Influence of Windows on Daylight Entrance and Energy Demand of Housing based on the Dutch Building Code

A comparison of daylight calculation method NEN 2057 and simulation method NEN-EN 17037, and a parametric study of window position and window size for high daylight entrance and low energy demand.

Tom Sebastiaan Ooms

Master's thesis report

Date: April 11, 2024

TU Delft SWECO

Cover image: Taken from internal Sweco templafy website,
Sweco Nederland b.v. (2023). kv_rördrommen_10. https://pickitmedialive.blob.core.windows.net/sweco-thumbnails/onnAe8hG?sv=2020-10-02&st=2024-02-26T10%3A44%3A10Z&se=2024-02-26T11%3A14%3A10Z&sr=c&sp=r&sig=vnjOMdZmYc2fnX2g3dQCNyZPtmqqr1Hpa%2BeF9Wkm7FQ%3D

Influence of Windows on Daylight Entrance and Energy Demand of Housing based on the Dutch Building Code

A comparison of daylight calculation method NEN 2057 and simulation method NEN-EN 17037, and a parametric study of window position and window size for high daylight entrance and low energy demand.

by

Tom Sebastiaan Ooms

to obtain the degree of Master of Science in Civil Engineering
at Delft University of Technology.
to be defended publicly on Thursday April 18, 2024 at 12:00 PM.

Name:	Tom Sebastiaan Ooms	
Student number:	4719506	
Project duration:	June 2023 - April 2024	
Date:	April 11, 2024	
Graduation Committee:		
Chair:	Ir. Sander Pasterkamp	CITG - Materials, Mechanics, Management & Design
Supervisor:	Dr. Ir. Roel Schipper	CITG - Materials, Mechanics, Management & Design
Supervisor:	Ir. Christien Janssen	BK- Architectural Engineering and Technology
Supervisor:	Dr. Regina Bokel	BK- Architectural Engineering and Technology
Company Supervisor:	Ir. Ruben van Ruijven	Sweco Nederland B.V.

An electronic version of this thesis is available at http://repository.tudelft.nl/.

Preface

Over the course of recent months, I conducted research for my Master's thesis project. This research is done in relation to my graduation from the Delft University of Technology Building Engineering Master's Degree and in cooperation with Sweco Nederland B.V.

Readers particularly interested in the comparison of the two different daylight norms should study Chapter 2. This chapter also describes the theory behind the study. Readers who are more interested in the outcomes of the parametric model can read Chapter 5. The conclusions and recommendations in terms of architectural findings and practical workflow of this study are elaborated in Chapter 6 and 7.

I would like to express my gratitude to my Graduation Committee members — Sander Pasterkamp, Roel Schipper, Regina Bokel and Christien Janssen from TU Delft, as well as Ruben van Ruijven from Sweco — for their invaluable guidance throughout my academic journey. I am also thankful to Jantje Edelbroek and Sander Goesten from Sweco for their assistance in diving into the deeper aspects of my research topic. A special note of appreciation is reserved for Richard van den Brink for offering me an intern position that gave me the opportunity in my professional growth. Finally, my deepest thanks go to my friends and family for their support and encouragement from the very start of this process to its successful completion. Your belief in me has been a constant motivation.

I hope that reading my report will provide new insights into the new Dutch daylight regulations and the energy demand of the building while providing much reading pleasure on an exciting topic.

Tom Sebastiaan Ooms
April 11, 2024

Abstract

This research investigates the effect of window position and size on building facades on daylight entry, energy consumption, and thermal comfort of buildings. The aim is to find a feasible way to make housing more sustainable and energy efficient in compliance with the Dutch Building Regulations while providing good daylit spaces. This knowledge can be helpful to architects and engineers at an early stage in the design process who intend to design a sustainable building. This research is done in relation to the graduation from the TU Delft Building Engineering Master's degree in cooperation with the company Sweco Nederland B.V. located in De Bilt.

This study developed a parametric model based on the NTA 8800 calculation method for energy demand and the NEN-EN 17037 daylight norm. Two different types of reference building are investigated, a middle apartment in an apartment building and a middle terraced house. The parameters used for this study are the orientation of the building, the height and width of the window (and therefore WWR), as well as vertical and horizontal positioning of the windows, and a balcony cantilever in front of the apartment windows. The results show that:

The lower WWR boundaries are independent of orientation, and therefore, the minimum WWR values per orientation are the same. The lower boundary of the apartment (33%) is strongly influenced by the present overhangs, while the terraced housing requires a minimum WWR of 12%. The results show that the maximum WWR for terraced housing is mostly restricted by the BENG1 requirement (25% -38%), except for the south orientation (36%) which is limited by TO_{juli}. The maximum WWR of the apartment is restricted mainly by TO_{juli} (33% - 60%). The BENG1 results show that a north-south orientation for terraced housing is best to minimise energy demand (WWRs of around 38% are possible until requirements are exceeded). For the geometries studied, this research suggests a WWR for an apartment building roughly between 30% and 45% and for terraced housing roughly between 13% and 25% as a starting point. On top of that, it is recommended to install windows in the middle of a facade in terms of horizontal position and in the upper part of the facade in terms of vertical position to maximise daylight entry. Glass below the reference surface height of 0.85m should be avoided.

The results of this research indicate certain guidelines, rules, and statements that can be used when working with the new regulations, of which the most fundamental statement: As a consequence of the updated daylight standard from NEN 2057 to NEN-EN 17037, an increase in WWR no longer directly leads to a higher daylight factor, as it did under the current regulation. Furthermore, this study reveals clearly that despite the fact that energy demand and daylight are theoretically closely related, regulations are separated more. Daylight and energy demand are better separable (and individually optimised) in regulations than expected beforehand.

The methodology used demonstrates its robustness and practicality in analysing complex problems and obtaining validated results. Therefore, the methodology used can be recommended for further research and larger design projects in practice.

Nomenclature

Index or Symbol	**Meaning**	**Unit**
$A_{c,op,k}$	Projected area of opaque element op,k	[m^2]
$A_{e,i}$	Equivalent daylight surface of opening i	[m^2]
$A_{d,i}$	Surface of opening i	[m^2]
$A_{g;tot}$	Usable area of the total calculation area	[m^2]
$A_{wi,k}$	Area of the window wi,k	[m^2]
$C_{b,i}$	Obstruction factor of opening i	[-]
C_{LTA}	Reduction factor for material	[-]
$C_{u,i}$	External reduction factor of opening i	[-]
DF	Daylight factor	[%]
D_T	Target daylight factor	[%]
D_{TM}	Minimum target daylight factor	[%]
E_i	Illuminance due to daylight indoors	[lx]
E_o	Illuminance outdoors at the same time and location	[lx]
E_T	Target illuminance	[lx]
E_{TM}	Minimum target illuminance	[lx]
$E_{v,d,med}$	Median diffuse horizontal skylight illuminance	[lx]
$Ewe_{H+C,nd}$	Weighted energy performance / Energy demand indicator	[kWh/m^2]
$F_{fr,wi,k}$	Frame fraction of window wi,k	[-]
$F_{sh,obst}$	Shading reduction factor for external obstacles	[-]
H_C	Heat transfer coefficient transmission and ventilation	[W/K]
$H_{C,D}$	Direct heat transfer coefficient for transmission to outside	[W/K]
$H_{C,ve}$	Heat transfer coefficient for ventilation	[W/K]
$H_{H,A}$	Heat transfer coefficient through adjacent heated spaces	[W/K]
$H_{H,D}$	Direct heat transfer coefficient between the room and the outside air	[W/K]
$H_{H,U}$	Heat transfer coefficient through adjacent unheated spaces	[W/K]
$H_{H,p}$	Heat transfer coefficient through vertical pipes	[W/K]
$H_{H,tr(excl.gf,m)}$	Total heat loss coefficient through transmission excl. the ground floor	[W/K]
$H_{H,ve}$	Total heat transfer coefficient for ventilation	[W/K]
$H_{gr,an}$	Heat transfer coefficient for elements regarding the ground floor	[W/K]
$I_{sol,mi}$	Monthly average total solar radiation	[W/m^2]
LT	Light transmittance	[-]
N_{woon}	Number of residential functions	[-]
$N_{P,woon}$	Average number of occupants per residential function	[-]
P	Maximum grid size	[m]
$Q_{C,HP}$	Energy extracted from cold distribution system by the booster heat pump	[kWh]
$Q_{C,gn}$	Total heat gain for cooling	[kWh]
$Q_{C,ht}$	Total heat transfer for cooling	[kWh]
$Q_{C,nd}$	Annual cooling demand	[kWh]
$Q_{C,nd,zi,mi}$	Cooling demand per calculation zone zi for each month mi	[kWh]
$Q_{H,gn}$	Total heat gain for heating	[kWh]
$Q_{H,ht}$	Total heat transfer for heating	[kWh]
$Q_{H,int}$	Total internal heat gain	[kWh]
$Q_{H,nd}$	Annual heating demand	[kWh]
$Q_{H,nd,zi,mi}$	Heating demand per calculation zone zi for each month mi	[kWh]
$Q_{H,sol}$	Total solar heat gain	[kWh]

Table 1: Nomenclature of the used symbols and indexes in this Master's Thesis

Index or Symbol	Meaning	Unit
$Q_{H,sol,op,k}$	Solar heat gain through opaque element op,k	[kWh]
$Q_{H,sol,wi,k}$	Solar heat gain through transparent element/ window wi,k	[kWh]
$Q_{H,tr}$	Total heat loss through transmission	[kWh]
$Q_{H,ve}$	Total heat loss through ventilation	[kWh]
$Q_{H+C,nd}$	Annual energy demand	[kWh]
$Q_{sky,op}$	Monthly add. heat flow heat radiation to the sky, opaque surfaces	[kWh]
$Q_{sky,wi}$	Monthly add. heat flow heat radiation to the sky, windows	[kWh]
$R_{C,floor}$	Thermal resistance floor	[m^2K/W]
$R_{C,roof}$	Thermal resistance roof	[m^2K/W]
$R_{C,wall}$	Thermal resistance wall	[m^2K/W]
R_{se}	Heat transfer resistance on exterior	[m^2K/W]
R_{si}	Heat transfer resistance on interior	[m^2K/W]
TO_{juli}	Temperature overshoot juli	[K]
$U_{c,op,k}$	Heat transfer coefficient of opaque element op,k	[W/(m^2K)]
$a_{H,red,mi}$	Reduction factor for non-continuous heating	[-]
$a_{H,red,wknd,mi}$	Reduction factor non-continuous heating in weekend	[-]
d	Longer dimension of the calculation area	[m]
$f_{red,day}$	Relative part of the day with reduced setpoint for heating	[-]
$f_{H,red,low,day}$	(Relative) length of the period until the reduced setpoint temperature has been reached	[-]
g	Solar factor or Total solar energy transmittance	[-]
$g_{gl,wi,k,H}$	Average effective total solar factor	[-]
t_{mi}	Length of month mi	[h]
$u_{site,mi}$	Monthly average wind speed	[m/s]
$\alpha_{C,red,zi,mi}$	Reduction factor for non-continuous cooling	[-]
α_{sol}	Absorption coefficient for solar radiation	[-]
$\eta_{H,gn,zi,mi}$	Utilisation factor for heat gain	[-]
$\eta_{C,ht,zi,mi}$	Utilisation factor for heat transfer	[-]
$\theta_{e,avg,an}$	Average outdoor temperature for the entire year	[$°C$]
$\theta_{e,avg,mi}$	Average outdoor temperature in month mi	[$°C$]
$\theta_{int,calc,H,zi,mi}$	Calculation temperature for heating of the calculation zone in month mi	[$°C$]
$\theta_{int,set,C}$	Setpoint temperature for cooling	[$°C$]
$\theta_{int,set,H}$	Setpoint temperature for heating	[$°C$]
$d\theta_{H,red,mn,day}$	Average (relative) reduction in temperature difference during the period with a reduced setpoint temperature	[-]
$d\theta_{float}$	(Relative) reduction in the difference between indoor and outdoor temperature at 'free-floating' conditions (no heating)	[-]
$d\theta_{set,low}$	(Relative) reduction of the setpoint temperature related to the difference with the outdoor temperature	[-]
ρ_{ceil}	Reflectance ceiling	[-]
ρ_{wall}	Reflectance interior walls	[-]
ρ_{floor}	Reflectance floor	[-]

Table 1: Nomenclature of the used symbols and indexes in this Master's Thesis

Abbreviation	**Meaning**	**Translation**
AMvB	Algemene Maatregel van Bestuur	Order in Council
Bbl	Besluit bouwwerken leefomgeving	Environmental Building Decree
BENG	Bijna Energieneutrale Gebouwen	Nearly Zero Energy Buildings (nZEB)
BREEAM	Building Research Establishment Environmental Assessment Method	-
CBS	Centraal Bureau voor de Statistiek	Central Bureau of Statistics
DGMR	Van Dalfsen, Gies, Meerdink en van Rangelrooij	-
EN	European Standard (European Norm)	
EPC	Energieprestatiecoëfficiënt	Energy performance coefficient
ERC	Externally reflected component	-
GO	Gebruiksoppervlak	Usable area (A_g)
GPR	Gemeentelijke Praktijk Richtlijn	Municipal practice guideline
GRESB	Global Real Estate Sustainability Benchmark	-
IRC	Internally reflected component	-
LEED	Leadership in Energy and Environmental Design	-
LR	Living room	-
LTA	Lichttoetredingsfactor of Lichttransmissie	Visible Light transmittance (VLT)
MOO	Multi-Objective Optimisation	-
NEN	Nederlandse Norm	Dutch Standard
NPR	Nederlandse Praktijk Richtlijn	Dutch Practice Guideline
NTA	Nederlandse Technische Afspraak	Dutch technical agreement
nZEB	Nearly Zero Energy Building	-
PM	Parametric model	-
PV	Photovoltaic (panels)	-
RMSE	Root Mean Square Error	-
RVO	Rijksdienst voor Ondernemend Nederland	Dutch Authority for Enterprise
–	Rijtjeshuis (doorzon woning)	Terraced house
SC	Sky component	-
–	Verblijfsgebied	Staying area
–	Verblijfsruimte	Staying space
VLT	Visible Light Transmittance	-
VP	Visual Programming	-
WWR	Window-to-Wall Ratio	-

Table 2: Nomenclature of the used abbreviations and translations in this Master's Thesis

Table of Content

List of Figures

List of Tables

1 Introduction

In the early stage of the building design stage, the selection of window areas and proportions is crucial because it affects energy demand and visual comfort. These choices are difficult to modify later, emphasising the need for a careful design process that considers multiple factors simultaneously. Additionally, new building standards and certifications emphasise the importance of achieving optimal performance in various aspects. However, there may be conflicting requirements when trying to minimise energy consumption (resulting in smaller windows) while maximising visual aspects (resulting in larger windows). Although optimisation techniques can help find a solution, this thesis focuses primarily on effectively utilising energy and visual criteria to find a balance and useful design guidelines regardless of the specific method used.

This chapter covers a short introduction to daylight in Section 1.1 and another small introduction to energy consumption in Section 1.2. Section 1.3 will state the framework in which this work is established. The following Sections 1.4 to 1.6 discusses the research gap, the problem statement, and the objective of the study and define the research questions to guide the work. Furthermore, the scope and restraints are discussed in Section 1.7 to further delimit the research field. Then, in Section 1.8 an objective motivation is given as to why this topic is of interest. Finally, the thesis outline is given in the following section 1.9.

1.1. Background on daylight

Daylight is indispensable inside buildings. Daylight has been shown to be favourable for the social and physical well-being of humans (Boubekri et al., 2014), (Evans, 2003), (Legates et al., 2014) and is the best quality light available due to its high light output and good colour rendering. Most people prefer the experience of the dynamics of daylight because balanced daylight has a positive impact on people's productivity and learning performance (Shishegar and Boubekri, 2016). Daylight reduces sick leave and reduces the recovery time of patients in hospitals (Nederlands Normalisatie Instituut, 2022b). For many people, the amount of daylight has an important influence on their mood. Dark winter days can be perceived very negatively since light is the basis for the human biorhythm (Brandi, 2006). In addition, people strongly prefer daylight through windows as a way to save energy for electrical lighting and adequately illuminate the interior surfaces.

In the Netherlands, for a room in a house or office to become a staying area according to the Building Decree, there must be sufficient daylight access. Each room should have a significant source of natural light in the form of a window. A daylight calculation is mandatory under the building code for both new and renovation building projects. In this way, the municipality can check whether the buildings meet the minimum daylight requirements. The standard for daylight is laid down in Besluit bouwwerken leefomgeving (Bbl) Article 4.3.10 (see Appendix A), which refers to NEN 2057. Presumably, in 2026, NEN-EN 17037 will substitute NEN 2057. New regulations on daylight calculations could have a significant influence on the design of new residential buildings with respect to the placement and dimensioning of windows.

1.2. Background on energy consumption

The transition from fossil fuels to renewable energy sources is a large ongoing project. Increasing energy demand and limitations on the use of available fossil fuels can lead to energy scarcity. With a greener future in mind, buildings must be made more efficient in energy use and built more sustainably. The European Union has decided that all new buildings must be nearly zero energy by 2021 (European Commission, 2016).

The member states can decide for themselves how they fill in the legislation. The rules and regulations on this topic are relatively new and are continually being improved. There are various indicators such as BREEAM, LEED, GPR, GRESB, and Greencalc to determine the performance and sustainability of a building, although this research focusses on BENG since this technique is legally required in the Netherlands.

BENG (**B**ijna **EN**ergieneutrale **G**ebouwen) is one of the most well-known and widely applied techniques for the energy efficient built environment in the Netherlands and was created by Rijksdienst voor Ondernemend Nederland (RVO). The BENG calculation method is described in the NTA 8800 standard (Nederlands Normalisatie Instituut, 2023) and consists of a three-step process based on Trias Energetica (Rijksdienst voor Ondernemend Nederland, 2013). The first step towards sustainability according to the theory (Alavirad et al., 2022) is the reduction of energy demand. The other two steps state that as much of the remaining share of the energy demand should come from renewable sources and eventually improve the efficiency of the remaining portion of fossil fuel usage. Since reducing energy use is the primary step, the focus of this research report is on reducing energy demand. Large glazing fronts can result in significant solar heat gains and therefore initiate overheating of a building in summer. Therefore, thermal comfort must also be taken into account. Given the importance of windows in the management of daylight entrance, solar gain and heat exchange processes, they are typically regarded as the element that must be designed correctly for energy efficiency purposes (Stegou-Sagia et al., 2007).

1.3. Framework

This research is done in relation to the graduation from the TU Delft Building Engineering Master's degree in cooperation with the company Sweco Nederland B.V.. Sweco (originally short for Swedish Consultants) is an architecture and engineering consultancy company established in the north of Europe. With the takeover of Grontmij in 2015, the company expanded its reach to the Netherlands and other parts of western Europe. Today, Sweco is Europe's leading architecture and engineering consultancy on diverse issues of tomorrow's sustainable cities and communities. As an advisor on durability and sustainability in the built environment, Sweco would like to use this research for projects where they are asked for advice on facade design. Building managers or operators often contact Sweco with questions about how to sustainably improve their building envelope. Thus, Sweco wants to know the impact of the new daylight standard on this advice. They would like to have a vision that they can consider in their advice, for which a study in this area can help. Therefore, this research aims to investigate the effect of window dimensions and window positions in building facades on daylight entry, energy consumption, and thermal comfort of buildings. Part of this research will include a literature study on the background of the standards and what the set requirements are for daylight based on the current and new method. By doing a parametric study, an answer will be found on what the optimal window properties are, taking into account energy consumption and daylight according to NEN-EN 17037.

1.4. Research gap and problem statement

Single-objective optimisation of a building component is a common topic in the literature. There are numerous examples, including high visual performance (Greenup and Edmonds, 2004), or lower energy consumption (Kusiak et al., 2010), (Nair et al., 2012). Previous studies tried to prove that optimising window size could simultaneously reduce energy consumption and improve daylight integration (Ghisi and Tinker, 2005). Furthermore, the literature can be found on multi-objective optimisation (MMO) of windows in building facades. The article of Ochoa et al. (2012) is a good example and offers guidance in selecting criteria to balance energy demand and visual comfort. However, the literature does not show many optimisations on the level of the regulations. Especially in terms of energy demand, BENG calculations can differ significantly from the real energy demand of the building. Therefore, it is interesting to optimise for the energy calculations according to the NTA 8800 and the daylight calculations according to NEN-EN 17037, since, in the end, the design has to be made according to these Dutch regulations. New regulations in the form of NEN-EN 17037 bring a whole new methodology for daylight simulations and the unknowns and uncertainties that come with it. New housing must be designed according to these rules to account for sufficient daylight by dimensioning the windows in the building envelope. These design choices will have an impact on building properties such as window-to-wall ratio (WWR) and thus also on the energy demand of the building. Therefore, it is helpful to find useful design guidelines in the design properties of the facade, so that daylight entry will be high without causing overheating and energy demand will be low.

1.5. Research objective

This research investigates the effect of window position and size in building facades on daylight entry, energy demand for heating and cooling, and thermal comfort of buildings. The goal is to find design guidelines to make the building more sustainable and energy efficient in compliance with the Dutch Building Regulations while providing good daylit spaces. This knowledge can be helpful to architects and engineers at an early stage in the design process who intend to design a sustainable building.

1.6. Research questions

To reach the main objective, this thesis finds an answer to the following main research question:

> **"What is the influence of window position and window size on daylight entrance according NEN-EN 17037, energy demand indicator BENG1 and TO_{juli} according NTA 8800, for typical Dutch dwellings using a parametric model?"**

The following sub-questions can be a guide along the way to finding an answer to the main research question. Sub-questions 2.x cover the daylight subject and sub-questions 3.x cover the subject of energy demand. The final sub-questions cover the combination of these subjects.

1. How does typical housing in the Netherlands look like and what parameters influence daylight and energy demand?
2. Sub-questions on daylight entrance:
   - 2.1. What methodologies and (different) boundary conditions are used to determine daylight entrance in a building according to NEN 2057 vs NEN-EN 17037?
   - 2.2. What is the influence of the transition from NEN 2057 to NEN-EN 17037 on the optimal window properties in a facade with regard to daylight?
3. Sub-questions on energy demand:
   - 3.1. What methodologies and boundary conditions are used to determine the energy demand according to NTA 8800?
   - 3.2. How does the orientation of the building influence the optimal window properties of a building with respect to energy demand?
4. What are the optimal window position and window size considering energy demand and daylight?

1.7. Scope and restrains

This research is focused on energy demand (BENG1) and daylight in residential reference buildings in the Netherlands. The main focus will be apartment buildings, as the requirements set are the most challenging. This is because the regulation of thermal comfort, specifically TO_{juli}, is only applicable to residential buildings that are not equipped with cooling systems. On top of that, future Sweco projects will include many residential buildings, since the housing market is scarce and offices are fighting emptiness. Sweco is mostly interested in apartment buildings in the first place, since the majority of the projects of Sweco Team "Fire Safety and Building Physics" will be these kinds of residence. In addition to that, it is interesting to look at ground-level dwellings, the so-called terraced housing, since this type of housing is the most common (42%) in the Netherlands compared to a multifamily house (36%) such as an apartment for example (Centraal Bureau voor de Statistiek, 2022). This study does not consider skylights. Also, blinds are excluded. However, the balconies of the upper apartments and other types of cantilevers are taken into account.

This research excludes studies on green building certificates such as BREEAM and LEED, as this is already extensively covered by the research of Tim Schouws (2022) and allows this research to focus more on the balance between energy demand requirements and the required daylight in buildings. Furthermore, the urban context that can have a significant impact on daylighting in buildings will be ignored, as this is also not considered in the Dutch Building Code. People interested in the integration of the urban context in daylight simulation will be referred to the thesis of Daniel Koster (2023). The impact of daylight entrance on the health of individuals within the built environment is not included in this research, as it would require a separate investigation into the well-being of humans and their biological systems.

1.8. Motivation

The quality of a building's daily use is greatly influenced by the level of performance achieved in terms of indoor climate: Thermal comfort, air quality, daylight, artificial light acoustics, etc. There is also a strong relationship between the way these building physics components are handled and the energy use of the buildings (Van der Linden et al., 2018). In addition, durability and sustainability are a substantial part of future engineering jobs and are highly relevant in today's society. Future engineers should not only think about new and beautiful buildings, but critically think about how to sustain the buildings of today with new technologies towards a more circular economy. A good balance between a pleasant experience and a durable and sustainable building is always a challenging task, especially when estimating daylight. Glazing inside a facade significantly influences these tasks and is therefore an interesting parameter to investigate. On top of that, rules and regulations on daylight entrance are about to change in the Netherlands, making daylight and energy demand a hot topic in the building physics discipline. According to Versteeg and Tilma (2023) building physics can still make considerable steps in the field of parametric design when looking at the Dutch laws and regulations on BENG and daylight requirements.

1.9. Thesis outline

The thesis content is divided into seven chapters. Chapter 1 gives an introduction to the research. This chapter explains the problem that leads to the main research question. The objective and scope of the research are discussed here as well. In Chapter 2 the background theory is explained and the most relevant research results on daylight, energy use, and thermal comfort are presented. The methodology of the research is explained in Chapter 3 and the simulation model are explained in Chapter 4. An overview of the descriptive results is discussed in Chapter 5 as well as an in-depth analysis of the gathered simulation results. The conclusions of the thesis are given in Chapter 6. Finally, recommendations are made and documented in Chapter 7.

2

Literature Study

This chapter first provides an overview of the state-of-the-art literature on daylight and energy use of buildings and dives deeper into the existing Dutch Building Regulations. First, the structure of the Dutch Building Regulation is explained in Section 2.1. After that, the theory of daylight in buildings is discussed in Section 2.2. The next section 2.3 covers the use of energy in buildings and the theory behind it. Finally, the essence of thermal comfort is given in Section 2.4.

2.1. Building regulations

Building regulations in the Netherlands emerged in the mid-19th century and have undergone major developments over the past 150 years. To this day, considerable modifications continue to arrive. When a new building is being built, it must comply with various regulations and standards. An overview of these regulations and standards directing calculations for BENG and daylight are given in Figure 2.1.

The Housing Act known as "Woningwet" was introduced in 1901 to diminish the occupancy of unsafe and unhealthy housing and promote the construction of good housing. The Housing Act of 1901 established the foundation for housing regulation. It was the first law on housing in the Netherlands. From the Housing Act, building regulations are organised, and the Building Decree "Bouwbesluit 2012" is designated. In the beginning, the building regulations were mostly determined by each municipality. The first Bouwbesluit came into force in 1992, making building regulations the same for the whole country. This decree formulates technical regulations and requirements regarding the construction of buildings, the condition of existing structures, the installation of a structure, the execution of construction work, and demolition (Obex b.v., 2017). By the 1st of January 2024, it was replaced by the "Besluit bouwwerken leefomgeving" (Bbl). The Bbl has only a limited number of changes when it comes to the content of the Building Decree 2012. The main change is a change in structure. Next to the Bbl, there is the official Regulation Building Decree called "Omgevingsregeling". The Regulation specifies not only which version of a standard must be applied, but may also contain further conditions. This includes regulations on CE marking and the connection of gas, electricity, emergency power, and water. The standards referenced in the Bbl and the accompanying Regulation provide methods for various calculations, such as the NEN 2057 for daylight calculations, discussed in Section 2.2.2 and NTA 8800 discussed in Section 2.3.2.

2.2. Daylight

Daylight is a combination of direct and indirect sunlight during the day. This includes three components, direct sunlight, diffuse skylight, and reflected light, as visualised in Figure 2.2. Direct sunlight is typically very high intensity light and is in constant movement. In the Netherlands, the illuminance delivered on the earth's surface can exceed 100.000 lux. The brightness of direct sunlight varies throughout the day and year, and location and sky conditions can also heavily influence direct sunlight. In a sunny climate, thoughtful architectural design is needed to reduce direct sunlight to prevent overheating of the housing. Skylight is characterised by sunlight scattered by the atmosphere and clouds. This leads to a soft and diffuse light source. The illuminance of an overcast sky will reach 10.000 lux in winter and around 30.000 lux on a bright overcast day in summer. Often diffuse skylight is the main source of daylight in a cloudy environment like the Netherlands, especially on the north-facing facade. Reflected light is characterised by light (sunlight and skylight) that is

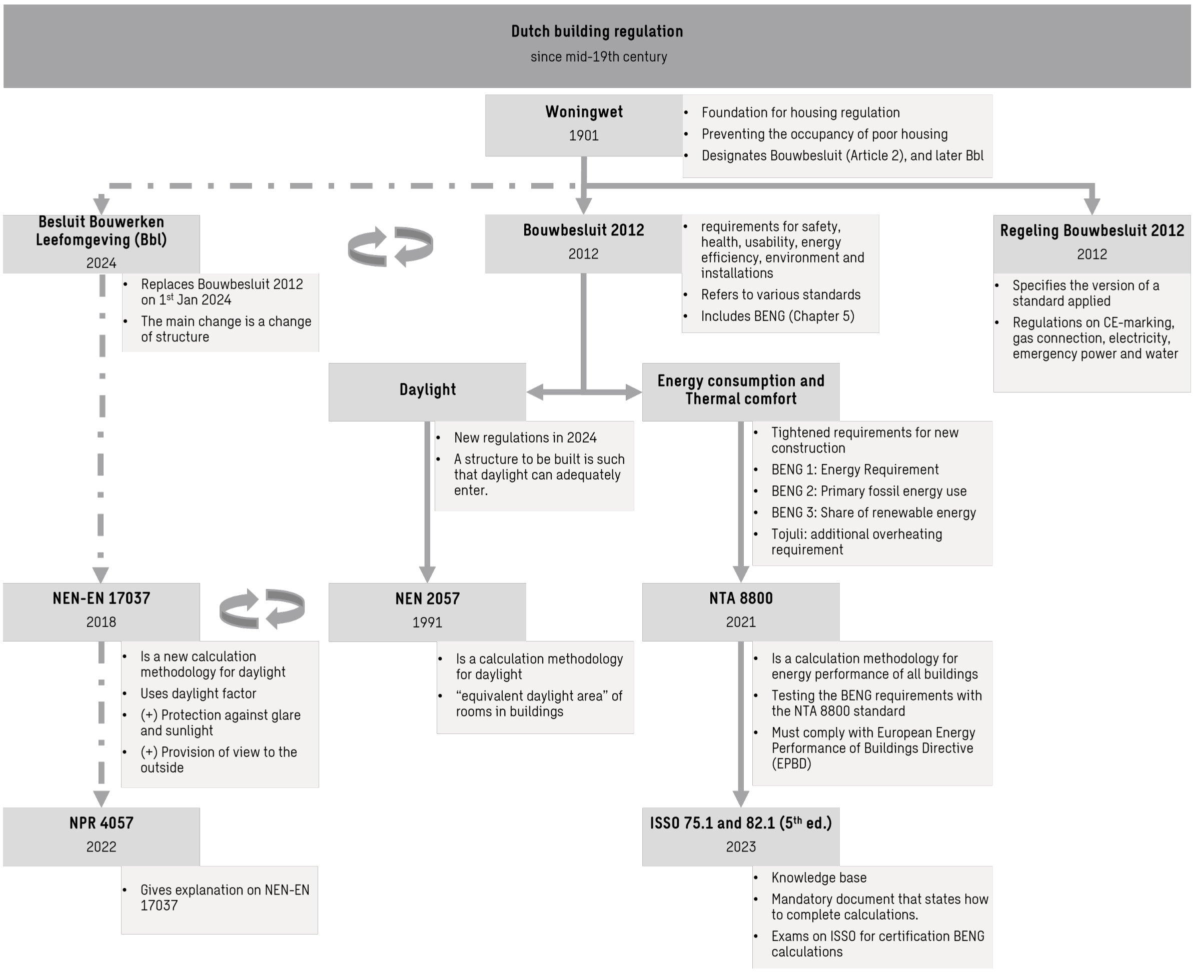


Figure 2.1: Overview of Dutch building regulation regarding the implementation of the Bbl and the new daylight calculation norm NEN-EN 17037. NTA 8800 and the current NEN 2057 are shown as well.

reflected by all sorts of object, like, for example, buildings, vegetation, and surrounding terrain. The amount of reflected light reaching a building facade is influenced by the surface reflectance of the surroundings. In densely built areas, light reflected from the surroundings can significantly contribute to indoor daylight conditions. Sunlight scattered or reflected by astronomical objects is commonly not considered to be daylight. Although moonlight is reflected sunlight, it is still excluded from the term daylight.

Daylighting describes the controlled use of natural light in and around buildings (Reinhart, 2020). In practice, windows or other transparent elements and reflective surfaces are placed so that natural light provides effective internal illumination. Successful daylighting requires considering it throughout the entire building design process, from the draft design to the interior design and lighting design in the final stage. Daylighting in buildings is strongly correlated with the energy demand and the indoor climate of a building. The size and placement of the windows should be specified based on the total energy use of the building and the characteristic requirements for daylight entrance.

2.2.1. Daylight factor

The daylight factor (DF) (Waldram, 1925) is the ratio of the light level inside a structure to the light level outside the structure at the same time. This factor will be used for the new daylight calculations in NEN-EN17037 discussed in section 2.2.3. The factor is calculated as shown in equation (2.1). Illuminance is the measure of the amount of light received on a surface. It is typically expressed in lux (lx), which is lumen per square metre (lm/m^2).

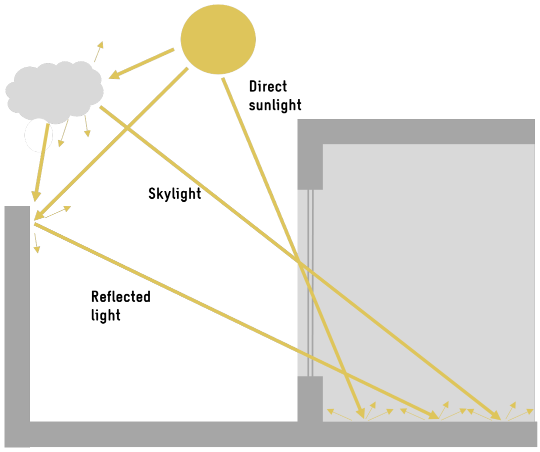


Figure 2.2: Components of daylight in building design split into direct sunlight, reflected light and skylight.

$$DF = \frac{E_i}{E_o} * 100\% \tag{2.1}$$

Where,

DF	Daylight factor	[%]
E_i	Illuminance due to daylight indoors	[lx]
E_o	Illuminance outdoors at the same time and location	[lx]

When calculating daylight for buildings, three components are considered: the Sky component (SC), the externally reflected component (ERC), and the internally reflected component (IRC) (Willems, 2022), where the mathematical description of the sky component is established in ISO 15469 (International Organization for Standardization, 2004). The reflected components are not defined in the norms. Various calculation methods are mentioned in the literature to mathematically model the reflection component. The results can differ between methods, but the largest contribution to the daylight factor is determined by the sky component. A visual explanation of the three parts of the DF can be seen in Figure 2.3.

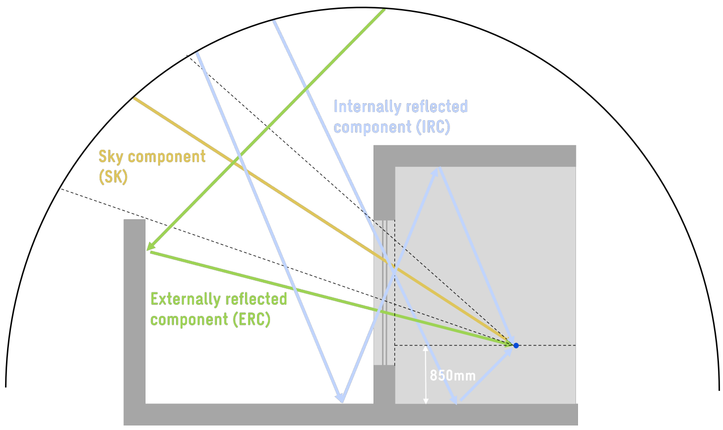


Figure 2.3: Three components of the daylight factor, the Sky component (SC), the externally reflected component (ERC) and the internally reflected component (IRC).

To achieve a daylight factor, various elements have to be taken into account, like the sizes and locations of windows, and obstructions due to surroundings or the building itself. The transparency of the glass, the blinds, and the dirt on the windows also plays a role, and the reflection of the walls, floor, and ceiling inside is also important. Keep in mind that the spatial distribution of daylight from the sky can differ per direction. However, the calculations used for the daylight factor assume a cloudy sky, since the strength of the sun varies too much. Therefore, the starting point for the sky is a general distribution illuminance level determined by the Commission Internationale de l'Éclairage (CIE) based on research by Moon and Spencer with three times the illuminance in the zenith than at the horizon (Van der Linden et al., 2018). For the Netherlands, this distribution shows a reliable approach, since most cloudy skies match these values. The uniform sky (with illuminance levels the same over the whole sky) is better just in the case of a scenario with very heavy low clouds.

2.2.2. Current daylight norm NEN 2057

In the Netherlands, a daylight calculation is mandatory under the Dutch Building Code for both new and existing building projects. As a first design rule for the new housing, the glass surface area of the facade should be at least 10% of the usable floor area of the staying area to achieve the desired amount of daylight inside. The current standard for daylight, the NEN 2057 (Nederlands Normalisatie Instituut, 2011), which states this requirement, is established in the Environmental Building Decree Section 4.3.10 (found in Appendix A). The determination method in NEN 2057 describes the current daylight standard for new buildings. These requirements have been in place for more than 30 years. At the time, it was a pragmatic choice to keep it relatively simple. But the Netherlands is the only country in Europe that still calculates with a simplified determination method for daylighting in buildings today (Verbaan, 2022).

The result of the NEN 2057 calculation is an equivalent daylight area. According to NEN 2057, the formula is written in equation (2.2) is used to calculate daylight. This method of hand calculation was introduced in 1991 to make it easier for architects to calculate daylight quickly. The obstruction factors can be calculated with the help of angles α and β according to NEN 2057. These angles depend on the obstructions that can be found in front of the window. The angle α is based on the opposite obstruction of the building and β depends on the cantilever of a balcony. Measurement of these angles is visualised in Figure 2.4.

$$A_{e,i} = A_{d,i} * C_{b,i} * C_{u,i} * C_{LTA} \tag{2.2}$$

Where,

$A_{e,i}$	Equivalent daylight surface of opening i	[m^2]
$A_{d,i}$	Surface of opening i	[m^2]
$C_{b,i}$	Obstruction factor opening i	[-]
$C_{u,i}$	External reduction factor opening i	[-]
C_{LTA}	Reduction factor for material with LTA lower 0.6	[-]

When performing the seven steps described below, the daylight calculation according to NEN 2057 is completed.

1. **Determine the daylight openings:** The first step of daylight calculation is to determine the daylight openings (translucent surfaces) per usable area. Different parts of the facades can be combined. Glass surfaces below 0.6 metres will not be taken into account, see Figure 2.4.
2. **Determine angle α:** For each daylight opening, an obstruction angle α can be determined. If α is uniformly obstructed, it can be determined with the main rule pictured in Figure 2.4. The minimum value of the obstruction angle α is 20°. If the obstruction is not uniform, α can be determined in ten sectors of 10°. A visualisation is given in Figure 2.5.
3. **Determine angle β:** For each daylight opening, an obstruction angle β can be determined. If β is uniformly restricted across the width of the window, for example, in a gallery, it can be determined with the main rule in Figure 2.4. If the obstruction is not across the hole width, the obstruction can be determined in eight sectors of 15°. This can result in a favourable outcome.
4. **Determine $C_{b,i}$, $C_{u,i}$ and C_{LTA}:** $C_{b,i}$ (obstruction factor for opening i) is determined based on α and β of each separate opening and can be found in Table 1 in NEN 2057. $C_{u,i}$ is the reduction used if there is a separating structure in front of the opening i. Otherwise, $C_{u,i}$ = 1. This is the case in the vast majority of situations. C_{LTA} is only used for materials with visible light transmission (VLT) below 0.6. Then C_{LTA} = VLT / 0.6, otherwise C_{LTA} = 1.
5. **Determine $A_{e,i}$:** $A_{e,i}$ (equivalent daylight surface of opening i) will be calculated with the formula given in equation (2.2)
6. **Test residence areas against the 10% requirement:** Determine the residence areas and measure the surface floor area. The equivalent daylight surface of a residence area must be at least 10% of the surface floor area.
7. **Test the residence rooms against the requirement of 0.5 m^2:** Each room must comply with at least 0.5 m^2 of equivalent daylight surface.

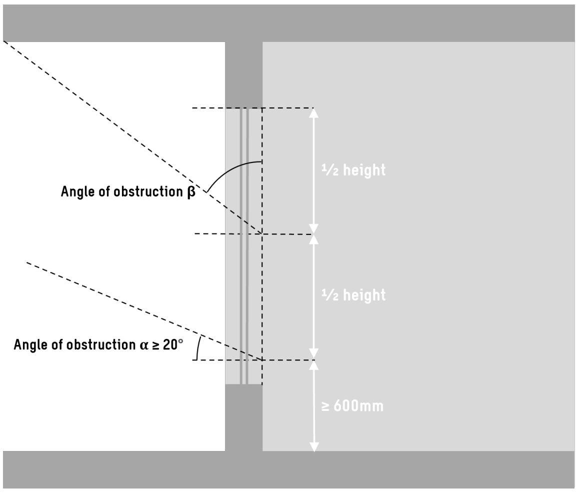


Figure 2.4: Calculation of the angles of obstruction α and β according to the NEN 2057 if the angles are uniformly obstructed.

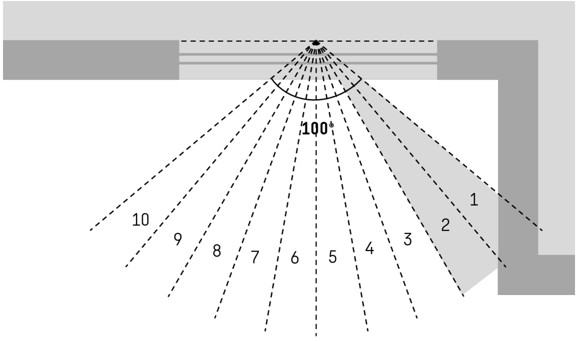


Figure 2.5: Calculation of non uniform obstruction angle α according to the NEN 2057.

2.2.3. New daylight norm NEN-EN 17037

NEN-EN 17037 (Nederlands Normalisatie Instituut, 2022a) introduces a new daylight standard for new buildings that comes into force at the beginning of 2026. The calculation results of the new standard are daylight factors expressed as a percentage, with which at least 50% of the floor area of a staying area and staying space must comply. This introduces a change in philosophy because the current method (NEN 2057) says something about the window, but nothing about the quality of daylight in the room or how light is distributed. In addition to daylight, NEN-EN 17037 also contains recommendations for the view out, sunlight exposure, and glare protection. This makes sense since visual comfort is often essential for the requirements of the building. Therefore, the implementation of these visual comfort elements into the new standard is the right step to take. However, the future requirement for daylight refers only to the method of daylight factor calculation from the norm. Only parts of a standard explicitly mentioned by the Bbl are mandatory.

NEN-EN 17037 mentions two methods to assess daylight entrance using validated software: Method 1 is a calculation method based on the daylight factor (DF) and the cumulative data on daylight availability. Method 2 is a calculation method based on the direct prediction of illuminance levels (E) using hourly climate data for the exact location and time. Both methods use the same approach. They used suitable data for the location of the project's external horizontal illuminance to determine a value of the internal illuminance. The second method is more extensive and requires more work. Especially for sun-orientated areas, more favourable calculation results can be obtained than with the calculation with daylight factors.

The daylight factor method 1 assumes a uniform internal and external illumination ratio. Using method 1, daylight factors can be calculated using a reliable technique based on the ISO 15469:2004 (International Organization for Standardization, 2004) standard overcast sky, as visualised in Figure 2.6. Daylight factors are to be predicted across a grid of points 0.85 m above the floor of the room unless otherwise specified. Small parts of the reference plane can be neglected to account for singularities. The grid size should be consistent with the size given by the formula in equation (2.3). Once the daylight factors are calculated, the norm specifies two target values that must be equal or exceeded. These are a target daylight factor (D_T) and a minimum target daylight factor (D_{TM}) across a fraction of the plane for at least half of the daylight hours. Daylight hours are defined as the 4380 hours ($365 * 24 * 50\%$) with the most diffuse horizontal illuminance in the weather file. D_T and D_{TM} are based on the recommended values for the target illuminance (E_T) and the minimum target illuminance (E_{TM}) and depend on the values given in Table A.1 of NEN-EN 17037 (see Table 2.1). In addition to the baseline requirement (minimum), rooms can achieve medium and high compliance by meeting higher illuminance targets.

$$P = 0.5 * 5^{\log_{10}(d)} \tag{2.3}$$

Where,

P	Maximum grid size, and < 10 metre	[m]
d	Longer dimension of the calculation area	[m]

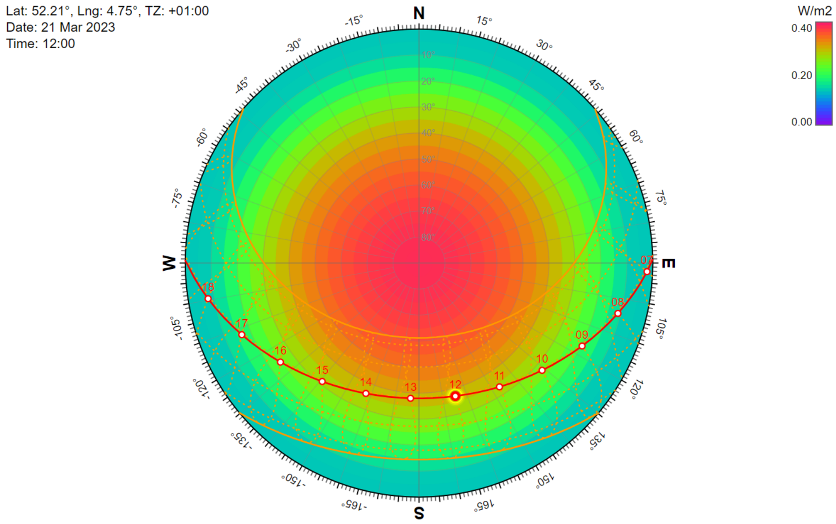


Figure 2.6: Standard overcast sky (TYPE 1) based on the ISO 15469, visualised with the help of the CIE sky generator by Marsh (2018).

Level of recommendation for vertical and inclined daylight opening	**Target illuminance** E_T lx	**Fraction of space for target level** $F_{plane,\%}$	**Minimum target illuminance** E_{TM} lx	**Fraction of space for minimum target level** $F_{plane,\%}$	**Fraction of daylight hours** $F_{time,\%}$
Minimum	300	50 %	100	95 %	50 %
Medium	500	50 %	300	95 %	50 %
High	750	50 %	500	95 %	50 %
NOTE Table A.3 gives target daylight factor (D_T) and minimum target daylight factor (D_{TM}) corresponding to target illuminance level and minimum target illuminance, respectively, for the CEN capital cities.					

Table 2.1: Table A.1 form NEN-EN 17037 which specifies the target illuminance E_T and minimum target illuminance E_{TM} for three levels of recommendation, minimum, medium and high (Nederlands Normalisatie Instituut, 2022a).

The target daylight factor D_T suggests that daylight factors should exceed this target for 50% of the area and 50% of daylight hours. For example, to exceed the criterion of 300 lux in a building in Amsterdam, a D_T of 2.1% is required, see equation (2.4).

The minimum target daylight factor D_{TM} suggests that daylight factors should exceed this target for 95% of the area and 50% of daylight hours. For example, to exceed the 100 lux criterion in a building in Amsterdam, a D_{TM} of 0.7% is required, see equation (2.5). The D_{TM} can be seen as a safeguard to prevent poorly lit spaces.

$$D_T = \frac{\text{illuminance level [lx]}}{E_{v,d,med}} = \frac{300}{14400} * 100\% = 2.1\% \tag{2.4}$$

Where,

D_T	Target daylight factor	[%]
$E_{v,d,med}$	Median diffuse horizontal skylight illuminance (Amsterdam = 14400 lx)	[lx]

$$D_{TM} = \frac{\text{illuminance level [lx]}}{E_{v,d,med}} = \frac{100}{14400} * 100\% = 0.7\% \tag{2.5}$$

Where,

D_{TM}	Minimum target daylight factor	[%]
$E_{v,d,med}$	Median diffuse horizontal skylight illuminance (Amsterdam = 14400 lx)	[lx]

Although NEN-EN 17037 states two different target values (D_T and D_{TM}), the requirements given in the Bbl, only use the target daylight factor (D_T) for 50% of the staying area (DF > 1.0%) and for a staying space (DF > 0.8 %). Thus, official daylight requirements in The Netherlands are lower than NEN-EN 17037 might suggest.

2.2.4. Comparison between NEN 2057 and NEN-EN 17037

When comparing the current standard with his successor, differences appear. The method of determination is radically different between the two standards. Also, it seems clear that NEN 2057 has limitations. For example, in a situation without overhangs, it does not matter where the window is placed; the standard only looks at the façade plane and not at daylight in the room. A wide low window has the same equivalent daylight surface A_E as a narrow high window (for the same dimensions), and a window in the corner of a room scores equally well as a window in the middle of the facade. Furthermore, the approach with obstruction angles α and β sometimes leads to double counting and unrealistic values. One of the biggest disadvantages of NEN 2057 is the fact that it does not assess the quality of daylight illuminance inside the room, which should be the ultimate goal of the standard. These flaws are obsolete with the new technique.

The engineering firm DGMR conducted a policy study in 2018-2019 to see what the differences were (Ridder, 2021). First, DGMR calculated a substantial number of standard situations that comply exactly with NEN 2057 and then looked at which target daylight factor D_T corresponds to them. The current and the new method differ so much that a 100% fit is not possible. Nevertheless, on average, the new requirement is not stricter than the current requirement. In fact, NEN-EN 17037 is less strict in situations where cantilevers cover part of the daylight opening but more rigid with regard to opposite obstructions. Table 2.2 provides a comprehensive breakdown of the similarities and differences between the standards.

