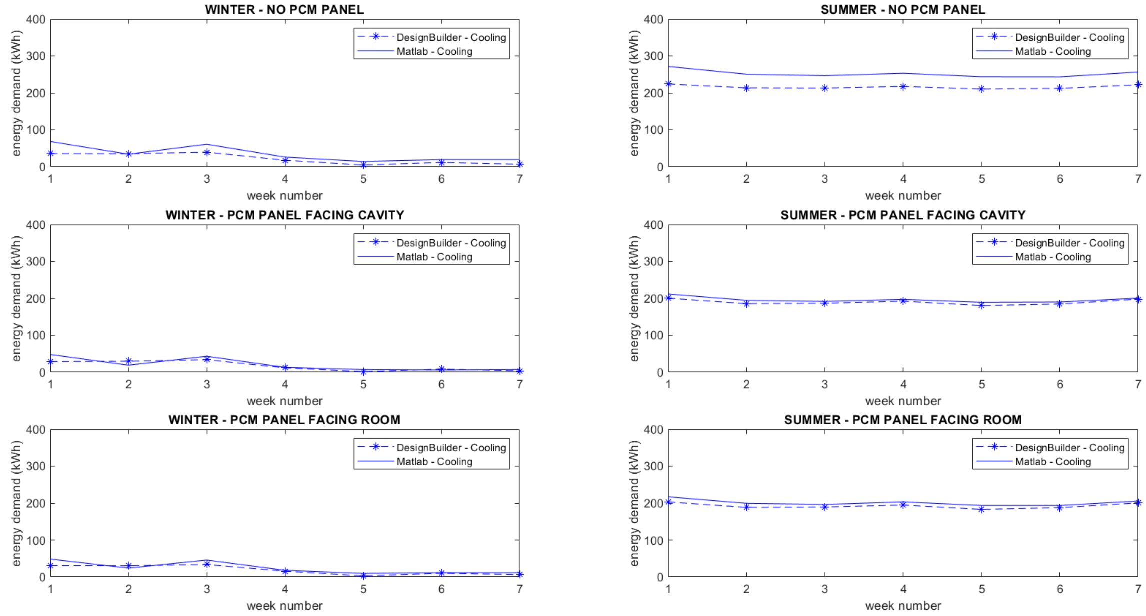


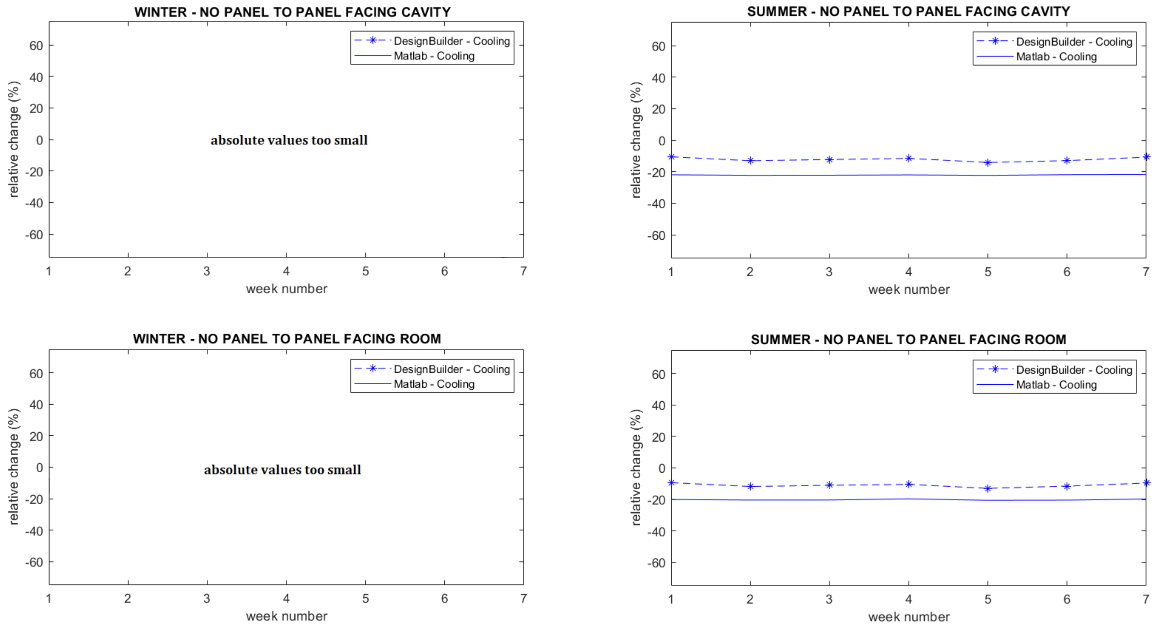




Room model 9:

Office – Dry climate – Western orientation – Single clear glazing – Small room – Heavyweight structure – New building

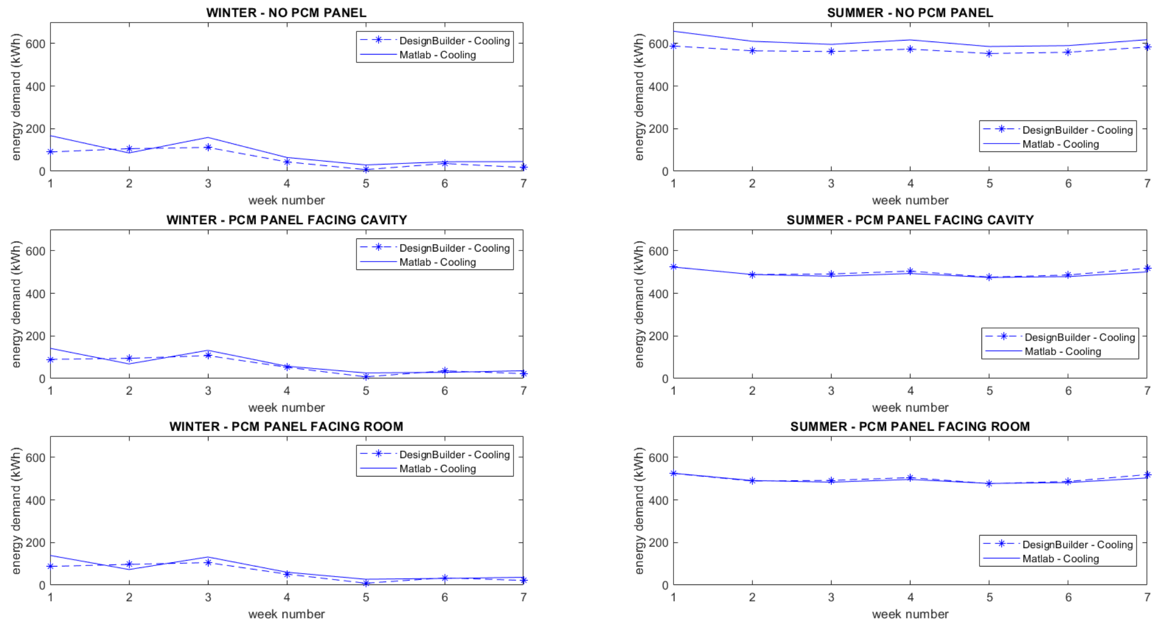


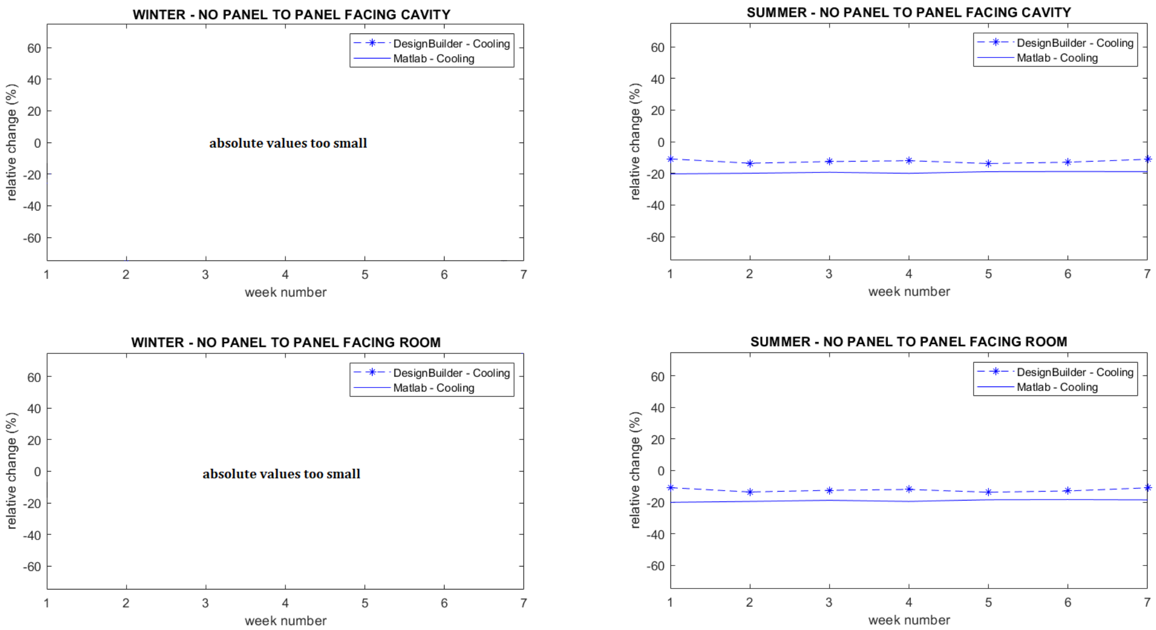


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 10:

Office – Dry climate – Eastern orientation – Single clear glazing – Big room – Heavyweight structure – New building

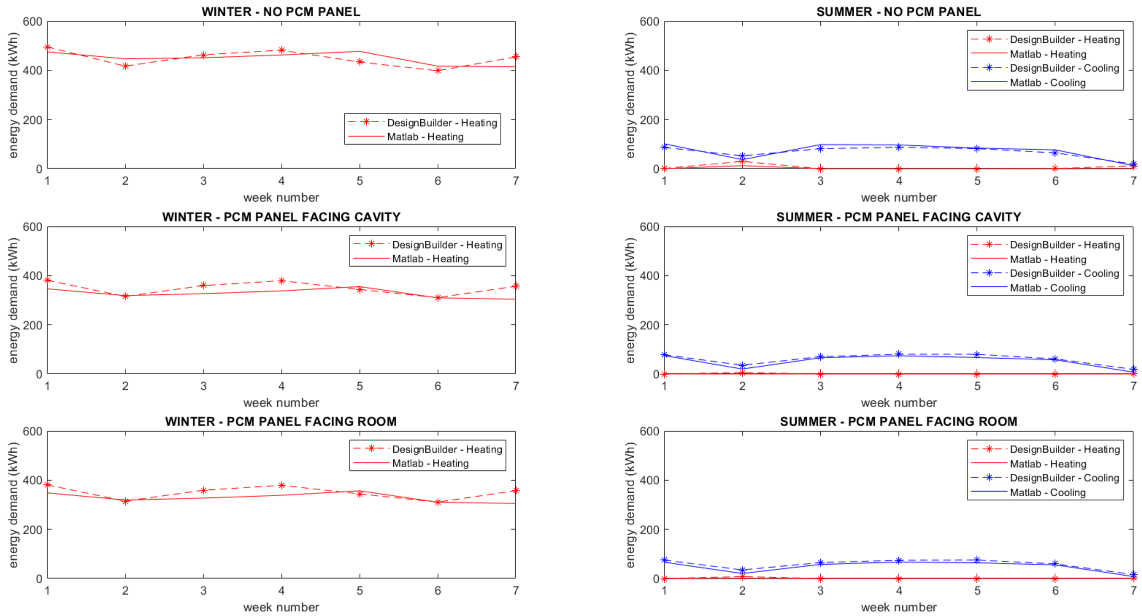


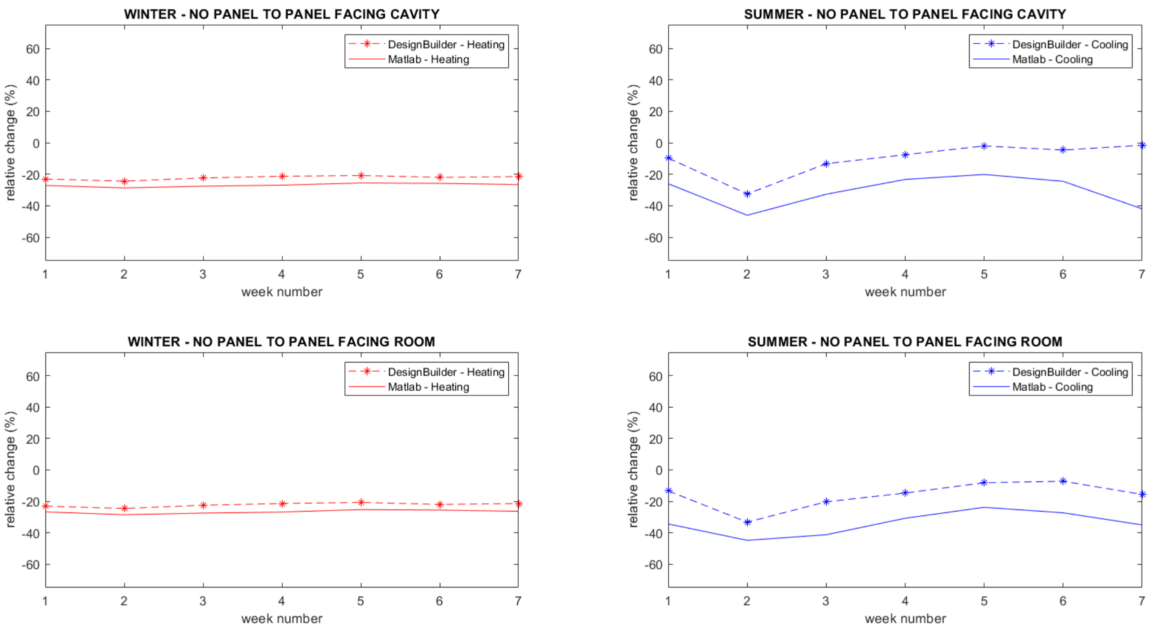


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 11:

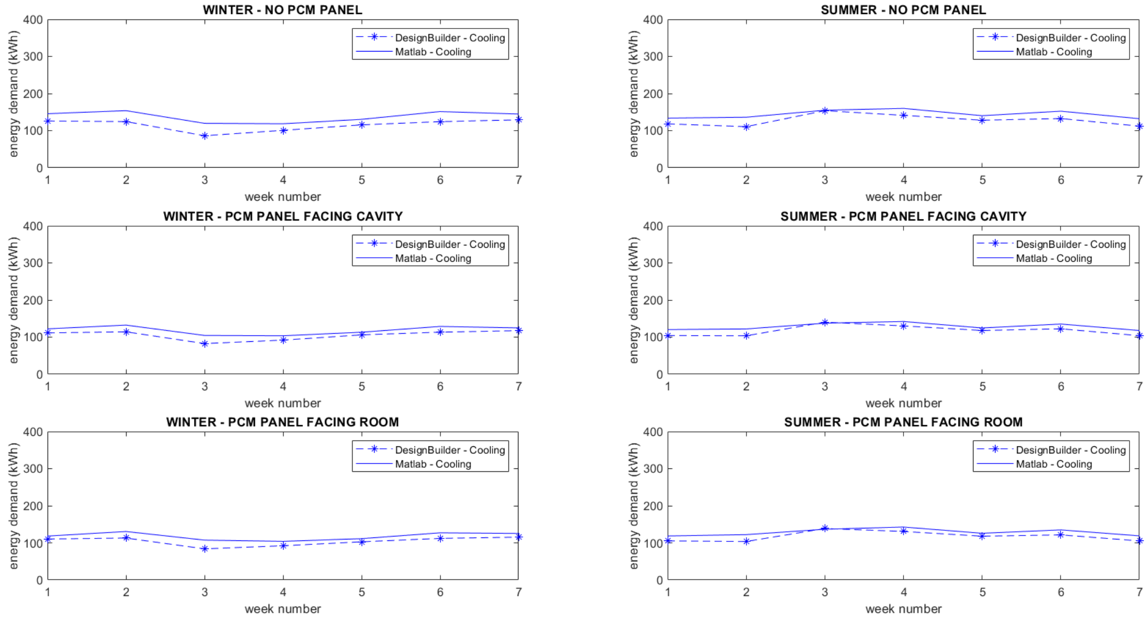
Residence – Cold climate – Northern orientation – Single clear glazing – Big room – Lightweight structure – Old building

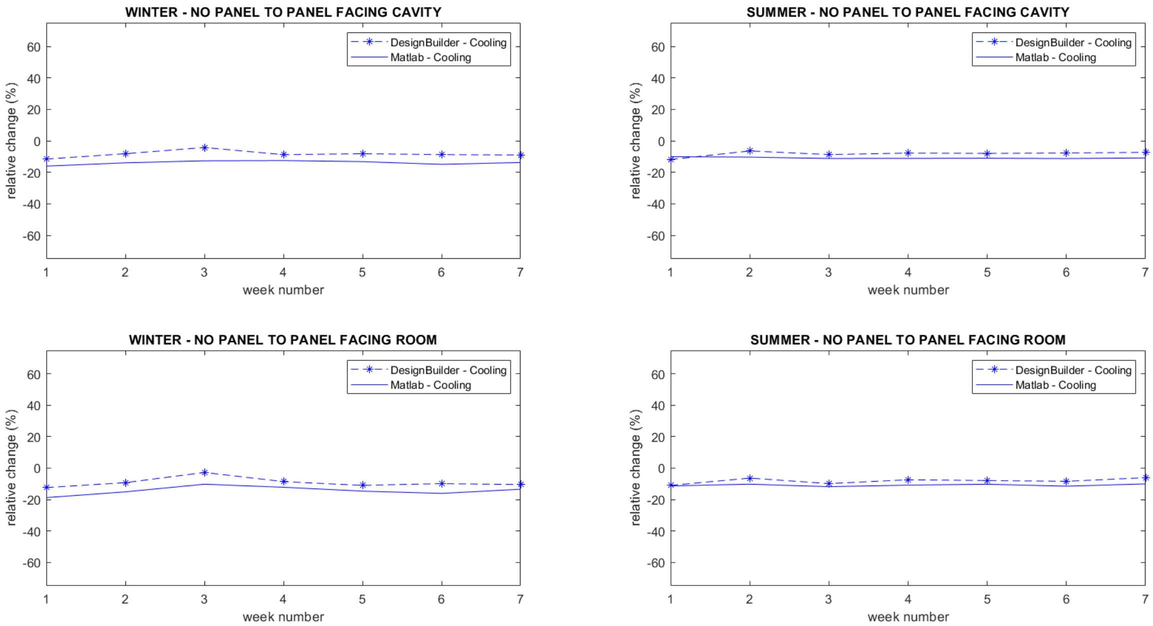




Room model 12:

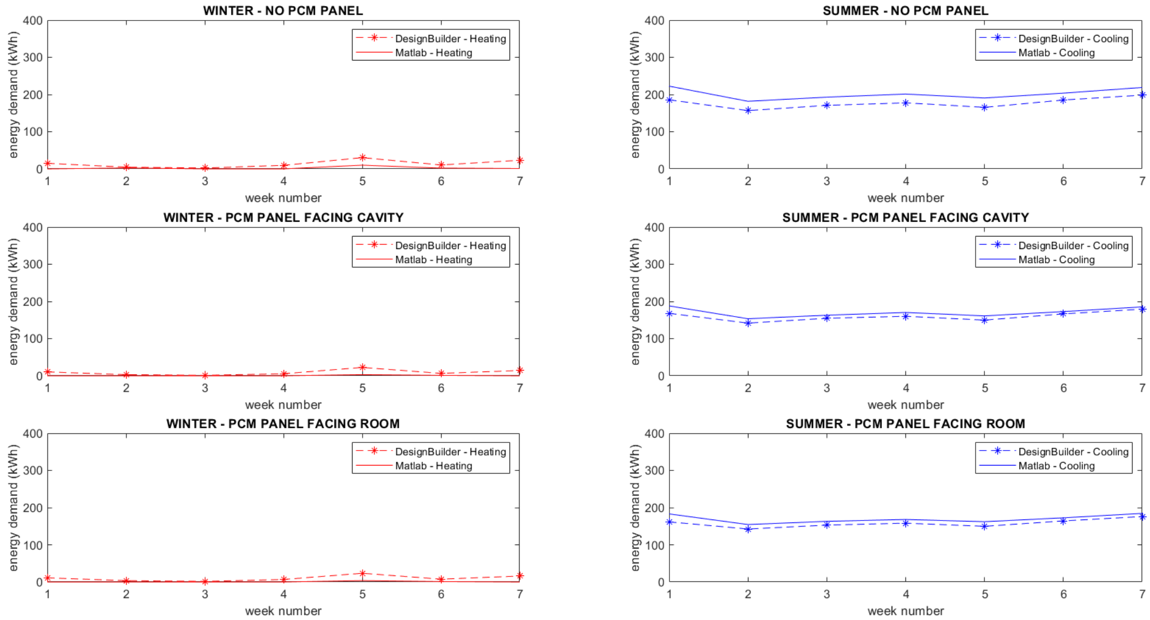
Residence – Tropical climate – Southern orientation – Triple coated glazing – Big room – Lightweight structure – Old building

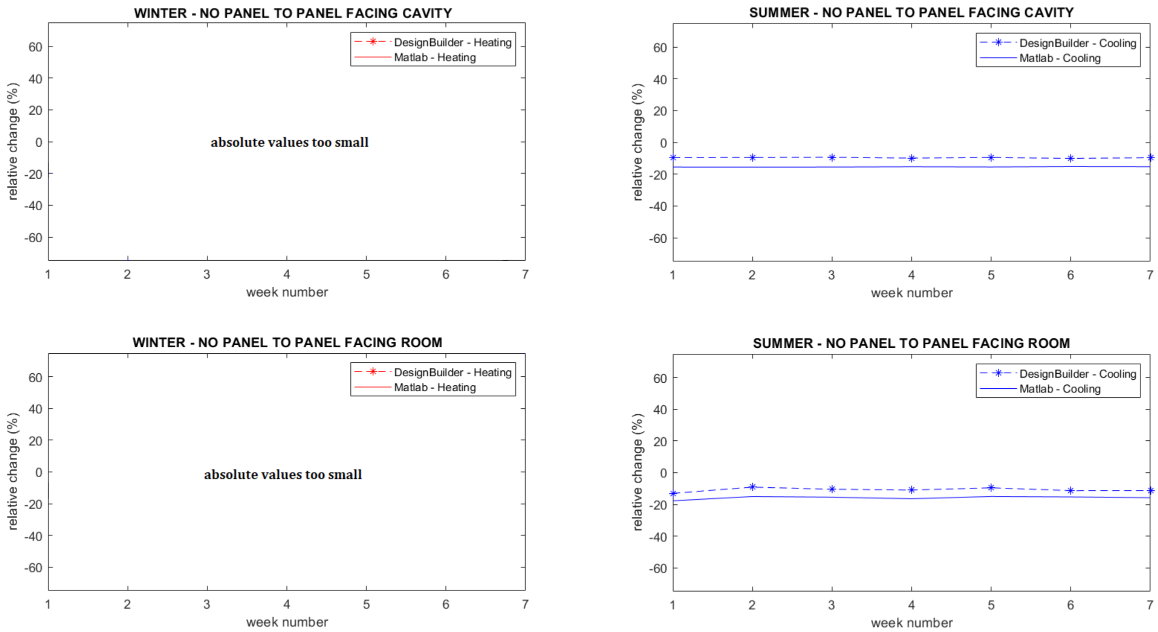




Room model 13:

Residence – Dry climate – Western orientation – Triple coated glazing – Big room – Lightweight structure – Old building

