MSc thesis
Alexandros Christodoulou

Parametric Massing Optimization
Tools

TU Delft
Delft University of Technology
Faculty of Civil Engineering and Geosciences
BEMNext Lab

BEMNext Laboratory
MSc thesis
Alexandros Christodoulou

Parametric Massing Optimization Tools
Disclaimer
Published in the Netherlands
copyright © 2013 by Alexandros Christodoulou

All rights reserved. No part of this publication may be reproduced in any form without the written permission of the copyright holder. The rights to publication of (results of) projects, including sketches, drawings, texts, photographs, audiovisual material, computer-files, etc. which have originated during the graduation project, are and remain property of the copyright holder. The copyright holder reserved the right to attach conditions to consented publication of graduation project results. The contents of this project are published in the sole responsibility of the copyright holder. The copyright holder does not acknowledge any responsibility for possible damage caused by any use of this publication.

First edition published 2013
PREFACE

This is the final version of the Master thesis report of Alexandros Christodoulou on parametric massing optimization tools, completed in October 2013.

In the preface, an overview of the thesis and its basic information and terms will be presented.
1. Committee

The graduation committee and the external advisors for this thesis are the following:

Andy van den Dobbelsteen
e-mail: A.A.J.F.vandenDobbelsteen@tudelft.nl
affiliation: Delft University of Technology
Faculty of Architecture
Department of Architectural Engineering + Technology
address: room 01.West.130, Julianalaan 134, 2600 GA, Delft

Jeroen Coenders
e-mail: jeroencoenders@gmail.com
affiliation: White Lioness Technologies
Delft University of Technology
Faculty of Civil Engineering and Geosciences
BEMNext Laboratory
address: Room 6.66, Stevinweg 1, 2628 CN, Delft

Anke Rolvink
e-mail: A.Rolvink@tudelft.nl
affiliation: White Lioness Technologies
Delft University of Technology
Faculty of Civil Engineering and Geosciences
address: Room 6.66, Stevinweg 1, 2628 CN Delft

Eric van den Ham
e-mail: E.R.vandenHam@tudelft.nl
affiliation: Delft University of Technology
Faculty of Architecture
Department of Architectural Engineering + Technology
address: 01+.West.210, Julianalaan 132-134, 2600 GA, Delft

Jan-Pieter den Hollander
e-mail: janpieter@bouwenmetstaal.nl
affiliation: Bouwen met Staal
address: Postbus 190, 2700 AD Zoetermeer
2. Acknowledgements

In this paragraph the main contributors of the thesis will be presented.

To begin with, a lot of gratitude goes to the committee members and external advisors for their large contribution and feedback throughout the thesis process.

I would like to thank Jeroen Coenders and Anke Rolvink who have helped since the first day of this thesis, into formulating the subject, finding it’s boundaries and proposing extensions and improvements to the developing and research part.

I would like to thank also Andy van den Dobbelsteen for his feedback, but also for sharing insight on the typology study he performed in his PhD dissertation, which served as an invaluable basis for the validation and the extension of the massing research.

Jan-Pieter den Hollander is also thanked for his detailed remarks throughout the process, both concerning the report evolution but also in finding the boundaries and suggesting possible points of focus for the subject.

Apart from the thesis committee, Eric van den Ham is also thanked for his large contribution into the Building Physics related guidance. Since Building Physics have taken up a large part of this research, his contribution into directing towards the methods that would be most suitable for parametric energy assessment has been indispensable.

I would also like to thank K.K.Howorko for sharing material and information on her design project for the first case study and giving valuable feedback on the use of the MEOtoolbox on the design process.

Also a big thank you goes to Veronika, Dion and Tasos and the rest of the fellow BEMNext lab members, with whom we stepped into similar ventures at around the same time, and whose company has made the road towards the thesis aims, a less lonely exploration.

Finally, my family is thanked for their immense support throughout my studies.

3. Personal Motivation

The reason’s why my academic interests strongly gravitated around the themes of this thesis are multiple.

To begin with, during the two years of my TU Delft MSc studies in Build-
ing Engineering, I have participated in a series of multidisciplinary design projects, aiming towards integrated design. In these projects I have experienced design through different points of view and realized the importance of clear suggestions and visualizations in the integrated design process. In these projects, engineering consultancy often lacked in explaining and visualizing exactly the effect of following certain suggestions in the preliminary design phase. Apart from general rules of thumb that might be available, engineering students had little to offer in the initial design phase, waiting for a finished design from architects in order for them to start analysing and dimensioning the structure and installations needed. Thus, during these courses the need for making engineering consultancy a quantifiable and visualizable design element, even in very early stages of the design, became evident for me. I felt the urge to acquire this ability, by any means that already exist or had to be made for this aim.

Another realization during the various study workshops was how simple questions like the overall gross floor area or the effect of orientation where not always easy to answer after several architectural gestures that might modify the initial design. There was an obvious need for tools that would always show the effect of design changes in the basic demands of a design.

A passion for architecture that works, and for the great architects who have managed to integrate in their designs architectural and engineering considerations in one holistic functional building entity was another reason why this subject was chosen. The reason why I started researching on massing optimization is that I was aiming to be able to participate in building designs that manifestate their concepts and ambitions throughout their systems and in all scales, starting from the geometry of the design itself. It is my strong belief that beauty and functionality are intertwined and thus, engineering and architectural inquisitions, if analysed properly, will actually move towards similar solutions. Having followed studies of civil engineering for five years, building engineering for two, and having followed architectural design courses for one year has only reaffirmed this persistent belief.

On the first year, for the course “Smart & Bioclimatic Design”, taught by two of this thesis five supervisors (Eric van den Ham and Andy van den Dobbelsteen), I researched vernacular and animal architecture for the course’s assignment, which was to make a design manual on a selected topic. My manual was named “Bioclimatic Architecture without Architects” and through it’s research I came ac-
cross the astonishingly simple design techniques through which nature and non-technically educated people have managed to live harmoniously with their climatic context for centuries, in contrast to modern man facing multiple dangers due to his unreasonable behaviors nowadays. Massing design has often played an important role in the success of vernacular and animal “designs” making use of passive solar gains (in the case of termites buildings) or minimizing the envelope’s surface (in the case of the eskimo’s igloo). These no-tech and no-budget climate techniques have been an important lesson for me, and I believe that this mindset has to be re-implemented in any design project, before applying additional high-tech and expensive installations, if still needed.

4. Report Overview

This report will start by describing the main observations leading to the description of the main problem and the main research questions that it will attempt to address. The methodologies through which this attempt will be made will follow on the second chapter.

The third and fourth chapter will describe the development and validation process of tools needed to fulfill the research aims. After that, chapter five will attempt to employ the tools and methodologies, to address the research questions and main problems.

The Discussion chapter will address the research questions of the Introduction chapter, describing the answers that the thesis did provide and the assumptions through which these answers were provided. The Conclusions chapter will concisely highlight the main findings of the research while the recommendations future research continuation of the themes of the thesis will conclude the report.

In the annex, more insight will be given into specific aspects of the research like the use of the tool, the validation process and the case studies.

5. Notes

The images used in this report are generated by the report’s author, if not noted otherwise.

The use of images found through the internet are considered to have the characteristics of “fair use of images for teaching, research and study notes”. Ac-
According to the The Visual Resources Association (VRA) in its statement on fair use of images¹, “the use of images in scholarship is fundamental to the advancement of collective knowledge”. The requirements for the fair use for academic purposes are the following: a) the use should take place to support a scholarly argument or commentary and are not for purely aesthetic purposes, b) they feature significant commentary on the image, c) they are positioned in a resolution and size chosen in order to make the best scholarly argument, d) copyright is attributed to it’s owner, where known and e) the circulation and distribution of the thesis through online websites or repositories is consistent with academic practices of the degree-granting institutions.

Attention has also been given in proper referencing of strong statements of the report, especially at the first time they are used as arguments. When these statements are repeated and also in the case of statements considered less controversial, based on the general literature study and knowledge of the author, the referencing has not been considered essential.

6. Glossary

This report will use extensively the following terms, which are hereby defined to avoid confusion on the way they will be used.

**Massing:** The terms “massing” or “massing design stage” will be used to describe the architectural initial design process of positioning basic design geometries into the design space. More on this process will be discussed on chapter 1.1.

**Massing gesture:** The action of rotating, tilting or otherwise transforming a massing’s form, in order to improve it’s features and/or performance on one or more of it’s objectives. (See figure 0.1)

**Optimization:** make the best or most effective use of a situation or resource.²

**Toolbox:** In computing, a set of software tools.¹

¹ Available at: http://www.vraweb.org/organization/pdf/VRAFairUseGuidelinesFinal.pdf
² http://oxforddictionaries.com/definition/english/optimize?q=optimization#optimize__14
Building envelope: This term is used often instead of the term façade, to include cases of buildings where the distinction between roof and facade is unclear (ex.g TU Delft Library by Mecanoo, 30 St Mary Axe (The Gherkin) by Foster + Partners).

Gross Floor Area: The area within the perimeter of the outside walls of a building as measured from the inside surface of the exterior walls, without excluding hallways, stairs, closets, thickness of walls, columns, or other interior features.4

Net Floor Area: The net floor area is usually defined as the total usable floor area in a building, measured from the inside of the walls of the building envelope.5

BIM: BIM may commonly refer to both the process of Building Information Modelling, and the digital artifact model of a Building Information Model. In both cases, BIM is used to describe an integrated 3d-model where each line and element is not only a picture, like traditional design, but features also information/properties.6 For example, in a BIM model, the software “knows” that a concrete column is a concrete column and that a glass panel has a specific transparency, U-value etc. More on BIM will be discussed in paragraph 1.1.

---

**Integrated Design:** (Also referred to as holistic or integral design) The design approach of integrating building systems to achieve optimized designs. This approach opposes the traditional sequential design of systems leading to sub-optimal solutions due to each system set to satisfy only aspects related to each system.⁷

**Parametric Design:** A definition of parametric design could be based on the description of Tamoko Sakamoto:

“Parametric design, is a process based not on fixed metric parameters, but on consistent relationships between objects, allowing changes on a single element to propagate corresponding changes throughout the system.”⁸

**Bioclimatic Design:** Bioclimatic analysis and design methods aim to support climate responsive design decisions for the early design stages.⁹

**Rhinoceros (or Rhino):** In this thesis these words will refer to a popular 3d-modelling software, developed by Robert McNeel & Associates.

**Grasshopper:** Grasshopper is a plug-in for Rhino software, adding parametric design possibilities to the software.

---

SUMMARY

The distinction between architect and engineer is a relatively recent event, in comparison to the long history of human constructions. In modern times the separation of the two professions and the involvement of engineers in later design stages has proved problematic, because of the large effort needed to make changes in later design stages.

On the other hand, the rising importance of engineering and financial objectives that building projects have to meet, calls for a more integrated design approach since the very early design stages. Contemporary parametric tools give the possibility to enhance multidisciplinary communication by providing the ability to quickly extract needed values from preliminary design geometries (or “massings”) and assess them through properly defined evaluation scripts.

This thesis investigated this prospect, focusing on the aspect of energy demand, which emerges as a central design consideration in contemporary architecture. The thesis report identified the main objectives that would serve as fitness values for it’s assessment optimization systems, including in them the main parameters of influence for each of these objectives. These objectives have been the minimization of solar gains, annual heating and cooling demand, annual total energy demand per GFA, annual total energy demand per NFA, and embodied + operational (for 1, 10, 50 years) CO₂ emissions. The choice of the optimization objective and thus the optimization system that has to be set to assess it, was proved to have great influence on the optimization process and results. Because of that, this thesis concluded that it this is a point that has to be considered carefully, according to the design’s priorities, to find out which specific objective is set as fitness value, for each design project. That is because an extension of the optimization in unneeded areas, might diminish the accuracy of the results and increase the computational demand needed.

To support these assessment and optimization systems, a parametric toolbox has been developed, named MEOtoolbox (MEO derived from the initials of the words Massing Energy Optimization). The components developed mainly aimed to facilitate the calculation of the annual demand for heating and cooling,
Alexandros Christodoulou - Parametric Massing Optimization Tools

using the quasi-steady state method for energy demand calculations described in
the ISO13790 international standard. The MEOtoolbox will be made available to
download after the end of this thesis project, through MEOtoolbox.blogspot.com.
Possible design scenarios where the MEOtoolbox could be particularly useful, have been outlined through design dilemmas that also formed the case studies
of this thesis. To validate the results of these case studies, results, relevant to the
case studies, have been beforehand compared to results of similar studies and software.
The design case studies have investigated the effect of tilting the facades of
a recreation centre in Paris (France), and the effect of orientation and the effect of
self shading in a design of a highrise building for the European Union in Brussels
(Belgium). The study showed that:
•
•

•

Tilting downwards a south facing facade, in Paris, can reduce the solar load
in half during summer, while not greatly reducing solar load in winter.
For the climate of Brussels, the maximum effect that orientation could have,
for the particular design geometry, was an increase of 5% in the annual cooling
demand and 1% in the annual heating demand.
The effect of shifting in order to self-shade building geometries proved that
it is an effective way of reducing cooling demand, without increasing greatly
the heating demand.

The two case studies also exemplified some of the additional benefits and
shortcomings of the parametric tools. In the advantages, it has been shown how
design choices can be visually supported, forming arguments for a specific design
decision. On the shortcomings, the unavailability of tools to assess the multiplicity of parameters that a designer might consider and the sensitivity of the results
in certain parameters, (which could, if not set properly, lead to invalid feedback)
are issues that have to be addressed by parametric design software developers, for
example through detailed manuals.
For the comparative research, six basic building typologies (“Warehouse”,

15


“Cube”, “Tower”, “Caterpillar”, “Fence”, “Slab”) were compared with regards to their operational energy per area in different climates and with different glass percentages in the facades. The thesis concluded that:

- For all the typologies studied, with the absence of external shading and for the glass percentages studied, cooling demand seems to be more critical for the determination of optimal energy massing, due to it’s greater fluxuation depending on the typology.
- As far as the absolute energy demand values are concerned, location seems to be the most largely influencing parameter, followed by glass percentage. Orientation and programmatic function seem to have much less influence on the absolute value of the energy demand of the typologies.
- As far as the ratio between the typologies is concerned, the switch of the assessment value from Energy per GFA to Energy per NFA, strongly influences the energy demand per area ratio between the typologies, as spaces with less rentable space often seem to be good energy solutions. Minimizing the expected Energy/NFA gives different results than Energy/GFA, taking into account also space efficiency. Since NFA is usually a primary goal for construction and real-estate companies, it is a realistic aim to try to minimize energy costs to cover a specific programmatic NFA demand. Location also influences largely the ratio between typologies, which seems to be similar in locations with similar ratio between the needs in heating and cooling.
- The typology study showed that the energy per NFA can be reduced in the magnitude of 40% by selecting an optimal typology for the climate of the Netherlands.
- For the climate of Amsterdam, and for the characteristics for facade and structure employed for the analysis, embodied energy seems to correspond, roughly, to 10 years of operational energy for all of the typologies. The fact that this was the result for all the typologies studied, suggests that it could potentially be used as a rule of thumb, when assessing the importance of embodied energy for a specific project, depending on it’s expected functional lifetime.
(page intentionally left blank)
# TABLE OF CONTENTS

Preface..........................................................................................................................5

Summary..........................................................................................................................14

1. Introduction..................................................................................................................21
   1.1 Motivation............................................................................................................22
   1.2 Research aim........................................................................................................37
   1.3 Research questions..............................................................................................38

2. Methodology..............................................................................................................41
   2.1 Optimization research methodology.................................................................42
   2.2 Energy assessment methodology........................................................................49
   2.3 Software development methodology.................................................................51
   2.4 Validation methodology......................................................................................52

3. Software Development..............................................................................................54
   3.1 Main objective......................................................................................................55
   3.2 Principles.............................................................................................................58
   3.3 Assumptions..........................................................................................................60
   3.4 Implementation......................................................................................................60
   3.5 Components..........................................................................................................62
   3.6 Workflow...............................................................................................................108
   3.7 User Interface.......................................................................................................109
   3.8 Script structure.....................................................................................................116

4. Validation....................................................................................................................136
   4.1 Massing Energy Optimization toolbox validation..................................................137
   4.2 Assessment/Optimization systems validation.........................................................148

5. Applications................................................................................................................154
   5.1 Case Study 1: Leisure Centre in Paris.....................................................................155
   5.2 Case Study 2: Highrise Massing Optimization.......................................................159
   5.3 Typology Study......................................................................................................169

6. Discussion.....................................................................................................................203

7. Conclusions................................................................................................................210

8. Recommendations.......................................................................................................212

Bibliography...................................................................................................................218

Appendix..........................................................................................................................222
   Annex A: Setting up a simple massing energy assessment model..................................222
   Annex B: Implementation background..........................................................................227
   Annex C: Additional information on Paris leisure centre case study...............................229
   Annex D: Detailed validation process and results..........................................................232
   Annex E: Detailed results of typology studies...............................................................242
1. INTRODUCTION

In this chapter the motivation for the thesis and the consequent research questions, aims and scope will be presented.
1.1 Motivation

**Integrated Building Design**

The distinction between architect and engineer is a relatively recent event, in comparison to the long history of human constructions. Until modern times, the terms “architect” and “engineer” have been interchangeable\(^1\), for the master builder who was the one to design building solutions in a holistic way. The word itself “architect” comes from the Greek word ἀρχιτέκτων (architekton) meaning the chief builder.

With the distinction of the two professions emerged also a conventional building process of sequenced hand-offs, from owner to architect, to engineer, to builder, to occupant. What has been identified as the main problem on this procedure is that in later design stages effort needed for changes of design is larger. This realization has been often represented graphically through the MacLeamy graph, whose popularization is credited to Patrick MacLeamy, CEO of HOK.\(^2\)

---

The graph visualizes the importance of repositioning design effort towards the beginning of the design process, to increase effectiveness.

The need for integrated conceptual design is growing due to a number of parameters. One, of rising importance, is the current global energy crisis.

Another development adding urgency for clever building massing designs is the ever growing need for maximum profit, underlined even more in recent years in Europe by the financial crisis, imposing severe construction budget cuts. The rapid progress of materials and technologies also might modify the optimal form characteristics for a specific project and thus pose additional weight to this design phase.

It is thus essential that all these parameters be taken into account from the very beginning of the design, when the first building volumes are positioned into the graphic environment, with tools that provide quick visualization of the multidisciplinary effect of design choices and gestures.

**Energy Crisis**

The sustainability demands that a design currently has to fulfil, are based on the realization of the dangers that humanity is facing due to the outcome of it’s activity.

Since the late 18th century’s industrial revolution, the human need for energy has largely depended on burning fossil fuels. Thus, human activity has become largely intertwined with large CO$_2$ emissions, beyond the capacity of natural reabsorption systems.

The growing awareness on the effect of these emissions to the global warming effect, along with the realisation of the finite nature of economically exploitable fossil fuels has obligated man to rethink energy production and consumption.

Globally, 75% of the fossil fuels burned is used to produce energy\(^3\). This energy is used for transportation, industrial manufacturing, agriculture and food production and the operation of buildings: lighting, heating, cooling etc.

This last part is a big percentage of the total. For example, in the European Union “buildings account for the 40% of total energy consumption in the Union.”\(^4\)

---

4 EU Directive 2010/31/EU
The realisation of the effect that a better Energy Performance for buildings would have, makes energy an increasingly important parameter for building design. What is more, building regulations are becoming more and more demanding on that field.

According to the Article 9 of the EU Directive 2010/31/EU all new buildings have to be “nearly-zero energy” by 31 December 2020, while new public buildings have to fulfil this requirement two years earlier.\(^5\)

These “nearly-zero energy” buildings should require minimal amount of energy, which they should be able to acquire from renewable sources nearby the building site.\(^5\)

A big part of the energy demand of buildings is currently used for heating and cooling, as shown in the following graphs. This is the reason why the European Union appointed the CEN to make a set of methods for the calculation of the Energy Performance of buildings in simplified but transparent ways in order for the implementation of building energy regulations to be possible.

Although energy concepts usually refer to installations for energy production or optimized energy use, the form of a building can be the first to manifestate and facilitate it’s low energy ambitions. With optimized massings, the energy demand can be reduced and thus also the need for expensive renewable energy technologies, in order to meet the low energy regulations. This design mindset of trying to design forms that could reduce the need for technologic installations and energy

---

\(^5\) EU Directive 2010/31/EU
is described by architect Bjarke Ingels as “Engineering without Engines”.  

**HISTORY OF INTEGRATED DESIGN**

Architects have always addressed, in some extent, holistically the demands that a building has to fulfil. Since the earliest surviving architectural theory document of Roman architect Vitruvius, “De architectura”, a good design has been described as one that carries three main characteristics: durability, convenience and beauty. 

---

On the other hand, certain schools of architecture have been often accused of designing mainly with regards to superficial appearance, rather than function. A notable example of such criticism is the backlash of Viollet-le-Duc and Le Corbusier towards the French Ecole des Beaux-Arts in the start of the 20th century. At that time, the emerging modern architecture, emphasised functionality in architectural design, through which beauty would also be attained. Characteristic of the new architectural mindset is Sullivan’s “form follows function” imperative and Le Corbusier’s praise for engineers of the time, who “relying on “calculations”, use geometric forms, “satisfying our eyes through geometry and our minds through mathematics;” and are thus on the way to “great art”. He was suggesting that architects could learn a lot from the innovative works of engineering of the time, like the car and the airplane, which led him in envisioning a similar solution to the problem of dwelling that for him had not been posed yet. For Le Corbusier, houses should be a “machine for living in.”

In this way, modern architecture moved towards the simpler functionalistic forms of the “International Style”, which attempted to give an integrated answer through simple geometry to the demands of economics, sociology, materials and function.

This architectural style, characterized mainly by large stripped-down, glass-covered rectangular box building geometries, has been criticized for the absence of dialogue with the environmental and urban context of the buildings. A renegotiation of modern forms in order to incorporate also the, more and more important towards the end of the 20th century, sustainability considerations, has been attempted by Malaysian architect Ken Yeang. In his books and designs he experiments with passive low-energy solutions for multi-storey buildings, aiming to improve the impact on the site’s ecology and the building’s use of energy and materials.

Since the end of the 20th century sustainability as a word has entered the consciousness of architects, becoming an essential design concern and leading to revised conceptualization of architecture, in response to multiple concerns on the

---

11 Pevsner, N. & Games, S., 2002. Pevsner on art and architecture: the radio talks, Methuen.
effects of human activity.\textsuperscript{14} It has also spawned a renewed concern for context, as “green” architecture often finds its first design strategies with a starting point from the environmental context.\textsuperscript{15}

**Massing energy optimization history**

In the brief integrated design history that was presented above, the importance of sustainability considerations in the contemporary architectural mindset concluded the passage, underlining the very strong influence it has in nowadays’ architectural design.

The idea of optimal climate specific masses is of course not new. In fact vernacular architecture and even animal “architecture” provide a great “database” of climate-specific solutions that improve the indoor climate conditions, without the technological products that are today available.

The examples of this kind of optimal building volumes are plenty. As characteristic examples, we could give those of termites’ “buildings” in the North territory of Australia (orientated and massed ideally for a constant temperature during the day, having the largest “facades” towards the sun in the morning and afternoon, and a small area facing the sun on midday) and that of the igloo of Eskimos (whose hemispherical shape encloses needed interior volume with the least amount of facade surface possible).

![Figure 1.4 Energy “Massing principles” in vernacular architecture (The Eskimo’s igloo)](image)

Vernacular and animal architecture can be an inspiring resource for designers, trying to find optimal climate specific massings. On the other hand modern building technologies, scale and complexity are potentially outdating these optimal massings.

climate-specific solutions. Thus, “blindly” replicating vernacular architecture might be a reasonable option, relevant as its principles might still be.