<table>
<tr><th colspan="2">Similarities</th></tr>
<tr><td colspan="2">- On average, standards are equally strict according to DGMR
- Alternative method available for more complicated cases
- Calculation is done with CIE Overcast Sky (NEN 2057: comprehensive calculation method)
- Cover the topic of daylight entry in buildings
- Orientation of building and windows do not matter</td></tr>
<tr><th colspan="2">Differences</th></tr>
<tr><th>NEN 2057</th><th>NEN-EN 17037</th></tr>
<tr><td>- Equivalent daylight surface (A_E)</td><td>- (Min) target daylight factor (D_T and D_{TM})</td></tr>
<tr><td>- Calculations that can be done by hand</td><td>- Calculations done by simulation software</td></tr>
<tr><td>- Covers daylight entrance only</td><td>- Covers view out, sunlight and glare as well (although not mandatory for Bbl)</td></tr>
<tr><td>- Looks at the facade plane</td><td>- Looks at the horizontal plane of a room</td></tr>
<tr><td>- A minimum obstruction angle α of 20 degrees</td><td>- No minimum angle</td></tr>
<tr><td>- Overhangs are counted heavily</td><td>- Overhangs are counted less heavily</td></tr>
<tr><td>- Reference plane height 0.6 metre</td><td>- Reference plane height 0.85 meter</td></tr>
<tr><td>- Window location does not matter</td><td>- Window location does matter</td></tr>
<tr><td>- Method used only in the Netherlands</td><td>- Method is already in use in Europe</td></tr>
<tr><td>- Fixed value for VLT of 0.6</td><td>- Value according to window properties</td></tr>
<tr><td></td><td>- Better understanding of the light quality in the room itself
- Link with building design possible (Revit models)
- Possibility for parametric design
- Complex cases are better modelled
- Compares better with voluntary method for artificial light design</td></tr>
</table>

Table 2.2: Similarities and differences of the current and the new daylight standards, NEN 2057 and NEN-EN 17037.

2.2.5. Software modelling daylight

Various software packages like Radiance, Dialux Evo 12.0, Dialux 4.13, Velux, or Rhino plug-ins can perform daylight calculations. Most of them are using the theory of Radiance as a baseline, so, in theory, the choice of software should not make significant differences in results. In practice, however, the choice of software does make a significant difference! Willems (2022) studied the results of different software packages and showed that the results vary from case to case and can differ up to 39% compared to the calculation examples in NPR 4057 (Nederlands Normalisatie Instituut, 2022b). A couple of points are mentioned and show the sensitivity to errors in the modelling of daylight.

- Reflection values of floors, walls and ceilings must be determined.
- The calculation grid must be determined by hand since choices of grid size do have a significant influence on the result, especially in smaller rooms.
- VLT-values (or LTA-values) have to be determined. For the daylight factor, the VLT value is one of the most important parameters. The Bbl proposes a base value of at least 0.6.

Every daylight simulation program has its specific input. In some daylight simulation programs, additional details can be entered compared to other daylight simulation programs. In other software, the most basic input is poorly adjustable (VLT value of glass). This can lead to the interpretation of the input and thus to a different calculation result.

Daylight in Rhino Grasshopper

For this research, the choice is made to work with the Ladybug + Honeybee Rhino Grasshopper plug-in (Ladybug Tools, 2022). In Honeybee, the component "HB Daylight Factor" is used. Because the daylight factor is computed using an overcast sky, it does not change with orientation (N/E/S/W). Therefore, it is more suitable for assessing daylight in climates where cloudy conditions are common. The "HB Annual Daylight" recipe yields a much more accurate assessment of daylight and is suitable for all climates, though it requires a significantly longer calculation time than the daylight factor component.

2.3. Energy efficiency and Trias Energetica

The term "Trias Energetica" was introduced in 1996 by Novem (E. Lysen). As a strategy, it was elaborated by TU Delft (C. Duijvestein), emphasising the sequence of successive steps. In its simplest form, the Trias Energetica (Rijksdienst voor Ondernemend Nederland, 2013) for an energy-neutral building is based on the three steps given in Figure 2.7 and the following list:

- Step 1. Reduce energy demand
- Step 2. Use energy from renewable (sustainable) sources
- Step 3. Use finite (fossil) energy resources efficiently

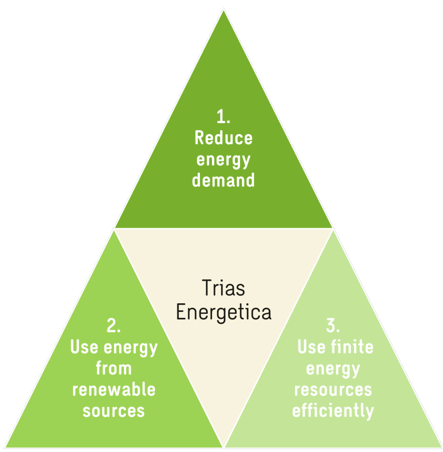


Figure 2.7: Visualisation of the Trias Energetica strategy stating the three steps needed for energy-efficient building.

The steps are graded according to their effectiveness in sustainability. Step 1 is the most effective because it diminishes the required energy, and step 3 is the least since it uses finite energy resources. Therefore, the steps are also taken in this order. Step 1 focusses on (urban) building measures, which are passive measurements such as increasing insulation and air-tightening the building envelope or building with the heat from the sun in mind. If these measures are taken, step 2 is implemented to supply the building with the necessary energy. Ideally, all the needed energy is generated from renewable sources, such as solar, wind, or water-generated electricity. Finally, if the renewable energy sources are not sufficient, the energy demand can be satisfied with fossil energy resources in step 3. The focus of step 3 lies on the economical and efficient use of this fossil energy. This strategy clearly shows where the priority lies in building cost-effective and sustainable buildings: Reducing energy demand is predominantly considered better than using more green energy.

"De Nieuwe Stappenstrategie" by Dobbelsteen (2008) states that Trias Energetica has not (yet) reached the desired sustainability improvements and that an additional step will be added to further improve the strategy. This step includes the use of waste energy before using energy from renewable sources. The waste energy could be waste heat from industry or energy from heat recovery. Additionally, if building energy neutral is the goal, step 3 must be completely avoided. The combined strategy of Trias Energetica and De Nieuwe Stappenstrategie is applied by Rijksdienst voor Ondernemend Nederland (2013) and looks as presented below.

- Step 1. Reduce energy demand
- Step 2a. Use energy from waste streams
- Step 2b. Use energy from renewable (sustainable) sources
- Step 3. Use finite (fossil) energy resources only if unavoidable. Use highly efficient and compensate on a yearly basis

2.3.1. BENG - Bijna Energieneutrale Gebouwen

Since the 1st of January 2021, new energy performance requirements have been applied for new buildings; the "Bijna-energieneutrale-gebouwen" (BENG) requirements (Rijksdienst voor Ondernemend Nederland, 2017). After exactly twenty-five years, the "energieprestatiecoëfficiënt" (EPC) has therefore been replaced. Article 4.149 of the Besluit bouwwerken leefomgeving (attached in Appendix A) states these requirements for BENG. To calculate the BENG conditions, a new determination method has been developed. This is described in "Nederlands Technische Afspraak" NTA 8800, which is covered in section 2.3.2. The BENG requirements are based on Trias Energetica and are formulated into three parts. The final goal of these three new requirements is to reduce CO_2 emissions in new buildings by:

- BENG 1: Reducing energy demand
- BENG 2: Reducing fossil energy use
- BENG 3: Use of Renewable Energy

BENG1 sets requirements for the maximum amount of energy needed to account for the heating and cooling of a building. This energy requirement is expressed in "thermal" kilowatt hours per square metre (kWh/m^2) of usable area A_g per year(= Gebruiksoppervlak, GO). Therefore, BENG1 is concerned with reducing the overall energy consumption of the building. Factors that can influence the BENG1 value include the quality of the building envelope (facade, roof, and floor insulation), air tightness, glazing, solar penetration, and shading. Additionally, elements like the building's compactness and orientation (e.g. north-south) can positively affect energy requirements. BENG1 does not distinguish properly between ventilation types, even if heat recovery systems are installed in the building. It always calculates with natural air supply and mechanical air exhaust. Hence, BENG1 cannot be taken as a straightforward indicator for step 1 of Trias Energetica.

BENG 2 specifies the maximum amount of primary fossil fuel required to heat, cool, and ventilate a building and prepare hot water. This value is also expressed in kWh/m^2 of usable area per year. BENG 2 is supplemented for utility buildings by the energy used for lighting and (de)humidification. If a building generates its own energy - for example, with photovoltaic (PV) panels - the primary fossil energy consumption can be reduced by the amount of generated energy. Elements that influence the BENG 2 value are the energy demand of the building, the efficiency of the building services for indoor climate, domestic hot water, the type of ventilation system (with/without heat exchanger), heat loss through hot water pipes, and the use of renewable energy. Other domestic energy uses, such as computers, televisions, or ovens, are not taken into account.

BENG 3 relates to the minimum share of renewable energy as a percentage of total energy use (i.e., the sum of the primary fossil energy consumption share plus the renewable energy share). By dividing the amount of renewable energy by the total amount of energy consumed, the value of BENG 3 is determined. This is subject to the condition that the energy is generated using a facility in, on, or attached to the building. Therefore, participation in a central solar park or participation in a wind farm does not count for BENG3. Installations that do affect the BENG 3 value are, for example, heat pumps, PV panels, or solar boilers.

2.3.2. Energy performance determination method NTA 8800

The NTA 8800 (Nederlands Normalisatie Instituut, 2023) is a new determination method that allows calculating whether a building meets the new BENG requirements. With the NTA 8800 methodology, the distinction between the calculation method for existing buildings and new buildings is removed. The new energy label of a building is also based on NTA 8800. Since more than 30 Dutch parties contributed to the creation of the NTA 8800, a wide support base has been created. When determining the energy requirement, the calculation method takes into account, among other things, the degree of insulation, the efficiency of the installations and the use of renewable energy. The calculation method makes use of the climate data given in NEN 5060 (Nederlands Normalisatie Instituut, 2021). The primary output for BENG1 is the annual energy demand indicator $\text{Ewe}_{\text{H+C,nd,ventsys=C1}}$, which represents the fundamental energy performance of the building. Therefore, the focus will only be on a subset of the NTA 8800 norm, including mainly parts of Chapters 5, 6, 7, and 8. This indicator, delivered in [kWh/m^2], can be calculated with the formula in equation (2.6). Figure 2.8 demonstrates the components that make up the indicator, consisting of heat loss through transmission, heat loss through ventilation, internal heat gain, and solar heat gain.

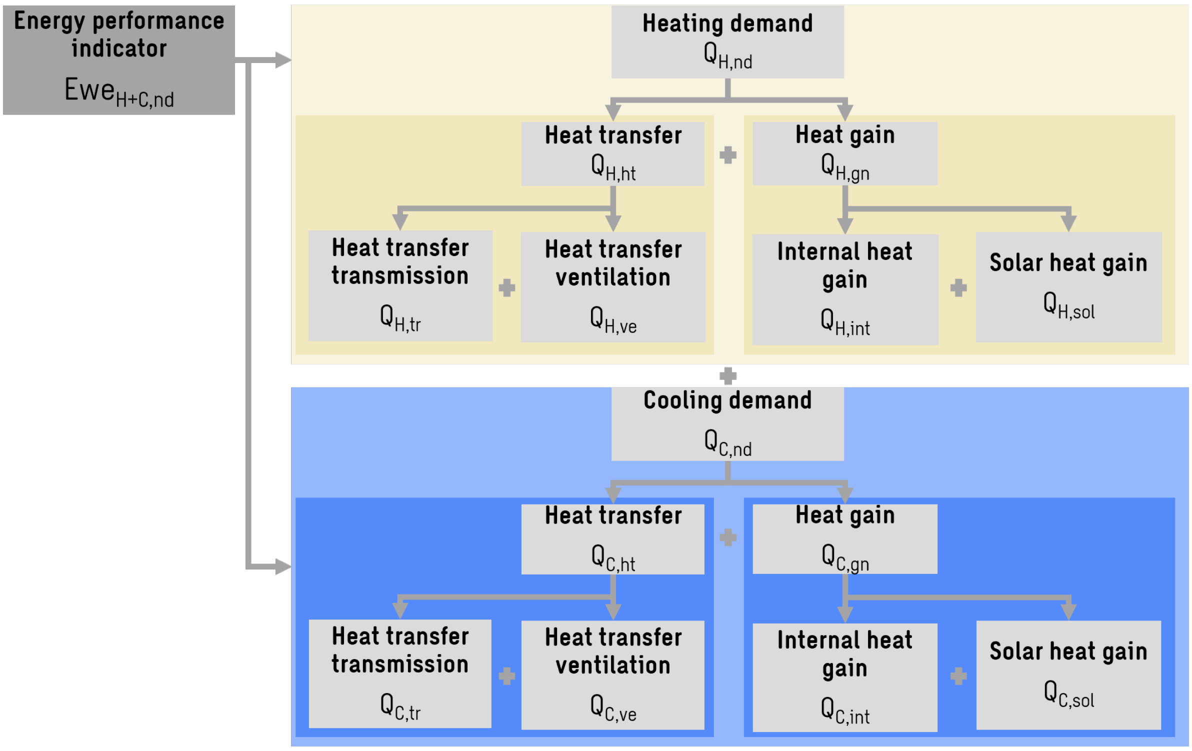


Figure 2.8: Visual presentation of the components that make up the energy performance indicator $Ewe_{H+C,nd}$.

$$Ewe_{H+C,nd,\text{ventsys=C1}} = \frac{Q_{H+C,nd}}{A_{g;tot}} \tag{2.6}$$

Where,

$Ewe_{H+C,nd,\text{ventsys=C1}}$	Weighted energy performance / energy demand indicator (for sys C1)	[kWh/m^2]
$Q_{H+C,nd}$	Annual energy demand	[kWh]
$A_{g;tot}$	Usable area of the total calculation area	[m^2]

The ventilation system C1, which is fixed for BENG1 and represents the natural supply and mechanical discharge, is supplied with the values specified by NTA 8800. It also presents values for internal heat load, lighting, and tap water. For simplicity and readability, the subscript "$_{\text{ventsys=C1}}$" is left out from here onwards. The energy demand $Q_{H+C,nd}$ consists of a heating demand and a cooling demand ($_{H+C}$) which are added together in the equation (2.7).

$$Q_{H+C,nd} = Q_{H,nd} + Q_{C,nd} \tag{2.7}$$

Where,

$Q_{H,nd}$	Annual heating demand	[kWh]
$Q_{C,nd}$	Annual cooling demand	[kWh]

The total annual heating demand is the sum of the heating demands per calculation zone ($_{zi}$) for each month ($_{mi}$), described in equation (2.8). The same logic can be used to formulate the expression for the annual cooling demand; therefore, the subscript for heating ($_{H}$) can be replaced by the subscript for cooling ($_{C}$).

$$Q_{H,nd} = \sum_{mi}\sum_{zi} Q_{H,nd,mi,zi} \tag{2.8}$$

Where,

$Q_{H,nd,zi,mi}$	Heating demand per calculation zone zi for each month mi	[kWh]

The heating demand per calculation zone ($_{zi}$) and month ($_{mi}$) can be calculated with equation (2.9). To simplify the calculation rule of NTA 8800 (p. 151, equation 7.3), the recoverable losses are neglected in this equation.

$$Q_{H,nd,zi,mi} = Q_{H,ht,zi,mi} - \eta_{H,gn,zi,mi} * Q_{H,gn,zi,mi} \tag{2.9}$$

For every calculation zone zi in month mi where,

$Q_{H,ht,zi,mi}$	Total heat transfer	[kWh]
$Q_{H,gn,zi,mi}$	Total heat gain	[kWh]
$\eta_{H,gn,zi,mi}$	Utilisation factor for heat gain, simplification $\eta = 1$	[-]

The cooling demand per calculation zone ($_{zi}$) and month ($_{mi}$) can be calculated with equation (2.10). Here, recoverable losses are neglected as well, simplifying the calculation rule.

$$Q_{C,nd,zi,mi} = \alpha_{C,red,zi,mi}(Q_{C,gn,zi,mi} - \eta_{C,ht,zi,mi} * Q_{C,ht,zi,mi}) \tag{2.10}$$

For every calculation zone zi in month mi where,

$\alpha_{C,red,zi,mi}$	Reduction factor for non-continuous cooling	[-]
$\eta_{C,ht,zi,mi}$	Utilisation factor for heat transfer , simplification $\eta = 1$	[-]

For each calculation zone and month, the total heat transfer for heating $Q_{H,ht,zi,mi}$ and cooling (replace subscript $_{H}$ with $_{C}$), can be calculated using the following equation (2.11).

$$Q_{H,ht,zi,mi} = Q_{H,tr,zi,mi} + Q_{H,ve,zi,mi} \tag{2.11}$$

For every calculation zone zi in month mi where,

$Q_{H,tr,zi,mi}$	Total heat loss through transmission	[kWh]
$Q_{H,ve,zi,mi}$	Total heat loss through ventilation	[kWh]

The total heat gain $Q_{H,gn,zi,mi}$ consists of two parts, the internal heat gain from people and appliances and the heat gain from solar radiation. These can be summarised as sown in equation (2.12).

$$Q_{H,gn,zi,mi} = Q_{H,int,zi,mi} + Q_{H,sol,zi,mi} \tag{2.12}$$

For every calculation zone zi in month mi where,

$Q_{H,int,zi,mi}$	Total internal heat gain	[kWh]
$Q_{H,sol,zi,mi}$	Total solar heat gain	[kWh]

Heat loss through transmission

The total heat transfer through transmission for heating $Q_{H,tr,zi,mi}$ is described by equation (2.13) and (2.14) below. Transmission losses depend on the gradient between the calculation temperature inside $\theta_{int,calc,H,zi,mi}$ and the average temperature on the outside $\theta_{e,avg,mi}$. The same equations can be used for cooling transmission transfers by replacing the subscript for heating ($_H$) with the subscript for cooling ($_C$).

$$\begin{aligned} Q_{H,tr,zi,mi} = \big(H_{H,tr(excl.gf,m),zi,mi} &* (\theta_{int,calc,H,zi,mi} - \theta_{e,avg,mi}) \\ + H_{gr,an,zi,mi} &* (\theta_{int,calc,H,zi,mi} - \theta_{e,avg,an})\big) * 0.001\, t_{mi} \end{aligned} \tag{2.13}$$

Where,

$$H_{H,tr(excl.gf,m),zi,mi} = H_{H,D,zi,mi} + H_{H,U,zi,mi} + H_{H,A,zi,mi} + H_{H,p,zi} \tag{2.14}$$

And for every calculation zone zi in month mi where,

$H_{H,tr(excl.gf,m),zi,mi}$	Total heat loss coefficient through transmission excl. the ground floor	[W/K]
$H_{gr,an,zi,mi}$	Heat transfer coefficient for elements regarding the ground floor	[W/K]
$H_{H,D,zi,mi}$	Heat transfer coefficient between the room and the outside air	[W/K]
$H_{H,U,zi,mi}$	Heat transfer coefficient through adjacent unheated spaces	[W/K]
$H_{H,A,zi,mi}$	Heat transfer coefficient through adjacent heated spaces	[W/K]
$H_{H,p,zi}$	Heat transfer coefficient through vertical pipes	[W/K]
$\theta_{int,calc,H,zi,mi}$	Calculation temperature of the calculation zone	[$°C$]
$\theta_{e,avg,mi}$	Average outdoor temperature in month mi	[$°C$]
$\theta_{e,avg,an}$	Average outdoor temperature for the entire year	[$°C$]
t_{mi}	Length of month mi	[h]

Heat loss through ventilation

Equation (2.15) describes heat loss through ventilation $Q_{H,ve,zi,mi}$. The same as transmission, it depends on the gradient between the calculation temperature inside and outside. Equation (2.15) can be used for heating as well as cooling situations.

$$Q_{H,ve,zi,mi} = H_{H,ve,zi,mi} * (\theta_{int,calc,H,zi} - \theta_{e,avg,mi}) * 0.001 * t_{mi} \tag{2.15}$$

For every calculation zone zi in month mi where,

$H_{H,ve,zi,mi}$	Total heat transfer coefficient for ventilation	[W/K]

Ventilation losses according to NTA 8800 are based on an airflow model. The temperature difference, along with the ventilation rate, is used to determine the amount of heat that will be lost or gained when new air is introduced into the building. In addition to intentional ventilation, the standard also considers various unintentional air leakages through the building envelope, which can also lead to significant heat loss.

Internal heat gain

Based on multiple sources, NTA 8800 states that the value of the average heat production per person is $180W$. Internal heat gain $Q_{H,int,dir,zi,mi}$ in equation (2.16) includes both the production of internal heat by people and equipment. Equation (2.16) can be used for both heating and cooling situations.

$$Q_{H,int,zi,mi} = 180 * N_{woon,zi} * N_{P,woon,zi} * 0.001 * t_{mi} \tag{2.16}$$

For every calculation zone zi in month mi where,

$Q_{H,int,zi,mi}$	Internal heat gain	[kWh]
$N_{woon,zi}$	Number of staying functions	[-]
$N_{P,woon,zi}$	Average number of occupants per staying function	[-]

Heat gain from solar radiation

The heat gain from solar radiation $Q_{H,sol,zi,mi}$ is made up of two parts. The first part is the heat gain through transparent parts such as windows ($_{wi}$). The second part is the solar heat gain through all the opaque ($_{op}$) surfaces. The heat gain from solar radiation is described in Chapter 7.6.3 of the NTA 8800 with the formula presented in equations (2.17) to (2.19). In case of cooling, the subscripts $_H$ can be replaced with the subscript $_C$.

$$Q_{H,sol,zi,mi} = \sum_k Q_{H,sol,wi,k,mi} + \sum_k Q_{H,sol,op,k,mi} \tag{2.17}$$

For every month mi where,

$Q_{H,sol,zi,mi}$	Solar heat gain	[kWh]
$Q_{H,sol,wi,k,mi}$	Solar heat gain through transparent element/ window wi,k	[kWh]
$Q_{H,sol,op,k,mi}$	Solar heat gain through opaque element op,k	[kWh]

$$\begin{aligned} Q_{H,sol,wi,k,mi} = \big(g_{gl,wi,k,H,mi} * A_{wi,k} * (1 - F_{fr,wi,k}) * F_{sh,obst,wi,k,mi} * I_{sol,wi,k,mi}\big) \\ *0,001\, t_{mi} - Q_{sky,wi,k,mi} \end{aligned} \tag{2.18}$$

For every calculation zone zi and every window wi,k in month mi where,

$g_{gl,wi,k,H,mi}$	Average effective total solar factor	[-]
$A_{wi,k}$	Area of the window wi,k	[m^2]
$F_{fr,wi,k}$	Frame fraction of window wi,k	[-]
$F_{sh,obst,wi,k,mi}$	Shading reduction factor for external obstacles	[-]
$I_{sol,wi,k,mi}$	Monthly average total solar radiation	[W/m^2]
$Q_{sky,wi,k,mi}$	Monthly additional heat flow due to heat radiation to the sky	[kWh]

$$\begin{aligned} Q_{H,sol,op,k,mi} = \big(\alpha_{sol} * R_{se} * U_{c,op,k} * A_{c,op,k} * F_{sh,obst,op,k,mi} * I_{sol,op,k,mi}\big) \\ *0,001\, t_{mi} - Q_{sky,op,k,mi} \end{aligned} \tag{2.19}$$

Where,

α_{sol}	Absorption coefficient for solar radiation	[-]
R_{se}	Heat transfer resistance on the exterior	[m^{2}K/W]
$U_{c,op,k}$	Heat transfer coefficient of opaque element op,k	[W/(m^{2}K)]
$A_{c,op,k}$	Projected area of opaque element op,k	[m^2]

2.3.3. Sensitivity study on NTA 8800

The literature shows few studies on local regulations such as NTA 8800, but some information can still be found. Technical University of Eindhoven conducted a sensitivity study of the NTA 8800 input parameters on the BENG1 score. That study aimed to determine the prioritisation of the most influential and least influential parameters for determining the total heating and cooling energy demand (Kafaei, 2021). Table 2.3 presents the results of the study of TU Eindhoven. The most influential parameters are geometric properties, such as the loss area A_ls divided by the usable area A_g (compactness) and the window-to-wall ratio. The compactness is based on the general shape of the building and is of interest when looking at general form-finding questions such as the thesis of Dorresteijn (2020). The window-to-wall ratio is of interest when looking at the layout of the facade of given reference buildings. Additionally, elements that normally contribute a lot to energy loss, such as windows and infiltration, are parameters that appear as important parameters in this sensitivity study.

Priority level	Sensitivity measure	Parameters	Change pattern	Source of information	Acceptable uncertainty
1	Greater than 0.05	Als/Ag	Linear	Geometrical properties	As exact as possible
		Window to Wall Ratio			
		Window U		Glazing	
		Infiltration Rate		Construction year	
2	Between 0.01 and 0.05	Facades Rc	non-linear	Thermal properties	Uncertainty should be minimized as values approach to the lower limits
		Roof Rc			
		Floor Rc			
		Specific Internal Heat Capacity	Almost linear	Construction mass	
3	Less than 0.001	Window Obstruction	no distinct pattern	Sun radiation	Better to be known if the information is available
		Window G			
		Orientation			
		Sunblind Type			
		Frame Fraction			
		Sunblind Colour			
		Sunblind Control			

Table 2.3: Input parameters' categorization based on sensitivity measures range Kafaei (2021).

2.3.4. Software modelling energy demand

To link the energy demand of a building to a parametric design in a suitable way, the Rhino Grasshopper plug-in Archsim Energy Modelling could be used. It is a plug-in that brings EnergyPlus simulations to Grasshopper and therefore links the EnergyPlus simulation engine with parametric design and a modelling environment (Timur, 2014). Another option to evaluate buildings for energy efficiency, daylight access, electrical lighting performance, and visual and thermal comfort is the plug-in ClimateStudio (Solemma, 2023).

In practice, calculations on energy performance are done with Uniec3 or Vabi Software. These programmes are based on the NTA 8800 calculation method and comply with the Dutch Building Code. Uniec3 and Vabi are also used to calculate energy labels for all types of buildings. However, these validated software packages are not suitable for parametric design, since they are designed to assess one specific building at a time. Changing the design and reassessing it can be challenging and time consuming. Still, Uniec3 is used for the validation of the results.

NTA 8800 is primarily intended to test buildings against requirements of the Dutch law. Therefore, the method should be transparent, verifiable, and enforceable. The determination method thus includes fixed values for building use and uses climate data according to NEN 5060 (Nederlands Normalisatie Instituut, 2021). These values are as closely related to practice as possible and are realistic and representative of average Dutch conditions. The consequence of this choice is that a connection with the actual energy use in a building at a precise location cannot be made directly. Given the primary purpose of NTA 8800 and the limitation of the number of parameters, no total accuracy is reached. Many small differences can be found, for example, the amount of sun hours in Vlissingen compared with De Bilt. Influence factors that have an effect on the final result of <2% are not included in NTA 8800 (Projectgroep NTA 8800, 2020).

Therefore, for this study on building regulation, the Archsim Energy model is not suitable. For this research, a Rhino Grasshopper framework is used using the calculation rules of the NTA 8800 to assess the buildings on the BENG1 requirements on energy demand. This has already been done in previous studies, such as the master's thesis by Mengying (2023) or the study by Sewtahal (2023) at DGMR.

2.4. Thermal comfort

Since the three BENG requirements focus on conserving energy within the building, the thread of overheating arises. Therefore, in NTA 8800, "Temperatuuroverschrijding juli" (TO_{juli}) is established as an additional requirement for new buildings that provides information on the risk of temperature overshoot for residential buildings without an installed active cooling system. The measurement is dimensionless and is determined using the calculated cooling requirement for the month of July in the BENG calculation according to the NTA 8800. The TO_{juli} is calculated using the subsequent equation (2.20). Formally, Kelvin (K) is the unit of TO_{juli}. However, it has no meaning in practice and is therefore omitted. The higher the value, the greater the risk of overshooting the temperature. TO_{juli} is calculated for the month of July, for each orientation of the facade plane ($_{or}$) and for each calculation zone ($_{zi}$). For orientation ($_{or}$) the following orientations are distinguished: N, NE, E, SE, S, SW, W, NW. Nevertheless, there is no guarantee to prevent temperature overshoot since it depends on the user's behaviour and is only meant as an indicator. However, a TO_{juli} below 1.0 indicates that there will be minimal risk of overheating. The limit value for TO_{juli} is stated as 1.2 according to Article 4.149b of the Bbl. The text on the requirements of TO_{juli} can be found in Appendix A.

$$TO_{juli;or;zi} = \frac{(Q_{C;nd;juli;or;zi} - Q_{C;HP;juli;or;zi}) * 1000}{(H_{C;D;juli;or;zi} + H_{gr;an;juli;or;zi} + H_{C;ve;juli;or;zi}) * t_{mi}} \tag{2.20}$$

For every calculation zone zi and orientation or where,

TO_{juli}	Temperature overshoot juli	[K]
$Q_{C,nd}$	Annual cooling demand	[kWh]
$Q_{C,HP}$	Energy extracted from cold distribution system by the booster heat pump	[kWh]
$H_{C,D}$	Direct heat transfer coefficient for transmission to outside	[W/K]
$H_{gr,an}$	Heat transfer coefficient for elements in the ground floor	[W/K]
$H_{C,ve}$	Heat transfer coefficient for ventilation	[W/K]
t_{mi}	Length of month i (juli = 744 h)	[h]

The formula presented in (2.20) can be simplified by leaving out the energy extracted from the booster heat pump. This device can reduce the amount of heating but is mainly used to produce hot tap water. Also, a booster heat pump is not habitual in every house and is therefore neglected in the calculations. If the heat transfer coefficients are combined into one variable, the formula will be presented as seen in equation (2.21) below.

$$TO_{juli} = \frac{Q_{C,nd} * 1000}{H_C * 744} \tag{2.21}$$

Where,

$Q_{C,nd}$	Annual cooling demand	[kWh]
H_C	Heat transfer coefficient transmission and ventilation	[W/K]

3

Methodology

In the following chapter, the methodology of the study is discussed. Section 3.1 covers the theoretical setup used to create the model. The next Section 3.2 discusses the possible variables and parameters that the model could use and how they are expected to influence daylight and energy demand. The way to verify the correctness of the result is analysed is described in Section 3.3. In Section 3.4 the desired results and deliverables of the model are debated.

3.1. Theoretical setup

For research on visual comfort and building energy demand based on specific building properties, a computational model of multiple reference buildings is made in the 3D graphic software Rhinoceros (Robert McNeel & Associates, 2023) and its Visual Programming (VP) language Grasshopper (Scott Davidson, 2023). The housing will be based on the reference buildings published by Rijksdienst voor Ondernemend Nederland (2022). For Building Typologies in the Netherlands, the RVO is a reliable source, as it has been frequently used in the literature.

Rhino Grasshopper features multiple plug-ins like Ladybug + Honeybee (Ladybug Tools, 2022), Archsim Energy (Timur, 2014) or ClimateStudio(Solemma, 2023) that can be used to add daylight and energy simulation. For the daylight analysis based on daylight factors, these plug-ins do offer suitable support. However, to model energy use according to the calculation method NTA 8800, which is used for BENG indicators, the framework of Mengying (2023) can be used as a benchmark. Additionally, parametric analysis plug-ins like Colibri can be used to test many different scenarios and optimise building properties for energy demand and daylight entrance simultaneously. Figure 3.1 gives a theoretical format based on the study of Touloupaki and Theodosiou (2017) of how the model should be set up.

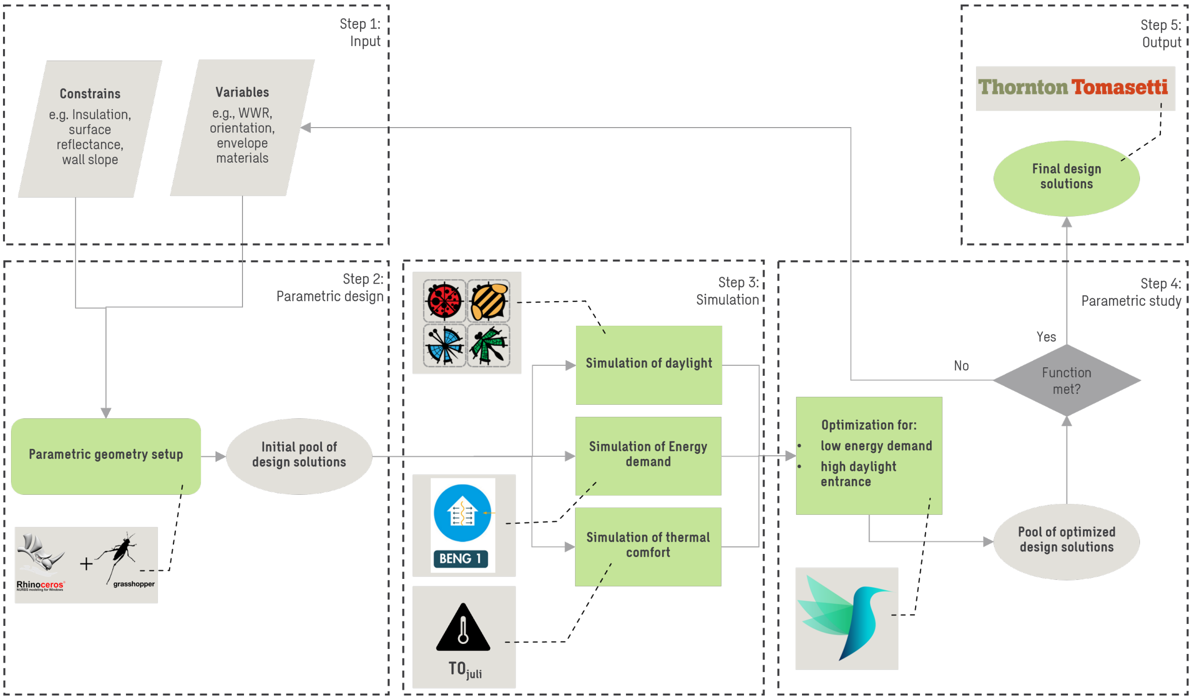


Figure 3.1: Flowchart explaining the theoretical setup of the parametric model (PM) with applied parametric study using Colibri in visual programming Rhino Grasshopper. Based on the theory of Touloupaki and Theodosiou (2017).

Modelling in Rhino Grasshopper is divided into five main components; the first step is to determine the variables and fixed parameters for the model. This component allows for multiple parameters to make it a parametric design. Step two is the parametric design of the geometry of the building. Then, the daylight simulation is completed. These calculations are done according to the new NEN-EN 17037. The energy simulation is performed according to the NTA 8800. This calculation method is genuinely extensive and is usually only performed in Uniec3 (Bouwtrend B.V., 2023) or Vabi (Vabi, 2023) but does not allow for quick geometry changes and is thus not reasonable for parametric optimisation purposes. With the framework of Mengying (2023), the calculation can be done on-the-fly. The fourth component will be the optimisation of daylight entrance and energy consumption in compliance with TO_{juli}. Lastly, the results are analysed with the help of the Thread tool of Thornton Tomasetti (2024), which can visualise the outcome of all parametric solutions of a building.

- Geometric modelling
  - Setup of all geometric parameters
  - Allow for variables to optimise
- Daylight simulation
  - According to NEN-EN 17037
  - Use Ladybug tools (daylight factor component)
- Energy simulation
  - According to NTA 8800
  - Adding in the formulas step by step
  - Make adjustments so that geometry can be adjusted within Rhino Grasshopper
- Parameter study
  - Boundary conditions and realistic shifts in parameters
  - Minimize energy demand
  - Maximize daylight entrance
  - Check TO_{juli}
- Output
  - Analyse and visualise data with Thread

3.2. Parameters

Table 3.1 displays used simulation parameters. Some of them will be fixed to narrow down the scope and simplify the modelling. In accordance with Kafaei (2021), WWR will most certainly have a great influence on energy performance, so the window measurement values are of interest. These values should not be fixed to optimise energy performance while taking into account daylight requirements. To identify trends in the results, at least ten steps in window height and window width will be needed. Combining these steps will result in a variety of possible window-to-wall ratios. The maximum width of the window is depending on the width of the facade, which is different for every room. The window placement could also play a significant role for daylight entrance, since a high placed window will possibly be better than a lower-placed one. The orientation of the building affects the way direct radiation hits the building envelopes and how it is absorbed, which influenced the BENG1 result. Although the sensitivity study shows small sensitivities in orientation, it is taken into consideration. This is done because it is a basic geometry parameter that can be taken into account without changing the geometry of the reference building itself. In addition, other studies show that orientation matters and show variations in energy consumption per orientation (Ochoa et al., 2012) (Bokel, 2007). The orientation does not have any influence on the daylight entrance, as NEN-EN 17037 uses an overcast sky as a basis. Eight steps in orientation are taken as a basis and are divided in the known cardinal directions. The presence or absence of cooling is regarded as an input parameter. Although it does not affect BENG1 or daylight entrance, it enables the exclusion of TO_{juli} when implemented.

Parameter	**Symbol**	**Unit**	**Fixed**	**Steps**	**Range**	**Influence**	
						BENG1	**Daylight**
Window-to-wall ratio	WWR	[%]	No	-	0 - 100%	+++	+++
Window height	h	[m]	No	>10	0.5 - 2.4m	++	+++
Window width	w	[m]	No	>10	0.5 - x m	++	++
Window placement z-axis	z	[-]	No	5 - 10	0 - 1	0	++
Window placement x-axis	x	[-]	No	5 - 10	0 - 1	0	+
Cooling / No cooling	C_{nd}	[-]	No	2	Yes / No	0	0
Cantilever obstacle	d_{cant}	[m]	No	2	Yes / No	++	+++
Wall slope	α	[°]	Yes	-	-	0	+
Interior surface reflectance	R_s	[%]	Yes	-	-	0	+
Light transmittance	VLT	[-]	Yes	-	-	0	++
Solar transmittance	g	[-]	Yes	-	-	++	0
Orientation	or	[°]	No	8	N, NE, E...	++	0
Room depth	d_{room}	[m]	Yes	-	-	0	++

Table 3.1: Variables and constraints for the parametric grasshopper model and its validation measurements.

3.3. Validation

To validate the correctness of the parametric model, the outcome of the PM should be checked with verified software. This should be done for daylight as well as for the energy demand calculations.

To verify the daylight results of the parametric model, the known and verified daylight software DiaLux Evo 12.0 is used. By modelling terraced housing with the same properties in this software, the results between the two models can be compared. This means that the geometric properties of the rooms should be the same, the windows' sizes need to match, the light transmittance of the glass, and the reflection values of all surfaces must be consistent. On top of that, the reference plane should be the same. The models are compared based on the average daylight factor per room. This will be the leading parameter to verify the calculations, since Dialux Evo does not yet have the possibility to calculate the target daylight factors D_T and D_{TM} according to the standard. All results should be within a reasonable range from each other.

Since the simulation of energy demand will be carried out according to the BENG regulations, it is not feasible to validate the model based on measurements in practice. This is because BENG is a simplification of the actual energy demand of a building designed to indicate the sustainability of a structure based on various factors. The correctness of the model with respect to energy demand can be achieved by performing a BENG calculation of a (simple) building in Uniec3 and comparing these results with the model. The values that are compared are a combination of parameters on energy gains and losses, such as BENG1, total heating demand QH_{nd} and total cooling demand QC_{nd}. Their underling parameters such as transmission and ventilation losses, as well as internal and solar heat gains are also considered. TO_{juli} is also selected as a parameter to compare the models. All the different parameters are further specified and discussed in section 4.4.2. The results should be within a range of 5% to 10% of each other.

3.4. Expected results

The following results will be examined. For daylight factors, the average DF per room is an important value, as well as a check if the daylight factor meets the targets set in the Bbl. In the case of energy demand, the leading result will be the energy demand indicator $Ewe_{H+C,nd}$ (BENG1), this value is made up of different values shown in Figure 2.8. The heating and cooling demand are of interest and can be seen as useful results. Bbl requirement for BENG1 is 55 kWh/m^2. Energy demand and daylight factors can be presented in one graph showing the minimum requirements according to the Bbl. Therefore, a zone can be determined where all possible solutions comply with the building decree and in which optimal solutions can be found. Additionally, the DF is calculated on the level of the room, while energy consumption is usually calculated on the level of the building. For meaningful results, one has to decide how to compare daylight with energy demand. Based on other studies (Zheng et al., 2023) (Alhagla et al., 2019), the expectation is that WWR has a significant influence on the outcome of energy efficiency and daylight within the building. Also the effect of the balcony cantilever of 2.1 metres is expected to be significant on daylight entrance and also on energy demand.

4 Simulation

Chapter 4 discusses the execution of the research. Section 4.1 states the setup of the model, and Section 4.2 discusses the assumptions made. Section 4.3 presents the verification of daylight simulation in the parametric model. This is done on the basis of other software. The next Section 4.4 verifies the energy demand calculations based on verified software. The last Section 4.5 presents the different setting used for the model and what the exact parameter choices were for all model runs.

4.1. Setup of the model

For the setup of the model, a handful of things are of interest. First, the geometric measurements of the housing. Along with geometry, the material properties of the building elements such as R_C and U values are important. Then, properties of the glass are of interest in determining the solar heat gains and the daylight entrance. Finally, the reflectance properties of the inside surfaces are essential, since they determine for a considerable part how the light is scattered inside the room.

4.1.1. Reference buildings

Two different housing types are investigated, which are of interest for daylight entrance and energy calculations. These housing types are based on reference buildings of the Rijksdienst voor Ondernemend Nederland (2022). The selection for this research includes one middle apartment in an apartment building and a middle terraced housing. The middle apartment will only have one wall facing the outside. It is chosen because it will be most vulnerable to insufficient daylight entry. The gallery flat can also be quite vulnerable to insufficient daylight entrance, but since gallery flats are built far less frequently nowadays, this type of building is disregarded in this research. It is also attractive to look at terraced houses, as this type of housing is the most common (42%) in the Netherlands compared to a multifamily house (36%) like an apartment for example (Centraal Bureau voor de Statistiek, 2022). More specifically, this research focusses on the middle house, since the windows are only found on two opposite sides of the building. Many other reference housings exist but are less critical for daylight analysis, since villas, (semi-)detached houses, and corner houses usually receive sufficient daylight.

For daylight analysis, the information given by the Rijksdienst voor Ondernemend Nederland (2022) is not sufficient, as no typical floor plan of the buildings is shown. Therefore, an older reference is used to use a specific orientation of the rooms and windows. Floor plans and side views of the apartment and the terraced house can be seen in Figures 4.1 and 4.2 respectively.

The starting points in terms of reference buildings for this model are listed in Table 4.1. Tables 4.2 and 4.3 provide additional information on the drawings with exact measurements of the specific rooms inside the buildings.

Parameter		**Flatwoning Tussen - midden Middle apartment**	**Rijwoning (doorzon) Tussenwoning Terraced-middle house**
Usable area	[m^2]	92.27	124.32
# Building layers	[-]	1	3
Form factor	[m^2/m^2]	0.44	1.33
Floor			
Surface	[m^2]	-	50.93
R_C	[m^2K/W]	-	3.70
Facade			
Surface	[m^2]	variable	variable
R_C	[m^2K/W]	4.50	4.70
Tilted/ flat roof			
Surface	[m^2]	-	70.18
R_C	[m^2K/W]	-	6.30
Windows			
Surface	[m^2]	variable	variable
U-value	[W/m^2K]	1.6	1.6
Doors			
Surface	[m^2]	-	2.42
U-value	[W/m^2K]	-	2.0
Standard for housing insulation (based on existing buildings 2015-2018)			
Standard value	[kWh/m^2]	45.00	61.99
Heating demand $Q_{H,nd}$	[kWh/m^2]	51.04	68.83

Table 4.1: Information of two types of houses partly based on the reference buildings of the Rijksdienst voor Ondernemend Nederland (2022) and the floor plans of CenterNovem (2006).

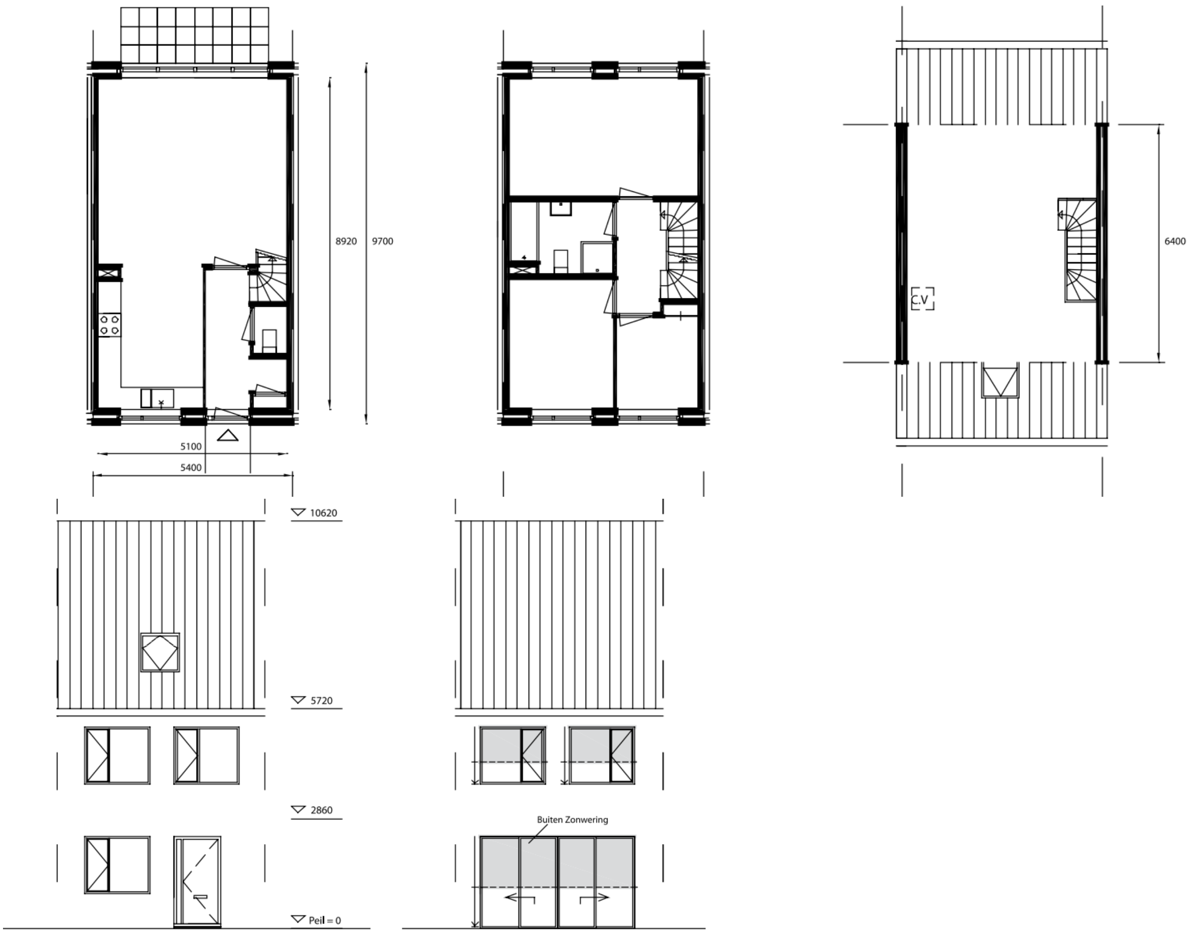


Figure 4.2: Floor plan and side view of a typical terraced middle house (doorzon) in the Netherlands with three floors (CenterNovem, 2006)

Figure 4.1: Floor plan and side view of the front facade of a typical apartment in the Netherlands (CenterNovem, 2006), the red boxes show the middle apartment with windows on one of the four sides.

Floor	**Room**	**Width [m]**	**Depth [m]**	**Height [m]**	**A_{floor} [m^2]**
Second floor	Living room	5.73	7.22	2.60	39.58
	Room L	3.40	5.05	2.60	17.16
	Room M	2.63	3.71	2.60	9.75

Table 4.2: Room measurement on the inside of the apartment building rooms for daylight analysis.

Floor	**Room**	**Width [m]**	**Depth [m]**	**Height [m]**	**A_{floor} [m^2]**
Ground floor	living room	5.10	8.92	2.60	36.83
First floor	Room L	5.10	3.15	2.60	16.07
	Room M	2.80	3.45	2.60	9.66
	Room S	2.20	2.45	2.60	5.39

Table 4.3: Room measurement on the inside of the terraced middle house rooms for daylight analysis.

The minimum cleared height of a room is 2.6 metres for newly constructed houses (which are not in private ownership), so this is fixed for all rooms. The width and depth of the rooms vary based on the specific floor plan of the building. Especially the depth of a room can be key for daylight in buildings, so a variation in room depths is desirable for this study to compare them.

4.1.2. Recommended values of reflectance

The recommended values of the reflectances according to NEN-EN 17037 for the main interior surfaces would be in the following ranges stated in table 4.4 bleow. Deviations from these ranges are, of course, permitted, but justification should be given. NEN-EN 17037 provides default values for these internal surfaces, which are also used in the parametric model and in Dialux Evo 12.0 which was used for validation.

Surface	Range refl. [-]	Default refl. [-]
Ceiling	0.7 - 0.9	–> 0.7
Interior walls	0.5 - 0.8	–> 0.5
Floor	0.2 - 0.4	–> 0.2

Table 4.4: Range and default recommended values for surface reflections according to NEN-EN 17037. The PM uses the default values.

4.2. Simulation assumptions

When modelling energy use based on NTA 8800, certain simplifications are made. Essentially, only energy demand (BENG1) is taken into account, which means that the architectural aspects of the building are analysed. In other words, the performance of the building is evaluated based on the BENG1 criterion (energy demand), while installations are not taken into account.

Furthermore, in the BENG1 calculations, some simplifications have been made. Ventilation losses are simplified and are based on fixed infiltration values. It is calculated by multiplying the volumetric flow of air per square metre by the usable area. The volumetric flow can then be used to determine the heat transfer coefficient by multiplying by the specific heat capacity and the density. Using one volumetric flow means that ventilation losses are constant between all parametric solutions. Because this simplification is carried out for all design choices, the solutions can still be effectively compared with one another. Only linear thermal bridges are taken into account, where as point thermal bridges are left out of the equation. Linear thermal bridges are expected to have a greater influence on the results than point thermal bridges. Energy savings methods for heat recovery are assumed not to be present in the building.