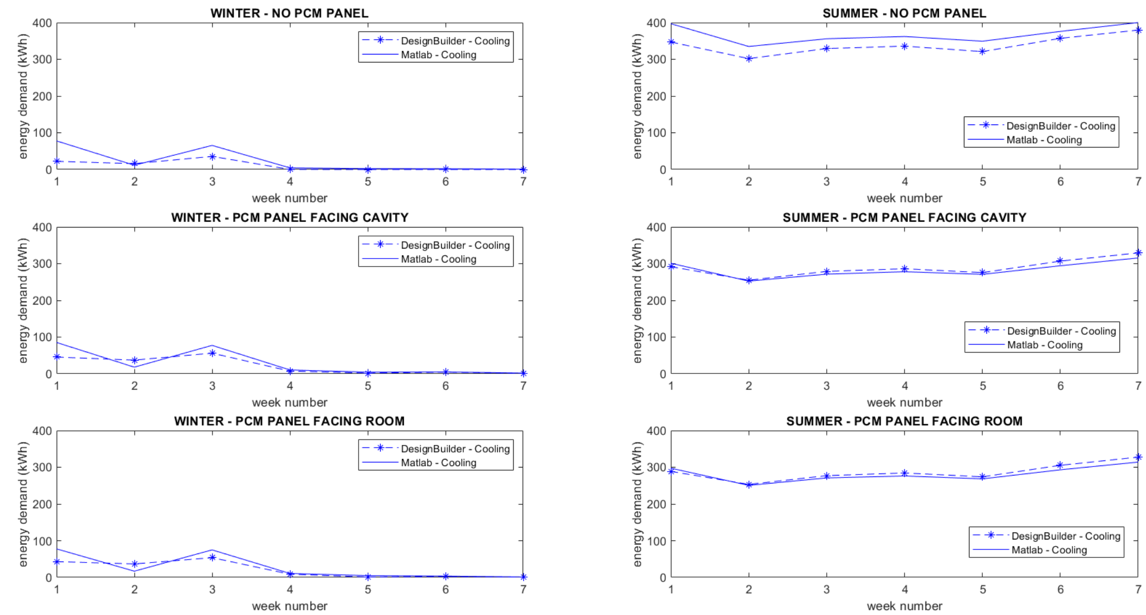


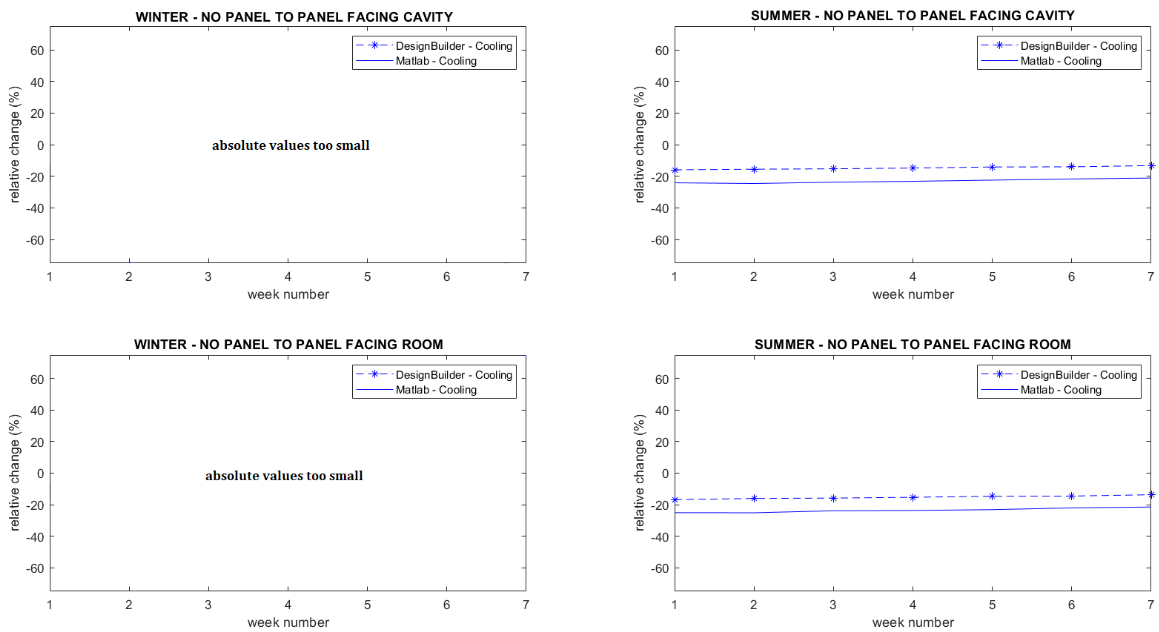


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 14:

Residence – Dry climate – Northern orientation – Single clear glazing – Big room – Heavyweight structure – Old building

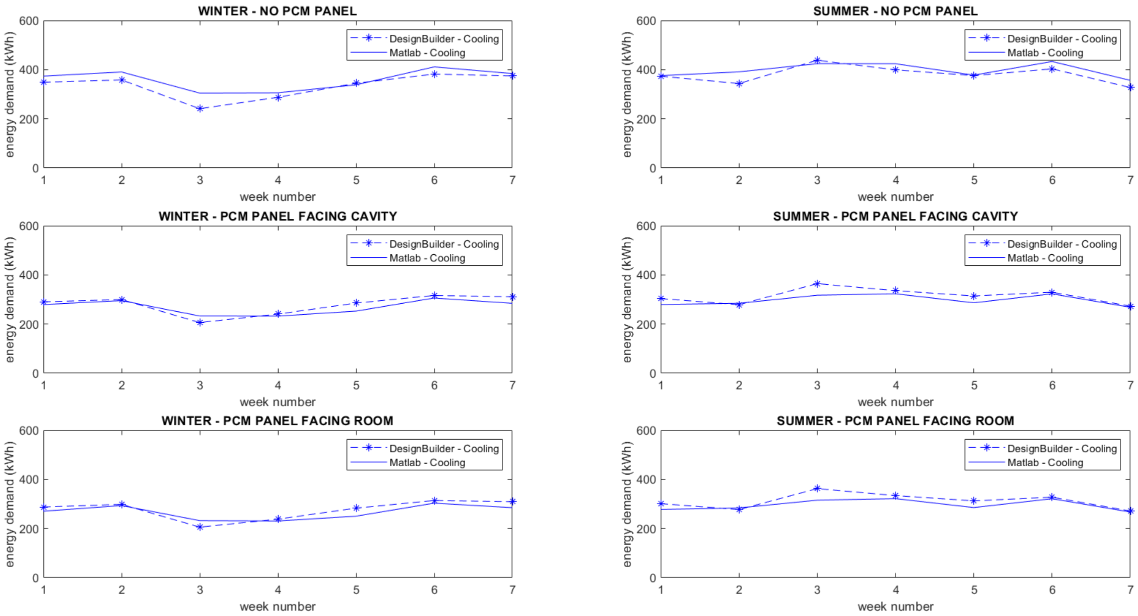


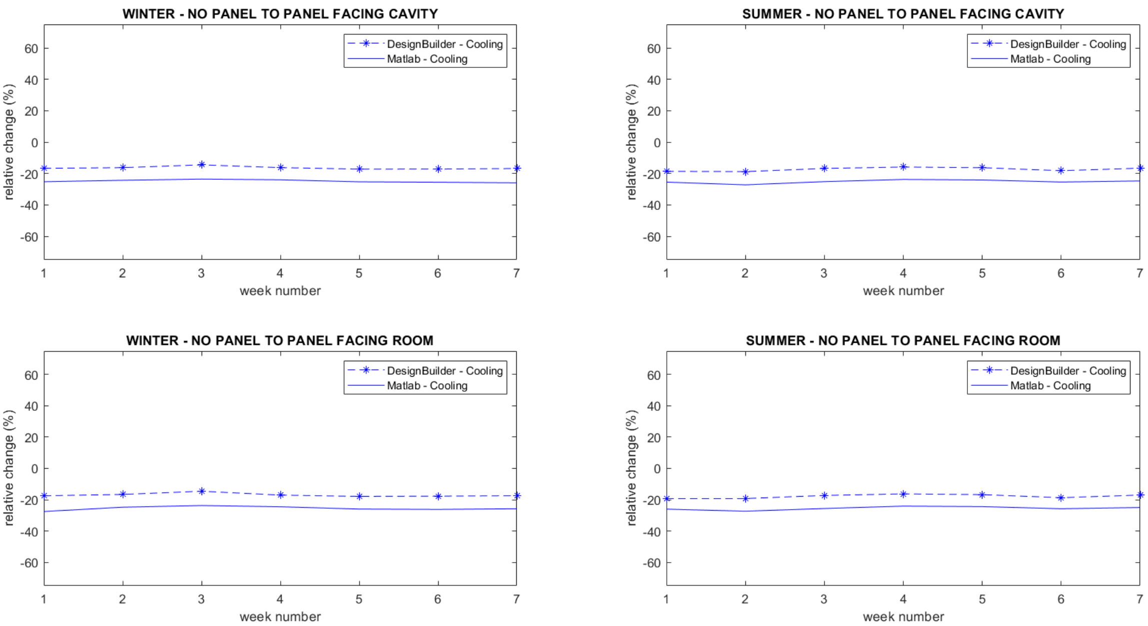


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 15:

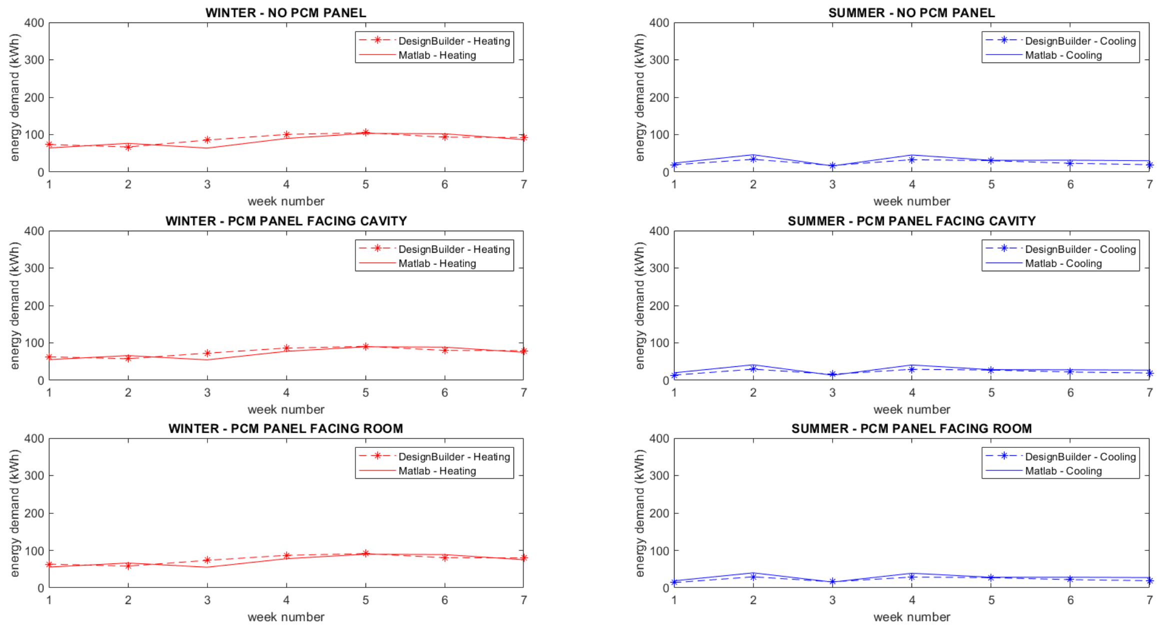
Residence – Tropical climate – Eastern orientation – Single clear glazing – Big room – Heavyweight structure – Old building

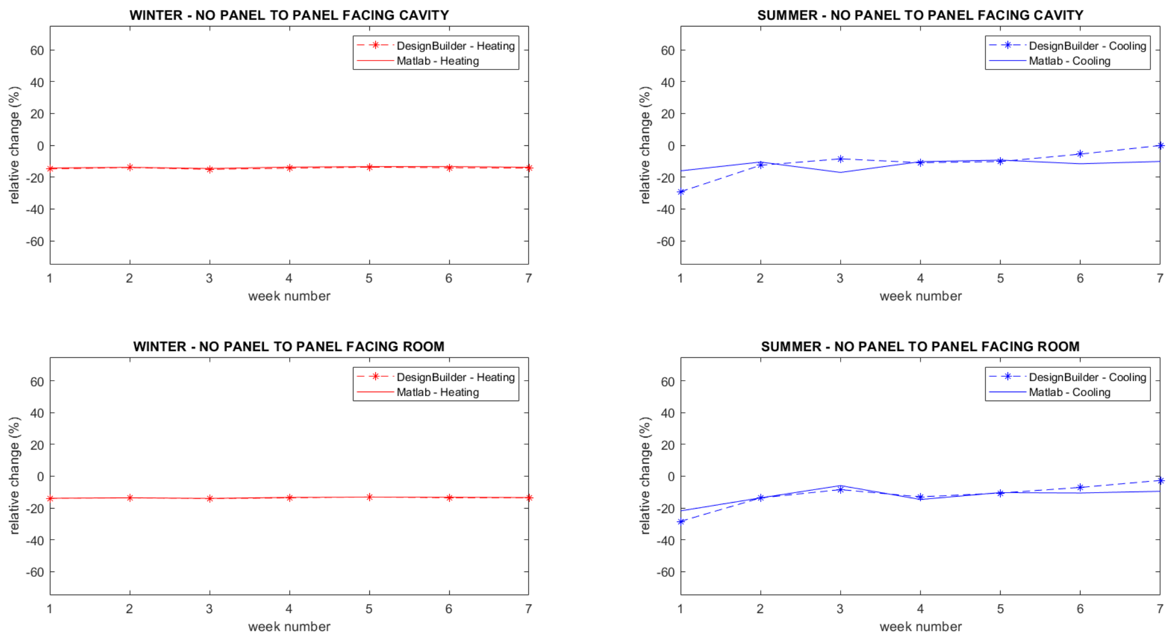




Room model 16:

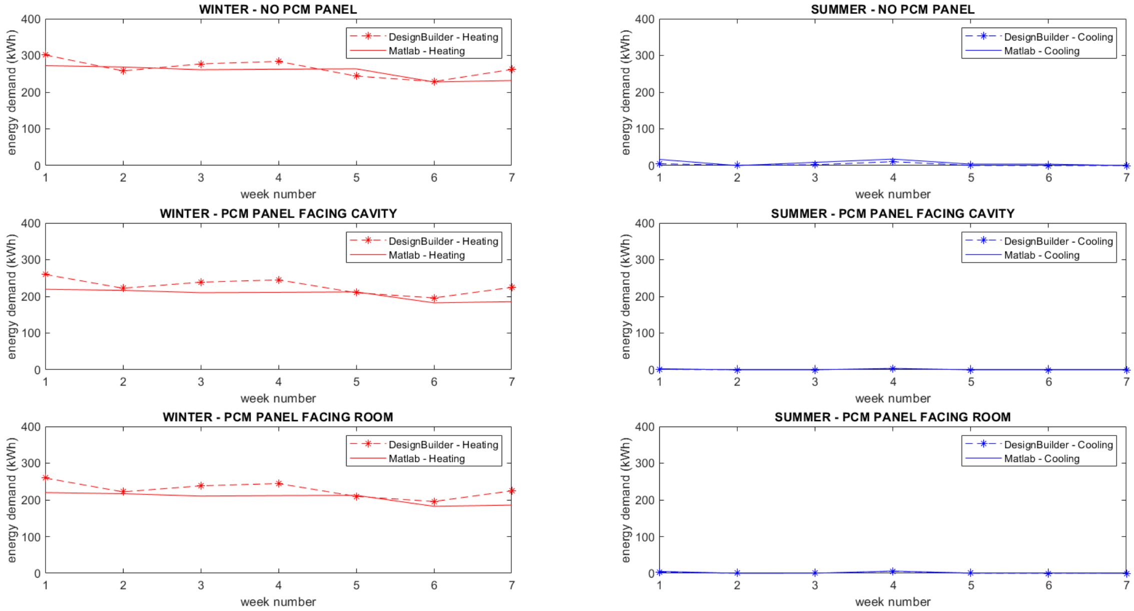
Residence – Temperate climate – Eastern orientation – Triple coated glazing – Small room – Lightweight structure – New building

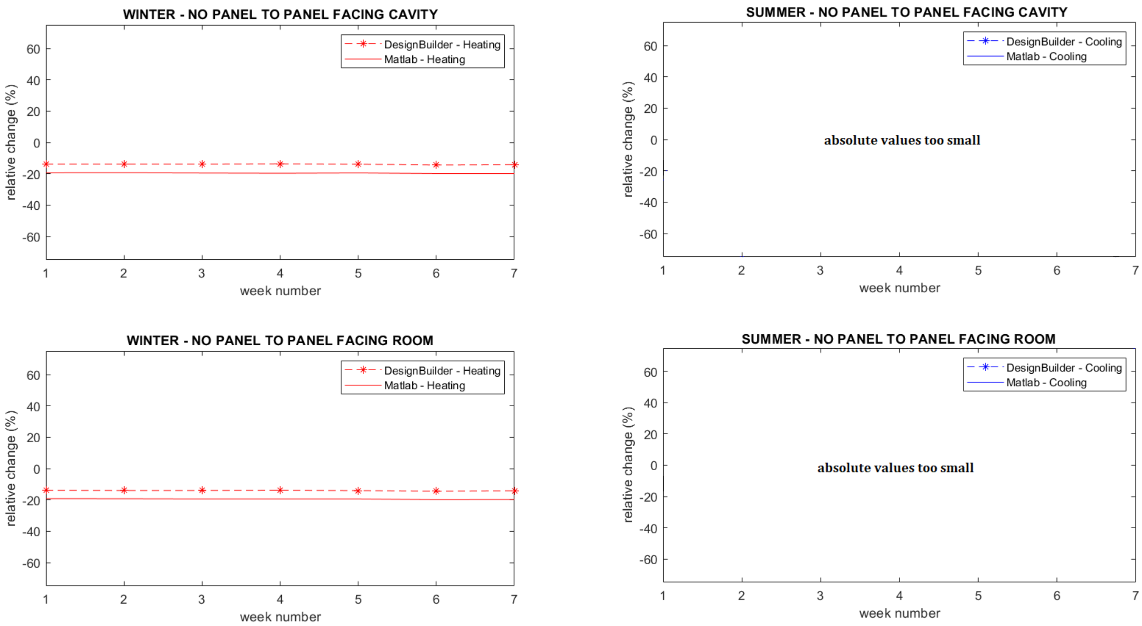




Room model 17:

Residence – Cold climate – Western orientation – Triple coated glazing – Big room – Lightweight structure – New building

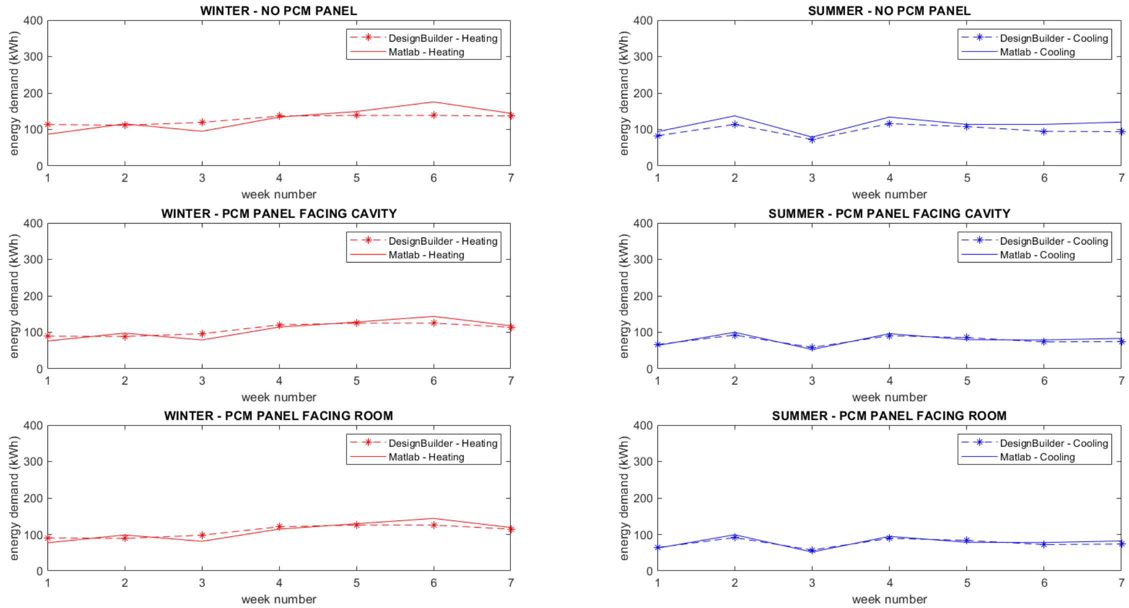


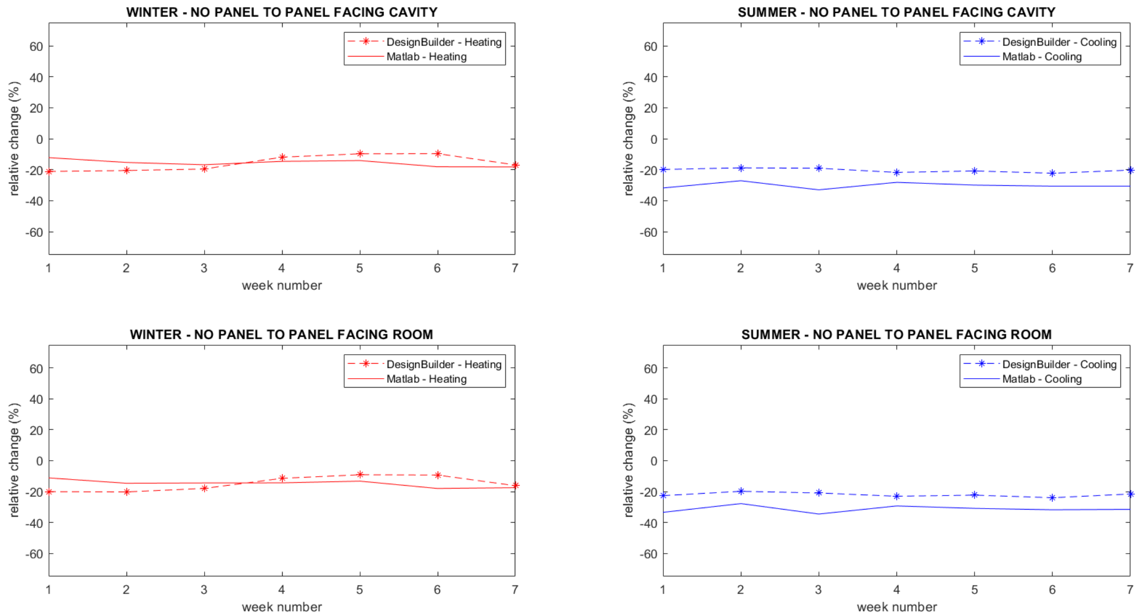


*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.