Ken Yeang who is often referred to as the “father” of the sustainable bioclimatic tall building, has extensively researched in his books, climate specific design strategies for tall buildings. In his book “Bioclimatic skyscrapers”\(^\text{17}\), recommendations are given especially for highrises on the tropical areas. The position of curtain walls on the north and south side, the position of the core to the east and west warm sides of the tropical areas, to be used as thermal buffer zone, the type of shadings per orientation are some of the ideas discussed. These are issues of course vernacular architecture did not have to address in that scale.

![Figure 1.7 Principles of the Menara Mesiniaga bioclimatic building in Kuala Lumpur, Malaysia, designed by Ken Yeang. (Image courtesy: Hamzah & Yeang)](image)

Since then, and with the importance of green buildings rising, various studies have been released on the ways to reduce the energy demand of buildings through their form and positioning into space. Certain guidelines like the importance of orientation for glazed facades and the optimal shading for each orientation have been popularized by architects like Ken Yeang and Le Corbusier.


Studies of course have been made in order to give more depth to these generic guidelines. As an example, the studies of Andy van den Dobbelsteen et al. in the abstract “Ecology of the Building Geometry”\textsuperscript{20} could be mentioned, where office typologies of equal gross floor area are compared, based on water, energy and material expected performance. What is more building alternatives of equal net floor area are also compared in the abstract.\textsuperscript{21}

Modern day tools provides increased possibilities in such research, allowing researchers and designers to demonstrate the effect of guidelines and quickly perform comparisons, acquiring thus, information depending on the climate of the location where the building designs are to be realised.

The optimization algorithms can help “accelerate” the optimization processes, through trial and error processes, similar to the ones that have been done in the physical world over large amounts of time in the past, while also quickly quantifying and visualizing the benefits of optimal design solutions compared to non-optimal design alternatives.

Thus, the optimized massings can give to the designer the kind of insight and inspiration traditionally gained from vernacular architecture, but this time taking into account also new building technologies and the effect of the complexity and scale of modern building projects.

\textsuperscript{19} Source: http://www.technomc.info/Architecture bio climatique/Le Corbusier esprit nouveau.htm

\textsuperscript{20} van den Dobbelsteen et al., 2007

\textsuperscript{21} This particular study will be revisited in chapter 5 where its results will be compared to the ones of the parametric scripts generated for this thesis. It will also serve as a starting point for the research that will be described in chapter 6.
**INTEGRATED DESIGN TODAY**

“Oh bigness means surrender to technologies; to engineers, contractors, manufacturers; to politics; to others. It promises architecture a kind of post-heroic status—a realignment with neutrality.”

(Koolhaas, R., 1997. S M L XL)

Contemporary architecture is characterized more and more by the growing awareness of the inherent complexity of building design. Building Information Modelling (BIM) software sees growing popularity while renowned building designers readily advertise their integrated approach and the early involvement of in-house specialists.

**BIM vs PARAMETRIC SOFTWARE FOR INTEGRATED DESIGN**

With Building Information Modelling (BIM) software is defined as data-rich 3D modelling software, where all modelled lines carry properties, and thus all disciplines can extract information, reports and drawings from the BIM model.

This way, BIM software can indeed translate design procedure to earlier design stages (moving the design effort closer to the green curve of the MacLeamy curve as shown on Figure 1). On the other hand the BIM graphic environment is not friendly towards the testing of fast design alternatives, taking place in the preliminary design phase. This has led many users in forming the initial basic volumes (or massing) of the building in other 3D modelling software like Trimble Sketchup and Rhino by Robert McNeel & Associates.

The emergence of parametric design software has given even more possibilities to accommodate contemporary architectural design workflows, which will be discussed below.

---


23 For example, the website of Foster+Partners (http://www.fosterandpartners.com/profile/integrated-design/[Accessed June 10, 2013] states: “Foster + Partners understands that the best design comes from a completely integrated approach from conception to completion. We have a strong creative team, in which structural and environmental engineers work alongside the architects from the beginning of the design process. By doing so, we believe that they can learn from one another and combine their knowledge to devise wholly integrated design solutions. The design teams are supported by numerous in-house disciplines, ensuring that we have the knowledge base to create buildings that are environmentally sustainable and uplifting to use.”

CONTEMPORARY ARCHITECTURE WORKFLOWS

Architectural design has always been considered one of the arts, despite having to address also very pragmatic demands, like for example the ones for sheltering, warmth, privacy and others. Still, it has kept elements inherent to artistic procedures, like intuition and inspiration, central in it’s process. The source of inspiration for the concept and form of the building can vary greatly and thus a certain standardized flowchart is probably impossible to produce.

On the other hand the rising design objective complexity, has led architects in front of important technologic, engineering, financial, political and other issues, whose interrelations and complexity is growing.

Furthermore, modern architectural practice with the rise of the importance of the signature of “starchitects”\textsuperscript{25} in a design, hoping to increase a building’s impact in a similar way to the “Bilbao effect”\textsuperscript{26}, mean that a great percentage of designs is actually designed by the back-office of the architectural firms\textsuperscript{27}. These two facts, result in a need for a more systematic approach towards the design process.

An interesting attempt of describing a rough outline of the architectural design process taking place in the office of Bernard Tschumi, can be found on the firm’s website\textsuperscript{28}. In the 8 steps described there, parameters that are mentioned as priorities are, among others: spatial concepts, the programmatic requirements, circulation vectors, number of different volumes in the envelope, material options, site constraints and limitations, the concept (or “overriding idea”), technical and budget constraints.

Of course even in this systematic approach, the ability to break the rules is always given to the designer, if the concept requires it. Also the concept, or “overriding element” of the design, is still unrestricted (“There can be no restriction to what a concept or overriding idea is”).

This “rough approximation” of Bernard Tschumi’s office approach is an example of elements taken into account in the early design stage and this could provide evidence towards which processes could be facilitated through the tools simi-

\textsuperscript{25} “Starchitects” is a commonly used abbreviation for “star-architects”.

\textsuperscript{26} Referring to the Guggenheim Museum in Bilbao designed by Frank Gehry. After four years from it’s opening in 1997 it had attracted 4 millions of tourists and paid back it’s worth in taxes to local council, from the money visitors have spent on hotels, restaurants, shops and transport (Crawford 2001)


\textsuperscript{28} http://www.tschumi.com/approach/
lar to the ones developed for this thesis.

While choices like the determination of the overriding concept are difficult to facilitate through numeric assessment, elements like site constraints, costs, technical constraints could be assessed for all the spatial configurations and programmatic distributions that the designer might generate, to provide him comparative feedback.

### Massing Design Stage

“In the preform - in the beginning, in the first form - lies more power than in anything that follows”

*Louis Kahn*

This report uses extensively the term “massing”, to refer to the initial positioning of theoretical building volumes into the theoretical design space.

The massing process, whether or not referred to with this name, is often used in architectural design to speculate on possible space configurations, programmatic distribution, circulation vectors, site constraints. It is a design stage with a brainstorming character, in the sense that a lot of ideas can be generated and discarded.

In this phase simplified representations of a building are used, often out of context and without structure and floors, mainly to experiment and communicate building ideas in order to ultimately, keep the best ones for further detailing.

---

31 Source: Photographer’s personal collection, used under permission.
It is not rare that energy considerations are taken into account in this phase, to generate architectural gestures like twists towards the south (e.g. Grove at Grand Bay by B.I.G.\textsuperscript{33}), tilting of facades (e.g. Rodovre Tower by B.I.G.)\textsuperscript{34}.

According to the architect’s website “By slanting the facades of the alternating floors of office and residential program to the optimum angle with respect to the sun, we have developed a new kind of architecture (Image courtesy: BIG architects\textsuperscript{35}).

\textsuperscript{33} Bjarke Ingels interview: https://www.youtube.com/watch?v=txOD_dR2c-A
\textsuperscript{34} Ingels, B., 2009. Yes is More: An Archicomic on Architectural Evolution, BIG ApS.
\textsuperscript{35} Source: Big.dk
It should be noted at this point that, although massing is a very early design process, it is not the first: Site analysis, or analysis of the context in which the building will be situated, usually precedes any design proposal. Still, the choice of opposing or submerging into the urban or social context (usually referred to as “contextualism”) lies in the hands of the architect. Nevertheless, context is, usually, a strong point of reference for architectural design.  

In this sense, modern design tools can enhance instead of restrict designers, by adding depth to the context that they probably always, at some level, analyse, in the outset of the design process.

Figure 1.12 Blue foam massing models in the studio of OMA. (Image courtesy: Borix1.)

PARAMETRIC DESIGN

“...one of the biggest leaps that we’ve experienced has been the introduction of Grasshopper. Grasshopper – the plug-in for Rhino that makes parametric scripting more intuitive – is, to my mind, as big a revolution as Steve Jobs’ development of the graphic user interface for Mac OS.”

(Bjarke Ingels, Klat magazine, Fall 2010 issue)

For the generation of quick feedback for different massings, a software has to acquire information on the massings in a systematic way. Contemporary parametric design tools, provide instant update on input parameters, making the vision of fast design feedback, possible.


37 Source: http://www.flickr.com/photos/borix1/
In the definition of parametric design by Tamoko Sakamoto, referenced also in the preface of this report, the key point of parametric design, is the establishment of logical relationships between objects allowing design changes to propagate within the design system.\textsuperscript{38}

This allows designers to establish connections between their design objectives and parameters that can aid them in achieving optimized designs. This process allows designers to investigate how their designs could respond to the site’s context and how to take advantage of it’s specific potential. What is more they can also facilitate the visualization of a design’s reasoning.

\section*{Lack of Massing Assessment Tools}

The analysis up to now has discussed how the integrated design logic has been manifested in different time periods and for different design objectives and how there exists a need for even more integration of design systems to meet complex design goals. Despite the eagerness, at different levels, the existing BIM software often does not accommodate seamlessly the architectural massing workflow, “forcing” design integration to start in later design stages.

For example, until the time that this report was being written, there did not exist a tool, that would allow the instant feedback on the expected heating and cooling demand of massings, the amount of gross floor area that can be generated within a massing and other important design criteria like these.

A designer that wants to take these aspects into account early in the design has to either do it intuitively (which should in no means be considered inferior to algorithmic methods per se), or perform time-consuming connections between different software, with severe delay in the traditional workflow. This might have the effect that, instead of really using the potential of each location to form the building’s geometry, parametric tools could be used in a kind of backwards-engineering logic, to support designs that have not really been designed through evolutionary processes, as if they had.

Thus, this thesis will attempt to address this problem trying to develop scripts & tools towards that direction.

1.2 Research aims

This thesis aims to address the aforementioned issues in the following ways:

• 1. Set different design criteria to suit contemporary design considerations of rising importance and describe assessment and optimization systems of different scale, that can be used to assess the effect of massing gestures, in contemporary important design criteria. The thesis will set up assessment and optimization systems of different precisions and scale, because for different design objectives, different parameters have to be taken into account. These systems will focus around energy and sustainability concepts, which are currently gaining more and more importance, as form-defining parameters.

• 2. Develop a parametric energy assessment toolbox and describe possible utilization scenarios. As discussed in the motivation paragraph above, sustainability demands, and especially energy performance are arguably the “game-changer” for contemporary design, gaining importance among traditionally important design criteria. The lack of tools to assess the energy performance at this stage usually leaves energy performance as a consideration for the later design stages. This thesis has attempted to cover partly this specific gap, developing tools that can provide this kind of feedback. The validity of the results provided by the toolbox will be tested in applications close to the ones of the case studies, before they are expanded to respond to specific design dilemmas and the typology study’s research questions.

• 3. Test the use parametric massing assessment and optimization tools and scripts in design dilemmas, through the case studies.

• 4. Use the same tools and scripts, to generate a typology study on the effects of various initial design parameters on the ranking of the typologies’ energy performance. The multiple effects of diverse design parameters, like orientation, glass percentage, space efficiency in the energy performance of a design will be researched. Comparative tables can show the lengths at which climate can affect the energy performance of the typologies, but also what is the total
effect of these parameters in the total embodied and operational CO$_2$ emission ranking.

1.3 Research questions

The specific research questions, that will motivate this thesis towards it’s aims, are the following:

1. **ON THE ASSESSMENT/OPTIMIZATION SYSTEMS**

   After the identification of the main design objectives that the thesis will analyse, the following questions will be posed:
   
   • 1.1 Which parameters can influence the choice of a certain massing optimization fitness value?
   
   • 1.2 How does the choice of the optimization system influence the assessment and optimization’s results and process?

2. **ON THE DEVELOPED TOOLBOX**

   As far as the scripts and tools developed for this thesis are concerned, the following questions are posed:

   • 2.1 What could be design scenarios where these tools could prove useful?
   
   • 2.2 How can the use of the tools in the case studies and the typology research and thus their results be validated?

3. **ON THE CASE STUDIES**

   In the case studies of this thesis, the questions of particular interest for the specific design assignments posed are the following:

   • 3.1 For the climate of Paris (France), what is the effect of tilting a south facing facade upwards and downwards, to the monthly heating and cooling demand?

   • 3.2 For the climate of Brussels (Belgium), what is the effect of orientation in the heating and cooling demand of the designed building?

   • 3.3 For the climate of Brussels (Belgium), what is the effect of horizontal shifting of parts of the designed geometry, in order to change the amount of self-shading, in the heating and cooling demand of the designed building?

   • 3.4 What additional benefits were observed during the use of the tools in the massing design process?
• 3.5 What additional shortcomings were observed during the use of the tools in the massing design process?

4. **On the Typology Study**

For the typology study, six typologies will be studied, with the following parameters switched consecutively:
1) Solar Gains: With and without taking into account solar gains.
2) U-Value: Uniform U-value / Different U-value for facades (glazing percentage dependent) and roof and base
3) Function: Dwelling / Office function
4) Orientation: East-South main axis / North - West main axis
5) Assessment fitness value: Comparison of energy demand per GFA / Comparison of energy demand per NFA
6) Glass percentage: 30% / 50% / 80% for the facades of the typologies.
7) Location: Amsterdam (Netherlands) / Athens (Greece) / Quebec (Canada) / Dubai (United Arab Emirates)

to determine the effect of changing these parameters on the annual heating and cooling demand, the annual total energy demand and the embodied + operational (for 1, 10 and 50 years) CO₂ emissions.

In the above way the following research questions will be answered:
• 4.1 Usually the reduction of heating demand and the reduction of cooling demand call for opposite design solutions. Which of the two seems to be most critical for the optimal massing determination?
• 4.2 How do the aforementioned parameters rank with regards to their effect on the
  a) the absolute energy demand per area values,
  b) the ranking of the massing for a specific location?
• 4.3 What is the percentage of energy demand reduction that can be achieved through the choice of the optimal typology?
• 4.4 What is the ratio between expected operational and embodied energy for the different typologies? After how many years of operational energy does embodied energy lose form-influencing significance?
The methodologies with which this thesis will try to address these questions will be described in the following chapter, while the answers provided by the thesis will be presented on the Discussions chapter, with the main conclusions highlighted in the Conclusions chapter.
2. METHODOLOGY

In this chapter the ways that this thesis will attempt to respond to it’s research aims will be presented.
2.1 Optimization research methodology

**Optimization as a concept**

Optimization, as a concept, implies that there exists a unanimously agreed value, the maximization or minimization of which should be achieved. It has always been embedded in human spirit to do things “smarter”, starting by simple things, like minimizing effort, for example by selecting the shortest route to a destination, or maximizing income through reducing the cost of the material one might need for making a tool.

Even in these simple dilemmas that even the primitive man can be imagined to have faced, the “best solution” is not always obvious. On the aforementioned generic decision of routes and material for example, it might be the case that the shortest route might have been more dangerous or that minimizing the cost of material, needed for the production of a tool, could be diminishing the price that it could be sold, if, for example, the cheaper material has worse appearance or performance.

It becomes obvious that, even in simple problems, optimization of one value might largely worsen other parameters of importance. It is thus very important to set in a smart way an evaluation value, which might also be a weighted average of multiple values of importance.

Since the 1960’s, computation has been used to approach optimal solutions of complex problems, through the imitation of the evolutionary processes in nature. The algorithms used for these purposes are called evolutionary algorithms, and are based in an evaluation function rating solutions, usually called the “fitness value”.

Even with computational optimization, the problem of setting the evaluation value remains. Back in building designs, possible evaluation values could be, among others, the following:

- Construction cost minimization,
- Operational cost minimization,
- Operational Energy minimization,
- Gross floor area (GFA) maximization,

• Net floor area (NFA) maximization,
• Value maximization,
• Aesthetics maximization,
• Embodied CO$_2$ minimization.

A direct reaction on the above, would be the suggestion that these design optimizations need to become “smarter”, as one could argue that, for example, an obvious way to minimize construction or operational costs and embodied energy is not to build at all. On the other hand, the option to “do nothing” is not always available, if a certain demand for enclosed space exists.

What is thus important is to start an optimization only after all the important objectives have been taken into account, through boundaries or constants. For example if there exists a minimum or constant requirement for Net Floor Area that has to be enclosed within a building envelope, the optimal for construction costs, operational costs and embodied energy is no more the “do nothing”-option.

The consideration, as to which parameters should be included within the optimization system and which not is very important, both for common human logic optimization, described in the beginning of this chapter, and for computational evolution algorithms. That is because parameters that are not important for a specific problem could be making a decision harder for the human mind and the computer, while, if an important parameter is not taken into account, the optimization could lean towards invalid feedback.

For the massing optimization aims of this thesis, different systems will be used. The research will begin with smaller optimization systems, with less parameters and constraints involved, used to address less complex problems. Gradually the optimization systems will be enlarged, in an attempt to address the complexity of design decisions. The systems presented will be used in the “Applications” chapter to address design problems.

It should be noted, at this point, that smaller optimization systems do not necessarily mean less accurate and “worse”. On the contrary smaller optimization systems can be even more accurate because their inputs can be more precise due to the smaller size and the less interconnections within the system, which means that it can be more easily visualized and understood, in contrast to complex large systems. Even the fact that simple systems can be, at times, predictable (for example the un-
constrained minimization of construction/operational costs leaning towards the “no building” option), this predictability is a very useful feature for double-checking the proper functioning of an algorithm.

**Massing Optimization Systems**

The first massing optimization systems that could provide useful results, due to being in fields that have not yet been addressed extensively through parametric design, could be a solar gain optimization system. The choice of this specific optimization is done, because optimizing solar radiation has always been an architectural concern, as explained in the massing energy optimization paragraph of chapter 1.1, but the effect can now be directly quantified with the use of contemporary parametric design software.

![Diagram of Massing, Solar Gains, and Weather](image)

*Figure 2.1 Example of monoparametric optimization of passive solar gains.*

Assessing masses only with regards to their solar gains optimization can lead to an overemphasizing of their benefits. It is thus important to put the benefits of solar gains into context by comparing it to other gains and losses within the building envelope during the year. For example, according to the Environmental
Design Pocketbook of Sofie Pelsmakers, the radiation from a window of 1m$^2$ facing south in the location of South England typically receives the amount of energy released by a human body working in that space. 41

This kind of realisations can be done by looking at the bigger picture and seeing the effect of massing changes in the overall heating and cooling demand. This system is illustrated in the following image.

![Diagram showing the assessment/optimization system through a design’s expected heating and cooling demand](image)

The easiest way to make zero-energy buildings is arguably to simply pull the plug on their energy input. On the other hand, buildings are made to serve certain demands, to shelter a certain amount or to provide enough space for a certain amount of workers, whose comfort has to remain within certain limits. Thus, the optimization of massings can be set in a more robust way, setting it’s objective, not to the minimization of heating and cooling demand, but to the minimization of the heating and cooling energy demand per square meter of Gross Floor Area or Net Floor Area.

Broadening the system to include also operational energy for appliances, lighting and hot water, in order to calculate the overall operational energy demand, can again add more perspective to the effect of massing gestures. On the other hand, these numbers are less affected by massing gestures\textsuperscript{42}, as usually they are mainly dependent on the square meters of Gross or Net Floor Area (considering this area as defining a space that is not too far from the facade, thus is lit by daylight in a satisfying level). For this reason, it is plausible to use benchmark values for purposes close to the aims of this thesis. If more exact methods were used, dependent on the

\textsuperscript{42} With the exception of lighting demand reduction, on massings where great percentage of the floor area is receiving enough sunlight to be able to avoid the use of electricity during the day.
amount of users, this step would be much more demanding, although potentially aiding to the accuracy of the assessment/optimization performed.

A more complete but also more demanding assessment/optimization system, would be an even further extension of the system, in order to include structural and facade aspects into the system. In such a case, the effect of costs and embodied CO₂ emissions of structure, facade and energy, can be compared. It then can be really assessed if an architectural gesture that minimizes heating and cooling demand, is really “sustainable” taking into account extra structure that it might be demand-
ing which might result in a disproportional increase of embodied energy.

The difficulty of this step is finding and updating the values needed for the translation of structure and facade amount needed into cost and embodied CO$_2$ emissions. These values are, additionally, location, facade & structure system dependent. Given these issues, the accuracy of this system is largely questionable,
at least until it is connected to data from the market for a specific project size and location and to the specific massing geometry.

The systems, presented above, will be used in the case studies of this thesis, in order to address design dilemmas, through the scripts and tools developed for this thesis.

2.2 Energy Assessment methodology

**ISO 13790**

For the assessment of expected energy performance the ISO/FDIS 13790 “Energy performance of buildings — Calculation of energy use for space heating and cooling” international standard, has been used as a basis for the heating and cooling demand calculation methods, programmed within the tools developed for this thesis. The reasons that this standard’s methods are used are the following:

1. It offers a quasi-steady state energy performance assessment method which gives the possibility of quick energy performance assessment feedback.
2. It is an international standard mandated by the European union to support the requirements of the EU Directive 2002/91/EC on the energy performance of buildings.  
3. The standard states that it can be used for comparing the energy performance of various design alternatives for a planned building, which corresponds well to this thesis aim to study the effects of massing gestures (like rotation and tilting) on important design criteria like the energy expected.

**Quasi-steady-state Method**

According to Dijk and Spiekman, the application of stricter energy performance regulations by the European Union, urgently required calculation methods with transparency (with a method that enables the user (and developer) to keep...
track of each step in the calculation procedure), robustness (with a method that can handle a wide variety of situations, with perhaps loss of accuracy, but without going out of control) and reproductability (with a method that, for a specific case, always leads to the same result, notwithstanding the user).

The quasi-steady state method of the ISO 13790 standard features these characteristics, which are also important for the aim of this thesis to research, within a parametric design software environment, massing design alternatives. The advantage of this method, for the scope of this thesis, is that it does take into account dynamic effects, but not through dynamic thermal models, but through utilization factors. These factors do take into account that not all of the internal and solar heat gains can be considered to contribute in the decrease of the energy need of the building, part of it potentially contributing in an undesired increase in temperature above the set point.\textsuperscript{46}

The same method can take into account also the effect of thermal inertia in the case of intermittent heating.

Similar, to the quasi-steady state annual heating demand calculation is the quasi-steady state method for the annual cooling demand estimation, also described in the ISO 13790 standard.

**Main Assumptions of the Method**

The ISO 13790 standard gives the following conditions to apply a single zone model:

- Interior set-point temperatures for heating and cooling should not differ more than 4 degrees.
- The spaces are either all cooled or all not cooled at any given time.
- The spaces are heated by the same heating system (if any) and cooled by the same cooling system (if any).
- At least 80% of the floor areas are serviced by the same ventilation system.
- The ventilation of spaces in cubic metres should not differ more than a factor of 4 in the 80% of the floor area, or the doors between the spaces are likely to be frequently open.\textsuperscript{47}

Since the tools of this thesis will use this model, these conditions should also apply to the designs of the building, in order for the results to be considered

\textsuperscript{46} ISO/FDIS 13790 2007-11

\textsuperscript{47} ISO/FDIS 13790 2007-11
Intermittent heating and cooling during the week (for example, at night or in the weekends) can be taken into account in this method, by applying a correction factor to the monthly heating and cooling demand.