In addition, some simplifications are made when determining the calculation temperature $\theta_{int,calc}$ that is used to determine transmission and ventilation losses. Calculating these losses requires a temperature difference, which is based on the monthly average outdoor temperature and the calculation temperature $\theta_{int,calc}$, see equation 4.1. The calculation temperature according NTA 8800 takes into account temperature equalisation between spaces with different assumed uses and non-continuous heating and cooling (night reduction and weekend interruption, see equation 4.2). In the parametric model, it is assumed that all rooms are heated equally, so temperature equalisation between spaces will not play a role. On the contrary, the reduction factors for the night are taken into account in a simplified way. The term that takes into account the thermal mass with the help of a time constant is left out due to its complexity. The simplified formula is seen in equation 4.3. In addition, the value of $f_{H,red,low,day}$ will be based on Uniec3, since this term is again dependent on the thermal mass and various other factors. Trying to guess or omit this factor is not acceptable as it significantly affects the overall energy demand of the building. By adjusting $f_{H,red,low,day}$ to match $\theta_{int,calc}$ of the PM with the Uniec3 results, using the Root Mean Square Error (RMSE), a compromise is made. It is expected that the overall energy demand is expected to remain quite accurate, but the effect on TO_{juli} is less favourable.

$$\theta_{int,calc,H,mi} = a_{H,red,mi} * (\theta_{int,set,H} - \theta_{avg,mi}) + \theta_{avg,mi} \tag{4.1}$$

Where,

$\theta_{int,calc,H,mi}$	Calculation temperature for heating in month mi	[$°C$]
$\theta_{int,set,H}$	Setpoint temperature for heating (20$°C$)	[$°C$]
$a_{H,red,mi}$	Reduction factor for non-continuous heating	[-]
$\theta_{avg,mi}$	Average outdoor temperature in month mi	[$°C$]

$$a_{H,red,mi} = 1 - (1 - (1 - f_{red,day} + f_{red,day} * d\theta_{H,red,mn,day})) - (1 - a_{H,red,wknd,mi}) \tag{4.2}$$

Where,

$f_{red,day}$	Relative part of the day with reduced setpoint for heating (= 5/12 for housing)	[-]
$a_{H,red,wknd,mi}$	Reduction factor non-continuous heating in weekend (= 0 for housing)	[-]
$d\theta_{H,red,mn,day}$	Average (relative) reduction in the temperature difference during the period with a reduced setpoint temperature	[-]

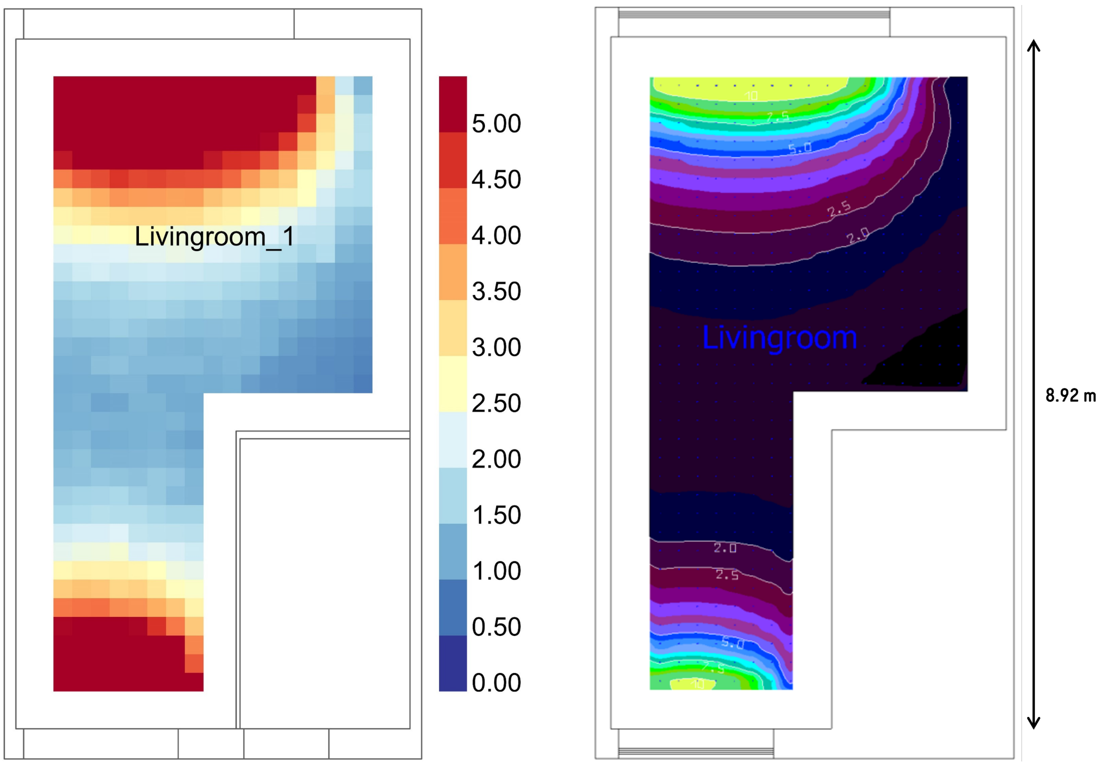
$$d\theta_{H,red,mn,day} = f_{H,red,low,day} * d\theta_{float} + (1 - f_{H,red,low,day}) * d\theta_{set,low} \tag{4.3}$$

Where,

$f_{H,red,low,day}$	(Relative) length of the period until the reduced setpoint temperature has been reached	[-]
$d\theta_{float}$	(Relative) reduction in the difference between indoor and outdoor temperature at 'free-floating' conditions (no heating)	[-]
$d\theta_{set,low}$	(Relative) reduction of the setpoint temperature related to the difference with the outdoor temperature	[-]

4.3. Verification of daylight simulation

For the verification of the daylight results produced by the parametric model, the established and validated software DiaLux Evo 12.0 is utilised. The process involves simulating terraced housing with identical characteristics in this software to enable a comparison of results between the two models. Ensuring uniformity in geometric room properties, matching window sizes, maintaining consistent light transmittance of the glass, and uniform reflection values of all surfaces is crucial. In addition, it is important to keep the reference plane constant. This means that the height of 0.85m should be met and a distance of 0.5m to each wall should be used. Also, the size of the grid should be the same. In this comparison, a 0.24m x 0.24m grid is used, since this is the minimum grid size needed according to NEN 17037 for the smallest room. The outcomes should exhibit similar daylight factor values and display a consistent grid pattern. Figures 4.3a and 4.4a present the obtained daylight factor results of the parametric model for room L and the living room. Figures 4.3b and 4.4b display the Dialux results in Isolux lines, which are based on the same calculation grid as the parametric model.

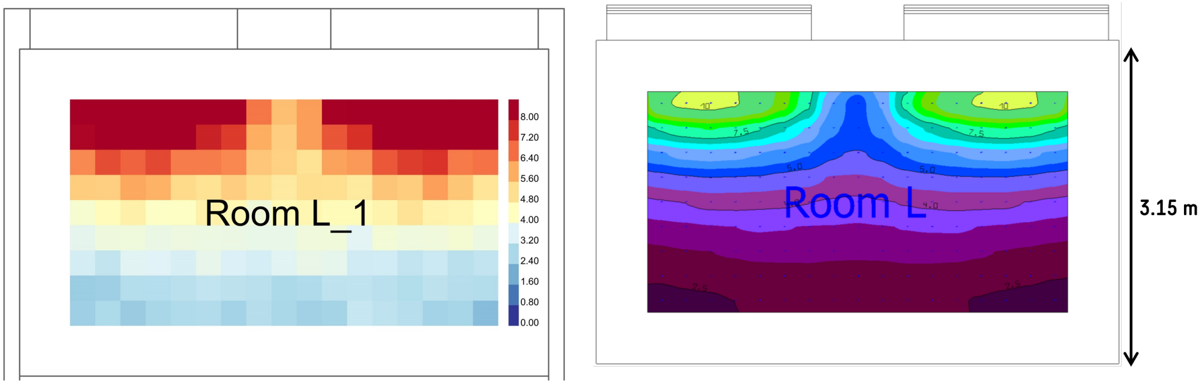


(a) Parametric model results of the daylight factor calculation of the LR.

(b) Dialux Evo results of the daylight factor calculation of the LR.

Figure 4.3: Comparison of daylight factors in living room between parametric model and Dialux Evo.

The two models will be compared in terms of the values of the daylight factor of four different rooms; the living room of the terraced house and three rooms on the first floor of the house, which are different in size. Dialux Evo presents the values of the DF in three values: Minimum daylight factor, maximum daylight factor,



(a) Parametric model results of the daylight factor calculation of the room L. (b) Dialux Evo results of the daylight factor calculation of room L.

Figure 4.4: Comparison of daylight factors in living room between parametric model and Dialux Evo.

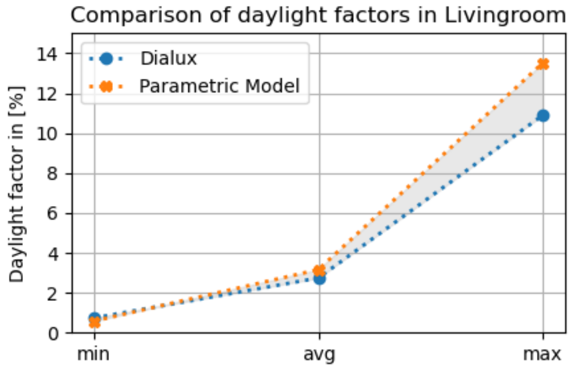
and average daylight factor. In the following Figures 4.5a and 4.5b, all these values are compared, but the minimum and maximum values are less important. First, because the regulations aim to provide sufficient daylight, in general. The main requirement is to evaluate the quality of daylight in a room for 50% of the space, so the most extreme values are always ignored. Second, due to the nature of the numeric calculation method in the Rhino Grasshopper component "HB daylight factor". To ensure the consistency of the "HB Daylight Factor" component, the same daylight calculation is run for a small sample of seven runs. When the command is repeated multiple times, the results differ slightly, as can be seen in Figure 4.6. The average and standard deviations between these runs are also visualised in the bar graph. As can be seen, the extremes have a higher spread (standard deviations between 0.063 and 0.163), while the average DF has a small standard deviation (0.005, 0.018, 0.017, 0.013 for each room respectively). Additionally, extremes are more susceptible to changes in grid size.

In general, the results of both models are of the same order of magnitude and are comparable for all rooms tested. Generally, the parametric model in Rhino Grasshopper recovers higher daylight values than the Dialux Evo model, as can be seen in the figures and also in Table 4.5, which show the results of the living room an room L. The average DF appears to be around 15-20% higher in the PM. For the maxima, the differences are slightly greater, around 24-25%. The minima are for all rooms relatively close to the Dialux Evo results, except for the living room. The results can be seen in Table 4.5. Figures for the comparison of daylight factors of room M and room S can be found in the Appendix C, Section C.1. The results are in line with the findings for room L.

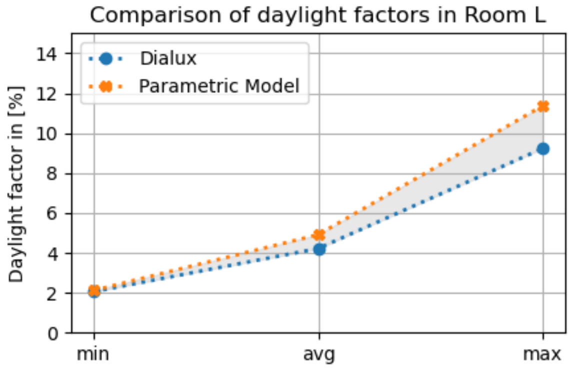
Comparison daylight factor in [%]				
	Parametric model	**Dialux Evo 12.0**	**% diff**	**abs diff**
Living room (Figure 4.5a)				
min	0.581	0.741	22 %	0.160
avg	3.162	2.740	15 %	0.422
max	13.513	10.893	24 %	2.620
Room L (Figure 4.5b)				
min	2.116	2.056	3 %	0.060
avg	4.912	4.217	16 %	0.695
max	11.365	9.231	23 %	2.134

Table 4.5: Numerical values of daylight factors in [%] for validation of the parametric model. The minimum, average and maximum values of the daylight factor are presented for the living room and room L.

As already mentioned in Section 2.2.5 the relatively large differences between daylight modelling software are known. Willems (2022), investigated the differences between software packages based on the calculation rules of daylight in the new regulation. The findings show significant differences of up to 39% compared to the calculation examples in NPR4057 (Nederlands Normalisatie Instituut, 2022b). Willems also mentioned that Dialux Evo applies a pollution factor of at least 0.9, which cannot be easily changed to 1.0. This could also



(a) Minimum, average, and maximum daylight factors in living room.



(b) Minimum, average, and maximum daylight factors in Room L.

Figure 4.5: Comparison of daylight factors in different rooms.

explain a large share of the discrepancies between Rhino and Dialux, assuming that the simple Grasshopper component does not take advanced parameters like this into account. However, this cannot be checked to guarantee the reason for the relative differences. By changing the LTA value of the Dialux model to correct for the pollution factor (LTA = 0.7/0.9), the average daylight factors for each room will differ around 4% - 8%.

With these considerations in mind, the daylight factor results of the Rhino Grasshopper model can be validated and accepted. Especially since the use of the model intends to be useful in the early stages of the design process, where quick changes can be made in the form-study of a building. users will mostly be interested in a first estimation of the daylight factor rather than an exact value. Therefore, an exact and accurate value for the daylight factor is not yet needed. On top of that, a less accurate but faster calculation method is preferred, since the parametric design process intends to have many different iterations to explore the design space. Therefore, a time-consuming but more accurate calculation method will be less useful.

4.4. Verification of energy demand calculation

Since the simulation of energy consumption will be carried out according to the BENG regulations, it is not feasible to validate the model based on measurements in practice. This is because BENG is a simplification of the actual energy consumption of a building that is meant to indicate the sustainability of a structure based on various factors. The correctness of the model with respect to energy consumption could be achieved by performing a BENG calculation of a (simple) building in Uniec3 and comparing these results with the model. The results should be within a reasonable range of each other.

4.4.1. Uniec3

By modelling the same terraced housing with the same characteristics in this software, the results between Rhino Grasshopper and Uniec3 can be compared. Figure 4.7 shows the different categories that Uniec 3 uses to gather all the necessary information. This implies that the geometric features of the house should be identical, as should the dimensions of the windows. For the BENG calculation, the precise location of the windows is not essential, only the orientation is of importance. The U and g values of the glass and the Rc values of the construction components should be consistent. Additionally, the BENG calculation takes into account the linear thermal bridges around the connections of the building elements, so they should also be the same. The air tightness of the building is set to unknown, so NTA 8800 describes a conservative default value of 0.7 dm^3/sm^2 for infiltration based on the type of building and the year of renovation. In Uniec3, it is essential to select at least three types of installation to execute the calculation. These include a heating system, a hot water supply, and a ventilation system. They mainly influence the consumption of primary fossil fuels and renewable energy, which are presented in BENG2 and BENG3. Neither of the first two installations has any effect on the BENG1 indicator, which is the focus of this research, so the input can be chosen freely. For both systems, a gas boiler is selected. The ventilation system for the BENG1 indicator is already prescribed, so a standard C1 ventilation system with natural supply and mechanical exhaust is applied.

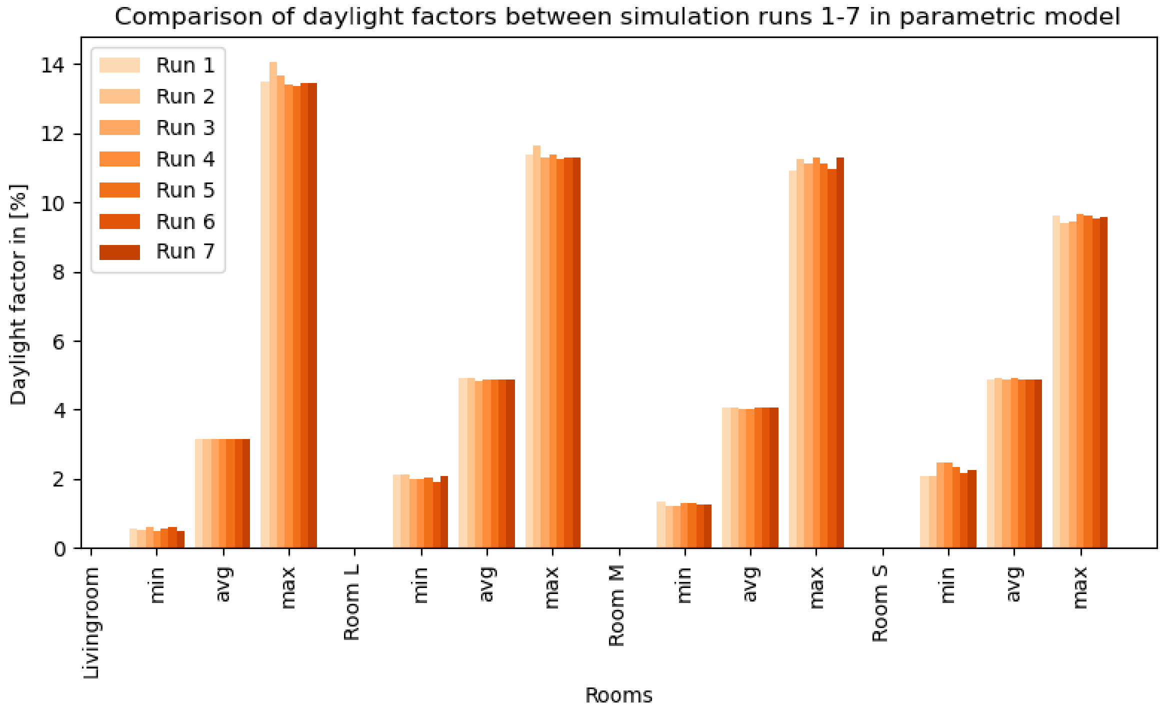


Figure 4.6: Comparison of daylight factors between repeated simulation runs in parametric model to check consistency of the HB daylight factor component.

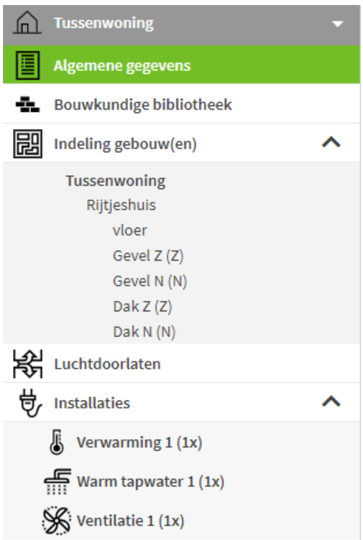


Figure 4.7: Menu tab of Uniec3 showing the basic (Dutch named) categories for the information input.

4.4.2. Results

To compare the results of Uniec3 and the Grasshopper model, the primary parameters selected are as follows. First, the BENG1 indicator Ewe is chosen, which represents the ultimate result to categorise the energy demand of a building. The BENG1 indicator is based on the total heating demand QH_{nd} and the total cooling demand QC_{nd} divided by the total usable area A_g (which is defined exactly the same in both models). The energy demand is determined by four factors that can be calculated monthly. These factors are transmission and ventilation losses, as well as internal and solar heat gains. Last, TO_{juli} is also selected as a parameter to compare the models. These values can be found in Table 4.6. Monthly values of heating an cooling demand are compared in Figures 4.8 and 4.9.

Comparison Energy demand parameters				
Parameter	**Symbol**	**Unit**	**Parametric model**	**Uniec3**
BENG1	Ewe	$[kWh/m^2]$	57.48	60.33
Heating demand	QH_{nd}	$[kWh]$	7144.25	7238.68
Cooling demand	QC_{nd}	$[kWh]$	2.17	260.60
TOjuli	TO_{juli}	[-]	0.17	0.62

Table 4.6: Numerical values verification parameters for validation of the parametric model.

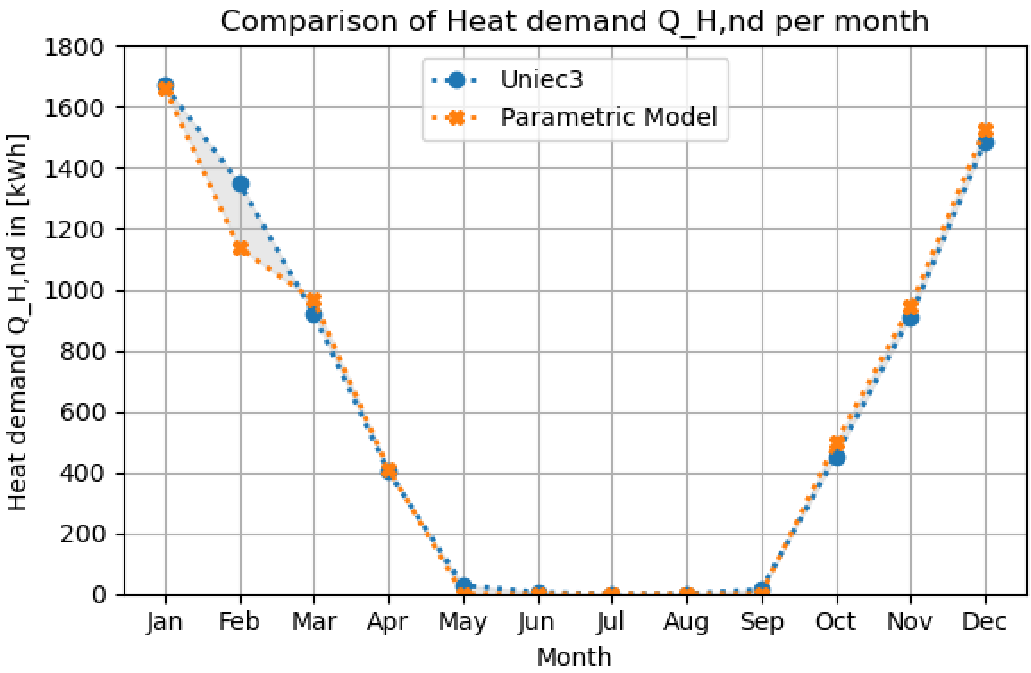


Figure 4.8: Comparison between the monthly heat demand $Q_{H,nd}$ of Uniec3 and the parametric model.

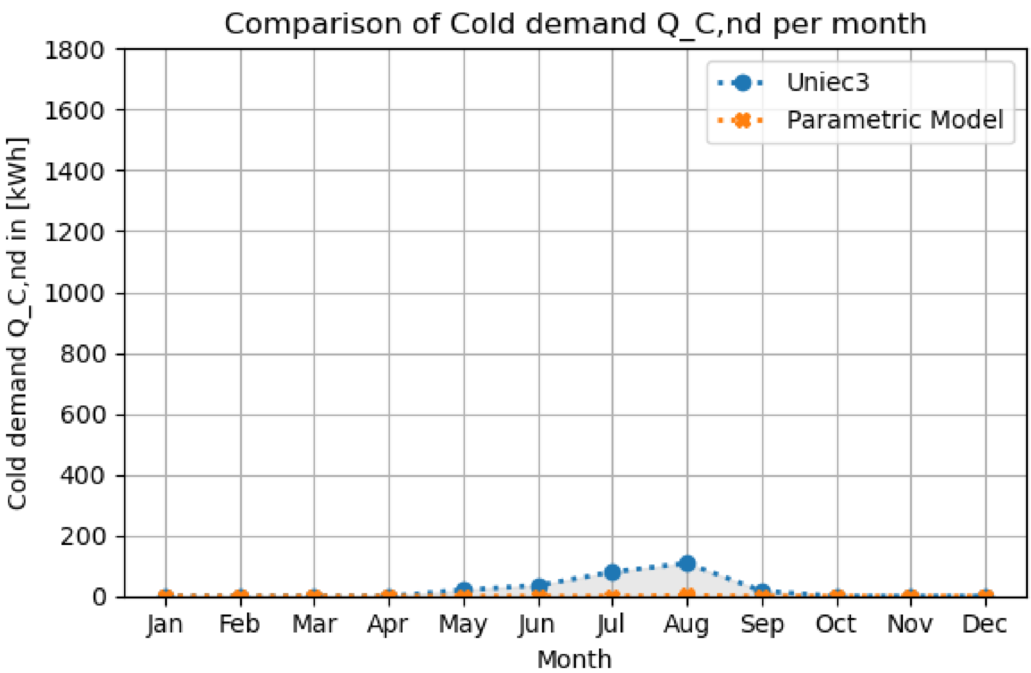


Figure 4.9: Comparison between the monthly cold demand $Q_{C,nd}$ of Uniec3 and the parametric model.

In general, the values obtained from the Parametric Grasshopper model are close to the results of the Uniec3 calculation. Despite the simplifications in the calculations, the BENG1 indicator differs only 5% between the models. The total heating demand QH_{nd} for the building also matches the expected results well (1% difference). The total cooling demand QC_{nd} is underestimated by the grasshopper model. At first glance, the relative difference between the models seems quite large, but in practice, both values are quite low when comparing in absolute values to the heating demand. This chosen building, which is used to verify the model, requires little cooling. This becomes clearer when one looks at the monthly energy demand shown in Figures 4.8 and 4.9. Setting the y-axis of the demand on the same scale puts the cooling demand in a bit more context. Looking at the monthly heating demand in Figure 4.8, one directly sees the difference in demand for the month of February. This difference is not directly understandable until one looks further into the calculations. Where internal heat gain and solar heat gain compare well between the models (see Figures C.2, C.3, C.4 and C.5 in Appendix C), ventilation and transmission losses are not as easily validated.

Transmission and ventilation losses vary each month and are influenced by the temperature difference between inside and outside a building. Figure 4.10 illustrates the comparison of the calculation temperature between the parametric model and Uniec3. The PM's calculation temperature is adjusted to match Uniec3 results using the Root Mean Square Error (RMSE), as described in section 4.2. The smallest RMSE occurred when using a reduction factor $f_{H,red,low,day}$ of 0.4. Corrections in the case of non-continuous cooling are applied to the cooling demand and not to the calculation temperature. The calculation temperature of the calculation zone for cooling, $\theta_{int,calc,C}$, in °C, remains equal to the setpoint temperature. This straightforward validation can be found in Figure C.8 in Appendix C.

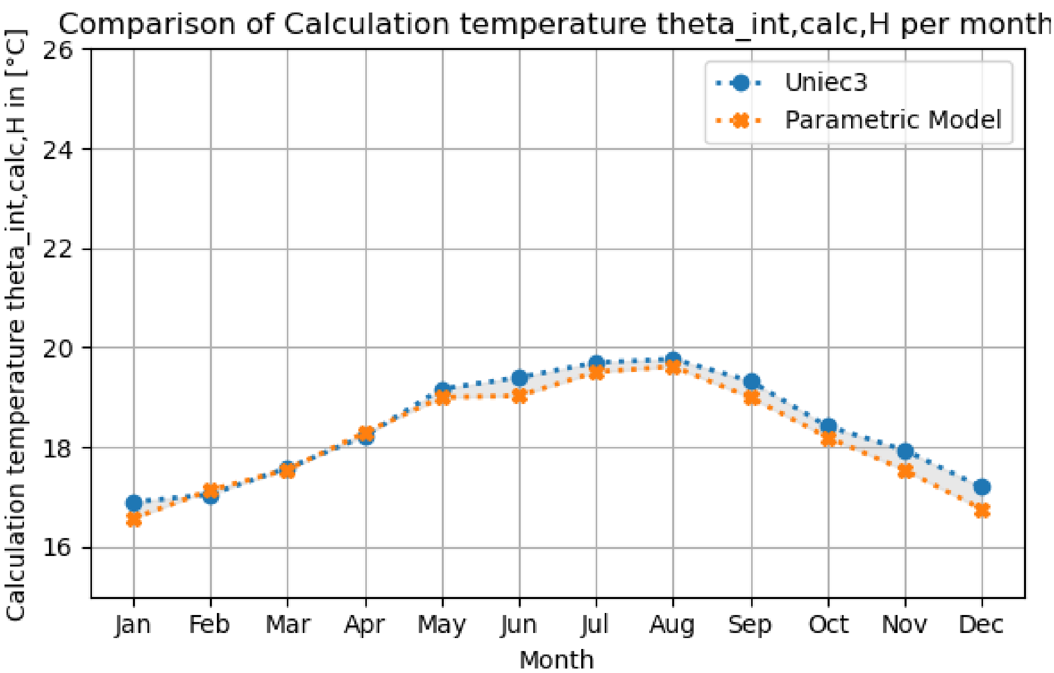


Figure 4.10: Comparison of the monthly calculation temperature $\theta_int,calc,H$ of terraced housing for heating of Uniec3 and the parametric model.

With the determination of the right calculation temperature $\theta_{int,calc}$ the results of transmission losses are well matched. When comparing two Figures 4.11 and 4.12 the same trends around the year can be seen. Note that transmission losses are logically higher in the case of cooling. This is because cooling involves using an internal calculation temperature of 24 °C, whereas the calculation temperature for heating, as well as the monthly average outdoor air temperature, never exceed 20 °C.

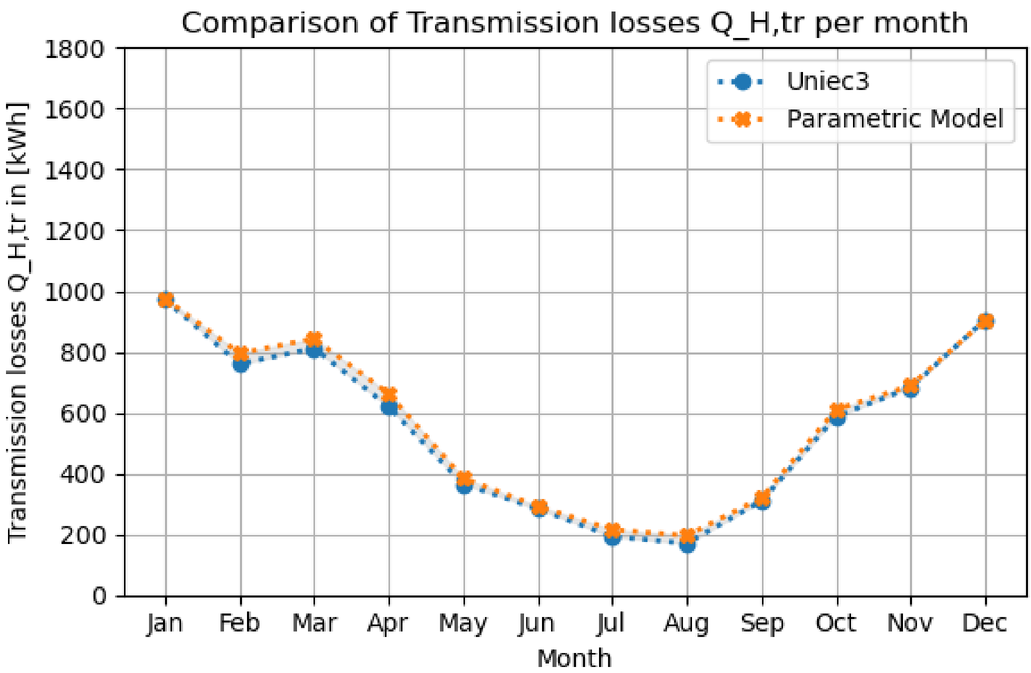


Figure 4.11: Comparison of transmission losses $Q_{H,tr}$ per month of terraced housing in case of heating.

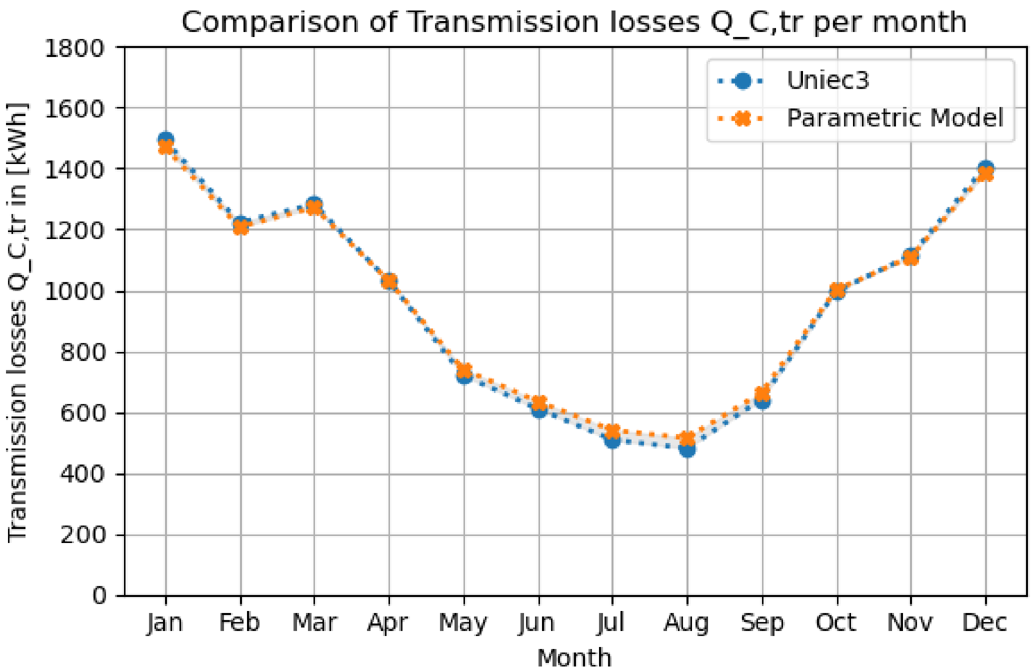


Figure 4.12: Comparison of transmission losses $Q_{C,tr}$ per month of terraced housing in case of cooling.

Ventilation losses, as per NTA 8800, involve an extensive process based on an airflow model. However, the parametric model simplifies this by considering only the conservative default qv10 value, without breaking it down into six different volumetric flows.

When comparing ventilation losses in the case of heating, seen in Figure 4.13, the parametric model aligns closely with the Uniec3 results. The monthly values differ only between 1% and 10% except for the month of February. The relatively high heat loss through ventilation in February according to Uniec3 seems to be caused by a high pressure difference between indoors and outdoors, resulting in relatively high infiltration airflow in this month. This, in turn, appears to be due to the monthly average wind speed ($u_{site,mi}$). The wind speed is highest in February, as stated in Table 17.1 of NTA 8800 (see Table 4.7). This is not included in the PM, and therefore this small discrepancy is found in the results.

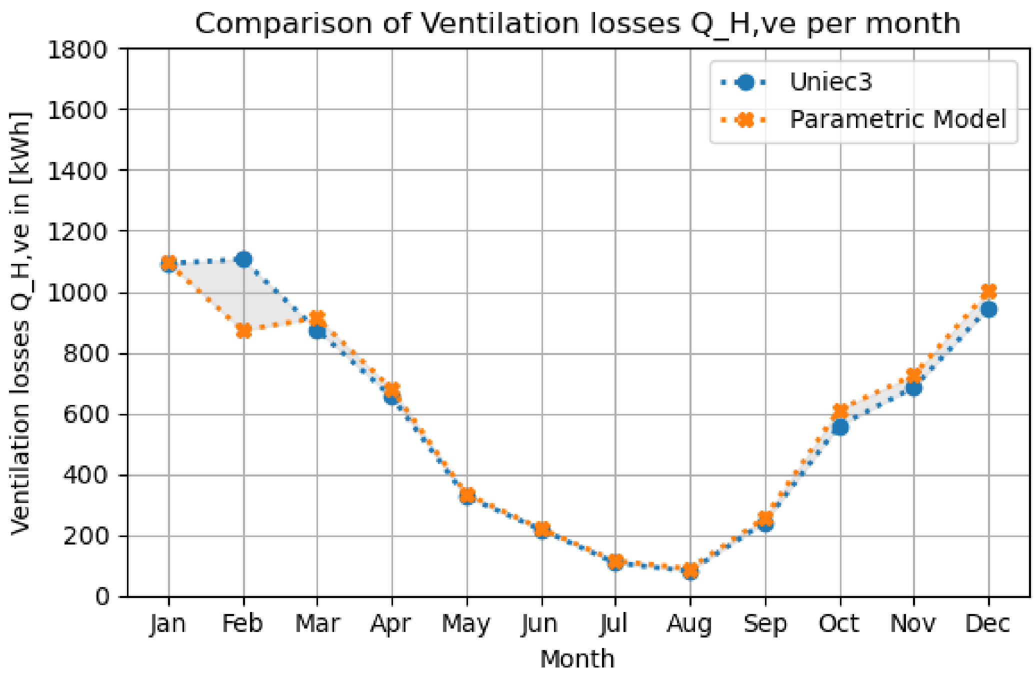


Figure 4.13: Comparison of ventilation losses $Q_{H,ve}$ per month of terraced housing in case of heating.

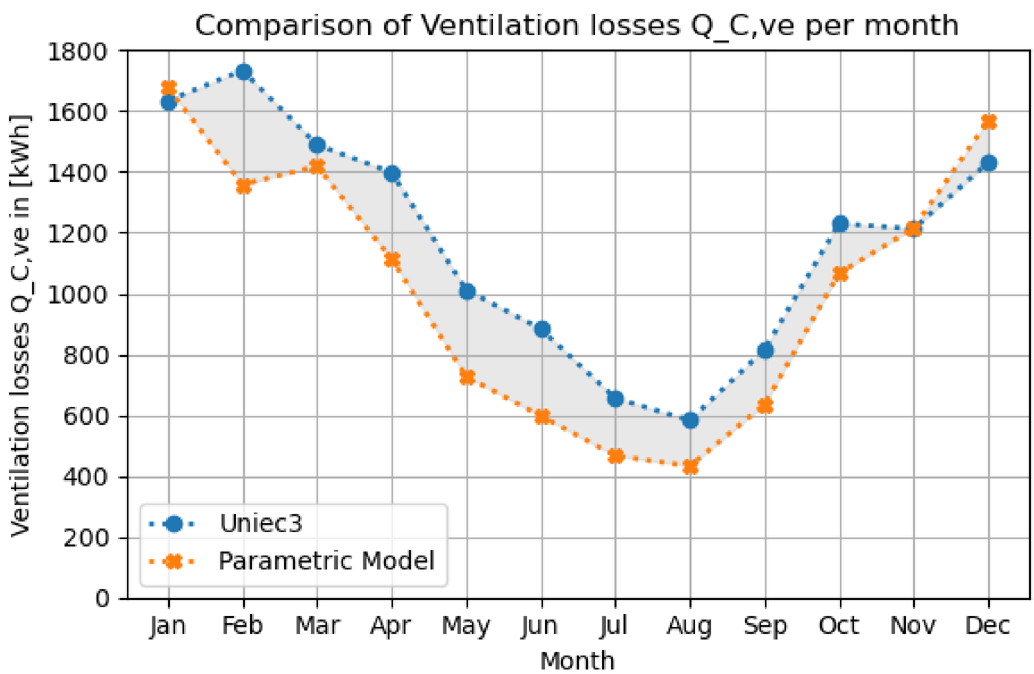


Figure 4.14: Comparison of ventilation losses $Q_{C,ve}$ per month of terraced housing in case of cooling.

Comparison of ventilation losses in the case of cooling, seen in Figure 4.14, do have the most substantial deviations. The parametric model results in lower values in most months. This is because the heat transfer coefficient for cooling is underestimated by the PM. Since the ventilation losses are constant between all the parametric design options, the fault will be of the same size in all models. So, comparing models relative to each other is still possible. Absolute values of cooling demand are less accurate.

The simplified approach of the parametric model results in the same heat transfer coefficient per month, where Uniec3 shows different values for each month, as can be seen in Figures 4.15 and 4.16. These differences in heat transfer coefficients for ventilation losses result in the discrepancies in the ventilation losses $Q_{H,ve}$, $Q_{C,ve}$. The relatively high heat transfer in the month of February can also be seen in Figure 4.15 and Figure 4.16.

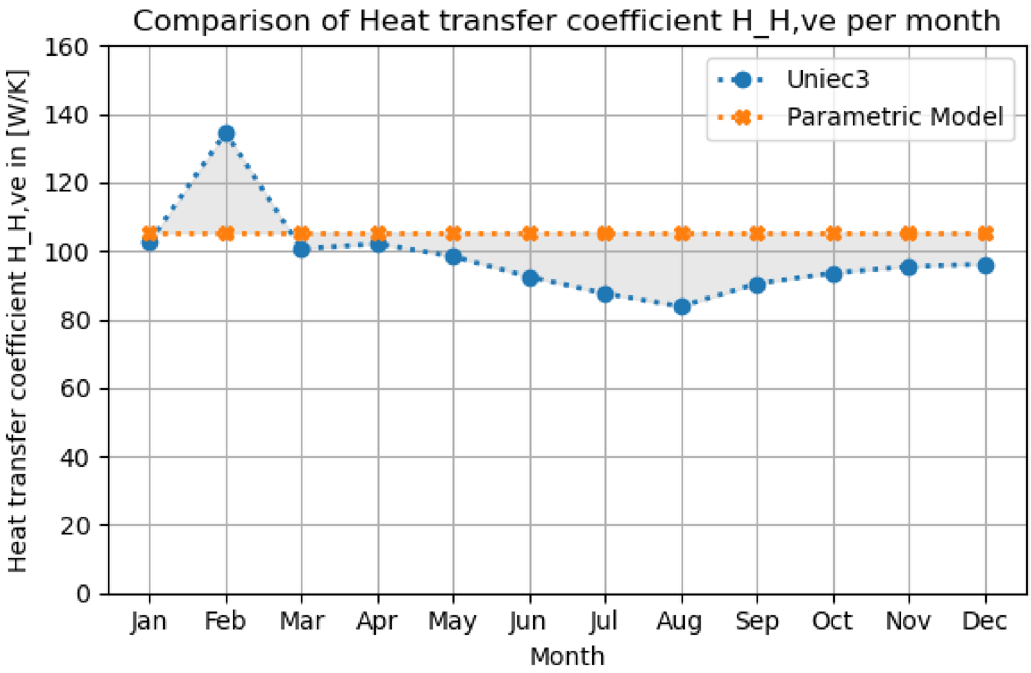


Figure 4.15: Comparison of heat transfer coefficient $H_{H,ve}$ per month of terraced housing in case of heating.

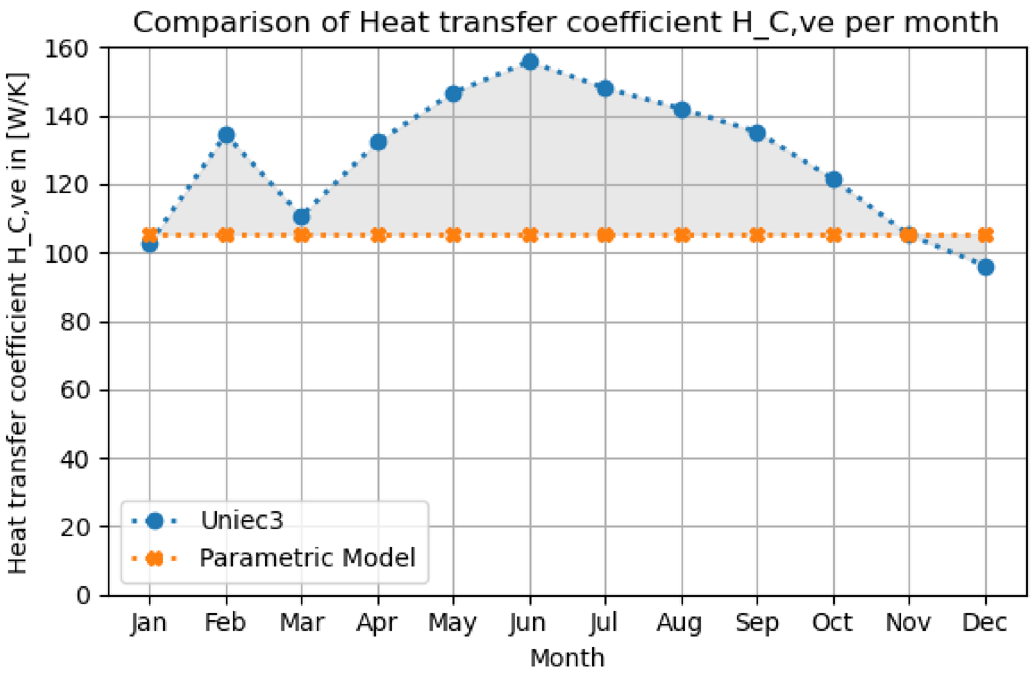


Figure 4.16: Comparison of heat transfer coefficient $H_{C,ve}$ per month of terraced housing in case of cooling.

Tabel 17.1 — Lengte van de maand, t_{mi}, maandgemiddelde buitenluchttemperatuur, $\vartheta_{e;avg;mi}$, maandgemiddelde buitenluchttemperatuur voor zomernachtventilatie, $\vartheta_{e;argII,mi}$, maandgemiddelde windsnelheid, $u_{site;mi}$, en de maandgemiddelde temperatuur van de toevoerlucht vóór de WTW gedurende de periode dat er sprake is van koudeterugwinning via de WTW, $\vartheta_{ODA;preh;WTWC;zi;mi}$

Maand	t_{mi}	$\vartheta_{e;avg;mi}$	$\vartheta_{e;argII,mi}$	$u_{site;mi}$	$\vartheta_{ODA;preh;WTWC;zi;mi}$
	h	°C	°C	m/s	°C
Januari	744	2,61	-	3,04	0,00
Februari	672	4,82	13,97	4,15	0,00
Maart	744	5,91	13,00	2,99	0,00
April	720	9,32	13,70	3,06	0,00
Mei	744	14,73	14,56	2,97	25,63
Juni	720	16,12	15,62	2,78	27,49
Juli	744	18,05	16,17	2,63	26,34
Augustus	744	18,48	16,90	2,51	27,29
September	720	15,63	15,11	2,71	25,30
Oktober	744	10,40	15,04	2,78	0,00
November	720	7,99	13,43	2,83	0,00
December	744	4,00	-	2,83	0,00

Table 4.7: Table 17.1 from the NTA8800 stating the high wind speed $u_{site,mi}$ of $4.15 m/s$ in the month of February.

A factor that is left out in the calculation is, for example, the effective internal heat capacity of the building. This results in over all lower energy demand in case of cooling. This effect can be seen in the heat transfer coefficient $H_{C,ve}$ in Figure 4.16 but also in the calculation of TO_{juli} in Figure 4.17. Because the internal heat capacity of the building is left out, the results of the PM enlarge the spread in TO_{juli} results significantly. This is as expected, because thermal mass has an inhibiting effect on temperature inside the building. Therefore, the chance of overheating (and thus high TO_{juli} values) is also smaller in the Uniec3 model. This is where the parametric model runs short. Since TO_{juli} is one of the tree requirements used to determine the range of possible WWR it is desirable to have a more accurate calculation. Therefore, it is decided to calculate the TO_{juli} values with Uniec3 additionally. While TO_{juli} values from Uniec3 and the PM may differ, the PM values still offer a rough indication of potential overheating issues but cannot be used for clear decisions on meeting Bbl requirements. In general, the TO_{juli} values of the PM will fail the requirement much faster.

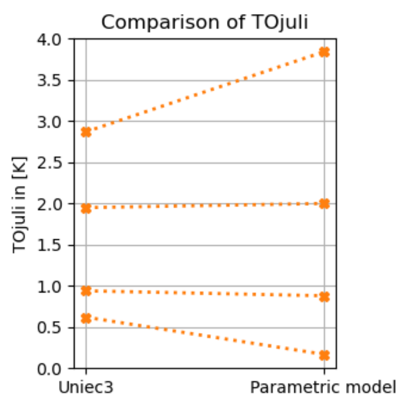


Figure 4.17: Comparison of TO_{juli} in four different cases calculated with the PM and Uniec3. The spread of TO_{juli} values is extensively larger in the PM than in Uniec3.

4.5. Simulation settings

This Section 4.5 covers the exact details of the settings that are used and which runs are performed. Table 4.8 shows the fixed data used for all runs carried out. R_C-values are based on the minimum values stated by the Bbl, the setpoint temperatures, the thermal resistances of the surfaces, and the climate data are given by the NTA 8800 and the reflection values of the surfaces are given by the NEN-EN 17037.

Parameter	Symbol	Unit	Value
Thermal resistance floor	$R_{C,floor}$	[m^{2}K/W]	3.7
Thermal resistance wall	$R_{C,wall}$	[m^{2}K/W]	4.7
Thermal resistance roof	$R_{C,roof}$	[m^{2}K/W]	6.3
Surface resistance exterior	R_{se}	[m^{2}K/W]	0.04
Surface resistance interior	R_{si}	[m^{2}K/W]	0.13
Surface resistance exterior floor	$R_{se,floor}$	[m^{2}K/W]	0.17
Surface resistance interior floor	$R_{si,floor}$	[m^{2}K/W]	0.17
Heat transfer coeff. windows	U_{win}	[W/m^{2}K]	1.6
Heat transfer coeff. door	U_{door}	[W/m^{2}K]	2.0
Min. distance to wall	-	[m]	0.1
Min. window size	-	[m]	0.5
Yearly avg temp outside	$\theta_{avg,an}$	[$°C$]	10.67
Int. setpoint temp heating	$\theta_{int,set,H}$	[$°C$]	20
Int. setpoint temp heating low	$\theta_{int,set,H,low}$	[$°C$]	16
Int. setpoint temp cooling	$\theta_{int,set,C}$	[$°C$]	24
Solar energy transmittance	g_{gl}	[-]	0.6
Light transmittance	VLT	[-]	0.7
Reflectance ceiling	ρ_{ceil}	[-]	0.7
Reflectance interior walls	ρ_{wall}	[-]	0.5
Reflectance floor	ρ_{floor}	[-]	0.2

Table 4.8: Fixed parameters and boundary conditions for the PM, most of them given by the Bbl, NTA 8800 or NEN-EN 17037.

The terraced housing is first analysed by placing the windows in the top corner and increasing the height and width of the window. In this way, the WWR can be examined without the influence of location change. Increment steps of 0.1m are made, which results in 20 different heights and 11 different widths. This is more than the expected minimum of 10 steps needed. The WWR changes are made for all eight different orientations. The settings of run 1 can be found in Table 4.9. After that, the same runs are done again, but then with the windows placed in the bottom corner in order to find the difference in possible WWR range between high and low placed windows.