Room model 18:

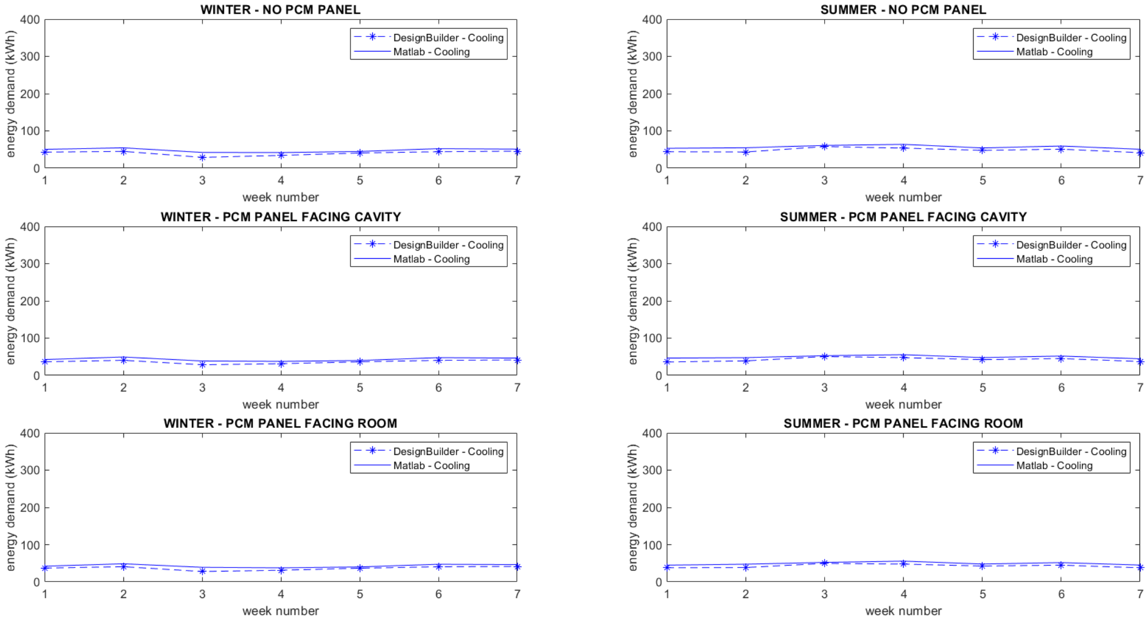
Residence – Temperate climate – Southern orientation – Single clear glazing – Small room – Heavyweight structure – New building

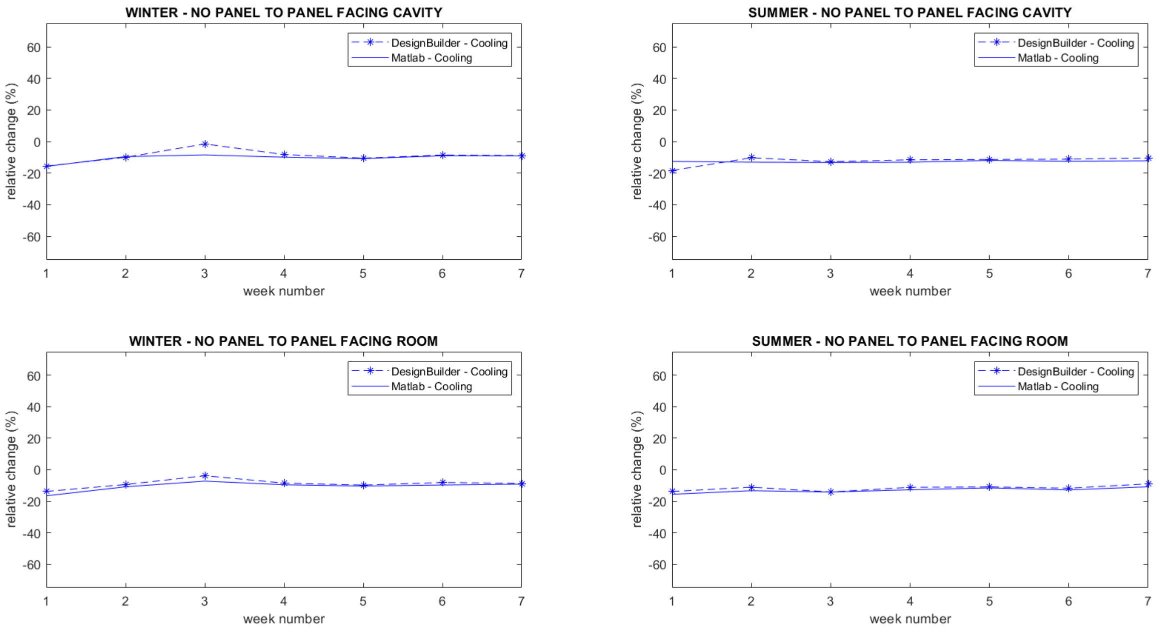




Room model 19:

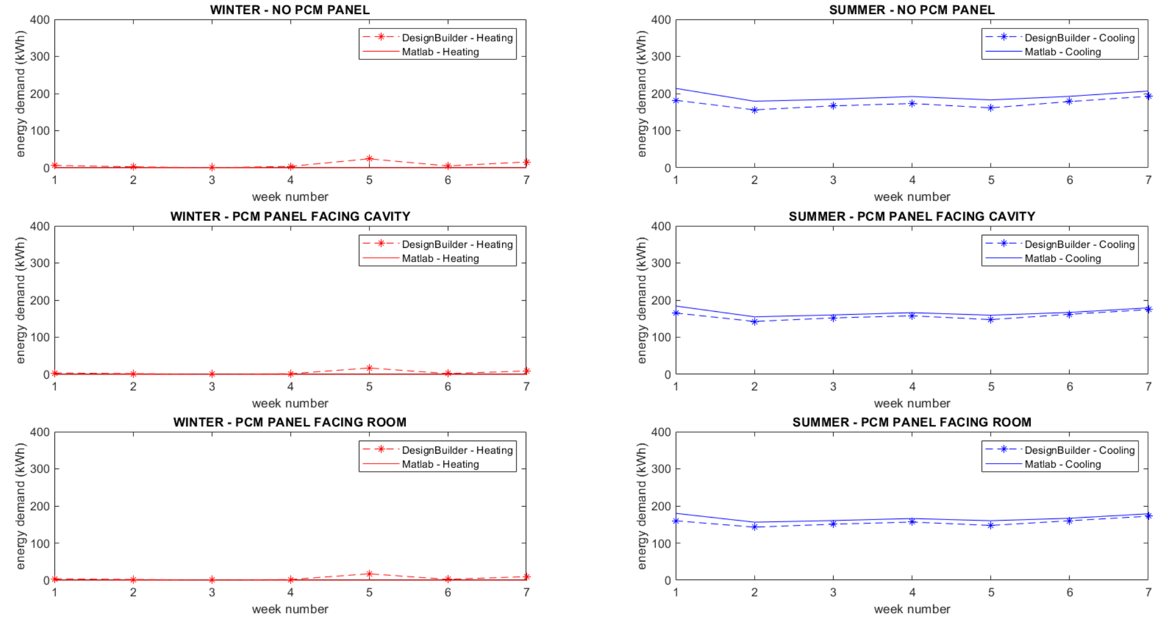
Residence – Tropical climate – Northern orientation – Triple coated glazing – Small room – Heavyweight structure – New building

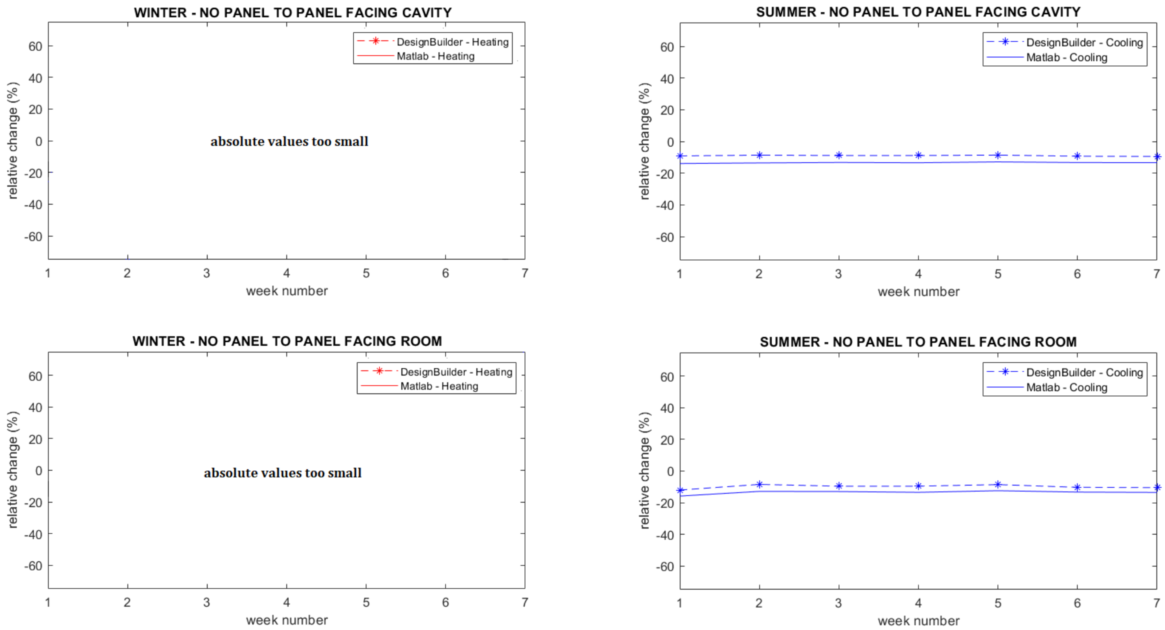




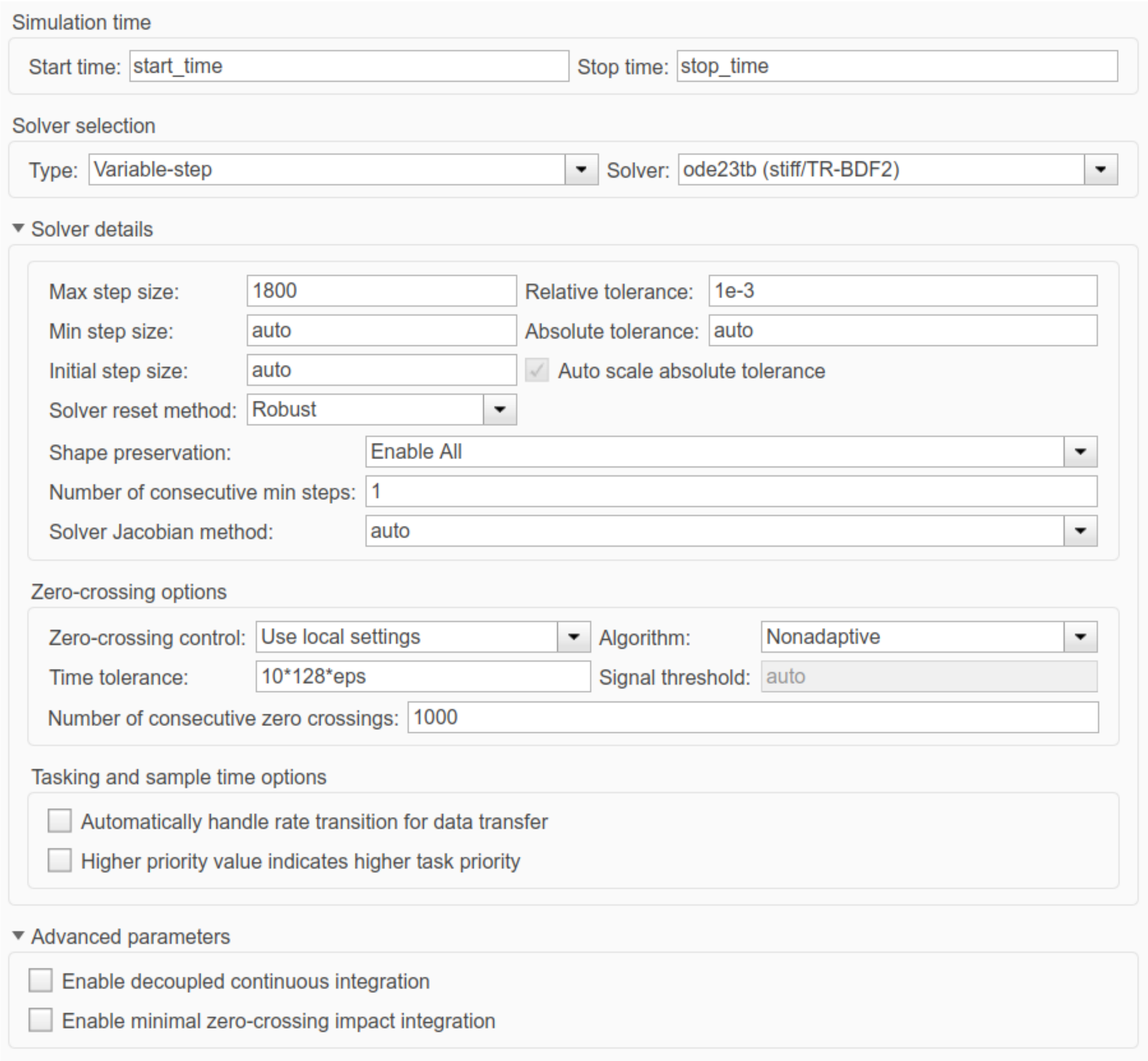
Room model 20:

Residence – Dry climate – Eastern orientation – Triple coated glazing – Big room – Heavyweight structure – New building





*absolute values too small: ratio between difference in energy demand (kWh) per week is not representative anymore and values for relative change are therefore not shown. Example of situation with too small values: energy demand in week 1 goes from 0.001 kWh to 0.1 kWh = 100% increase.



Simulation time
Start time: start_time
Stop time: stop_time
Solver selection
Type: Variable-step
Solver: ode23tb (stiff/TR-BDF2)
Solver details
Max step size: 1800
Relative tolerance: 1e-3
Min step size: auto
Absolute tolerance: auto
Initial step size: auto
Auto scale absolute tolerance
Solver reset method: Robust
Shape preservation: Enable All
Number of consecutive min steps: 1
Solver Jacobian method: auto
Zero-crossing options
Zero-crossing control: Use local settings
Algorithm: Nonadaptive
Time tolerance: 10*128*eps
Signal threshold: auto
Number of consecutive zero crossings: 1000
Tasking and sample time options
Automatically handle rate transition for data transfer
Higher priority value indicates higher task priority
Advanced parameters
Enable decoupled continuous integration
Enable minimal zero-crossing impact integration

APPENDIX C

Additional designer tables – Energy demand without LTATW

TABLE 7: HEATING ENERGY DEMAND WITHOUT LTATW (KWH/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Age ↓	Room size ↓	Type of glazing ↓	Window size ↓	Building method / Orientation	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
New building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	219	190	89	186	512	438	250	426	61	49	25	50	216	182	101	182	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	203	173	59	169	486	415	214	401	40	28	5	28	198	163	78	164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	196	165	45	160	486	408	205	395	27	15	0	15	189	155	66	156	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	580	490	240	487	1005	863	514	840	199	154	86	162	439	358	225	358	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	596	500	183	488	992	834	384	807	193	138	49	142	425	333	162	333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	595	497	150	480	982	822	332	794	180	122	26	125	413	318	126	319	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	271	251	196	250	615	576	474	570	95	89	70	90	298	280	238	280	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	257	236	174	233	593	554	449	547	77	70	49	71	279	261	220	261	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	252	231	166	228	590	552	445	545	64	58	36	58	272	252	212	252	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	778	700	530	701	1322	1204	940	1182	355	322	249	325	702	647	529	646	1	0	0	0	4	1	0	0	0	0	0	0	0	0	0	0
				Medium-weight	814	732	529	723	1310	1191	905	1172	358	325	240	328	694	633	508	634	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	819	734	517	723	1299	1184	890	1164	352	318	227	320	683	618	492	621	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	90	77	28	76	304	262	137	256	14	10	5	11	110	91	43	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	65	52	8	52	280	240	109	233	1	0	0	0	93	74	30	74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	52	39	2	38	276	234	100	227	0	0	0	0	83	66	21	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	178	143	44	138	409	345	139	331	31	21	11	21	131	89	35	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	164	125	18	122	396	329	94	314	14	5	1	5	119	75	15	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	151	109	5	105	385	317	68	303	3	0	0	0	106	63	1	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	114	108	86	108	379	360	307	357	28	27	21	27	163	157	137	157	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	89	83	60	83	354	336	283	333	10	8	4	8	146	140	120	140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	77	72	47	71	353	334	278	330	2	1	0	1	138	132	113	132	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	269	247	176	245	605	558	427	549	93	85	64	86	287	266	213	267	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	260	236	158	233	595	545	409	536	78	69	42	70	275	256	200	256	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	251	226	144	223	586	535	397	525	63	55	28	55	262	245	187	246	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	288	252	132	246	1210	1059	646	1032	69	61	36	61	425	367	199	368	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	167	137	30	133	1143	993	574	969	2	1	0	1	372	315	157	316	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	107	79	6	76	1119	962	527	941	0	0	0	0	336	276	115	277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	951	808	369	801	2322	1993	1056	1934	261	210	108	216	916	732	393	733	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	914	759	230	742	2281	1941	871	1885	164	112	30	115	869	685	284	688	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	863	699	149	679	2243	1895	746	1836	101	54	3	57	820	637	234	640	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	340	322	258	322	1410	1337	1129	1321	94	91	78	91	563	539	460	539	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	212	199	128	198	1345	1270	1060	1255	11	9	4	10	514	489	406	489	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	151	137	71	136	1317	1245	1029	1229	0	0	0	0	480	454	372	454	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	1223	1123	859	1127	2955	2734	2145	2692	457	416	331	423	1411	1313	1075	1314	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	1209	1102	768	1090	2933	2702	2081	2659	366	329	218	332	1371	1276	1027	1277	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1170	1058	710	1044	2899	2661	2032	2615	307	269	158	271	1328	1229	976	1230	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	120	104	63	105	762	680	417	669	29	26	16	25	224	188	101	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	15	11	2	10	701	622	341	610	0	0	0	0	174	142	61	142	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1	0	0	0	674	584	291	580	0	0	0	0	137	95	18	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	243	198	73	191	1001	866	351	836	47	37	19	38	272	187	62	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	138	104	3	96	962	823	243	793	0	0	0	0	232	154	19	155	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	75	49	0	42	918	779	181	744	0	0	0	0	184	113	0	114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	145	137	117	137	903	871	766	863	38	37	33	37	310	300	265	300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	21	20	11	19	838	806	704	799	0	0	0	0	258	248	216	248	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1	1	1	1	815	781	679	773	0	0	0	0	220	210	174	210	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	347	328	239	326	1394	1304	1031	1284	99	92	76	93	549	519	413	519	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	229	212	117	211	1353	1265	980	1245	14	11	4	11	514	481	375	481	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	161	144	56	142	1310	1223	937	1204	1	0	0	0	471	437	330	438	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Old building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	1098	988	760	988	1778	1617	1280	1587	534	485	382	492	965	890	735	889	2	0	0	0	11	4	0	2	0	0	0	0	0	0	0	0
				Medium-weight	1167	1054	778	1042	1771	1601	1234	1575	559	507	388	510	960	881	713	880	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1228	1110	811	1094	1820	1652	1273	1626	583	529	399	531	988	903	726	903	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	1273	1095	708	1105	2066	1832	1348	1803	585	495	358	513	1073	950	714	950	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	1388	1182	674	1166	2064	1774	1145	1733	626	525	321	536	1061	923	610	923	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1423	1204	652	1178	2076	1771	1079	1722	635	528	290	535	1057	913	563	914	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	1225	1170	1069	1171	1991	1913	1775	1901	623	601	556	603	1098	1065	998	1065	8	5	1	4	49	32	6	22	0	0	0	0	0	0	0	0
				Medium-weight	1298	1241	1129	1239	1990	1906	1764	1897	658	635	583	637	1096	1063	994	1063	1	0	0	0	39	24	3	16	0	0	0	0	0	0	0	0
				Heavy-weight	1360	1300	1183	1296	2051	1961	1809	1950	687	662	607	663	1127	1093	1021	1093	0	0	0	0	34	20	0	14	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	1570	1447	1216	1455	2544	2377	2055	2347	814	764	662	771	1414	1340	1185	1337	13	6	0	4	63	31	5	16	0	0	0	0	0	0	0	0
				Medium-weight	1703	1576	1309	1570	2549	2369	2022	2343	885	828	705	833	1417	1341	1175	1340	4	1	0	0	50	22	0	11	0	0	0	0	0	0	0	0
				Heavy-weight	1742	1618	1337	1607	2562	2367	2012	2343	903	843	712	846	1422	1343	1173	1343	1	0	0	0	41	17	0	8	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	951	867	688	865	1567	1439	1166	1416	455	417	338	421	846	790	666	789	2	0	0	0	9	4	0	2	0	0	0	0	0	0	0	0
				Medium-weight	1001	917	703	907	1558	1424	1143	1405	470	431	342	434	841	781	650	781	0	0	0	0	7	1	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	1059	970	741	958	1610	1475	1187	1456	492	452	355	454	870	806	667	806	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	863	745	454	744	1427	1248	859	1219	370	312	209	321	717	631	442	630	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Medium-weight	918	782	421	768	1425	1220	744	1187	382	316	180	323	704	611	375	612	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	938	796	402	775	1435	1221	720	1185	383	314	154	318	699	606	352	608	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	1055	1024	966	1024	1743	1697	1617	1691	525	514	488	515	955	936	897	935	5	4	1	3	39	29	9	22	0	0	0	0	0	0	0	0
				Medium-weight	1106	1074	1010	1073	1740	1691	1609	1685	549	536	506	537	951	933	894	933	0	0	0	0	30	21	7	17	0	0	0	0	0	0	0	0
				Heavy-weight	1164	1129	1061	1127	1801	1748	1660	1741	574	560	529	561	982	963	921	963	0	0	0	0	25	18	3	15	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	1090	1030	904	1032	1805	1717	1544	1703	544	521	466	524	988	952	869	951	5	3	0	3	31	17	3	11	0	0	0	0	0	0	0	0
				Medium-weight	1157	1096	956	1093	1805	1710	1528	1697	574	547	483	549	988	950	864	950	0	0	0	0	22	13	0	9	0	0	0	0	0	0	0	0
				Heavy-weight	1182	1124	977	1118	1817	1712	1527	1699	580	552	485	553	992	952	863	952	0	0	0	0	18	10	0	6	0	0	0	0	0	0	0	0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	3760	3496	2952	3505	7029	6591	5697	6513	1787	1677	1452	1696	3776	3593	3181	3588	16	8	0	5	53	26	6	18	0	0	0	0	0	0	0	0
				Medium-weight	4107	3839	3170	3817	7017	6547	5604	6479	1896	1776	1499	1786	3773	3579	3143	3577	0	0	0	0	43	19	0	7	0	0	0	0	0	0	0	0
				Heavy-weight	4263	3990	3267	3958	7117	6612	5673	6554	1930	1809	1513	1816	3823	3619	3164	3619	0	0	0	0	34	8	0	0	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	4106	3610	2621	3672	7549	6772	5213	6634	1899	1670	1297	1714	3989	3607	2821	3611	8	1	0	0	20	4	0	4	0	0	0	0	0	0	0	0
				Medium-weight	4575	4002	2690	3967	7540	6706	4831	6538	2045	1797	1242	1821	3971	3560	2678	3561	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	4695	4090	2660	4024	7538	6699	4691	6533	2048	1795	1164	1812	3948	3506	2593	3515	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	4023	3913	3703	3919	7524	7347	7029	7319	1961	1919	1829	1926	4082	4009	3857	4007	28	23	11	21	134	100	35	79	0	0	0	0	0	0	0	0
				Medium-weight	4383	4267	4026	4264	7529	7338	7013	7314	2099	2053	1944	2056	4080	4009	3853	4008	1	1	0	0	101	74	28	61	0	0	0	0	0	0	0	0
				Heavy-weight	4531	4417	4164	4409	7652	7445	7101	7422	2141	2092	1978	2095	4139	4063	3899	4063	0	0	0	0	83	64	15	52	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	4765	4495	3994	4518	8788	8384	7613	8316	2374	2269	2056	2289	4805	4634	4264	4627	37	25	3	20	165	97	21	64	0	0	0	0	0	0	0	0
				Medium-weight	5281	5004	4411	4997	8810	8376	7553	8310	2603	2487	2218	2497	4817	4642	4252	4640	4	1	0	1	125	70	4	47	0	0	0	0	0	0	0	0
				Heavy-weight	5401	5137	4505	5115	8824	8359	7512	8300	2626	2503	2219	2510	4816	4634	4235	4634	0	0	0	0	98	57	0	37	0	0	0	0	0	0	0	0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	3454	3252	2832	3259	6556	6213	5537	6161	1624	1542	1372	1556	3509	3370	3058	3366	15	9	0	6	50	28	6	20	0	0	0	0	0	0	0	0
				Medium-weight	3747	3546	3041	3530	6543	6176	5466	6125	1703	1615	1408	1623	3504	3358	3027	3357	0	0	0	0	40	22	0	11	0	0	0	0	0	0	0	0
				Heavy-weight	3888	3685	3145	3661	6648	6245	5526	6201	1733	1644	1424	1650	3555	3401	3055	3401	0	0	0	0	31	11	0	1	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	3227	2867	2106	2894	6090	5491	4219	5368	1437	1280	991	1305	3180	2893	2294	2891	5	1	0	0	12	1	0	1	0	0	0	0	0	0	0	0
				Medium-weight	3535	3121	2144	3092	6069	5455	3996	5333	1499	1333	934	1349	3156	2849	2192	2849	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0
				Heavy-weight	3601	3172	2110	3121	6072	5454	3896	5334	1487	1313	871	1326	3135	2807	2136	2812	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	3665	3604	3485	3606	6957	6855	6674	6840	1762	1739	1688	1742	3756	3715	3628	3714	24	21	14	20	112	94	45	80	0	0	0	0	0	0	0	0
				Medium-weight	3967	3903	3767	3901	6959	6850	6664	6836	1864	1839	1778	1840	3752	3712	3624	3711	0	0	0	0	82	69	38	61	0	0	0	0	0	0	0	0
				Heavy-weight	4103	4038	3893	4034	7083	6964	6765	6950	1900	1873	1808	1875	3809	3766	3673	3766	0	0	0	0	70	59	27	52	0	0	0	0	0	0	0	0
			Large window (wwr=0.75)	Light-weight	3741	3608	3348	3620	7104	6895	6496	6862	1802	1752	1641	1760	3834	3750	3559	3747	25	20	7	17	98	69	22	54	0	0	0	0	0	0	0	0
				Medium-weight	4082	3950	3644	3946	7111	6889	6472	6858	1921	1867	1729	1871	3838	3752	3554	3752	1	0	0	0	71	53	11	43	0	0	0	0	0	0	0	0
				Heavy-weight	4155	4030	3704	4019	7124	6881	6446	6849	1916	1860	1716	1863	3834	3744	3538	3744	0	0	0	0	59	42	0	32	0	0	0	0	0	0	0	0