Intermittent ventilation can also be taken into account by giving an average weekly value to the ventilation rate of the mass volume, thus reducing the ventilation heat transfer coefficient $H_v$.

2.3 Software development methodology

Rhino3D’s parametric plug-in, Grasshopper, has become probably the most widely used parametric software, offering a user-friendly environment to generate geometry through algorithms. Through this software design massing alternatives can be assessed rapidly, given that a robust assessment script has been set up beforehand.

Despite the user-friendliness of the program, scripting complicated procedures in Grasshopper can become chaotic. To make sure that the correct inputs and outputs are given in the system, special components needed to be scripted to simplify the process and inform the user on the exact inputs and outputs expected in each step. These components were scripted using the C# programming language.

As this thesis focused on the analysis of the energy demand of massings, the produced components will also focus on this field. On the other hand, since the research extended to other fields, for example in the case of the comparison of embodied and operational energy for different building typologies, rules of thumb and general guidelines will be used to get values needed from other fields of design, apart from energy. Since this information comes from various sources and is specific for the research of this thesis, the scripts used are not intended to be included in the tools that will be made available to interested designers, after the end of this thesis.

The main development principles of the tools, which will be released after the end of the thesis, will be discussed on the next chapter.
2.4 Validation methodology

The toolbox validation will take place in two phases:
1. Component validation
2. Overall script validation

For the validation of the components of the toolbox, firstly it should be ensured that the output values are the expected ones. This is done with hand calculations and/or Excel sheet reproduction of the results. Another way that will be employed for the validation of energy analysis components, is the comparison of their results to the ones of the worked example of Annex J of the ISO 1379048.

The only component that is not covered by this standard but was needed in the Massing Energy Optimization Toolbox was the one to calculate the solar radiation on a surfaces. The ISO gives factors only for vertical and horizontal surfaces of the building envelope, while this thesis desired to investigate also the effect of various massing gestures that tilted facades. This tool will be validated by comparing it’s outcome, with excel calculations, with the results of the worked example of the annex J and with other software that can provide similar feedback.

On the overall script validation, the influence of massing typologies in embodied and operational costs and embodied CO$_2$ emissions, calculated through the tools and scripts which will be presented in the following chapter, will be validated by comparing the results with similar research attempts of the past for the same design geometries.

As the total validation of the developed scripts and tools was not possible within the limited time of a thesis, the validation mainly focused on validating the components and scripts, firstly, for applications close to the case studies that would be performed in the fifth chapter of this thesis. The correspondence of validation chapters to case study chapters of this thesis report can be found in the following figure.

---

48 The accuracy of the quasi-steady state method will also be discussed briefly, in the validation chapter.
Case Study

§5.1
Test of the effect of tilting the south facades of a Paris Leisure Center design.

§5.2
Test the effect of self shading of blocks into the heating and cooling annual energy demand.

§5.3
Compare building typologies with regards to their Heating and Cooling energy.

§5.3
Compare building typologies with regards to their Total Energy Demand.

§5.3
Compare building typologies with regards to their Embodied and Operational CO2.

(General for Energy Analysis applications)

Validation Method

§4.1.4
Comparison of the outcome of the MEOtoolbox solar load component for tilted surfaces to PV panel calculation website and Environmental Design Pocketbook inclination table.

§4.1.3:
Compare to the feedback of the block shift to the feedback from the Ladybug solar component for this specific location and geometry.

§4.2
Compare to the Heating and Cooling demand improvement factors of Andy van den Dobbelsteen’s PhD comparison of the same typology geometries.

§4.2
Compare to the Energy Demand improvement factors of Andy van den Dobbelsteen’s PhD comparison of the same typology geometries.

§4.2
Compare to the Total Environmental impact improvement factors of Andy van den Dobbelsteen’s PhD comparison for the same typology geometries.

§4.1.2
Comparison of the output of the MEOtoolbox to the results of the worked example found on the Annex J of the ISO13790 standard + comparison of solar radiation values to other relevant software like Ecotect and Ladybug.

Figure 2.6 Correspondence of validation chapters to case study chapters of this thesis report.
3. SOFTWARE DEVELOPMENT

In this chapter the Massing Energy Optimization toolbox and other scripts, developed to achieve the aims of this thesis, will be presented.
3.1 Main objective

To formulate the assessment and optimization systems described in the previous chapter, in order to organize, simplify and facilitate the way designers can obtain information, needed during their massing studies in a parametric software environment, new tools had to be programmed. These tools intend to reduce the amount of effort and parametric connections needed to obtain values on important design criteria, while keeping clear the processes and limitations of the methods used to obtain the feedback data.

As has been stated before in this thesis report, the feedback on expected energy performance of design alternatives, has attracted the most focus of the research, due to its rising importance and its optimization potential, during the massing design phase. Thus, while in fields like structure material assessment, very rough estimations will be implemented, in the field of energy, the calculation of heating and cooling demand, the tools will follow in detail the quasi-steady state calculation method of the ISO 13790 standard.

Thus, the energy tools are the ones for which most attention has been given, in order for them to be also shareable and usable by designers who might have diverse reasons for wanting to research the energy performance of a building volume.

Figure 3.1 METoolbox concept: massing, analysis, assessment, optimization.

The toolbox, developed for this thesis, was given the name Massing Energy
Optimization toolbox. From this point on in the report, the shorthand writing ME-Otoolbox will be used.

Figure 3.2 One of the analysis systems presented in the previous chapter, with the MEOtoolbox’s main area of attention marked within the red dotted boundary.

49 Although massing optimization with regards to lighting can be an important massing optimization factor, this diagram seems not to take into account the effect that optimal daylight can have in the minimization of the energy demand of a designed building. At this point the graph is misleading, as this effect is addressed in the following way: A massing with less daylit spaces, will have less NFA and thus will seem like a least favourable idea in a massing comparison of Energy
The name is chosen so as to communicate the basic use that the toolbox intends to fulfil:

**Massing:** The MEOtoolbox is designed primarily to aid the massing design phase, aiming at assessing the energy performance of massing design geometries.

**Energy:** The MEOtoolbox is designed primarily to assess the energy performance of a building design by calculating the heating and cooling demand of a design using the quasi-steady state method of the ISO 13790 standard.

**Optimization:** The MEOtoolbox can aid the designer in finding optimal for the energy performance solutions in two different ways: Manually and algorithmically. Manual optimization can take place when a designer takes into account the energy performance assessment value of a massing and makes changes to it by himself, for example trying a different orientation for a volume of the massing. Algorithmic optimization can take place by assigning the computer to change design parameters in order to optimise a specific design. Although energy performance has a rising importance in the building design it is not, of course, the only parameter for it. Urban, aesthetic, structural economic and other considerations all play an important role. The MEOtoolbox can be set within the constraints that these other aspects can impose. To give an example, urban considerations might allow building orientation within certain limits, structural reasons might allow tilting a facade up to a certain limit etc. These boundary values can be input in the MEOtoolbox so it can find optimal solutions only within these values.

**Toolbox:** The MEOtoolbox will not be a one inseparable calculation tool but will have different components that if put into right order, can provide energy performance assessment values. It can also be a case that some of the components might be useful by themselves for different functions. For example there are components that help the massing process which can be used in any building design process, without having in mind to use the rest of the MEOtoolbox afterwards. What is more, the user can decide to replace some of the tools of the MEOtoolbox, with other components. For example, he might decide to use other software to calculate NFA.
calculate, for example, solar loads, which he can still input into the MEOtoolbox’s heating demand component to calculate heating demand.

For these reasons the software developed is named MEOtoolbox, a set of tools, that can aid the building designer to assess and optimize the energy performance of massing design geometries.

3.2 Principles

The basic toolbox design objectives, that were pursued during its development have been the following:

1. Instantaneous feedback
2. As designer friendly as possible
3. All calculations within the designed components
4. Compatible to Sustainability-Open framework

1. **Instantaneous feedback**: The intention to provide quick energy performance assessment feedback has been central in the scope of this thesis and has determined, not only the quasi-steady state method used for the assessment, but also various software designing decisions that had to be made during the process (preset values for non-crucial parameters or setting non-crucial parameters, for example heating intermittency, as optional).

2. **As designer friendly as possible**: The toolbox is designed, not only for building engineer consultants who might probably be familiar with the calculation’s terms, but also for building designers/architects who might not be familiar with some of the main terms. For this reason:
   - Attention has been given to the “pop-up” explanatory notes of the components.
   - A site has been set up (MEOtoolbox.blogspot.com), to provide more information and explanatory notes on the components’ calculation methods. The MEOtoolbox aims to provide as much insight as possible, into the processes and calculations taking place within the tool.
   - In cases when the designer has to decide upon a value, the input name uses building practice terms (air change rate, heat capacity) instead of short hand names (Q, C etc).
   - In cases when the designer is required just to connect an output with an input
the short hand name (for example $H_1$, $H_2$) was used so the designer knows that he doesn’t have to decide on the value but just connect it from the output of a component suggested in the components description.

- Suggested values are included in the “pop-up” explanatory notes of the components, to instruct the designers on the expected input values (for example, for the internal capacity per area depending on the “heaviness” of the construction).

- Preset-values are also given, in case the designer does not want to make a specific choice, on an input that is not of crucial importance.
- Terms like “effective solar collecting area” of the ISO 13790 standard are replaced by more widely known terms like “solar transmittance” and “area” of a facade surface on the requested inputs of the “Solar Gains” component etc.

3. All calculations within the designed components: The MEOtoolbox is willing to provide its analysis on a massing design’s energy demand with all calculations taking place within the components of the toolbox, in order for all processes to be fully understood and exposed to the designer. The toolbox needs only the input of the massing, a small number of design values and location specific weather data that can be acquired from various sources.

4. Compatible to the SustainabilityOpen platform: The components designed for this thesis aim to be integrated on a larger platform facilitating sustainable de-
sign assessment and optimization, envisioned by the BEMNext Laboratory of TU Delft. This integration process and the additional benefits from it will be discussed in the Discussion chapter.  

3.3 Assumptions

Since ISO13790 standard quasi-steady state monthly method has been used, the assumptions of the method have to be satisfied. The assumptions where described in the previous chapter (paragraph 2.2), where it was explained under what conditions the results of the method can be valid.

It should be underlined that the method does provide monthly values but it’s use is to produce accurate yearly energy demand values. Thus the monthly demand values could be inaccurate especially in the beginning and the end of the heating and cooling seasons.

3.4 Implementation

**MEO toolbox programming**

The MEO toolbox involved the programming of Grasshopper components, in the C# programming language which is an object-oriented .NET framework programming language developed by Microsoft. Annex B explains the main characteristics of the programming language, after a short overview of it’s historic evolution.

In this point it will only briefly be explained, that, in object-oriented programming, methods inherit properties by parent objects. The MEO toolbox components inherited the structure and methods of a grasshopper component (GH_Component), which is an object of the Grasshopper Library that can be accessed using the Grasshopper.dll file, downloaded during with the installation of Grasshopper.

By inheriting the GH_Component the components of the MEO toolbox inherited the following structure:

- **Component Guid**: Guid is an acronym for “Globally Unique Identifier”, used to identify the specific programmed “object”.
- **Icon Bitmap**: The .bmp icon that will represent the component.

---

50 In the first version of the MEO toolbox, the components are designed to “inherit” only the Grasshopper component class, due to the fact that the SustainabilityOpen framework is still under construction. When the new version of SustainabilityOpen is made available, the components will be transformed to SustainabilityOpen “Designer” and “Analysis” components.
Also, by inheriting the GH_Component, the components of the MEOtoolbox inherited the following methods:

- **RegisterInputParams()**: This method is used to input the data that will be processed.
- **RegisterOutputParams()**: This method is used to describe the output values that the component will give.
- **SolveInstance()**: This method describes how the input data will be processed to retrieve the output data.

![UML diagram showing the inheritance of Massing Components from the GH_Component objects.](image)

Figure 3.4 UML diagram showing the inheritance of Massing Components from the GH_Component objects.
3.5 Components

**Component Overview**

The overview of the script categories that will be presented in this chapter in this chapter is shown in figure 3.5. The next chapters will present these components and scripts one by one, with the following format:

1. Icon: Designed icon representing schematically the component on the Grasshopper interface and on the MEO toolbox website.

![Figure 3.5 Assessment & Optimization values calculated in the Grasshopper script.](image)
2. Aims: The aims which the components are designed to achieve.
3. Appearance: The appearance of the components on the Grasshopper interface.
4. Inputs and Outputs: The inputs and the outputs of the components, where also the “pop-up” explanatory notes that the components are designed to provide will be provided.
5. Description: Explanation on the methods and assumptions employed by the components in order to accomplish the aims according to the MEO toolbox principles, as described on chapter 4.2
<table>
<thead>
<tr>
<th>COMPONENT NAME</th>
<th>CATEGORY</th>
<th>MAIN USE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Massing M2</td>
<td>Massing</td>
<td>Generates a building volume-geometry, given the base perimeter and the amount of GFA that the volume should enclose.</td>
</tr>
<tr>
<td>Massing H</td>
<td>Massing</td>
<td>Generates a building volume-geometry, given the base perimeter and the desired height for the volume.</td>
</tr>
<tr>
<td>Massing Scaler</td>
<td>Massing</td>
<td>Scales a building geometry, in order for it to meet it's GFA objective.</td>
</tr>
<tr>
<td>Massing Analyzer</td>
<td>Massing</td>
<td>Separates the horizontal surfaces (roofs) from the non-horizontal surfaces (facades) of a massing envelope and gives the GFA of a massing geometry.</td>
</tr>
<tr>
<td>Facade Heat Transfer</td>
<td>Thermal Analysis</td>
<td>Calculates the heat transfer through the input surfaces of a massing geometry given the outdoor monthly temperatures for a location and the desired indoor temperature.*</td>
</tr>
<tr>
<td>Ventilation Heat Transfer</td>
<td>Thermal Analysis</td>
<td>Calculates the heat transfer due to the ventilation needs of a massing geometry given the outdoor monthly temperatures for a location and the desired indoor temperature.*</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td>Thermal Analysis</td>
<td>Calculates the solar radiation on the input surface(s) of a massing geometry given the data for the diffuse and direct radiation of a location as well as the location's sun path.</td>
</tr>
<tr>
<td>Solar Gains</td>
<td>Thermal Analysis</td>
<td>Calculates the solar gains entering a certain geometry given it's glass percentages and U-value.*</td>
</tr>
<tr>
<td>Function Data</td>
<td>Utilities</td>
<td>Provides data for the Interior gains per square meter, ventilation rate etc, depending on the designed programmatic function for the massing.*</td>
</tr>
<tr>
<td>Heating Demand</td>
<td>Thermal Analysis</td>
<td>Calculates the Annual Heating Demand given the monthly facade, ventilation, solar and internal losses and gains.*</td>
</tr>
<tr>
<td>Cooling Demand</td>
<td>Thermal Analysis</td>
<td>Calculates the Annual Cooling Demand given the monthly facade, ventilation, solar and internal losses and gains.*</td>
</tr>
<tr>
<td>PV</td>
<td>Utilities</td>
<td>Calculates the potential for energy production of a specific surface with a PV surface percentage, given the PV characteristics.</td>
</tr>
<tr>
<td>Grapher</td>
<td>Utilities</td>
<td>Provides line and bar chart for the input data.</td>
</tr>
<tr>
<td>Material Data</td>
<td>Utilities</td>
<td>Provides cost and embodied energy information for concrete, steel and glass.**</td>
</tr>
<tr>
<td>Energy Data</td>
<td>Utilities</td>
<td>Provides cost and embodied energy information for electricity and gas.***</td>
</tr>
</tbody>
</table>

* Formulas and data from the ISO13790 International Standard

Table 3.1 Table of developed Grasshopper components
Table 3.2 Table of the sources of the Energy components of the MEOtoolbox’s formulas.

<table>
<thead>
<tr>
<th>name</th>
<th>icon</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facade Heat Transfer</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PARAGRAPH 8.3</td>
</tr>
<tr>
<td>Ventilation Heat Transfer</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PARAGRAPH 9.2.9.3</td>
</tr>
<tr>
<td>Solar Radiation</td>
<td></td>
<td>(VELDS &amp; HOEVEN 1992)</td>
</tr>
<tr>
<td>Solar Load</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PARAGRAPH 11.3.3</td>
</tr>
<tr>
<td>Heating Demand</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PARAGRAPH 12.2.1, 13.2.2.1, 7.4</td>
</tr>
<tr>
<td>Cooling Demand</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ANNEX D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PARAGRAPH 13.2.2.2, 7.4</td>
</tr>
<tr>
<td>Function Data</td>
<td></td>
<td>ISO 13790</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ANNEX G</td>
</tr>
</tbody>
</table>

Figure 3.6 The MEOtoolbox, as seen within the Grasshopper software
3.5.1. Massing Input Components

The massing components are done to facilitate quick generation of building volumes, with floors to floor height specified by the user, which helps in keeping a sense of scale when creating building forms. The designer can choose if he wants to create a building form of a certain height and then calculate the amount of Gross Floor Area generated, or inversely, setting the desired Gross Floor Area and seeing the amount of floors needed to achieve it for a specific base curve. This distinction is the reason why there are two different massing generation components (Massing M2 and Massing H). The other two components are used to analyse massings generated directly in Rhino by the designer.

3.5.1.1. Massing Generation Component 1 (Massing H)

Aims

- Formulate the massing volume(s) of a desired height.
- Formulate the curves of the perimeters of the floors of the mass created.
Introduction

Methodology

Development

Input

- **Mass Height**: The height of the mass. (Type: Number)
- **Perimeter**: The base perimeter of the mass. (Type: Curve)
- **Min Floor Height**: The minimum height for the floors. (Type: Number)
- **Z translation**: The amount of desired translation for the whole generated mass in the Z direction. (Type: Number)

Output

- **Massing**: The Massing Output (Type: Brep i.e. Boundary Representation)
- **Floor perimeter Curves**: The perimeter of the floors created to fulfill the square meter requirement. (Type: Curve List)

The Massing H component (named H for Height) is a component that generates a massing volume by inputting a base perimeter and a height for the desired volume. This tool might be useful for example, when the height of the building is a design requirement.

The base curve for this extrusion can be an angled polyline or a curve. These two inputs (height and base curve) are enough for the generation of the volume, but not for setting the floor perimeters at a desired position. To do this, the extra numeric input of minimum desired floor height, is also needed.

The basic logic is outlined in table 3.3.

An example for the process taking place in step 3 of the logic steps described in table 3.3, is the following:

- if the total desired height of the volume is set to 40m
- and the minimum floor to floor height is set to 3.6m,
- the program divides 40/3.6 = 11.11
- and then makes 11 floor curves
- with a floor to floor height of 40/11 = 3.63 (which is over 3.6 as desired).

A second example, explaining the necessity of the if-statement, described within the parentheses of step 3 of table 3.3, is the following:

- if the desired height for the mass is 39m and
- the minimum floor to floor height is set again to 3.6,
- the program divides 39/3.6 = 10.83
• then makes an integer for 11 floors. By dividing 40m by 11 floors we get 3.54m, which is lower than the minimum desired floor to floor height! For these cases, when the round-up to the closest integer results in a larger number than the real numerical division result, an if-statement is applied to subtract one floor.

• Indeed 40/10 = 4m which is over 3.6, which was the minimum floor to floor height

<table>
<thead>
<tr>
<th>LOGIC STEPS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Get Input</td>
<td>Gets the input for the base perimeter, desired height, minimum floor to floor height and optional z-axis translation (for the whole mass)</td>
</tr>
<tr>
<td>2. Extrusion</td>
<td>Extrudes the base perimeter to the desired height.</td>
</tr>
<tr>
<td>3. Floor height determination</td>
<td>Divides the desired height with the minimum floor to floor height. Convert the result to an integer. (As this conversion might lead to a floor height less than the minimum floor to floor height desired the following check is necessary: Calculate real number to integer difference. If the real number is smaller than the integer subtract one from the number of floors.)</td>
</tr>
<tr>
<td>4. Create curves on floor heights</td>
<td>Calculate actual floor to floor height by dividing the number of floors, determined in the previous step, to the desired height. For i=0 to i=(number of floors determined on the previous step), duplicate the base curve and move it in the z direction (i*actual floor to floor height).</td>
</tr>
<tr>
<td>5. Output</td>
<td>Gives the mass geometry (as a Grasshopper “Brep” i.e. “Boundary REPresentation”). The output also gives the curves created on the previous step. (In case a z-axis translation is set, the whole geometry and Curves are translated in the z-axis direction, at the desired height.)</td>
</tr>
</tbody>
</table>

Table 3.3 Basic Logic steps of Massing H component algorithm.

The output “Floor perimeter Curves” gives the perimeter curves of the generated floors. These curves can be used to calculate the gross floor area created and to generate the geometry of the floors if needed.

Multiple blocks with different or identical base curves can be made with the use of this component. By testing this component it became clear that for the case of multiple block generation it is useful to add the possibility to translate the generated mass in the Z axis directly, through this component. This input is optional with the preset value set to zero. This extra feature allows fast placement of massing blocks one on top of the other. The translation in the other axis has not been added because it seems to be a less essential feature, as the user can always translate the input base curve in the XY plane as desired.
3.5.1.2 Massing generation component 2 (Massing M2)

Figure 3.9 Massing M2 component icon

Aims

- Formulate the massing volume(s).
- Formulate the curves of the perimeters of the floors of the mass created.

Figure 3.10 Grasshopper appearance of Massing m2 component

Input

- **Program m2**: The square meters of the program. (Type: **Number**)
- **Floor Height**: The desired floor to floor height. (Type: **Number**)
- **Perimeter**: The Perimeter of the Base Surface. (Type: **Curve**)
- **Z translation**: The amount of desired translation for the whole generated mass in the Z direction. (Type: **Number**
Output

- **Massing**: The Massing Output. (Type: Brep i.e Boundary Representation)
- **Floor perimeter Curver**: The perimeter of the floors created to fulfill the square meter requirement. (Type: Curve List)

The Massing M2 has the inverse logic than the previous component, as it determines the number of floors and the height of the mass, given the required gross floor area for the volume, floor height and the shape of the base perimeter Curve to be extruded.

To do that it divides the Gross Floor Area of the program with the area of the base perimeter Curve. In case the result is not an integer it always rounds up to the next integer, as it is assumed that the program’s square meters are the minimum acceptable gross floor area.

To do this, an if-statement, similar to the previous component is required. The logic steps of the component are explained in the following table:

<table>
<thead>
<tr>
<th>LOGIC STEPS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
</table>
| 1. Get Input                  | Gets the input for the base perimeter, minimum square meter requirement, floor to floor height and optional 
                               | z-axis translation (for the whole mass)                                     |
| 2. Floor height determination | Divides the minimum square meter requirement with the area of the base perimeter. Converts the result to an integer. (As this conversion might lead to a total square meters less than the minimum square meter requirement desired, the following check is necessary: Calculate real number to integer difference. If the real number is smaller than the integer add one to the number of floors.) |
| 3. Extrusion                  | Extrude the base perimeter Curve to a height equal to the multiplication 
                               | result of the number of floors determined in the previous step and the floor to floor height that was registered in the first step. |
| 4. Create curves on floor heights | For i=0 to i=(number of floors determined on step 2), duplicate the base curve 
                               | and move it in the z direction (floor to floor height).                     |
| 5. Output                     | Gives the mass geometry (as a Grasshopper “Brep” i.e. “Boundary REPresentation”). The output also gives the curves created on the previous step. (In case a z-axis translation is set, the whole geometry and Curves are translated in the z-axis direction, at the desired height.) |

Table 3.4 Basic Logic steps of Massing M2 component algorithm.

For example:
• if the total desired square meters of the program are 30,000m²
• and the floor to floor height is set to 3.6m,
• the program calculates the area of the base perimeter to, for example 2,123m²
• the program divides 30,000m²/2,123m² = 14.13 floors needed. Then it converts the previous number to an integer and checks if the rounded-up number (14) is bigger than the real number (14.13). If not it adds one floor to the integer number of floors (14) making the final number of floors 15. Thus the GFA requirement is fulfilled.