Run 1 - Variable window sizes, positions in corner				
Parameter	**Symbol**	**Unit**	**Steps**	**Range**
Window height	h	[m]	20	0.5 - 2.4m
Window width	w	[m]	11	0.5 - x m
Window placement z-axis	z	[-]	1	0
Window placement x-axis	x	[-]	1	0
Cooling / No cooling	C_{nd}	[-]	1	No
Cantilever obstacle	d_{cant}	[m]	1	No
Orientation	or	[°]	8	N, NE, E...

Table 4.9: Variables used for the first run of the PM on the terraced housing. Analysing the effects of increasing WWR on daylight and energy demand.

With the knowledge gained from the first runs, the subsequent runs also take into account the window positions. Because the runtime of the PM will increase greatly with more parameters, the number of steps is decreased. Since run 1 already investigated the window height in depth, the steps are heavily reduced to five different heights. Also, both window placement parameters are set to only seven instead of ten, to reduce runtime and create a symmetrical distribution across the facade. In all cases, the hole range of the parameters is considered. Further details can be seen in Table 4.10.

Run 2 - Added variations in window positions				
Parameter	**Symbol**	**Unit**	**Steps**	**Range**
Window height	h	[m]	5	0.5 - 2.4m
Window width	w	[m]	11	0.5 - x m
Window placement z-axis	z	[-]	7	0-1
Window placement x-axis	x	[-]	7	0-1
Cooling / No cooling	C_{nd}	[-]	1	No
Cantilever obstacle	d_{cant}	[m]	1	No
Orientation	or	[°]	8	N, NE, E...

Table 4.10: Used variables for the second run of the PM on the terraced housing. Analysing the effects of increasing WWR and window position on daylight and energy demand.

As a follow-up, a run is done to investigate the effect of different window locations of daylight entrance better. The seven steps used in the previous runs were just short. Therefore, the window placement parameters are increased in number of steps to 11 (steps of 0.1) and the window size is fixed to 0.5x0.5 metres, as can be seen in Table 4.11. Since orientation does not matter for the daylight entrance, the orientation parameter is fixed to NE. The energy demand will be the same for all 220 solutions in this run.

Run 3 - 0.5x0.5m windows, variable positions				
Parameter	**Symbol**	**Unit**	**Steps**	**Range**
Window height	h	[m]	1	0.5 m
Window width	w	[m]	1	0.5 m
Window placement z-axis	z	[-]	11	0-1
Window placement x-axis	x	[-]	11	0-1
Cooling / No cooling	C_{nd}	[-]	1	No
Cantilever obstacle	d_{cant}	[m]	1	No
Orientation	or	[°]	1	NE

Table 4.11: Used variables for the third run of the PM on the terraced housing. Analysing the effect of different window locations on daylight entrance.

The second case study of the middle apartment mainly involves the same runs that are performed as for the terraced housing. In addition, some runs are done to compare the difference between the situation with a cantilever and the situation without a cantilever. The parameter settings are given in Table 4.12. The 2.1-meter long balcony cantilever is placed in front of the living room and room M of the apartment.

Run 4 - 0.5x0.5m windows, variable positions, cantilever				
Parameter	**Symbol**	**Unit**	**Steps**	**Range**
Window height	h	[m]	1	0.5 m
Window width	w	[m]	1	0.5 m
Window placement z-axis	z	[-]	11	0-1
Window placement x-axis	x	[-]	11	0-1
Cooling / No cooling	C_{nd}	[-]	1	No
Cantilever obstacle	d_{cant}	[m]	2	Yes/ No
Orientation	or	[°]	1	NE

Table 4.12: Used variables for the fourth run of the PM on the middle apartment. Analysing the effect of different window locations and the cantilever on daylight entrance.

5

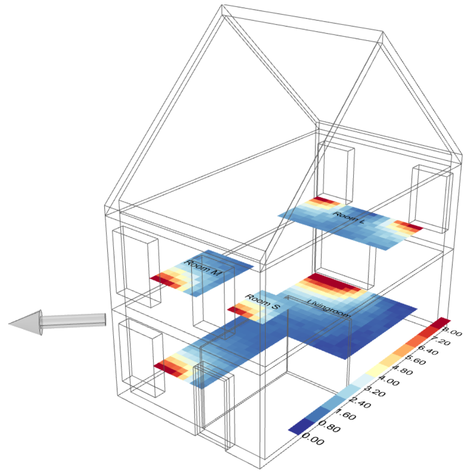
Results and Discussion

In Chapter 5 the results of the study are presented and analysed. Section 5.1 discusses the general shape of the data. It states what possibilities there are to analyse the immense amount of data. Section 5.2 discusses the results of the terraced housing model. Section 5.3 discusses the results of the middle apartment.

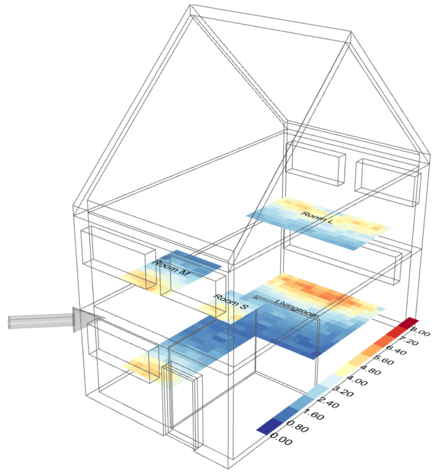
5.1. General results

The type of results for a parametric geometric model in Rhino Grasshopper can vary greatly depending on the specific design and the parameters chosen. Every possible solution can be visualised in the form of a geometric shape and appended with the calculated values for energy demand, daylight entrance, and thermal comfort. Figure 5.1 gives four examples of a possible solution.

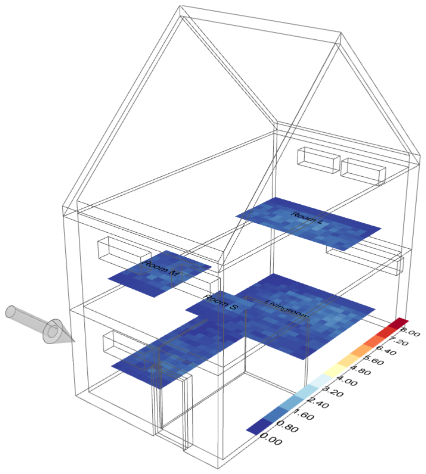
By the shear number of possible parameters, an infinite pool of solutions can be created. Even with large restrictions on the investigated parameters, the solutions space is still giant. For example, a terraced house with only five parameters (orientation, window height, window width, distance to side, and distance to ceiling) results in 212.960 different combinations, each taking around 30 seconds to calculate. This would take months to find all the possible solutions. Therefore, the art lies in selecting the right parameter settings and then generating the data. Then the right data have to be converted into useful information. With the help of modern software, design spaces can be investigated and data can be visualised in various ways. In this case Thread by Thornton Tomasetti (2024) is used. Thread provides a brought selection of interactive charting, data visualisation, and control widgets that allow one to find the best way to display and learn from project data. Thread can be useful for every engineer or consultant to get a better grasp of his results by quickly generating different plots and understanding the relations between parameters. Therefore, there is no requirement to create all the visuals from scratch, which ultimately leads to time savings.



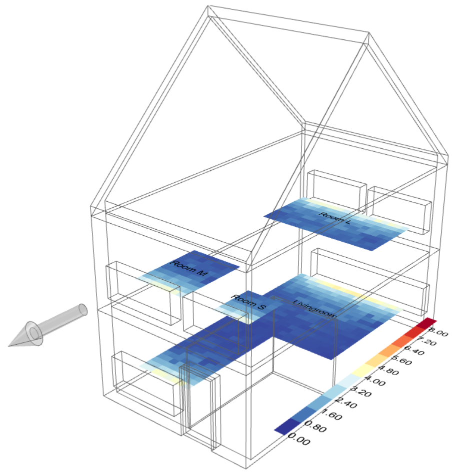
(a) Orientation = SE, height = 1.9m, width = 40%, top corner, Result BENG1 = 54.29 kWh/m^2.



(b) Orientation = NW, height = 1.0m, width = 90%, top corner, Result BENG1 = 55.04 kWh/m^2.



(c) Orientation = W, height = 0.5m, width = 50%, top, Result BENG1 = 54.24 kWh/m^2.



(d) Orientation = S, height = 1.0m, width = 90%, lower, Result BENG1 = 53.66 kWh/m^2.

Figure 5.1: Example of four possible design solution given by the parametric model for the terraced housing. The figure displays specific configurations of the windows, the orientation of the house, and its impact on the daylight entrance and BENG1. The reference surface of each room gives the daylight factors in a grid formation (DF: blue = 0 %, red = 8 %).

5.2. Results terraced housing

All the possible results that are generated with the parametric model by iteration of all variables can be visualised in a parallel coordinate line graph. The coordinate plot allows one to compare the properties of several individual results on a set of variables. Every vertical axis represents a variable and has its own scale, and every line represents one possible solution. The colour of the line can be chosen to represent one of the variables. Figure 5.2 illustrates lines that are coloured based on the WWR value, so the red values are high values and the blue values are low values.

Due to its influence on energy demand and visual comfort, the window-to-wall ratio must be optimised for more than one objective. The solution space has to be defined through a set of clearly defined criteria, as can be seen in Bbl. Setting boundaries is necessary to fulfill both energy demand and daylighting requirements without favoring one over the other. To incorporate the total error margin on BENG1 and the DF ranges of ±2.5% and ±7.5% respectively are used. This range is based on the validation done in Chapter 4. The relative error of the sample multiplied by the critical value will give the margin of error. Between these boundaries, the range of solutions can be explored and optimised to find a suitable solution. However, it is important to take into account that the complexity of the system being studied can make it challenging to meet the predetermined criteria. To regulate the amount of solar radiation and daylight, it may be necessary to incorporate additional building elements, such as blinds, shades, and improved glazing. It is also worth noting that the solution space can vary based on different room sizes and configurations.

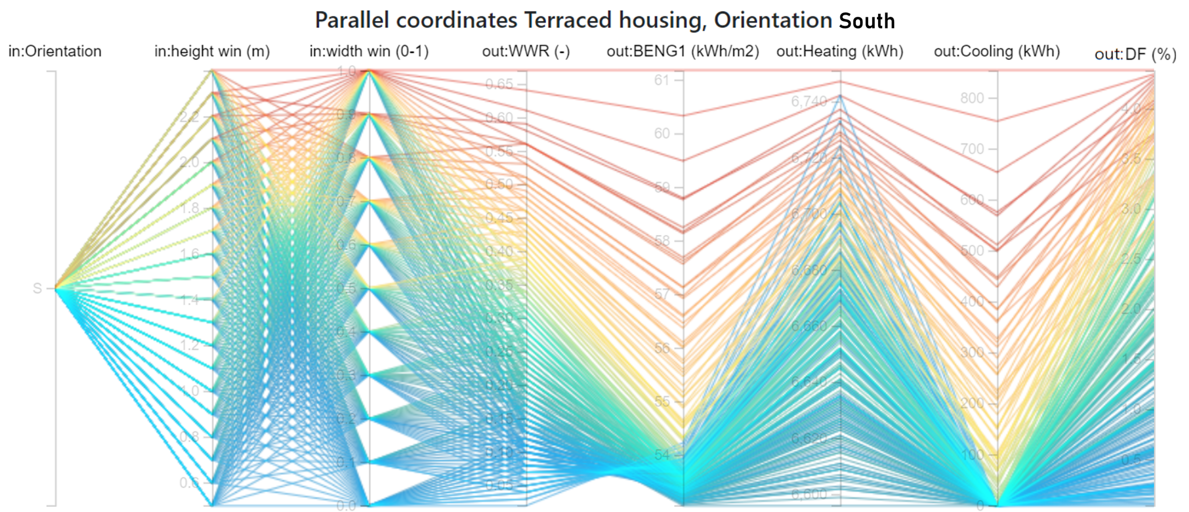


Figure 5.2: Thread Parallel coordinate chart displaying 220 different solutions for a terraced housing facing in south direction. Each vertical axis represents a variable and has its own scale. Color represents the WWR in [-] (red = high, blue = low).

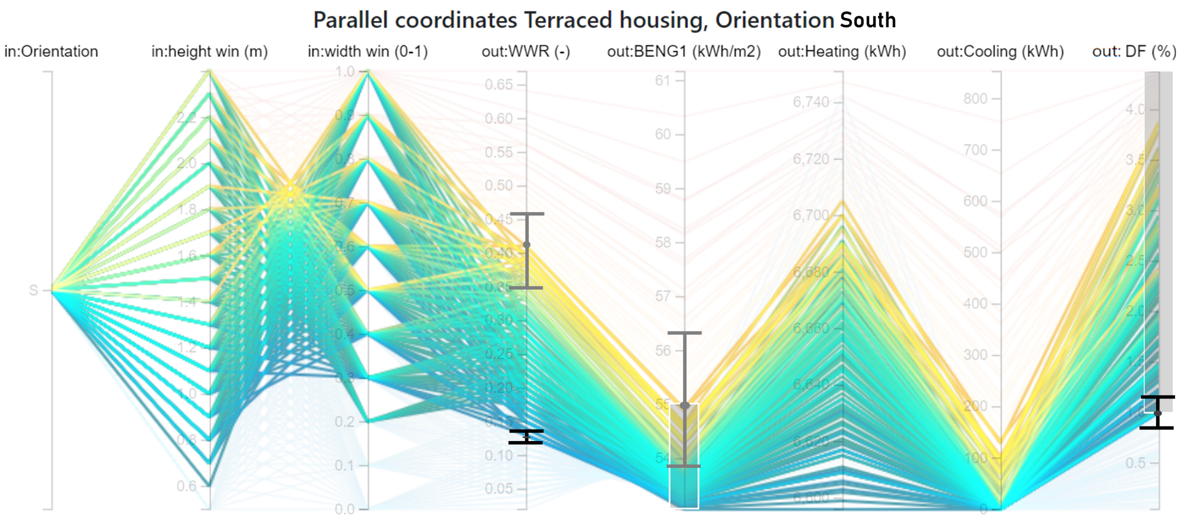


Figure 5.3: Thread Parallel coordinate chart displaying different solutions for a terraced housing facing in south direction. The results narrowed down to the requirements of BENG1 value below 55 kWh/m^2 and an daylight factor of 1.0. WWR between 0.13 and 0.37 satisfies these conditions.

Bbl requirements that are of importance to assess the solutions are as follows. The BENG1 value must be below 55 kWh/m^2, TO_{juli} less than 1.2 and an daylight factor of 1.0 for 50% of the reference plane. As mentioned earlier, TO_{juli} will be analysed separately with Uniec3 in Section 5.2.6 to ensure more accurate results. When the desired requirements of BENG1 and DF are enforced on the solution space, the results are narrowed down. Of the 220 possible combinations, around 110 results satisfy the requirements. These results can be observed in Figure 5.3 where the grey boxes visualise the solution space. The graph displays the daylight factor of the living room since this is the most critical room regarding the daylight requirements. One can conclude that in the situation where the terraced housing is orientated to the South, the window-to-wall ratio must be between 12% and 37% on both sides of the building to meet the requirements. These boundary conditions are read from Figure 5.3 and visualised with the black markers on the WWR axis. For south-oriented, standard situations (minimal RC-value requirements, g value = 0.6), the daylight factor of the living room should not exceed 3.7% because then BENG1 will not meet the requirements. All WWR ranges based on BENG1 and daylight for each orientation are listed in Table 5.1. The corresponding parallel coordinates figures can be found in Appendix D. Table 5.1 takes into account windows placed from the top and windows placed from the bottom. The results show that the windows placed from the bottom require a higher minimal WWR to meet the requirements. This is due to the fact that the lower boundary is determined by the daylight requirement. also, the lower boundary is the same for all orientations, since daylight requirement is independent form orientation. The upper boundary of the WWR depends on the BENG1 result, which is the same in both situations, so no differences are found between lower and higher placed windows. The upper boundary changes per orientation. The large margin of error for the upper limit could lead to the absence of feasible designs, such as those for, e.g., the east orientation with low-placed windows, since the lower limit determined by daylight is 22%, which is a relatively high value.

To gain a clearer understanding of the proportion of glass, such as 30% glass, in the context of a typical apartment, Appendix E provides specific measurements in square meters of glass.

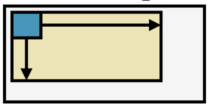
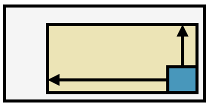
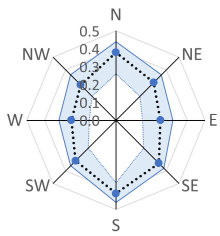
Terraced House			
Orientation	**Lower WWR boundary in [%]**		**Upper WWR boundary in [%]**
	From top 	**From bottom** 	**Top and bottom** (independent of Pos.)
	Depending on Daylight		**Depending on BENG1**
North North-East East South-East South South-West West North-West	13 ± 1	22 ± 1	38 (26 - 44) 30 (19 - 36) 25 (15 - 32) 34 (22 - 38) 41 (35 - 46) 32 (22 - 36) 25 (15 - 32) 28 (19 - 36) 

Table 5.1: Window-to-wall ratio range for every orientation of the terraced housing based on a fixed geometric design with the window increasing form the top or the bottom, Rc value wall = 4.7 m^2K/W, floor = 3.7 m^2K/W, roof = 6.3 m^2K/W U value window = 1.6 $W/(m^2K)$, g-value glass = 0.6. The range is determined through the Bbl requirements of BENG1 value below 55 kWh/m^2 and an daylight factor of 1.0 for 50% of the reference plane.

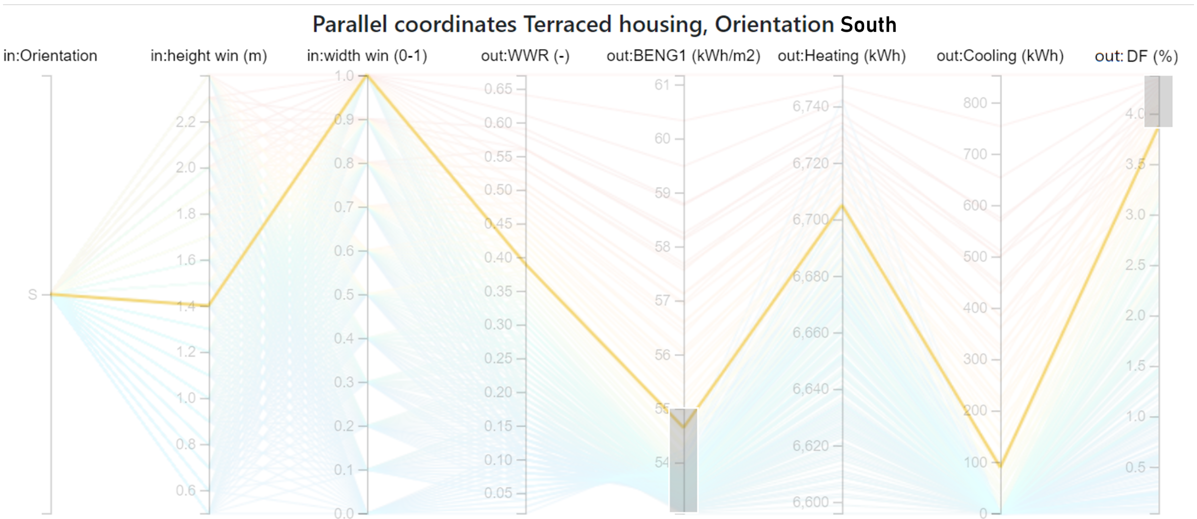


Figure 5.4: Thread Parallel coordinate chart displaying one single possible solution as one line from left to right. It displays a specific configuration of the windows (height = 1.4m, width = 90 %, in the top corner of the facade), the orientation of the house (S) Results: WWR = 0.36, BENG1 = 54.2 kWh/m^2, QH_{nd} = 6690 kWh, QC_{nd} = 48 kWh, ave DF living room = 3.61.

In the next step, individual design solutions can be analysed to better understand the possibilities. As can be observed in Figure 5.4 one solution is selected, displaying one line that connects all the different parameter values. The output values in this case are as follows: WWR = 0.36, BENG1 = 54.2 kWh/m^2, Total heating demand QH_{nd} = 6690 kWh, total cooling demand QC_{nd} = 48 kWh, daylight factor in the living room DF =

3.61, TO_{juli} = 1.05. Of course, a design of a building has to satisfy many other requirements (also non-building physics related), and now this solution space can be explored and assessed further in order to find the best result for the design.

The line result of Figure 5.4 is also displayed in Figure 5.5 as a 3D image to get an idea of how this terraced house would look. The 3D image shows clearly that a WWR of 0.36 is a lot of glass for a terraced house. Furthermore, daylight factors near the windows are extremely high, since no blinds or cantilevers are applied. On the other hand, daylight reaches the deeper parts of the room without any problems.

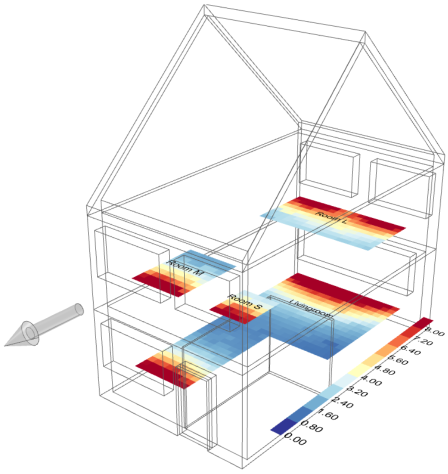


Figure 5.5: 3D image of a possible design solution given by the parametric model for the terraced housing in Figure 5.4. It illustrates a specific configuration of the windows (height = 1.4m, width = 90 %, in the top corner of the facade), the orientation of the house (S) and its impact on the daylight entrance. Result BENG1 = 54.2 kWh/m^2.

5.2.1. Window-to-wall ratio and daylight factor

First, the relationship between the window-to-wall ratio and the daylight factor is investigated. Since the calculation of the daylight factor is independent form orientation (N/E/S/W) all DF-figures are valid for every orientation. Figure 5.6 illustrates the results produced by the PM for terraced housing. The x-axis indicates the WWR, and the y-axis is the daylight factor of the living room in percentages. The data points are coloured based on the width of the window (red = narrow, blue = wide) and the size of the dot indicates the BENG1 value (big dot = high BENG1 value). The windows are placed and fixed to the top corner of the facade and gradually increase in size by lowering the bottom parapet. The figure illustrates a clear distinction between the window widths. Narrow windows logically do not reach high WWR and therefore also result in a lower daylight factor. With a window width of 0.5m, which is indicated with the red coloured dots, the daylight factor does not reach beyond a daylight factor of 0.26. With the maximum amount of glass possible, daylight values exceed a DF of 4.3%. The first takeaway is that a larger WWR does not always directly result in a higher daylight factor. With a WWR of 0.2 the daylight factor can be as low as 1.0% but could also be close to 2%. Increasing one of the dimensions of a window (e.g. the height of the window) always increases the daylight entrance. However, at some point, the additional glass in the facade does not contribute much anymore to the increase in daylight factor and will mainly result in higher BENG1 values. This can be seen for all widths of the windows. To understand this relation better, the x-axis should show the height of the window in metres instead of the WWR. This can be observed in Figure 5.7.

5.2.2. Window height and daylight factor

Figure 5.7 clearly demonstrates that the relationship between the window height and daylight factor is linear up to a window height of approximately 1.15 metres. For heights larger than approximately 1.65 metres the relation is also linear, but with a much flatter slope. In between, there is a transition phase. This behaviour can be explained as follows: According to NEN-EN 17037, the daylight factor is measured at a height of 0.85 metres. Also, the windows in this data set are placed at the top end of the facade, so if the window becomes larger than 1.65 m (2.6m clear height - 0.1m edge - 0.85m height of the reference plane = 1.65m), the window will be partly below the reference plane. Therefore, the additional glass of the window below will only contribute to the daylight factor by reflecting on the interior surface areas. As a consequence, one can conclude

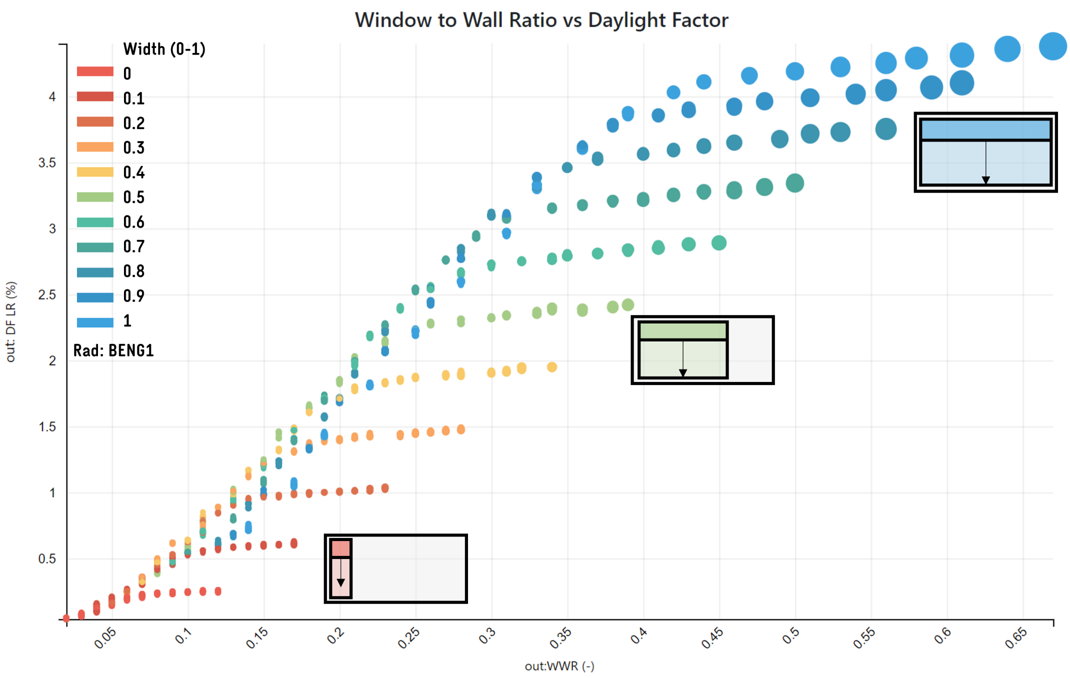


Figure 5.6: Window-to-wall ratio on the x-axis compared with the daylight factor of the living room on the y-axis, for all orientations. The windows are placed in the top corner of the facade. Red = narrow window, blue = wide window. Big dot = high BENG1 value. A larger WWR does not always directly result in a higher daylight factor.

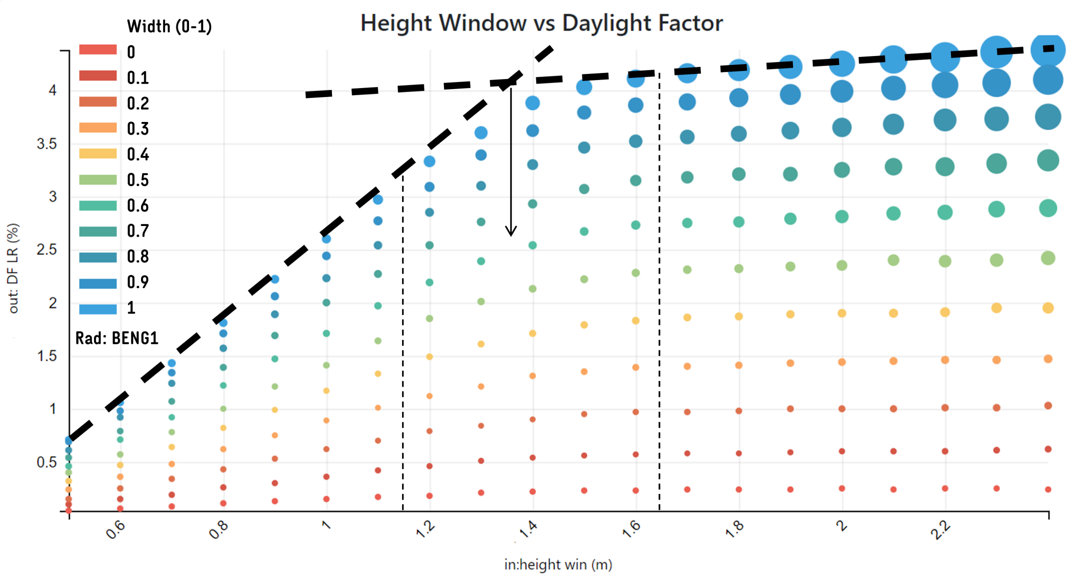


Figure 5.7: Height of the windows (x-axis) plotted against the daylight factor of the living room (y-axis). The radius of the data points represents BENG1 (small value = small dot) and the points are color-sorted per width of the window (blue = wide window, red = narrow window). Data presents linear behavior in two areas between window height and daylight factor.

that glass below the reference surface of 0.85 m contributes very little to the daylight factor. Because of the transition phase, one can also say that glass surfaces slightly above the reference plane of 0.85 metres will contribute less to the daylight factor than windows higher up in the facade but more than glass below the reference plane. This could be the result of the fact that the reference plane disregards areas closer than 0.5 metres from the walls where the daylight of these glass parts would fall.

Figures 5.6 and 5.7 also show, with a rapid increase in the dot diameter, that the amount of glass has a great influence on the energy demand. The results show an exponential increase in BENG1 values as the windows get larger (e.g., the top right corner of Figure 5.7). As a consequence, it is recommended to limit the size of the windows. In this case, a height larger than 1.65 metres will mostly contribute to a higher, more unfavorable BENG1 value and only a slight increase in the daylight factor. Further investigation of the relationship between WWR and BENG1 will be carried out in section 5.2.5 below.

5.2.3. Window width and daylight factor

The width of the window has a different impact on the daylight factor than the height of the window. Where the change in height creates a clear curve in the graph, the relationship between the width of the window and the daylight factor is mainly linear as can be observed in Figure 5.8. The wider the window, the higher the daylight factor. The x-axis visualises the width of the window (0 = narrow, 1 = wide) and the y-axis is the daylight factor of the living room in percentages. Figure 5.8 again visualises that the glass in the lower part of the facade does not contribute to the increase in daylight entrance. The green and blue data points (green = middle window height, blue = large window height) do only differ slightly in daylight factor value, while the BENG1 value increases a lot.

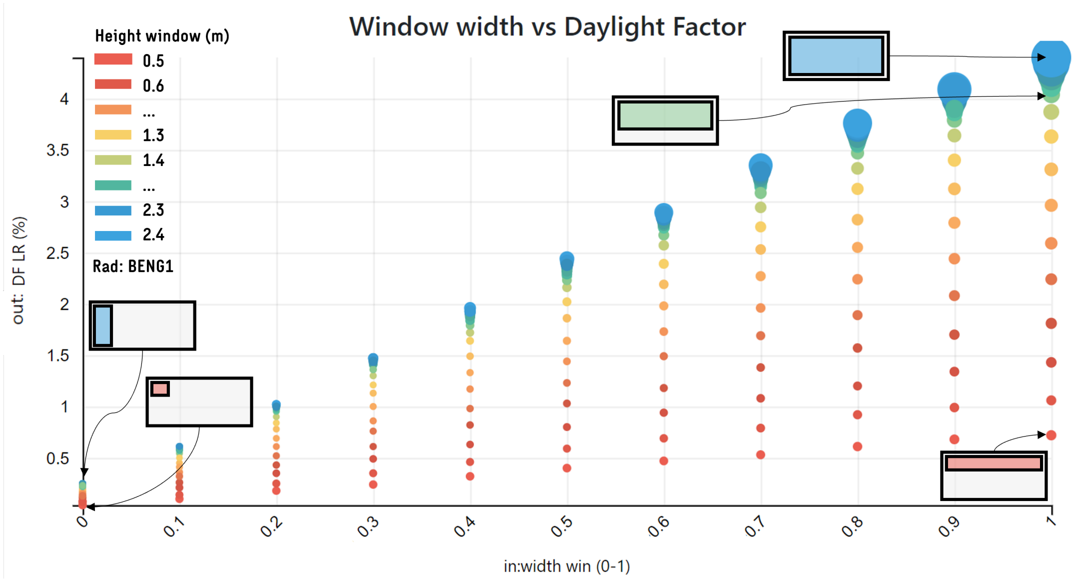


Figure 5.8: Width of the windows (x-axis) plotted against the daylight factor of the living room (y-axis). The radius of the data points represents BENG1 (small value = small dot) and the points are color-sorted per width of the window (blue = wide window, red = narrow window). Data indicates linear behavior between window width and daylight factor.

5.2.4. Window placement and daylight factor

Next, the relationship between window placement and the daylight factor is investigated with the help of another data set. Window placement can differ in height and in positioning from left to right. To analyse the effect of position height, Figure 5.9 is used. The x-axis again represents the width of the window (0 = narrow, 1 = wide), and the y-axis is the daylight factor of the living room in percentages. The data points are coloured according to the distance to the ceiling (blue = low window, red = high window), and the size of the dot states the BENG1 value (big dot = high BENG1 value). The height of the window in this data set is 1.8 m and is placed in the middle of the facade in terms of movements from left to right.

Moreover, Figure 5.9 illustrates a distinct contrast among the various coloured datasets: The higher the window is placed on the building's facade, the higher the daylight factor in the living room. This trend holds true for all widths of the windows. For the scenario described (window height = 1.8 m, without cantilevers), it can be concluded that, in terms of daylight factor, a higher-placed window consistently outperforms a lower one of the same dimensions. Since the NTA 8800 standard does not account for variations in window placement (meaning that it gives the same BENG1 value for the same area of glass), placing the window as high as possible is recommended for multi-objective optimisation of maximising daylight and minimising energy demand, particularly for a window height of 1.8m. Section 5.3.1 below dives deeper into the analysis of the positioning of the windows of the apartment building, where cantilevers of 2.1 metres are present and what the effect is on the daylight factor.

When investigating a bit further, smaller windows do not result in linear behaviour between the height of

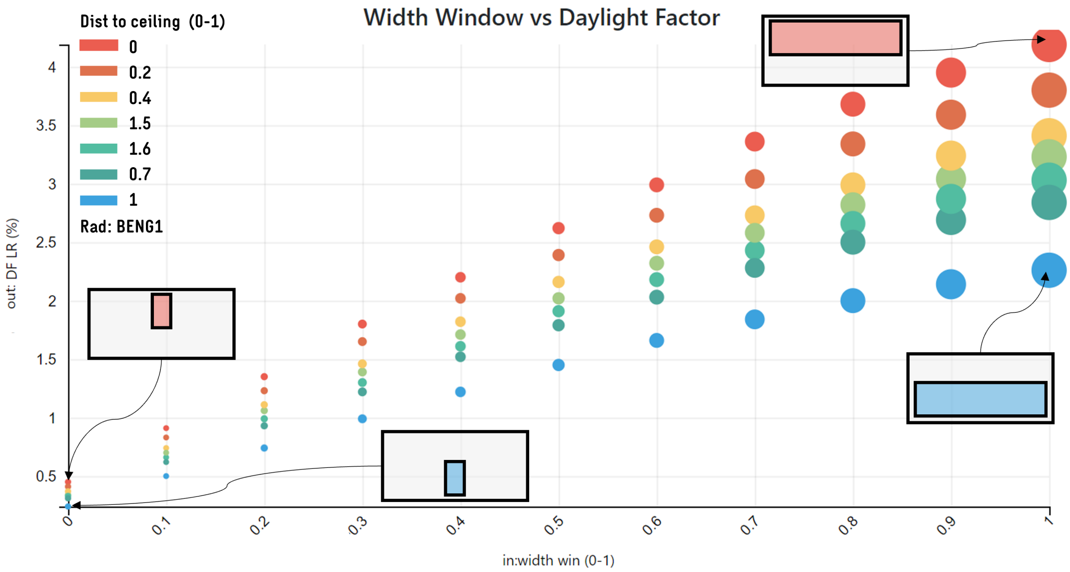


Figure 5.9: Width of the window on the x-axis compared with daylight factor of the living room of the terraced housing, for all orientations (N/E/S/W). Radius = BENG1 (small value = small dot), color is based on the distance to the ceiling (blue = low window, red = high window). Window height is 1.8m. The figure indicates that a window of 1.8m that is placed higher is favorable for a increased daylight factor.

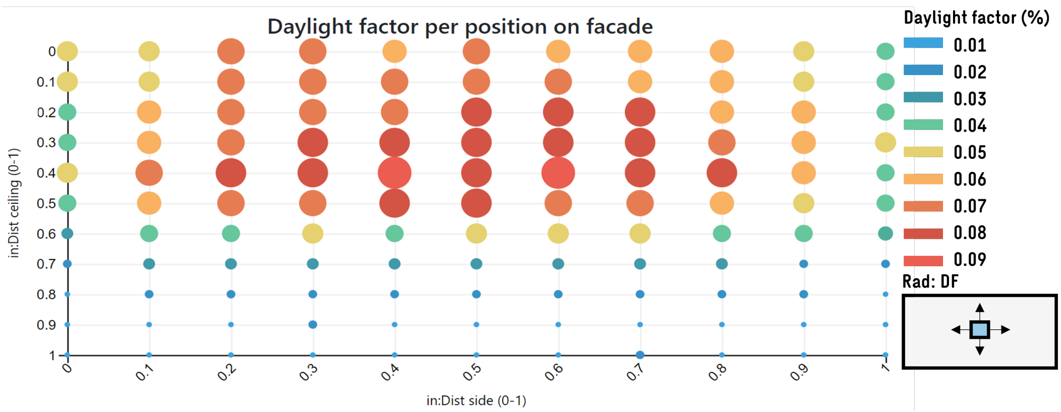


Figure 5.10: Figure states the daylight factor (color red & big dot = high DF) of the living room of a terraced house per window position (window size = 0.5mx0.5m). The x-axis indicates the distance from the side wall (0-1), the y-axis the distance from the ceiling (0-1). Glass in the upper middle part contributes the most to DF increase.

the window and the DF. Therefore, the PM is run to create solutions with a window size of 0.5mx0.5m in 121 possible positions (11 different heights, 11 different horizontal positions). With these results, a clear overview can be created stating which positions do contribute the most to the DF increase. Figure 5.10 reveals the best window positions to maximise daylight entrance: Again, glass below the reference plane has a limited contribution to daylight entrance, which is demonstrated with the small blue dots in the lower parts of the figure. A window size of 0.5 m x 0.5 m on the bottom line of the facade will only result in an daylight factor of 0.01% for the living room. Window(-parts) right at the sides of the room will contribute less to the daylight factor increase than in the centre of the facade plane. Expressed in absolute values, 0.25m^2 of glass in the middle of the facade result in an daylight factor of 0.08-0.09%, where as the same window on the side of the facade will only result in a DF of 0.04-0.05%. This is possibly due to the fact that part of the light through these windows will fall on to the wall, ceiling, and floor surfaces, and thus will only indirectly reach the reference surface via reflection. In addition, the reference plane disregards the area closer than 0.5m to the wall. A decrease in reduction is visible near the ceiling of the room. Daylight factor values range from 0.05% to 0.07%. Therefore, the DF values are even lower in the corners, where more light is absorbed by the surrounding surfaces. One can conclude that glass in the upper middle part contributes the most to the increase in daylight factor. To reach the highest daylight factor values, the window should be positioned away from any walls and floors and above 0.85m. The positioning of the window does not have any influence on BENG1 so all the dots in Figure 5.10 do have the same BENG1 score depending on the orientation. Some individuals may also argue that the result that glass below the reference surface makes a negligible contribution to daylight in buildings is not logical. However, this argument is closely related to the underlying objective of the regulations. The decision was made to evaluate daylight at a table height of 0.85m, as this is the height where daylight is needed to read, write, or use display devices. Therefore, this choice is rational and serves its purpose effectively.

5.2.5. Window-to-wall ratio and BENG1

The next step is to look a bit deeper into the effects of windows on the BENG1 indicator values. As is known, the energy demand calculations do not differentiate between the window positions and dimensions, but only look at the orientation of the facade and the amount of square metres of glass. Figure 5.11 displays eight data sets based on orientation with increasing WWR. The x-axis represents the window-to-wall ratio and the energy demand is represented as well on the y-axis as with the dot size. An exponential-like relationship is suggested between WWR and BENG1, where BENG1 increases exponentially when WWR increases. Energy demand differs per orientation, where west and east orientation result in the highest values, north and south in the lowest, and the orientations in between result in average values. Since the terraced housing has two facades opposite each other with approximately the same amount of glass, the opposite direction should indeed result in comparable BENG1 results.

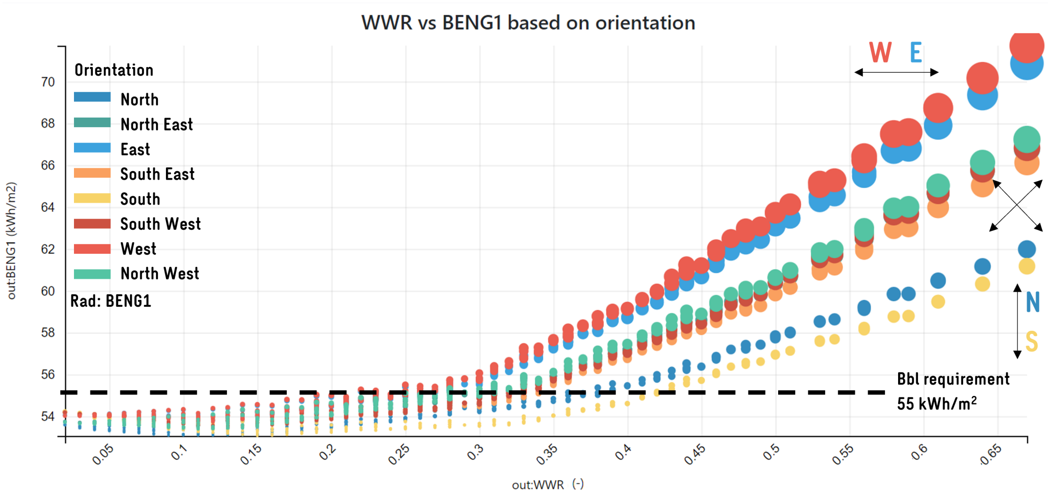


Figure 5.11: Figure presents window-to-wall ratio on x-axis and energy demand on y-axis. Radius = BENG1 (small value = small dot), colour is based on the orientation of the building. It presents the maximum possible window-to-wall ratios to fulfil the Bbl requirements for BENG1.

Figure 5.11 displays that with standard Rc values given by Bbl, BENG1 of the terraced housing never falls below 52 kWh/m^2 per year. If lower BENG1 values are desirable, it will be necessary to increase the thermal resistance values or decrease thermal losses through infiltration and ventilation. Figure 5.11 also displays the maximum window-to-wall ratio per orientation when practising the Bbl requirement of 55 kWh/m^2. For east-west orientated buildings this results in a WWR of 0.2 - 0.25, where as north-south orientated buildings can accept a WWR of 0.35 - 0.42. If the building is orientated in the north west-south east or north east-south west direction, the window-to-wall ratio can be a maximum of 25 - 32 %. Thus, when optimising for energy demand, a north - south orientation is favourable. Since daylight is independent of orientation, this applies to the MOO of daylight and energy demand as well. Figure 5.11 suggests, that that there is an optimum BENG1 score around a window-to-wall ratio of 0.1 - 0.25, slightly depending on the orientation.

5.2.6. Temperature overshoot in July

Figure 5.12 reveals the relationship between the window-to-wall ratio and TO_{juli} per orientation calculated with Uniec3. The x-axis displays the window-to-wall ratio and the y-axis displays TO_{juli}. The colour of the data points indicates the eight different orientations. The first takeaway is that TO_{juli} stays zero for the lower WWR until around 5%. Since smaller window-to-wall ratios do not result in cooling demands, and therefore no temperature overshoot is expected. It can also be stated that the four orientations mainly orientated to the south score slightly higher for TO_{juli} than their northern counterparts. Furthermore, TO_{juli} increases non-linearly as WWR increases. For every orientation, a polynomial trend line is fitted, which is then used to calculate the intersection at which the TO_{juli} values pass the 1.2 requirement of Bbl. The intersected values for every orientation are given in Table 5.2.

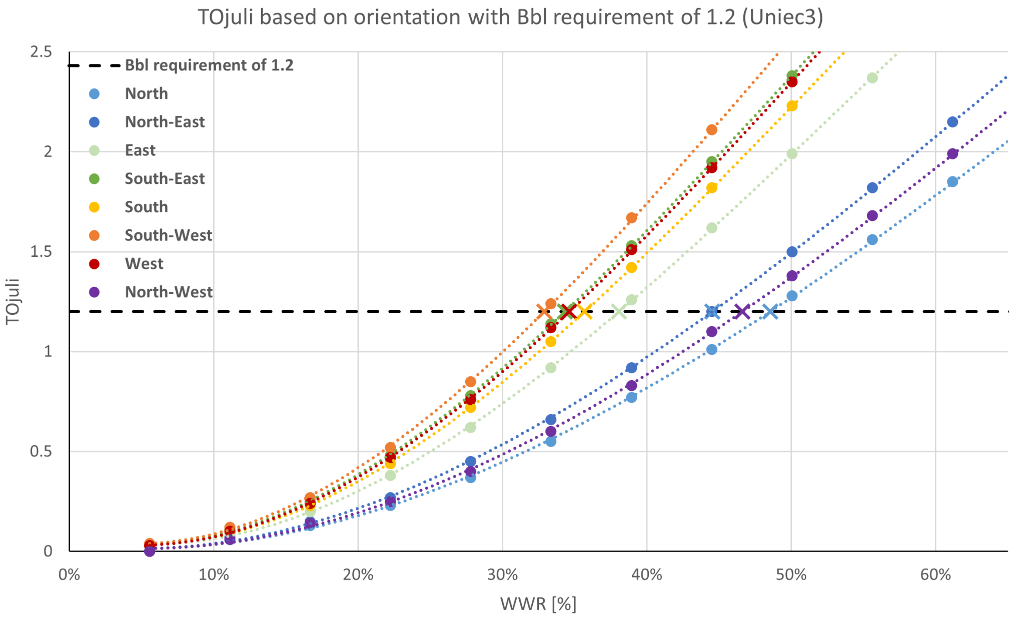


Figure 5.12: X-axis displays WWR and y-axis displays TO_{juli}, Color indicates the eight different orientations. The TO_{juli} values of the terraced house are calculated with Uniec3.

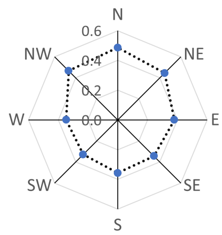
Orientation	max WWR in [%]	
North	49%	
North-east	45%	
East	38%	
South-east	34%	
South	36%	
South-west	33%	
West	35%	
North-west	47%	

Table 5.2: Maximum window to wall ratio per orientation of the terraced house based on a TO_{juli} of 1.2 (Bbl requirement), calculated with Uniec3. fixed boundaries, Rc value wall = 4.7 m^2K/W, floor = 3.7 m^2K/W, roof = 6.3 m^2K/W U value window = 1.6 $W/(m^2K)$, g-value glass = 0.6.

Figure 5.13 illustrates the correlation between BENG1 and TO_{juli}. Please note that in Figures 5.13 and 5.14 both values are determined with the help of the PM, so the TO_{juli} values should not be used as an exact value. The findings vary across all orientations, displaying a curved pattern. Initially, TO_{juli} starts at zero. As BENG1 increases, there is a sudden sharp rise in TO_{juli} at a certain point, followed by a gradual deceleration in the growth of TO_{juli}. The sharp rise happens at different BENG1 values for every orientation. The south oriented terraced housing expect a TO_{juli} increase at a lower BENG1 value where the east orientation TO_{juli} comes into play at higher BENG1 values.

To explore the correlation between TO_{juli} and the daylight factor, Figure 5.14 illustrates the relationship between these two variables. It can be seen that for the terraced house, TO_{juli} does not compromise daylight entry because a maximum TO_{juli} of 1.2 still allows for an daylight factor well above the required 1%, no matter the exact TO_{juli} value. In addition, multiple orientations are possible with a TO_{juli} of zero and a DF above 1%. However, no direct relation can be formulated between TO_{juli} and the daylight entrance.

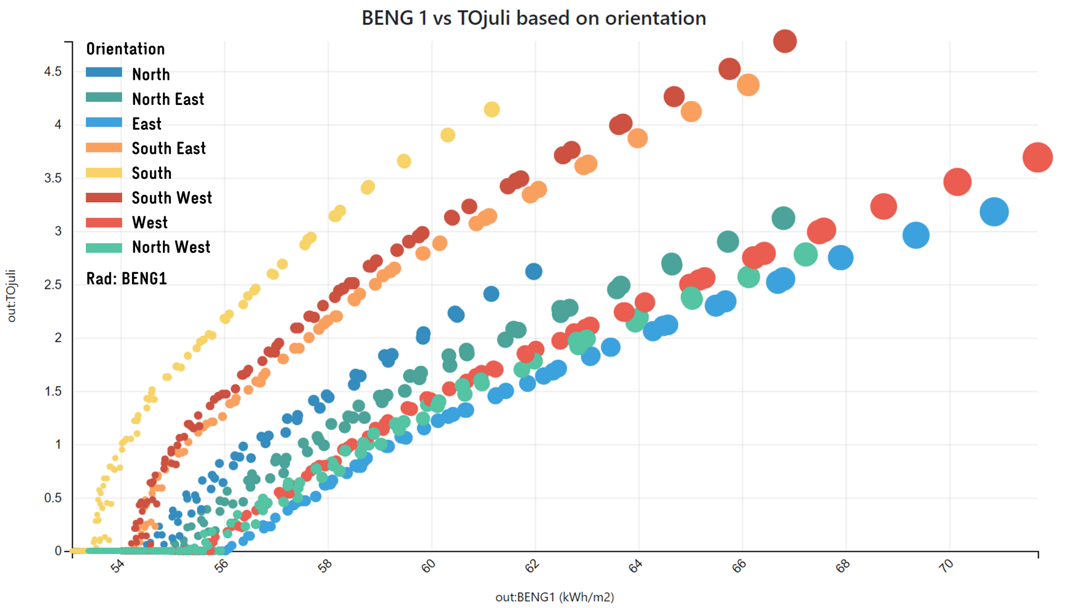


Figure 5.13: X-axis displays BENG1 and y-axis displays TO_{juli}, Color indicates the eight different orientations, Radius states BENG1 values (small value = small dot).