TABLE 8: COOLING ENERGY DEMAND WITHOUT LTATW (KWH/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Room size ↓	Window size ↓	Type of glazing ↓	Age ↓	Orientation / Building method	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=20m²)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	5	12	17	13	2	9	15	9	166	192	193	186	119	146	151	147	780	870	895	960	560	662	691	781	1755	1814	1755	1801	1279	1346	1281	1338
				Medium-weight	0	2	3	2	0	1	2	2	136	156	159	154	113	140	144	140	745	834	848	927	554	657	683	775	1767	1828	1766	1816	1275	1342	1277	1333
				Heavy-weight	0	0	1	0	0	0	0	0	122	145	146	143	104	133	136	132	731	822	834	920	550	653	679	772	1766	1828	1765	1817	1272	1341	1273	1330
			Old building	Light-weight	3	8	8	6	0	2	3	2	141	165	166	160	79	100	102	101	836	928	945	1013	630	725	737	839	1891	1953	1890	1936	1460	1532	1462	1525
				Medium-weight	0	1	1	0	0	0	0	0	113	132	134	131	70	91	91	91	816	908	919	997	618	717	727	830	1925	1991	1925	1976	1467	1541	1469	1531
				Heavy-weight	0	0	0	0	0	0	0	0	99	122	121	117	59	81	79	81	805	899	908	996	613	719	729	834	1942	2009	1940	1996	1480	1556	1481	1545
		Double glazing (coated)	New building	Light-weight	2	3	3	2	0	0	0	0	108	117	118	115	53	60	61	60	648	680	684	709	418	449	453	484	1501	1521	1500	1516	984	1008	985	1004
				Medium-weight	0	0	0	0	0	0	0	0	81	89	88	88	45	52	51	52	616	645	649	674	408	441	444	476	1498	1519	1498	1515	976	1000	977	996
				Heavy-weight	0	0	0	0	0	0	0	0	68	75	75	75	38	46	46	46	600	630	633	661	403	434	437	470	1494	1515	1493	1512	973	997	973	993
			Old building	Light-weight	0	2	2	1	0	0	0	0	95	107	105	104	34	42	42	42	717	754	758	783	503	541	544	581	1650	1675	1649	1667	1169	1198	1169	1195
				Medium-weight	0	0	0	0	0	0	0	0	67	76	76	75	23	31	31	31	696	733	736	765	488	525	529	567	1668	1694	1667	1688	1170	1200	1170	1196
				Heavy-weight	0	0	0	0	0	0	0	0	54	63	62	62	16	24	24	24	687	725	728	761	486	526	528	568	1680	1707	1678	1702	1182	1214	1182	1209
		Triple glazing (clear)	New building	Light-weight	4	8	10	8	1	5	9	6	149	167	168	164	104	125	128	125	721	787	803	853	495	573	594	661	1629	1674	1629	1664	1130	1181	1132	1174
				Medium-weight	0	1	1	1	0	0	0	0	119	134	138	133	99	119	122	119	682	749	757	817	489	566	586	654	1632	1678	1631	1669	1124	1174	1125	1167
				Heavy-weight	0	0	0	0	0	0	0	0	106	123	124	122	89	112	115	111	668	736	744	808	485	563	582	651	1629	1675	1628	1667	1120	1171	1122	1164
			Old building	Light-weight	2	5	5	4	0	1	1	1	125	143	144	139	65	81	82	82	778	849	861	912	564	638	645	722	1773	1821	1772	1808	1315	1370	1316	1364
				Medium-weight	0	0	0	0	0	0	0	0	97	114	114	112	55	71	71	72	755	828	834	894	552	629	636	713	1798	1848	1797	1837	1317	1374	1318	1367
				Heavy-weight	0	0	0	0	0	0	0	0	84	102	102	100	46	63	61	63	745	818	825	891	548	629	637	718	1811	1863	1809	1853	1330	1389	1331	1380
		Triple glazing (coated)	New building	Light-weight	2	3	2	2	0	0	0	0	101	108	107	107	49	54	55	54	610	630	632	647	379	399	400	420	1420	1433	1419	1430	892	907	892	905
				Medium-weight	0	0	0	0	0	0	0	0	75	81	80	80	42	47	47	47	576	594	596	612	371	390	392	412	1412	1426	1412	1423	883	897	883	895
				Heavy-weight	0	0	0	0	0	0	0	0	62	67	67	67	35	40	40	40	561	579	581	598	364	384	387	406	1407	1421	1407	1418	879	894	879	891
			Old building	Light-weight	0	1	1	1	0	0	0	0	88	96	94	94	29	35	35	35	681	707	709	726	462	489	491	516	1576	1594	1575	1588	1079	1100	1079	1098
				Medium-weight	0	0	0	0	0	0	0	0	62	68	68	68	19	25	25	25	659	684	686	706	448	474	477	502	1588	1607	1587	1602	1077	1099	1077	1096
				Heavy-weight	0	0	0	0	0	0	0	0	48	55	55	55	12	19	19	19	650	677	679	702	446	474	477	505	1598	1618	1597	1614	1089	1113	1089	1109
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	39	87	143	95	45	107	157	121	336	425	448	409	301	392	414	398	1169	1419	1598	1681	990	1271	1455	1634	2463	2616	2464	2576	2150	2328	2156	2310
				Medium-weight	11	43	72	49	26	89	136	98	289	367	375	358	292	385	401	385	1135	1388	1488	1661	987	1278	1450	1633	2533	2695	2534	2659	2169	2353	2176	2329
				Heavy-weight	4	23	51	30	14	71	115	80	277	350	358	345	284	377	391	376	1126	1380	1464	1663	983	1278	1441	1629	2553	2716	2552	2684	2168	2353	2174	2328
			Old building	Light-weight	21	58	97	64	13	43	74	53	289	374	389	356	228	295	309	303	1191	1431	1563	1673	1014	1271	1371	1613	2552	2706	2555	2662	2284	2460	2290	2448
				Medium-weight	5	20	37	24	2	22	46	27	248	314	320	307	216	283	293	285	1172	1412	1482	1665	1010	1281	1359	1612	2639	2800	2640	2762	2319	2504	2326	2483
				Heavy-weight	2	10	17	11	0	7	26	11	235	298	304	293	206	273	281	274	1165	1408	1466	1673	1005	1282	1351	1610	2669	2832	2669	2799	2326	2514	2332	2489
		Double glazing (coated)	New building	Light-weight	4	9	9	7	0	1	2	2	140	156	156	153	73	86	87	87	784	849	861	914	555	621	626	703	1758	1804	1758	1793	1288	1339	1290	1334
				Medium-weight	0	0	0	0	0	0	0	0	108	121	121	119	65	77	76	78	753	818	824	884	545	614	618	695	1777	1825	1777	1815	1291	1344	1293	1338
				Heavy-weight	0	0	0	0	0	0	0	0	95	109	108	106	57	70	67	70	736	801	806	871	535	607	611	689	1779	1827	1778	1818	1288	1342	1289	1334
			Old building	Light-weight	2	6	5	4	0	0	1	1	129	147	146	141	57	68	68	70	835	902	910	963	625	691	694	771	1868	1914	1868	1902	1428	1481	1430	1477
				Medium-weight	0	0	0	0	0	0	0	0	94	107	107	105	44	56	55	56	815	882	886	945	610	679	681	758	1903	1952	1903	1940	1441	1496	1443	1489
				Heavy-weight	0	0	0	0	0	0	0	0	80	94	93	92	34	46	45	46	804	870	873	937	600	670	672	750	1913	1963	1913	1953	1444	1500	1445	1493
		Triple glazing (clear)	New building	Light-weight	30	63	99	71	46	98	137	107	284	349	364	338	267	341	359	343	1003	1188	1307	1387	814	1028	1186	1297	2137	2252	2138	2225	1731	1863	1736	1847
				Medium-weight	7	28	47	32	33	85	119	90	243	300	305	294	261	335	351	334	964	1153	1218	1356	811	1030	1181	1294	2177	2297	2176	2273	1736	1871	1741	1852
				Heavy-weight	2	13	29	16	23	66	103	74	234	285	291	282	253	328	343	326	952	1141	1197	1351	806	1027	1174	1290	2184	2305	2183	2283	1732	1867	1736	1847
			Old building	Light-weight	14	37	60	41	7	27	45	33	239	300	307	287	181	231	241	235	1029	1205	1285	1387	825	1019	1086	1265	2234	2349	2236	2319	1870	2001	1875	1989
				Medium-weight	3	11	17	12	1	11	25	15	202	249	253	243	172	222	229	223	1003	1181	1226	1369	821	1022	1075	1263	2292	2412	2292	2386	1888	2024	1893	2007
				Heavy-weight	0	6	7	5	0	2	8	3	190	234	238	231	163	214	220	214	992	1173	1207	1368	817	1022	1071	1261	2309	2432	2308	2407	1891	2029	1895	2010
		Triple glazing (coated)	New building	Light-weight	4	5	5	4	0	0	0	0	123	131	130	129	62	70	70	70	676	711	714	744	438	472	473	514	1537	1562	1537	1557	1023	1050	1024	1047
				Medium-weight	0	0	0	0	0	0	0	0	92	99	99	98	54	62	60	62	641	675	676	709	431	466	467	508	1539	1564	1539	1559	1020	1048	1021	1044
				Heavy-weight	0	0	0	0	0	0	0	0	79	86	86	85	46	55	53	55	624	657	657	693	423	460	460	503	1534	1559	1534	1555	1014	1042	1015	1038
			Old building	Light-weight	2	4	3	2	0	0	0	0	108	119	118	115	42	48	47	48	732	767	770	799	505	540	540	581	1658	1684	1658	1677	1168	1197	1170	1195
				Medium-weight	0	0	0	0	0	0	0	0	77	85	84	85	31	37	36	37	707	741	741	776	491	526	526	568	1674	1701	1674	1695	1171	1202	1173	1198
				Heavy-weight	0	0	0	0	0	0	0	0	63	72	70	71	24	29	28	30	693	727	727	764	483	520	519	561	1678	1705	1677	1700	1172	1203	1173	1199
Big room (A=100m²)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	63	97	100	86	5	12	20	15	785	856	851	829	412	467	477	469	3461	3667	3726	3861	2180	2406	2459	2668	7574	7706	7572	7675	4997	5150	5002	5130
				Medium-weight	4	12	10	7	0	0	0	0	596	647	656	639	390	446	452	445	3246	3450	3481	3643	2152	2380	2424	2639	7571	7708	7568	7679	4981	5134	4985	5112
				Heavy-weight	0	1	1	1	0	0	0	0	533	580	578	576	352	411	417	410	3160	3362	3384	3567	2133	2364	2406	2624	7550	7688	7547	7662	4962	5119	4969	5095
			Old building	Light-weight	23	50	43	35	0	2	3	3	682	757	745	727	264	305	308	308	3710	3923	3964	4101	2495	2709	2731	2953	8183	8322	8181	8282	5762	5924	5767	5909
				Medium-weight	2	7	4	2	0	0	0	0	495	544	554	539	220	265	261	265	3558	3774	3796	3960	2438	2660	2679	2907	8254	8400	8251	8364	5780	5947	5783	5927
				Heavy-weight	0	0	0	0	0	0	0	0	437	488	488	480	179	230	225	227	3497	3714	3733	3917	2409	2639	2659	2895	8277	8426	8272	8395	5801	5977	5805	5951
		Double glazing (coated)	New building	Light-weight	35	50	47	44	1	0	0	0	644	682	677	675	265	284	286	284	3147	3224	3244	3287	1852	1926	1935	2006	7002	7048	7000	7037	4328	4381	4329	4373
				Medium-weight	0	1	1	1	0	0	0	0	461	483	483	481	231	250	251	249	2953	3021	3029	3085	1824	1897	1904	1975	6970	7017	6969	7007	4303	4356	4305	4348
				Heavy-weight	0	0	0	0	0	0	0	0	405	425	423	423	204	221	220	220	2867	2934	2941	3001	1796	1874	1882	1956	6943	6990	6941	6981	4282	4336	4284	4328
			Old building	Light-weight	15	22	20	18	0	0	0	0	560	596	593	586	166	184	184	184	3436	3521	3532	3585	2205	2292	2300	2388	7646	7702	7643	7683	5100	5167	5101	5160
				Medium-weight	0	1	3	2	0	0	0	0	391	413	413	410	118	137	136	137	3288	3372	3381	3443	2143	2231	2239	2324	7681	7740	7678	7724	5102	5171	5104	5162
				Heavy-weight	0	0	0	0	0	0	0	0	331	354	354	352	89	106	106	106	3228	3315	3322	3394	2115	2209	2216	2306	7693	7755	7689	7741	5120	5194	5121	5183
		Triple glazing (clear)	New building	Light-weight	60	88	83	70	5	7	11	8	751	804	804	786	378	419	426	420	3315	3479	3511	3616	2029	2199	2240	2393	7286	7385	7284	7363	4658	4772	4661	4756
				Medium-weight	3	5	6	5	0	0	0	0	555	597	606	592	356	398	403	397	3100	3252	3275	3394	2004	2174	2206	2364	7266	7367	7263	7347	4637	4752	4641	4734
				Heavy-weight	0	0	0	0	0	0	0	0	495	528	526	525	318	363	367	362	3013	3170	3181	3320	1986	2158	2189	2347	7241	7343	7238	7324	4615	4732	4621	4714
			Old building	Light-weight	23	39	33	28	0	2	2	1	640	700	698	679	232	264	265	266	3574	3741	3774	3874	2344	2510	2529	2692	7916	8023	7913	7991	5430	5554	5432	5542
				Medium-weight	1	3	1	0	0	0	0	0	460	509	506	496	188	223	221	223	3421	3585	3603	3734	2287	2458	2473	2646	7966	8079	7964	8051	5438	5567	5441	5550
				Heavy-weight	0	0	0	0	0	0	0	0	402	448	443	444	153	183	182	183	3359	3525	3541	3687	2260	2439	2452	2633	7983	8098	7978	8074	5457	5592	5461	5573
		Triple glazing (coated)	New building	Light-weight	34	43	41	39	0	0	0	0	628	651	649	645	259	271	272	271	3060	3104	3113	3143	1765	1810	1815	1859	6819	6848	6817	6840	4118	4152	4119	4147
				Medium-weight	0	1	1	0	0	0	0	0	448	462	461	460	225	238	238	238	2863	2903	2906	2940	1738	1783	1787	1830	6778	6808	6777	6801	4090	4123	4091	4118
				Heavy-weight	0	0	0	0	0	0	0	0	392	405	404	404	198	210	210	209	2776	2817	2820	2858	1713	1758	1763	1811	6748	6778	6747	6772	4068	4102	4069	4097
			Old building	Light-weight	15	19	18	17	0	0	0	0	544	568	565	560	154	168	168	168	3354	3415	3420	3452	2111	2174	2179	2238	7480	7519	7477	7505	4896	4944	4896	4938
				Medium-weight	0	0	1	1	0	0	0	0	378	394	394	392	108	121	121	121	3204	3262	3266	3309	2051	2112	2118	2178	7502	7544	7499	7532	4892	4941	4893	4934
				Heavy-weight	0	0	0	0	0	0	0	0	318	335	335	334	80	95	94	94	3141	3203	3207	3259	2023	2091	2098	2161	7511	7555	7507	7545	4909	4963	4909	4954
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	146	236	351	248	54	146	224	167	1173	1382	1423	1338	800	976	1008	987	4375	4929	5273	5518	3158	3786	4056	4572	9216	9565	9218	9477	7001	7411	7017	7366
				Medium-weight	24	66	104	73	12	78	156	94	925	1081	1094	1060	769	947	972	948	4139	4692	4856	5278	3136	3784	4014	4555	9336	9702	9334	9622	7030	7451	7046	7394
				Heavy-weight	8	33	42	31	0	26	94	43	858	997	1011	991	744	917	938	915	4059	4611	4745	5223	3115	3772	3987	4537	9352	9722	9347	9650	7014	7437	7028	7377
			Old building	Light-weight	73	153	203	143	15	42	62	55	1018	1226	1225	1158	562	680	704	696	4533	5068	5271	5593	3357	3910	4024	4633	9700	10046	9703	9948	7653	8056	7669	8028
				Medium-weight	12	37	45	32	0	9	16	12	798	934	936	912	516	637	646	641	4375	4899	5000	5431	3320	3899	3981	4604	9880	10245	9881	10156	7735	8158	7751	8109
				Heavy-weight	1	16	22	14	0	0	0	0	733	854	859	842	474	601	605	600	4314	4833	4905	5391	3290	3879	3950	4581	9931	10300	9928	10222	7740	8170	7755	8113
		Double glazing (coated)	New building	Light-weight	49	81	72	62	3	5	4	6	745	799	785	772	310	344	345	345	3483	3638	3671	3782	2159	2318	2335	2509	7604	7707	7604	7683	5028	5147	5032	5134
				Medium-weight	2	8	7	6	0	0	0	0	532	571	574	564	272	306	307	306	3274	3434	3447	3578	2131	2292	2303	2478	7612	7720	7611	7697	5026	5148	5030	5132
				Heavy-weight	0	0	0	0	0	0	0	0	472	505	508	502	244	275	270	275	3193	3341	3361	3494	2100	2268	2278	2457	7592	7701	7591	7680	5005	5129	5011	5111
			Old building	Light-weight	19	36	30	26	0	1	0	0	649	709	704	690	220	246	244	248	3717	3880	3903	4014	2486	2643	2648	2821	8148	8253	8149	8224	5696	5817	5701	5808
				Medium-weight	1	5	3	2	0	0	0	0	462	505	500	493	168	195	192	195	3566	3722	3733	3866	2427	2584	2589	2766	8217	8327	8217	8300	5725	5851	5729	5837
				Heavy-weight	0	0	0	0	0	0	0	0	398	436	430	432	130	157	153	157	3501	3656	3666	3809	2381	2543	2546	2724	8225	8336	8223	8313	5722	5853	5727	5835
		Triple glazing (clear)	New building	Light-weight	125	180	250	192	43	114	170	127	1053	1203	1226	1171	701	834	857	839	3982	4383	4601	4816	2737	3200	3396	3769	8439	8697	8439	8636	6024	6324	6035	6287
				Medium-weight	17	43	60	45	7	53	111	69	831	923	928	909	676	809	827	808	3737	4135	4243	4564	2712	3192	3359	3751	8494	8764	8491	8708	6027	6333	6038	6290
				Heavy-weight	4	18	22	16	0	11	56	29	747	856	857	841	654	783	798	781	3647	4045	4131	4492	2693	3180	3339	3734	8487	8759	8482	8708	6007	6313	6016	6270
			Old building	Light-weight	59	114	141	105	6	22	31	27	902	1044	1042	1000	456	539	549	546	4150	4540	4668	4924	2920	3318	3390	3833	8953	9208	8954	9139	6690	6986	6701	6962
				Medium-weight	6	22	25	18	0	3	4	2	693	784	787	771	415	503	507	503	3987	4367	4424	4752	2880	3299	3348	3798	9071	9340	9070	9277	6735	7044	6746	7006
				Heavy-weight	0	8	9	6	0	0	0	0	629	713	715	707	375	464	465	464	3916	4292	4334	4697	2849	3279	3323	3778	9096	9368	9093	9312	6734	7047	6744	7005
		Triple glazing (coated)	New building	Light-weight	47	69	65	55	0	1	1	1	697	735	730	716	288	306	306	307	3226	3311	3330	3384	1899	1979	1982	2076	7087	7142	7087	7130	4416	4479	4419	4471
				Medium-weight	1	4	3	2	0	0	0	0	491	517	513	514	253	273	272	273	3017	3093	3097	3176	1875	1954	1955	2048	7062	7119	7063	7108	4401	4465	4405	4456
				Heavy-weight	0	0	0	0	0	0	0	0	433	454	449	452	225	243	239	243	2925	3000	3003	3082	1848	1931	1933	2028	7033	7090	7032	7079	4376	4441	4380	4431
			Old building	Light-weight	20	25	22	21	0	0	0	0	600	639	633	629	183	197	195	198	3480	3565	3570	3639	2211	2291	2291	2384	7667	7724	7668	7709	5098	5163	5100	5158
				Medium-weight	1	2	1	1	0	0	0	0	423	443	442	440	136	151	148	151	3318	3396	3397	3473	2152	2233	2232	2328	7696	7756	7696	7742	5106	5175	5109	5166
				Heavy-weight	0	1	0	0	0	0	0	0	357	378	375	377	105	119	117	118	3248	3326	3326	3407	2113	2196	2195	2291	7690	7751	7690	7739	5098	5169	5101	5159