For a second example, with the opposite result of the if-statement:
• if the total desired square meters of the program are 31,000m²
• and the floor to floor height is set to 3.6m,
• the program calculates the area of the base perimeter to, for example 2,123m², same as in the previous example.
• the program divides 31,000m² / 2,123m² = 14.6 floors needed. Then it converts the previous number to an integer and checks if the rounded-up number (15) is bigger than the real number (14.6). In this case, it is indeed greater than the real number, and no extra floor will be added, when the if-statement runs the aforementioned check.

As with the previous component, the base curve can be angled or curved and multiple geometries can be formed with the use of the component, the union of which geometries will eventually form the total massing.

### 3.5.1.3 Massing Analyzer

![Figure 3.11 Massing Analyzer component icon](image-url)
Aims

- Distinguish the horizontal from the non-horizontal surfaces of the envelope of a designed geometry.
- Give an estimation of the Gross Floor Area enclosed within a designed geometry.

![Figure 3.12 Grasshopper appearance of the Massing Analyzer component](image)

Input

- **Massing**: The input massing whose surfaces should be distinguished or whose maximum enclosed GFA should be calculated. (Type: Brep i.e. Boundary Representation)
- **Floor to floor height**: The floor to floor height for the massing. Preset = 4m. (Type: Number)

Output

- **Roofs**: The horizontal surfaces of the massing’s envelope. (Type: Surface List).
- **Facades**: The non horizontal surfaces of the massing’s envelope. (Type: Surface List).
- **GFA**: Gross Floor Area enclosed in the massing. (Type: Number)

The “Massing Analyzer” component is also not generating geometry, but serves in analysing an already designed geometry in two ways.

1) Distinguishing the horizontal surfaces from the non horizontal: This is a useful characteristic for the analysis of many building geometries as in most cases the horizontal surfaces (or “roofs”) have usually very different characteristics than
the non-horizontal (or “facades”). For example, they might have less -or even no-glass percentage and different insulation value.

2) The component gives an estimation of the Gross floor area within a certain mass, using the following equation:

\[
\text{GFA} = \frac{V}{H_{ff}} \quad (3.1)
\]

\( V \) = Volume

\( H_{ff} \) = Average floor to floor height

The above equation becomes evident when both sides of it get multiplied by \( H_{ff} \). It has to be noted that for some geometries with non straight facades the equation might not give very precise results and may serve only as an estimation of the Gross Floor Area enclosed within the designed envelope.

### 3.5.1.4 Massing Scaler

**Aims**

- Scale a massing geometry in order to meet a Gross Floor Area requirement.

![Massing Scaler component icon](image)

![Grasshopper appearance of Massing Scaler component](image)
Input

- **GFA objective**: The objective that the massing has to fulfil. (Type: Number)
- **Massing**: The geometry before scaling. (Type: Brep i.e. Boundary Representation)
- **Floor to Floor height**: The Floor to Floor height. Preset 4.00. (Type: Number)

Output

- **Scaled massing**: The scaled up massing in order to fulfil the objective. (Type: Brep i.e. Boundary Representation).

This component does not generate a building volume-geometry from scratch, but it scales an already existing geometry to meet a GFA objective. This is especially useful in case the designer does not to use the first two massing components to generate the massing.

The “Massing Scaler component”, uniformly scales the input geometry, in order for it to meet a total square meter programmatic requirement.

The formula through which the component calculates the Gross floor area, within a certain mass, is the same with the one explained in the “Massing Analyzer” component description (equation 3.1).

### 3.5.2. ENERGY CALCULATION COMPONENTS

The thermal energy calculation components perform the calculations needed for the ISO13790 quasi-steady state method, which takes into account dynamic effects into the final calculation of the annual heating and cooling demand calculation, which in the MEOtoolbox takes place within the “Heating Demand” and “Cooling Demand” components. Thus it should be noted that the values produced by components other than the two aforementioned, do not take into account dynamic effects.

On the other hand, their results can clearly provide an indication, on the expected contribution of each source of heat transfer, on the heating and cooling demand of a building, aiding the designer’s attempt to minimize it’s expected energy
demands through minimizing contributing parameters.\textsuperscript{51}

\textbf{3.5.2.1 Facade Heat Transfer Calculation Component}

Figure 3.15 Facade Heat Transfer component icon

Aims:

- Calculate the monthly heat transfer through the facade for the heating demand quasi-steady state calculation.
- Calculate the monthly heat transfer through the facade for the cooling demand quasi-steady state calculation.
- Provide the heat transfer coefficient by transmission (\(H_t\)) for heating and cooling demand quasi-steady state calculation.

Figure 3.16 Grasshopper appearance of Facade Heat Transfer component

\textsuperscript{51} The ISO 13790 standard allows that, stating in the introduction that “This standard provides the means (in part) to assess the contribution that building products and services make to energy conservation and to the overall energy performance of buildings.” These services could refer to, for example, ventilation and it’s impact to the heating and cooling demand.
Input

- **Facade**: The Massing’s Facade Surface. (Type: Surface)
- **U-value**: U-value of the Surface (in W/m$^2$K). (Type: Number)
- **Set Temperature Heating**: The desired interior temperature (°C or °K) for the heating period. (Type: Number).
- **Set Temperature Cooling**: The desired interior temperature (°C or °K) for the cooling period. (Type: Number)
- **Outdoor Temperature**: The monthly average outdoor temperature (°C or °K). (Type: Number)

Output

- **Heating Facade Heat Transfer**: The monthly heat losses through the input surface for heating demand calculation (in Wh). (Type: Number)
- **Cooling Facade Heat Transfer**: The monthly heat gains or losses through the input surface for cooling demand calculation (in Wh). (Type: Number)
- **Ht**: The transmission heat loss coefficient. (Type: Number)

The monthly heat transfer through a facade surface is calculated in this component, in compliance with the ISO 13790 international standard. The facade heat transfer is described in paragraph 8.3 of the international standard.

The formula for the calculation is:

$$Q_{\text{fac.loss}} = \sum (U A) (T_i - T_e) h$$  \hspace{1cm} (Wh) \hspace{1cm} (3.2)

$U$: The U value of the surface (W/m$^2$K)

$A$: The corresponding area of the surface (m$^2$)

$T_i$: The specified indoor temperature (°C or K)

$T_e$: The outdoor temperature (°C or K)

$h$: The period of the temperature measurements (h)

The above formula is a simplified version of the formula presented in the ISO13790, in the sense that it does not take into account thermal bridges (linear
or point thermal bridges), thus setting their results into 0 in the formula of the ISO13790. This has been set in this way, because thermal gaps were considered too detailed a concept, for the design stage that the MEOtoolbox addresses.

The component can be used multiple times to describe the heat transfer in different surfaces of the building envelope in case the U-value is not considered uniform throughout the facade.

The difference between “Heating Facade Heat Transfer” output and the “Cooling Facade Heat Transfer” output is that the set temperature ($T_i$), in the above formula, is different for the two energy demand calculations. Thus, for heating demand estimation, the calculation, described in equation 3.2, takes place with $T_i$ equal to the “set temperature heating” input and, for the cooling demand estimation, it takes place with $T_i$ equal to the “set temperature cooling” input.

The input facade for this component can be any surface curved or planar.

For the monthly outdoor temperatures there are different possibilities (manual input, input from Excel files or use of available external plug-ins that extract information from weather data files). The indoor temperature is set by the designer or can be input from the function data component.

The component gives positive values for heat losses and negative values for heat gains, following the ISO 13790 convention.

The components uses the terms “Heating Facade Heat Transfer” and “Cooling Facade Heat Transfer” instead of the traditional facade “losses” and “gains” following the ISO 13790 terminology. According to H. van Dijk, M. Spiekman and P. de Wilde, these terms are preferred because:

- in a cooling mode heat transfer through the facade and ventilation may result in gains instead of losses, and because
- from physics point of view it is important to keep a distinction between heat flows that should be modelled as a heat source (like solar radiation, internal heat sources) and heat flows that should be modelled as a thermal resistance with temperature difference.

This component does the exact calculation needed for the quasi-steady state calculations, which take into account dynamic effects into the total heating and cooling demand calculation which is done by the “Heating Demand” and “Cooling Demand” components of the MEO toolbox. Thus this component does not take into account dynamic effects. On the other hand, it’s outcome can clearly provide
an indication on the contribution of facade heat transfer on the heating and cooling demand, thus aiding the designer to minimize expected energy demands through minimizing contributing parameters.

![Flowchart and source of calculation methods for the Facade heat transfer component.](image)

### 3.5.2.2 Ventilation Heat Transfer Calculation Component

**Aims**

- Calculate the monthly heat transfer through ventilation, for heating demand quasi-steady state calculation.
- Calculate the monthly heat transfer through ventilation, for cooling demand
quasi-steady state calculation.

- Provide the heat transfer coefficient by ventilation ($H_v$), for heating and cooling demand quasi steady state calculation.

![Grasshopper appearance of Ventilation Heat Transfer component](image)

Figure 3.19 Grasshopper appearance of Ventilation Heat Transfer component

**Input**

- **Massing**: The building massing. (Type: **Brep** i.e. Boundary Representation)
- **Air Change Rate**: The amount of air changes per hour. (Type: **Number**)
- **Set Temperature Heating**: The desired interior temperature ($^\circ\text{C}$ or $^\circ\text{K}$) for the heating period. (Type: **Number**)
- **Set Temperature Cooling**: The desired interior temperature ($^\circ\text{C}$ or $^\circ\text{K}$) for the cooling period. (Type: **Number**)
- **Outdoor Temperature**: The monthly average outdoor temperature ($^\circ\text{C}$ or $^\circ\text{K}$). (Type: **Number**)

**Output**

- **Heating Ventilation Heat Transfer**: The monthly heat losses due to the exchange of air between the building and the environment for heating demand calculation (in Wh). (Type: **Number**)
- **Cooling Ventilation Heat Transfer**: The monthly heat losses due to the exchange of air between the building and the environment for cooling demand calculation (in Wh). (Type: **Number**)
- **$H_v$**: The ventilation heat loss coefficient, to be used for the Heating/Cooling
Demand components. (Type: Number)

The energy (heat) transfer due to space ventilation is calculated in this component. The component calculates ventilation heat transfer in accordance to paragraphs 9.2 and 9.3 of the ISO 13790 international standard.

The formula used for the calculation is the following:

\[ Q_{\text{vent.loss}} = \rho c_{\text{air}} Q (T_i - T_e) h \] (Wh) \ (3.3)

\[ \rho c_{\text{air}} = 1200 \] (J/m\(^3\)K)

\( Q \): The ventilation rate \ (m\(^3\)/h)

\( T_i \): The specified indoor temperature \ (°C or K)

\( T_e \): The outdoor temperature \ (°C or K)

\( h \): The period of the temperature measurements \ (h)

The aforementioned formula is fully compatible with the ISO 13790 formulas, just rewriting the two formulas of paragraphs 9.2 and 9.3 into one, and setting to 1 the parameter for pre-heating and pre-cooling, which is not taken into account in the MEOtoolbox, considered too detailed a concept for the design stage that the MEOtoolbox addresses.

In case of several ventilation flows (air infiltration, natural ventilation, mechanical ventilation and/or extra ventilation for night-time cooling) the component can be used to estimate and sum the ventilation heat transfer from these sources.

The input for this component can again be any surface, curved or planar, from the BRep\(^{53}\) output of the Massing components or from a BRep designed in Rhino, without the use of the Massing components of the Energy Massing Optimization.

The difference between “Heating Ventilation Heat Transfer” output and the “Cooling Ventilation Heat Transfer” output is that the set temperature\( (T_i) \), in the above formula, is different for the two energy demand calculations. Thus, for heating demand estimation, the calculation, described in equation 3.3, takes place with \( T_i \) equal to the “Set temperature heating” input and, for the cooling demand estimation, it takes place with \( T_i \) equal to the “set temperature cooling” input.

\(^{53}\) i.e. “Boundary representation” of Grasshopper, a way to describe geometries in the Rhino software.
For the monthly outdoor temperatures there are different possibilities (manual input, input from Excel files or use of plug-ins like Ladybug that extract information from weather data files). The indoor temperature is set by the designer or can be input from the function data component.

The component gives positive values for heat losses and negative values for heat gains, following the ISO 13790 convention.

The components use the terms “Heating Ventilation Heat Transfer” and “Cooling Ventilation Heat Transfer” instead of the traditional facade “losses” and “gains”, following the ISO 13790 terminology. According to H. van Dijk, M. Spiekman and P. de Wilde, these terms are preferred because:

- in a cooling mode, heat transfer through the facade and ventilation may result in gains instead of losses, and because
- from physics point of view it is important to keep a distinction between heat flows that should be modelled as a heat source (like solar radiation, internal heat sources) and heat flows that should be modelled as a thermal resistance with temperature difference.  

This component does the exact calculation needed for the quasi-steady state calculations, which take into account dynamic effects into the total heating and cooling demand calculation, which takes place in the “Heating Demand” and “Cooling Demand” components of the MEO toolbox. Thus this component does not take into account dynamic effects. On the other hand, it’s outcome can clearly provide an indication on the contribution of ventilation heat transfer on the heating and cooling demand, thus aiding the designer to minimize expected energy demands, through minimizing contributing parameters.

This component can take into account intermittent ventilation, as the designer is advised to provide an average weekly value to the ventilation rate of the mass volume. This way the ventilation heat transfer coefficient $H_v$, and consequently the facade heat transfer outcome, is reduced in comparison to what it would be if the designer would just input the air change rate during the building’s operation hours.

---

3.5.2.3 Solar Radiation Calculation Component

Aims

- Calculate the direct solar radiation on a facade surface.
- Calculate the diffuse solar radiation on a facade surface.
• Calculate the total solar radiation on a facade surface.

![Grasshopper appearance of Solar Radiation component](image)

**Figure 3.22 Grasshopper appearance of Solar Radiation component**

**Input**

- **Massing Surface**: The Surfaces of the Massing for which the Solar Radiation will be calculated. (Type: Surface)
- **Potentially Shading Brep**: All Breps that might shade the surface (including the massing’s own Brep. (Type: Brep i.e. Boundary Representation)
- **Sun Vector**: The vector of the sun rays (direction from sun to object) at a specified hour of the year. (Type: Vector)
- **Direct Normal Radiation**: The Direct Normal Radiation at a specified hour of the year (in Wh/m²). (Type: Number)
- **Diffuse Horizontal Radiation**: The Diffuse Radiation at a specified hour of the year (in Wh/m²). (Type: Number)

**Output**

- **Direct Radiation**: The direct radiation on the surface (in Wh). (Type: Number)
- **Diffuse Radiation**: The diffuse radiation on the surface (in Wh). (Type: Number)
- **Total Radiation**: The Total radiation on the surface (in Wh). (Type: Number)

The challenge for this particular component was to find a formula that can give a good estimation of the value for the solar load, but more importantly, that can facilitate the comparison of the solar load in different massings depending on the inclination their surfaces might have. Since ISO 13790 does not provide a formula
to calculate the radiation depending on the angles of incidence of the solar rays, the formulas used were taken from the book of Velds and Hoeven, Zonnenstraling in Nederland\textsuperscript{55}.

The formula used for the normal radiation on a surface is the following:

\[
B = I \left( \cos \beta \sin \gamma + \sin \beta \cos \gamma \cos(\alpha - \psi) \right) \quad \text{(Wh/m}^2\text{)} \quad (3.4)
\]

I : direct normal radiation (Wh/m\textsuperscript{2})
\( \beta \) : vertical angle of the normal of the surface (red angle of the image above) (degrees)
\( \zeta \) : \( 90 - \gamma \) = vertical angle of the sun (yellow angle of the image above) (degrees)
\( \alpha \) : angle from the south vector to the horizontal projection of the normal of the surface (light blue angle of the image above) (degrees)
\( \psi \) : angle from the south vector to the horizontal projection of sun’s vector (dark blue angle of the image above) (degrees)

![Figure 3.23 Diagram explaining the angles used in the calculations. Colours correspond to the angles of described under the equation 3.4.](image)

For the diffuse radiation, the formula used is the following:

\[
D = 0.5 \left( 1 + \cos \beta \right) D \quad \text{(Wh/m}^2\text{)} \quad (3.5)
\]

where
D: Diffuse radiation on a horizontal plane (Wh/m²)
β: (see previous equation)

The total radiation on the input surface is:

\[ G_s = B_s + D_s \] (3.6)

\( G_s \) is the total radiation per square meter falling on the surface, but not the amount of solar energy penetrating the mass. To calculate that, we have to reduce this value, depending on the transmittance factor of the facade’s glass and the glass percentage on the surface. This will take place in the “Solar Gains” component.

The scripting of this component required it to take into account the effect of shading of a surface, at least by the rest of the building volume. In order to check if a certain surface is shaded, a line starting from the centerpoint of the surface, we give as input and in the direction of the sun vector is created. The script of the program checks if the line intersects with the BRep-geometry. If the input BRep consists also of adjacent buildings then we can see if a certain surface is shaded not only by a surface of the building itself but also by adjacent buildings.

In cases where the surface is partly shaded, it should be divided in smaller parts in order to take this effect into account.

The reason why the line is done from the a point of the surface in the direction of the vector of the sun, and not from the sun position, is that the second case
Figure 3.25 Flowchart and sources of calculation methods for the Solar Load component.

would not give us a correct output (producing non-parallel sun-rays). We have to keep in mind that though the sun is a point in the graphic environment and a vis-
ible, from the earth, star in reality, it’s rays are always parallel to one another for the building engineering scale, and thus we could imagine the sun for our scale as a plane projector producing parallel rays.

Instead of really generating such a plane projector and seeing what percentage of the rays hits our surfaces, which could be another possibility, we do the opposite and project from the surface, in the direction of the sun rays.

The ISO 13790 also states that adequate, mean or conservative values can be selected that are appropriate for the heating and cooling demand calculation. On the next chapter the effect to which this is fulfilled by the tool generated will be tested.

### 3.5.2.4 Solar Gains Calculation Component

![Solar Gains Component Icon](image)

**Aims**

- Calculate the amount of radiation entering the building through a facade surface.

![Grasshopper Appearance of Solar Gains Component](image)
Input

1. **Solar Radiation on Facades**: The 12 (monthly average) daily solar radiation falling on the surfaces of the facade (in Wh), taken from the Solar Load component. The input for this component should be 12 lists of 24 numbers, representing the average hourly radiation day for each month. (Type: **Number**)

2. **Glass Percentage**: The percentage of the surface of the facade that is covered with glazing (Preset 50%). (Type: **Number**)

3. **Solar Transmission**: The percentage of solar energy that passes through the glazing element (g = 83% for single glazing, 65-76% for double glazing, 39% for double glazing-tinted, 40%-60% for triple glazing)(Pelsmakers, S., 2012. The Environmental Design Pocketbook RIBA Publishing). (Preset 70% double glazing). (Type: **Number**)

Output

- **Solar Gains**: The amount of Solar radiation penetrating the building (in Wh). (Type: **Number**).

This component gives the amount of radiation entering the building envelope through the facade, by multiplying the average day of solar radiation for each month, on a specific surface of the building envelope, with the glass percentage, the solar transmission factor of this facade and the number of days of each month. Thus the designer can instantly observe the effect of increasing and reducing glass percentage and glass transmission factors on the expected heating cooling demand.

The formula used in this component is the following:

\[ Q_s = G_s \cdot g \cdot A_w \]  \hspace{1cm} (3.7)

\( Q_s \): Total radiation on surface (Wh)

\( G_s \): Transmittance factor

\( A_w \): Area of the surface covered with glass.

The calculation is according to 11.3.3 of the ISO13790 international stand-
ard without taking into account external shading devices, which is beyond the scope of the MEOtoolbox.

3.5.2.5 Heating Demand

Aims

- Calculate the heating demand taking into account dynamic effects through utilization factors, according to the quasi-steady state method of the ISO 13790.
- Give values $\tau$ and $\gamma$, needed for the correction of the aforementioned value due to intermittent heating.

Figure 3.28 Component icon

Figure 3.29 Grasshopper appearance of Heating Demand component
Input

1. **Facade Losses**: The heat losses from the facade (in Wh) for a month that demands heating. (Type: Number)
2. **Ventilation Losses**: The heat losses due to ventilation (in Wh) for a month that demands heating. (Type: Number)
3. **Solar Gains**: The monthly gains due to solar radiation (in Wh). (Type: Number)
4. **Internal Gains**: The monthly gains due to people and machinery (in Wh). (Type: Number)
5. **Area of heat capacity layers**: The area of the heat capacity layers (in m$^2$). (Type: Number)
6. **Internal capacity per area**: The internal capacity per area: 80,000 J/m$^2$K for Very light construction, 110,000 J/m$^2$K for Light, 165,000 J/m$^2$K for Normal, 260,000 J/m$^2$K for Heavy, 370,000 J/m$^2$K for Very Heavy (ISO 13790 values) (in J/m$^2$K). (Type: Number)
   - $H_t$: The transmission heat loss coefficient, given from the Facade Losses/Gains component. (Type: Number)
   - $H_v$: The ventilation heat loss coefficient, given from the Ventilation Losses/Gains component. (Type: Number)
   - **Intermittency percentage**: The percentage of the number of hours in the week with a normal heating set-point e.g. $(14 \times 5)/(24 \times 7) = 0.42 = 42\%$. (Type: Number)

Output

- **Heating Demand**: The monthly heating demand (in Wh). (Type: Number)

The heating demand is calculated in this component.

In this component dynamic effects are taken into account according to the quasi-steady state method of ISO 13790. The heating demand calculation is described in paragraph 12.2.1 of the standard.

The formulas, used for the calculations of this component, are the follow-
\[
Q = Q_L - \eta Q_G \quad \text{(Wh)} 
\]

where:
- \( Q_G \): The sum of solar and interior gains (in Wh)
- \( Q_L \): The sum facade and ventilation heat transfer (in Wh)

The utilization factor \( \eta \) is used to take into account thermal dynamic effects. The factor is calculated through the following formula:\(^{56}\):

\[
\eta = \frac{1 - \gamma^a}{1 - \gamma^{a+1}} 
\]

where:
- \( \gamma = \frac{Q_G}{Q_L} \) (heat balance ratio, indicating the ratio of heat gains over losses)
- \( a = a_0 + \frac{\tau}{\tau_0} \) (dimensionless reference numerical parameter)
- \( \tau = \frac{C}{H_t + H_v} \) (the time constant for the building zone)

where \( C \) is the result of the multiplication of the area of heat capacity layers and the internal capacity per area giving an indicator of the thermal inertia of the building.

The value of \( a_0 \) is automatically set to 1, and \( \tau_0 \) to 15, which corresponds to the values for monthly calculation of heating load.

The component also takes into account intermittent heating, through the last input (“Intermittency percentage”). The calculation procedure for intermitted heating is described in paragraph 13.2.2.1 of the ISO13790 standard.

Finally, the component also takes into account paragraph 7.4 of the ISO 13790. This paragraph determines the fraction of a month that should be calculated as part of the heating season.

\(^{56}\) In case the heat gains are equal to the heat losses or the facade and ventilation heat transfer the formula for the utilization factor changes according to paragraph 12.2.1.1, but this would go into too much detail for the scope of this report.
Figure 3.30 Flowchart and sources of calculation methods for the “Heating Demand” component.
### 3.5.2.6 Cooling Demand Component

**Figure 3.31 Component icon**

**Aims**

- Calculate the cooling demand taking into account dynamic effects through utilization factors, according to the quasi-steady state method of the ISO 13790.
- Give values $\alpha_f$ and $\gamma$, needed for the correction of the aforementioned value due to intermittent cooling.