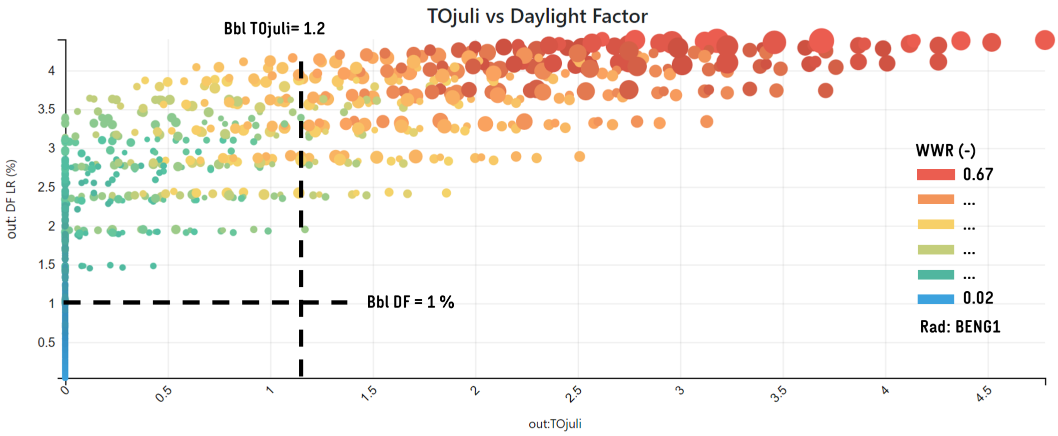
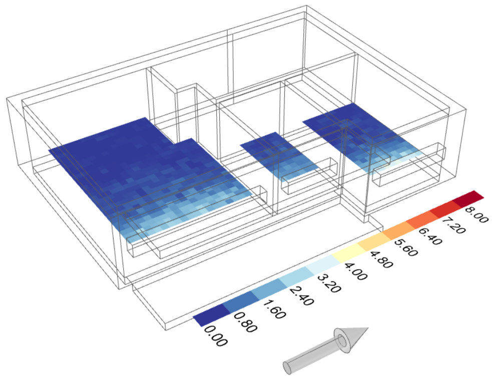


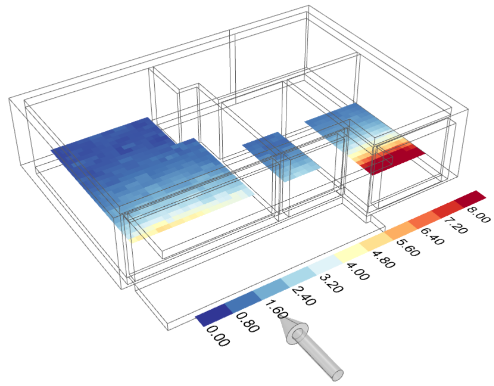
Figure 5.14: X-axis displays TO_{juli} and y-axis displays daylight factor of the living room. Color and radius states BENG1 values (small value = small dot).

5.3. Results middle apartment

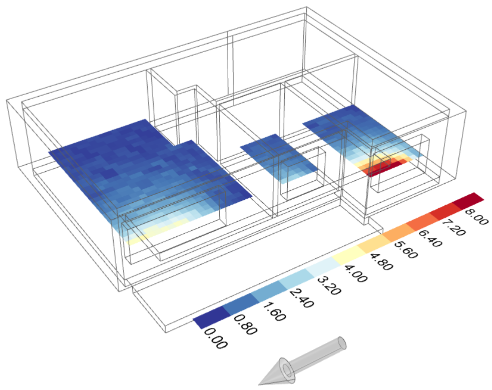
Given that many outcomes of the apartment building exhibit similarities to those of the terraced housing, Section 5.3 primarily highlights the different results of the apartment building compared to the terraced housing. The main differences between a terraced house and a middle apartment are that the loss area is notably smaller (no direct losses through roof and floor, also fewer walls bordering to the outside), there is only one side that lets in daylight through windows, and there are balcony cantilevers, which are mandatory according to Bbl, that prevent daylight entrance at specific angles. Therefore, the daylight entrance is expected to be lower. Same as the terraced house, the middle apartment presents various solutions in terms of window size and placement. Consequently, Figure 5.15 displays four examples in the form of a 3D image and is appended with the calculated values for the energy demand. Due to the lower loss area, the BENG1 values are significantly lower than for the terraced housing. The daylight factor values are also lower for two of the three rooms, since the windows are placed below a cantilever.



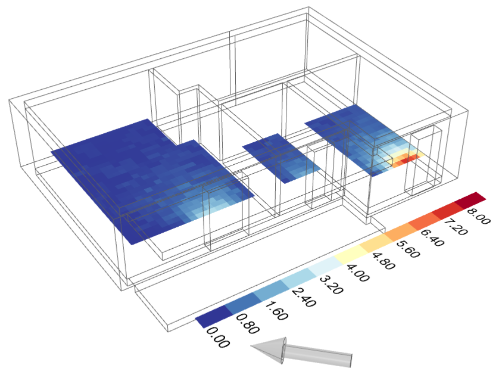
(a) Orientation = O, height = 0.5 m, width = 90 %, middle,
Result BENG1 = 36.63 kWh/m^2.



(b) Orientation = S, height = 2.4 m, width = 100 %, mostly glass
Result BENG1 = 48.56 kWh/m^2.



(c) Orientation = W, height = 1.4 m, width = 60 %, top corner,
Result BENG1 = 41.23 kWh/m^2.



(d) Orientation = SW , height = 2.4 m, width = 20 %, top middle,
Result BENG1 = 37.96 kWh/m^2.

Figure 5.15: Example of four possible design solutions given by the parametric model for the middle apartment. The figure displays specific configurations of the windows, the orientation of the building, and its impact on the daylight entrance and BENG1. The reference surface of each room gives the daylight factors in a grid formation (DF: blue = 0 %, red = 8 %).

When the desired requirements of BENG1 and DF are enforced on the solution space of the appartment, the results are narrowed down, as can be seen in Figure 5.16. The graph displays the daylight factor of the living room, as this is the most critical room regarding the daylight requirements. One can conclude that in the situation where the apartment is orientated to the south, the window-to-wall ratio must be greater than 33% to meet the requirements. An upper boundary cannot be given, because the apartment did not violate the BENG1 requirement in any design. In Figure 5.16 it can be seen that the heating demand is relatively low but the cooling demand is relatively high due to solar gains, compared to other orientations. The corresponding parallel coordinates figures can be found in Appendix D. All WWR ranges based on BENG1 and daylight for each orientation are listed in Table 5.3. The lower boundary is the same for all orientations and the upper boundary of the WWR depends on the BENG1 result, which changes per orientation. The middle apartment has a relatively high compactness compared to the terraced house and therefore has a lower heating demand compared to the terraced house. The west orientation will be restricted by the energy demand requirements the fastest (54%). The PM demonstrated that in some orientations (N, NE, SE, S) the middle apartment always meets the BENG1 requirements and therefore no upper boundary due to BENG1 can be given. For the geometries studied, this research suggests a WWR for an apartment building roughly between 30% and 55% when looking at BENG1 and the daylight factor.

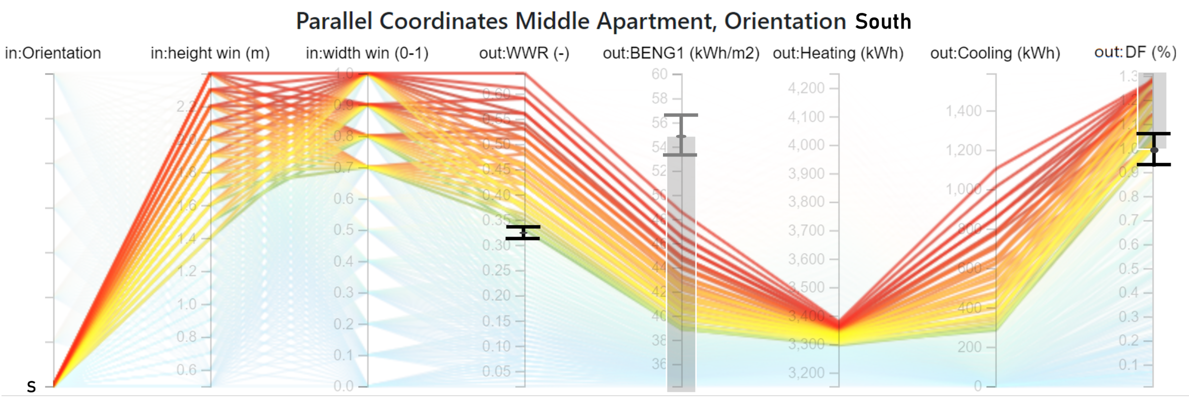


Figure 5.16: Thread parallel coordinate chart displaying different solutions for a middle apartment facing in south direction (with cantilever). The results narrowed down to the requirements of BENG1 value below 55 kWh/m^2 and an daylight factor of 1.0. WWR between 0.33 and 0.54 satisfies these conditions.

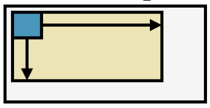
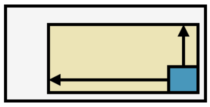
Middle Apartment			
Orientation	**Lower WWR boundary in [%]**		**Upper WWR boundary in [%]**
	From top 	**From bottom** 	**Top and bottom** **(independent of Pos.)**
	Depending on Daylight		**Depending on BENG1**
North	33 ± 1	46 ± 1	-
North-east			-
East			65 (62 - 68)
South-east			-
South			-
South-west			62 (59 - 65)
West			54 (52 - 57)
North-west			62 (59 - 65)

Table 5.3: Window-to-wall ratio range for every orientation of the middle apartment based on a fixed geometric design with the window increasing form the top or the bottom, Rc value wall = 4.7 m^{2}K/W, U value window = 1.6 W/(m^{2}K). The range is determined through the Bbl requirements of BENG1 value below 55 kWh/m^2 and an daylight factor of 1.0 for 50% of the reference plane.

5.3.1. Distance to ceiling and daylight factor

The following section investigates the influence of the positioning height of a window on the daylight entrance. In contrast to the terraced housing, the middle apartment exhibits different characteristics due to the shading provided by the balconies. Figures 5.17 and 5.18 reveal the daylight factor for two different situations. The first figure belongs to the living room, which is located underneath a balcony, and the second one is the same living room, but with the cantilever removed. The y-axes display the distance to the ceiling in metres. In the first place, it is noticed that the DF values are lower overall. In cases of the terraced housing, where the daylight factor was high for windows located in the upper section of the building's facade, here, Figure 5.17 illustrates reduced daylight factors for the living room when the windows are placed higher. In addition, the highest daylight values are reached at different position heights of the window. The optimal placement height of a window for the apartment living room with 2.1 metre cantilever is around 1.0 m from the ceiling, where for the living room without cantilever the optimal position is approximately 0.8 m from the ceiling.

5.3.2. Window placement and daylight factor

Figure 5.19 indicates the daylight factor of the living room of the apartment per window position. The PM is run to create solutions with a window size of 0.5mx0.5m in 121 possible positions (11 different heights, 11 different horizontal positions). With these results, a clear overview can be created that outlines which positions contribute the most to the increase in DF. Figure 5.19 reveals the best window positions to maximise daylight

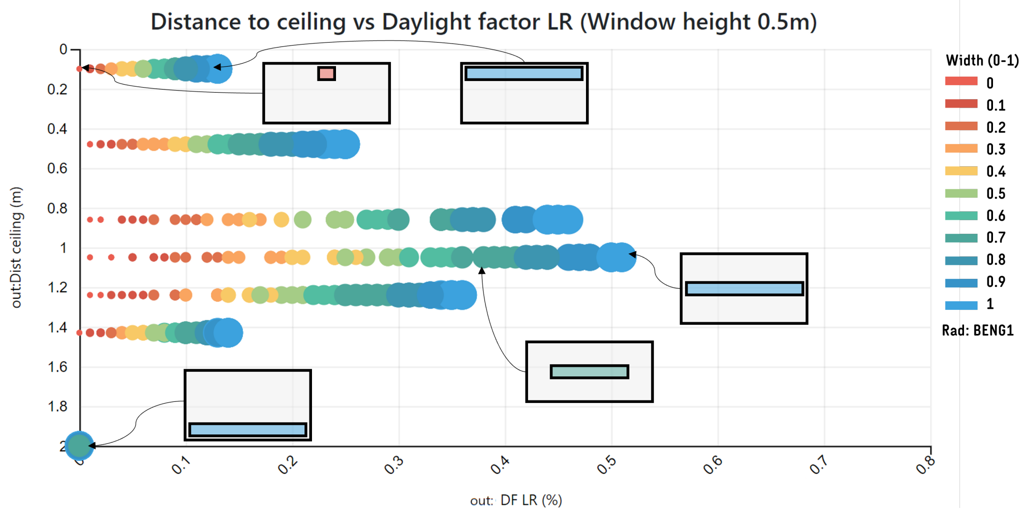


Figure 5.17: X-axis displays the DF. Y-axis displays distance to ceiling of a window in [m]. Windows have a height of 0.5m. The living room has a cantilever of 2.1m in front of the window. Blue colours represent wide windows, red narrow windows. Radius states BENG1 values (small value = small dot).

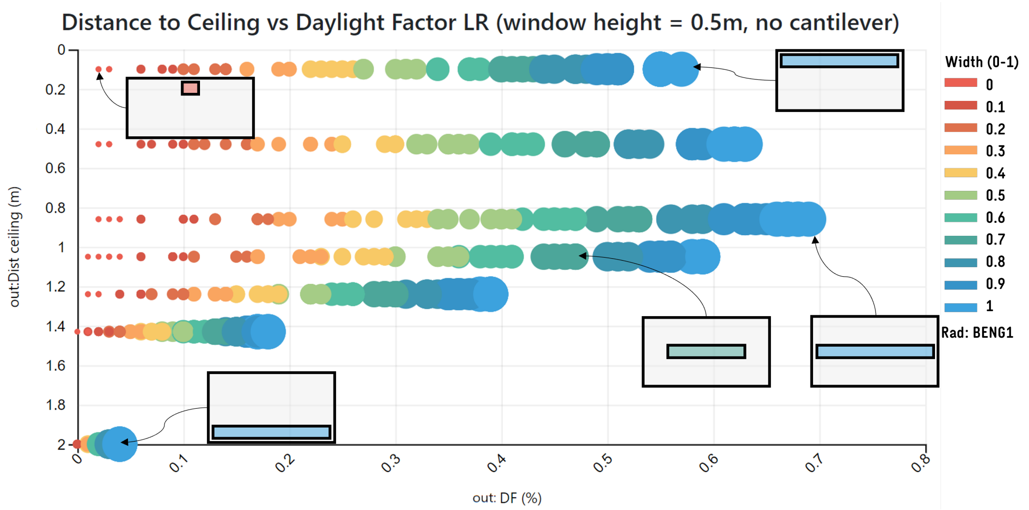


Figure 5.18: X-axis displays the DF. Y-axis displays distance to ceiling of a window in [m]. Windows have a height of 0.5m. No cantilever in front of the living room window. Blue colours represent wide windows, red narrow windows. Radius states BENG1 values (small value = small dot).

entry: The results are in line with the results of the terraced housing. Lower positions contribute almost nothing to daylight entry. values are lower over all and, as expected, due to the cantilever, the highest positions contribute much less daylight entry, so windows placed in the middle of the facade are best. Another small but noticeable effect can be seen to the far left of the facade, where the DF values are slightly higher. This is because the cantilever stops directly at the corner of the facade. So daylight can reach the window from the side here.

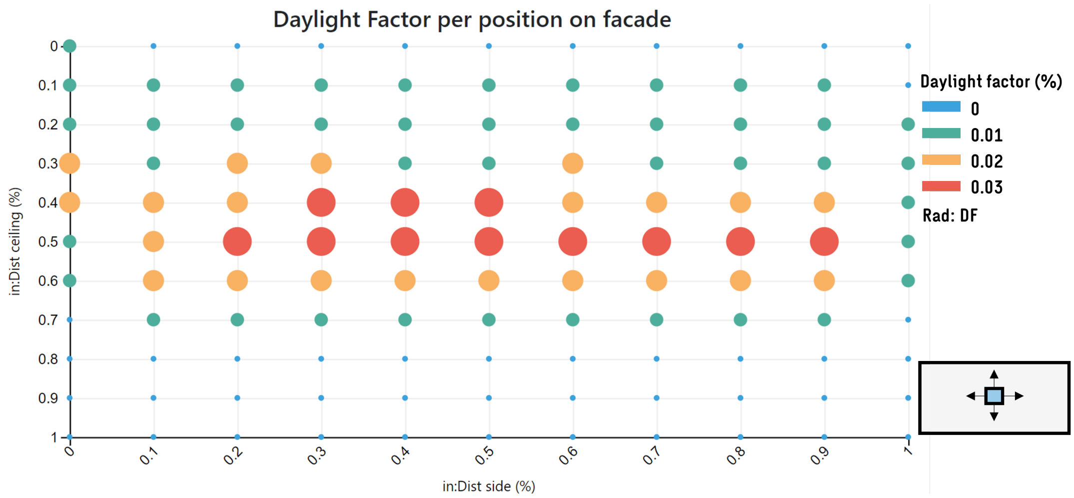


Figure 5.19: The daylight factor (color red & big dot = high DF) of the living room of the apartment per window position (window size = 0.5 m x 0.5 m). The x-axis indicates the distance from the side wall (0-1), the y-axis the distance from the ceiling (0-1). Impact of the balcony cantilever on the DF is highly visible.

5.3.3. Temperature overshoot in July

Figure 5.20 reveals the relationship between the window-to-wall ratio and TO_{juli} per orientation calculated with Uniec3 for the apartment. The x-axis displays the window-to-wall ratio and the y-axis displays TO_{juli}. The colour of the data points indicates the eight different orientations. Orientation west, south-west, east and south-east reach the highest temperature overshot values, where as north orientation allows for the highest WWR.

For every orientation, a polynomial trend line is fitted, which is then used to calculate the intersection at which the TO_{juli} values pass the 1.2 requirement of the Bbl. The intersected values for every orientation are given in Table 5.4. The limits are highest for the north orientation and lowest for the west orientation. The small graph shows the same percentages as visualised in a radar graph. Some symmetry can be seen in the results on the north-south axis. Note that all WWR values based on TO_{juli} are lower than the WWR values based on BENG1, therefore cooling can be of interest in the apartment building.

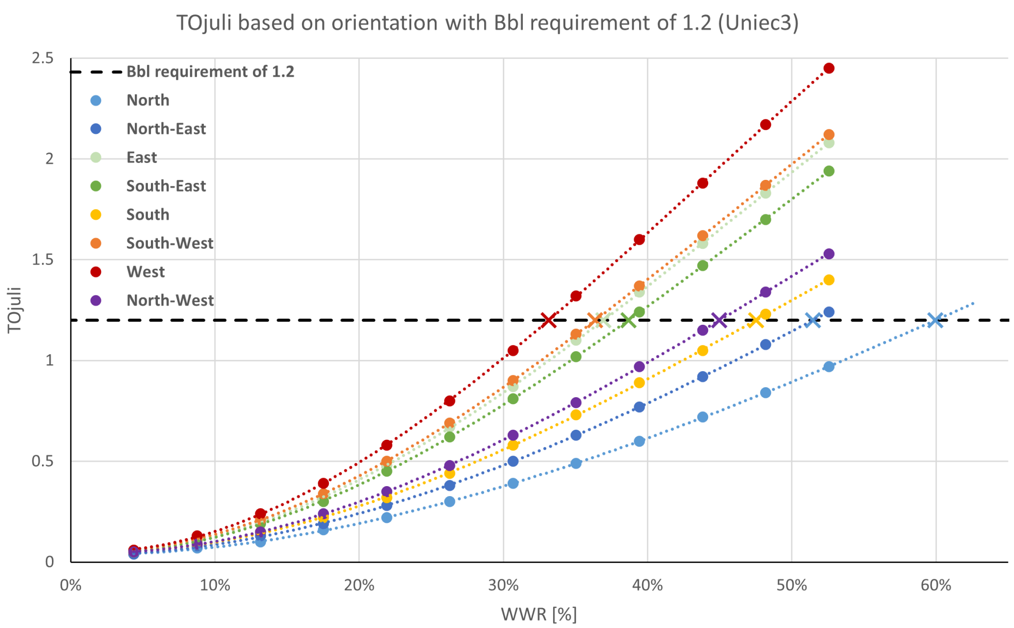


Figure 5.20: X-axis displays WWR and y-axis displays TO_{juli} of the apartment, Color indicates the eight different orientations. The TO_{juli} values are calculated with Uniec3.

Orientation	max WWR in [%]
North	60 %
North-east	52 %
East	37 %
South-east	39 %
South	48 %
South-west	36 %
West	33 %
North-west	45 %

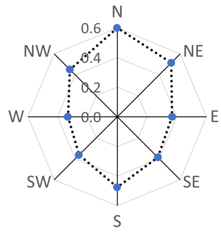


Table 5.4: Maximum window to wall ratio per orientation of the middle apartment based on a TO_{juli} of 1.2 (Bbl requirement), calculated with Uniec3. Fixed boundaries, Rc value wall = 4.7 m^2K/W, floor = 3.7 m^2K/W, roof = 6.3 m^2K/W U value window = 1.6 W/(m^2K), g-value glass = 0.6.

5.3.4. Apartment without cantilever

Although balconies are required by the Bbl to provide outdoor space for apartments, the analysis is conducted as if no cantilever is present. In this way, the cantilever effect on WWR based on BENG1 can be visualised. If a design can be created in which the balcony does not impact the entry of daylight and solar heat gains, this outcome could be of interest. Table 5.5 shows the same layout and values as for the apartment with cantilever. The lower boundaries determined by daylight entrance are significantly lower when the cantilever is removed (15% and 25%). This is a minimal WWR reduction of more than 50%. The requirements for the upper boundary based on BENG1 are slightly lower compared to the apartment with cantilever, but the differences are small (2% -8%). The west-orientated apartment still allows for the lowest WWR (51%). Orientations north and north-east do fulfil the BENG1 requirements in all cases.

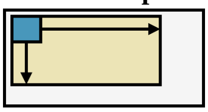
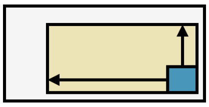
Middle Apartment - without cantilever			
Orientation	Lower WWR boundary in [%]		Upper WWR boundary in [%]
	From top 	From bottom 	Top and bottom (independent of Pos.)
	Depending on Daylight		Depending on BENG1
North			-
North-east			-
East			59 (56 - 62)
South-east			59 (56 - 62)
South	15 ± 1	25 ± 1	59 (56 - 62)
South-west			54 (51 - 57)
West			51 (49 - 54)
North-west			59 (56 - 62)

Table 5.5: Window-to-wall ratio range for every orientation of the middle apartment without cantilever based on a fixed geometric design with the window increasing form the top or the bottom, Rc value wall = 4.7 m^2K/W, U value window = 1.6 W/(m^2K). The range is determined through the Bbl requirements of BENG1 value below 55 kWh/m^2 and an daylight factor of 1.0 for 50% of the reference plane.

When looking at TO_{juli} in Figure 5.21 and Table 5.6, differences are clearly visible. Removing the cantilever and exposing the other two windows of the apartment to the solar heat gains, restrictions on temperature overshoot are inevitable. All orientations have been decreased, and the southern orientation has experienced the most significant reduction from a maximum WWR of 48% to 29%. The reduction in the orientation to the north is limited (2%). The symmetry is still visible in the radar graph.

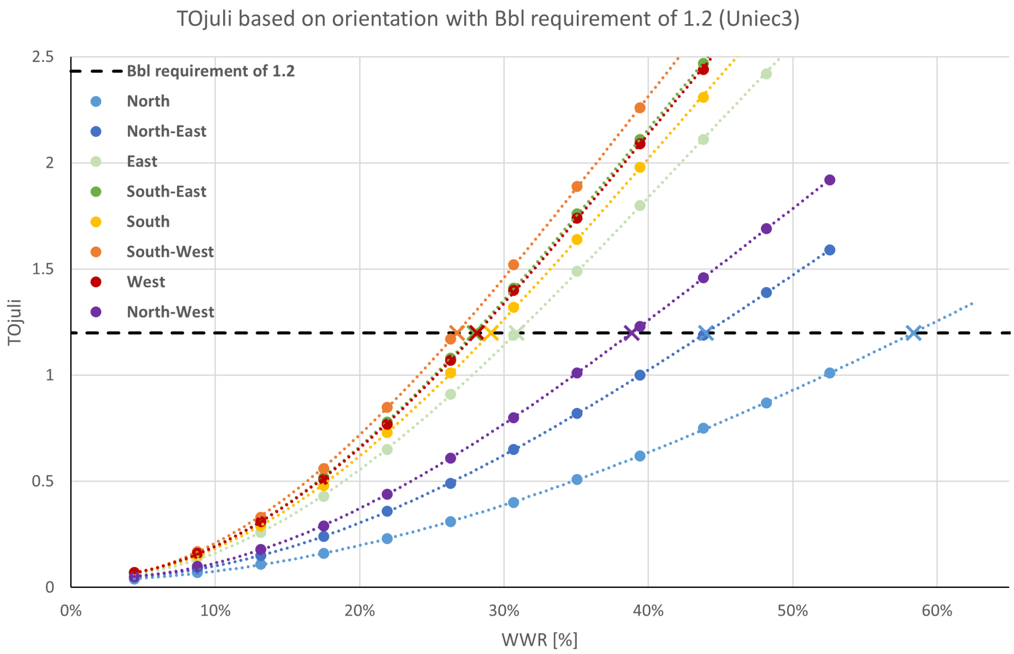


Figure 5.21: X-axis displays WWR and y-axis displays TO_{juli} of the apartment without cantilever, Color indicates the eight different orientations. The TO_{juli} values are calculated with Uniec3.

Orientation	max WWR in [%]
North	58 %
North-east	44 %
East	30 %
South-east	28 %
South	29 %
South-west	27 %
West	28 %
North-west	39 %

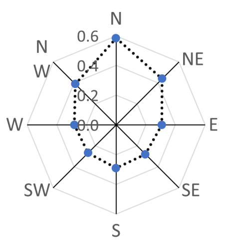


Table 5.6: Maximum window to wall ratio per orientation of the middle apartment without cantilever based on a TO_{juli} of 1.2 (Bbl requirement), calculated with Uniec3. Fixed boundaries, Rc value wall = 4.7 m^2K/W, floor = 3.7 m^2K/W, roof = 6.3 m^2K/W U value window = 1.6 $W/(m^2K)$, g-value glass = 0.6.

6
Conclusion

This chapter aims to provide an answer to the following question:

> **"What is the influence of window position and window size on daylight entrance according NEN-EN 17037, energy demand indicator BENG1 and TO_{juli} according NTA 8800, for typical Dutch dwellings using a parametric model?"**

For this purpose, a literature review is conducted in Chapter 2 on building regulations, daylight and energy efficiency, of which the conclusions are resented in Section 6.1. Following, a quantitative research has been carried out in Chapter 5 with the help of a parametric model created in Rhino Grasshopper and additional TO_{juli} values are calculated with Uniec3. The answers to the research questions answered with the help of the PM are found in Section 6.2. Finally, Section 6.3 presents some general conclusions and learnings on the methodology and workflow used.

6.1. Conclusion based on literature study

The literature shows that both sufficient daylight inside buildings and energy consumption are essential and relevant topics in research. Multiple methodologies exist using parametric design software, such as Rhino Grasshopper by Zhang et al. (2017) or energy plus by Méndez Echenagucia et al. (2015), thus indicating the usefulness of the approach. In combination with laws and regulations, the parametric approach to building physics is also a useful topic (Versteeg and Tilma, 2023).

After conducting extensive literature research, there are limited sources available covering the Netherlands. Although research conducted in China or Italy can provide guidance on methodology and scope, it cannot be used to determine results. Additionally, only limited research has been done on the (local) regulations that incorporate the theory of energy use by NTA 8800 and daylight by NEN-EN 17037. This is expected, since most academic research is done on theoretical models that follow the laws of physics and not on the simplifications or approximations made in the regulations. In case of a regulation change, the research done is considered negligent. Nevertheless, it can be useful to investigate regulations and find optimisations in the given regulation, since real-world projects are expected to comply with the regulation.

Ridder (2021) conducted a policy study in 2018-2019 to see what the differences were. The current and the new method differ so much that a 100% fit is not possible. The method of determination is radically different between the two standards (calculation rules vs. software simulation). Nevertheless, on average, the new requirement is not stricter than the current requirement. In fact, NEN-EN 17037 is less strict in situations where cantilevers cover part of the daylight opening but more rigid with regard to opposite obstructions. NEN 2057 is limited in that the positioning of the window is inconsequential in a scenario without any overhangs. Furthermore, a disadvantage of NEN 2057 is the fact that it does not assess the quality of daylight illuminance inside the room, which should be the ultimate goal of the standard. These flaws are obsolete with the new technique. The new standard asks for more determined boundary conditions for the simulation, such as reflection values of indoor surfaces (ceiling = 0.7, walls = 0.5, floor = 0.2), sizes of calculation grids (e.g.: 0.24m x 0.24m), and VLT-values (Bbl: VLT of 0.6). The outcomes are highly influenced by these factors, so making consistent selections is crucial for obtaining reliable results. For more information, see Table 2.2 in Chapter 2 which provides a comprehensive breakdown of similarities and differences between standards.

Furthermore, the NTA 8800 calculation method is quite comprehensive, requiring the need to make trade-offs in order to generate a manageable workload. Decisions must be made regarding which components are significant enough to be modelled and which ones can be omitted to reduce the workload while still obtaining meaningful outcomes.

6.2. Conclusions based on parametric model

In this parametric study, two different types of reference buildings are investigated, a middle apartment in an apartment building and a middle terraced house. The parameters used for this study are the orientation of the building, the height and width of the window (and therefore WWR), as well as vertical and horizontal positioning of the window.

6.2.1. Window-to-wall ratios

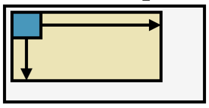
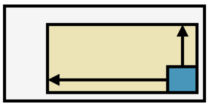
Orientation	**Lower WWR boundary in [%]**		**Upper WWR boundary in [%]**	
	From top 	**From bottom** 	**Top and bottom** (independent of Pos.)	
	Depending on Daylight		**BENG1**	**TO_{juli}**
		Terraced House		
North			**38** (26 - 44)	49
North-east			**30** (19 - 36)	45
East			**25** (15 - 32)	38
South-east	13 ± 1	22 ± 1	**34** (22 - 38)	**34**
South			41 (35 - 46)	**36**
South-west			**32** (22 - 36)	33
West			**25** (15 - 32)	35
North-west			**28** (19 - 36)	47
		Middle Apartment		
North			-	**60**
North-east			-	**52**
East			65 (62 - 68)	**37**
South-east	33 ± 1	46 ± 1	-	**39**
South			-	**48**
South-west			62 (59 - 65)	**36**
West			54 (52 - 57)	**33**
North-west			62 (59 - 65)	**45**

Table 6.1: Lower and upper WWR boundaries for every orientation of the terraced housing and middle apartment (with cantilever) based on a fixed geometric design with the window increasing form the top or the bottom, Rc value wall = 4.7 m^2K/W, floor = 3.7 m^2K/W, roof = 6.3 m^2K/W U value window = 1.6 $W/(m^2K)$, g-value glass = 0.6. The range is determined by the Bbl requirements of BENG1 below 55 kWh/m^2, TO_{juli} below 1.2 and an daylight factor of 1.0 for 50% of the reference plane.

Table 6.1 presents the ranges found of possible window-to-wall ratios for the two reference buildings investigated. The table presents two lower boundaries depending on the window position and two upper boundaries, which are based on BENG1 or TO_{juli} and are independent of the window position. The lower limit is defined by daylight requirements and the upper limit depends on BENG1 or TO_{juli}. If cooling is present in the building, TO_{juli} limit can be neglected and only BENG1 is applicable. The lower boundaries are independent of orientation, and therefore the WWR values are the same. The lower boundary of the apartment (33%) is strongly influenced by the present overhangs. The upper boundary values that are restricted by the BENG1 requirement come with an error margin stated in brackets, and TO_{juli} restrictions are stated with a single value. The results show that the maximum WWR for terraced housing is mostly restricted by the BENG1 requirement, except for the south orientation (36%), which is limited by TO_{juli}. Results showed that for the terraced house, TO_{juli} does not compromise daylight entry because a maximum TO_{juli} of 1.2 still allows for a daylight factor well above the required 1%. The BENG1 results show that a north-south orientation for terraced housing is best to minimise energy demand (WWRs of around 38% are possible until the requirements are exceeded). In contrast, the middle apartment is mainly restricted by the TO_{juli} requirement. This can be explained because the apartment has a relatively high compactness and therefore has a lower heating demand compared to the terraced house. Since the upper boundary of the WWR of the apartment is limited by TO_{juli} is can be interesting to apply cooling in the building. BENG1 will then be the limiting factor, in which the west orientation will be restricted by the energy demand requirements the fastest (54%). The PM demonstrated that the middle apartment always meets the BENG1 requirements in some orientations (N, NE, SE, S) and therefore no upper boundary due to BENG1 can be given. For the geometries studied, this research suggests a WWR for an apartment building roughly between 30% and 45% and for terraced housing roughly between 13% and 25 % as a starting point. These WWRs are highly dependent on the insulation values of the building, and it is also worth noting that the solution space can vary according to different room sizes and configurations.

6.2.2. Guidelines, rules, and statements

The results of this research indicate certain guidelines, rules, and statements that can be used when working with the new daylight regulations.

- **Linearity no longer valid:** As a consequence of the updated daylight standard from NEN 2057 to NEN-EN 17037, an increase in WWR no longer directly leads to a higher daylight factor, as it did under the current regulation. More specifically, the following cases are of interest:

- **Low glass has little contribution:** Based on the new standard NEN-EN 17037 glass below the reference surface of 0.85 metre contributes very little to the daylight factor. The glass situated beneath the reference surface is primarily valuable for providing a view outside.
- **Glass on sides less effective:** Based on the the new NEN-EN 17037 standard, glass located at the edges of a room has a lower impact on the daylight factor compared to glass positioned in the center of a facade. Therefore, it is recommended to install windows along the horizontal axis in the middle of the room for optimal daylighting.
- **Wide is better than high:** Based on the new standard NEN-EN 17037 wide and shallow windows are often better for daylight entry than narrow and high windows with the same WWR.
- **Focus on high positioning:** Based on the new NEN-EN 17037 standard, large windows can be best placed at the top of the facade to allow best daylighting of the room.
- **Cantilever influence:** The cantilever has a large influence on the lower WWR boundaries and TO_{juli}. In addition, the biggest daylight gains are made with glass approximately 0.8 m from the ceiling. A cantilever of 2.1 metres lowers that position to around 1.0 m from the ceiling.

Note that this categorisation is limited to analyses on the BENG1 value and is mainly valid for the parameters considered as input factors in this research. Changes in the properties of the glass g value, insulation, the addition of binds, or the change in the thermal mass of the building are not taken into account. The results and the influence of the parameters can differ, considering other indicators such as primary energy consumption (BENG2).

Furthermore, this study reveals clearly that despite the fact that energy demand and daylight are theoretically closely related, regulations are separated more. The daylight factor according to NEN-EN 17037 and BENG1 according to NTA 8800 are influenced by some separate parameters that have little influence on the other. For example, orientation is important for BENG1, but is irrelevant for daylight. The other way around, the position of the window is irrelevant for BENG1, but crucial for daylight entry. Therefore, daylight and energy demand are better separable (and individually optimised) in regulations than expected beforehand. The logic behind these decisions can be debated. Some may argue that in practice direct sunlight most definitely contributes a lot to daylight entry, hence orientation should also be considered in daylight regulations. This would lead to significantly different outcomes in daylight analysis. However, the standards are designed to guarantee a minimum daylight all year around and for north oriented facades a swell , so cloudy and overcast skies, which are very common in the Netherlands, are critical and thus the focus of attention.

6.3. General conclusions on methodology and workflow

Some general conclusions are drawn based on the methodology and workflow used to analyse a complex design problem in an early design stage:

- **Parametric modeling:** The development of a parametric model based on the NTA 8800 calculation method illustrates the potential of this approach. However, it highlights the need to make strategic simplifications to handle modelling tasks efficiently. This result states the importance of the balance between complexity and feasibility in parametric modelling.
- **Needed compromises:** Recognising the importance of making trade-offs in parameter selection for a parametric model is a key insight. Elements like scope, time management, modelling capability, model execution time, and data processing all play a role in making decisions in this study. Understanding these trade-offs is essential to obtain significant outcomes within the limitations of the project.
- **From data to information:** The parametric design approach provides a structure to address architectural challenges. By carefully selecting suitable parameters and then translating the data into practical knowledge, designers can access solutions to complex problems. This shows the ability of a PM to encourage creative exploration and problem solving.
- **Tools for exploration and optimisation:** The Thornton Tomasetti software Thread provides an excellent online data tool to investigate a parametric design and quickly find good solutions that meet specific requirements. However, the ability to visualise and edit your data in different ways is limited. Finding the strengths and limitations of tools is essential to maximise utility in the design process.
- **Robustness of the methodology:** The methodology used demonstrates its robustness and practicality in analysing complex problems and obtaining validated results. Its systematic approach provides clarity and reliability in the early design phase, enabling designers to avoid uncertainties and make decisions on quickly found results.

In conclusion, the adoption of a parametric design approach offers numerous advantages when looking at housing window design, significantly increasing the efficiency and flexibility of the architectural process. Therefore, the methodology used can be recommended for further research and larger design projects in practice.

7

Recommendation

7.1. Recommendations for future building designers and advisors

Recommendations for building designers mainly follow from the conclusions stated in the previous chapter.

For terraced housing, a north-south orientation is best to minimise energy demand. Windows should be placed in the middle of a facade in terms of horizontal position and in the upper part of the facade in terms of vertical position to maximise daylight entry. Glass below the reference surface height of 0.85m should be avoided. As a first design step, the WWR for terraced housing should be established between 13% and 25% to ensure that it meets the requirements of Bbl. For an apartment with cantilever balconies and no cooling, the WWR should be between 30% and 45% to allow enough daylight inside the rooms. Cooling is of interest for the apartment to allow to disregard TO_{juli} and increase WWR substantially.

Furthermore, when working on comprehensive design projects, make use of some sort of parametric analysis to quickly explore your possibilities. It is a great tool to quickly get a grasp of the situation and decide in which direction the most steps can be taken. Especially projects with complex geometries, projects asking for an optimisation, or projects in which a lot of changes are expected, are suitable for parametric analysis.

7.2. Recommendations for future research

Future research with a similar parametric model should consider analysing the WWR per orientation of the building facade independently. The choice of linking the sizes of the terraced housing windows to each other massively reduces the number of parameters and makes the model simpler but leaves out the possibility of creating facades with different sizes of windows. Since different orientated facades will result in different optimal WWRs, it will be better to disconnect the facade analysis for every orientation to get more adequate results. On top of that, some simplifications were made in terms of calculating ventilation losses Q_{ve} and the internal calculation temperature for heating $T_{int,calc,H}$ which caused some inaccuracy, especially for TO_{juli}. Therefore, it could not be used as a requirement tester but only as a rough indication. Future models could try to include these calculations in more detail to achieve more accurate outcomes.

This research does not take into account the cost of construction materials and options for different glass and other g-values. Opting for pricier windows with lower g values could potentially decrease the energy demand. Future research could explore variations in the U and g values of such glass and their impact on the ideal WWR of the structure. However, this aspect was not within the scope of the current study. Additionally, the external and internal blinds may be subject to further examination. When used effectively, energy conservation is achievable, although it may lead to a different optimal WWR.

Future successors may consider modelling larger structures, such as high-rise residential buildings. This study was limited to the BENG1 values of a single apartment in an apartment building. It can be of interest to model a hole building and also to take into account the shared spaces. In terms of kWh/m^2 other outcomes can be expected and a more complete picture of the energy demand can be created.

Bibliography

Alavirad, S., Mohammadi, S., Hoes, P. J., Xu, L., & Hensen, J. L. (2022). Future-Proof Energy-Retrofit strategy for an existing Dutch neighbourhood. Energy and Buildings, 260, 111914. https://doi.org/10.1016/J.ENBUILD.2022.111914

Alhagla, K., Mansour, A., & Elbassuoni, R. (2019). Optimizing windows for enhancing daylighting performance and energy saving. Alexandria Engineering Journal, 58(1), 283–290. https://doi.org/10.1016/J.AEJ.2019.01.004

Bokel, R. (2007). The effect of window position and window size on the energy demand for heating, cooling and electric lighting. IBPSA 2007 - International Building Performance Simulation Association 2007, 117–121.

Boubekri, M., Cheung, I., Reid, K., Wang, C.-H., & Zee, P. (2014). Impact of windows and daylight exposure on overall health and sleep quality of office workers: A case-control pilot study. Journal of Clinical Sleep Medicine, 10(6), 603–611. https://doi.org/10.5664/jcsm.3780

Bouwtrend B.V. (2023). Uniec3. uniec3.nl

Brandi, U. (2006). Lighting Design. Birkhäuser. https://doi.org/doi:10.11129/detail.9783034615693

CenterNovem. (2006). Referentiewoningen nieuwbouw (tech. rep.). https://zoek.officielebekendmakingen.nl/blg-214992.pdf

Centraal Bureau voor de Statistiek. (2022). 42 procent van alle woningen is een rijtjeshuis. https://www.cbs.nl/nl-nl/nieuws/2022/31/42-procent-van-alle-woningen-is-een-rijtjeshuis

Daniel Koster. (2023). Integrating urban context in daylighting simulation (tech. rep.). Delft University of Technology. http://resolver.tudelft.nl/uuid:ec15c377-36d0-412b-8ace-736db2492a5a

Dobbelsteen, A. (2008). De nieuwe stappenstrategie. Duurzaam Gebouwd. https://www.duurzaamgebouwd.nl/artikel/20080520-de-nieuwe-stappenstrategie

Dorresteijn, B. C. (2020). Shape optimisation of residential mid-rise buildings for reduction of energy demand in temperate climate (tech. rep.). http://resolver.tudelft.nl/uuid:bbdf4ff9-2cff-4756-a59f-33fa49ed4dc0

European Commission. (2016). Nearly zero-energy buildings. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/nearly-zero-energy-buildings_en

Evans, G. W. (2003). The built environment and mental health. Journal of Urban Health, 80(4), 536–555. https://doi.org/10.1093/jurban/jtg063

Ghisi, E., & Tinker, J. A. (2005). An Ideal Window Area concept for energy efficient integration of daylight and artificial light in buildings. Building and Environment, 40(1), 51–61. https://doi.org/10.1016/J.BUILDENV.2004.04.004

Greenup, P. J., & Edmonds, I. R. (2004). Test room measurements and computer simulations of the micro-light guiding shade daylight redirecting device. Solar Energy, 76(1), 99–109. https://doi.org/https://doi.org/10.1016/j.solener.2003.08.018

International Organization for Standardization. (2004). ISO 15469:2004 Spatial distribution of daylight — CIE standard general sky. https://www.iso.org/standard/38608.html

Kafaei, M. (2021). Sensitivity Analysis of NTA8800 for a Dutch Building Renovation Tendering System. https://tki-bouwentechniek.nl/wp-content/uploads/4.2_BTIC_Sensitivity_Analysis-MKafaei-Edited1.pdf

Kusiak, A., Li, M., & Tang, F. (2010). Modeling and optimization of HVAC energy consumption. Applied Energy, 87(10), 3092–3102. https://doi.org/10.1016/J.APENERGY.2010.04.008

Ladybug Tools. (2022). Ladybug. https://www.food4rhino.com/en/app/ladybug-tools#downloads_list

Legates, T. A., Fernandez, D. C., & Hattar, S. (2014). Light as a central modulator of circadian rhythms, sleep and affect. Nature Reviews Neuroscience, 15(7), 443–454. https://doi.org/10.1038/nrn3743

Marsh, A. J. (2018). CIE Sky Generator. https://andrewmarsh.com/software/cie-sky-web/

Méndez Echenagucia, T., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. Applied Energy, 154, 577–591. https://doi.org/10.1016/J.APENERGY.2015.04.090

Mengying, S. (2023). A Framework for On-the-fly Energy Calculation of BIM Models (tech. rep.). http://resolver.tudelft.nl/uuid:9fbcf4b1-7d98-47be-9195-8c5cf492a823
Nair, G., Mahapatra, K., & Gustavsson, L. (2012). Implementation of energy-efficient windows in Swedish single-family houses. Applied Energy, 89(1), 329–338. https://doi.org/10.1016/J.APENERGY.2011.07.040
Nederlands Normalisatie Instituut. (2011). NEN 2057 - Daglichtopeningen van gebouwen-Bepaling van de equivalente daglichtoppervlakte van een ruimte / Daylight openings of buildings-Determination method of the equivalent daylight of a space. https://www.nen.nl/nen-2057-2011-nl-160378
Nederlands Normalisatie Instituut. (2021). NEN 5060+A1 - Hygrothermische eigenschappen van gebouwen-Referentieklimaatgegevens / Hygrothermal performance of buildings-Climatic reference data (tech. rep.). www.nen.nl
Nederlands Normalisatie Instituut. (2022a). NEN-EN 17037+A1 - Daglicht in gebouwen / Daylight in buildings. https://www.nen.nl/nen-en-17037-2018-a1-2022-en-291224
Nederlands Normalisatie Instituut. (2022b). NPR 4057 - Daglicht in gebouwen - Toelichting op NEN-EN 17037 / Daylight in buildings - Guidance for NEN-EN 17037. https://connect.nen.nl/Standard/Detail/3666007?compId=10037&collectionId=0
Nederlands Normalisatie Instituut. (2023). NTA 8800:2023 - Energieprestatie van gebouwen-Bepalingsmethode / Energy performance of buildings-Determination method. https://www.nen.nl/nta-8800-2023-nl-304951
Obex b.v. (2017). Basisboek Algemene Brandpreventie.
Ochoa, C., Aries, M., van Loenen, E., & Hensen, J. (2012). Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort. Applied Energy, 95, 238–245. https://doi.org/10.1016/j.apenergy.2012.02.042
Projectgroep NTA 8800. (2020). Randvoorwaardendocument NTA 8800 (versie behorende bij NTA 8800:2020) (tech. rep.). https://www.gebouwenergieprestatie.nl/app/uploads/sites/8/2020/09/Randvoorwaardendocument-NTA-8800-1.pdf
Reinhart, C. (2020). Daylighting Handbook I (2nd ed.). Building Technology Press.
Ridder, H. (2021). NEN/beleidsstudie daglicht effect Europese norm (tech. rep.). https://www.rijksoverheid.nl/documenten/rapporten/2021/12/21/beleidsstudie-daglicht-effect-europese-norm
Rijksdienst voor Ondernemend Nederland. (2013). Infoblad Trias Energetica en energieneutraal bouwen (tech. rep.). Rijksdienst voor Ondernemend Nederland. Utrecht. https://www.rvo.nl/sites/default/files/Infoblad%20Trias%20Energetica%20en%20energieneutraal%20bouwen-juni%202013.pdf
Rijksdienst voor Ondernemend Nederland. (2017). Energieprestatie - BENG. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/beng
Rijksdienst voor Ondernemend Nederland. (2022). Voorbeeldwoningen 2022 bestaande bouw In opdracht van het ministerie van Binnenlandse Zaken en Koninkrijksrelaties (tech. rep.). Den Haag. https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/voorbeeldwoningen-bestaande-bouw#gebruik-voorbeeldwoningen
Robert McNeel & Associates. (2023). Rhino7. https://www.rhino3d.com/
Scott Davidson. (2023). Grasshopper. https://www.grasshopper3d.com/
Sewtahal, J. (2023). SO BENG 1 Script - Een parametrische BENG 1 tool voor de SO-fase (tech. rep.). https://dgmr.nl/wp-content/uploads/2023/07/Whitepaper-Een-parametrische-BENG-1-tool-voor-de-SO-fase.pdf
Shishegar, N., & Boubekri, M. (2016). Natural Light and Productivity: Analyzing the Impacts of Daylighting on Students' and Workers' Health and Alertness. https://www.researchgate.net/publication/303484362_Natural_Light_and_Productivity_Analyzing_the_Impacts_of_Daylighting_on_Students'_and_Workers'_Health_and_Alertness
Solemma. (2023). ClimateStudio. https://www.solemma.com/climatestudio
Stegou-Sagia, A., Antonopoulos, K., Angelopoulou, C., & Kotsiovelos, G. (2007). The impact of glazing on energy consumption and comfort. Energy Conversion and Management, 48(11), 2844–2852. https://doi.org/https://doi.org/10.1016/j.enconman.2007.07.005
Sweco Nederland b.v. (2023). kv_rördrommen_10. https://pickitmedialive.blob.core.windows.net/sweco-thumbnails/onnAe8hG?sv=2020-10-02&st=2024-02-26T10%3A44%3A10Z&se=2024-02-26T11%3A14%3A10Z&sr=c&sp=r&sig=vnjOMdZmYc2fnX2g3dQCNyZPtmqqr1Hpa%2BeF9Wkm7FQ%3D
Thornton Tomasetti. (2024). THREAD. https://www.thorntontomasetti.com/capability/thread

Tim Schouws. (2022). Measuring Daylight: the New European Standard and the effect on Green Building Certificates (tech. rep.). http://resolver.tudelft.nl/uuid:c78ad7cd-2ba2-4abe-abab-d7b8b97f1736

Timur. (2014). ARCHSIM energy modeling for GH. https://www.food4rhino.com/en/app/archsim-energy-modeling-gh

Touloupaki, E., & Theodosiou, T. (2017). Energy Performance Optimization as a Generative Design Tool for Nearly Zero Energy Buildings. Procedia Engineering, 180, 1178–1185. https://doi.org/10.1016/J.PROENG.2017.04.278

Vabi. (2023). Vabi. www.vabi.nl

Van der Linden, A., Kuijpers-van Gaalen, I., & Zeegers, A. (2018). Building Physics (A. Van der Linden, Ed.; 1st ed.). ThiemeMeulenhoff bv.