TABLE 9: ENERGY DEMAND FOR ARTIFICIAL LIGHTING WITHOUT LTATW (KWH/YEAR)			Climate →	Cold climate				Temperate climate				Dry climate				Tropical climate			
Room size ↓	**Type of glazing ↓**	**Building function ↓**	**Window size / Orientation**	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=20m²)	Clear	Office	Small window	206.2	192.4	167.7	185.8	148.3	133.6	118.6	131.6	98.6	98.4	91.8	91.7	57.8	63.3	57.2	57.8
			Large window	149.3	144.2	137.2	141.7	98.0	96.4	92.2	94.4	87.9	89.0	87.2	86.3	53.0	53.2	53.0	52.8
		Residence	Small window	163.2	164.3	162.7	161.6	154.1	155.9	154.4	152.4	163.7	163.3	163.3	163.8	156.3	158.4	156.8	154.6
			Large window	156.0	156.1	155.6	155.2	148.0	148.9	148.3	147.2	162.1	162.1	162.0	162.1	148.9	149.4	149.0	148.8
	Coated	Office	Small window	212.4	183.0	138.0	174.9	200.3	160.2	127.9	163.3	165.5	128.9	85.6	114.5	113.6	106.5	108.3	102.5
			Large window	272.5	243.2	188.5	230.5	221.8	186.5	147.5	187.3	143.0	125.1	100.5	120.9	77.1	90.7	77.6	80.8
		Residence	Small window	194.6	194.3	184.3	185.8	186.7	185.1	179.2	175.6	179.0	175.2	175.1	176.3	176.7	176.4	176.9	174.9
			Large window	174.2	174.9	171.0	170.8	162.9	165.7	162.7	160.1	166.4	166.2	165.4	166.9	164.1	165.6	164.2	162.8
Big room (A=100m²)	Clear	Office	Small window	1656.0	1437.1	1090.6	1362.2	1458.7	1185.2	954.0	1191.5	923.5	757.8	567.7	728.7	570.0	640.4	578.4	598.8
			Large window	1035.4	952.2	822.7	918.6	768.7	685.6	603.4	676.2	489.6	491.8	455.0	453.2	296.5	330.2	296.4	296.1
		Residence	Small window	895.2	898.8	870.1	866.7	845.9	854.5	835.7	817.4	837.9	833.1	832.9	840.1	840.1	843.7	841.8	836.7
			Large window	821.9	825.3	816.4	813.1	772.6	781.3	772.8	763.3	810.1	807.9	807.0	810.0	782.2	791.5	784.5	774.0
	Coated	Office	Small window	2376.9	2195.9	1854.3	2135.2	2328.8	2120.3	1977.2	2126.4	2173.8	1944.3	1664.7	1655.9	1976.4	1822.6	1967.6	1853.8
			Large window	2055.2	1766.3	1312.1	1685.9	1937.4	1561.3	1261.6	1569.9	1599.2	1234.0	888.0	1081.3	1138.1	1059.4	1147.8	1040.8
		Residence	Small window	1128.6	1082.9	1023.3	1040.5	1108.3	1047.7	1009.8	998.5	1058.4	992.3	959.0	955.1	1005.9	991.6	1007.0	985.1
			Large window	977.6	977.6	936.0	939.3	941.4	931.3	907.4	885.1	884.2	865.6	870.4	869.7	884.1	879.8	884.7	874.2

APPENDIX D

Additional designer tables - Energy demand per square meter

TABLE 10: ABSOLUTE REDUCTION OF HEATING ENERGY DEMAND (KWH/M²/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Age ↓	Room size ↓	Type of glazing ↓	Window size ↓	Orientation / Building method	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
New building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	6.0	5.5	3.7	5.4	9.7	8.2	6.6	8.2	2.4	2.1	1.2	2.1	5.2	4.8	3.4	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	5.7	5.3	2.6	5.2	8.7	7.5	5.8	7.3	1.9	1.4	0.3	1.4	4.7	4.3	2.6	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	6.2	5.7	2.2	5.7	9.3	7.7	6.3	7.6	1.4	0.8	0.0	0.8	4.8	4.5	2.6	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	7.1	6.8	7.5	7.5	10.1	9.7	13.7	10.3	3.8	3.7	3.2	4.2	5.8	6.2	7.3	6.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	7.5	7.1	5.6	7.8	9.9	9.0	8.6	9.1	3.8	3.4	1.9	3.7	5.6	5.2	4.6	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.8	7.3	4.7	8.2	10.3	8.9	8.3	9.5	3.8	3.5	1.2	3.7	5.8	5.5	3.4	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	7.0	6.5	6.0	6.6	10.4	10.0	9.3	10.2	3.1	2.9	2.5	3.0	6.1	5.7	5.5	5.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.9	6.3	5.4	6.3	9.7	9.2	8.7	9.4	2.9	2.7	2.1	2.7	5.5	5.1	5.0	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.4	6.8	6.1	6.9	10.0	9.7	9.1	9.9	2.9	2.7	1.8	2.7	5.7	5.3	5.1	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	8.7	7.9	8.3	8.8	11.5	10.9	12.0	11.7	5.3	4.8	4.7	5.0	7.0	6.8	7.0	7.1	0.1	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	9.2	8.5	8.3	9.0	11.3	10.4	10.6	11.3	5.3	4.8	4.6	5.0	7.0	6.5	6.7	6.8	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	9.6	9.0	8.7	9.4	11.3	10.8	11.0	12.0	5.5	5.1	4.6	5.3	7.1	6.6	6.7	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	3.7	3.3	1.4	3.3	7.7	6.7	5.1	6.7	0.7	0.5	0.3	0.6	3.9	3.6	2.2	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	3.0	2.4	0.4	2.5	6.8	5.9	4.2	5.9	0.1	0.0	0.0	0.0	3.4	3.2	1.5	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	2.6	2.0	0.1	1.9	7.3	6.4	4.2	6.4	0.0	0.0	0.0	0.0	3.5	3.1	1.1	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	2.8	2.8	2.2	2.7	4.2	4.6	5.5	4.8	1.2	0.9	0.6	0.9	2.5	2.4	1.6	2.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	2.7	2.3	0.9	2.6	4.0	4.2	3.2	4.4	0.7	0.3	0.1	0.3	2.5	2.2	0.8	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	2.9	2.3	0.3	2.6	4.0	4.6	2.4	4.8	0.2	0.0	0.0	0.0	2.4	2.0	0.1	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	4.3	4.1	3.7	4.2	8.6	8.3	7.8	8.4	1.2	1.2	1.0	1.2	4.5	4.5	4.2	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	3.9	3.6	2.8	3.6	7.7	7.5	7.0	7.5	0.5	0.4	0.2	0.4	4.1	4.0	3.7	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	3.8	3.5	2.4	3.5	8.2	8.0	7.5	8.0	0.1	0.1	0.0	0.1	4.2	4.1	4.0	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	3.6	3.4	3.2	3.5	4.8	4.8	5.0	5.0	1.7	1.6	1.6	1.7	3.0	2.7	2.9	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	3.5	3.2	2.8	3.3	4.7	4.5	4.7	4.7	1.7	1.6	1.2	1.6	2.8	2.6	2.7	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	3.8	3.4	3.1	3.5	4.9	4.8	4.9	4.9	1.8	1.7	1.2	1.7	2.8	2.8	2.7	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	1.6	1.5	1.0	1.4	4.2	3.6	2.9	3.5	0.5	0.4	0.3	0.4	2.0	1.9	1.2	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	1.7	1.6	1.1	1.6	4.2	4.0	3.7	4.0	0.1	0.1	0.0	0.1	2.2	2.1	1.9	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.4	1.3	0.7	1.3	4.3	4.1	3.9	4.1	0.0	0.0	0.0	0.0	2.3	2.2	2.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	4.0	3.6	3.6	3.8	6.1	5.8	5.5	6.2	2.0	1.8	1.6	1.9	3.8	3.4	3.3	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	4.4	4.0	3.4	4.0	6.2	5.9	5.6	6.2	1.9	1.7	1.3	1.8	3.6	3.4	3.3	3.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	4.5	4.1	3.8	4.2	6.4	6.0	5.6	6.1	2.0	1.8	1.2	1.8	3.7	3.3	3.3	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	1.9	1.8	1.5	1.8	4.6	4.4	4.1	4.4	0.5	0.5	0.5	0.5	2.3	2.3	2.1	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	1.7	1.6	1.1	1.6	4.2	4.0	3.7	4.0	0.1	0.1	0.0	0.1	2.2	2.1	1.9	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.4	1.3	0.7	1.3	4.3	4.1	3.9	4.1	0.0	0.0	0.0	0.0	2.3	2.2	2.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	4.0	3.6	3.6	3.8	6.1	5.8	5.5	6.2	2.0	1.8	1.6	1.9	3.8	3.4	3.3	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	4.4	4.0	3.4	4.0	6.2	5.9	5.6	6.2	1.9	1.7	1.3	1.8	3.6	3.4	3.3	3.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	4.5	4.1	3.8	4.2	6.4	6.0	5.6	6.1	2.0	1.8	1.2	1.8	3.7	3.3	3.3	3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	0.7	0.6	0.5	0.7	3.1	2.8	2.5	2.8	0.2	0.2	0.2	0.2	1.4	1.3	0.9	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	0.1	0.1	0.0	0.1	2.8	2.5	2.1	2.6	0.0	0.0	0.0	0.0	1.2	1.1	0.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.0	0.0	0.0	0.0	3.1	2.8	2.3	2.9	0.0	0.0	0.0	0.0	1.2	0.9	0.2	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	1.0	0.8	0.7	0.9	1.9	1.9	2.2	2.0	0.3	0.3	0.2	0.3	1.0	0.9	0.6	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	0.7	0.6	0.0	0.6	1.8	1.8	1.2	2.0	0.0	0.0	0.0	0.0	1.0	0.9	0.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.6	0.4	0.0	0.4	1.9	2.0	1.3	2.1	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	0.8	0.8	0.7	0.8	3.4	3.3	3.1	3.3	0.2	0.2	0.2	0.2	1.6	1.5	1.5	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	0.2	0.2	0.1	0.2	3.1	3.0	2.8	3.0	0.0	0.0	0.0	0.0	1.4	1.3	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.0	0.0	0.0	0.0	3.3	3.2	3.2	3.3	0.0	0.0	0.0	0.0	1.5	1.5	1.3	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	1.2	1.2	1.0	1.2	2.4	2.3	2.3	2.3	0.4	0.4	0.4	0.4	1.3	1.2	1.2	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	1.1	1.0	0.7	1.0	2.3	2.2	2.1	2.3	0.1	0.1	0.0	0.1	1.3	1.2	1.1	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.1	1.0	0.5	1.0	2.3	2.3	2.2	2.3	0.0	0.0	0.0	0.0	1.3	1.2	1.1	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Old building	Small room (A=20m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	13.6	12.7	12.2	13.0	20.0	19.0	17.8	18.5	8.1	7.8	7.3	7.9	11.9	11.7	11.2	11.7	0.1	0.0	0.0	0.0	0.5	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	15.1	14.4	12.4	14.5	19.8	18.2	16.3	17.9	8.8	8.4	7.6	8.4	11.8	11.5	10.7	11.5	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	18.1	17.2	14.9	17.0	22.8	21.2	19.6	21.0	10.4	9.6	8.6	9.9	13.8	13.4	12.1	13.5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	8.6	8.5	13.1	10.5	14.1	16.5	24.7	17.4	5.4	5.3	7.8	5.8	9.1	9.9	14.1	10.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	10.6	9.7	11.5	11.0	13.7	13.9	17.3	14.0	6.0	5.9	6.2	6.5	9.0	8.8	10.4	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	12.3	10.8	11.6	11.4	14.8	14.0	14.4	15.0	6.6	6.7	6.3	6.9	9.3	8.8	9.2	9.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	14.7	14.0	13.5	14.2	20.8	20.4	20.1	20.6	8.6	8.2	8.1	8.4	12.1	11.8	11.7	11.9	0.3	0.2	0.1	0.2	1.4	1.0	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	16.3	15.5	15.0	15.6	20.6	20.2	19.9	20.8	9.5	9.2	9.0	9.4	12.0	11.7	11.6	11.8	0.1	0.0	0.0	0.0	1.1	0.7	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	19.3	18.1	17.6	18.3	24.1	23.6	23.3	24.0	11.3	11.0	10.7	11.1	13.9	13.7	13.5	13.8	0.0	0.0	0.0	0.0	1.1	0.7	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	10.2	9.3	10.2	10.3	15.5	16.3	17.7	17.1	6.3	6.0	6.3	6.2	9.2	9.0	9.9	9.6	0.4	0.3	0.0	0.2	1.4	0.9	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	12.1	11.1	11.5	11.9	15.5	15.9	16.4	16.8	7.4	7.1	7.0	7.5	9.3	9.2	9.6	9.6	0.2	0.1	0.0	0.0	1.1	0.6	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	13.4	12.4	12.0	12.9	16.8	16.7	16.5	17.8	8.3	8.0	7.7	8.3	10.0	10.1	10.3	10.3	0.1	0.0	0.0	0.0	1.0	0.7	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	12.8	12.2	11.6	12.5	18.8	18.1	16.9	17.6	7.7	7.3	6.9	7.3	11.2	11.3	11.0	11.1	0.1	0.0	0.0	0.0	0.4	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	13.9	13.5	12.2	13.5	18.6	17.4	16.7	17.0	8.1	7.7	7.0	7.8	11.0	11.3	10.5	11.0	0.0	0.0	0.0	0.0	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	17.0	16.3	14.5	16.3	21.8	20.4	19.3	20.2	9.6	9.1	8.5	9.2	13.1	13.1	12.2	12.9	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	5.4	5.6	8.7	6.8	8.3	9.8	14.1	9.4	3.5	3.5	5.0	4.2	5.7	6.1	8.3	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.6	6.0	7.0	7.1	8.2	8.6	9.2	8.2	3.6	3.7	4.3	4.0	5.3	5.8	6.4	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.5	7.3	7.5	7.1	9.3	9.3	9.6	8.9	4.3	3.9	3.8	4.6	5.4	6.1	5.9	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	13.6	13.1	12.9	13.4	19.2	18.7	18.4	18.8	7.8	7.7	7.5	7.8	11.1	10.8	10.6	10.8	0.2	0.2	0.1	0.1	1.2	0.9	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	14.9	14.4	14.0	14.5	19.0	18.5	18.1	18.6	8.7	8.5	8.1	8.5	11.0	10.8	10.5	10.8	0.0	0.0	0.0	0.0	0.9	0.6	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	17.9	17.1	16.7	17.3	22.5	21.9	21.5	22.1	10.4	10.1	9.8	10.2	12.9	12.7	12.4	12.7	0.0	0.0	0.0	0.0	0.9	0.6	0.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	5.7	5.6	6.2	5.9	8.6	9.0	10.0	9.7	3.7	3.6	4.0	3.8	5.1	5.0	5.4	5.1	0.2	0.1	0.0	0.2	0.7	0.4	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.8	6.4	7.0	6.7	8.7	9.0	9.6	9.5	4.2	4.0	4.1	4.1	5.2	5.0	5.4	5.2	0.0	0.0	0.0	0.0	0.4	0.2	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.9	7.5	8.5	7.8	9.9	10.0	11.1	10.5	4.9	4.7	4.8	4.8	5.9	5.7	6.2	5.9	0.0	0.0	0.0	0.0	0.4	0.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Big room (A=100m²)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	5.6	5.4	5.3	5.5	8.9	8.8	8.3	8.4	3.3	3.2	3.2	3.3	5.1	5.3	5.1	5.0	0.1	0.1	0.0	0.0	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.5	6.2	5.9	6.1	8.8	8.5	7.7	8.1	3.7	3.7	3.3	3.6	5.2	5.3	5.0	5.1	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.8	7.6	6.9	7.5	10.4	9.8	8.9	9.5	4.4	4.3	4.0	4.2	6.1	6.1	5.8	6.1	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	4.5	4.3	6.1	5.3	8.0	8.0	10.0	8.2	2.8	2.5	3.8	3.1	5.0	5.0	5.8	5.1	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	5.6	5.2	5.8	5.6	7.8	7.2	7.8	7.1	3.3	3.2	3.4	3.1	4.7	5.2	5.1	4.7	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	6.4	5.9	6.1	5.8	8.0	7.8	7.6	7.4	3.4	3.4	3.1	3.4	5.1	5.0	5.1	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	6.0	5.8	5.6	5.8	9.1	8.9	8.8	9.1	3.4	3.3	3.3	3.4	5.3	5.2	5.3	5.2	0.1	0.1	0.1	0.1	0.5	0.4	0.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.9	6.6	6.3	6.7	9.1	8.8	8.7	9.0	4.0	3.9	3.8	3.9	5.2	5.1	5.2	5.2	0.0	0.0	0.0	0.0	0.4	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	8.1	7.9	7.7	7.9	10.6	10.4	10.1	10.6	4.7	4.6	4.4	4.6	6.1	6.0	6.0	6.1	0.0	0.0	0.0	0.0	0.3	0.3	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	5.2	4.9	5.0	5.2	8.4	8.5	9.2	9.0	3.2	3.0	3.1	3.3	5.0	4.8	5.2	5.0	0.2	0.2	0.0	0.1	0.6	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.3	5.9	5.9	6.2	8.4	8.5	8.8	8.9	3.9	3.7	3.5	3.8	5.0	4.9	5.1	5.0	0.0	0.0	0.0	0.0	0.5	0.2	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.0	6.6	6.6	6.9	9.0	9.2	8.8	9.7	4.3	4.0	4.0	4.2	5.4	5.2	5.5	5.5	0.0	0.0	0.0	0.0	0.3	0.2	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	5.1	5.0	4.8	5.0	8.0	8.3	7.9	8.0	2.9	2.8	2.8	2.9	4.7	4.9	5.1	4.8	0.1	0.1	0.0	0.0	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	5.8	5.8	5.5	5.6	8.0	8.1	7.6	7.8	3.3	3.2	3.1	3.3	4.7	4.9	4.9	4.7	0.0	0.0	0.0	0.0	0.2	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.1	7.1	6.6	6.9	9.5	9.4	8.8	9.1	4.0	3.8	3.7	3.9	5.6	5.8	5.7	5.6	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	2.3	2.4	3.9	3.3	4.4	4.8	6.3	4.4	1.6	1.6	2.6	1.8	2.9	3.5	4.4	3.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	2.9	3.0	3.5	3.2	4.2	4.5	5.3	3.9	1.7	1.8	2.4	2.0	2.7	3.3	4.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	3.6	3.5	3.6	3.6	4.6	4.8	5.5	4.5	2.1	2.1	2.2	2.4	3.0	3.2	3.7	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	5.3	5.1	5.0	5.1	8.0	7.8	7.7	7.9	3.0	2.9	2.8	2.9	4.7	4.6	4.5	4.6	0.1	0.1	0.1	0.1	0.4	0.4	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	6.0	5.8	5.6	5.9	8.0	7.8	7.7	7.8	3.4	3.4	3.3	3.4	4.6	4.5	4.4	4.5	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.3	7.1	6.9	7.2	9.6	9.3	9.3	9.4	4.2	4.1	4.0	4.1	5.5	5.4	5.3	5.4	0.0	0.0	0.0	0.0	0.3	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	2.5	2.4	2.7	2.5	4.1	4.3	4.9	4.5	1.6	1.5	1.6	1.6	2.4	2.3	2.5	2.4	0.1	0.1	0.1	0.1	0.3	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	3.2	3.0	3.3	3.0	4.1	4.2	4.8	4.4	1.9	1.8	1.8	1.9	2.4	2.4	2.5	2.4	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	3.7	3.5	3.9	3.8	4.7	4.8	5.4	4.9	2.2	2.1	2.1	2.2	2.8	2.7	2.9	2.8	0.0	0.0	0.0	0.0	0.2	0.1	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 11: ABSOLUTE REDUCTION OF COOLING ENERGY DEMAND (KWH/M^2/YEAR)