**Figure 3.32 Grasshopper appearance of Cooling Demand component**

**Input**

- **Facade Losses**: The heat losses from the facade (in Wh) for a month that de-
mands cooling. Negative values for gains through the facade. (Type: Number)

- **Ventilation Losses**: The heat losses due to ventilation (in Wh) for a month that demands cooling. Negative values for gains due to ventilation. (Type: Number)
- **Solar Gains**: The monthly gains due to solar radiation (in Wh). (Type: Number)
- **Internal Gains**: The monthly gains due to people and machinery (in Wh). (Type: Number)
- **Area of heat capacity layers**: The area of the heat capacity layers (in m²). (Type: Number)
- **Internal capacity per area**: The internal capacity per area: 80,000 J/m²K for Very light construction, 110,000 for Light, 165,000 for Normal, 260,000 for Heavy, 370,000 for Very Heavy (ISO 13790 values) (in J/m²K). (Type: Number)
- **Ht**: The transmission heat loss coefficient, given from the Facade Losses/Gains component. (Type: Number)
- **Hv**: The ventilation heat loss coefficient, given from the Ventilation Losses/Gains component. (Type: Number)
- **Intermittency percentage**: The percentage of the number of days in the week with, at least during daytime, normal cooling setpoint (e.g. 5/7 = 0.71 = 71%). (Type: Number)

**Output**

- **Cooling Demand**: The monthly cooling demand (in Wh). (Type: Number)

In the ISO13790 there two methods to calculate cooling demand, with both of them being very similar to the heating demand calculation method. The tool uses the method described in the Annex D of the ISO13790 standard. Since this method cannot calculate the cooling demand in a month that facade and ventilation heat transfer results in thermal gains, in these cases the component switches to the method of chapter 7.2.1.2 for cooling demand calculation. The ISO 13790 states that, the two methods should give identical results and in fact the reduction factor for the gains can be converted from one method to the second, through a simple formula.

The component also takes into account intermittent cooling, through the last input (“Intermittency percentage”). The calculation procedure for intermitted cool-
ing is described in paragraph 13.2.2.2 of the ISO13790 standard.

Finally, the component also takes into account paragraph 7.4 of the ISO 13790. This paragraph determines the fraction of a month that should be calculated as part of the cooling season.

3.5.2.7 PV

Aims

- Calculate the amount of electrical energy that can be produced by a facade surface if a certain percentage of it is covered with photovoltaics.
- Calculate the cost and the embodied carbon emissions of the aforementioned PV surfaces.

Input

- **Surface with PV**: The Surface on which the PV panels will be applied. (Type:
Surface)

- **Solar Radiation on Surface with PV**: The amount of Radiation on the surface in Wh (Direct or Total depending on PV system used). (Type: **Number**)
- **PV Percentage on Surface**: The percentage of PV on a Facade Surface. (Type: **Number**)
- **PV Efficiency**: Percentage of Solar Energy that is converted to Electricity. Suggested values: 10% for monocrystalline PV, 8% for polycrystalline PV, 6% for amorphous PV. (Pelsmakers, S., 2012. The Environmental Design Pocketbook RIBA Publishing). Preset value: 10%. (Type: **Number**)
- **PV Euro/m²**: PV cost per m² (in Euro/m²). Suggested values: 1120 - 1240 E/m² (Pelsmakers, S., 2012. The Environmental Design Pocketbook RIBA Publishing). Preset value: 1180 E/m². (Type: **Number**)
- **Embodied CO2/m²**: Embodied carbon emissions of PV System used (in kgCO₂/m²). Suggested values: 242kgCO₂ for monocrystalline PV, 208kgCO₂ for polycrystalline PV, 67kgCO₂ for amorphous PV (Pelsmakers, S., 2012. The Environmental Design Pocketbook RIBA Publishing). Preset value: 242 kgCO₂. (Type: **Number**)

**Output**

- **Produced Electrical Energy**: Produced Electrical Energy in Wh. (Type: **Number**)
- **PV Cost Estimation**: Cost Estimation (in Euro). (Type: **Number**)
- **Embodied CO2 Estimation**: Embodied Carbon Emissions (in kgCO₂). (Type: **Number**)

This component will also use the solar radiation component’s output value to calculate the potential of energy production if PV technologies are integrated in a specific envelope surface.

Apart from the electrical energy an estimation on the cost and the embodied CO₂ emissions is given as an input to participate in the estimation of cost and embodied carbon of the massing design research of this thesis.
3.5.3. UTILITIES

Apart from the massing and the energy calculation components, the ME-Otoolbox also provides few tools that provide useful design values and tools.

3.5.3.1 PROGRAM FUNCTION DATA

Figure 3.35 Program Function Data Component icon

Aims

- Provide ISO13790 standard values per function for:
  1. the set temperature for heating and cooling,
  2. air flow rate
  3. metabolic, appliance and total internal gains
  4. annual electricity
  5. hot water energy demands

Figure 3.36 Grasshopper appearance of Program Function Data component
Input

1. **Function**: One of the following texts should be provided as input depending on the function: “Single Family Houses” / “Apartment Blocks” / “Offices” / “Education Buildings” / “Hospitals” / “Restaurants” / “Trade Services” / “Sport Facilities” / “Meeting halls” / “Industrial Buildings” / “Warehouses” / “Indoor Swimming Pools”. The preset is Apartment Blocks. (Type: Text)

Output

1. **Set Temperature Heating**: The set temperature when heating is needed (in °C). (Type: Number)
2. **Set Temperature Cooling**: The set temperature when cooling is needed (in °C). (Type: Number)
3. **Air Flow Rate**: The air flow rate (in m³/(h·m²)). To get the air change rate (in 1/h) divide the output with the floor to floor height. (Type: Number)
4. **Monthly Metabolic Gains**: The internal gains from the building’s users’ metabolic function (in Wh/m²). (Type: Number)
5. **Monthly Appliances Gains**: The internal gains from appliances per area (in Wh/m²). (Type: Number)
6. **Monthly Total Internal Gains**: Total internal gains per area (in Wh/m²). (Type: Number)
7. **Annual Electricity Demand**: The annual electricity demand per gross conditioned area (in KWh/m²). (Type: Number)
8. **Annual Hot Water Energy Demand**: The annual hot water energy demand per gross conditioned area (in KWh/m²). (Type: Number)

This component gives standard input data values from the annex G of the ISO 13790 international standard. These values are needed as input in various components of the METootoolbox.

All the values taken from the **Annex G** of the ISO13790 can be found on the tables below.
### Table 3.5 Standard input values taken from the ISO 13790 (Annex G).

<table>
<thead>
<tr>
<th>Source</th>
<th>Set Temperature Heating</th>
<th>Set Temperature Cooling</th>
<th>Air flow rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISO13790</td>
<td>ISO13790</td>
<td>ISO13790</td>
</tr>
<tr>
<td>Unit</td>
<td>degrees Celsius</td>
<td>degrees Celsius</td>
<td>m3/(m²/h)</td>
</tr>
<tr>
<td>Apartment Block</td>
<td>20</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Single Family House</td>
<td>20</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Office</td>
<td>20</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Education Buildings</td>
<td>20</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Hospitals</td>
<td>22</td>
<td>26</td>
<td>1.0</td>
</tr>
<tr>
<td>Restaurants</td>
<td>20</td>
<td>26</td>
<td>1.2</td>
</tr>
<tr>
<td>Trade Services</td>
<td>20</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Sports Facilities</td>
<td>18</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Meeting Halls</td>
<td>20</td>
<td>26</td>
<td>1.0</td>
</tr>
<tr>
<td>Industrial Buildings</td>
<td>18</td>
<td>26</td>
<td>0.7</td>
</tr>
<tr>
<td>Warehouses</td>
<td>18</td>
<td>26</td>
<td>0.3</td>
</tr>
<tr>
<td>Indoor Swimming Pools</td>
<td>28</td>
<td>28</td>
<td>0.7</td>
</tr>
</tbody>
</table>

### Table 3.6 Standard input values taken from the ISO 13790 (Annex G).

<table>
<thead>
<tr>
<th>Source</th>
<th>Metabolic gain per area</th>
<th>Presence per day</th>
<th>Appliances gain per area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ISO13790</td>
<td>ISO13791</td>
<td>ISO13790</td>
</tr>
<tr>
<td>Unit</td>
<td>Wh/m²</td>
<td>hrs</td>
<td>Wh/m²</td>
</tr>
<tr>
<td>Apartment Block</td>
<td>1.2</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Single Family House</td>
<td>1.8</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Office</td>
<td>4.0</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Education Buildings</td>
<td>7.0</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Hospitals</td>
<td>2.7</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Restaurants</td>
<td>20.0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Trade Services</td>
<td>9.0</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Sports Facilities</td>
<td>5.0</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Meeting Halls</td>
<td>16.0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Industrial Buildings</td>
<td>5.0</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Warehouses</td>
<td>1.0</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>Indoor Swimming Pools</td>
<td>3.0</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

By inputting the function (as text) in the input of the component the output gives the ISO standard values.

The set temperature for heating and cooling is needed for the Ventilation.
and Facade Heat Transfer components and is given in degrees Celsius. The air flow rate is needed in the Ventilation Heat Transfer component and is given in \( m^3/(h \cdot m^2) \).

By multiplying the “Total monthly internal gains” values with the Gross Floor Area, an estimation of interior gains can be added to the values of solar gains, calculated through the components above, for an estimation of the thermal gains per month needed for the monthly heating and cooling demand, through the quasi-steady state method of ISO 13790.

If also an estimation of the total energy demand is desired, the lighting, hot water energy demand values are needed.

### 3.5.3.2 Grapher

![Figure 3.37 Grapher component icon](image)

**Aims**

- Generates a line graph and bar graph in the Rhino viewport

![Figure 3.38 Grasshopper appearance of Grapher](image)

**Input**

- **List**: The input list to be graphed (Type: Numerical List)
• **Point**: The point where the graph will start from. Preset point: (0,0,0). (Type: Point3D)

• **Scale factor**: The scale factor for the graph. Preset value: 1.00. (Type: Number)

**Output**

• **Line Graph**: The list of lines of the line graph. (Type: Line)

• **Bar Graph**: The list of cylinders that form the bar graph (Type: Geometry)

This component gives the possibility to graph lists of values in a line graph and a Bar Graph that is shown in the Rhino viewports. Figure 3.41 shows a visualization of possible uses of this component. With the use of this tool the user can see live the effect of his decisions without leaving the Rhino interface.

### 3.5.3.3 MATERIAL DATA

![Material Data component icon](image)

**Aims**

• Provide design standard values for different materials.

![Material Data](image)
Input

- **Material:** Input as text one of the following: Reinforced Concrete, Steel, Glass. Preset: Apartment Block. (Type: Text)

Output

- **Cost:** For Concrete and Steel this refers to the cost of frame structure and floors per Gross Floor Area taken from Get-a-quote.net. For Steel material the cost refers to a system with concrete floors and refers to m² of GFA. For glass this refers to the cost of a facade per m² of facade (in Euro/m²). (Type: Number)
- **Density:** The mass per volume of a material (in Kg/m³). (Type: Number)
- **Embodied CO₂ per kg:** The embodied CO₂ per kg, as found on the inventory of Carbon and Energy of the University of Bath. (in kgCO₂/kg). (Type: Number)
- **Tensile Strength:** The tensile strength (in MN/m²). (Type: Number)
- **Compressive Strength:** The compression strength (in MN/m²). (Type: Number)

For the CO₂ emissions of materials per kilograms where taken from the inventory of Carbon and Energy of the University of Bath. The prices per square meter where taken from the internet database of Get-a-quote.net, which features price approximations for various materials and works, as a rough estimation, which was considered adequate for this thesis aims.

It must be noted here that for the cost estimation of materials used the values used where per gross floor area and not per kilogram.

<table>
<thead>
<tr>
<th>Source</th>
<th>Cost</th>
<th>Density</th>
<th>Embodied CO₂ per kg</th>
<th>Tensile Strength</th>
<th>Compressive Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>get-a quote.net</td>
<td>wikipedia</td>
<td>Bath University Inventory</td>
<td>wikipedia</td>
<td>wikipedia</td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td>140 Euro/m²</td>
<td>2300 kg/m³</td>
<td>0.202 kgCO₂/kg</td>
<td>10 MN/m²</td>
<td>25 MN/m²</td>
</tr>
<tr>
<td>Steel</td>
<td>93 Euro/m²</td>
<td>8000 kg/m³</td>
<td>1.77 kgCO₂/kg</td>
<td>2000 MN/m²</td>
<td>350 MN/m²</td>
</tr>
<tr>
<td>Glass</td>
<td>1000 Euro/m²</td>
<td>2600 kg/m³</td>
<td>0.85 kgCO₂/kg</td>
<td>7 MN/m²</td>
<td>7 MN/m²</td>
</tr>
</tbody>
</table>

Table 3.7 Standard input values taken from the sources written on the second line of the table.

---

### 3.5.3.4 Energy Data

![Energy Data component icon](image)

**Aims**

- Provide cost and embodied CO$_2$ values for energy, depending on it’s source (electricity or gas).

![Energy Data component](image)

**Input**

- **Energy Type**: Input as text one of the following: Gas/Electricity. (Type: Text)
- **Function**: Input as text one of the following: Single Family Houses/Apartment Blocks/Offices/Education Buildings/Hospitals/Restaurants/Trade Services/Sport Facilities/Meeting halls/Industrial Buildings/Warehouses/Indoor Swimming Pools. Preset: Apartment Block. (Type: Text)
Output

- **Cost per KWh**: Cost per KWh taken from http://epp.eurostat.ec.europa.eu/estatistics_explained/images/e/e7/Half-yearly_electricity_and_gas_prices_2012s2.png (in Euro/KWh). (Type: Number)

- **Embodied CO2 per KWh**: The embodied CO2 per KWh per type of energy, taken from Pelsmakers, S., 2012. The Environmental Design Pocketbook, RIBA Publishing. (in KgCO2/KWh). (Type: Number)

The gas and electricity CO2 emissions per kilowatt-hour where taken from the Environmental Design Pocketbook of Sofie Pelsmakers59, while the cost of gas and electricity per kilowatt-hour was taken from the annual report of Eurostat for the European union average prices.60

<table>
<thead>
<tr>
<th>Source</th>
<th>Cost per KWh</th>
<th>CO2 per KWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity for Industry</td>
<td>0.124</td>
<td>0.517</td>
</tr>
<tr>
<td>Gas for Industry</td>
<td>0.042</td>
<td>0.198</td>
</tr>
<tr>
<td>Electricity for Households</td>
<td>0.206</td>
<td>0.517</td>
</tr>
<tr>
<td>Gas for Households</td>
<td>0.079</td>
<td>0.198</td>
</tr>
</tbody>
</table>

Table 3.8 Standard input values that the component provides, along with the sources of the values.

### 3.5.4. Other calculation scripts

#### 3.5.4.1 NFA calculation method

The parametric calculation of the NFA is a challenging issue. Although the GFA estimation can be done using the methods of the Massing Analyzer component (which divides the overall volume with the average floor to floor height), the same method cannot be used to estimate NFA as it strongly depends on the shape of the floor perimeter.

For this reason an alternative approach was used. The floor planes, determined by the desired floor to floor height are created. For example for designed floor to floor height 4m the script creates planes every 4m (at a height of 0m, 4m, 8m, 12m, 16m and so on, and then intersects these planes with the massing geometry (See also Figure below). This way it gets the actual intersection curves at each

---


floor height. By offsetting these curve inwards in the desired leasable floor depth (set for example at 7m from the facade), the Net floor area’s boundaries are defined. The Grasshopper “Area” component, calculates the NFA’s numerical value.

Figure 3.43 Step 1: Intersection of floor planes with building massing to get the floor perimeter curve at each floor level.

Figure 3.44 Step 2: Determination of NFA through the subtraction of the waste space from the total area of each floor perimeter curve.
### 3.5.4.2 Material Estimation Method

The estimation of the material used in different massings is challenging as the dimensioning of complex geometries through simplified methods would be a very demanding task which is beyond the scope of this thesis.

Since this thesis intends only to compare basic building typologies, taking into account their embodied energy, it can use rules of thumb like the one shown in the following graph.

![Diagram of structural needs for steel based on the diagram by Smith & Coull](image)

The values for the graph are based on a diagram by Smith & Coull, as found on their book “Tall Building Structures: Analysis and Design”, with the values of the graph converted into SI units.

---

To use this rule of thumb, in a parametric design environment, the total weight of steel per area from the graph should be approximated by a function of the number of floors. The values of the graph were interpolated using the Lagrange interpolation to the following equation:

\[
S = \frac{-GFA \times (26.3 \times N_{fl}^{11} - 15972 \times N_{fl}^{10} + 4225650 \times N_{fl}^9 - 639135750 \times N_{fl}^8 + 60945819000 \times N_{fl}^7 - 3808499310000 \times N_{fl}^6 + 156907811500000 \times N_{fl}^5 - 4172919217500000 \times N_{fl}^4 + 67830063180000000 \times N_{fl}^3 - 601278592200000000 \times N_{fl}^2 + 214287732000000000 \times N_{fl} - 1297296000000000000)}{332640000000000000}
\]

where:

- \( S \) = Weight of steel per area (in Kg/m\(^2\))
- \( GFA \) = Gross floor area (in m\(^2\))
- \( N_{fl} \) = Number of floors

The equation is used after 10 floors, because up to ten floors the relation between weight of steel and the number of floors is linear.

### 3.5.4.3 Cost and Embodied CO\(_2\) per Gross Floor Area Estimation Methods

In order to compare the effect of different decisions in the initial design phase, they have to be compared in a common measuring system. For this thesis the end assessment will be compared in terms of \( \text{CO}_2 \) emissions, while with the tools developed for this thesis also total cost comparison would be possible.

This can be the common denominator, where the overall effect of reducing the energy demand, for example, by reducing the annual gas demand for heating or the electricity demand for cooling, can be shown.

Thus, by relating gas and electricity kilowatt-hours with their \( \text{CO}_2 \) emissions and cost per kilowatt-hour, the impact of a design decision can be put into context.

To achieve the above the Energy Data and Material Data components can be used.
3.6 Workflow

All the components described above, do not have to be connected for each project separately. An example file with all the connections needed already set, can be made available for the user to download. What is more, this example file can be clustered\(^{63}\) for a more simple communication of the basic inputs and outputs of the system.

In this file the designer needs only to input the designed massing (if already designed) and the weather data information needed for the calculation. This can be done either manually, which would be a time-consuming process, or by using already available parametric plug-ins that can import this information from the weather data file, into the Grasshopper interface (for example, the Ladybug plug-ins, developed by Mostapha Sadeghipour). With the use of such plug-ins, the weather data needed for the aforementioned assessment/optimization systems can be set automatically by reading a file, of .epw type, which is a standardized way of writing weather data for different locations. This weather data can be downloaded from trustworthy sources of the internet. A large database for more than 2100 locations is available in the website of the U.S. Department of Energy (http://energy.gov).

After that, the designer has to input some basic values. As he changes these input values he can instantly see the effect of the changes on the monthly and annual heating demand and on his design criteria.

The designer can also “dive” into more detail in the script of Grasshopper to understand further how the values are produced and to change other parameters that he might consider important, and even connect different components and extend the scripts to better serve his design criteria. Then, the designer is free to experiment with different massing or numerical value inputs and thus different design alternatives.

More insight on possible workflow for a fast setup of a basic parametric massing optimization to minimize heating demand can be found on the Annex A. There the procedure in order to form a massing within a given context and calculate

\(^{63}\) Clustering is an option that grasshopper gives to it’s users to group components and transform them into one component. The user can “dive” into the clustered script by doubleclicking the clustered component
the heating demand for it, is described step by step\textsuperscript{64}.

More insight on how the user interface can look like, with the use of these tools, will be given in the following paragraph, while the step by step description of the model will follow after that.

### 3.7 User interface

Screenshots of the user interface, with additional explanations within the images and in their captions are included below. It should be noted that the user can change the interface in various ways, according to his needs, and thus the interface presented below is just an example of how the software could look like, when the full script for this thesis has been set.

---

\textsuperscript{64} It should be noted that, although in this thesis optimization seems to refer only to the calculation and manual minimization of the fitness values, once these have been set, it is also possible to perform algorithmic optimization using the genetic optimization component of Grasshopper, named Galapagos. The reasons for this are the following: Firstly, this process would be slightly harder to analyse, in comparison to the step by step manual changes that will be presented in the case studies. Secondly, in the opinion of the writer, manual optimization is a bit more in line with the aims of the designer, who usually wants to be in control and manually perform the massing gestures.
User interface
The user can change the massing geometry on Rhino[1] or the values at the basic input of Grasshopper[2] and see the effect on the basic output values that he has set[3].
Figure 3.47 The user interface with the massing (1), the parametric input (2) and the resulting values (3).
User interface
1: Step 1 - Massing & Basic input
2: Step 2 - Weather Data
3: Step 3 - Massing Analysis
4: Step 4 - Solar Radiation
5: Step 5 - Solar Gains
6: Step 6 - Facade, Ventilation heat transfer, Interior Gains
7: Step 7 - Heating & Cooling Demand
8: Step 8 - Total Operational Energy Demand and CO2
9: Step 9 - Total Embodied CO2
Figure 3.48 The full Grasshopper script, developed for the thesis, with the 9 distinct steps grouped.
Figure 3.49 Example file with the use of the massing assessment/optimization cluster. Inside the cluster the full script of the thesis is executed.
3.8 Script Structure

The step by step formation of the script, whose overview was shown in the previous paragraph, will be presently described. The distinct steps are shown in the pictures, that feature print-screens of the Grasshopper user interface. This Grasshopper script is only one example of how some of the MEOtoolbox components could be used. According to the design objectives, the user can decide to omit calculations or use the values to calculate or optimise geometries in other ways. For example he can make use of the Galapagos component of Grasshopper to achieve algorithmically optimized results or the Exposure component to take into account shading from adjacent buildings.

The script presented will actually be used in the following chapters for the validation and the case studies of the scripts and tools produced for this thesis.

The distinct steps of the Grasshopper script are the following:
1. Massing & Basic input
2. Weather data input
3. Massing analysis (GFA, NFA, Roof & Facade distinction)
4. Solar Radiation
5. Solar Gains
6. Ventilation & Facade losses, interior gains
7. Heating & Cooling Demand
8. Total Operational Energy Demand and CO2

Figure 3.50 The heating demand component in the detailed script, with the pop-up description providing a link to meotoolbox.blogspot.com for more information on the calculation methods.
9. Total Embodied CO2

Apart from the MEOtoolbox components the script makes use of Grasshopper components and also external components on Step 2 (Weather data input). The methods used to calculate specific values like the NFA or the amount of steel per square meter were explained in the previous paragraphs. The following images will only demonstrate the script developed for this thesis in Grasshopper, highlighting the MEOtoolbox components and giving a brief description of what takes place in each part. A more detailed explanation of the calculations taking place at each step can be found in Annex D, while a step by step setup of a fast model can be found in Annex A.

Figure 3.51 To get the exact values for the objectives, another possibility is to gather these values, using Grasshopper’s “Data Recorder” component, and then create databases and charts using other software (ex.g Excel)
Step 1: Massing & Basic Input
The initial massing is formed[1] using Grasshopper components to transform referenced geometry, and the basic input values are set[2].