Verbaan, G. (2022). Daglicht is Gezond. Bouwfysica, 2, 5–9. https://dgmr.nl/wp-content/uploads/2022/11/Artikel-Bouwfysicablad-Verbaan-2-2022.pdf

Versteeg, H., & Tilma, S. G. (2023). Bierviltje of parametrisch model: Concurrenten of onafscheidelijk duo? Bouwfysica, 1, 2–3.

Waldram, P. J. (1925). The natural and artificial lighting of buildings. The Journal of the Royal Institute of British Architects, 32(13), 9.

Willems, M. (2022). Licht op daglichtsimulaties. Bouwfysica, 2, 10–13.

Zhang, A., Bokel, R., van den Dobbelsteen, A., Sun, Y., Huang, Q., & Zhang, Q. (2017). Optimization of thermal and daylight performance of school buildings based on a multi-objective genetic algorithm in the cold climate of China. Energy and Buildings, 139, 371–384. https://doi.org/10.1016/j.enbuild.2017.01.048

Zheng, C., Xu, W., Wang, L., Cao, X., Li, M., & Zhang, A. (2023). Multi-objective optimization of energy, thermal and visual comfort for dormitory buildings in the cold climate of China. Indoor and Built Environment, 1420326X231194314. https://doi.org/10.1177/1420326X231194314

A

Besluit Bouwwerken Leefomgeving

In Appendix A, Article 4.3.10 and Article 4.149 of Besluit bouwwerken leefomgeving are presented for the use of daylight, energy, and overheating. This regulation is in effect from 2024. An exception is made for daylight regulations based on NEN-EN 17037. The BRIS states the following:

> "The entry into force of the new daylight requirements based on NEN-EN 17037 will not take effect until 1 January 2026. A decision on entry into force on 1 January 2026 will be taken in 2025."

§ 4.3.10 Daglicht

Artikel 4.146 (aansturingsartikel)

1. Een bouwwerk is zodanig dat daglicht in voldoende mate kan toetreden.

2. Als voor een gebruiksfunctie in tabel 4.146 regels zijn aangewezen, wordt voor die gebruiksfunctie aan het eerste lid voldaan door naleving van die regels.

[1] *De voorgenomen wijzigingen in het opschrift en lid 1, 2, 3 en 8 van artikel 4.147 in Stb. 2020, 360 (artikel II, onderdeel D) treden nog niet in werking. Zie inwerkingtredingsbesluit Stb. 2023, 113, onderdeel 63.*

[**BRIS opmerking**: ***De inwerkingtreding van de nieuwe daglichteisen op basis van NEN-EN 17037 treedt niet eerder in werking dan 1 januari 2026 Een beslissing over de inwerkingtreding op 1 januari 2026 wordt in 2025 genomen.]***

Tabel 4.146

	gebruiksfunctie	leden van toepassing								waarden	
		daglichtfactor								daglichtfactor	
	artikel	4.147								4.147	
	lid	1	2	3	4	5	6	7	8	1 [%]	2 [%]
1	Woonfunctie	1	2	3	–	–	–	–	–	1	0,8
2	Bijeenkomstfunctie										
	a voor kinderopvang	1	2	3	4	5	–	–	–	0,5	0,4
	b andere bijeenkomstfunctie	–	–	–	–	–	–	–	–	–	–
3	Celfunctie	1	2	3	4	–	6	–	–	0,4	0,4
4	Gezondheidszorgfunctie	1	2	3	4	–	–	7	–	0,5	0,4
5	Industriefunctie	–	–	–	–	–	–	–	–	–	–
6	Kantoorfunctie	1	2	3	4	–	–	–	–	0,4	0,3
7	Logiesfunctie	–	–	–	–	–	–	–	–	–	–
8	Onderwijsfunctie	1	2	3	4	–	–	–	8	0,5	0,4
9	Sportfunctie	–	–	–	–	–	–	–	–	–	–
10	Winkelfunctie	–	–	–	–	–	–	–	–	–	–
11	Overige gebruiksfunctie	–	–	–	–	–	–	–	–	–	–
12	Bouwwerk geen gebouw zijnde	–	–	–	–	–	–	–	–	–	–

Tabel 4.146[1] treedt in werking op een bij koninklijk besluit te bepalen tijdstip en komt te luiden zoals hierboven

Tabel 4.146

Toon aansturingstabel

Artikel 4.147 (daglichtoppervlakte)

Toon leden van toepassing en grenswaarden voor artikel 4.147

[**BRIS opmerking**: *De voorgenomen wijzigingen in het opschrift en lid 1, 2, 3 en 8 van artikel 4.147 in Stb. 2020, 360 (artikel II, onderdeel D) treden nog niet in werking. Zie inwerkingtredingsbesluit Stb. 2023, 113, onderdeel 63. Het opschrift van dit artikel treedt in werking op een bij koninklijk besluit te bepalen tijdstip. De tekst van dit opschrift luidt dan: (daglichtfactor).*

De inwerkingtreding van de nieuwe daglichteisen op basis van NEN-EN 17037 treedt niet eerder in werking dan 1 januari 2026 Een beslissing over de inwerkingtreding op 1 januari 2026 wordt in 2025 genomen.]

1. Een verblijfsgebied heeft een volgens NEN 2057 bepaalde equivalente daglichtoppervlakte in m^2 waarvan de getalswaarde niet kleiner is dan de getalswaarde van het in tabel 4.146 aangegeven deel van de vloeroppervlakte in m^2 van dat verblijfsgebied.

Dit lid treedt in werking op een bij koninklijk besluit te bepalen tijdstip. De tekst van dit lid luidt dan:

Een verblijfsgebied heeft op ten minste 50% van de vloeroppervlakte een volgens NEN-EN 17037 bepaalde daglichtfactor die niet kleiner is dan de in tabel 4.146 aangegeven getalswaarde.

2. Een verblijfsruimte heeft een volgens NEN 2057 bepaalde equivalente daglichtoppervlakte die niet kleiner is dan de in tabel 4.146 aangegeven oppervlakte.

Dit lid treedt in werking op een bij koninklijk besluit te bepalen tijdstip. De tekst van dit lid luidt dan:

Een verblijfsruimte heeft op ten minste 50% van de vloeroppervlakte een volgens NEN-EN 17037 bepaalde daglichtfactor die niet kleiner is dan de in tabel 4.146 aangegeven getalswaarde.

3. Bij het bepalen van de equivalente daglichtoppervlakte:

a. blijven buiten het bouwwerkperceel gelegen belemmeringen buiten beschouwing;
b. blijven daglichtopeningen in een uitwendige scheidingsconstructie die op een loodrecht op het projectievlak van die openingen gemeten afstand van minder dan 2 m vanaf de bouwwerkperceelsgrens liggen, buiten beschouwing, waarbij, als het bouwwerkperceel grenst aan een openbare weg, openbaar water of openbaar groen, de afstand wordt aangehouden tot het hart van die weg, dat water of dat groen; en
c. is de in rekening te brengen belemmeringshoek α, bedoeld in NEN 2057, voor elk te onderscheiden segment niet kleiner dan 20°

Dit lid treedt in werking op een bij koninklijk besluit te bepalen tijdstip. De tekst van dit lid luidt dan:

Bij het bepalen van de daglichtfactor:

a. *blijven buiten het bouwwerkperceel gelegen belemmeringen buiten beschouwing; en*
b. *blijven belemmeringen door bomen en andere objecten van tijdelijke aard of veranderlijke omvang buiten beschouwing;*
c. *blijven daglichtopeningen die minder dan 2 m vanaf de bouwwerkperceelgrens liggen, buiten beschouwing. Deze afstand wordt gemeten rechthoekig uit de buitenkant van de uitwendige scheidingsconstructie daar, waar de opening is gemaakt, tot aan de grenslijn van het bouwwerkperceel, of als het bouwwerkperceel grenst aan een openbare weg, openbaar water of openbaar groen, tot aan het hart van die weg, dat water of dat groen.*

4. Het eerste en tweede lid gelden niet voor een bouwwerk of een gedeelte daarvan voor de landsverdediging of de bescherming van de bevolking.

5. Het eerste en tweede lid gelden niet voor een bedgebied dat niet ook is bestemd voor spelactiviteiten.

6. In afwijking van het eerste lid en tweede lid kan in een celeenheid of andere ruimte voor het insluiten van personen worden volstaan met het waarneembaar zijn van de dag- en nachtcyclus.

7. Het eerste en tweede lid gelden alleen voor een bedgebied.

8. Bij de bepaling van de in het eerste lid bedoelde vloeroppervlakte van een verblijfsgebied blijft een verblijfsruimte met een vloeroppervlakte van meer dan 150 m2 buiten beschouwing. Op een dergelijke verblijfsruimte is het tweede lid niet van toepassing.

Dit lid treedt in werking op een bij koninklijk besluit te bepalen tijdstip. De tekst van dit lid luidt dan:

Het eerste en tweede lid zijn niet van toepassing op:

a. *een niet nader in te delen gebruiksgebied met een vloeroppervlakte van meer dan 150 m^2 ; of*
b. *een verblijfsruimte met een vloeroppervlakte van meer dan 150 m^2.*

Artikel 4.149 (bijna energieneutraal)

Verberg leden van toepassing en grenswaarden voor artikel 4.149

gebruiksfunctie	leden van toepassing					waarden		
	bijna energieneutraal					bijna energieneutraal		
artikel	4.149					4.149		
lid	1	2	3	4	5	1		
						Energiebehoefte	Primair fossiel energiegebruik	Aandeel hernieuwbare energie
						[kWh/m^2.jr]	[kWh/m^2.jr]	[%]
						(1) geldt als $A_{ls}/A_g \leq 1{,}83$ (2) geldt als $A_{ls}/A_g > 1{,}83$ en $\leq 3{,}0$ (3) geldt als $A_{ls}/A_g > 3{,}0$ (4) geldt als $A_{ls}/A_g \leq 1{,}5$ (5) geldt als $A_{ls}/A_g > 1{,}5$ en $\leq 3{,}0$ (6) geldt als $A_{ls}/A_g \leq 1{,}8$ (7) geldt als $A_{ls}/A_g > 1{,}8$		
1 Woonfunctie								
a woongebouw	1	–	3	4	5	(1) 65	50	40

							(2) 55 + 30 x $(A_{ls}/A_g - 1{,}5)$		
							(3) 100 + 50 x $(A_{ls}/A_g - 3{,}0)$		
	b woonwagen	1	–	–	4	–	100 + 30 x $(A_{ls}/A_g - 2{,}0)$	60	50
	c drijvend bouwwerk na 1 januari 2018 gerealiseerde ligplaats	1	–	–	4	–	80 + 30 x $(A_{ls}/A_g - 1{,}5)$	50	50
	d drijvend bouwwerk andere ligplaats	1	–	–	4	–	80 + 30 x $(A_{ls}/A_g - 1{,}5)$	70	50
	e andere woonfunctie	1	–	–	4	5	(4) 55	30	50
							(5) 55 + 30 x $(A_{ls}/A_g - 1{,}5)$		
							(3) 100 + 50 x $(A_{ls}/A_g - 3{,}0)$		
2	Bijeenkomstfunctie								
	a voor kinderopvang	1	2	–	–	–	(6) 160	70	40
							(7) 160 + 30 x $(A_{ls}/A_g - 1{,}8)$		
	b andere bijeenkomstfunctie	1	2	–	–	–	(6) 90	60	30
							(7) 90 + 30 x $(A_{ls}/A_g - 1{,}8)$		
3	Celfunctie	1	2	–	–	–	(6) 160	120	30
							(7) 160 + 35 x $(A_{ls}/A_g - 1{,}8)$		
4	Gezondheidszorgfunctie								
	a met bedgebied	1	2	–	–	–	350	130	30
	b andere gezondheidszorgfunctie	1	2	–	–	–	(6) 90	50	40
							(7) 90 + 35 x $(A_{ls}/A_g - 1{,}8)$		
5	Industriefunctie	–	–	–	–	–	–	–	–
6	Kantoorfunctie	1	2	–	–	–	(6) 90	40	30
							(7) 90 + 30 x $(A_{ls}/A_g - 1{,}8)$		
7	Logiesfunctie								
	a in een logiesgebouw	1	2	–	–	–	(6) 100	130	40
							(7) 100 + 35 x $(A_{ls}/A_g - 1{,}8)$		
	b andere logiesfunctie	1	2	–	–	5	(4) 55	40	50
							(5) 55 + 30 x $(A_{ls}/A_g - 1{,}5)$		
							(3) 100 + 50 x $(A_{ls}/A_g - 3{,}0)$		
8	Onderwijsfunctie	1	2	–	–	–	(6) 190	70	40

							(7) 190 + 30 x (A_{ls}/A_g - 1,8)		
9 Sportfunctie	1	2	–	–	–		(6) 40	90	30
							(7) 40 + 15 x (A_{ls}/A_g - 1,8)		
10 Winkelfunctie	1	2	–	–	–		(6) 70	60	30
							(7) 70 + 30 x (A_{ls}/A_g - 1,8)		
11 Overige gebruiksfunctie	–	–	–	–	–		–	–	–
12 Bouwwerk geen gebouw zijnde	–	–	–	–	–		–	–	–

1. Een gebruiksfunctie heeft, bepaald volgens NTA 8800, een energiebehoefte en een primair fossiel energiegebruik van ten hoogste de in tabel 4.148A aangegeven waarden en een aandeel hernieuwbare energie van tenminste de in die tabel aangegeven waarde.

2. In afwijking van het eerste lid worden bij een gebouw of een gedeelte daarvan, dat op niet meer dan een perceel ligt, met meerdere gebruiksfuncties niet van dezelfde soort, waarvoor volgens het eerste lid een eis geldt, bepaald volgens NTA 8800, de waarden voor energiebehoefte en primair fossiel energiegebruik en hernieuwbare energie naar gebruiksoppervlak gewogen. Bij het bepalen van die waarden wordt per gebruiksunctie uitgegaan van de in tabel 4.148A aangegeven waarden.

3. Bij toepassing van dit artikel gelden voor een nevengebruiksfunctie van de woonfunctie de eisen aan de woonfunctie.

4. Bij toepassing van dit artikel op een gebruiksfunctie in een gebouw of een gedeelte daarvan, met een naar gebruiksoppervlak gewogen gemiddelde specifieke interne warmtecapaciteit van 180 kJ/m²K of minder, bepaald volgens NTA 8800, worden de in tabel 4.148A aangegeven maximumwaarden voor energiebehoefte verhoogd met 5 kWh/m² .jr.

Artikel 4.149b (voorkomen oververhitting)

Verberg leden van toepassing en grenswaarden voor artikel 4.149b

gebruiksfunctie	leden van toepassing		
	voorkomen oververhitting		
artikel	4.149b		
lid	1	2	3
1 Woonfunctie			
a woongebouw	1	2	3
b woonwagen	–	–	–
c drijvend bouwwerk na 1 januari 2018 gerealiseerde ligplaats	–	–	–
d drijvend bouwwerk andere ligplaats	–	–	–
e andere woonfunctie	1	2	3
2 Bijeenkomstfunctie			
a voor kinderopvang	–	–	–
b andere bijeenkomstfunctie	–	–	–
3 Celfunctie	–	–	–
4 Gezondheidszorgfunctie			
a met bedgebied	–	–	–
b andere gezondheidszorgfunctie	–	–	–
5 Industriefunctie	–	–	–
6 Kantoorfunctie	–	–	–

7	Logiesfunctie			
	a in een logiesgebouw	–	–	–
	b andere logiesfunctie	–	–	–
8	Onderwijsfunctie	–	–	–
9	Sportfunctie	–	–	–
10	Winkelfunctie	–	–	–
11	Overige gebruiksfunctie	–	–	–
12	Bouwwerk geen gebouw zijnde	–	–	–

1. Een woonfunctie heeft, bepaald volgens paragraaf 5.7 van NTA 8800, een waarde voor oververhitting van ten hoogste 1,20 voor iedere rekenzone en oriëntatie.

2. Als de hoogst berekende waarde voor oververhitting bij een niet in een woongebouw gelegen woonfunctie meer dan 1,20 is, wordt met een berekening aangetoond dat het totaal aantal gewogen overschrijdingsuren in elke verblijfsruimte van die woonfunctie op jaarbasis niet meer dan 450 is.

3. Als in een woongebouw bij een of meer woonfuncties binnen dat woongebouw de hoogst berekende waarde voor oververhitting meer dan 1,20 is, wordt bij de woonfunctie met de hoogst berekende waarde voor oververhitting met een berekening aangetoond dat het aantal gewogen overschrijdingsuren in elke verblijfsruimte van die woonfunctie op jaarbasis niet meer dan 450 is.

B

Rhino Grasshopper Script and Python Codes

In Appendix B, the Grasshopper script and the corresponding Python codes are documented. The sections are structured in the same way as the script. First, the base geometry is discussed, followed by the parametric windows. Then the analysis is done on daylight and energy demand. The last section shows the script to complete the parameter study.

B.1. Base geometry

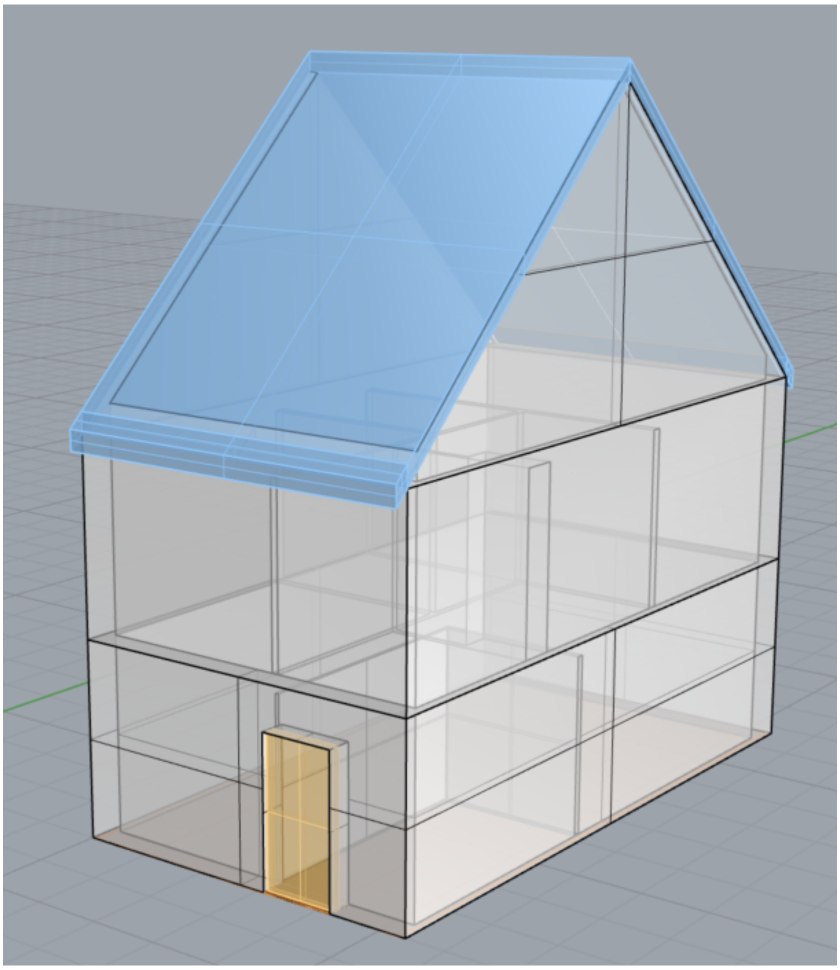


Figure B.1: The fixed 3D geometry of the terraced housing, which is created in Rhino.

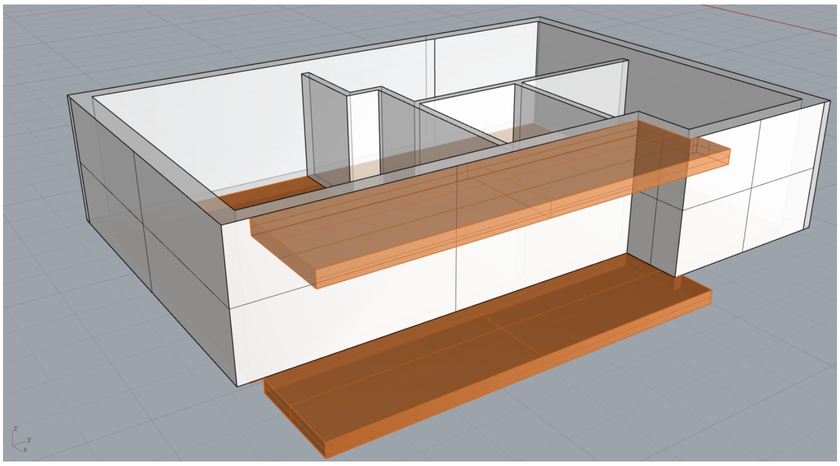
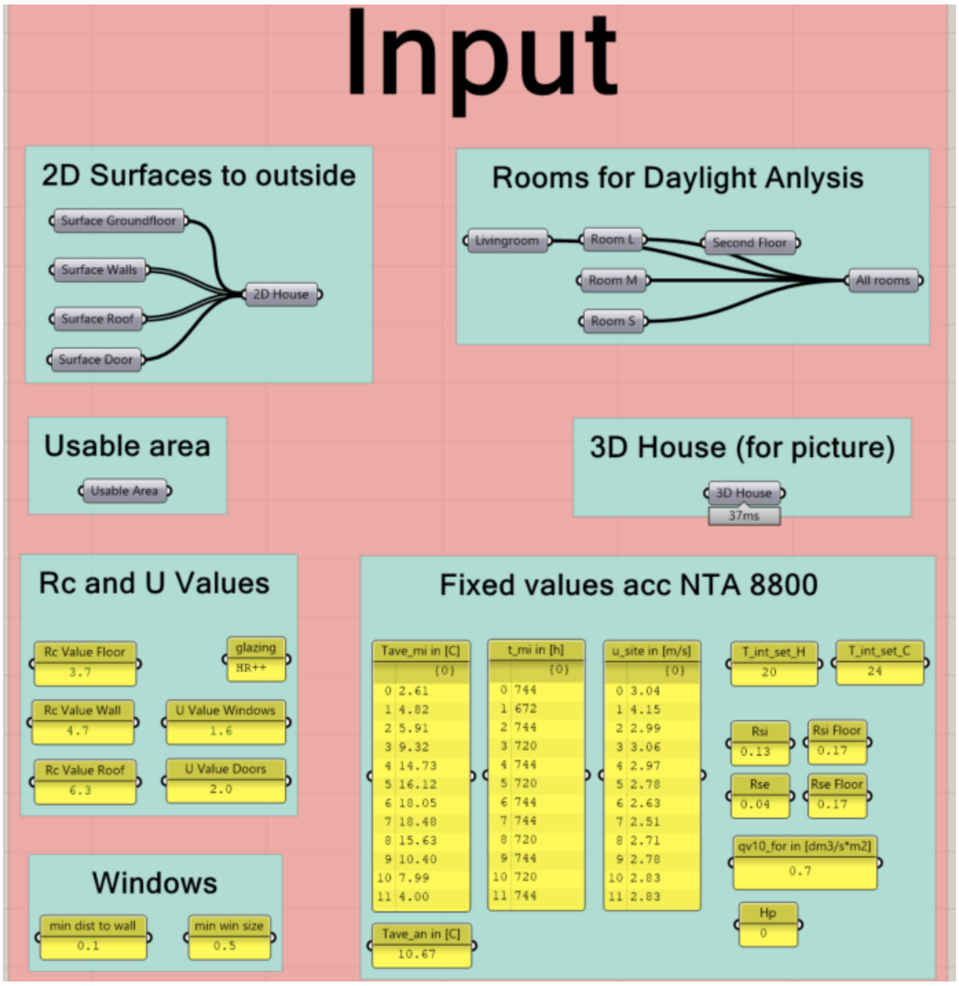
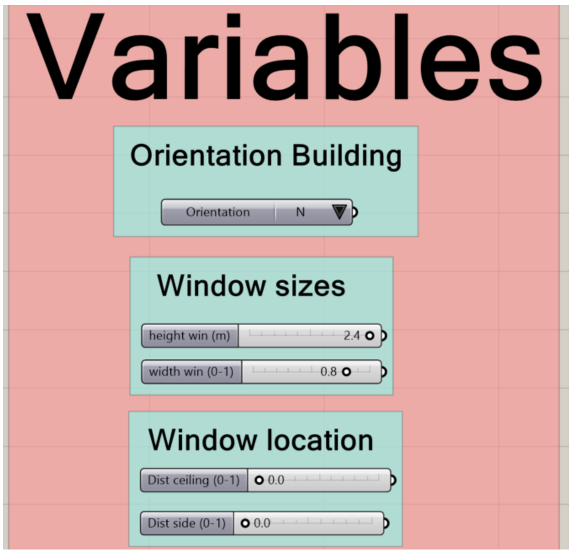


Figure B.2: The fixed 3D geometry of the middle apartment, which is created in Rhino.

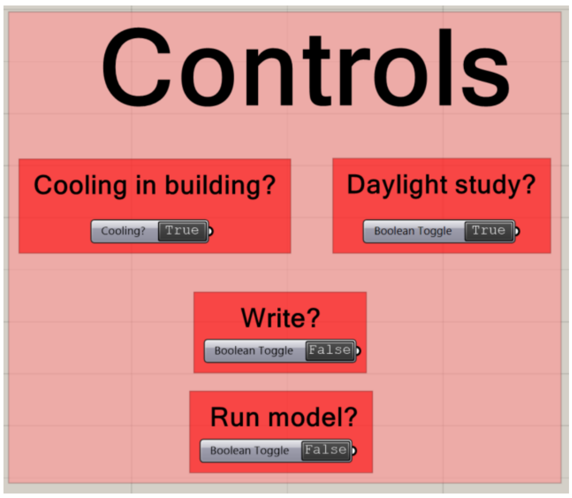


	Tave_mi in [C]	t_mi in [h]	u_site in [m/s]
0	2.61	744	3.04
1	4.82	672	4.15
2	5.91	744	2.99
3	9.32	720	3.06
4	14.73	744	2.97
5	16.12	720	2.78
6	18.05	744	2.63
7	18.48	744	2.51
8	15.63	720	2.71
9	10.40	744	2.78
10	7.99	720	2.83
11	4.00	744	2.83

Figure B.3: The input panel of the Grasshopper script incorporates the fixed geometry of the building. Additionally, it shows the values provided by the NTA 8800 and determines other important values such as Rc and U values.



(a) Variables used in the PM. The first parameter is the orientation of the building. To restrict the number of possible solutions to a manageable amount, the window parameters are bundled together. This results in windows that cannot change in size independently of each other.



(b) All the toggles of the script in one place.

B.2. Parametric windows

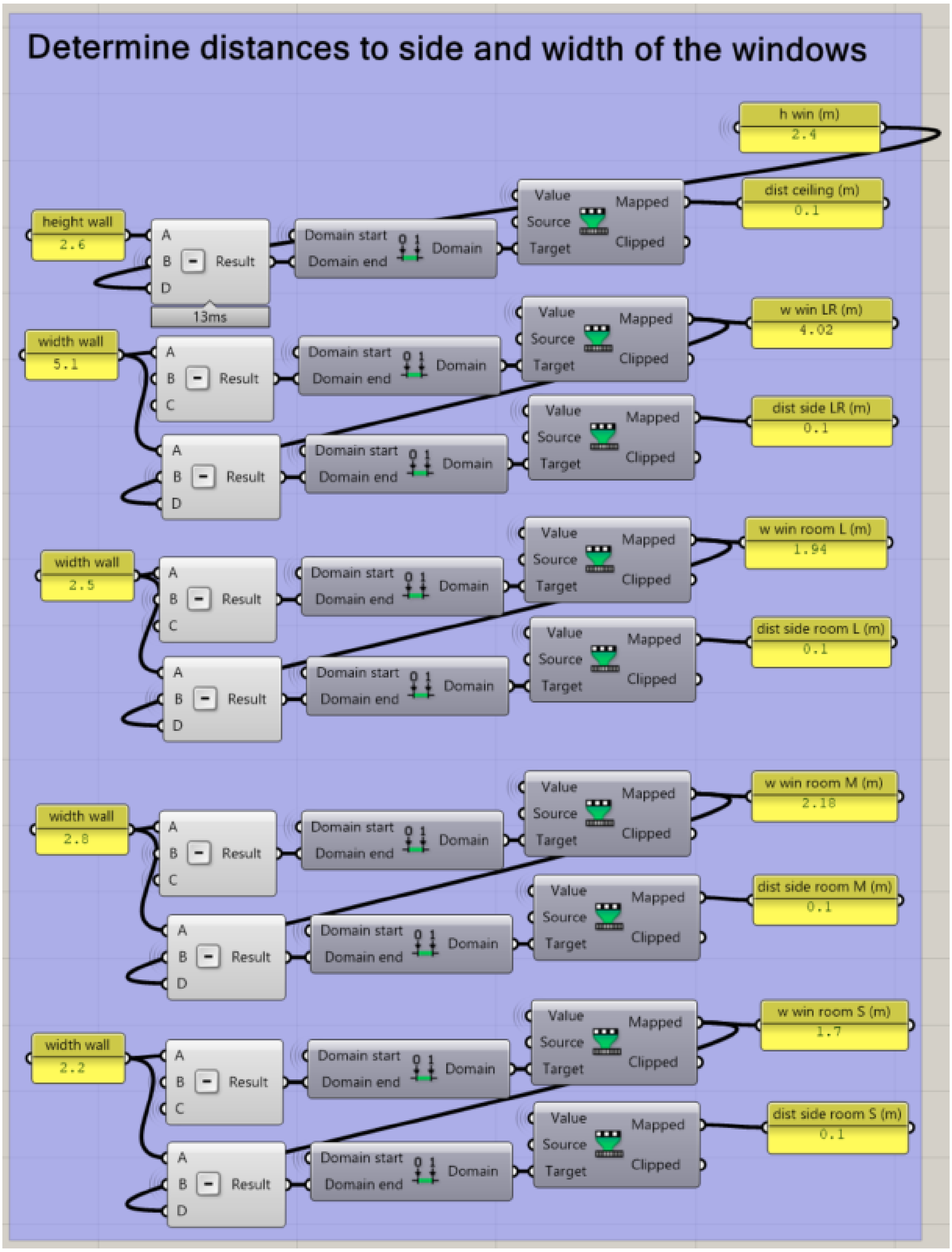


Figure B.5: Distances to sides and sizes of windows.

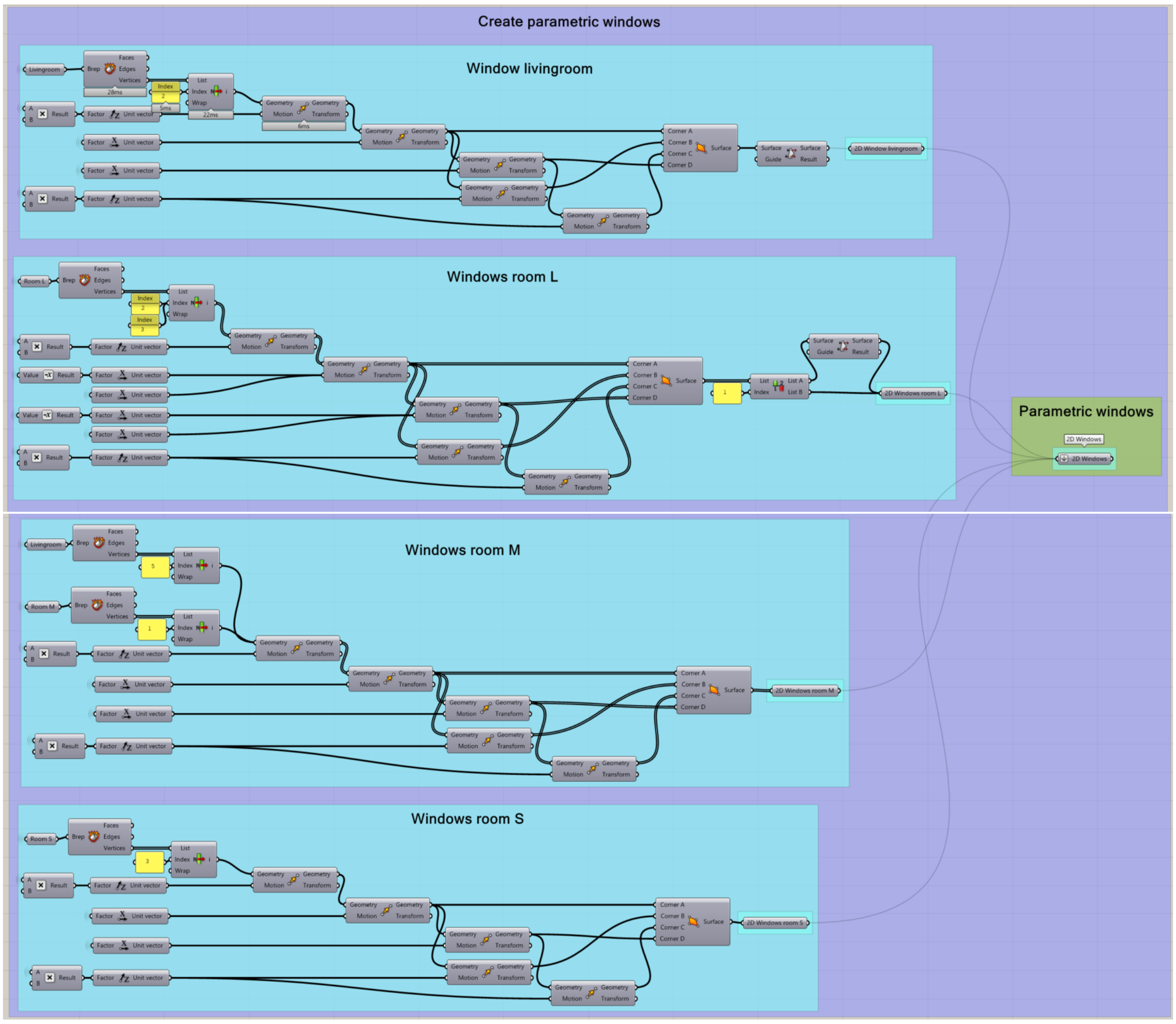


Figure B.6: Create parametric window based on the variables.

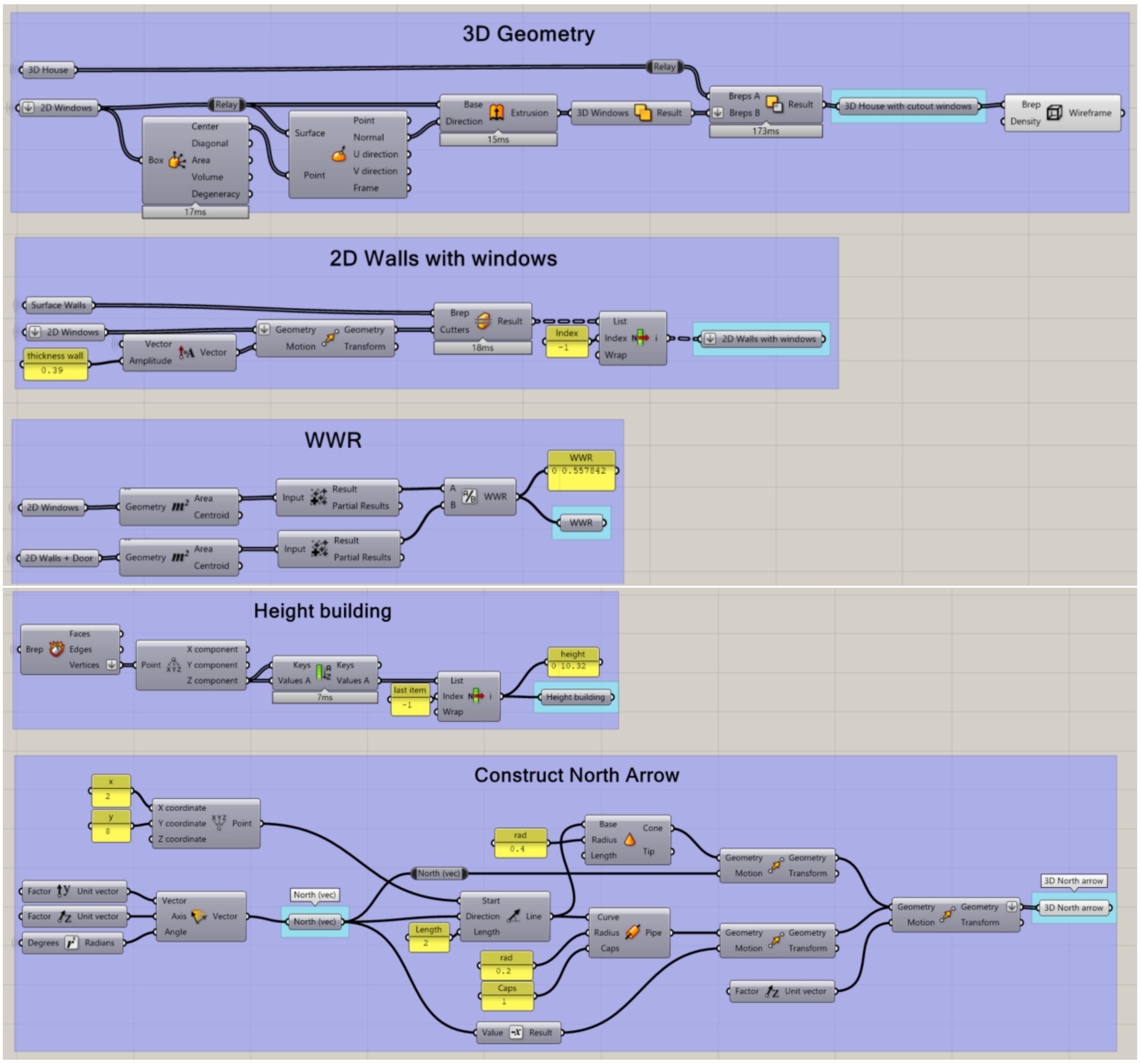


Figure B.7: Some additional steps like determine WWR, construct a north arrow, and calculate the usable area of the house.

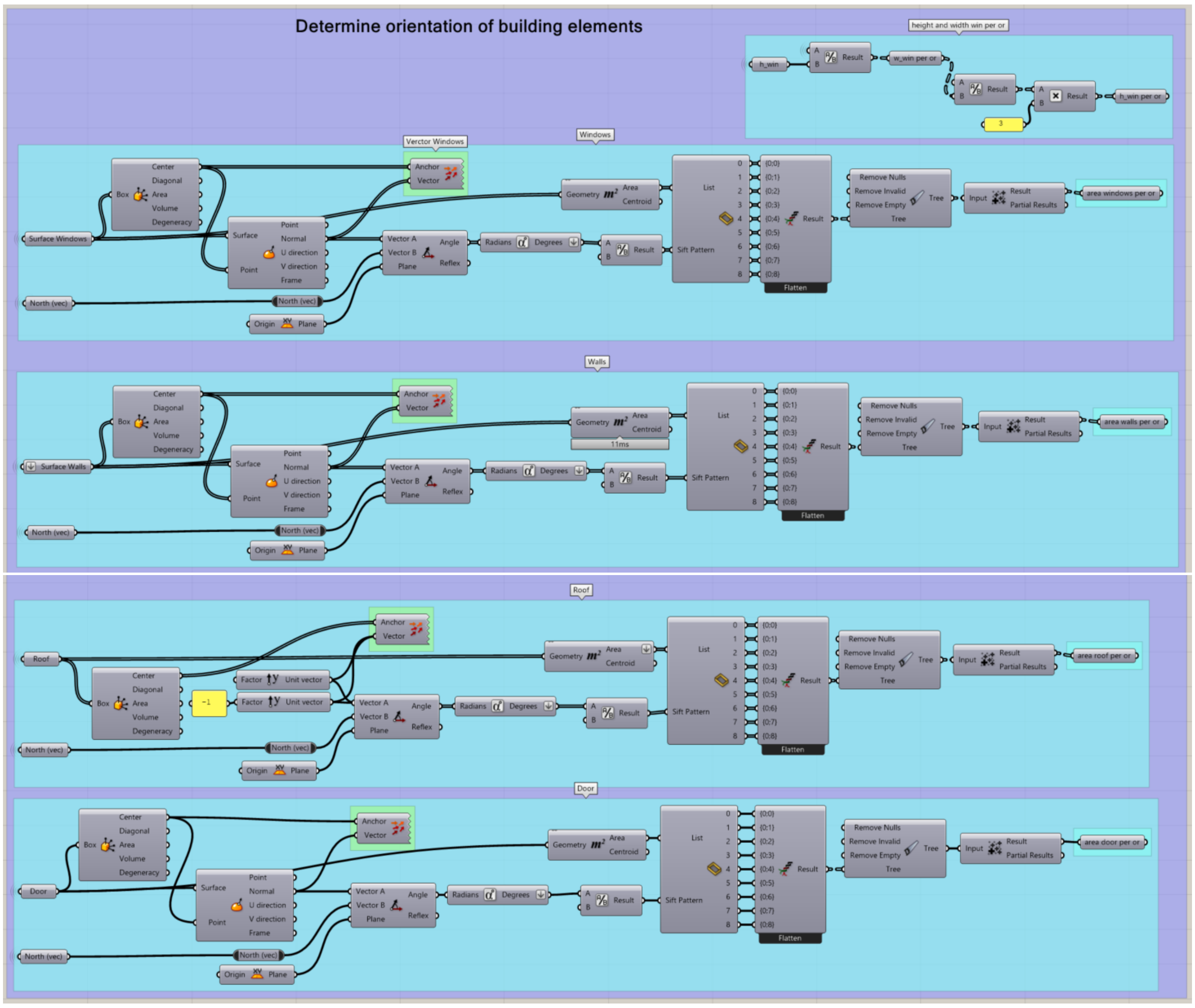


Figure B.8: Determine the Orientation of every building element for the calculation of TO_{juli}.

B.3. Daylight analysis

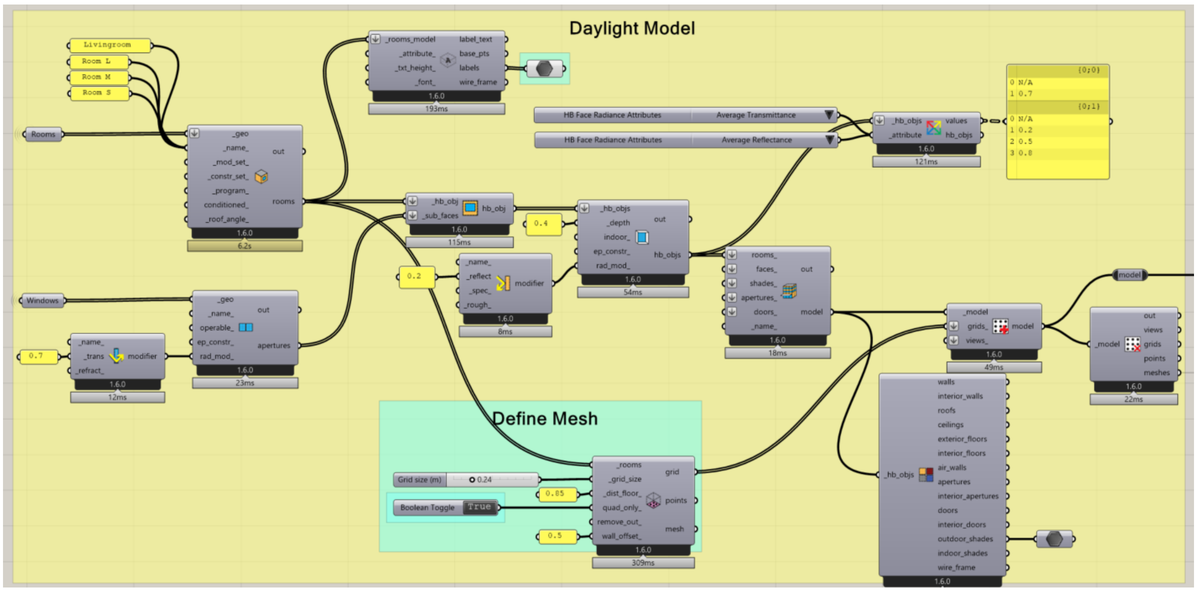


Figure B.9: Define the elements for the daylight model, like the rooms, the windows, the thickness of the walls and the mesh grid, which is used as a reference surface to calculate the daylight factor.

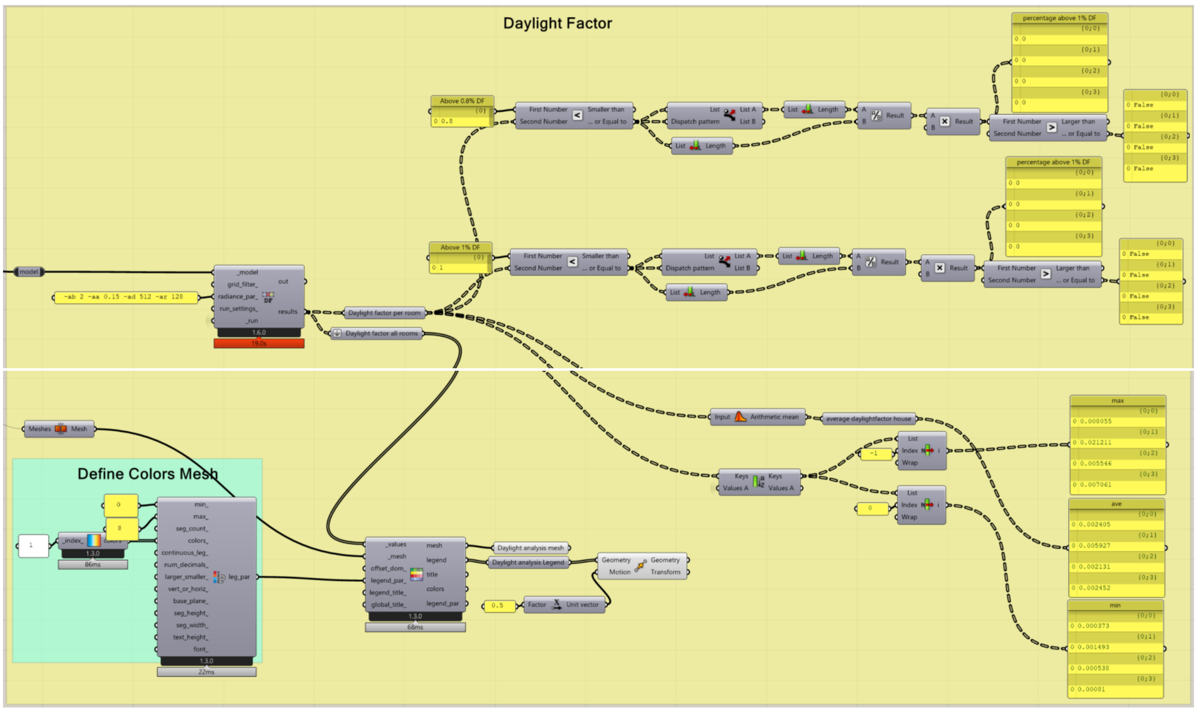


Figure B.10: Calculate the daylight factor with the component "HB Daylight Factor"and find the max, min and average value per room. Also calculate the daylight factor for 50% of the area.

B.4. Energy demand analysis

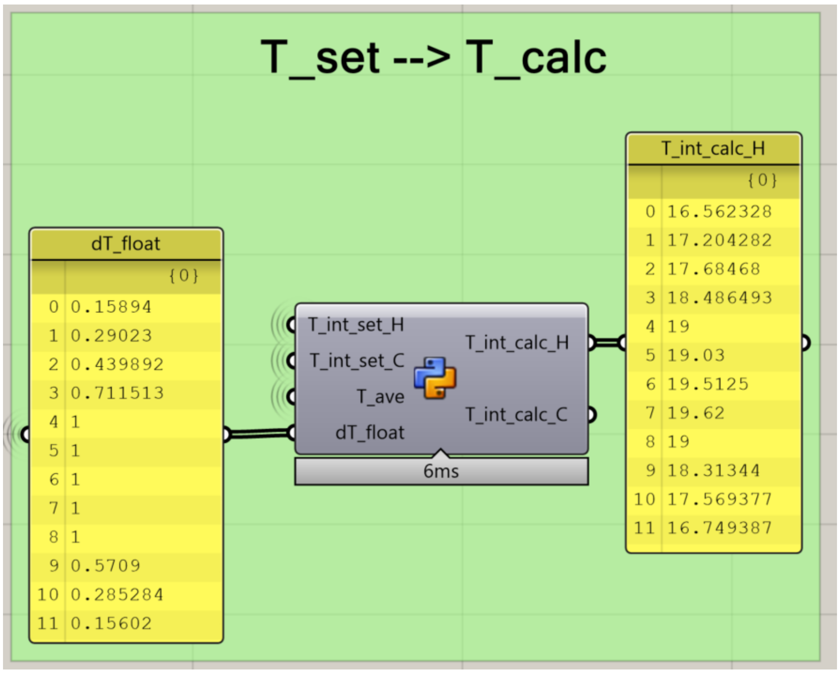


Figure B.11: Determining the calculation temperature is of great importance for the calculation of the transmission and ventilation losses. The internal temperature in the house is often not exactly the same as the setpoint temperature of 20 Degrees.