Climate →					Cold climate								Temperate climate							
Building function →					Office				Residence				Office				Residence			
Room size ↓	Window size ↓	Type of glazing ↓	Age ↓	Building method \ Orientation	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=20m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	-0.2	-0.3	-0.2	-0.1	0.1	0.4	0.7	0.4	2.0	1.9	2.4	2.3	4.2	4.8	5.2	5.0
				Medium-weight	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	2.8	3.1	3.3	3.1	4.6	5.2	5.6	5.4
				Heavy-weight	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	2.8	3.2	3.3	3.2	4.5	5.4	5.6	5.4
			Old building	Light-weight	0.0	-0.2	-0.1	0.1	0.0	0.1	0.1	0.1	1.4	1.2	1.7	1.7	2.4	2.8	3.0	2.9
				Medium-weight	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	2.0	2.2	2.3	2.2	2.7	3.2	3.3	3.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	2.4	2.4	2.3	2.5	3.2	3.1	3.2
		Double glazing (coated)	New building	Light-weight	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	1.4	1.4	1.6	1.5	2.4	2.6	2.7	2.6
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	1.9	2.0	2.0	2.2	2.5	2.5	2.5
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	1.9	2.0	2.0	1.9	2.3	2.3	2.3
			Old building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.2	1.2	1.3	1.3	1.6	1.6	1.6
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.4	1.4	1.4	1.0	1.4	1.4	1.4
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.4	1.4	1.4	0.8	1.2	1.2	1.2
		Triple glazing (clear)	New building	Light-weight	-0.2	-0.3	-0.3	-0.2	0.1	0.3	0.5	0.3	1.9	1.8	2.2	2.3	4.2	4.8	5.0	4.7
				Medium-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	2.6	2.8	3.1	3.0	4.5	5.1	5.3	5.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	3.0	3.1	3.0	4.3	5.1	5.3	5.1
			Old building	Light-weight	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.3	1.7	1.6	2.3	2.6	2.8	2.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.1	2.1	2.1	2.3	2.8	2.8	2.9
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.2	2.3	2.1	2.2	2.8	2.7	2.8
		Triple glazing (coated)	New building	Light-weight	0.0	-0.1	-0.1	-0.1	0.0	0.0	0.0	0.0	1.3	1.4	1.4	1.5	2.3	2.5	2.5	2.5
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	1.9	1.9	1.9	2.1	2.4	2.4	2.4
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	1.9	1.9	1.9	1.8	2.0	2.0	2.0
			Old building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.1	1.1	1.1	1.2	1.4	1.4	1.4
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.3	1.3	1.4	0.9	1.2	1.2	1.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.3	1.3	1.3	0.6	1.0	1.0	1.0
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	0.8	1.3	2.7	2.2	2.2	4.3	6.2	4.8	5.8	6.5	7.6	6.8	8.9	11.1	12.0	11.5
				Medium-weight	0.4	1.5	2.3	1.7	1.3	4.2	6.3	4.6	6.3	7.8	8.4	7.7	9.4	11.6	12.9	12.2
				Heavy-weight	0.2	0.8	1.9	1.2	0.7	3.5	5.6	3.9	6.5	7.6	8.3	7.9	9.7	11.8	12.8	12.2
			Old building	Light-weight	0.5	0.4	1.6	1.4	0.6	1.4	2.7	1.8	4.4	4.6	6.1	5.3	5.9	7.1	8.2	7.5
				Medium-weight	0.2	0.3	0.9	0.7	0.1	1.0	2.0	1.2	5.0	5.8	6.4	5.9	6.5	7.7	8.5	7.9
				Heavy-weight	0.1	0.2	0.3	0.3	0.0	0.3	1.2	0.5	5.1	5.6	6.4	6.1	6.5	7.5	8.3	8.0
		Double glazing (coated)	New building	Light-weight	0.2	0.1	0.3	0.3	0.0	0.1	0.1	0.1	3.1	2.9	3.3	3.4	3.2	3.7	3.8	3.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	3.2	3.4	3.4	3.2	3.7	3.6	3.7
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	3.3	3.4	3.3	2.9	3.5	3.4	3.5
			Old building	Light-weight	0.1	0.2	0.2	0.2	0.0	0.0	0.1	0.1	2.7	2.7	2.9	2.9	2.4	2.6	2.7	2.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	2.6	2.7	2.7	2.1	2.5	2.5	2.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.6	2.7	2.6	1.7	2.2	2.2	2.3
		Triple glazing (clear)	New building	Light-weight	0.7	1.4	2.0	1.7	2.3	4.7	6.4	5.0	5.6	6.4	6.9	6.4	9.8	12.1	13.2	12.4
				Medium-weight	0.3	1.1	1.9	1.3	1.7	4.2	5.9	4.5	6.3	7.5	8.0	7.7	10.3	12.4	13.6	12.7
				Heavy-weight	0.1	0.6	1.3	0.7	1.2	3.3	5.2	3.7	6.4	7.4	7.9	7.6	10.5	12.6	13.8	12.8
			Old building	Light-weight	0.3	0.5	1.0	1.0	0.4	1.2	2.1	1.5	4.2	4.5	5.3	5.1	6.0	7.1	7.8	7.3
				Medium-weight	0.2	0.3	0.5	0.4	0.1	0.6	1.2	0.8	4.7	5.4	5.8	5.5	6.5	7.5	8.3	7.9
				Heavy-weight	0.0	0.3	0.2	0.2	0.0	0.1	0.4	0.2	4.8	5.4	6.0	5.6	6.6	7.9	8.4	7.8
		Triple glazing (coated)	New building	Light-weight	0.2	0.1	0.1	0.2	0.0	0.0	0.0	0.0	3.0	2.9	3.0	3.1	3.1	3.4	3.4	3.4
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.2	3.2	3.2	2.7	3.1	3.0	3.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.1	3.2	3.1	2.3	2.8	2.7	2.8
			Old building	Light-weight	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	2.4	2.5	2.5	2.4	2.0	2.2	2.2	2.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.4	2.5	2.5	1.6	1.9	1.8	1.9
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	2.3	2.3	2.3	1.2	1.5	1.4	1.5
Big room (A=100m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	-0.1	-0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.4	0.5	0.6	0.5	1.8	2.0	2.1	2.0
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.1	1.2	1.1	1.9	2.1	2.2	2.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.1	1.0	1.1	1.9	2.1	2.2	2.2
			Old building	Light-weight	0.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.6	0.6	0.9	1.0	1.0	1.0
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.6	0.7	0.7	1.0	1.1	1.1	1.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.7	0.7	0.9	1.2	1.1	1.1
		Double glazing (coated)	New building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.4	0.5	1.4	1.5	1.5	1.5
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.6	0.6	1.5	1.5	1.6	1.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.7	0.8	1.4	1.5	1.5	1.5
			Old building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4	0.4	0.4	0.7	0.7	0.7	0.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.5	0.4	0.7	0.8	0.8	0.8
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.5	0.5	0.6	0.7	0.7	0.7
		Triple glazing (clear)	New building	Light-weight	0.0	-0.2	-0.1	-0.1	0.1	0.1	0.1	0.1	0.4	0.5	0.5	0.5	1.9	2.0	2.1	2.0
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.1	1.2	1.1	2.0	2.1	2.2	2.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.0	0.9	1.0	1.9	2.1	2.2	2.1
			Old building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.6	0.5	0.9	1.0	1.0	1.0
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.7	0.6	0.6	1.0	1.1	1.1	1.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.7	0.7	0.9	1.0	1.0	1.0
		Triple glazing (coated)	New building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4	1.5	1.6	1.6	1.6
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.6	0.7	0.7	1.5	1.6	1.6	1.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.8	0.8	1.5	1.5	1.5	1.5
			Old building	Light-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.4	0.3	0.7	0.8	0.8	0.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.6	0.7	0.7	0.7
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.5	0.5	0.6	0.7	0.7	0.7
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	0.3	0.4	1.1	0.7	0.5	1.1	1.7	1.3	2.2	2.3	3.1	2.7	3.5	4.1	4.4	4.2
				Medium-weight	0.2	0.2	0.4	0.4	0.1	0.7	1.4	0.8	2.2	2.6	2.8	2.6	3.5	4.3	4.5	4.4
				Heavy-weight	0.1	0.1	0.1	0.2	0.0	0.3	0.9	0.4	2.2	2.6	2.7	2.7	3.7	4.3	4.6	4.4
			Old building	Light-weight	0.2	0.2	0.7	0.5	0.1	0.2	0.3	0.3	1.8	1.8	2.3	2.2	2.1	2.3	2.6	2.5
				Medium-weight	0.1	0.1	0.2	0.2	0.0	0.1	0.1	0.0	1.8	1.9	2.1	2.1	2.0	2.2	2.5	2.5
				Heavy-weight	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	1.7	1.9	2.0	2.0	2.1	2.2	2.4	2.5
		Double glazing (coated)	New building	Light-weight	0.2	0.1	0.2	0.2	0.0	0.1	0.0	0.1	1.6	1.5	1.4	1.5	1.9	2.0	2.1	2.0
				Medium-weight	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	1.5	1.5	1.5	1.5	1.9	2.0	2.1	2.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.4	1.5	1.5	1.8	2.0	1.9	2.0
			Old building	Light-weight	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	1.2	1.1	1.3	1.3	1.2	1.3	1.3	1.3
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	1.2	1.2	1.1	1.3	1.3	1.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	1.1	1.2	1.0	1.2	1.2	1.2
		Triple glazing (clear)	New building	Light-weight	0.2	0.3	0.7	0.5	0.4	1.0	1.6	1.2	2.0	2.2	2.6	2.5	3.8	4.3	4.6	4.4
				Medium-weight	0.1	0.2	0.3	0.3	0.1	0.5	1.1	0.7	2.4	2.4	2.7	2.5	3.7	4.4	4.7	4.5
				Heavy-weight	0.0	0.1	0.1	0.1	0.0	0.1	0.6	0.3	2.1	2.5	2.6	2.4	3.9	4.4	4.7	4.5
			Old building	Light-weight	0.2	-0.1	0.5	0.3	0.1	0.1	0.1	0.1	1.7	1.5	2.0	2.0	2.1	2.4	2.5	2.4
				Medium-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	1.7	1.8	1.9	1.9	2.1	2.4	2.6	2.4
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	1.8	1.9	1.9	2.1	2.4	2.5	2.4
		Triple glazing (coated)	New building	Light-weight	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	1.5	1.4	1.5	1.4	2.1	2.2	2.2	2.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.5	1.4	1.5	2.0	2.2	2.1	2.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.5	1.5	1.5	2.0	2.0	2.0	2.0
			Old building	Light-weight	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	1.1	1.2	1.2	1.2	1.1	1.2	1.2	1.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.1	1.1	1.1	1.0	1.1	1.1	1.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.1	1.1	1.1	0.9	1.0	1.0	1.0

Climate →					Dry climate								Tropical climate							
Building function →					Office				Residence				Office				Residence			
Room size ↓	Window size ↓	Type of glazing ↓	Age ↓	Building method \ Orientation	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=20m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	4.3	4.3	5.0	5.8	7.0	8.0	9.4	9.7	3.3	3.4	3.3	3.7	4.5	4.6	4.4	4.8
				Medium-weight	4.5	4.8	5.3	6.1	7.3	8.5	9.9	10.4	3.2	3.3	3.2	3.5	4.3	4.3	4.2	4.5
				Heavy-weight	4.6	5.0	5.6	6.4	7.5	8.9	10.3	10.9	3.3	3.3	3.3	3.6	4.4	4.5	4.3	4.7
			Old building	Light-weight	4.1	4.4	4.9	6.0	6.2	6.9	7.7	8.6	4.5	4.8	4.5	5.0	6.5	6.8	6.5	7.0
				Medium-weight	4.5	4.9	5.5	6.3	6.4	7.4	8.2	9.0	4.8	5.1	4.8	5.3	6.6	6.9	6.5	7.0
				Heavy-weight	4.7	5.3	5.7	6.8	6.6	8.0	8.9	9.9	5.5	5.8	5.4	6.0	7.5	7.8	7.3	7.9
		Double glazing (coated)	New building	Light-weight	3.4	3.6	3.7	4.1	5.6	6.1	6.4	6.6	2.7	2.7	2.6	2.8	4.3	4.5	4.3	4.5
				Medium-weight	3.8	3.9	4.1	4.2	5.7	6.1	6.4	6.7	2.7	2.7	2.7	2.8	4.1	4.3	4.1	4.3
				Heavy-weight	3.7	3.9	4.1	4.3	5.7	6.1	6.5	6.8	2.8	2.9	2.8	3.0	4.3	4.4	4.2	4.4
			Old building	Light-weight	3.5	3.9	4.1	4.4	5.5	6.1	6.4	6.8	4.0	4.3	4.0	4.2	6.5	6.8	6.4	6.8
				Medium-weight	3.9	4.4	4.6	4.9	5.4	6.1	6.3	6.8	4.5	4.7	4.4	4.7	6.5	6.9	6.4	6.9
				Heavy-weight	4.2	4.7	4.9	5.4	5.8	6.5	6.8	7.4	5.2	5.5	5.1	5.6	7.4	7.8	7.3	7.8
		Triple glazing (clear)	New building	Light-weight	4.1	4.2	4.8	5.2	6.9	7.7	8.9	9.0	2.7	2.8	2.7	3.0	4.0	4.1	3.9	4.2
				Medium-weight	4.2	4.4	4.8	5.4	7.2	8.0	9.2	9.6	2.6	2.7	2.6	2.8	3.8	3.8	3.6	3.9
				Heavy-weight	4.4	4.6	5.0	5.6	7.3	8.3	9.5	9.9	2.7	2.8	2.7	2.9	3.9	4.0	3.8	4.1
			Old building	Light-weight	3.8	4.1	4.6	5.3	6.0	6.6	7.2	7.7	4.0	4.3	4.0	4.4	6.1	6.4	6.0	6.5
				Medium-weight	4.2	4.7	5.0	5.6	6.0	6.9	7.7	8.3	4.4	4.6	4.3	4.7	6.1	6.4	5.9	6.5
				Heavy-weight	4.4	5.0	5.3	6.2	6.4	7.4	8.3	9.1	5.1	5.4	5.0	5.5	7.0	7.4	6.8	7.3
		Triple glazing (coated)	New building	Light-weight	3.3	3.5	3.6	3.6	5.6	6.0	6.1	6.4	2.4	2.5	2.3	2.5	4.1	4.3	4.0	4.3
				Medium-weight	3.6	3.8	3.9	4.0	5.7	6.1	6.3	6.5	2.4	2.5	2.3	2.5	3.9	4.0	3.8	4.0
				Heavy-weight	3.6	3.8	3.9	4.1	5.6	6.0	6.2	6.5	2.5	2.7	2.5	2.6	4.0	4.2	3.9	4.1
			Old building	Light-weight	3.3	3.8	3.9	4.1	5.4	6.0	6.2	6.5	3.8	4.1	3.7	4.0	6.2	6.6	6.1	6.6
				Medium-weight	3.8	4.3	4.4	4.7	5.2	5.8	6.1	6.4	4.3	4.6	4.2	4.5	6.2	6.7	6.1	6.6
				Heavy-weight	4.1	4.7	4.8	5.2	5.6	6.3	6.6	7.1	5.0	5.4	4.9	5.3	7.1	7.6	7.0	7.5
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	8.7	9.2	13.4	14.2	11.8	13.8	22.1	18.7	5.9	6.0	6.1	7.1	5.4	5.1	5.4	5.8
				Medium-weight	8.9	10.0	13.8	14.2	12.4	15.1	23.6	19.7	5.5	5.5	5.8	6.7	5.5	5.3	5.6	5.9
				Heavy-weight	9.1	10.4	13.7	14.2	12.7	15.5	23.6	20.2	5.3	5.2	5.6	6.4	5.5	5.3	5.6	5.9
			Old building	Light-weight	7.6	7.6	11.6	12.3	9.4	10.4	14.8	14.6	5.7	5.8	6.0	6.9	5.9	5.7	6.0	6.4
				Medium-weight	7.8	8.1	11.1	12.1	10.0	11.7	15.6	15.6	5.6	5.6	5.9	6.7	6.3	6.2	6.4	6.8
				Heavy-weight	7.8	8.6	11.0	12.3	10.3	12.4	16.2	16.4	5.6	5.5	5.9	6.8	6.6	6.5	6.6	7.0
		Double glazing (coated)	New building	Light-weight	6.2	6.2	7.0	7.1	7.6	7.7	8.4	8.7	3.6	3.7	3.7	3.9	5.2	5.1	5.3	5.4
				Medium-weight	6.2	6.4	6.8	7.2	7.4	8.0	8.6	9.1	3.8	3.8	3.9	4.1	5.2	5.1	5.2	5.3
				Heavy-weight	6.0	6.1	6.7	7.0	7.4	8.1	8.7	9.2	4.0	3.9	4.0	4.2	5.3	5.3	5.2	5.4
			Old building	Light-weight	5.6	5.7	6.2	6.6	6.9	7.1	7.8	8.0	3.9	4.0	4.0	4.3	5.8	5.9	5.8	6.1
				Medium-weight	5.8	6.0	6.5	6.9	6.7	7.3	7.8	8.2	4.3	4.3	4.4	4.5	6.1	6.1	6.0	6.2
				Heavy-weight	5.8	6.1	6.5	6.9	6.8	7.3	8.0	8.3	4.6	4.6	4.6	4.9	6.4	6.4	6.3	6.6
		Triple glazing (clear)	New building	Light-weight	8.3	8.8	12.4	12.1	12.1	14.1	22.1	18.4	4.5	4.6	4.7	5.4	4.0	3.7	3.8	4.2
				Medium-weight	8.5	9.5	12.4	12.7	12.6	15.3	22.6	19.2	4.1	4.1	4.3	4.8	3.7	3.7	3.9	3.9
				Heavy-weight	8.5	9.7	12.2	13.0	12.8	15.6	22.9	19.7	3.9	3.9	4.1	4.6	3.8	3.6	3.7	3.9
			Old building	Light-weight	7.0	7.2	10.1	10.5	8.7	10.1	13.0	12.9	4.5	4.6	4.7	5.4	4.5	4.3	4.5	4.8
				Medium-weight	7.3	7.8	10.0	10.8	9.4	11.2	14.0	14.0	4.3	4.4	4.5	5.2	4.6	4.6	4.6	4.7
				Heavy-weight	7.2	7.9	9.6	11.0	9.7	11.7	14.4	14.7	4.3	4.5	4.5	5.1	4.8	4.8	4.8	5.1
		Triple glazing (coated)	New building	Light-weight	5.5	5.7	6.0	6.1	7.0	7.3	7.7	7.9	2.6	2.7	2.6	2.8	4.2	4.0	4.1	4.2
				Medium-weight	5.7	5.9	6.1	6.2	7.1	7.3	7.8	8.0	2.8	2.8	2.8	2.8	4.1	4.1	4.1	4.1
				Heavy-weight	5.5	5.7	5.9	6.0	6.9	7.4	7.7	8.2	2.8	2.8	2.8	2.9	4.1	4.0	4.1	4.2
			Old building	Light-weight	4.9	5.2	5.5	5.5	6.2	6.6	6.8	6.8	3.0	3.1	3.0	3.1	4.8	4.9	4.8	5.0
				Medium-weight	5.3	5.6	5.7	5.9	6.0	6.4	6.8	6.9	3.3	3.4	3.3	3.4	4.8	5.0	4.9	5.0
				Heavy-weight	5.2	5.4	5.7	5.8	6.0	6.6	6.8	7.2	3.6	3.6	3.5	3.7	5.1	5.2	5.1	5.3
Big room (A=100m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	1.5	1.6	1.7	2.1	3.1	3.4	3.9	4.0	1.3	1.3	1.3	1.4	2.0	2.1	2.0	2.2
				Medium-weight	1.6	1.6	1.8	2.0	3.2	3.6	3.9	4.2	1.3	1.3	1.2	1.4	1.9	1.9	1.9	2.0
				Heavy-weight	1.5	1.6	1.8	2.2	3.4	3.8	4.2	4.4	1.3	1.3	1.3	1.4	2.0	2.0	2.0	2.1
			Old building	Light-weight	1.4	1.5	1.7	2.1	2.6	2.8	3.1	3.3	1.8	1.8	1.7	2.0	2.8	3.0	2.8	3.1
				Medium-weight	1.6	1.7	1.8	2.2	2.6	3.0	3.2	3.5	1.9	2.0	1.9	2.1	2.9	3.0	2.8	3.1
				Heavy-weight	1.7	1.8	2.0	2.4	2.8	3.2	3.5	3.9	2.2	2.3	2.2	2.4	3.3	3.5	3.2	3.5
		Double glazing (coated)	New building	Light-weight	1.2	1.2	1.3	1.4	2.6	2.8	2.9	3.0	1.1	1.1	1.0	1.1	1.8	1.9	1.8	1.9
				Medium-weight	1.5	1.5	1.5	1.5	2.9	3.0	3.1	3.2	1.0	1.1	1.0	1.1	1.7	1.8	1.7	1.8
				Heavy-weight	1.4	1.4	1.4	1.5	2.9	3.0	3.1	3.3	1.1	1.1	1.1	1.2	1.8	1.8	1.8	1.9
			Old building	Light-weight	1.3	1.3	1.4	1.6	2.4	2.7	2.7	2.9	1.6	1.7	1.5	1.6	2.7	2.8	2.6	2.8
				Medium-weight	1.5	1.6	1.7	1.8	2.3	2.6	2.7	2.9	1.7	1.8	1.7	1.8	2.7	2.8	2.7	2.9
				Heavy-weight	1.6	1.7	1.8	2.0	2.5	2.8	2.9	3.2	2.1	2.2	2.0	2.2	3.1	3.3	3.0	3.3
		Triple glazing (clear)	New building	Light-weight	1.3	1.4	1.5	1.7	3.0	3.3	3.7	3.7	1.0	1.0	1.0	1.1	1.7	1.7	1.6	1.8
				Medium-weight	1.5	1.5	1.6	1.7	3.2	3.5	3.7	3.9	0.9	0.9	0.9	1.0	1.6	1.6	1.5	1.6
				Heavy-weight	1.4	1.5	1.5	1.8	3.3	3.7	3.9	4.1	1.0	1.0	1.0	1.1	1.6	1.7	1.6	1.7
			Old building	Light-weight	1.3	1.3	1.5	1.8	2.4	2.6	2.9	3.0	1.5	1.6	1.5	1.6	2.5	2.6	2.5	2.7
				Medium-weight	1.5	1.5	1.7	1.9	2.5	2.8	3.0	3.3	1.6	1.7	1.6	1.8	2.5	2.6	2.5	2.7
				Heavy-weight	1.6	1.7	1.8	2.1	2.7	3.1	3.3	3.6	1.9	2.0	1.9	2.1	2.9	3.1	2.9	3.1
		Triple glazing (coated)	New building	Light-weight	1.1	1.2	1.2	1.2	2.6	2.8	2.8	2.9	0.9	0.9	0.8	0.9	1.6	1.7	1.6	1.7
				Medium-weight	1.4	1.4	1.4	1.4	2.9	3.0	3.0	3.1	0.9	0.9	0.8	0.9	1.5	1.6	1.5	1.6
				Heavy-weight	1.3	1.3	1.3	1.4	2.9	3.0	3.1	3.2	0.9	0.9	0.9	0.9	1.6	1.6	1.5	1.6
			Old building	Light-weight	1.2	1.3	1.4	1.4	2.3	2.6	2.7	2.8	1.4	1.5	1.4	1.5	2.5	2.7	2.4	2.6
				Medium-weight	1.4	1.5	1.6	1.7	2.2	2.5	2.6	2.8	1.6	1.7	1.5	1.7	2.5	2.6	2.4	2.6
				Heavy-weight	1.5	1.7	1.7	1.9	2.4	2.7	2.8	3.1	1.9	2.0	1.8	2.0	2.9	3.1	2.8	3.0
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	3.8	3.8	5.5	5.7	5.2	6.0	8.3	7.9	2.6	2.6	2.7	3.1	3.2	3.3	3.3	3.6
				Medium-weight	3.5	3.8	4.9	5.4	5.3	6.2	8.3	8.0	2.6	2.5	2.6	3.0	3.2	3.3	3.3	3.6
				Heavy-weight	3.5	3.9	4.9	5.5	5.5	6.4	8.3	8.3	2.6	2.5	2.7	3.1	3.3	3.2	3.3	3.6
			Old building	Light-weight	3.2	3.1	4.1	5.0	4.1	4.2	5.2	5.8	2.6	2.6	2.7	3.2	3.5	3.5	3.6	3.8
				Medium-weight	3.2	3.0	3.8	4.6	4.1	4.5	5.4	6.1	2.6	2.6	2.7	3.1	3.6	3.7	3.7	4.0
				Heavy-weight	3.1	3.1	3.7	4.6	4.3	4.9	5.6	6.3	2.7	2.6	2.8	3.3	3.8	3.8	3.8	4.2
		Double glazing (coated)	New building	Light-weight	2.9	2.8	3.1	3.2	3.7	3.8	4.0	4.2	1.8	1.8	1.8	1.9	2.6	2.6	2.6	2.7
				Medium-weight	2.9	3.0	3.0	3.1	3.8	4.0	4.1	4.3	1.9	1.9	1.9	2.0	2.5	2.5	2.5	2.6
				Heavy-weight	2.8	2.8	3.0	3.0	3.8	4.0	4.2	4.5	1.9	1.9	1.9	2.0	2.6	2.6	2.6	2.7
			Old building	Light-weight	2.6	2.5	2.8	2.9	3.3	3.5	3.5	3.6	1.9	1.9	1.9	2.0	2.8	2.9	2.9	3.0
				Medium-weight	2.6	2.6	2.8	3.0	3.2	3.3	3.5	3.7	2.0	2.1	2.0	2.2	2.9	2.9	2.9	3.0
				Heavy-weight	2.6	2.6	2.8	3.1	3.1	3.4	3.6	3.7	2.2	2.2	2.2	2.3	3.1	3.1	3.0	3.2
		Triple glazing (clear)	New building	Light-weight	3.4	3.3	4.5	4.7	5.1	5.6	7.6	7.2	1.6	1.6	1.7	2.0	2.0	2.0	2.1	2.2
				Medium-weight	3.1	3.3	4.0	4.5	5.2	5.9	7.5	7.4	1.6	1.5	1.6	1.9	1.9	1.9	1.9	2.1
				Heavy-weight	3.1	3.2	3.8	4.5	5.3	6.1	7.6	7.5	1.5	1.5	1.6	1.9	2.0	1.9	1.9	2.1
			Old building	Light-weight	2.7	2.5	3.4	3.9	3.6	3.7	4.3	4.6	1.7	1.7	1.8	2.1	2.2	2.2	2.3	2.4
				Medium-weight	2.8	2.7	3.1	3.8	3.8	4.0	4.5	5.0	1.7	1.7	1.7	2.0	2.3	2.3	2.3	2.5
				Heavy-weight	2.8	2.4	2.9	3.8	3.9	4.3	4.7	5.3	1.8	1.7	1.8	2.1	2.4	2.4	2.4	2.6
		Triple glazing (coated)	New building	Light-weight	2.5	2.5	2.7	2.6	3.5	3.6	3.7	3.8	1.1	1.1	1.1	1.1	1.7	1.7	1.7	1.8
				Medium-weight	2.6	2.6	2.7	2.7	3.7	3.8	3.9	4.0	1.1	1.1	1.1	1.2	1.6	1.7	1.6	1.7
				Heavy-weight	2.4	2.4	2.5	2.6	3.6	3.8	3.9	4.0	1.2	1.1	1.1	1.2	1.7	1.7	1.7	1.7
			Old building	Light-weight	2.2	2.2	2.4	2.4	2.9	3.0	3.1	3.1	1.2	1.2	1.2	1.3	2.0	2.0	2.0	2.1
				Medium-weight	2.3	2.3	2.4	2.4	2.7	2.9	3.0	3.0	1.3	1.4	1.3	1.4	2.0	2.1	2.0	2.1
				Heavy-weight	2.2	2.3	2.4	2.5	2.7	2.9	3.0	3.1	1.5	1.5	1.4	1.5	2.1	2.2	2.1	2.2