Figure 3.52 Step 1: Massing & Basic input script.
Basic Input

- Glass Transmittance: 50
- Roof+Ground U-value: 0.14
- Glass Percentage: 51
- Glass U-value: 0.8
- Roof + Base U-value
- Facade U-value
- Average U-value
- U-value
- Massing Input
- Brep
- BP
- Cube
- Fence
- Warehouse
- Slab
- Caterpillar
- Tower
- Floor Leasable Depth: -7,000
- Floor Height: 0.2
- Floor to floor height: 4.0
- Offices
- Program Function
- Ventilation Factor on ISO Value: 1.000
- Internal Gain Factor: 1.0
- Number 3
- U
- Number 5
- V
Step 2: Weather data

Figure 3.53 Step 2: Weather data input script.
Step 3.1: Massing Analysis (GFA, Roofs, Facades)
The massing and the floor to floor height established at Step 1 is now analyzed using the Massing Analyzer MEOtoolbox component[1]. The surfaces are also divided in the step[2] to take into account differences in shading on areas of facade surfaces (due to self shading or shading due to adjacent buildings).
Step 3.2: Massing Analysis (NFA)
The NFA is calculated using entirely components from Grasshopper. The clustered components[3] intersect the massing geometry with planes situated at the floor heights determined on step 1 to give the floor perimeter curves. The inward offset[4] of these curves in a leasable depth defined on step 1, defines, along with the curves themselves the area that can be considered NFA.
Step 4: Solar Radiation
The facade surfaces, determined in the previous step, are input in the MEOtoolbox’s Solar Radiation component[1], along with weather data from step 2, to get the hourly solar radiation on the facades. The potentially shading Brep is the Massing Geometry itself, in this example. The results are then partitioned[2] as needed by Step 5.

Figure 3.55 Step 4: Solar radiation script.
Introduction
Step 5: Solar Gains
The solar radiation determined on the previous step is input on this component along with the facade characteristics determined on step 1. The Solar Radiation data should be in the form of the average radiation day (24 numbers) for each of the 12 months and for each surface.

Figure 3.56 Step 5: Solar gains script.
Gains

Solar Radiation on Surface
Glass Percentage
Solar Transmission

Solar Gains
Figure 3.57 Step 6: Ventilation, Facade and Interior heat transfer script.
Step 6: Facade, Ventilation heat transfer, Interior Gains

In this step the facade[1], roof[2], ventilation[3] and interior[4] losses and gains are determined using weather data from step 2, massing data from step 3, and standard design values, depending on the input programmatic function, given by MEtoolbox’s Function Data component[5].
Step 7: Heating and Cooling Demand
In this step the annual heating[1] and cooling[2] energy demand is calculated using input from steps 5 and 6. Input on the construction type and the intermittency percentage can also be given in this step. The reason they haven’t been part of step 1, is that they might be too detailed parameters for the preliminary massing process.
Cooling Demand

1

2

Figure 3.58 Step 7: Heating and Cooling demand script.
Figure 3.59 Step 8: Total operational demand and CO₂ emissions script.
Step 8: Total Operational Energy Demand and CO2

In this step, the heating and cooling energy demand is transformed to actual gas and electricity energy demand through the coefficients of performance [1,2] and then added to the other operational energy demands [3,4] using output from the Function Data component (Step 6). The conversion to costs and CO2 is done through MEOtoolbox’s Energy Data component.
Step 9: Total Embodied CO\textsubscript{2}
In this step an estimation of the embodied CO\textsubscript{2} is given using MEOtoolbox’s Material Data component\cite{1,2,3,4} and the output from the massing analysis (Step 3). To estimate the steel depending on the number of floors a custom component is used which uses the Smith & Coull table for Steel per area, depending on the number of floors of the geometry.
4. **VALIDATION**

In this chapter the validation of the toolbox and scripts created for this thesis will be presented.
4.1 Massing Energy Optimization toolbox validation

4.1.1 Accuracy of the Quasi-steady state Method

The Massing Energy optimization toolbox makes use of the quasi-steady state method described in the ISO 13790 European standard, which is a method taking into account dynamic effects through utilization factors.

The accuracy of the method is tested in the Annex H of the ISO 13790 standard itself. The results from the calculated monthly energy needs for three different locations, Paris, Rome, Stockholm, were compared to a) the results of detailed simulation methods and b) the results of the simple hourly method also described on the ISO standard. The results show a maximum relative difference of 5% for Paris and Stockholm and 4% for Rome.

The standard concludes from the above that the uncertainties are acceptable, compared to other uncertainties, especially when taking into account the needs that the quasi-steady state method has to accomplish, in terms of the transparency, robustness and reproducability characteristics needed, in order for a method to be used in building regulations. These characteristics, as has been explained earlier on this report, are also important for a parametric energy assessment of a massing design.

4.1.2. Component validation

To make sure that the energy analysis components produce valid results, their numeric output was compared to the results of the worked example of Annex J of the ISO 13790. The worked example did provide many of it’s input values, thus allowing a step by step validation of the components of this thesis. Given where the dimension and the use characteristics for an office room in Paris, with it’s facade facing west and featuring glazing in defined dimensions. The validation procedure for each component is described in more detail in Annex D.

As shown in the comparative tables of the Annex D, the results of facade and ventilation losses, interior gains and heating and cooling demand are almost identical to the ones of the ISO worked example when the same inputs are given. Thus the results of the respective components (Facade Heat Transfer, Validation Heat Transfer and Heating and Cooling Demand) can be considered validated, as they use the same method as the worked example and give the same results.

ISO/FDIS 13790 2007-11
This exact validation procedure could not be applied on the “Solar Radiation” component, as this component is using formulas from the book Zonnestraling in Nederland of Velds, C.A. & Hoeven and not from the ISO standard, in order for it to be able to calculate the solar radiation on any plane surface with any orientation. This would not be possible with the ISO 13790 solar radiation methods, which give solar loads only for vertical and horizontal surfaces.

Thus for the validation of the “Solar Radiation” component the output value was first compared to excel calculations, to assure firstly that the results of the script are the same as the results of an excel sheet performing the same calculation.

As shown in the following figure, the results through both software, using the same formulas and inputs, are identical. (The less than 0.3% difference that is observed in some cases, like in the example above, can be attributed to the precision through which the Grasshopper component has calculated the area of the surface. For Grasshopper, the area might feature much more decimals, while in the excel calculation the value is provided by the user with two decimals).
What was also verified, is if through the use of the above formulas the results are close to results taken from other relevant software.\textsuperscript{66}

The comparison of the values given through the Massing Energy Optimization toolbox’s component and the Annex J’s results for solar gains is shown in the

\textsuperscript{66} This is mostly a verification of the calculation method of Velds, C.A. & Hoeven than of the work of this thesis.
While the same dimensions and glazing characteristics of the Annex J’s worked example room where given as input into the MEOtoolbox, the weather data that the ISO example used, could not be retrieved, thus making the use of a different weather data file inescapable. And although the sun path used by ISO is not expected to be very different than the one used by the MEOtoolbox, the direct normal and the diffuse horizontal radiation might be very different in the weather data file used in the ISO calculation. The main difference is observed in the month of March where probably the ISO weather file used, must have had much more intense radiation attributed to this month.

The overall difference of the solar load during the year is 3%.\textsuperscript{67} The differences observed are negligible, especially taking into account that the solar load is only a percentage of the heating demand reduction in winter and the cooling demand increase in summer, thus the inaccuracy “transferred” on these demands is even less. Overall the different solar loads result in less than 2% on the total energy demand estimation difference In the Annex D, a more detailed comparison of the heating and cooling demand using the two different solar loads as input, is presented.

\textsuperscript{67} It should be reminded at this point that the quasi-steady state method is not a method to calculate monthly heating and cooling demand, but mainly annual. This is why this paragraph focuses on the comparison of the annual difference in heating and cooling demand, with the two different solar loads as inputs.
Another validation of the solar component was attempted in a more complex massing, which partly shades itself at some points of the day, especially in summer. The validation geometry is based on the case study of the next chapter, where the project will be explained further. This paragraph only aims to present how the results are similar to results to other solar radiation tools, in order to strengthen the arguments of the case study.

As a first comparison an identical geometry was analysed by MEOtoolbox and Ecotect, to compare the amount of monthly solar radiation that the two programs would calculate.

The massing that is used for the comparison is shown in the following picture.

![Figure 4.4 Basic validation massing. The surfaces are colour coded, with red depicting the places with the most annual solar radiation per square meter.](image)

The basic validation massing comprises of two cubes, one over the other with a 3.6m shift of the upper cube towards the east. The weather data input for the validation is the one for Brussels, Belgium. Firstly, a comparison was made between the total annual solar radiation on the facades given by the MEOtoolbox component and the one given by another parametric solar component, Ladybug68.

68 Ladybug is a free parametric plug-in for Rhino/Grasshopper created by Mostapha Sadeghipour. It is available at http://www.grasshopper3d.com/group/
In this comparison, the difference in the absolute value of the annual solar load, was under 4%, despite the different methods and formulas used to calculate the solar radiation and the different surface division grids. (The absolute values were 4.08GWh for the MEOtoolbox, 4.19GWh for Ladybug.)

Apart from the comparison with Ladybug, the results of the MEOtoolbox for the geometry were compared also to Autodesk’s Ecotect. In this comparison, the glass transmission was set to 1.0 and the glass percentage was set in both software to 100%, in all the surfaces of the building envelope. 69

Figure 4.5 The geometry inserted in Ecotect. In this comparison the upper block shifted towards the north and the roof’s solar load is also considered.

Ladybug. Although it does have similar objectives with the MEOtoolbox aiming to “help designers create an environmentally-conscious architectural design”, it’s functionality overlaps with MEOtoolbox only in the solar radiation tool it features. Ladybug does not provide any tools for the rest of the energy analysis taking place in MEOtoolbox. It’s functionality of reading weather data files was used on the scripts of this thesis for the weather data input that the MEOtoolbox required. 69 This is in contrast with the Ladybug comparison where the roof was considered to feature no glass.
The total annual solar energy difference given by the two programs difference remained within 15%, despite the different calculation methods used by Ecotect. It should be noted that the exact method through which the calculation of Ecotect takes place is not fully explained in the software, thus the exact assumptions that it has taken for the calculation remain unknown.
In the table we can see that the MEOtoolbox is giving larger values for all months, but the two lines have very similar behaviour. For example, the solar load in both software is going slightly down in June in comparison to May and July, probably due to the smaller angle with which the sun hits the facades, but also due to the shading of the lower block by the upper block during summer. A 3% difference can be accounted also to the number of days of each month, since the comparison is done in Wh.

To compare all three software used above and which all feature possibilities to calculate the annual solar load in a massing, the same massing was also imported to Ladybug:

![Figure 4.8 The same geometry analysed in by the Ladybug solar component. The results of the component are in KWh.](image)

The comparison of the total annual solar load, as given by the three programs, is shown in the following graph:
Introduction

Methodology

Development

Validation

Figure 4.9 Comparison of the annual incident solar radiation calculated by three different programs.

In this comparison it is shown that the annual solar load difference between Ecotect and Ladybug is more than between the Ecotect and MEOtoolbox. MEOtoolbox is the software giving the largest solar load, making it the most conservative software to calculate cooling demand and the least conservative software to calculate heating demand.

In the comparison of the three software beyond the final values, it has to be noted that the MEOtoolbox offers the results without connecting to other software and needing the least amount of time, with Ecotect needing 14 minutes to provide the results and Ladybug running another program (GenCumulativeSky) to provide the results, thus breaking slightly the parametric design workflow.

Finally, Ecotect and Ladybug offer much less insight on the calculation methods, while the formulas and methods of the MEOtoolbox solar load compo-
ent, (as presented on paragraph 3.5.2.3), will be available through the MEOtoolbox website.

4.1.3. GESTURE FEEDBACK VALIDATION

It was also essential to test if possible cube shifts would have similar effect in the annual solar load of a massing, thus allowing users to base preliminary design decisions on the results. Thus, the upper cube was shifted for 3.6 and 7.2m towards the south to observe the difference in the result using the two different parametric solar components.

As it is visible in the graph 4.6 above, MEOtoolbox and Ladybug both confirm the reduction of the annual solar radiation on the facades of the massing due to the increased self-shading effect of the southward shift of the upper cube. The
Ladybug estimates the solar radiation decrease to 3% while the MEOtoolbox to 2%. Despite the different calculation methodologies and the different surface division grid, both parametric tools provide similar feedback to the designer, in case he wants to reduce the solar radiation on the massing.

The aforementioned results are considered satisfactory, as they give the same type of feedback to the designer for the same massing gesture (shift of upper block towards south). Also the absolute values are very close in comparison to the large uncertainties of the actual annual weather conditions, design uncertainties and also given that the surfaces were divided in different grids and the calculations of the two components are done using different calculation formulas.

On the other hand, given the differences between the three programs, the user of the MEOtoolbox will be advised to cross reference the solar load with other software, given the challenges and uncertainty inherent in this calculation.

4.1.4. Tilted Solar Validation

To test also the results of the solar radiation component in tilted surfaces, a comparison was done with a table included in the “The environmental design pocketbook” of Sofie Pelsmakers.\(^70\) The table was showing the ideal inclination of PV panels per orientation for maximum energy generation during the year. An orientation towards the south and an inclination of 30° to 40° from the horizontal was there considered the most beneficial while the percentage per tilting was also presented. It has to be noted that it was not specified to which location this corresponds but it can be assumed that the table is referring to England where most of the examples of the book are from.

This seemed as a good opportunity for an additional test of the solar load component. The results were also compared to the results of energy production per inclination estimation for pv-panels, provided by the internet site powerrouter.com. The following comparative graphs were generated.

There it is shown that the behaviour of the solar load line calculated through the MEOtoolbox Solar Load component is similar to the values of the table of “The Environmental Design Pocketbook”\(^71\) and the powerrouter.com energy prediction per orientation for London. The maximum annual solar load for all three lines is occurring in surfaces inclined towards the south, in an angle of 20° to 30° from the

---


horizontal plane. Also for all three solar load calculators, surfaces orientated towards the west gather maximum solar load on almost horizontal planes.

![South inclination annual solar load ratio](image)

**Figure 4.12** Comparison of solar load ratio per inclination towards the south

![West inclination annual solar load ratio](image)

**Figure 4.13** Comparison of solar load ratio per inclination towards the west

### 4.2 Assessment/Optimization systems validation

The final assessment/optimization model presented in paragraph 2.1 had to be validated before it’s use, on the next chapter, as it extends beyond the methods
described in the ISO 13790, to include also elements of facade and structure embodied CO2 emissions. The study by A.A.J.F. van den Dobbelsteen on office buildings typologies, from his doctorate thesis “The Sustainable office: an exploration of the potential for factor 20 environmental improvement of office accommodation”\(^\text{72}\), will be used as a basis for this extension.

In this study, six building typologies that enclose the same amount of gross floor area where defined and compared with regards to their environmental impact. The effect of energy, materials and water was taken into account.

The last massing assessment/optimization system of paragraph 2.1 also addressed the first two parameters, energy and materials. For water, the consumption was set equal for all building typologies, as it was considered as being dependent only to the amount of gross floor area. Thus the comparison of the outcome of the aforementioned typology study through the methods of A.A.J.F. van den Dobbelsteen’s PhD dissertation and the parametric systems of this thesis is possible.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Height</th>
<th>Width</th>
<th>Length</th>
<th>GFA</th>
<th>NFA</th>
<th>Façade Area</th>
<th>Roof Area</th>
<th>Base Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse</td>
<td>12</td>
<td>24</td>
<td>48</td>
<td>3456</td>
<td>2158</td>
<td>1728</td>
<td>1152</td>
<td>1152</td>
</tr>
<tr>
<td>Cube</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>3456</td>
<td>2592</td>
<td>2304</td>
<td>576</td>
<td>576</td>
</tr>
<tr>
<td>Tower</td>
<td>96</td>
<td>12</td>
<td>12</td>
<td>3456</td>
<td>3456</td>
<td>4608</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>12</td>
<td>12</td>
<td>96</td>
<td>3456</td>
<td>3456</td>
<td>2592</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>Fence</td>
<td>24</td>
<td>12</td>
<td>48</td>
<td>3456</td>
<td>3456</td>
<td>2880</td>
<td>576</td>
<td>576</td>
</tr>
<tr>
<td>Slab</td>
<td>48</td>
<td>12</td>
<td>24</td>
<td>3456</td>
<td>3456</td>
<td>3456</td>
<td>288</td>
<td>288</td>
</tr>
</tbody>
</table>

Figure 4.14 The building typologies used for the typology study of van den Dobbelsteen’s dissertation, which will also be used for the typology study of the following chapter.

Table 4.1 Main characteristics of the typologies of van den Dobbelsteen’s dissertation, imported in the

\(^\text{72}\) Dobbelsteen, van den, AAJF, 2004, The Sustainable office: an exploration of the potential for factor 20 environmental improvement of office accommodation, Delft Copie Sjop
As far as energy is concerned, van den Dobbelsteen’s study divided the energy needs into energy for heating & cooling, lighting and other energy use. The assumption used for the heating and cooling demand, was that it is proportional to the area of the building envelope and equally divided between transmission and ventilation losses.

Thus to compare the outcome of the MEOtoolbox for the six different typologies at first the effect the internal and solar gains was not taken into account. The U-value for the whole building envelope(facades, roof and base) was set to 0.69W/m²K, determined as such, in order for the facade and ventilation losses to be equal, as was the assumption in van den Dobbelsteen’s study.

The results of the typology comparison can be seen in the graph below. The cube has been used as the reference geometry and the heating demand of the other typologies is the demand of the cube, plus the this demand multiplied by the factor percentage of the graph:

In the graph it is obvious that, without taking into account the gains, the lines have the same behaviour with MEOtoolbox having output values of smaller range in comparison to van den Dobbelsteen’s study.

As NFA (Net floor area) for these typologies the amount of area that is within 6 meters from the facades is used. This means that for the last four typologies the whole Gross floor area is considered as NFA. Of course, this a simplification of the term which does also exclude from the GFA, unrentable area due to vertical circulation and installations etc. On the other hand it is important to use the NFA idea to take into account that these typologies have much more area in close proximity to the facades, in contrast to the “Cube” and the “Warehouse.”
The reason for this is that, while in the formulas of ISO 13790, used in the MEOtoolbox, the facade losses are proportional to the facade area, as was the assumption of van den Dobbelsteen’s study, for the ventilation losses they are proportional to the volume which remains the constant for all the masses. This is why the effect is almost exactly the half in comparison to van den Dobbelsteen’s study, where both ventilation and facade transmission losses, considered equal and the half of the heating and cooling demand, where considered proportional to the facade area.

As far as the comparison of the total energy for the different typologies is concerned, van den Dobbelsteen’s study calculated it as a weighted average of heating & cooling, lighting and other energy use factors to end up with the demands shown in the graph with the blue line. In this study, the cube is not the least energy demanding typology because of lighting demands considered larger in typologies with bigger depth. The MEOtoolbox model calculates electricity demands proportionately to the Gross Floor Area and thus the ranking for total energy, if no gains are taken into account, does not change in comparison to the previous graph.

A way to take into account the floor depth within the parametric model of the MEO toolbox is to rank the typologies not only using the ratio of energy demand over Gross Floor Area but also over the Net Floor Area (shown in Table 4.1.). Since for some typologies the net floor area is less than the gross floor area, these
typologies are then “penalised” for their larger floor depth. This comparison will be studied further in the next chapter, where the typology study will be extended.

In the following chapter also, the embodied CO₂ of the typologies will be compared with the operational energy of each typology. To perform this comparison, the methods of calculating the embodied energy. As explained in the previous chapter, this thesis will calculate embodied energy through Material Data component for facades, roofs and floors while for columns beams and wind bracing the table of Smith & Coull will be used, as found on their book “Tall Building Structures: Analysis and Design” (paragraph 3.5.4.2).

![Comparison of environmental impact for the different typologies in the study of van den Dobbelsteen with the embodied CO₂ calculation through the methods of the MEOtoolbox](image)

Figure 4.17 Comparison of environmental impact for the different typologies in the study of van den Dobbelsteen with the embodied CO₂ calculation through the methods of the MEOtoolbox

More insight into the assumptions for the embodied CO$_2$ calculations are given in the Annex E.

These equal gross floor area typologies will be used as a beginning for the typology study in different climates, that this thesis will perform in the next chapter.
5. APPLICATIONS

In this chapter the toolbox and scripts developed will be used to respond to the research aims of this thesis.
5.1 Case Study 1: Leisure Centre in Paris

This MEO toolbox found one of its first applications on an architecture student project. The designer K.K. Howorko, wanted to investigate the effect of tilting the south facade to optimise the interior climate.

The building is positioned next to the River Seine in Paris, with its south facade facing the river. It is designed to reactivate the area acting as a public indoor leisure space. It’s spaces are underlining the relation of leisure with water, with spaces that create diverse experiences of water and light.

The massing consisted of two building volumes, positioned side by side, in which the solar radiation was used in two different ways. In the eastern volume the designer wanted to maximize solar load, also during summer, as the sun rays would be used to cause evaporation to the water situated exactly behind the facade causing evaporative cooling.

In the western volume on the other hand, the designer wanted to research the effect of tilting the facade to minimize cooling demand without affecting the benefits of solar radiation for heating demand reduction. While tilting towards the south seemed reasonable some quantification of the effect could prove useful when presenting the project, in order to support the gestures.

To research this, it was considered adequate to take into account only the difference in solar gains inside the building and not the difference in costs (due to a larger area of the facade when tilted, more structurally challenging) or even the difference that the change would make in the actual heating and cooling demand.
This was because the application just needed a brief support of the massing gestures and not a calculation of energy demand values.

To investigate that, an example Grasshopper file, which has all the connections ready was used. Thus the designer only had to input the urban context of the leisure centre, the weather data file for Paris and the massing to get the first feedback on the estimated heating and cooling demand.

Then the designer could start tweaking the parameters of the file, settling for values that seem reasonable for the specific design. For example, for this design the glass percentage differed largely in the different facades, which meant that the solar gains component had to be used two times, one for the radiation on the closed facades (setting a very low glass percentage) and one for the radiation on curtain wall facade towards the south (with a very high glass percentage).

For the U-value estimation a specific tool, under the tab “Utilities” of the MEOtoolbox, can be used, setting the glass percentage of the whole envelope close to 40%.

When all parameters where plausibly set, the designer could experiment
with different tilting towards the north and the south. The effect of the tilting of the facades in the solar gains of the building during the year can be seen in the following graphs.

The effect of tilting towards the south is proved to be very positive as the decrease in solar load during summer is around 50% while in winter, when the solar gains are desirable, the decrease is less than 20%.

![Figure 5.3 Comparison of annual Solar Gains (in Wh) through the south facade when this is tilted and straight](image)

In the eastern volume on the other hand the solar gains are increased by rotating the facade towards the sky. This is desirable for the specific room, as it will cause evaporation of the water which is adjacent to the facade and will also increase daylight. In this space, additionally, external shading was added that can decrease solar loads in case they are beyond the desired point.
It is important to note that the massing gestures performed for this project where multiple while the scripts and tools generated for this thesis could only address a small part of them. For example the design also generated form in order to guide the views of visitors in certain directions, maximize infiltration through the inclination of the green roof, avoid inundation through lifting the geometry in pilotis etc. In the annex C more insight will be given to the specific additional parameters that formed the massing of this design, according to the architect.

It could be a future field of extension of the research to aim to analyse and facilitate the optimization of all of these gestures through computational tools.

Figure 5.4 Comparison of annual Solar Gains (in Wh) through the south facade when this is tilted and straight
5.2 Case Study 2: Highrise massing optimization

As a second case study a recent group design project of the author was used. The design project was concerning a highrise mixed-use building hosting among other functions the new European Union offices and dwellings. The design was an interdisciplinary group work by the author and Wouter van der Linde, Jouke Lughtendorf, Thao Le and Walter Woodington.

Since the author was mainly responsible for the architectural design, along with Thao Le, the main massing dilemmas faced during the design process can be described, along with the criteria which determined the decisions made. Then, with the use of the scripts produced for this thesis, possible alternatives for the massing will be tested to see if the massing of the design, shown in the pictures below could be optimized further, without sacrificing it’s basic design concepts.

Figure 5.5 Render of the European Union highrise design by A.Christodoulou, T.Le, W. Woodington, J. Lughtendorf, W. van der Linde. Render by A. Christodoulou.

In different phases of the design, the design process could have benefited from feedback from the parametric scripts of this thesis. These phases will be described in chronological order in the following paragraphs.
**PHASE 1: BRAINSTORMING PROCESS**

During the initial brainstorming process different massing designs were tested in order to serve the objectives that the design group wanted to achieve through the highrise design.