The Python code used to determine the setpoint temperature is illustrated below.

```
"""Provides a scripting component.
    Inputs:
        T_int_set_H:  Indoor setpointtemperature for heating
        T_int_set_C:  Indoor setpointtemperature for cooling
        T_ave:        Avg outdoor temp of the year
    Output:
        T_int_calc_H:   Indoor calculationtemperature for heating
        T_int_calc_C:   Indoor calculationtemperature for cooling"""
### Variables ###
t_H_wknd = 0          # voor woningfunctie, Tabel 7.15 hoofdstuk 7.9.5.2
t_H_day = 10          # Tabel 7.15
f_H_red_low_day = 0.4      # based on Uniec3
T_int_set_H_low = 16    # see table 7.14


### heating ###
# weekend
f_H_red_wknd = t_H_wknd / (24 * 7)                      # formula 7.63

if t_H_wknd == 0:
    dT_H_red_mn_wknd = 0


# day
f_H_red_day = (t_H_day * (7-(t_H_wknd/24))) / (24 * 7)    # formula 7.62

if T_int_set_H - T_ave <= 0:
    dT_set_low = 1
elif T_int_set_H_low - T_ave <= 0:
```

```
    dT_set_low = 0
else:
    dT_set_low =  (T_int_set_H_low - T_ave) / (T_int_set_H - T_ave)                     # formula 7.72

print(dT_set_low)

if t_H_day == 0:
    dT_H_red_mn_day = 0
elif f_H_red_low_day >= 1:
    dT_H_red_mn_day = dT_float
else:
    dT_H_red_mn_day = f_H_red_low_day * dT_float +  (1-f_H_red_low_day) * dT_set_low  # formula 7.65 (simplified)

# calucation reduction factors for weekend and day
aH_red_wknd = 1 - f_H_red_wknd + f_H_red_wknd * dT_H_red_mn_wknd    # formula 7.61, --> 1 for woningbouw
aH_red_day = 1 - f_H_red_day + f_H_red_day * dT_H_red_mn_day        # formula 7.61
aH_red = 1 - (1 - aH_red_day) - (1 - aH_red_wknd)                   # formula 7.60

T_int_calc_H = aH_red * (T_int_set_H - T_ave) + T_ave               # formula 7.59



### cooling ###
T_int_calc_C = T_int_set_C  # see first paragraph chapter 7.9.3
# for aC_red (formula 7.74) see calculation of QC_nd
```

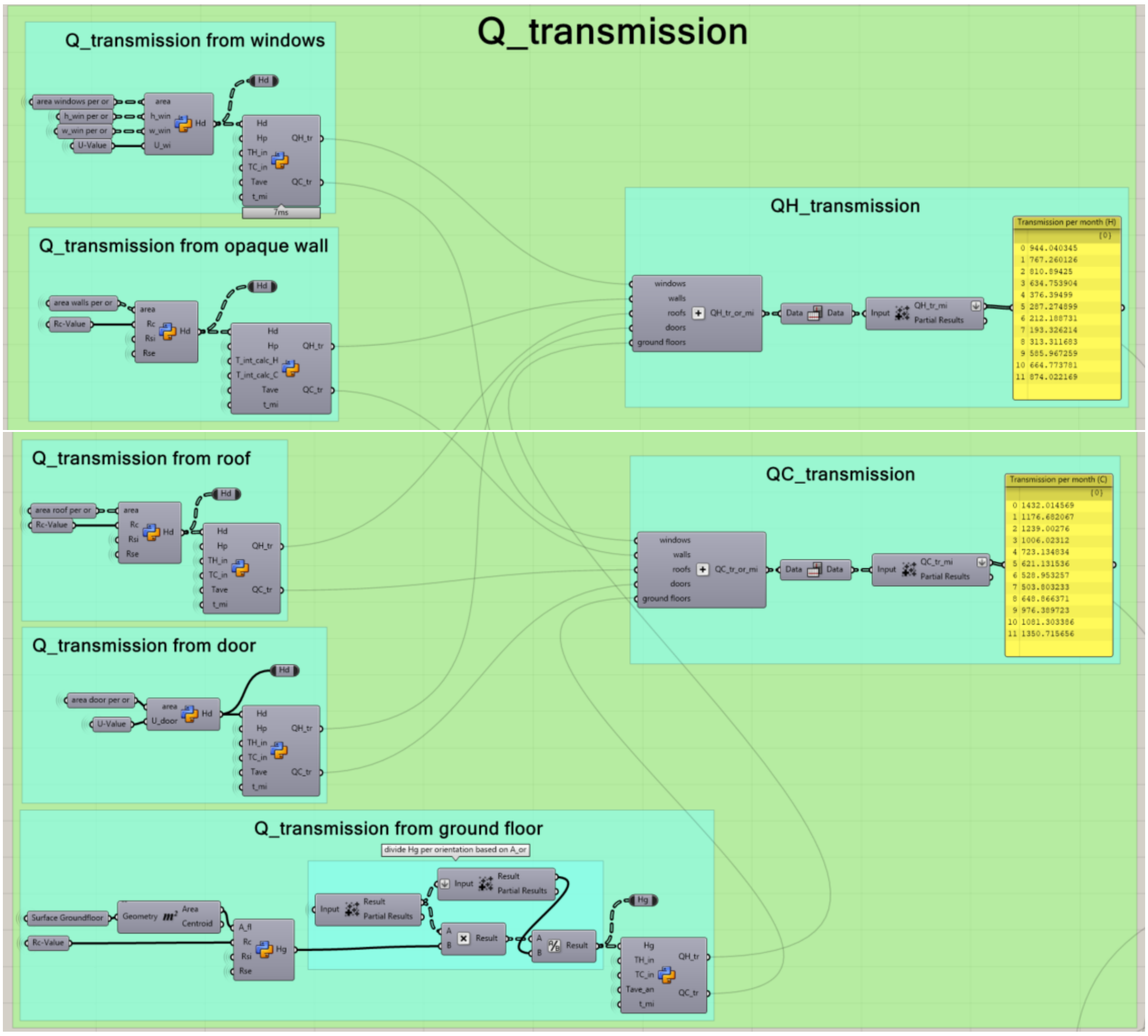


Figure B.12: Transmission is determined in five parts. Windows, walls, roof doors and the ground floor. The transmission is calculated for a heating situation and a cooling situation.

The Python code to calculate the direct heat transfer coefficient for windows:

```
"""Provides a scripting component.
    Inputs:
        area:       Area of the opaque surface i [m2]
        h_win:      Height of the window [m]
        w_win:      Width of the window [m]
        U_wi:       Thermal transmittance of the window [W/(m2K)]
    Output:
        Hd:     Direct heat loss coefficient between the heated space and the outside
    air"""

f_prac = 1.0                    # practice performance factor = 1 (8.2.2)
dU = 0.0                        # The surcharge factor for any convection,
# point fixing aids (anchors) and drainage (inverted roof)
# assumed dU = 0

Ut = U_wi
Uc = (Ut/f_prac) + dU           # Thermal transmittance of the opaque surface i [W/(m2K)],
    (8.2.2.2)
```

```
Hd = area * Uc + (2 * h_win * 0.09 + w_win * 0.1 + w_win * 0.15) # formula 8.1
```

The code for calculating the total heat transfer through transmission for both heating and cooling is shown below.

```
"""Provides a scripting component.
    Inputs:
        Hd:     Direct Heat transfer coefficient between inside and outside
        Hp:     Heat transfer coefficient of zone zi via vertical pipes that pass through
↪   the thermal envelope and in direct connection with outside air, NTA 8800 7.3.3
        TH_in:  Indoor temperature for heating
        TC_in:  Indoor temperature for cooling
        Tave:   Avg outdoor temp of the year
        t_mi:   Length of month i
    Output:
        QH_tr:  Total heat transfer through transmission for heating
        QC_tr:  Total heat transfer through transmission for cooling"""



Ha = 0.0    # can be neglected according to NTA 8800 chapter 8.5

QH_tr = (Hd + Hp + Ha) * (TH_in - Tave) * 0.001 * t_mi
QC_tr = (Hd + Hp + Ha) * (TC_in - Tave) * 0.001 * t_mi
```

Determining the stationary heat loss coefficient through the ground floor.

```
"""Provides a scripting component.
    Inputs:
        A_fl:   Area of the opaque surface i [m2]
        Rc:     Thermal resistance construction
        Rsi:    Thermal surface resistance interior
        Rse:    Thermal surface resistance exterior
    Output:
        Hg:     Stationary heat loss coefficient through the ground (8.3.3)"""

dU = 0.0                    # could be taken further into account, assumed 0 for
↪   simplicity
f_prac = 1.0                # practice performance factor = 1 (8.2.2)

Rt = Rsi + Rc + Rse
Ut = 1/Rt
U_fl = (Ut/f_prac) + dU      # Thermal transmittance of the opaque surface i [W/(m2K)],
↪   (8.2.2.2)

Hg = A_fl * U_fl + 9.4 * 0.6             # formula 8.1
```

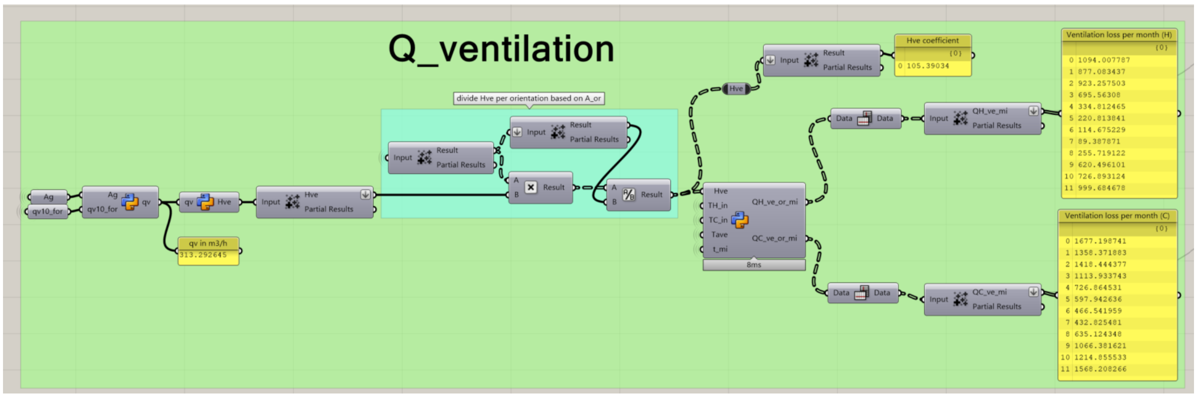


Figure B.13: The ventilation is simplified, since the this part is quite extensive. The ventilation is based on the given infiltration capacity of$qv10_for0.7$ [dm3/s*m2] in case of the terraced housing.

Determine the direct heat transfer coefficient between inside and outside in [W/K] based on the default qv10 values given in the NTA 8800. The ventilation part is simplified because the calculation is very extensive. Leaving out ventilation is impossible as it contributes a lot to the energy demand indicator of BENG1.

```
    """Provides a scripting component.
    Inputs:
        qv10_for:     Volumetric flow of outside air   [dm3/s*m2]"""

qv = qv10_for * 3600 * Ag / 1000

"""Provides a scripting component.
    Output:
         Hve:       Direct Heat transfer coefficient between inside and outside [W/K]"""

# Ventilation natural supply and mechanical exhaust

fv = 1          # Dynamic correction factor = 1 (7.4.3)
rho = 1.205     # Density of air = 1,205 kg/m3
Ca = 1005       # Specific heat capacity of air = 1005 J/kgK
bv = 1          # Correction factor for supply temperature, = 1 for nat. supply and infiltration (7.4.4)

Hve = rho * Ca * (qv * bv * fv) / 3600      # formula 7.19 chapter 7.4.3
```

```
    """Provides a scripting component.
    Inputs:
        Hve:        Direct Heat transfer coefficient between inside and outside [W/K]
        TH_in:      Indoor temperature for heating [C]
        TC_in:      Indoor temperature for cooling [C]
        Tave:       Avg outdoor temp of the year [C]
        t_mi:       Length of month mi [h]
    Output:
        QH_ve:      Total heat transfer through ventilation for heating [kWh]
        QC_ve:      Total heat transfer through ventilation for cooling [kWh]"""

QH_ve_or_mi = Hve * (TH_in - Tave) * 0.001 * t_mi
QC_ve_or_mi = Hve * (TC_in - Tave) * 0.001 * t_mi
```

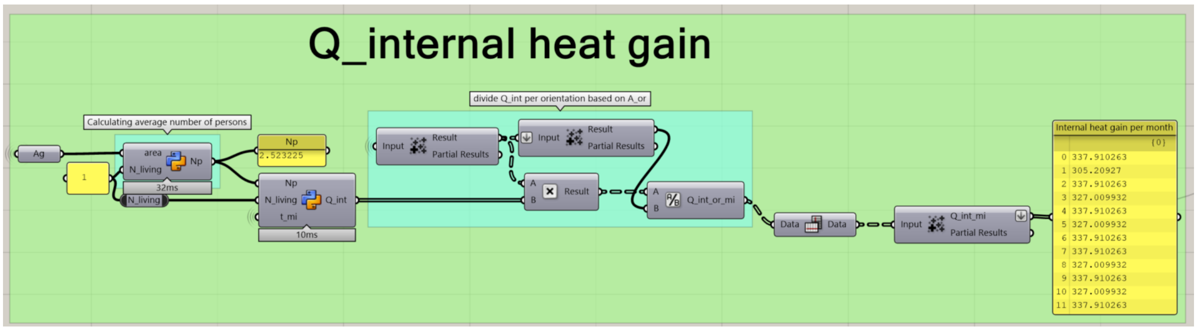


Figure B.14: Internal heat gain is a fixed value per square metre of usable area Ag based on boundary conditions.

For the internal heat gain the number of average persons in the calculation zone are of interest. These are calculated as shown below.

```
    """Provides a scripting component.
    Inputs:
        area:       Usable area NTA 8800 6.6.4
        N_living:   Number of staying functions in calculation zone zi, NTA 8800 6.6.7
    Output:
        Np:         Avg number of persons in calculation zone"""

if area/N_living <= 30.0:
    Np = 1
elif area/N_living > 30 and area/N_living <= 100:
    Np = (2.28 - (1.28/70) * (100 - area/N_living))
elif area/N_living > 100:
    Np = (1.28 + 0.01 * area/N_living)
print(Np)
```

```
    """Provides a scripting component.
    Inputs:
        Np:         Avg numer of persons in calculation zone
        N_living:   Number of staying functions in calculation zone zi, NTA 8800 6.6.7
        t_mi:       Length of month mi
    Output:
        Q_int:      Internal heat gain in [kWh]"""

Q_int = 180 * Np * N_living * 0.001 * t_mi
```

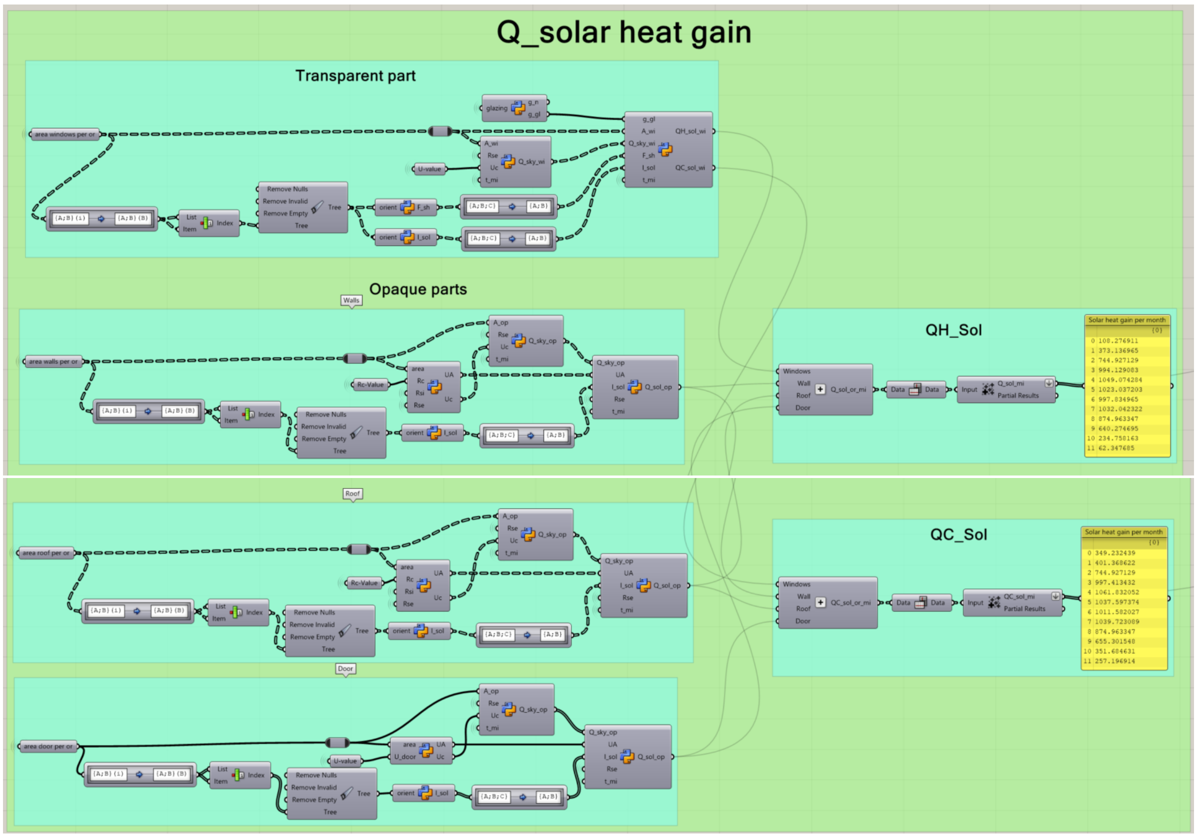


Figure B.15: Solar heat gain is calculated in four parts, the windows, walls, roof and doors. The solar gain is the same in heat as in cooling conditions.

```
    """Provides a scripting component.
    Inputs:
        A_wi:       Area of the window wi [m2]
        Rse:        Thermal surface resistance exterior [m2K/W]
        Uc:         Thermal transmittance of the window [W/(m2K)]
        t_mi:       Length of month mi [h]
    Output:
    Q_sky_mi:       Monthly additional heat flow through heat radiation to the sky from window [kwh]"""

F_sky = 0.5             # for vertical element, 1 for horizontal, 0.75 for angled surface like a incl roof
dT_sky= 11              # Kelvin 7.6.5
hlr = 4.14              # w/m2K 7.6.5

Q_sky_wi = 0.001 * F_sky * Rse * Uc * A_wi * hlr * dT_sky * t_mi
```

The orientation of the window is important for the shading reduction factor F_{sh} of the solar heat gain component. So, based on the orientation, a selection of values per month is made in this code. The same is done for the monthly average total incident solar radiation I_{sol}.

```
    """Provides a scripting component.
    Inputs:
        orient:     orientation of window
    Output:
        F_sh:      Shading reduction factor for external obstructions [-] """

fsh = {
```

```
    '180': [0.23,   0.91,   1.0,    1.0,    1.0,    1.0,    1.0,    1.0,    1.0,    0.97,
    ↪ 0.61,   0.19],
    '225': [0.49,   0.83,   0.93,   0.92,   0.99,   1.0,    1.0,    0.99,   0.91,   0.88,
    ↪ 0.71,   0.58],
    '270': [0.85,   0.85,   0.89,   0.82,   0.88,   0.93,   0.92,   0.89,   0.85,   0.83,
    ↪ 0.9,    0.87],
    '315': [0.97,   0.97,   0.96,   0.87,   0.85,   0.91,   0.9,    0.88,   0.96,   0.97,
    ↪ 0.99,   1.0],
    '0':    [1.0,    1.0,    1.0,    0.99,   0.97,   0.97,   0.97,   0.98,   1.0,    1.0,
    ↪ 1.0,    1.0],
    '45':  [1.0,    0.96,   0.97,   0.97,   0.93,   0.88,   0.91,   0.98,   0.97,   0.96,
    ↪ 0.98,   1.0],
    '90':  [0.92,   0.79,   0.82,   0.91,   0.95,   0.9,    0.93,   0.94,   0.87,   0.84,
    ↪ 0.92,   0.86],
    '135': [0.48,   0.81,   0.87,   0.95,   1.0,    1.0,    0.99,   0.98,   0.92,   0.86,
    ↪ 0.7,    0.4]}

if orient == 4:
    F_sh = fsh['180']
elif orient == 5:
    F_sh = fsh['225']
elif orient == 6:
    F_sh = fsh['270']
elif orient == 7:
    F_sh = fsh['315']
elif orient == 0:
    F_sh = fsh['0']
elif orient == 1:
    F_sh = fsh['45']
elif orient == 2:
    F_sh = fsh['90']
elif orient == 3:
    F_sh = fsh['135']
```

```
"""Provides a scripting component.
    Inputs:
        g_gl:       Average effective total solar factor of window wi [-]
        A_wi:       Area of the window wi [m2]
        F_sh:       Shading reduction factor for external obstructions of window [-]
        I_sol:      Monthly average total incident solar radiation per m2 area of window
 ↪  [W/m2]
        t_mi:       Length of month mi [h]
        Q_sky_wi:   Monthly additional heat flow through heat radiation to the sky from
 ↪  window [kwh]
    Output:
        QH_sol_wi:   Solar heat gain through transparent parts in case of heating [kWh]
        QC_sol_wi:   Solar heat gain through transparent parts in case of cooling
 ↪  [kWh]"""

F_fr = 0.25             # windowframe fraction, forfaitair = 0.25 (7.6.6.2)

QH_sol_wi = g_gl * A_wi * (1 - F_fr) * F_sh * I_sol * 0.001 * t_mi - Q_sky_wi
QC_sol_wi = g_gl * A_wi * (1 - F_fr) * 1 * I_sol * 0.001 * t_mi - Q_sky_wi
```

The monthly additional heat flow through heat radiation to the sky from the opaque surface $Q_{sky,op}$ is needed. It is determined as shown in the following.

```
    """Provides a scripting component.
    Inputs:
```

```
        A_op:       Area of the opaque surface [m2]
        Rse:        Thermal surface resistance exterior [m2K/W]
        Uc:         Thermal transmittance of the window [W/(m2K)]
        t_mi:       Length of month mi [h]
    Output:
    Q_sky_op:       Monthly additional heat flow through heat radiation to the sky from opaque surface [kwh]"""

F_sky = 0.5            # for vertical element, 1 for horizontal, 0.75 for angled surface like a incl roof
dT_sky= 11             # Kelvin 7.6.5
hlr = 4.14             # w/m2K 7.6.5

Q_sky_op = 0.001 * F_sky * Rse * Uc * A_op * hlr * dT_sky * t_mi
print(A_op)
```

The solar heat gain of the opaque surfaces $Q_{sol,op}$ is calculated as follows:

```
    """Provides a scripting component.
    Inputs:
        Q_sky_op:   Monthly additional heat flow through heat radiation to the sky from the opaque surface [kwh]
        UA:         U-value * area of the opaque surface
        I_sol:      Monthly average total incident solar radiation per m2 area of the opaque surface [W/m2]
        Rse:        Thermal surface resistance exterior [m2K/W]
        t_mi:       Length of month mi [h]
    Output:
        Q_sol_op:   Solar heat gain of the opaque surfaces"""

a_sol = 0.6       # for opaque surfaces a_sol = .6 (7.6.6.3)
F_sh = 1.0        # shadow reduction factor extern =  1 (7.6.3)

Q_sol_op = a_sol * Rse * UA * F_sh * I_sol * 0.001 * t_mi - Q_sky_op
```

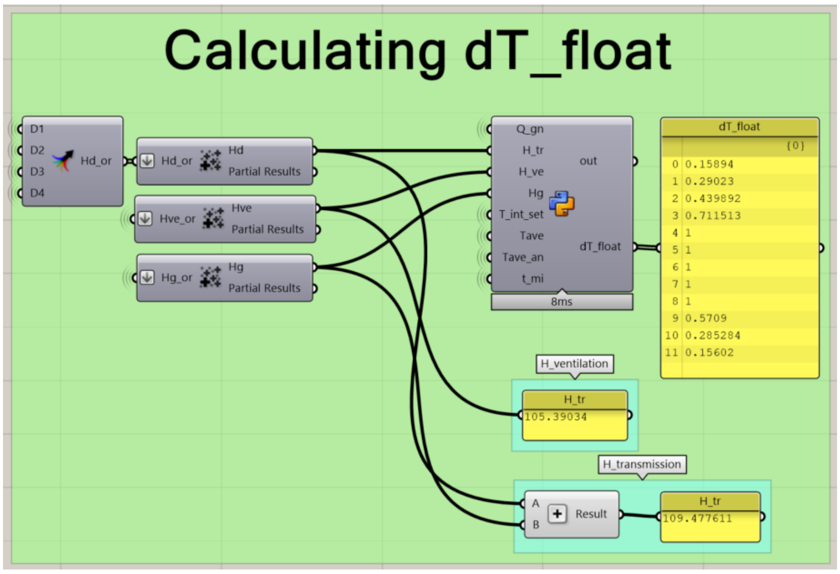


Figure B.16: dT_{float} is needed to determine the setpoint temperature. dT_{float} is based on the heat loss coefficients of transmission and ventilation. (this creates a loop in the calculation, because the setpoint temperature determines the size of the heat loss coefficients).

```
    """Provides a scripting component.
    Inputs:
        QH_gn:      Heat gain in case of heating
        H_tr:       Heat loss coefficient for transmission
        H_ve:       Heat loss coefficient for ventilation
        Hg:         Heat loss coefficient through the ground (8.3.3)
        T_int_set:  Indoor setpointtemperature
        Tave:       Avg outdoor temp per month
        Tave_an:    Avg outdoor temp of the year
        t_mi:       Length of month mi
    Output:
        dT_float:   Dimensionless (relative) reduction in the difference between indoor
    and outdoor temperature at 'free-floating' conditions (no heating)"""

dT_float = (Q_gn * 1000) / (((H_tr + H_ve)*(T_int_set - Tave)+ Hg * (T_int_set -
    Tave_an))* t_mi)

if dT_float >= 1:
    dT_float = 1
if dT_float <= 0:
    dT_float = 0

print(dT_float)
```

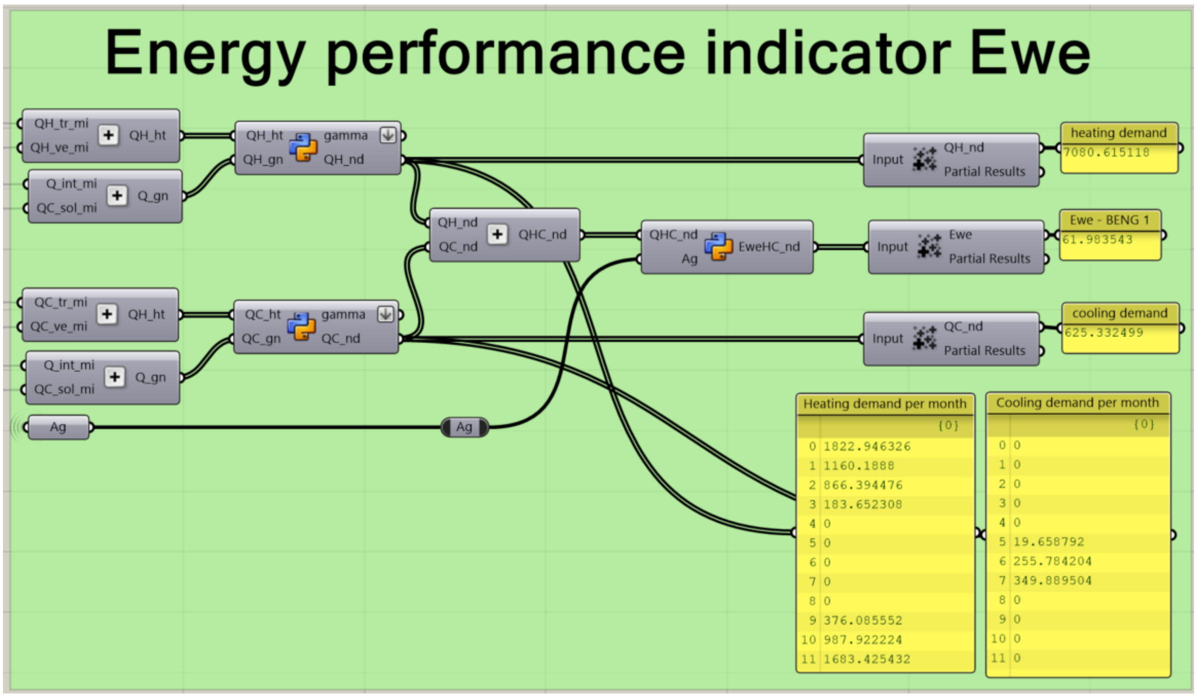


Figure B.17: The Energy Performance indicator Ewe is determined based on the heat transfer and the heat gain. also the Heating demand and cooling demand per month are calculated.

Determine monthly energy demand in case of heating QH_{nd}.

```
    """Provides a scripting component.
    Inputs:
        QH_gn: Total heat gain for heating [kWh], 7.2.3
        QH_ht: Total heat transfer for heating [kWh], 7.2.3
    Output:
        QH_nd: Monthly energy demand for heating [kWh] 7.2.1"""
```

```python

eta = 1                  # simplification eta = 1
gamma = QH_gn / QH_ht    # (7.8.2)
print(gamma)

if gamma <= 0 and QH_gn > 0:
    QH_nd = 0
elif gamma > 2:
    QH_nd = 0
else:
    QH_nd = QH_ht - eta * QH_gn

if QH_nd < 0:           # see formula 7.3 in NTA 8800
    QH_nd = 0
```

Determine energy demand in case of cooling QC_{nd}.

```python
    """Provides a scripting component.
    Inputs:
        QC_gn: Total het gain for cooling [kWh], 7.2.3
        QC_ht: Total heat transfer for cooling [kWh], 7.2.3
    Output:
        QC_nd: Monthly energy demand for cooling [kWh] 7.2.1"""

eta = 1              # simplification eta = 1
t_C_wknd = 0         # voor woningfunctie, Tabel 7.15 hoofdstuk 7.9.5.2
b_C_red_wknd = 0.3   # hoofdstuk 7.9.3


gamma = QC_gn / QC_ht    # (7.8.2)

# reduction factor non-continuous cooling
f_C_red_wknd = t_C_wknd / (24 * 7)
aC_red = (1 - f_C_red_wknd) + b_C_red_wknd * f_C_red_wknd    # formula 7.74, --> 1 for woningbouw


if (1/gamma) > 2:
    QC_nd = 0
else:
    QC_nd = aC_red * (QC_gn - eta * QC_ht)

if QC_nd < 0:           # see formula 7.7 in NTA 8800 chapter 7.2.2
    QC_nd = 0
```

Determine BENG 1 Parameter $Ewe_{HC,nd}$.

```python
    """Provides a scripting component.
    Inputs:
        Ag:         Usable area of the total calculation area [m2]
        QHC_nd:     Annual energy demand [kWh]
    Output:
        EweHC_nd:   Weighted energy performance / Energy demand indicator (for sys C1) [kWh/m2]"""



EweHC_nd = QHC_nd / Ag      # NTA 8800 5.3.1.1
```

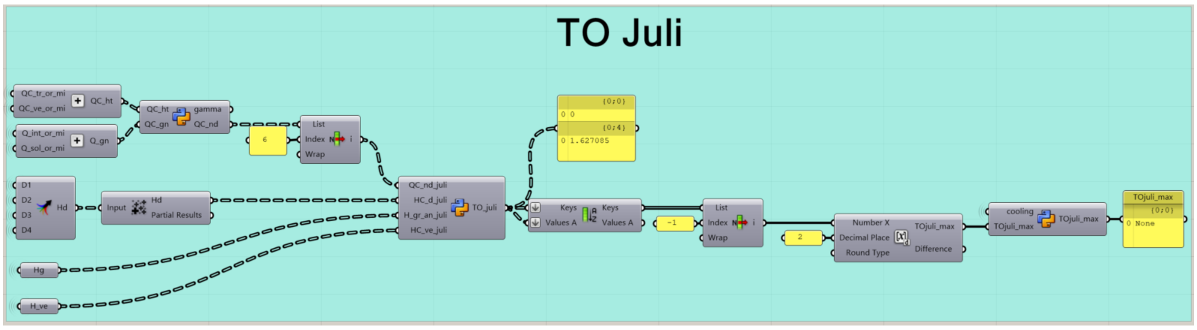


Figure B.18: TO_{juli} is based on the cooling demand and is determined per orientation.

To determine a numerical value of the risk of overheating, the code below is used.

```
    """Provides a scripting component.
    Inputs:
        QC_nd_juli:      Energy demand for cooling for the month of July [kWh]
        HC_d_juli:       Direct heat transfer coefficient due to transmission between the heated space and the outside air in the month july [W/K]
        H_gr_an_juli:    Heat transfer coefficient by transmission of the ground floor in the month of July [W/K]
        HC_ve_juli:      Heat transfer coefficient due to ventilation in the month of July [W/K]
    Output:
       TO_juli:          Numerical value for the risk of excessively high temperatures in the month of July in [K]"""


QC_HP_juli = 0      # Simplification = 0, Energy withdrawn from the cold distribution system by the booster heat pump energy
t_juli = 744        # Length of month juli in h (table 17.2)


TO_juli = ((QC_nd_juli - QC_HP_juli) * 1000) / ((HC_d_juli + H_gr_an_juli + HC_ve_juli) * t_juli)

print(HC_d_juli, H_gr_an_juli, HC_ve_juli)
print(TO_juli)
```

B.5. Parameter study

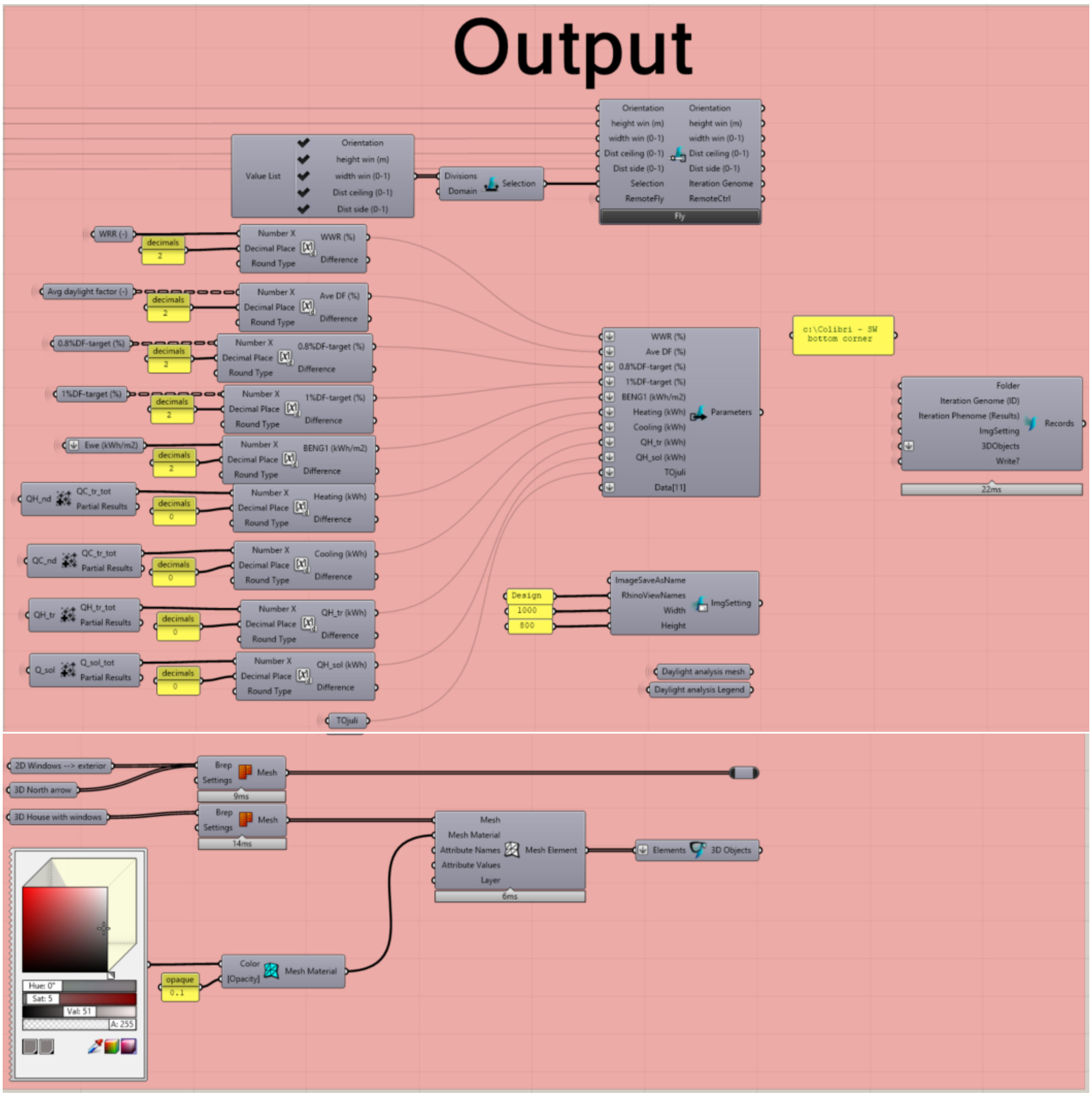


Figure B.19: With the Colibri plugin all the possible solutions are iterated through to generate all the results for a parametric study.

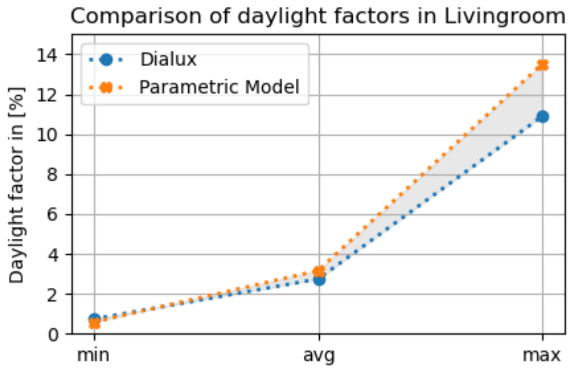
C

Validation

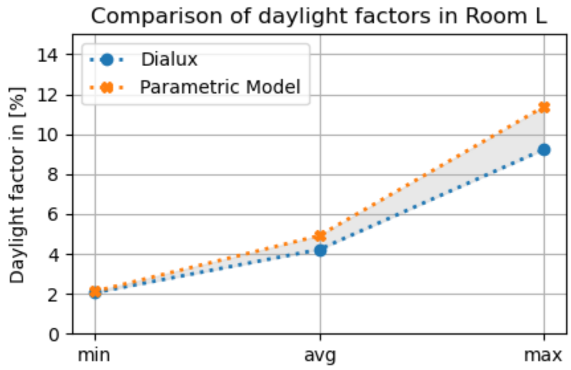
This Appendix C presents additional graphs which are used to verify the accuracy and correctness of the parametric model made in Rhino Grasshopper. The daylight factor calculations in this model are verified on the basis of a Dialux Evo model of the same building.

C.1. Verification of daylight factors

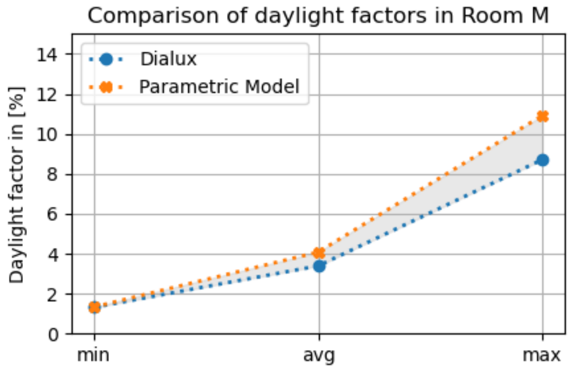
In the four following Figures C.1 all the verification results of the daylight factors of the four rooms are displayed. The results are similar to those of Figure 4.5b of room L. On average, the values of the daylight factor for all four rooms are higher in the parametric model than the results of Dialux Evo. Further evaluation can be found in the main chapters of the thesis.



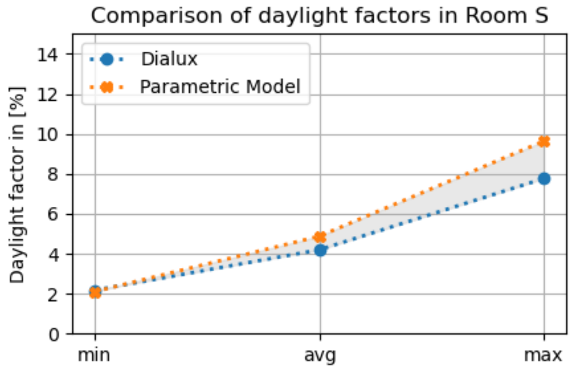
(a) Comparison of minimum, average, and maximum daylight factors in living room of terraced house.



(b) Comparison of minimum, average, and maximum daylight factors in room L of terraced house.



(c) Comparison of minimum, average, and maximum daylight factors in room M of terraced house.



(d) Comparison of minimum, average, and maximum daylight factors in room S of terraced house.

Figure C.1: Comparison of daylight factors in different rooms of terraced housing.

C.2. Verification of energy demand

The following Figures C.2 and C.3 show the internal heat gain in case of heating and in case of cooling. Both graphs are the same, since the NTA 8800 does not differentiate between the two. The results of the parametric model match exactly the Uniec3 values. The results of the Uniec3 calculation can also be found in the appendix C.3.

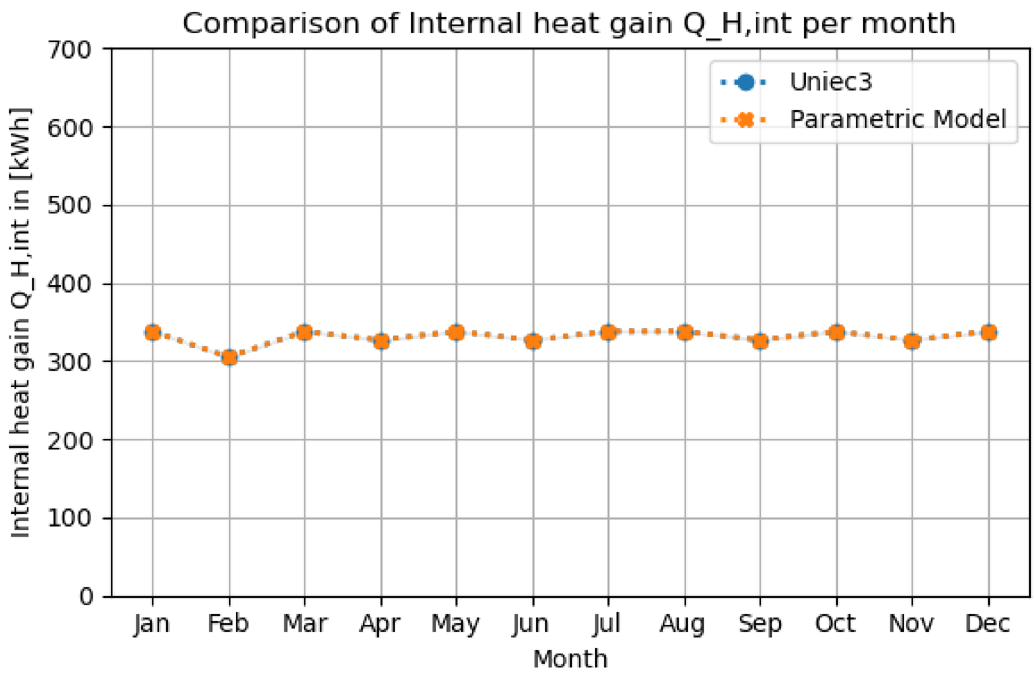


Figure C.2: Comparison of internal heat gain $Q_{H,int}$ per month of terraced housing in case of heating.

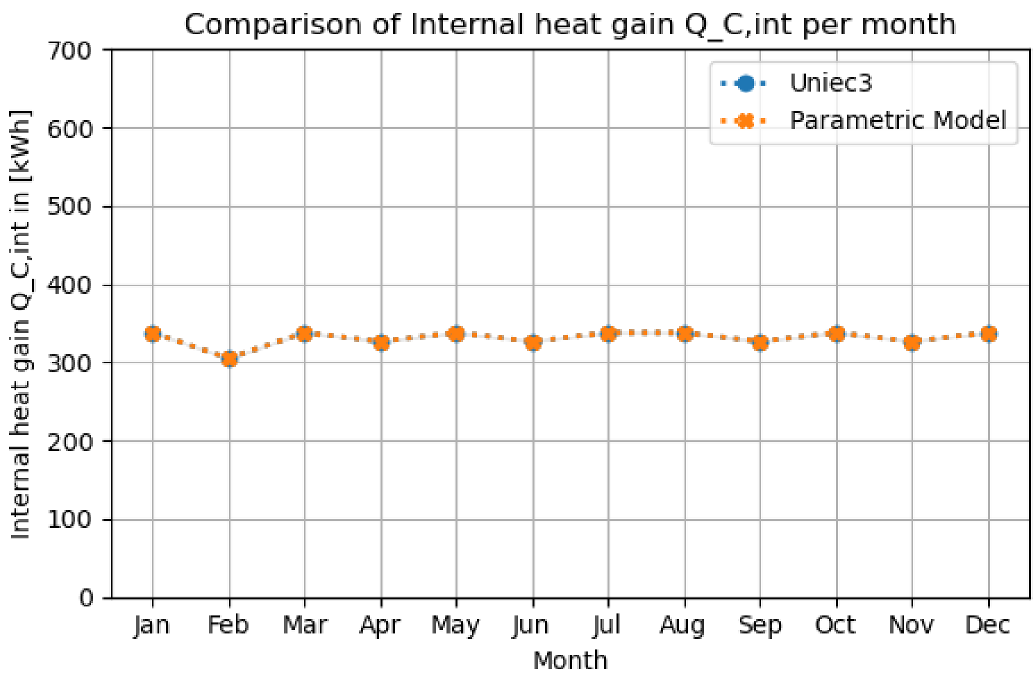


Figure C.3: Comparison of internal heat gain $Q_{C,int}$ per month of terraced housing in case of cooling.

Figures C.4 and C.5 show the solar heat gain in case of heating and in case of cooling. The solar heat gain of the parametric model matches the verification results of Uniec3 well, with an average relative discrepancy of 3%. The results show slightly different values for the cooling and heating situation. This is because, according to NTA 8800, the calculation for cooling requirements runs differently from heating requirements in some aspects. For example, if there are obstructions, different values are used. In some cases, the obstruction is even ignored when calculating the cooling requirement. This decision can be seen in the results for the solar heat gain calculations in the winter month (Jan./Nov./Dec.), where the difference between $Q_{H,sol}$ and $Q_{C,sol}$ of considerable size.

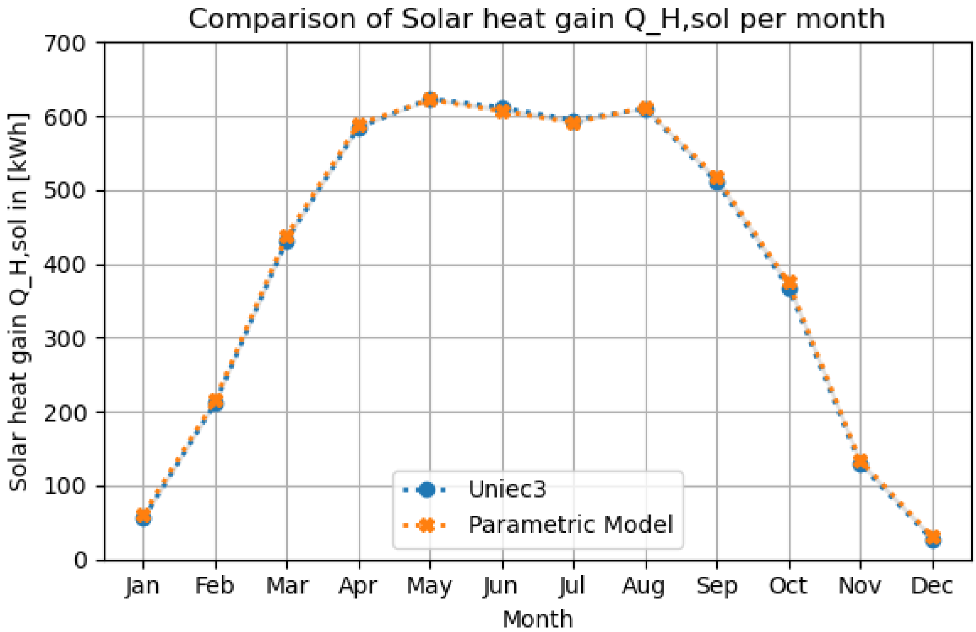


Figure C.4: Comparison of solar heat gain $Q_{H,sol}$ per month of terraced housing in case of heating.

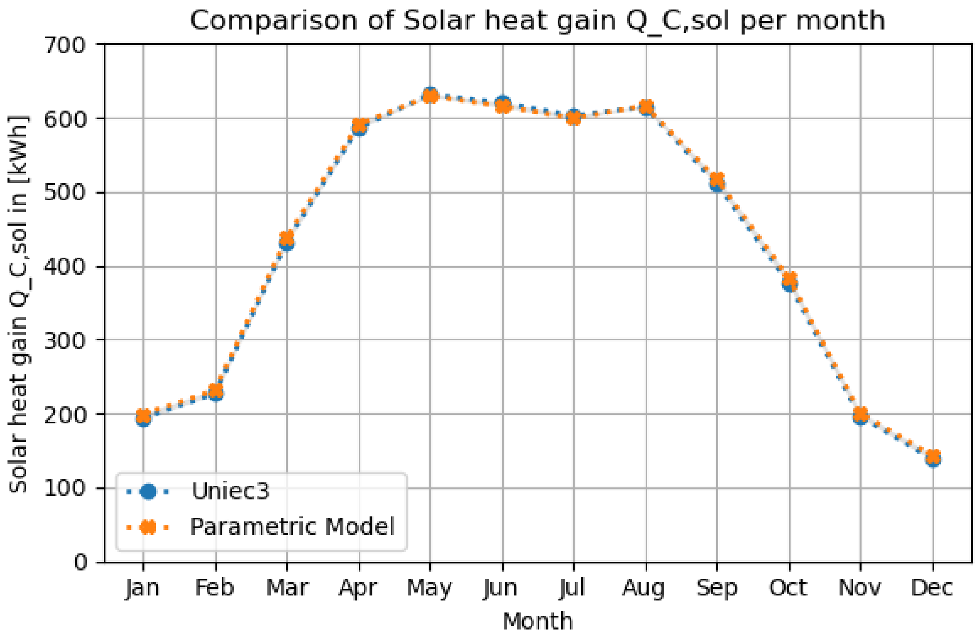


Figure C.5: Comparison of solar heat gain $Q_{C,sol}$ per month of terraced housing in case of cooling.

The validation of Heat transfer coefficients for transmission is relatively straightforward. Values do not differ by month. Figures C.6 and C.7 show a deviation of only 4% between the models, which is in range of the acceptable differences.