TABLE 12: ABSOLUTE INCREASE IN ENERGY DEMAND FOR ARTIFICIAL LIGHTING (KWH/M²/YEAR)			Climate →	Cold climate				Temperate climate				Dry climate				Tropical climate			
Building function ↓	**Room size** ↓	**Window size** ↓	**Orientation** / **Type of glazing**	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Office	Small room (A=20m²)	Small window (wwr=0.25)	Clear	8.0	5.9	3.0	5.4	9.1	6.2	3.9	6.5	7.6	5.0	2.0	4.4	3.8	4.2	4.0	4.1
			Coated	13.8	13.5	12.9	13.2	14.0	13.7	13.8	13.6	14.7	14.2	14.5	25.9	14.9	13.4	15.1	13.9
		Large window (wwr=0.75)	Clear	3.3	2.6	1.5	2.4	3.2	2.2	1.5	2.5	0.6	0.3	0.1	0.3	0.3	0.5	0.3	0.6
			Coated	7.8	6.1	4.3	6.2	9.4	6.9	5.6	7.4	10.8	7.4	5.1	6.4	8.6	6.8	8.7	7.6
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	6.2	6.0	5.3	6.0	7.5	7.3	7.6	7.4	10.7	9.1	7.6	6.9	11.3	8.9	11.1	9.5
			Coated	1.5	2.7	4.8	3.0	1.8	3.2	4.1	3.2	2.8	4.3	6.1	6.0	4.1	5.1	4.2	4.9
		Large window (wwr=0.75)	Clear	7.4	5.2	2.9	5.3	8.4	5.6	3.9	6.1	6.0	3.2	1.4	3.5	3.7	3.7	3.8	4.3
			Coated	3.5	4.7	6.2	5.2	4.1	6.0	7.9	6.2	6.2	7.7	8.7	6.8	9.1	8.4	9.0	9.1
Residence	Small room (A=20m²)	Small window (wwr=0.25)	Clear	1.7	1.4	1.3	1.3	1.7	1.5	1.5	1.3	0.9	0.7	0.9	0.8	1.2	1.0	1.1	1.2
			Coated	2.1	1.6	1.5	1.8	2.3	1.8	1.5	2.1	2.4	2.0	1.4	1.4	1.7	1.7	1.7	1.5
		Large window (wwr=0.75)	Clear	0.8	0.9	0.8	0.7	0.7	0.9	0.8	0.6	0.2	0.2	0.2	0.3	0.9	1.0	0.9	0.8
			Coated	1.8	1.5	1.4	1.4	2.0	1.6	1.4	1.3	1.3	0.9	1.0	0.7	1.0	1.0	1.0	0.9
	Big room (A=100m²)	Small window (wwr=0.25)	Clear	2.2	1.7	1.5	1.7	2.4	1.8	1.6	1.8	1.7	1.4	1.1	1.0	1.2	1.2	1.2	1.2
			Coated	0.9	1.1	1.3	1.4	1.0	1.3	1.5	1.7	1.3	1.7	1.7	1.5	1.6	1.6	1.6	1.6
		Large window (wwr=0.75)	Clear	1.5	1.3	1.3	1.1	1.6	1.4	1.4	1.0	0.8	0.6	0.8	0.5	1.0	1.0	1.0	1.0
			Coated	1.9	1.5	1.2	1.5	2.1	1.6	1.4	1.7	2.2	1.7	1.2	1.2	1.5	1.5	1.5	1.4

TABLE 13: HEATING ENERGY DEMAND WITHOUT LTATW (KWH/M^2/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Age ↓	Room size ↓	Type of glazing ↓	Window size ↓	Orientation / Building method	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
New building	Small room ($A=20m^2$)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	11.0	9.5	4.4	9.3	25.6	21.9	12.5	21.3	3.1	2.4	1.2	2.5	10.8	9.1	5.0	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	10.2	8.7	2.9	8.4	24.3	20.8	10.7	20.0	2.0	1.4	0.3	1.4	9.9	8.1	3.9	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	9.8	8.2	2.2	8.0	24.3	20.4	10.3	19.8	1.4	0.7	0.0	0.8	9.5	7.8	3.3	7.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	29.0	24.5	12.0	24.4	50.3	43.1	25.7	42.0	9.9	7.7	4.3	8.1	22.0	17.9	11.2	17.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	29.8	25.0	9.1	24.4	49.6	41.7	19.2	40.3	9.7	6.9	2.4	7.1	21.3	16.7	8.1	16.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	29.8	24.8	7.5	24.0	49.1	41.1	16.6	39.7	9.0	6.1	1.3	6.3	20.6	15.9	6.3	16.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	13.6	12.6	9.8	12.5	30.8	28.8	23.7	28.5	4.8	4.4	3.5	4.5	14.9	14.0	11.9	14.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	12.8	11.8	8.7	11.7	29.7	27.7	22.4	27.4	3.8	3.5	2.5	3.5	14.0	13.0	11.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	12.6	11.5	8.3	11.4	29.5	27.6	22.2	27.3	3.2	2.9	1.8	2.9	13.6	12.6	10.6	12.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	38.9	35.0	26.5	35.0	66.1	60.2	47.0	59.1	17.8	16.1	12.4	16.3	35.1	32.3	26.5	32.3	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	40.7	36.6	26.4	36.2	65.5	59.6	45.2	58.6	17.9	16.3	12.0	16.4	34.7	31.6	25.4	31.7	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	41.0	36.7	25.8	36.2	64.9	59.2	44.5	58.2	17.6	15.9	11.3	16.0	34.1	30.9	24.6	31.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	4.5	3.9	1.4	3.8	15.2	13.1	6.8	12.8	0.7	0.5	0.2	0.6	5.5	4.5	2.2	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	3.2	2.6	0.4	2.6	14.0	12.0	5.5	11.7	0.1	0.0	0.0	0.0	4.6	3.7	1.5	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	2.6	1.9	0.1	1.9	13.8	11.7	5.0	11.4	0.0	0.0	0.0	0.0	4.2	3.3	1.1	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	8.9	7.1	2.2	6.9	20.4	17.2	7.0	16.5	1.5	1.0	0.5	1.1	6.6	4.4	1.8	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	8.2	6.3	0.9	6.1	19.8	16.4	4.7	15.7	0.7	0.2	0.1	0.2	5.9	3.8	0.8	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	7.5	5.5	0.2	5.3	19.2	15.9	3.4	15.1	0.1	0.0	0.0	0.0	5.3	3.2	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	5.7	5.4	4.3	5.4	19.0	18.0	15.3	17.8	1.4	1.3	1.1	1.3	8.2	7.9	6.8	7.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	4.4	4.2	3.0	4.1	17.7	16.8	14.1	16.6	0.5	0.4	0.2	0.4	7.3	7.0	6.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	3.9	3.6	2.3	3.5	17.7	16.7	13.9	16.5	0.1	0.1	0.0	0.1	6.9	6.6	5.6	6.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	13.5	12.3	8.8	12.3	30.2	27.9	21.3	27.4	4.7	4.2	3.2	4.3	14.4	13.3	10.7	13.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	13.0	11.8	7.9	11.7	29.7	27.3	20.5	26.8	3.9	3.5	2.1	3.5	13.7	12.8	10.0	12.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	12.5	11.3	7.2	11.1	29.3	26.8	19.9	26.3	3.2	2.7	1.4	2.8	13.1	12.2	9.4	12.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Big room ($A=100m^2$)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	2.9	2.5	1.3	2.5	12.1	10.6	6.5	10.3	0.7	0.6	0.4	0.6	4.2	3.7	2.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	1.7	1.4	0.3	1.3	11.4	9.9	5.7	9.7	0.0	0.0	0.0	0.0	3.7	3.2	1.6	3.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.1	0.8	0.1	0.8	11.2	9.6	5.3	9.4	0.0	0.0	0.0	0.0	3.4	2.8	1.1	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	9.5	8.1	3.7	8.0	23.2	19.9	10.6	19.3	2.6	2.1	1.1	2.2	9.2	7.3	3.9	7.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	9.1	7.6	2.3	7.4	22.8	19.4	8.7	18.9	1.6	1.1	0.3	1.2	8.7	6.9	2.8	6.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	8.6	7.0	1.5	6.8	22.4	19.0	7.5	18.4	1.0	0.5	0.0	0.6	8.2	6.4	2.3	6.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	3.4	3.2	2.6	3.2	14.1	13.4	11.3	13.2	0.9	0.9	0.8	0.9	5.6	5.4	4.6	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	2.1	2.0	1.3	2.0	13.4	12.7	10.6	12.6	0.1	0.1	0.0	0.1	5.1	4.9	4.1	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.5	1.4	0.7	1.4	13.2	12.4	10.3	12.3	0.0	0.0	0.0	0.0	4.8	4.5	3.7	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	12.2	11.2	8.6	11.3	29.6	27.3	21.4	26.9	4.6	4.2	3.3	4.2	14.1	13.1	10.8	13.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	12.1	11.0	7.7	10.9	29.3	27.0	20.8	26.6	3.7	3.3	2.2	3.3	13.7	12.8	10.3	12.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	11.7	10.6	7.1	10.4	29.0	26.6	20.3	26.2	3.1	2.7	1.6	2.7	13.3	12.3	9.8	12.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	1.2	1.0	0.6	1.0	7.6	6.8	4.2	6.7	0.3	0.3	0.2	0.2	2.2	1.9	1.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	0.1	0.1	0.0	0.1	7.0	6.2	3.4	6.1	0.0	0.0	0.0	0.0	1.7	1.4	0.6	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.0	0.0	0.0	0.0	6.7	5.8	2.9	5.8	0.0	0.0	0.0	0.0	1.4	1.0	0.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	2.4	2.0	0.7	1.9	10.0	8.7	3.5	8.4	0.5	0.4	0.2	0.4	2.7	1.9	0.6	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	1.4	1.0	0.0	1.0	9.6	8.2	2.4	7.9	0.0	0.0	0.0	0.0	2.3	1.5	0.2	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.8	0.5	0.0	0.4	9.2	7.8	1.8	7.4	0.0	0.0	0.0	0.0	1.8	1.1	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	1.4	1.4	1.2	1.4	9.0	8.7	7.7	8.6	0.4	0.4	0.3	0.4	3.1	3.0	2.6	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	0.2	0.2	0.1	0.2	8.4	8.1	7.0	8.0	0.0	0.0	0.0	0.0	2.6	2.5	2.2	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	0.0	0.0	0.0	0.0	8.1	7.8	6.8	7.7	0.0	0.0	0.0	0.0	2.2	2.1	1.7	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	3.5	3.3	2.4	3.3	13.9	13.0	10.3	12.8	1.0	0.9	0.8	0.9	5.5	5.2	4.1	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	2.3	2.1	1.2	2.1	13.5	12.6	9.8	12.5	0.1	0.1	0.0	0.1	5.1	4.8	3.7	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	1.6	1.4	0.6	1.4	13.1	12.2	9.4	12.0	0.0	0.0	0.0	0.0	4.7	4.4	3.3	4.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Old building	Small room ($A=20m^2$)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	54.9	49.4	38.0	49.4	88.9	80.8	64.0	79.3	26.7	24.2	19.1	24.6	48.2	44.5	36.8	44.4	0.1	0.0	0.0	0.0	0.5	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	58.3	52.7	38.9	52.1	88.5	80.1	61.7	78.8	27.9	25.3	19.4	25.5	48.0	44.0	35.7	44.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	61.4	55.5	40.6	54.7	91.0	82.6	63.7	81.3	29.1	26.4	20.0	26.6	49.4	45.2	36.3	45.2	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	63.6	54.7	35.4	55.3	103.3	91.6	67.4	90.1	29.2	24.7	17.9	25.7	53.6	47.5	35.7	47.5	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	69.4	59.1	33.7	58.3	103.2	88.7	57.3	86.6	31.3	26.3	16.1	26.8	53.0	46.2	30.5	46.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	71.2	60.2	32.6	58.9	103.8	88.5	54.0	86.1	31.8	26.4	14.5	26.8	52.9	45.7	28.1	45.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	61.2	58.5	53.5	58.6	99.6	95.7	88.7	95.1	31.1	30.1	27.8	30.2	54.9	53.3	49.9	53.2	0.4	0.3	0.0	0.2	2.5	1.6	0.3	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	64.9	62.0	56.4	61.9	99.5	95.3	88.2	94.8	32.9	31.8	29.1	31.8	54.8	53.2	49.7	53.2	0.1	0.0	0.0	0.0	2.0	1.2	0.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	68.0	65.0	59.2	64.8	102.5	98.0	90.4	97.5	34.3	33.1	30.3	33.2	56.3	54.7	51.0	54.7	0.0	0.0	0.0	0.0	1.7	1.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	78.5	72.4	60.8	72.7	127.2	118.9	102.7	117.4	40.7	38.2	33.1	38.6	70.7	67.0	59.2	66.9	0.6	0.3	0.0	0.2	3.2	1.5	0.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	85.2	78.8	65.5	78.5	127.5	118.5	101.1	117.2	44.3	41.4	35.2	41.6	70.9	67.0	58.8	67.0	0.2	0.0	0.0	0.0	2.5	1.1	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	87.1	80.9	66.9	80.3	128.1	118.4	100.6	117.1	45.1	42.1	35.6	42.3	71.1	67.2	58.6	67.2	0.1	0.0	0.0	0.0	2.1	0.8	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	47.6	43.4	34.4	43.3	78.4	71.9	58.3	70.8	22.8	20.9	16.9	21.0	42.3	39.5	33.3	39.4	0.1	0.0	0.0	0.0	0.5	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	50.1	45.8	35.1	45.4	77.9	71.2	57.2	70.2	23.5	21.6	17.1	21.7	42.1	39.1	32.5	39.1	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	52.9	48.5	37.0	47.9	80.5	73.7	59.4	72.8	24.6	22.6	17.8	22.7	43.5	40.3	33.4	40.3	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	43.1	37.2	22.7	37.2	71.4	62.4	43.0	61.0	18.5	15.6	10.5	16.0	35.8	31.5	22.1	31.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	45.9	39.1	21.0	38.4	71.3	61.0	37.2	59.4	19.1	15.8	9.0	16.2	35.2	30.6	18.7	30.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	46.9	39.8	20.1	38.8	71.7	61.1	36.0	59.3	19.2	15.7	7.7	15.9	35.0	30.3	17.6	30.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	52.7	51.2	48.3	51.2	87.2	84.8	80.8	84.5	26.3	25.7	24.4	25.7	47.7	46.8	44.9	46.8	0.3	0.2	0.1	0.2	1.9	1.4	0.4	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	55.3	53.7	50.5	53.6	87.0	84.6	80.4	84.2	27.4	26.8	25.3	26.8	47.5	46.6	44.7	46.6	0.0	0.0	0.0	0.0	1.5	1.1	0.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	58.2	56.5	53.1	56.3	90.1	87.4	83.0	87.1	28.7	28.0	26.4	28.1	49.1	48.1	46.1	48.1	0.0	0.0	0.0	0.0	1.3	0.9	0.2	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	54.5	51.5	45.2	51.6	90.3	85.8	77.2	85.1	27.2	26.0	23.3	26.2	49.4	47.6	43.5	47.5	0.3	0.2	0.0	0.1	1.5	0.9	0.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	57.9	54.8	47.8	54.6	90.3	85.5	76.4	84.9	28.7	27.3	24.2	27.4	49.4	47.5	43.2	47.5	0.0	0.0	0.0	0.0	1.1	0.6	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	59.1	56.2	48.9	55.9	90.9	85.6	76.3	85.0	29.0	27.6	24.3	27.7	49.6	47.6	43.2	47.6	0.0	0.0	0.0	0.0	0.9	0.5	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Big room ($A=100m^2$)	Double glazing (clear)	Small window (wwr=0.25)	Light-weight	37.6	35.0	29.5	35.0	70.3	65.9	57.0	65.1	17.9	16.8	14.5	17.0	37.8	35.9	31.8	35.9	0.2	0.1	0.0	0.0	0.5	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	41.1	38.4	31.7	38.2	70.2	65.5	56.0	64.8	19.0	17.8	15.0	17.9	37.7	35.8	31.4	35.8	0.0	0.0	0.0	0.0	0.4	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	42.6	39.9	32.7	39.6	71.2	66.1	56.7	65.5	19.3	18.1	15.1	18.2	38.2	36.2	31.6	36.2	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	41.1	36.1	26.2	36.7	75.5	67.7	52.1	66.3	19.0	16.7	13.0	17.1	39.9	36.1	28.2	36.1	0.1	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	45.7	40.0	26.9	39.7	75.4	67.1	48.3	65.4	20.4	18.0	12.4	18.2	39.7	35.6	26.8	35.6	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	47.0	40.9	26.6	40.2	75.4	67.0	46.9	65.3	20.5	18.0	11.6	18.1	39.5	35.1	25.9	35.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Double glazing (coated)	Small window (wwr=0.25)	Light-weight	40.2	39.1	37.0	39.2	75.2	73.5	70.3	73.2	19.6	19.2	18.3	19.3	40.8	40.1	38.6	40.1	0.3	0.2	0.1	0.2	1.3	1.0	0.3	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	43.8	42.7	40.3	42.6	75.3	73.4	70.1	73.1	21.0	20.5	19.4	20.6	40.8	40.1	38.5	40.1	0.0	0.0	0.0	0.0	1.0	0.7	0.3	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	45.3	44.2	41.6	44.1	76.5	74.5	71.0	74.2	21.4	20.9	19.8	20.9	41.4	40.6	39.0	40.6	0.0	0.0	0.0	0.0	0.8	0.6	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	47.6	45.0	39.9	45.2	87.9	83.8	76.1	83.2	23.7	22.7	20.6	22.9	48.1	46.3	42.6	46.3	0.4	0.2	0.0	0.2	1.7	1.0	0.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	52.8	50.0	44.1	50.0	88.1	83.8	75.5	83.1	26.0	24.9	22.2	25.0	48.2	46.4	42.5	46.4	0.0	0.0	0.0	0.0	1.3	0.7	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	54.0	51.4	45.1	51.1	88.2	83.6	75.1	83.0	26.3	25.0	22.2	25.1	48.2	46.3	42.4	46.3	0.0	0.0	0.0	0.0	1.0	0.6	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (clear)	Small window (wwr=0.25)	Light-weight	34.5	32.5	28.3	32.6	65.6	62.1	55.4	61.6	16.2	15.4	13.7	15.6	35.1	33.7	30.6	33.7	0.1	0.1	0.0	0.1	0.5	0.3	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	37.5	35.5	30.4	35.3	65.4	61.8	54.7	61.3	17.0	16.2	14.1	16.2	35.0	33.6	30.3	33.6	0.0	0.0	0.0	0.0	0.4	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	38.9	36.9	31.4	36.6	66.5	62.4	55.3	62.0	17.3	16.4	14.2	16.5	35.5	34.0	30.5	34.0	0.0	0.0	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	32.3	28.7	21.1	28.9	60.9	54.9	42.2	53.7	14.4	12.8	9.9	13.1	31.8	28.9	22.9	28.9	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	35.4	31.2	21.4	30.9	60.7	54.6	40.0	53.3	15.0	13.3	9.3	13.5	31.6	28.5	21.9	28.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	36.0	31.7	21.1	31.2	60.7	54.5	39.0	53.3	14.9	13.1	8.7	13.3	31.3	28.1	21.4	28.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		Triple glazing (coated)	Small window (wwr=0.25)	Light-weight	36.7	36.0	34.9	36.1	69.6	68.6	66.7	68.4	17.6	17.4	16.9	17.4	37.6	37.1	36.3	37.1	0.2	0.2	0.1	0.2	1.1	0.9	0.5	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	39.7	39.0	37.7	39.0	69.6	68.5	66.6	68.4	18.6	18.4	17.8	18.4	37.5	37.1	36.2	37.1	0.0	0.0	0.0	0.0	0.8	0.7	0.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	41.0	40.4	38.9	40.3	70.8	69.6	67.7	69.5	19.0	18.7	18.1	18.7	38.1	37.7	36.7	37.7	0.0	0.0	0.0	0.0	0.7	0.6	0.3	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
			Large window (wwr=0.75)	Light-weight	37.4	36.1	33.5	36.2	71.0	69.0	65.0	68.6	18.0	17.5	16.4	17.6	38.3	37.5	35.6	37.5	0.2	0.2	0.1	0.2	1.0	0.7	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Medium-weight	40.8	39.5	36.4	39.5	71.1	68.9	64.7	68.6	19.2	18.7	17.3	18.7	38.4	37.5	35.5	37.5	0.0	0.0	0.0	0.0	0.7	0.5	0.1	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
				Heavy-weight	41.5	40.3	37.0	40.2	71.2	68.8	64.5	68.5	19.2	18.6	17.2	18.6	38.3	37.4	35.4	37.4	0.0	0.0	0.0	0.0	0.6	0.4	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