![Massing Process Diagram]

*Figure 5.6 Massing Process for two alternative massing designs during the brainstorming session of the Highrise workshop.*

Various other massing designs were produced at this stage, the selection
among which was done intuitively. With the scripts of this thesis the different designs could be tested fast and specific potentials for each design might be discovered. For example the effect of self shading from the second design could have been optimized and compared to the first alternative design to find out if the extra structural costs could be reasoned through substantially optimized solar gains. What is more, the amount of GFA for each design, which was not always easy to calculate after every design gesture, would be automatically calculated by the scripts, if they were available at the time.

**Phase 2: Optimization Process**

Through various trial and error procedures, in order to make a highrise that would communicate its “vertical village” aspirations, the aforementioned massing process ended up in the designed form shown in the image below.

![Figure 5.7 Render of the European Union highrise design by A. Christodoulou, T. Le, W. Woodington, J. Loutgendorf, W. van der Linde. Render by A. Christodoulou and T. Le.](image)

Even when the basic dimensions and forms where decided, the design team faced difficult dilemmas that the software that was available at the time could not
readily solve. The effect of these decision on the heating and cooling demand could be strong arguments, given that the choices are limited to options that do not lead to significantly more structurally challenging solutions. Thus, to study how optimal the decisions taken have been, as far as heating and cooling demand is concerned, the following optimization system was used.

**PHASE 2.1: ORIENTATION STUDY**

The first of the design decisions, studied here, is the orientation of the building “blocks” of the upper levels. As is shown in the following site plan illustration, the road is not entirely parallel to the east-west axis. The design team was wondering if the effect of orienting the blocks of the upper part of the building exactly towards the south would be substantial or not. After all, due to the lack of available tools and time, the orientation of the road (Rue de la Loi) was kept for these blocks.
Using the scripts developed for this thesis, such questions can be answered quickly. The basic set-up of the middle tower was used consisting of the following geometry:

![Figure 5.10 Basic case study geometry. Isometric and top view. Gradient on facades indicates the surfaces with the most annual radiation per area (red).](image)

The data input that was given to perform the orientation study is shown on the following image:
Figure 5.11 Basic input on the Grasshopper assessment system.

The first three sliders determine the facade characteristics of the geometry. The glass transmittance is set to 40%, because of the fritting that had been used in the facades of the building. The U-value is set to 0.70 W/m²K, because of the use of double glass.

The “Brep” is where the input geometry of the previous image is set. The floor to floor height is set to 3.6m, which was the decided floor to floor height for the highrise. The vertical and the horizontal strips’ sliders refer to the number of vertical and horizontal divisions of the facades, for the solar radiation study. As discussed in the paragraph explaining how the solar radiation component works, the solar radiation component tests if a surface is shaded by testing if the centerpoint of a surface is shaded or not. Thus, for this geometry, a division into smaller surfaces is needed, to take into account that the facades are partly shaded by the geometry itself, especially during summer.

The U-value of the roofs and the ground was set to 0.19 W/m²K. The function of the upper blocks was residential. Intermittency was not taken into account, and there was no need to take into account shading from adjacent buildings as the highrise would be much higher than its surrounding buildings and the positioning was done in a way that the three designed towers would not shade each other. This is also the reason why the modelling of the tower can be simplified in the aforementioned basic geometry.
The results of the orientation study are shown in the following graph. There it can be seen that the effect of orientation in the heating demand is much less than for the cooling demand. The cooling demand for 30° (which was the final design choice) is 3% more than if the blocks would have been rotated to face south. This could have been useful information during the design of the building.

Figure 5.12 Orientation Study Graph

Also from this example, a very useful feature of fast parametric assessment is apparent: The design team can have an estimation of what effect the change of orientation could make on a geometry and can decide faster as to if this effect is substantial, in comparison to the aesthetic and structural benefits of keeping the orientation of the adjacent road (Rue de la Loi) on the upper blocks, like, for example, the fact that in that case the structural grid of the basement would be the same as in the upper blocks. On the imaginary scenario that this project would be referring to a real-life design of a highrise, the designers would have been able to reply to possible questions on the reasons for not rotating towards the south orientation, with a numerical reply, showing graphically that the effect of changing the orientation was
studied and was not found to be substantial for this particular geometry.

**PHASE 2: OPTIMIZATION PROCESS: SHIFT DIRECTION STUDY**

Another question that the design team faced on the final days of the design had been the block shift direction. Although the dimensions of the blocks and the facade characteristics had been decided, the shift direction had not been established according to a certain design criteria. In the end the design team decided to shift the blocks so as to expose more the designed garden terraces towards the south.

![Figure 5.13 Garden terrace render (Render by A.Christodoulou and T.Le)](image)

Below, five shift alternatives were tested with regards to the heating and cooling demand to see how their values would be affected by the shifting of the blocks. The basic input of the model for the orientation study was used also for this study while the blocks were orientated towards the south.

In the graphs of the following page, it can be seen that the effect on the cooling demand is larger than the effect on the heating demand. This is logical because the shifts towards the south shade a great percentage of the facade during the summer, when the cooling demand is mainly occurring. On winter the sun is lower
and thus the facades are shaded much less because of the block shifts, resulting in only slightly larger heating demand. This can also be seen on the monthly demand graphs were the two most extreme cases are compared. The heating demand lines are almost indiscernible from each other, while the monthly cooling demand differs substantially, for the two massings, especially during spring.

Figure 5.14 Annual Heating and Cooling Demand of five design alternatives.
Figure 5.15 Monthly Heating and cooling demand for design alternatives A and E.

The important benefits of shifting the blocks further towards the south could
have been an argument for the design team to consider, maybe, also the 7.2m shift. It would be interesting to see if it would have been substantially more structurally demanding than the 3.6m shift that was chosen after all, given that the core was positioned in such a way that the eccentricity loads would negate each other.

Useful as these tools have been to address the design dilemmas in this case study, an important shortcoming was also evident. The results proved to be sensitive to the number of division on the surfaces, which might lead the inexperienced user of the tools in wrong decisions that would not take into account the effect of self-shading. For example dividing the surface in only 2 or 4 subsurfaces did not show the effect of the self-shading in the solar load. On the other hand after a certain point of divisions the result was almost the same. This kind of try-outs are essential to find out the least amount of surface subdivision that gives valid results.

5.3. Typology study

The use of the scripts and tools developed for this thesis allows the comparison of typologies per location. Six building typologies will be compared, using different systems and inputs. The analysis systems will expand gradually, taking into account more and more parameters.

Through this study the effect of the changing inputs and systems into the ranking of the massings will be studied.

The basic typologies compared will be the same as the ones used in the previous chapter (paragraph 4.2). The results will be presented through dotted line graphs and stacked area graphs, to attempt to visualize how the values change as the massings evolve from one typology to the next, as a “Warehouse” becomes a “Cube” and then a “Tower” and as a “Caterpillar” becomes a “Fence” that becomes “Slab”. The massings were divided like this in order for the inbetween massings to be easily imaginable. For example between the “Cube” and the “Tower”, one can imagine the massing becoming gradually thinner and taller.
The second set of massings ("Caterpillar", "Fence", "Slab") has massings with more clear orientation with the largest areas of the building envelope facing the north and the south. The "Cube" and the "Tower" have equal facades towards north, south, west and east.

With the above assumptions the analysis will try to respond to a number of research questions and see the effect of changing a single parameter, while keeping other parameters constant.

Additional insight on the typology’s study’s calculation methods and results can be found in the graphs, tables and explanation of Annex E.

1. **Solar effect**

The first question that was studied had to do with the effect of solar gains on the thermal analysis, depending on the typology:

**What is the effect of taking into account solar gains through the facades in the ranking of the massings with regards to their heating and cooling de-**
The heating and cooling demand of the six typology study massings was compared in the previous chapter (paragraph 4.2), in order to compare the results to the study of Andy van den Dobbelsteen and thus validate this thesis scripts and tools heating and cooling demand results.

In the figure 4.15, it was shown that the massing with the least facades, the “Cube” is expected to have less heating and cooling demand if the solar gains are not taken into account.

The analysis system for the question is the following:

Figure 5.17 Analysis system used to investigate the effect of solar gains in the ranking of the typology study massings’ heating and cooling demand.

The relevant input that was given to the above analysis system, is the following.
1. Weather data for Amsterdam, Netherlands.
2. U-value for the whole building envelope: 0.69W/m²K.
3. Office function.
4. COP$_{heating}$ = 4.
5. COP$_{cooling}$ = 2.
6. Normal weight construction: 165,000J/m²K.
7. No intermittence for heating and cooling.
8. Glass percentage on roof: 0%.
9. Glass percentage on facades: 80%.

Input values 4 to 8 will be constant throughout the rest of the analysis. Input values 1, 2, 3 and 9 will be changing. Their values will be always written at the bottom left of the graphs. In this first initial step, the glass transmittance through the facades was switched from 0% (in order to ignore solar gains) to 61%.

Figure 5.18 Screenshot from the analysis script in Grasshopper. The six typologies are input as the geometry (“Brep”) for analysis.

The following figure shows how the massings ranking of expected heating and cooling demand changes if solar gains through the facades are taken into account.
A first conclusion from the above graph can be that the ranking of the massings changes drastically taking into account the solar gains, especially with such high glass percentage on the facades. Especially on the Caterpillar to Fence to Slab line graph, the ranking is actually inverse.

Also the magnitude of the ratio of heating & cooling demands between different massings can be very drastically changed by taking into account solar loads. For example the “Tower” considered only 10% more heating and cooling energy demanding without taking into account the solar load, is demanding 150% more energy for the same use with the input mentioned above.

Another observation is that with this input, the heating and cooling demand increases with the increase of facade area. The typologies with more facade and less roof, are increasing their heating and cooling demand when solar gains are taken into account, while the opposite happens for typologies with more roof area (caterpillar, warehouse). This happens because in the parametric model, the facade is modelled to feature glazing in 80% of it’s area, while the roof is modelled to have no glazing percentage.

Thus a useful conclusion from this, is that for climates similar to the Neth-

---

75 In graphs like this one, it should be noted that for each colour line the cube reference value is different. That is because for these graphs, the interrelation between the geometries is what is mainly demonstrated. The absolute values of the results of these analyses are given in the energy breakdown graphs of this chapter and on the graphs and tables of annex E.
erlands, solar gains up to a certain limit are beneficial, reducing the heating demand more than they are increasing the cooling demand.

2. HEATING AND COOLING FLUCTUATION EFFECT

This leads us to wonder how do the values of heating and cooling change for the different typologies, which will be addressed on research question 2:

How do cooling and heating demands fluctuate for the different typologies? How do they relate to the total annual energy demand of each typology?

Figure 5.20 Analysis system used to investigate the fluctuation of heating and cooling demand and their relation to the total energy demand.
To respond to this question the analysis system is expanded to take into account the total energy demand.

The relevant input that was given to the analysis system, shown in the figure above, can be found again at the bottom left of the graph\textsuperscript{76}.

![Figure 5.21 Stacked Graph showing the comparison of the six typologies expected total energy demand.\textsuperscript{77}](image)

The graph above is confirming the last conclusion of the previous question. Indeed the increased solar gains of typologies with more facade area, and thus more glass, increase the cooling demand more than they decrease heating, resulting to much higher expected energy demands.

Up to now, the whole building envelope is considered to have the same U-value throughout, whose value was determined to 0.69W/m\(^2\)K, in order for the facade losses to be equal to the ventilation losses, which were already determined by the ISO standard ventilation rate per function. On the other hand, in the previous example, we assumed solar gains from the facade and no solar gains from the roof (where glass percentage was assumed zero). This would mean that the roof area would probably have a better insulation value than the facades, especially in con-

\textsuperscript{76} This does not apply for the coefficients of performance for heating and for cooling, the normal weight of construction, the intermittence for heating and cooling and glass percentage on the roof, which, as stated in the first comparison of this chapter (5.3), will be steady throughout the typology study.

\textsuperscript{77} In these graphs, “operational” is the sum of electric demand from lighting and appliances, as taken from the function data component, in the output electricity use per area, multiplied by the area. It could be also named electricity, which would also not be a satisfying one-word description, as the cooling demand could also be an electricity demand. For these reasons this explanatory note is added.
temporary construction, where regulations demand a roof U-value of 0.14W/m²K. Thus, the typologies with more roof and less facade, like the “warehouse”, should be considered to have better insulation properties than the typologies with less roof and more facade (like the “tower”). This applies especially in cases where facades are considered to have large glass percentage and the glass has significantly lower insulation properties than the wall.78

3. The U-value Effect

The effect of having a different U-value input for the roofs and the facades, will be studied in the next research question.

How much does taking a different U-value for the glazed facades and unglazed roof influence the heating and cooling typology study?

The results of the study for two different U-values for the building envelope’s surfaces are shown in the graphs below:

Figure 5.22 Stacked Graph showing the comparison of the energy breakdown of the six typologies ex-

78 It should be noted that contemporary glass technologies, currently developed, decrease the distance between the U-value of glass and wall through concepts like the triple glass, low-e coatings and special infills in the cavities between the glass panes, like Argon, Krypton and Sulfur hexafluoride.
pected total energy demand with a uniform U-value for the building envelope.\textsuperscript{79}

![Figure 5.23 Stacked Graph showing the comparison of the energy breakdown of the six typologies expected total energy demand with a different U-value for facades and roof/base.\textsuperscript{81}](image)

Keeping all the parameters of the last analysis constant, the procedure was repeated, with the only change being that this time the U-value of the roof and the base was set to 0.14 W/m\textsuperscript{2}K and the U-value of the facades 0.59 W/m\textsuperscript{2}K, in order for it to correspond to a glass percentage of 80%, if the U-value of the glass is taken 0.7 W/m\textsuperscript{2}K and the U-value of the wall 0.14 W/m\textsuperscript{2}K.

As expected, the improved U-value given to all the typologies reduced their heating demand significantly. On the other hand the cooling demand slightly increases with better insulation, due to the fact that the internal and solar gains can escape the building envelope easier if it is less insulated. The effect of insulation in the summer energy performance of buildings has been outlined in various studies like, for example, the one by Chvatal and Corvazo on their study on the “The impact of envelope insulation and ventilation on summer performance”\textsuperscript{82}.

Another notable result is that the differences between the typologies, as far

\textsuperscript{79} The parameters in bold letters in the bottom left of the graphs will refer to the parameters that are changing between two graphs, while normal weight letters are used for parameters that are constant between the two graphs.
\textsuperscript{80} See footnote 77, for explanation on operational definition for these graphs.
\textsuperscript{81} See footnote 77, for explanation on operational definition for these graphs.
as the heating demand is concerned, are now almost negligible. That is because, the positive effect of increased solar loads for heating, of typologies with larger facade areas, is balanced by the fact that the insulation of these typologies’ envelope is now considered worse. That is because they have less roof and base areas (which are considered to have good insulation properties due to their lack of glass) and more facade areas (which are considered to have worse insulation properties due to the high percentage of glass\(^{83}\)).

In the following graph, the typology comparison for uniform U-value and for different U-value for the horizontal and the vertical surfaces of the building envelope can be seen:

![Graph showing the differentiation of the ratio of heating and cooling demand for two different assumptions for the U-value of the building envelope.](image)

As expected, the warehouse seems to benefit most from the assumption of different U-values for the horizontal and the vertical surfaces, having the largest horizontal surfaces.

This graph shows that the assumption is important, as it does not affect all typologies in the same way. For this reason, the assumption of different U-values for the horizontal and the vertical surfaces will be used in the rest of the analysis.

The next research question will investigate if also different programmatic functions affect in different ways the typologies.

\(^{83}\) At this point a high percentage of glass was used to demonstrate the maximum effect of using different U-value for the facade and roof and base.
4. The Program Function Effect

How much does taking the ISO standard values for dwellings instead of offices, influences the typologies’ study?

The program function affects both the internal loads for the massing but also it’s ventilation rate and the operational and hot water demand.

Figure 5.25 Stacked Graph showing the comparison of the six typologies expected total energy demand taking office and residential program function for the massings.84

84 See footnote 77, for explanation on operational definition for these graphs.
Overall, for the above settings, offices seem to have generally larger energy demand, for all the geometries. This is mainly because of the significantly larger operational demand standard value proposed by the ISO standard for offices, as well as the larger internal gains leading to a larger cooling demand.
The graphs show that, in contrary to the diverse effect that the U-value has to the different typologies, the program function does not prove equally diverse. That is because the program-related values are per GFA and since all the typologies have equal GFA, overall effect is similar to all the typologies. This is why from now on, the program function will be taken as constant, choosing the function of offices from the two previous functions.
5. Orientation Effect

The aspect of orientation, arguably the most common energy optimization concept will be studied in the following research question:

What is the effect of non-optimal orientation (for example north-south instead of east-west) in the ranking of the typologies, with regards to the energy demand per Gross Floor Area?
The figure 5.28 shows that the ranking of the massings does not change, significantly.

The total energy demand of the “Tower” for the assumptions made above is calculated to have almost double total energy demand for the same amount of GFA, than the “Warehouse”, which seems up to now to be the most energy efficient solution. On the other hand the Warehouse has least area. On the other hand using the simplified Net floor area for the typologies as explained in paragraph 4.2, it can be studied, if this is also true when the Energy demand is divided with the NFA, instead of the GFA. This will be the subject of the next research question.

6. GFA/NFA effect

How much does the typology ranking change by dividing the total energy demand with the NFA of each typology?

Dividing the energy demand is a way to take into account both space efficiency and energy demand of the typologies. It also makes sense because it will demonstrate with which typology we will achieve the lowest energy demand per rentable space.

Dividing the energy demand with the NFA of table 4.1. is bound to favor the typologies of the “Tower”, the “Fence”, the “Slab” and the “Caterpillar”, as they have all of their area within small length from the facade, contrary to the “Warehouse” and the “Cube”.
Indeed that is the case. Dividing the with the NFA instead of the GFA, changes a lot the ranking of the massings, making the “Tower” and the “Warehouse” be the equally “bad” options, and making the “Caterpillar”, the “Fence” and even the “Slab” be better options from the reference geometry (the “Cube”). That is, of course, because the “Tower”, the “Caterpillar”, the “Fence” and the “Slab” are divided by a larger number, featuring more NFA within their building envelope.

This is a very important conclusion: Massings that are not so space efficient might appear to be energy efficient, but dividing energy demand with the rentable area might show that they are less favourable design options.

For this reason in the following research questions both the Energy/GFA and the Energy/NFA will be visualized while varying the glass percentage and the location of the massings.

### 7. Glass Percentage Effect

The following research question will try to demonstrate the effect of changing the glass percentage on the facades of the massings to their ranking. This will prove that the facade can have a great effect on the ranking of the massings, especially when comparing the energy over Net Floor Area ratio of the six typologies.
What is the effect of changing the glass percentage on the facades of the typologies, in their energy per area ranking and in their total energy demand?

The following line and stacked graphs give interesting results in this question, providing, absolute and relative values of energy demand per GFA and NFA for each typology.
Figure 5.32 Line Graph showing the ratio of the total energy demand per area over the energy demand of the reference geometry (“Cube”), for three different glass percentages on the facades.
Figure 5.33 Stack Graph showing the fluctuation of the energy demands of the typologies for three different glass percentages on the vertical surfaces (facades). See footnote 77, for explanation on operational definition for these graphs.
Figure 5.34 Point Graph showing the differentiation of the energy demand per NFA depending on the Glass Percentage and the typology.

The graphs above show that for low glass percentages, the differences between the expected energy demands of the massings are small.

As glass percentage rises, so does also the importance of massing. With a facade glass percentage of 80%, the total energy demand per area can be almost 40% less: Through the MEOtoolbox script, the annual energy demand of the “Tower” was calculated 249KWh/m² while the one of the “Caterpillar” 152KWh/m².86

86 These values are both per GFA and per NFA since these two values are the same for these two typology massings (see Table 4.1).
This means that one can have the same amount of square meters of Gross and Net floor area, but be paying 40% less in energy with the “Caterpillar” option. This is so, because one the Tower has maximum facades taking in solar gains through the glass while the “Caterpillar” has two of the “Towers” facades “blocked” from solar radiation through the roof and the ground.

It is of course true that not both options are always possible and desirable, for example because of the lack of area on the ground floor. On the other hand, towers are built also in places without great congestion in the ground floor, for example in countries like Qatar and Dubai.

Up to now the analysis has been done using the weather file for the Netherlands. In order to see how the typologies rank in different climates and what is the ratio between the different energy demands in these climates, four different climate files will be used.

8. Location effect

In order to investigate the effect of the location the following research question was addressed:

**How do the typologies rank, with regards to their energy demand per area and in total energy demand, in different climates?**

In order to be able to see how the typologies rank in different locations the weather data files of Amsterdam(NL), Athens(GR), Quebec(CA) and Abu Dhabi(UAE) were downloaded from the website of the USA’s Energy Department (Energy.gov).

Athens was chosen as a city with warmer average temperatures than Amsterdam, Quebec as a city with even colder average temperatures in winter, and Abu Dhabi as an even warmer city than Athens.

The monthly average temperatures for the four locations are shown in the following line graph.
Figure 5.35 Average monthly temperatures of the four cities studied. Data from the weather data file downloaded through the Energy.gov website and used in the parametric script.

The results of the analysis for the different locations are shown in the line, stacked and point graphs that follow:

Figure 5.36 Line Graph showing the ratio of the total energy demand per area over the energy demand of the reference geometry (“Cube”) for the typologies in Amsterdam.
Figure 5.37 Line Graph showing the ratio of the total energy demand per area over the energy demand of the reference geometry (“Cube”) for the typologies in Athens, Quebec and Abu Dhabi.
Figure 5.38 Stack Graph showing the fluctuation of the energy demands of the typologies for Amsterdam and Athens.\textsuperscript{87}

\textsuperscript{87} See footnote 77, for explanation on operational definition for these graphs.
Figure 5.39 Stack Graph showing the fluctuation of the energy demands of the typologies for Quebec and Abu Dhabi. See footnote 77, for explanation on operational definition for these graphs.
Figure 5.40 Point Graph showing the differentiation of the energy demand per GFA depending on the location and the typology.
Figure 5.41 Point Graph showing the differentiation of the energy demand per NFA depending on the location and the typology.

In the graphs above very interesting observations can be done. In the warm climates of Abu Dhabi and Athens, heating and cooling demand seem to be insignificant for all the climates. Of course this is not true for Athens: From personal experience, it can be verified that heating is needed during winter. But it is needed in buildings with deep facades and balconies over the glass exterior, which are traditionally built like this, in order to block summer sun.
Typologies like the ones studied in this typology study, with no external shading and no balconies are highly unsuitable for this climate, increasing very much the cooling demand in summer. So it might be the case for this kind of offices with this kind of facades to indeed have only cooling demands in these climates.

Another interesting observation is the following: Despite the fact that Abu Dhabi has much higher total energy demand than Athens in all typologies because of the higher temperatures, the ratio of energy demands between the different typologies is almost identical. Similarly, despite the fact that Quebec has much colder winters and thus higher total energy demand than Amsterdam the energy ratio be-
between the typologies is again almost identical. It seems that the effect of temperature gets eliminated when one typology’s energy demand is divided by another typologies energy demand. The only thing that seems to determine the ratio between the typologies’ energy demand, is the ratio between heating and cooling demand. Further study would be needed to verify this claim.

9. **Embodied Energy Effect**

The final step of the typology study will extend the analysis system, in order to take into account the embodied energy of the building typologies.

The typologies are expected to have different embodied energy, given their different height, envelope area and ratio of horizontal over vertical envelope surfaces.

The embodied energy is calculated through the Material Data component for facades, roofs and floors while for columns beams and wind bracing the table of Smith & Coull will be used, as found on their book “Tall Building Structures: Analysis and Design”89 (see chapter 3).

![Embodied Energy Graph](image)

*Figure 5.43 Embodied Energy of the typologies calculated through the parametric script of this thesis.*

The methods for calculating the embodied energy of the typologies where validated on chapter 4 by comparing the results of the MEOtoolbox to the results of the study by Andy van den Dobbelsteen on the same building typology geometries.