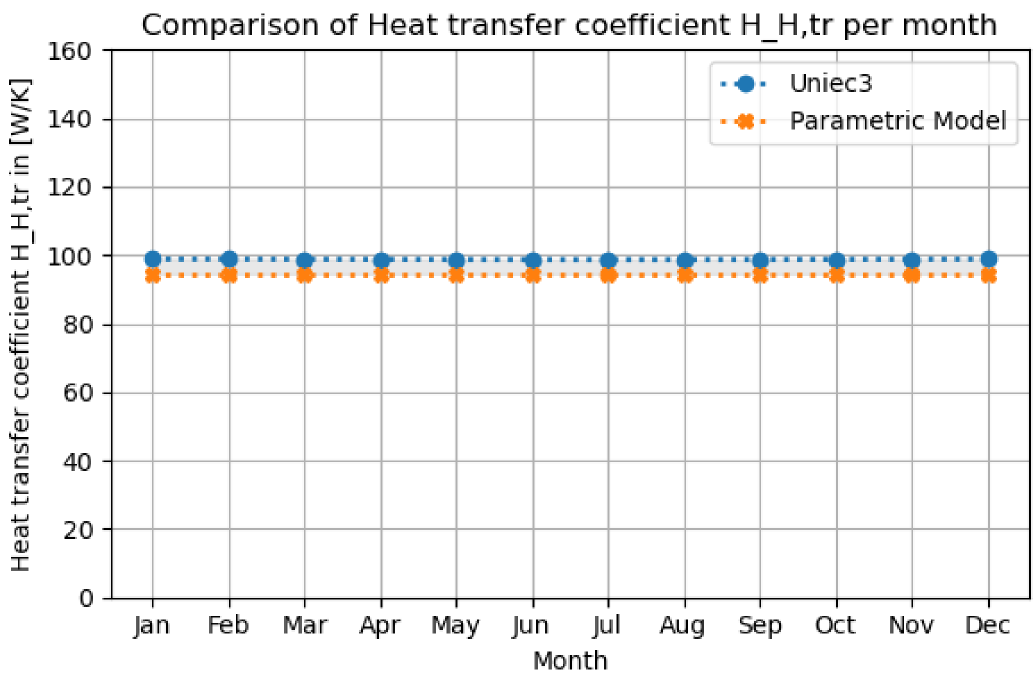


Figure C.6: Comparison of heat transfer coefficient $H_{H,tr}$ per month of terraced housing in case of heating.

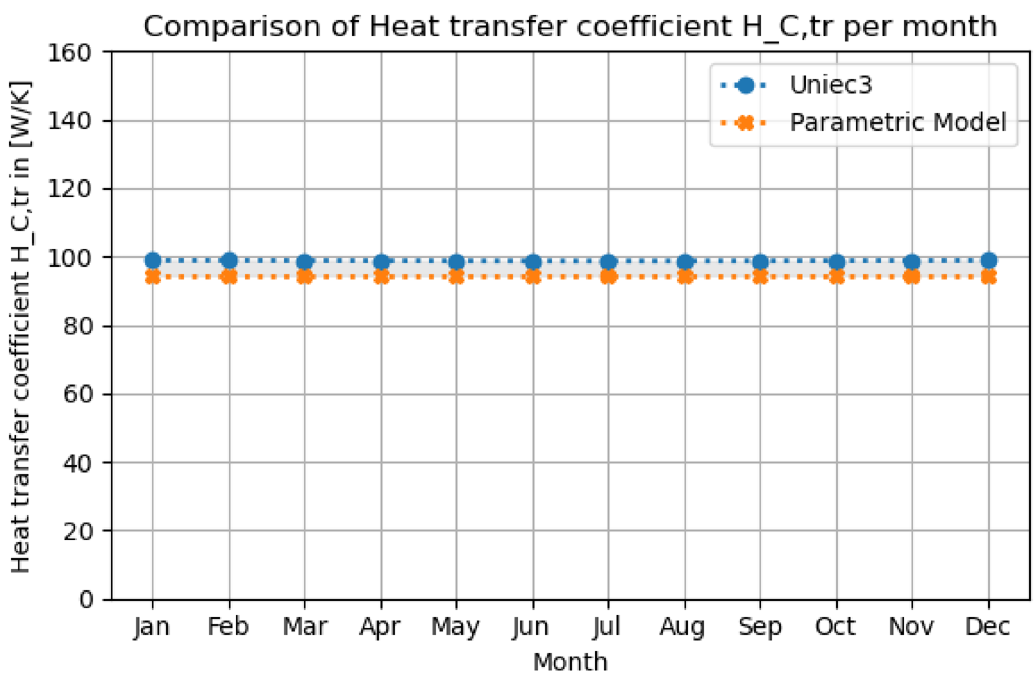


Figure C.7: Comparison of heat transfer coefficient $H_{C,tr}$ per month of terraced housing in case of cooling.

The last Figure C.8 show the calculation temperature in case of cooling. Differently from the calculation temperature for heating, the temperature for cooling is fixed at 24 degrees all year round. Therefore, no differences appear between the models for this value.

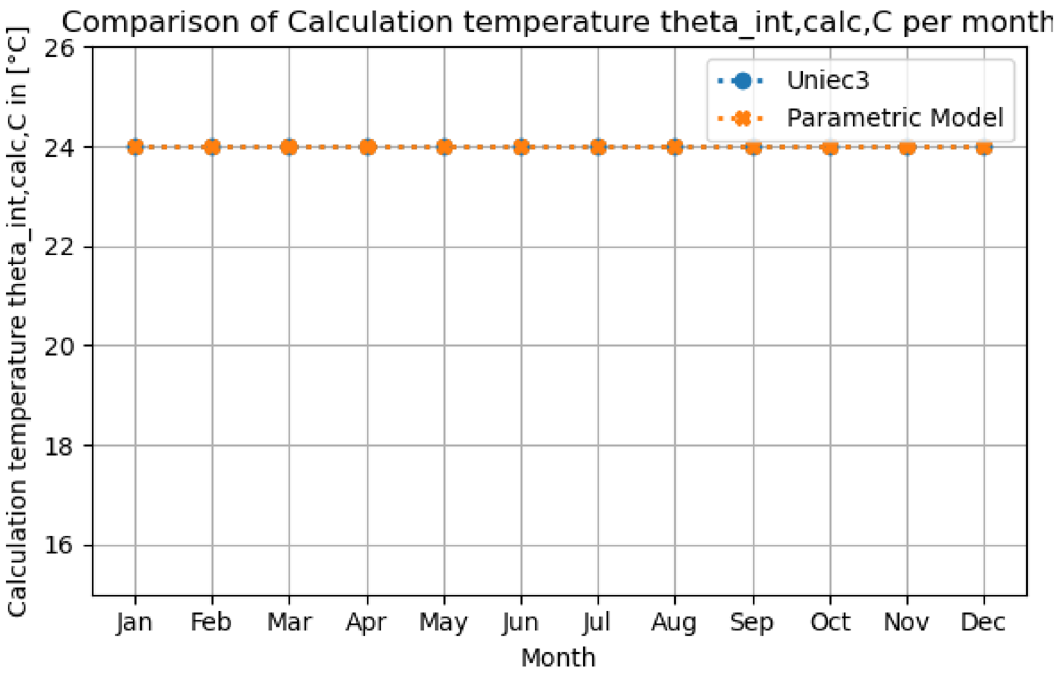


Figure C.8: Comparison of the monthly calculation temperature $\theta_int,calc,C$ of terraced housing for cooling.

C.3. Verification documentation Uniec3

Algemene gegevens

omschrijving	Tussenwoning - verificatie
plaats	Amsterdam
type gebouw	grondgebonden woning
soort bouw	nieuwbouw
bouwjaar	2023
eigendom	onbekend
opname	detailopname
datum berekening	17-11-2023

Registratie

Deze berekening is niet geregistreerd in de landelijke database van de Rijksoverheid (EP-Online) en mag daarom **niet gebruikt worden bij aanvraag van een omgevingsvergunning**.

Berekeningen voor de aanvraag van een omgevingsvergunning dienen geregistreerd te zijn in EP-Online. Dit geldt voor zowel grondgebonden woningen, appartementen als utiliteitsgebouwen.

Bouwkundige bibliotheek

Definieer dichte constructies (vloeren, gevels, daken, panelen)

dichte constructie	vlak	methodiek	R_c [m²K/W]
Gevel	gevel	vrije invoer	4,50
Dak	dak	vrije invoer	6,00
Begane grond vloer	vloer	vrije invoer	3,50

Definieer transparante constructies (ramen, deuren, panelen in kozijn)

transparante constructie	type	methodiek	U_W / U_D [W/m²K]	$g_{gl;n}$
Raam	raam	vrije invoer	1,8	0,60
Deur	deur	vrije invoer	2,0	0,00

Indeling gebouw

energieprestatie berekenen	per gebouw

Definieer rekenzones

type zone	omschrijving	bouwwijze vloeren	bouwwijze wanden	$n_{bouwlaag}$
rekenzone	Rijtjeshuis	massief beton	dragend metselwerk	3

Definieer woning

omschrijving	type woning	rekenzone	A_g [m²]
Tussenwoning	tussenwoning met kap	Rijtjeshuis	124,32

Constructies

Geometrie dichte constructie - Tussenwoning - Rijtjeshuis

dichte constructie	opmerking	L [m]	B [m]	oppervlakte [m²]
vloer - op/boven mv; boven kruipruimte - 50,93 m²				
Begane grond vloer - R_c = 3,50				50,93
Gevel Z - buitenlucht, Z - 30,03 m² - 90°				
Gevel - R_c = 4,50				17,71
Gevel N - buitenlucht, N - 30,03 m² - 90°				
Gevel - R_c = 4,50				16,53
Dak Z - buitenlucht, Z - 35,07 m² - 44°				
Dak - R_c = 6,00				35,07
Dak N - buitenlucht, N - 35,07 m² - 44°				
Dak - R_c = 6,00				35,07

Geometrie transparante constructies (ramen en deuren) - Tussenwoning - Rijtjeshuis

transparante constructie	opmerking	L [m]	B [m]	oppervlakte [m²]	beschaduwing	zonwering	zomernachtventilatie
Gevel Z - buitenlucht, Z - 30,03 m² - 90°							
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Keuken	1,80	2,00	3,60	minimale belemmering	geen zonwering	niet aanwezig
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Room M	1,80	2,00	3,60	minimale belemmering	geen zonwering	niet aanwezig
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Room S	1,80	1,50	2,70	minimale belemmering	geen zonwering	niet aanwezig

Geometrie transparante constructies (ramen en deuren) - Tussenwoning - Rijtjeshuis							
transparante constructie	opmerking	L [m]	B [m]	oppervlakte [m²]	beschaduwing	zonwering	zomernachtventilatie
Deur - U = 2,0 / $g_{gl;n}$ = 0,00		2,20	1,10	2,42		geen zonwering	niet aanwezig
Gevel N - buitenlucht, N - 30,03 m² - 90°							
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Woonkamer	1,80	3,50	6,30	minimale belemmering	geen zonwering	niet aanwezig
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Room L	1,80	2,00	3,60	minimale belemmering	geen zonwering	niet aanwezig
Raam - U = 1,8 / $g_{gl;n}$ = 0,60	Room L	1,80	2,00	3,60	minimale belemmering	geen zonwering	niet aanwezig

Kenmerken vloerconstructie- Tussenwoning - Rijtjeshuis - vloer

omtrek van het vloerveld (P)	10,20 m

Kenmerken kruipruimte en onverwarmde kelder- Tussenwoning - Rijtjeshuis - vloer

kruipruimteventilatie (ε)	0,0012 m²/m
warmteweerstand van de boven de vloer liggende gevel (R_{bw})	Gevel - R_c = 4,50 m²K/W
warmteweerstand v.d. onverwarmde kelder-, kruipruimtevloer (R_{bf})	m²K/W

Luchtdoorlaten

Infiltratie

buitenwerkse gebouwhoogte	10,32 m
invoer infiltratie	geen meetwaarde voor infiltratie

Definieer infiltratie	
gebouw	$q_{v,10;lea;ref}$ [dm³/s per m² gebruiksoppervlak]
gebouw	0,70

Verticale leidingen in directe verbinding met buitenlucht

invoer verticale leidingen in directe verbinding met buitenlucht	geen verticale leidingen door thermische schil

Verwarming 1

Aantal identieke systemen

1

Aangesloten rekenzones

Rijtjeshuis

Opwekking

Opwekker 1

type opwekker	CV-ketel - gas
invoer opwekker	forfaitair
functie(s) van opwekker	verwarming en warm tapwater
gemeenschappelijke of niet-gemeenschapellijke installatie	niet-gemeenschappelijke installatie
CW-klasse	CW klasse onbekend
positie opwekker	binnen thermische zone
toestel / warmteleveringssysteem	HR(-107) ketel met indirect verwarmde warm watervoorraadvat(en)
warmtebehoefte verwarmingssysteem	8377 kWh
door opwekker geleverde warmte (per toestel)	8377 kWh
opwekkingsrendement	0,950
energiefractie	1,000
hulpenergie per toestel	165 kWh

Distributie

type distributiesysteem	eenpijpssysteem
ontwerp aanvoertemperatuur	60°C
waterzijdige inregeling	inregeling onbekend

Binnen verwarmde zone

invoer leidingen	leidinggegevens onbekend
totale leidinglengte	74,56 m
isolatie leidingen	geïsoleerd
isolatie kleppen en beugels	kleppen en beugels - geïsoleerd

Buiten verwarmde zone

invoer leidingen	leidinglengte bekend - overige leidinggegevens bekend
totale leidinglengte	5,00 m
isolatie leidingen	geïsoleerd, in bouwconstructie
isolatie kleppen en beugels	kleppen en beugels - geïsoleerd

Eigenschappen distributieleidingen

ruimten	$Ø_{binnen}$ [mm]	$Ø_{buiten (incl. isolatie)}$ [mm]	dekking [mm]	$\lambda_{constructie}$ [W/mK]	$\lambda_{isolatie}$ [W/mK]
buiten verwarmde zone	100	300	400	1,000	1,000

aanvullende distributiepomp	aanvullende distributiepomp niet aanwezig

distributiepompen

omschrijving
pomp 1

Afgifte

Afgiftesysteem 1

type afgiftesysteem	stralingsverwarming
vertrekhoogte	h > 8 m
type stralingsverwarming	verwarmingselementen aan wand - zonder aanv. recirculatie
ruimtetemperatuur regeling	forfaitair
type ruimtetemperatuur regeling	onbekende regeling
temperatuurcorrectie type regeling ($\Delta\theta_{ctr}$)	2,5 K
temperatuurcorrectie automatische regeling ($\Delta\theta_{roomaut}$)	0,0 K

Ventilatoren voor afgifte

invoer ventilator
geen ventilatoren aanwezig

Warm tapwater 1

Aantal identieke systemen

1

Aangesloten op warm tapwatersysteem

Tussenwoning

Opwekking

Opwekker 1

type opwekker	CV-ketel - gas
invoer opwekker	forfaitair
indirect verwarmde warm watervoorraadvat(en)	geen indirect verwarmde warm watervoorraadvat(en)
functie(s) van opwekker	verwarming en warm tapwater

gemeenschappelijke of niet-gemeenschapellijke installatie	niet-gemeenschappelijke installatie
CW-klasse	CW klasse onbekend
positie opwekker	binnen thermische zone
toestel / warmteleveringssysteem	HR(-107) ketel met Gaskeur
warmtebehoefte tapwatersysteem	2160 kWh
opwekkingsrendement	0,563
energiefractie	1,000
hulpenergie per toestel	0 kWh

Distributie

circulatieleiding	geen circulatieleiding aanwezig

distributiepompen
omschrijving
pomp 1

Afgifte

gemiddelde leidinglengte naar badruimte	leidinglengte naar badruimte < 2 m
gemiddelde leidinglengte naar aanrecht	leidinglengte naar aanrecht < 2 m
inwendige diameter leiding naar aanrecht	diameter leiding naar aanrecht onbekend

Ventilatie 1

Aantal identieke systemen

1

Aangesloten rekenzones

Rijtjeshuis

Type ventilatiesysteem

ventilatiesysteem	C. natuurlijke toevoer en mechanische afvoer
invoer ventilatiesysteem	forfaitair
systeemvariant	C.1 standaard
f_{ctrl}	1,00
passieve koeling	geen passieve koelregeling

Voorverwarming natuurlijke toevoer

voorverwarming natuurlijke toevoer	geen voorverwarming natuurlijke toevoerroosters

Ventilatoren

invoer ventilator vermogen	forfaitair ventilator vermogen

Ventilatiedebieten

werkelijk geïnstalleerde / te installeren ventilatiecapaciteit	werkelijk geïnstalleerde / te installeren ventilatiecapaciteit onbekend

Distributie en regelingen

luchtdichtheidsklasse ventilatiekanalen	LUKA A, B, C

Resultaten

Energieprestatie volgens NTA8800

indicator		eis	resultaat	
energiebehoefte	$Ewe_{H+C;nd;ventsys=C1}$	55,00 kWh/m²	60,33 kWh/m²	×
primaire fossiele energie	Ewe_{PTot}	30,00 kWh/m²	106,52 kWh/m²	×
aandeel hernieuwbare energie	$RER_{PrenTot}$	50,0 %	0,0 %	×
hernieuwbare energie indicator	$E_{wePRenTot}$		0,00	
temperatuuroverschrijding	$TO_{juli;max}$	1,20	0,62	✓
energielabel			A	
netto warmtebehoefte (EPV)	$E_{H;nd;net}$		58,23 kWh/m²	

Jaarlijkse hoeveelheid energiegebruik voor de energiefunctie volgens NTA 8800

functie		energie niet-primair	energie primair	hulpenergie niet-primair	hulpenergie primair
verwarming	$E_{H;ci}$				
elektrisch		0 kWh	0 kWh	165 kWh	239 kWh
gas		8817 kWh	8817 kWh	0 kWh	0 kWh
warm tapwater	$E_{W;ci}$				
gas		3836 kWh	3836 kWh	0 kWh	0 kWh
ventilatoren	$E_{V;ci}$	241 kWh	349 kWh	0 kWh	0 kWh
Totaal			13002 kWh		239 kWh

Jaarlijkse karakteristieke energiegebruik volgens NTA 8800

primaire energiegebruik inclusief hulpenergie		13242 kWh
opgewekte elektriciteit		0 kWh
jaarlijkse karakteristieke energiegebruik	E_{Ptot}	13242 kWh

Jaarlijkse hoeveelheid hernieuwbare energie volgens NTA 8800

verwarming	$E_{Pren;H}$	0 kWh

Jaarlijkse hoeveelheid hernieuwbare energie volgens NTA 8800

warm tapwater	$E_{Pren;W}$	0 kWh
koeling	$E_{Pren;C}$	0 kWh
elektriciteit	$E_{Pren;el}$	0 kWh
totaal	$E_{PrenTot}$	0 kWh

Elektriciteitsgebruik op de meter volgens NTA 8800

gebouwgebonden installaties	406 kWh
niet gebouwgebonden installaties	2600 kWh
opgewekte elektriciteit	0 kWh
totaal	3006 kWh

Aardgasgebruik (exclusief koken) volgens NTA 8800

gebouwgebonden installaties	1295,2 m^3aeq

Oppervlakten

totale gebruiksoppervlakte	$A_{g;tot}$	124,32 m²
verliesoppervlakte	A_{ls}	165,85 m²
compactheid		1,33

CO_2-emissie volgens NTA 8800

CO_2-emissie	2453 kg

Alle bovenstaande energiegebruiken zijn genormeerde energiegebruiken gebaseerd op een standaard klimaatjaar en een standaard gebruikersgedrag. Het werkelijke energiegebruik zal afwijken van het genormeerde energiegebruik. Aan de berekende energiegebruiken kunnen geen rechten ontleend worden.

TO_{juli} conform NTA 8800

rekenzone	Rijtjeshuis
noord	0,31

TO_{juli} conform NTA 8800

rekenzone	Rijtjeshuis
zuid	0,62
$TO_{juli;max}$	0,62

D

Additional Results

In addition to the results presented in Chapter 5, this appendix gives some more figures for the sake of completeness. The results were narrowed to the Bbl requirements for a BENG1 value below 55 kWh/m^2 and a daylight factor of 1.0 for 50% of the reference plane.

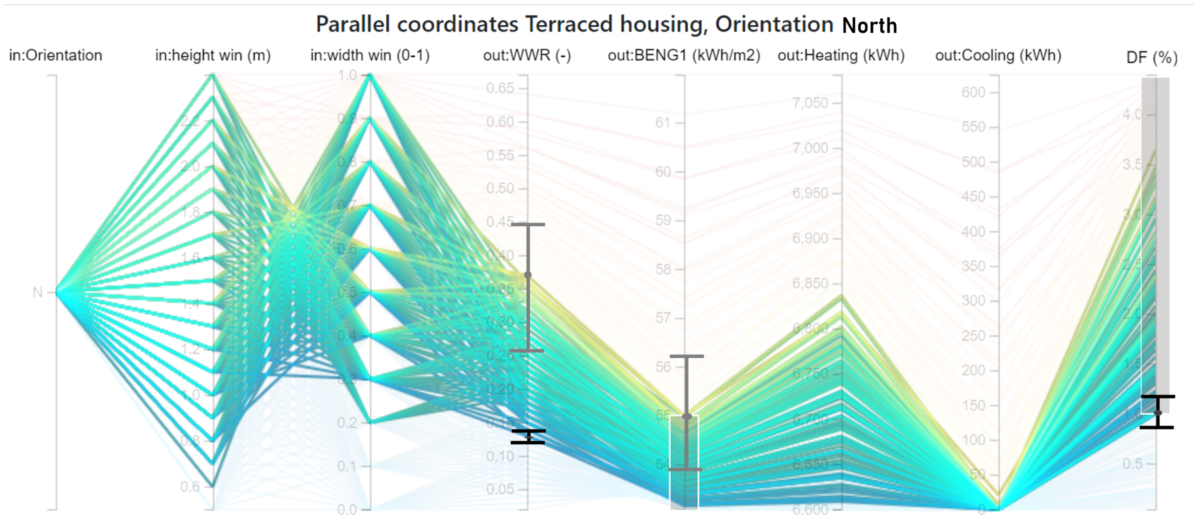


Figure D.1: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in north direction.

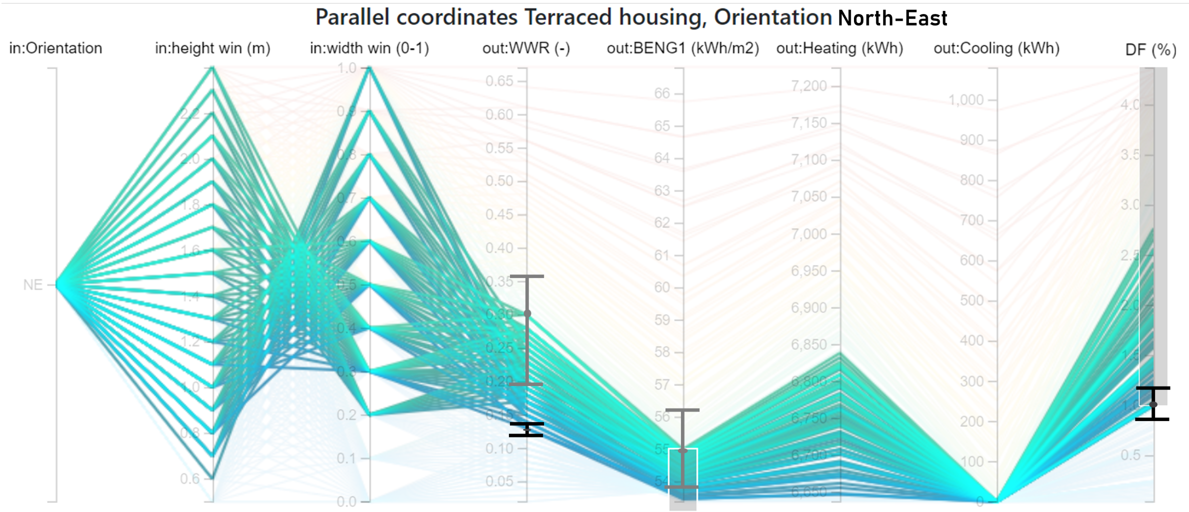


Figure D.2: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in north-east direction.

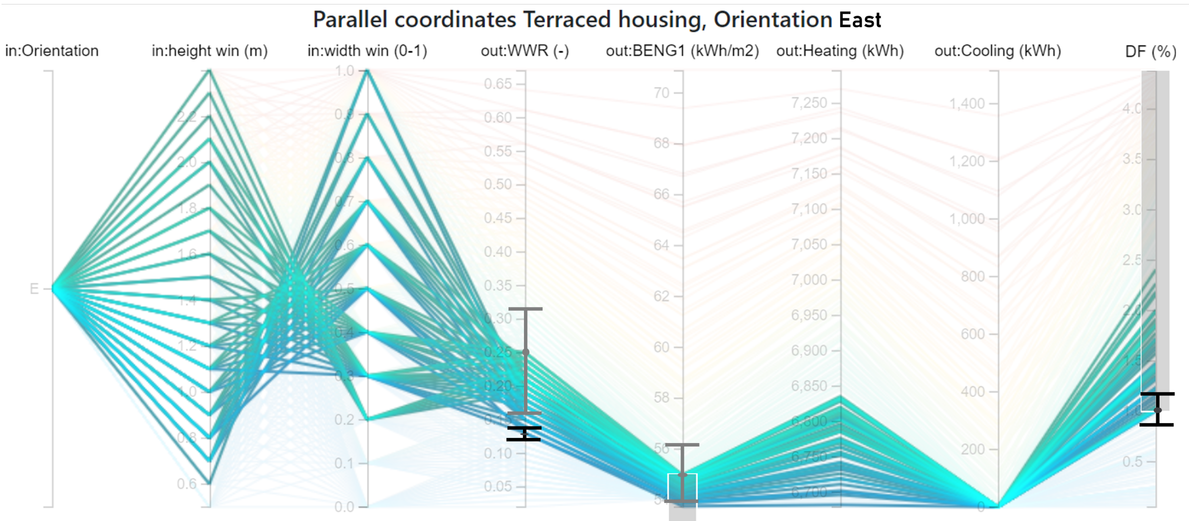


Figure D.3: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in east direction.

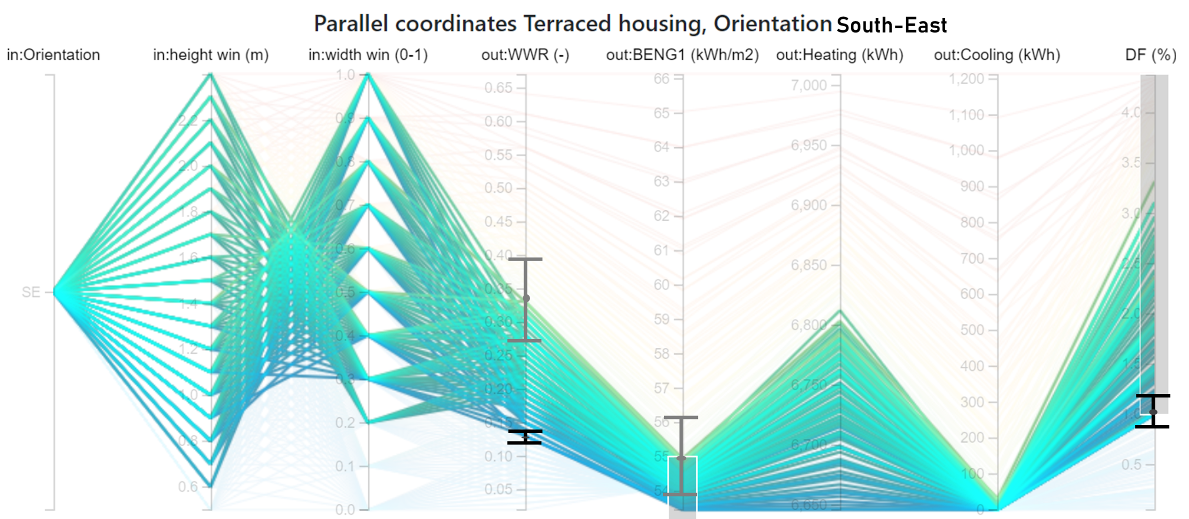


Figure D.4: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in south-east direction.

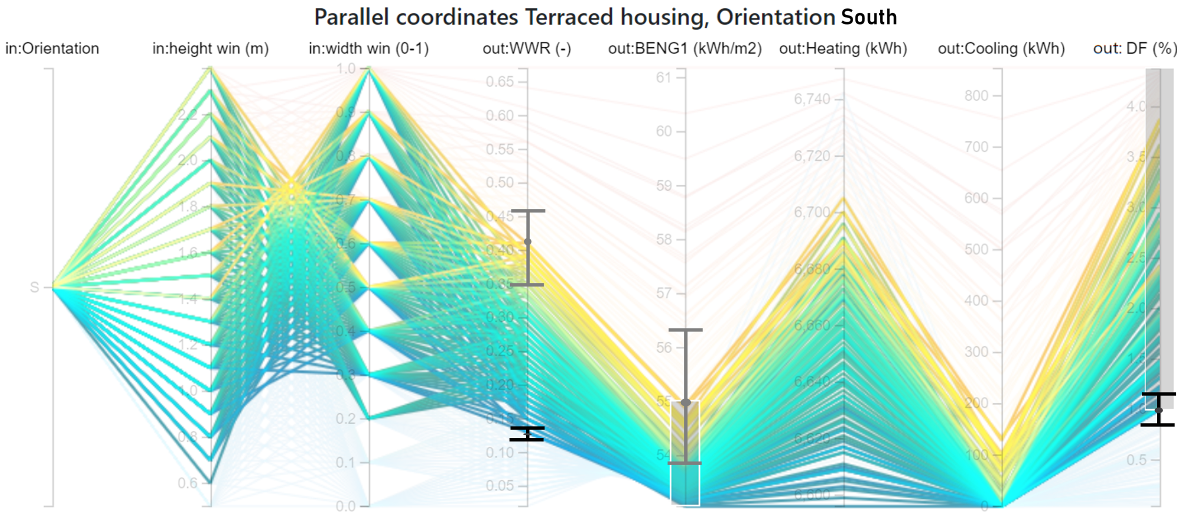


Figure D.5: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in south direction.

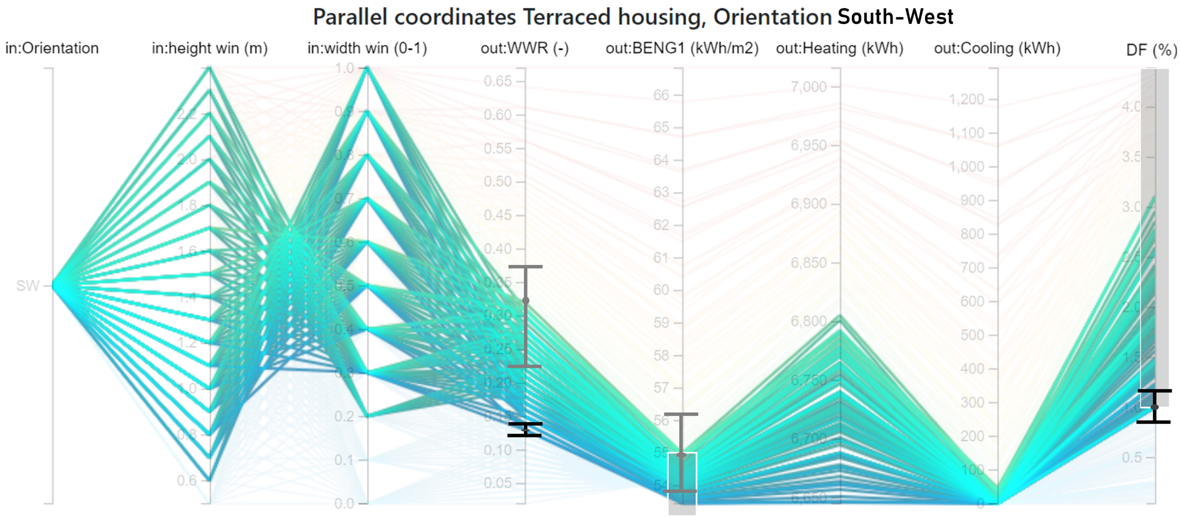


Figure D.6: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in south-west direction.

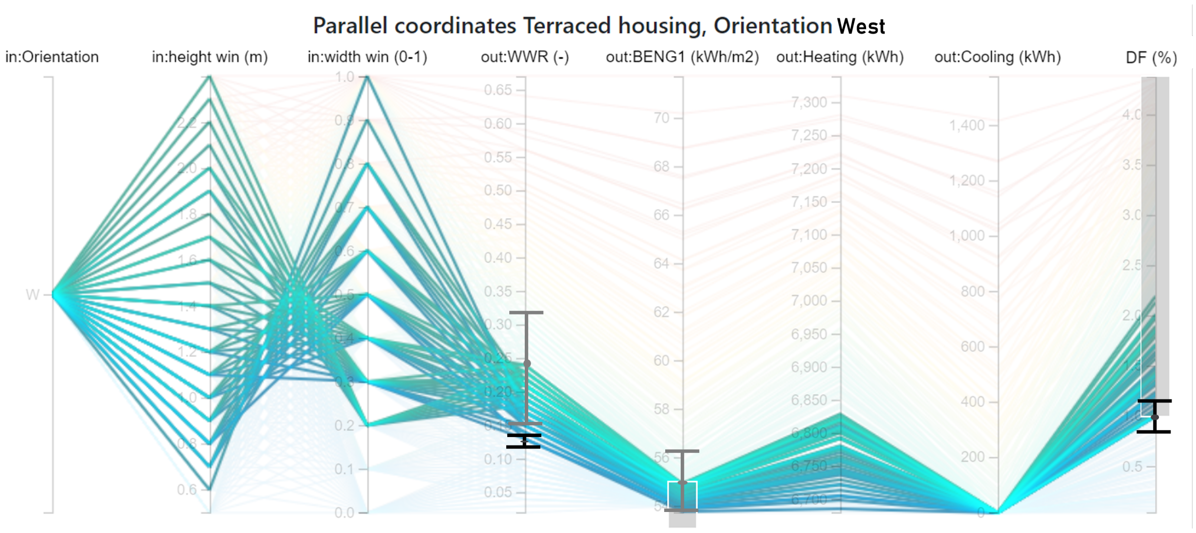


Figure D.7: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in west direction.

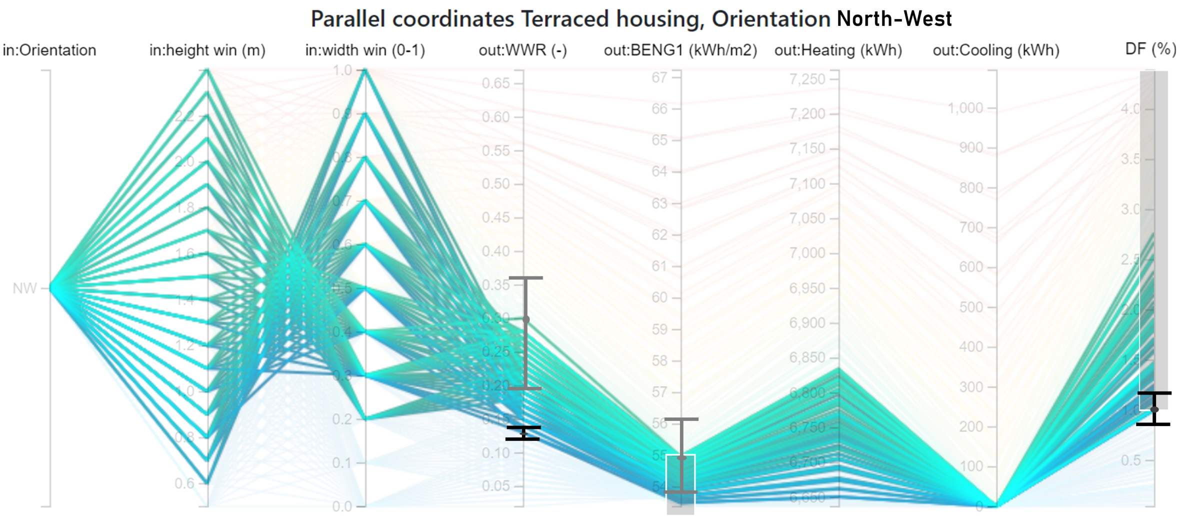


Figure D.8: Thread parallel coordinates chart displaying different solutions for a terraced housing facing in north-west direction.

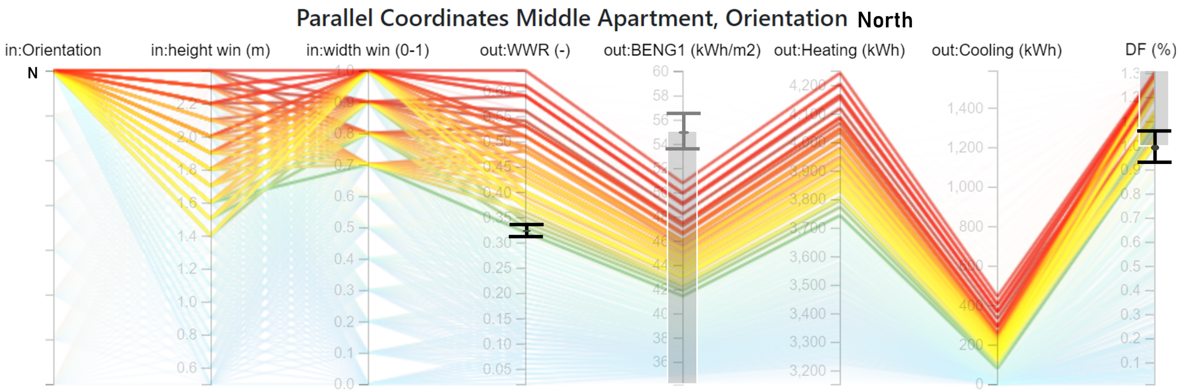


Figure D.9: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in north direction.

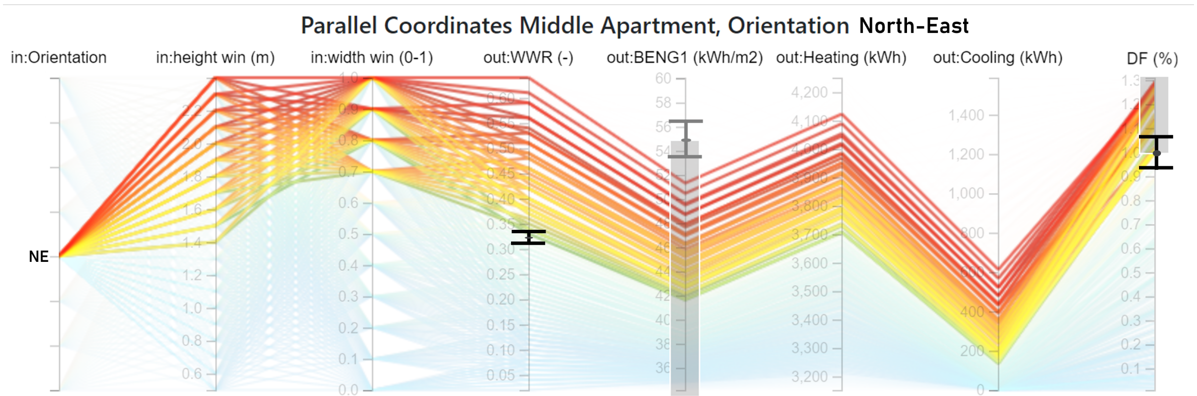


Figure D.10: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in north-east direction.

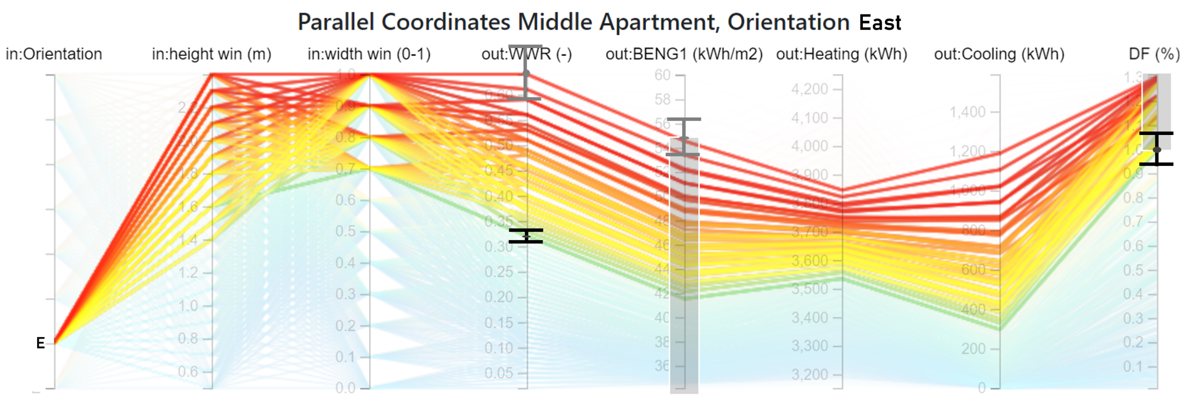


Figure D.11: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in east direction.

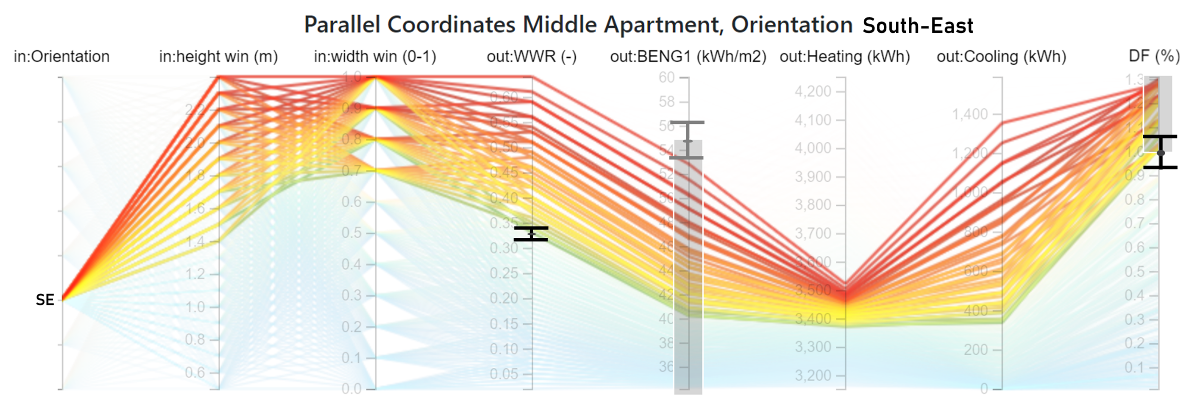


Figure D.12: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in south-east direction.

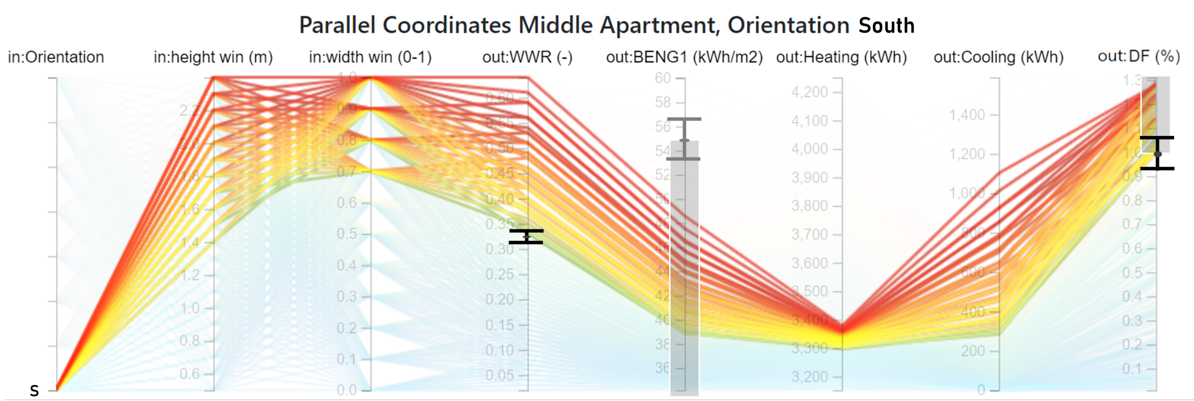


Figure D.13: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in south direction.

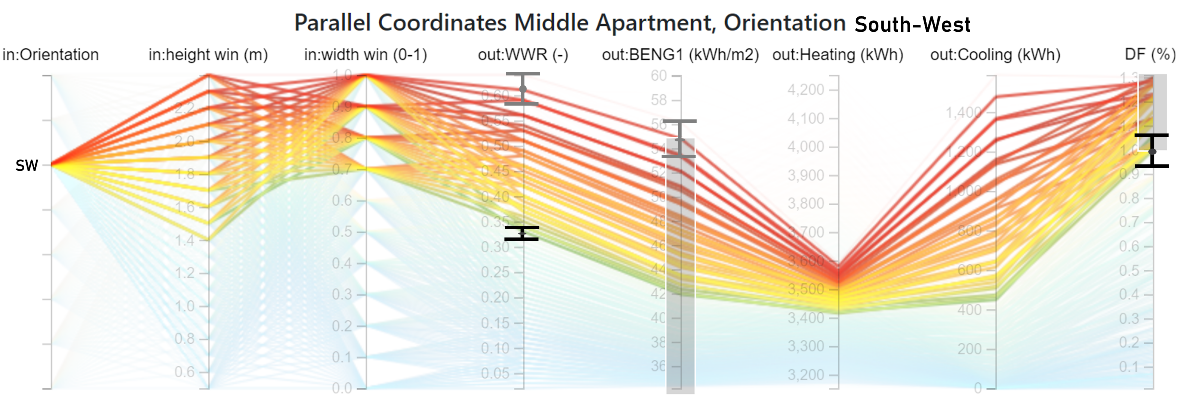


Figure D.14: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in south-west direction.

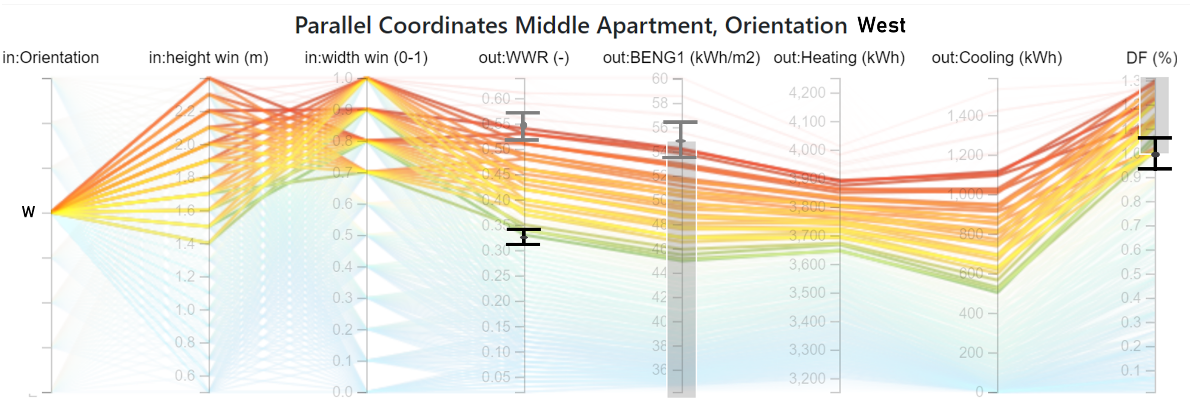


Figure D.15: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in west direction.

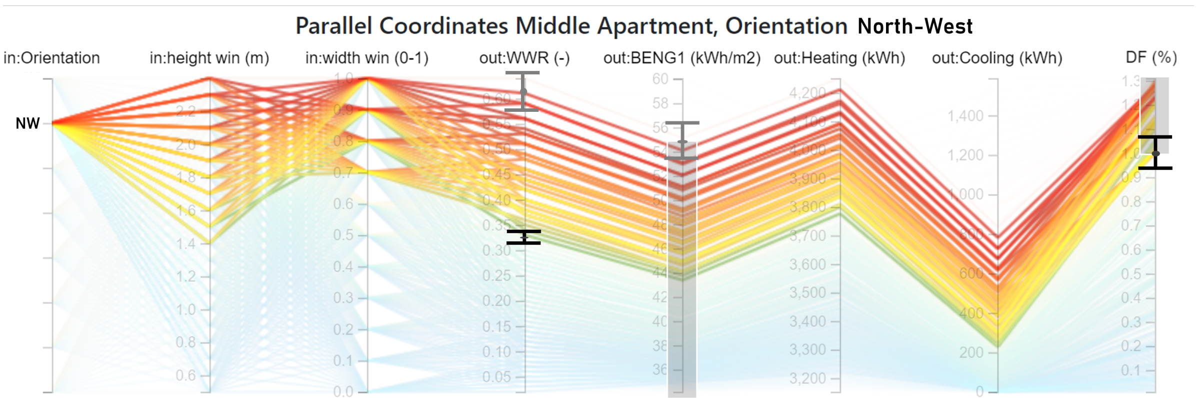


Figure D.16: Thread parallel coordinates chart displaying different solutions for the middle apartment facing in north-west direction.

E

WWR in Absolute Values

In addition to the data of the relative window-to-wall ratio (WWR), the table below gives information on what WWR can be associated with real-world measurements in square metres of surface area. This is meant to give some indication of how much glass is actually used in one facade.

WWR in [%]	Total Facade Area in [m^2]	Window Area in [m^2]
10	30.03	3.00
20	30.03	6.01
30	30.03	9.01
40	30.03	12.01
50	30.03	15.02
60	30.03	18.02
70	30.03	21.02
80	30.03	24.02
90	30.03	27.03
100	30.03	30.03

Table E.1: Window-to-wall ratio (WWR) expressed in square metre of glass in the specific situation of a terraced house facade.

WWR in [%]	Total Facade Area in [m^2]	Window Area in [m^2]
10	36.98	3.70
20	36.98	7.40
30	36.98	11.09
40	36.98	14.79
50	36.98	18.49
60	36.98	22.19
70	36.98	25.89
80	36.98	29.58
90	36.98	33.28
100	36.98	36.98

Table E.2: Window-to-wall ratio (WWR) expressed in square metre of glass in the specific situation of a middle apartment facade.