TABLE 14: COOLING ENERGY DEMAND WITHOUT LTATW (KWH/M^2/YEAR)				Climate →	Cold climate								Temperate climate								Dry climate								Tropical climate							
				Building function →	Office				Residence				Office				Residence				Office				Residence				Office				Residence			
Room size ↓	Window size ↓	Type of glazing ↓	Age ↓	Orientation / Building method	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West
Small room (A=20m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	0.2	0.6	0.8	0.6	0.1	0.4	0.7	0.5	8.3	9.6	9.6	9.3	5.9	7.3	7.5	7.3	39.0	43.5	44.8	48.0	28.0	33.1	34.5	39.1	87.8	90.7	87.7	90.0	64.0	67.3	64.1	66.9
				Medium-weight	0.0	0.1	0.2	0.1	0.0	0.1	0.1	0.1	6.8	7.8	7.9	7.7	5.7	7.0	7.2	7.0	37.3	41.7	42.4	46.3	27.7	32.8	34.2	38.8	88.3	91.4	88.3	90.8	63.7	67.1	63.8	66.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1	7.2	7.3	7.2	5.2	6.6	6.8	6.6	36.6	41.1	41.7	46.0	27.5	32.7	34.0	38.6	88.3	91.4	88.3	90.8	63.6	67.0	63.7	66.5
			Old building	Light-weight	0.1	0.4	0.4	0.3	0.0	0.1	0.2	0.1	7.0	8.2	8.3	8.0	4.0	5.0	5.1	5.0	41.8	46.4	47.3	50.6	31.5	36.2	36.8	41.9	94.6	97.7	94.5	96.8	73.0	76.6	73.1	76.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	6.6	6.7	6.5	3.5	4.5	4.5	4.5	40.8	45.4	45.9	49.8	30.9	35.9	36.4	41.5	96.3	99.6	96.2	98.8	73.3	77.0	73.4	76.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	6.1	6.0	5.9	3.0	4.1	4.0	4.1	40.3	45.0	45.4	49.8	30.7	35.9	36.4	41.7	97.1	100.4	97.0	99.8	74.0	77.8	74.1	77.3
		Double glazing (coated)	New building	Light-weight	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	5.4	5.8	5.9	5.8	2.6	3.0	3.0	3.0	32.4	34.0	34.2	35.4	20.9	22.5	22.6	24.2	75.0	76.1	75.0	75.8	49.2	50.4	49.2	50.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.4	4.4	4.4	2.3	2.6	2.6	2.6	30.8	32.2	32.4	33.7	20.4	22.0	22.2	23.8	74.9	76.0	74.9	75.7	48.8	50.0	48.9	49.8
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	3.7	3.8	3.8	1.9	2.3	2.3	2.3	30.0	31.5	31.6	33.0	20.1	21.7	21.9	23.5	74.7	75.8	74.7	75.6	48.6	49.8	48.7	49.6
			Old building	Light-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	4.7	5.3	5.3	5.2	1.7	2.1	2.1	2.1	35.9	37.7	37.9	39.2	25.1	27.0	27.2	29.1	82.5	83.7	82.4	83.4	58.5	59.9	58.5	59.8
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	3.8	3.8	3.8	1.2	1.5	1.5	1.5	34.8	36.6	36.8	38.3	24.4	26.3	26.4	28.3	83.4	84.7	83.3	84.4	58.5	60.0	58.5	59.8
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	3.1	3.1	3.1	0.8	1.2	1.2	1.2	34.4	36.2	36.4	38.0	24.3	26.3	26.4	28.4	84.0	85.4	83.9	85.1	59.1	60.7	59.1	60.4
		Triple glazing (clear)	New building	Light-weight	0.2	0.4	0.5	0.4	0.0	0.2	0.4	0.3	7.5	8.4	8.4	8.2	5.2	6.2	6.4	6.2	36.0	39.3	40.1	42.6	24.8	28.6	29.7	33.0	81.5	83.7	81.4	83.2	56.5	59.0	56.6	58.7
				Medium-weight	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	6.0	6.7	6.9	6.6	4.9	6.0	6.1	5.9	34.1	37.5	37.8	40.8	24.5	28.3	29.3	32.7	81.6	83.9	81.6	83.5	56.2	58.7	56.3	58.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	6.1	6.2	6.1	4.5	5.6	5.7	5.6	33.4	36.8	37.2	40.4	24.2	28.1	29.1	32.5	81.5	83.8	81.4	83.4	56.0	58.6	56.1	58.2
			Old building	Light-weight	0.1	0.2	0.2	0.2	0.0	0.0	0.1	0.0	6.3	7.1	7.2	7.0	3.2	4.0	4.1	4.1	38.9	42.4	43.1	45.6	28.2	31.9	32.3	36.1	88.6	91.0	88.6	90.4	65.7	68.5	65.8	68.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	5.7	5.7	5.6	2.8	3.6	3.6	3.6	37.8	41.4	41.7	44.7	27.6	31.4	31.8	35.7	89.9	92.4	89.8	91.8	65.9	68.7	65.9	68.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	5.1	5.1	5.0	2.3	3.1	3.1	3.1	37.2	40.9	41.2	44.6	27.4	31.5	31.8	35.9	90.5	93.1	90.5	92.6	66.5	69.5	66.5	69.0
		Triple glazing (coated)	New building	Light-weight	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	5.0	5.4	5.4	5.3	2.5	2.7	2.7	2.7	30.5	31.5	31.6	32.3	19.0	19.9	20.0	21.0	71.0	71.6	71.0	71.5	44.6	45.3	44.6	45.2
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	4.0	4.0	4.0	2.1	2.4	2.3	2.4	28.8	29.7	29.8	30.6	18.5	19.5	19.6	20.6	70.6	71.3	70.6	71.1	44.1	44.9	44.2	44.8
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	3.4	3.3	3.3	1.7	2.0	2.0	2.0	28.1	29.0	29.0	29.9	18.2	19.2	19.4	20.3	70.4	71.0	70.3	70.9	43.9	44.7	44.0	44.6
			Old building	Light-weight	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	4.4	4.8	4.7	4.7	1.5	1.8	1.8	1.8	34.1	35.4	35.5	36.3	23.1	24.4	24.5	25.8	78.8	79.7	78.7	79.4	54.0	55.0	54.0	54.9
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.1	3.4	3.4	3.4	1.0	1.2	1.2	1.2	32.9	34.2	34.3	35.3	22.4	23.7	23.8	25.1	79.4	80.3	79.3	80.1	53.9	54.9	53.9	54.8
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4	2.8	2.7	2.7	0.6	1.0	0.9	0.9	32.5	33.8	33.9	35.1	22.3	23.7	23.8	25.2	79.9	80.9	79.8	80.7	54.5	55.6	54.4	55.4
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	2.0	4.3	7.1	4.7	2.2	5.4	7.8	6.1	16.8	21.3	22.4	20.4	15.0	19.6	20.7	19.9	58.4	70.9	79.9	84.0	49.5	63.5	72.7	81.7	123.1	130.8	123.2	128.8	107.5	116.4	107.8	115.5
				Medium-weight	0.5	2.1	3.6	2.5	1.3	4.4	6.8	4.9	14.4	18.3	18.7	17.9	14.6	19.2	20.0	19.3	56.8	69.4	74.4	83.0	49.4	63.9	72.5	81.6	126.7	134.7	126.7	133.0	108.5	117.6	108.8	116.4
				Heavy-weight	0.2	1.2	2.6	1.5	0.7	3.6	5.8	4.0	13.9	17.5	17.9	17.2	14.2	18.9	19.5	18.8	56.3	69.0	73.2	83.1	49.2	63.9	72.0	81.4	127.6	135.8	127.6	134.2	108.4	117.7	108.7	116.4
			Old building	Light-weight	1.1	2.9	4.8	3.2	0.6	2.1	3.7	2.6	14.4	18.7	19.5	17.8	11.4	14.7	15.5	15.1	59.6	71.6	78.1	83.7	50.7	63.5	68.5	80.6	127.6	135.3	127.7	133.1	114.2	123.0	114.5	122.4
				Medium-weight	0.2	1.0	1.8	1.2	0.1	1.1	2.3	1.4	12.4	15.7	16.0	15.3	10.8	14.2	14.7	14.3	58.6	70.6	74.1	83.3	50.5	64.0	67.9	80.6	131.9	140.0	132.0	138.1	116.0	125.2	116.3	124.1
				Heavy-weight	0.1	0.5	0.9	0.5	0.0	0.3	1.3	0.6	11.7	14.9	15.2	14.7	10.3	13.7	14.1	13.7	58.2	70.4	73.3	83.7	50.3	64.1	67.5	80.5	133.5	141.6	133.4	140.0	116.3	125.7	116.6	124.5
		Double glazing (coated)	New building	Light-weight	0.2	0.4	0.4	0.3	0.0	0.1	0.1	0.1	7.0	7.8	7.8	7.6	3.7	4.3	4.4	4.4	39.2	42.4	43.0	45.7	27.7	31.0	31.3	35.2	87.9	90.2	87.9	89.6	64.4	67.0	64.5	66.7
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.4	6.1	6.0	6.0	3.2	3.9	3.8	3.9	37.7	40.9	41.2	44.2	27.2	30.7	30.9	34.7	88.9	91.2	88.9	90.8	64.6	67.2	64.7	66.9
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	5.5	5.4	5.3	2.8	3.5	3.4	3.5	36.8	40.1	40.3	43.6	26.7	30.4	30.6	34.4	88.9	91.3	88.9	90.9	64.4	67.1	64.5	66.7
			Old building	Light-weight	0.1	0.3	0.3	0.2	0.0	0.0	0.0	0.0	6.4	7.4	7.3	7.1	2.9	3.4	3.4	3.5	41.8	45.1	45.5	48.1	31.3	34.6	34.7	38.6	93.4	95.7	93.4	95.1	71.4	74.1	71.5	73.9
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	5.3	5.3	5.2	2.2	2.8	2.7	2.8	40.8	44.1	44.3	47.2	30.5	34.0	34.1	37.9	95.1	97.6	95.1	97.0	72.0	74.8	72.1	74.5
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.7	4.7	4.6	1.7	2.3	2.2	2.3	40.2	43.5	43.7	46.8	30.0	33.5	33.6	37.5	95.7	98.1	95.7	97.7	72.2	75.0	72.3	74.6
		Triple glazing (clear)	New building	Light-weight	1.5	3.2	5.0	3.5	2.3	4.9	6.9	5.3	14.2	17.4	18.2	16.9	13.3	17.0	17.9	17.1	50.2	59.4	65.3	69.4	40.7	51.4	59.3	64.9	106.8	112.6	106.9	111.2	86.5	93.2	86.8	92.4
				Medium-weight	0.3	1.4	2.3	1.6	1.7	4.2	6.0	4.5	12.2	15.0	15.3	14.7	13.0	16.8	17.5	16.7	48.2	57.6	60.9	67.8	40.5	51.5	59.0	64.7	108.8	114.9	108.8	113.6	86.8	93.5	87.0	92.6
				Heavy-weight	0.1	0.6	1.5	0.8	1.2	3.3	5.2	3.7	11.7	14.3	14.5	14.1	12.6	16.4	17.1	16.3	47.6	57.0	59.8	67.5	40.3	51.4	58.7	64.5	109.2	115.3	109.1	114.2	86.6	93.3	86.8	92.4
			Old building	Light-weight	0.7	1.9	3.0	2.0	0.4	1.3	2.3	1.7	12.0	15.0	15.4	14.4	9.0	11.6	12.0	11.8	51.4	60.3	64.2	69.3	41.3	50.9	54.3	63.2	111.7	117.4	111.8	116.0	93.5	100.1	93.7	99.5
				Medium-weight	0.1	0.6	0.8	0.6	0.0	0.5	1.3	0.7	10.1	12.4	12.6	12.2	8.6	11.1	11.5	11.1	50.1	59.1	61.3	68.5	41.0	51.1	53.8	63.1	114.6	120.6	114.6	119.3	94.4	101.2	94.6	100.3
				Heavy-weight	0.0	0.3	0.3	0.2	0.0	0.1	0.4	0.1	9.5	11.7	11.9	11.6	8.1	10.7	11.0	10.7	49.6	58.6	60.4	68.4	40.8	51.1	53.5	63.1	115.5	121.6	115.4	120.4	94.5	101.4	94.7	100.5
		Triple glazing (coated)	New building	Light-weight	0.2	0.3	0.2	0.2	0.0	0.0	0.0	0.0	6.1	6.5	6.5	6.4	3.1	3.5	3.5	3.5	33.8	35.5	35.7	37.2	21.9	23.6	23.7	25.7	76.9	78.1	76.9	77.8	51.1	52.5	51.2	52.3
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	5.0	4.9	4.9	2.7	3.1	3.0	3.1	32.1	33.8	33.8	35.5	21.6	23.3	23.3	25.4	76.9	78.2	76.9	78.0	51.0	52.4	51.1	52.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	4.3	4.3	4.3	2.3	2.8	2.7	2.7	31.2	32.8	32.8	34.7	21.1	23.0	23.0	25.1	76.7	78.0	76.7	77.8	50.7	52.1	50.8	51.9
			Old building	Light-weight	0.1	0.2	0.1	0.1	0.0	0.0	0.0	0.0	5.4	5.9	5.9	5.8	2.1	2.4	2.3	2.4	36.6	38.3	38.5	40.0	25.3	27.0	27.0	29.0	82.9	84.2	82.9	83.9	58.4	59.9	58.5	59.7
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	4.3	4.2	4.2	1.5	1.9	1.8	1.9	35.3	37.0	37.1	38.8	24.6	26.3	26.3	28.4	83.7	85.0	83.7	84.8	58.6	60.1	58.6	59.9
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	3.6	3.5	3.6	1.2	1.5	1.4	1.5	34.6	36.3	36.4	38.2	24.2	26.0	26.0	28.1	83.9	85.2	83.9	85.0	58.6	60.2	58.7	59.9
Big room (A=100m^2)	Small window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	0.6	1.0	1.0	0.9	0.0	0.1	0.2	0.1	7.8	8.6	8.5	8.3	4.1	4.7	4.8	4.7	34.6	36.7	37.3	38.6	21.8	24.1	24.6	26.7	75.7	77.1	75.7	76.8	50.0	51.5	50.0	51.3
				Medium-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	6.0	6.5	6.6	6.4	3.9	4.5	4.5	4.5	32.5	34.5	34.8	36.4	21.5	23.8	24.2	26.4	75.7	77.1	75.7	76.8	49.8	51.3	49.9	51.1
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.3	5.8	5.8	5.8	3.5	4.1	4.2	4.1	31.6	33.6	33.8	35.7	21.3	23.6	24.1	26.2	75.5	76.9	75.5	76.6	49.6	51.2	49.7	51.0
			Old building	Light-weight	0.2	0.5	0.4	0.3	0.0	0.0	0.0	0.0	6.8	7.6	7.4	7.3	2.6	3.1	3.1	3.1	37.1	39.2	39.6	41.0	25.0	27.1	27.3	29.5	81.8	83.2	81.8	82.8	57.6	59.2	57.7	59.1
				Medium-weight	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	4.9	5.4	5.5	5.4	2.2	2.6	2.6	2.7	35.6	37.7	38.0	39.6	24.4	26.6	26.8	29.1	82.5	84.0	82.5	83.6	57.8	59.5	57.8	59.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	4.9	4.9	4.8	1.8	2.3	2.2	2.3	35.0	37.1	37.3	39.2	24.1	26.4	26.6	28.9	82.8	84.3	82.7	83.9	58.0	59.8	58.1	59.5
		Double glazing (coated)	New building	Light-weight	0.3	0.5	0.5	0.4	0.0	0.0	0.0	0.0	6.4	6.8	6.8	6.7	2.7	2.8	2.9	2.8	31.5	32.2	32.4	32.9	18.5	19.3	19.3	20.1	70.0	70.5	70.0	70.4	43.3	43.8	43.3	43.7
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	4.8	4.8	4.8	2.3	2.5	2.5	2.5	29.5	30.2	30.3	30.8	18.2	19.0	19.0	19.8	69.7	70.2	69.7	70.1	43.0	43.6	43.0	43.5
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.1	4.2	4.2	4.2	2.0	2.2	2.2	2.2	28.7	29.3	29.4	30.0	18.0	18.7	18.8	19.6	69.4	69.9	69.4	69.8	42.8	43.4	42.8	43.3
			Old building	Light-weight	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	5.6	6.0	5.9	5.9	1.7	1.8	1.8	1.8	34.4	35.2	35.3	35.9	22.0	22.9	23.0	23.9	76.5	77.0	76.4	76.8	51.0	51.7	51.0	51.6
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	4.1	4.1	4.1	1.2	1.4	1.4	1.4	32.9	33.7	33.8	34.4	21.4	22.3	22.4	23.2	76.8	77.4	76.8	77.2	51.0	51.7	51.0	51.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.3	3.5	3.5	3.5	0.9	1.1	1.1	1.1	32.3	33.1	33.2	33.9	21.1	22.1	22.2	23.1	76.9	77.5	76.9	77.4	51.2	51.9	51.2	51.8
		Triple glazing (clear)	New building	Light-weight	0.6	0.9	0.8	0.7	0.0	0.1	0.1	0.1	7.5	8.0	8.0	7.9	3.8	4.2	4.3	4.2	33.1	34.8	35.1	36.2	20.3	22.0	22.4	23.9	72.9	73.9	72.8	73.6	46.6	47.7	46.6	47.6
				Medium-weight	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	5.6	6.0	6.1	5.9	3.6	4.0	4.0	4.0	31.0	32.5	32.8	33.9	20.0	21.7	22.1	23.6	72.7	73.7	72.6	73.5	46.4	47.5	46.4	47.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	5.3	5.3	5.2	3.2	3.6	3.7	3.6	30.1	31.7	31.8	33.2	19.9	21.6	21.9	23.5	72.4	73.4	72.4	73.2	46.2	47.3	46.2	47.1
			Old building	Light-weight	0.2	0.4	0.3	0.3	0.0	0.0	0.0	0.0	6.4	7.0	7.0	6.8	2.3	2.6	2.7	2.7	35.7	37.4	37.7	38.7	23.4	25.1	25.3	26.9	79.2	80.2	79.1	79.9	54.3	55.5	54.3	55.4
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	5.1	5.1	5.0	1.9	2.2	2.2	2.2	34.2	35.8	36.0	37.3	22.9	24.6	24.7	26.5	79.7	80.8	79.6	80.5	54.4	55.7	54.4	55.5
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.5	4.4	4.4	1.5	1.8	1.8	1.8	33.6	35.2	35.4	36.9	22.6	24.4	24.5	26.3	79.8	81.0	79.8	80.7	54.6	55.9	54.6	55.7
		Triple glazing (coated)	New building	Light-weight	0.3	0.4	0.4	0.4	0.0	0.0	0.0	0.0	6.3	6.5	6.5	6.5	2.6	2.7	2.7	2.7	30.6	31.0	31.1	31.4	17.6	18.1	18.2	18.6	68.2	68.5	68.2	68.4	41.2	41.5	41.2	41.5
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	4.6	4.6	4.6	2.3	2.4	2.4	2.4	28.6	29.0	29.1	29.4	17.4	17.8	17.9	18.3	67.8	68.1	67.8	68.0	40.9	41.2	40.9	41.2
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.9	4.0	4.0	4.0	2.0	2.1	2.1	2.1	27.8	28.2	28.2	28.6	17.1	17.6	17.6	18.1	67.5	67.8	67.5	67.7	40.7	41.0	40.7	41.0
			Old building	Light-weight	0.1	0.2	0.2	0.2	0.0	0.0	0.0	0.0	5.4	5.7	5.7	5.6	1.5	1.7	1.7	1.7	33.5	34.2	34.2	34.5	21.1	21.7	21.8	22.4	74.8	75.2	74.8	75.1	49.0	49.4	49.0	49.4
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.8	3.9	3.9	3.9	1.1	1.2	1.2	1.2	32.0	32.6	32.7	33.1	20.5	21.1	21.2	21.8	75.0	75.4	75.0	75.3	48.9	49.4	48.9	49.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.2	3.4	3.3	3.3	0.8	0.9	0.9	0.9	31.4	32.0	32.1	32.6	20.2	20.9	21.0	21.6	75.1	75.6	75.1	75.5	49.1	49.6	49.1	49.5
	Large window (wwr=0.25)	Double glazing (clear)	New building	Light-weight	1.5	2.4	3.5	2.5	0.5	1.5	2.2	1.7	11.7	13.8	14.2	13.4	8.0	9.8	10.1	9.9	43.8	49.3	52.7	55.2	31.6	37.9	40.6	45.7	92.2	95.6	92.2	94.8	70.0	74.1	70.2	73.7
				Medium-weight	0.2	0.7	1.0	0.7	0.1	0.8	1.6	0.9	9.2	10.8	10.9	10.6	7.7	9.5	9.7	9.5	41.4	46.9	48.6	52.8	31.4	37.8	40.1	45.6	93.4	97.0	93.3	96.2	70.3	74.5	70.5	73.9
				Heavy-weight	0.1	0.3	0.4	0.3	0.0	0.3	0.9	0.4	8.6	10.0	10.1	9.9	7.4	9.2	9.4	9.2	40.6	46.1	47.5	52.2	31.1	37.7	39.9	45.4	93.5	97.2	93.5	96.5	70.1	74.4	70.3	73.8
			Old building	Light-weight	0.7	1.5	2.0	1.4	0.1	0.4	0.6	0.5	10.2	12.3	12.2	11.6	5.6	6.8	7.0	7.0	45.3	50.7	52.7	55.9	33.6	39.1	40.2	46.3	97.0	100.5	97.0	99.5	76.5	80.6	76.7	80.3
				Medium-weight	0.1	0.4	0.5	0.3	0.0	0.1	0.2	0.1	8.0	9.3	9.4	9.1	5.2	6.4	6.5	6.4	43.8	49.0	50.0	54.3	33.2	39.0	39.8	46.0	98.8	102.4	98.8	101.6	77.3	81.6	77.5	81.1
				Heavy-weight	0.0	0.2	0.2	0.1	0.0	0.0	0.0	0.0	7.3	8.5	8.6	8.4	4.7	6.0	6.1	6.0	43.1	48.3	49.1	53.9	32.9	38.8	39.5	45.8	99.3	103.0	99.3	102.2	77.4	81.7	77.5	81.1
		Double glazing (coated)	New building	Light-weight	0.5	0.8	0.7	0.6	0.0	0.1	0.0	0.1	7.5	8.0	7.9	7.7	3.1	3.4	3.5	3.5	34.8	36.4	36.7	37.8	21.6	23.2	23.3	25.1	76.0	77.1	76.0	76.8	50.3	51.5	50.3	51.3
				Medium-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	5.3	5.7	5.7	5.6	2.7	3.1	3.1	3.1	32.7	34.3	34.5	35.8	21.3	22.9	23.0	24.8	76.1	77.2	76.1	77.0	50.3	51.5	50.3	51.3
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.7	5.1	5.1	5.0	2.4	2.8	2.7	2.7	31.9	33.4	33.6	34.9	21.0	22.7	22.8	24.6	75.9	77.0	75.9	76.8	50.0	51.3	50.1	51.1
			Old building	Light-weight	0.2	0.4	0.3	0.3	0.0	0.0	0.0	0.0	6.5	7.1	7.0	6.9	2.2	2.5	2.4	2.5	37.2	38.8	39.0	40.1	24.9	26.4	26.5	28.2	81.5	82.5	81.5	82.2	57.0	58.2	57.0	58.1
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	5.1	5.0	4.9	1.7	1.9	1.9	1.9	35.7	37.2	37.3	38.7	24.3	25.8	25.9	27.7	82.2	83.3	82.2	83.0	57.3	58.5	57.3	58.4
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	4.4	4.3	4.3	1.3	1.6	1.5	1.6	35.0	36.6	36.7	38.1	23.8	25.4	25.5	27.2	82.2	83.4	82.2	83.1	57.2	58.5	57.3	58.3
		Triple glazing (clear)	New building	Light-weight	1.2	1.8	2.5	1.9	0.4	1.1	1.7	1.3	10.5	12.0	12.3	11.7	7.0	8.3	8.6	8.4	39.8	43.8	46.0	48.2	27.4	32.0	34.0	37.7	84.4	87.0	84.4	86.4	60.2	63.2	60.4	62.9
				Medium-weight	0.2	0.4	0.6	0.5	0.1	0.5	1.1	0.7	8.3	9.2	9.3	9.1	6.8	8.1	8.3	8.1	37.4	41.3	42.4	45.6	27.1	31.9	33.6	37.5	84.9	87.6	84.9	87.1	60.3	63.3	60.4	62.9
				Heavy-weight	0.0	0.2	0.2	0.2	0.0	0.1	0.6	0.3	7.5	8.6	8.6	8.4	6.5	7.8	8.0	7.8	36.5	40.5	41.3	44.9	26.9	31.8	33.4	37.3	84.9	87.6	84.8	87.1	60.1	63.1	60.2	62.7
			Old building	Light-weight	0.6	1.1	1.4	1.1	0.1	0.2	0.3	0.3	9.0	10.4	10.4	10.0	4.6	5.4	5.5	5.5	41.5	45.4	46.7	49.2	29.2	33.2	33.9	38.3	89.5	92.1	89.5	91.4	66.9	69.9	67.0	69.6
				Medium-weight	0.1	0.2	0.2	0.2	0.0	0.0	0.0	0.0	6.9	7.8	7.9	7.7	4.1	5.0	5.1	5.0	39.9	43.7	44.2	47.5	28.8	33.0	33.5	38.0	90.7	93.4	90.7	92.8	67.4	70.4	67.5	70.1
				Heavy-weight	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	6.3	7.1	7.2	7.1	3.8	4.6	4.6	4.6	39.2	42.9	43.3	47.0	28.5	32.8	33.2	37.8	91.0	93.7	90.9	93.1	67.3	70.5	67.4	70.1
		Triple glazing (coated)	New building	Light-weight	0.5	0.7	0.6	0.5	0.0	0.0	0.0	0.0	7.0	7.3	7.3	7.2	2.9	3.1	3.1	3.1	32.3	33.1	33.3	33.8	19.0	19.8	19.8	20.8	70.9	71.4	70.9	71.3	44.2	44.8	44.2	44.7
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	5.2	5.1	5.1	2.5	2.7	2.7	2.7	30.2	30.9	31.0	31.8	18.7	19.5	19.6	20.5	70.6	71.2	70.6	71.1	44.0	44.7	44.1	44.6
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	4.5	4.5	4.5	2.2	2.4	2.4	2.4	29.2	30.0	30.0	30.8	18.5	19.3	19.3	20.3	70.3	70.9	70.3	70.8	43.8	44.4	43.8	44.3
			Old building	Light-weight	0.2	0.3	0.2	0.2	0.0	0.0	0.0	0.0	6.0	6.4	6.3	6.3	1.8	2.0	2.0	2.0	34.8	35.7	35.7	36.4	22.1	22.9	22.9	23.8	76.7	77.2	76.7	77.1	51.0	51.6	51.0	51.6
				Medium-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2	4.4	4.4	4.4	1.4	1.5	1.5	1.5	33.2	34.0	34.0	34.7	21.5	22.3	22.3	23.3	77.0	77.6	77.0	77.4	51.1	51.8	51.1	51.7
				Heavy-weight	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	3.8	3.8	3.8	1.1	1.2	1.2	1.2	32.5	33.3	33.3	34.1	21.1	22.0	22.0	22.9	76.9	77.5	76.9	77.4	51.0	51.7	51.0	51.6