---

In this step the following questions will be replied.

**What is the ratio between expected operational and embodied energy for the different typologies?**

**After how many years of operational energy does embodied energy lose form-influencing significance?**

**Figure 5.44 Extended analysis system to take into account also embodied CO₂ emissions.**
In this step the following questions will be replied. What is the ratio between expected operational and embodied energy for the different typologies? After how many years of operational energy does embodied energy lose form-influencing significance?

Figure 5.44 Extended analysis system to take into account also embodied CO$_2$ emissions.

Figure 5.45 Stacked graph showing the embodied energy compared to the operational energy of 1, 10 and 50 years. In these graphs the operational energy is the sum of heating, cooling, hot water, appliances...
In the graphs above it can be seen that first of all, embodied energy and operational energy are not always considerations leading towards the same optimal massings. The embodied energy of the “Cube” seems to be the lowest in embodied energy, due to it’s compactness, while the Warehouse is the least energy demanding design solution.

Another interesting result is that the embodied energy CO$_2$ emissions more or less corresponds to 10 years of operational energy emissions, which gives an intuitive figure as to their ratio.

The final observation is that the embodied energy CO$_2$ emissions seem to lose form-influencing significance after 50 years of operation. In the graph of 50 years the difference in embodied energy is almost indiscernible.

This analysis might provide a good way of determining which of the two, the embodied or the operational energy, should be a higher design priority in the massing considerations, depending on the years that the project is expected to be functional.

10. Overview

The different cases taken for the typology study and corresponding energy demand per GFA and NFA, will be presented in the following two point graphs. These graphs give the maximum insight on the comparative effects of each parameter. Through these graphs it can be observed that location and glass percentage influence more the absolute value than orientation and program function.

Also it can be observed that space efficiency can severely change the ranking and the energy demand ratio between the typologies, followed by the effect that the glass percentage can have in this ranking and ratio.

In comparison to these effects, the effect of orientation seems to be much less substantial as is also the change from office to residential function. It should be noted though, that the change of location is hardly ever changeable (although some designs do get repeated in various locations), while also typology cannot be changed in most design cases. Thus the effect of smaller impact parameters should not be overlooked.

and lighting demand, as shown on the analysis system of figure 5.44.
11. Further research of the typology study

The above analysis could be extended almost endlessly. The complexity of building and the technologies that could be applied in the system could change the optimal typologies for a specific location.

A simple example would be to imagine how different the above results would be if the facades had also a PV percentage, that would generate electricity through the facades. In this way, the solar load would not only be a burden, increa-
Figure 5.47 Point Graph showing the differentiation of the energy demand per NFA depending on the typology, for all the different cases studied.

Sing cooling demands disproportionately to the decrease of heating demands, but also a source of energy.

Also if an external shading was modelled on the facades in order to block summer sun but allow winter sun, solar gains and thus facade area could also become again a positive feature.

A research into such detail into the effect of facade differentiation in the energy performance of a building would extend further than the scope of this thesis.
6. DISCUSSION

In this chapter the main findings of the research will be discussed.
6.1 Analysis system discussion

This thesis has used the following values as fitness values for the assessment of massing designs:
- solar gains,
- annual heating and cooling demand,
- annual total energy demand per GFA,
- annual total energy demand per NFA, and
- embodied + operational (1, 10, 50 years).

The change of the aforementioned objectives gradually increased the number of parameters that had to be taken into account, which might in turn have diminished the precision of the resulting values (through the use of rules of thumb).

For example, the floor and roof embodied CO$_2$ was considered proportional to the respective square metres, besides the fact that the height of the building has possibly influence in the actual embodied CO$_2$ of these elements.

Thus it is suggested that the choice of the optimization fitness value should depend on the main design dilemma, which will determine if it is a plausible choice to extend the optimization system into more complex and computationally demanding systems, with the reduction of precision inherent to the use of generic rules of thumb that might be used in that case.

It should be noted that this suggestion is given taking into account the computational capacities of the average contemporary computer, but it can be imagined that soon these will be enlarged greatly, taking into account the current rate of technological progression in this field. In that case, having large assessment systems of adequate precision might not be very demanding for computers and could be used in all cases for informative reasons. Of course the designer will always be able to choose the parameter that he wants to demonstrate in each case, but it might be the fastest option, to have one large parametric script to calculate the most common assessment values, instead of modifying the script according to the specific assessment value that is relevant to a specific design.

6.2 Development discussion

A new toolbox that facilitates the energy optimization of massing design has
been developed for this thesis. This toolbox has been used in the initial design phase massing dilemmas of the case studies and the typology research of this thesis. In the case studies the tools have been proved particularly useful. The results for these applications have been validated beforehand through cross referencing results, relevant to these applications, with results provided from other software.

Although some of the scripts and tools of this thesis were developed in order to be distributed through the internet at the end of this thesis, the fact is that they have not yet been validated or tested in applications other than the case studies of this thesis. How the case study chapters corresponded to the validation chapters is shown in the figure 2.6. What is more, the tools have not been tested by other users besides it’s developer.

Thus, the MEOtoolbox should be considered still as a work in progress that will benefit greatly from feedback from it’s first users, and of course from more case studies. In the initial phase, the user will be advised to cross-check his results with other similar software, especially when using the solar radiation tool, whose results differ from other relevant software on this challenging issue, although not more than the results of the other two tools differ from one another, as shown in the validation chapter.

It might be the case that many features could be improved, in the way the MEOtoolbox script is structured as well. For example, issues that might need improvement are the following: Firstly, the results, that the MEOtoolbox provides, seem to be accurate as numerical values, while they often have used standard design input values (per function), that cannot justify such numerical precision. In this thesis, this obstacle has not been an issue, as the writer knew exactly the methods through which the results have been produced and for this reason the results have been presented mainly by percentages, or by point dots of considerable size in dotted line graphs, to communicate the roughness of the estimations provided. A user that will not read through the manual of the toolbox, might not be aware of this fact, and rely on the exact numerical values more than needed.

Another consideration has to do with the way data is given from one component to the next. Actually, one of the considerations during this thesis was before the dilemma to make or not custom input/output data types or use the data types that Grasshopper provides. This means, for example, that, instead of inputting number lists in the heating demand component, we would input data of “Monthly Energy
 Transfer” type, comprising of a list of twelve numbers which would be an output of the facade and ventilation heat transfer and the solar and interior gains components and scripts.

This choice might offer benefits and especially robustness to the script, as input that would not be of the required type (“Monthly Energy Transfer”) would not be accepted from the “Heating Demand” component, for example. But the biggest benefit would be that, from a software architecture point of view, having different data types might allow a gradual implementation of more characteristics in the data contained. For example the numerical data might carry also information on the accuracy of the numerical data provided, information on the methods used etc.

On the other hand, the shortcoming of custom data type input/outputs is that they would restrict partially the flexibility to use data from other components, software or databases. In the above example of the Heating Demand, the case might be that the designer might want to calculate the solar gains through an alternative software, for example Ladybug. This feature is essential especially in the first phase of the development, when the results using different sources will be cross-referenced.

Possible ways to improve the above issues will be discussed in the “Recommendations” chapter.

6.3 Case studies discussion

The effects of tilting a south-facing facade have been studied. The study has proved that tilting a south facade downwards, for the climate of Paris, can reduce solar loads to half, while keeping a large part of the solar loads during winter (when they are needed, in order to reduce heating demand). This way, through the self-shading effect, tilting could be used as an alternative to external shading, as far as energy is concerned. Tilting a south-facing facade upwards, in the same climate, has the inverse effect, increasing more the solar loads in summer than in winter.

For the climate of Brussels the orientation of a cubic massing geometry design was studied to see the effect of orientating the cubes of the highrise tower perfectly towards the south, or following the angle of the adjacent road of the design assignment (rue de la Loi, Brussels, BE). This study showed that the effect of the orientation of the cube in an angle less than 10° away from the East-West axis does
not increase significantly the heating and the cooling demand (less than 1%). These results would have made the choice of the design team to follow the axis of the road more robust, if such a tool had been available, as the design team would have been able to respond to any questions concerning this decision. The same study showed that the maximum effect that orientation could have, for the particular design geometry, was 5% in the annual cooling demand and 1% in the annual heating demand.

The effect of shifting, in order to increase the self-shading effect in the building geometries, was studied and proved to be an effective way of reducing cooling demand, without increasing greatly the heating demand. The study showed that the decision made by the design team, for a 3.6m shift of the upper block towards the south, thus shading the block below, mainly during the summer, reduced significantly the cooling demand (4%), while not affecting largely the heating demand (less than 0.5% more). The shift study showed that an even bigger shift would also be very positive, reducing cooling demand to as much as 7% without increasing heating demand more than 1%.

An additional benefit of the use of parametric software in the design process is the ability to produce visualizations, that show the comparative effect of design options, which can be used in the presentation and argumentation of the design.

On the other hand, current shortcomings of the use of parametric software in the massing design process were found to be the following: Firstly, the multiplicity of parameters, that the designer might have as objectives, was proved to be far more than the objectives that the present parametric software could assess at the time, through the developed tools. For example no parametric tools were available at the time, that would be able to assess values for views, inundation avoidance, water infiltration and more. Another important shortcoming is the considerable sensitivity of the result in some of the input parameters, most notably in the number of divisions of a surface. A designer might get wrong feedback if he doesn’t divide the surface enough. This feature is an important shortcoming that needs to be addressed.

### 6.4 Typology study discussion

On the typology study the following results can be highlighted:

For all the typologies studied, with the absence of external shading and for
the glass percentages studied, cooling demand seems to be more critical for the determination of optimal energy massing, due to it’s greater fluctuation depending on the typology.

As far as the absolute energy demand values are concerned, location seems to be the most largely influencing parameter, followed by glass percentage. Orientation and programmatic function seem to have much less influence on the absolute value of the energy demand of the typologies.

As far as the ratio between the typologies is concerned, the switch of the assessment value from Energy per GFA to Energy per NFA, strongly influences the energy demand per area ratio between the typologies, as spaces with less rentable space often seem to be good energy solutions. Minimizing the expected Energy/NFA gives different results than Energy/GFA, taking into account also space efficiency. Since NFA is usually a primary goal for construction and real-estate companies, it is a realistic aim to try to minimize energy costs to cover a specific programmatic NFA demand. Location also influences largely the ratio between typologies, which seems to be similar in locations with similar ratio between the needs in heating and cooling.

The typology study showed that the energy per NFA can be reduced in the magnitude of 40% by selecting an optimal typology for the climate of the Netherlands.

For the climate of Amsterdam, and for the characteristics for facade and structure employed for the analysis, embodied energy seems to correspond, roughly, to 10 years of operational energy for all of the typologies. The fact that this was the result for all the typologies studied, suggests that it could potentially be used as a rule of thumb, when assessing the importance of embodied energy for a specific project, depending on it’s expected functional lifetime.

Nonetheless, the aforementioned results of the typology study where made under various simplifications and assumptions, which will be discussed below.

Firstly, the typologies inherently represent simplifications of actual buildings. For example for the “Warehouse” typology, one would imagine that since it has so many dark areas, the roof of such a building would be opened up at some point to let in a bit more daylight.

Apart from this kind of simplifications, on the analysis of facade and structure embodied energy and costs, vast simplification and rules of thumb have been
used, as explained in the “Development” chapter.

What is more, the typology comparison was found to be very sensitive to the solar gains of the geometries. This makes it possible that the effect of facade external shading might change very much the ratio between the typologies.

Taking into account other systems and concepts, like heat recovery and natural ventilation, could also considerably affect the ranking of the typologies. Also, this rating could be affected if the electricity demand was not considered proportional to the GFA, as suggested from the standard design values of the ISO13790 annex, but would vary depending on the massing. Nonetheless, the effect of having deep floor plans in certain typologies was, indeed, taken into account into the Energy demand per NFA comparisons, making these options the worst design options for this objective.

The parameters that were considered constant throughout the analysis, like for example the average heat capacity per area or the coefficient of performance for heating and cooling, might have an effect on the conclusions of the thesis. For example the effect of changing the coefficient of performance for cooling or the effect of having analysing the typologies as lightweight constructions might reduce the possibly slightly disproportionate impact of cooling demand in the results.

Finally, in the embodied CO₂ comparison, the tower was often shown as the worst option. Nonetheless, the positive environmental effect of the reduced footprint of the tower typologies cannot be easily translated into CO₂ reduction. This feature might possibly improve the ranking of a tower in relation to the other typologies.
7. CONCLUSIONS

This chapter will highlight what can be concluded by this thesis research.
The main conclusions of the thesis are the following:

- The optimization system used per design should be selected carefully, depending on a design’s objectives, due to precision and computational speed considerations for larger optimization systems.
- The potential for parametric optimization tools, in the initial (massing) building design phase can be possibly considered reaffirmed by the use of the developed tools in the design case studies.
- An important advance of parametric design tools is that, through the aforementioned or similar tools, the effect of shifting and rotating of design geometries or tilting facade surfaces can be rapidly assessed, for a specific location, within the initial design process.
- An observed additional benefit of the use of parametric tools was the possibility to produce visual/graphic argumentation for a design while currently present shortcomings are:
  a) the sensitivity of the results to certain inputs and
  b) the lack of tools that could complement the full extent of the parameters considered in the design phase by architects.
- In the typology study and the case studies conducted, cooling demand was found to be more critical than heating, in the optimal form determination, as it fluctuated in a larger extent, depending on the massing.
- In the typology study, the location and the facade glass percentage were found to influence the absolute value of the energy demand per area more than orientation and programmatic function.
- Glass percentage and space efficiency considerations, were found to be more influential than orientation, programmatic function and location in the ranking of typologies, according to their energy performance.
- The choice of building typology was found to be able to influence largely the amount of energy per NFA needed (to the extent of 40%).
- Finally a rough parity of embodied energy to ten years of operational energy, regardless of the typology, was observed.
8. RECOMMENDATIONS

In this chapter, possible ways to address issues discussed in chapter 6, will be suggested.
8.1 Analysis system recommendations

The massing optimization research that took place attempted massing optimizations through smaller optimization systems addressing mainly energy performance issues or larger systems addressing objectives like the overall embodied CO2 emissions per area by including structural, facade additionally to the operational energy cost.

In the larger optimization systems the precision of the input was diminished through the application of generic techniques, for example by taking a generic rule of thumb for the amount of steel per area depending on the amount of floors, thus not being able to extend the research within more complex massings. What is more the application of these larger systems was restricted in more conservative designs as the imprecision of structure costs, for more structurally challenging designs, would be too big not to take into account.

It can be imagined though that the possibilities for improvement are great and could happen for example with additions in the system like the following:

- A parametric algorithm that would generate structure given the challenges of the massing (cantilevers, bridges etc).
- A parametric algorithm that would show how objective values, like the cost, embodied and operational energy are affected by the type of facade used.
- All elements used on the facade and the structure could be connected to internet databases, which would provide the current price, precise characteristics, embodied CO2 etc. of all the products that are currently available.

The research done for this thesis, is actually part of a larger research, on the development of a platform that will be developed towards the direction of large parametric optimization systems and design tools, through a design framework called “SustainabilityOpen”, as envisioned and currently programmed by the BEMNext lab of TU Delft.
The SustainabilityOpen aims to connect different design algorithms (for structure, facade, massing etc) into one Design which will inherit properties from the separate components. These properties will be fed into analysis components for values that the designer will want to take into account in the design.

Figure 8.2 Possible future redesign of the framework: Different designers feeding into one “Design”, that is fed to different analysis components.

Source: http://www.sustainability-open.com
The assessment can take into account diverse analysis values and could attempt to optimise a design through a fitness value that could be for example a weighted average of the analysis values generated in the analysis step.

The creation of a platform that could operate on designs and massings of any form, is a great challenge for the framework. The ability to generate analysis values for any massing that a design team might have generated, through parametric tools or through traditional architectural methods, without difficult and time consuming handling needed, is crucial for the success of the SustainabilityOpen framework as a design tool.

**8.2 Development recommendations**

As stated on the previous chapter, the software developed should be considered as work in progress, as it’s applications and validation has not extended in more cases than the ones presented on this thesis. What is more, they have not been used by users, other than their developer.

Some of the points to improve the issues discussed on the previous chapter would be the following:

To overcome the issue of precision of the given results, a solution might be to redevelop the tools so as to provide results only in relation to other design possibilities and give percentage results instead of energy result outputs.

The custom data type possibility, discussed on the previous chapter, could be explored further, to see if, in practice, the flexibility in inputting data from various sources is needed, especially after the initial testing period, or if, on the other hand, the custom data types would help users understand better the source of the data that they have to input into each component, making it easier to reach valid results.

**8.3 Case study recommendations**

As explained also on the previous chapter, a central concern of the thesis was not to extend applications much further than areas whose accuracy had been tested. This is why, although the tools and scripts can analyse more complex massings, the applications did not include such massings. An exciting prospect for the
continuation of this research would be to extend further into more and more complex massings, always hand in hand with validating the results, through other software. It might be the case that, after the tools are released, such studies could take place by other users of the tools as well.

Another interesting prospect would be to investigate case studies, where adjacent building shading, plays a particularly important role, which was not the case in the two case studies analysed.

8.4 Typology study extension

The typology study could be extended in many possible ways some of which were also discussed in the end of the previous chapter. Seeing that the effect of shading and facade characteristics can have a big effect in the energy performance makes it interesting to see how the results of this study would change with different shading devices in front of the facades.

Also other assumptions of this research could be challenged, like for example the fact that the MEOtoolbox did not differentiate the operational demand depending on the floor depth from the facade of each typology, using just a standard value per area taken from the Annex of the ISO13790. Also the coefficient of performance for heating and cooling, as well as the average heat capacity per area could be changed in future extension of this research.

The most interesting extension of the study would be to take into account more elaborate methods for calculating structural demand, facade and floors embodied energy and costs, as discussed also in the first paragraph of this chapter. Also interesting would be to repeat the study, taking into account the positive environmental impact of the reduced footprint of a “tower” typology and of systems like heat recovery, natural ventilation and others.

Finally an interesting prospect would be to input and compare geometries closer to the actual typologies, with their specific characteristics for external shading, structural material and system, embodied CO₂ per area etc.
BIBLIOGRAPHY

Alexandros Christodoulou - Parametric Massing Optimization Tools

- MobileReference, Bilbao Sights: a travel guide to the top thirty attractions in Bilbao, Basque Country, Spain, MobileReference.
- Pevsner, N. & Games, S., 2002. Pevsner on art and architecture: the radio talks, Methuen.
Wiley.

(page intentionally left blank)
APPENDIX

Annex A: Manual / Setting up a simple massing energy assessment model

The MEO toolbox provides a variety of tools that can be used for various aims as explained in the development chapters. Some tools can be used separately (for example the two massing components) while others are very closely interrelated (for example the Solar radiation component to the Solar load component).

As explained in the methodology chapter, designers might want to use different values of interest as fitness values for their systems, which would mean that they would have to transform the script to include the relevant parameters.

This chapter will give a detailed description of a possible workflow to set up a basic model.

1. Opening the software

1.1 Open Rhinoceros 5.0.

2. Importing the urban context

2.1 Draw or import the urban context of the building in Rhino.

3. Forming and analysing the Massing

3.1 Open the “Massing M” component from the “Massing” tab.
3.2 Input numeric sliders with the desired values for Program m² and Floor Height.
3.3 Draw the desired perimeter within the limits of the site plan.
3.4 Repeat for as many massing volumes as needed.
3.5 Use the Massing Analysis component to the total massing (which might be a union of geometries made in the previous steps). This component divides the massing into horizontal (roofs) and non-horizontal (facades) surfaces. It also calculates the GFA of the massing.

4. Facade Heat Transfer Calculation

4.1 Open Facade Heat Transfer Component from the “Energy Analysis” tab.
4.2 Input the facades of the massing (from step 3.5), an estimation of the average U-value of the building, the set temperature for heating and cooling, the monthly outdoor temperatures and the days of the months of the year. The simplest way to input this data is to insert manually the values from statistical data from a reliable source.
source, to the component input. For a more automatic procedure the values could be referenced from an Excel sheet or using freely available external plug-ins that import weather data values into the Grasshopper user interface.

4.3 The facade heat transfer for the 12 months of the year for heating and cooling calculation is calculated through the component.

5. Ventilation Heat Transfer Calculation

5.1 Open the Ventilation Heat Transfer Component from the “Energy Analysis” tab.
5.2 Input the Massing (as a “BRep” or “Boundary Representation”), the average weekly ventilation and the set-point and average temperatures also used for the previous component.
5.3 The ventilation heat transfer for the 12 months of the year for heating and cooling calculation is calculated through the components.

6. Internal Heat Gains Calculation

6.1 Open the “Function Data” component from the “Utilities” tab.
6.2 Set the function input to “Residential” (as a text).
6.3 Get the monthly average Wh/m² of internal gains (as a list of 12 numerical values).
6.4 Multiply with the GFA (step 3.5).
6.5 Get the total average monthly internal heat gains.

7. Solar Radiation Calculation

7.1 Open the “Solar Radiation” component from the “Radiation” tab.
7.2 Make the potentially shading adjacent buildings as Breps. (The “Massing H” component can be used to quickly create the volumes).
7.3 Input at the “Potentially Shading Breps” input, the potentially shading adjacent buildings created at the previous step (7.2) as well as the massing itself as created at step 1 (also the office tower).
7.4 This component needs information on the sun positions and the Direct and the diffuse radiation of the area. (Various components are available that produce these values. The writer usually used the components by Mikael Nilsson and Arend van
The solar path should be the average solar path for each month, thus 24 sun positions for each month. This is because the solar load component that is used afterwards, multiplies afterwards the average solar day to the number of days of each month.)

7.5 The average monthly day of direct normal radiation and diffuse horizontal radiation (again 24 numbers for each month) also has to be provided. The user can find this in various places or use freely available external plug-ins that provide these values from the weather data files of .epw format.

7.6 Using the partition component of Grasshopper, the results can be transformed to a 12 lists of the 24 numbers of the average radiation day in order to be input into the solar load component.

8. Solar Load Calculation

8.1 The result of step 7.6 is input into this component that multiplies each average radiation day with the number of days of each month and multiplies with the glass transmittance and the glass percentage for the facade.

9. Calculating the Heating Demand

8.1 Open the “Heating Demand” component from the “Assessment” tab
8.2 Input the facade heat transfer from step 4.3.
8.3 Input the ventilation heat transfer from step 5.3.
8.4 Input the internal heat gains from step 6.5.
8.5 Input the solar heat gains from step 8.1.
8.6 Input the area of heat capacity layers with the GFA (step 3.5).
8.7 Input the $H_t$ and $H_v$ output from the Facade and Ventilation Heat Transfer Components.
8.5 The annual Heating Demand is calculated by adding up the 12 monthly heating demand calculations.
In a similar way the Cooling Demand can also be calculated. The great advantage of going through this process, is that once it is done the designer can experiment with different architectural gestures and see the effect on the heating and cooling demand without any additional work.
Annex B: Implementation background

THE .NET FRAMEWORK

The .NET framework is a programming platform, developed by Microsoft, to address the growing challenges of modern distributed computer environment, consisting of devices (such as computers, pads and cellular phones), connected through a network. This framework provides a platform that allows different programming languages, like C++, VB.Net and C# to communicate.

Figure A.3 .NET Framework Architecture visualization

BRIEF HISTORY OF PROGRAMMING

C# is one of the languages of the .NET framework using the Object-Oriented programming paradigm. To explain the concept of Object-oriented programming a brief history of programming will be presented, based on the book Object-Oriented Programming: Fundamentals And Applications, written by Probal Sengupta & Bidyut Baran Chaudhuri.

In the beginning of the use of computation, programmers used to load to a machine it’s specific set of instructions. This proved to be troublesome, due to the amount of different machines by the same company that had to be loaded with different memories.

For this reason assembly languages were used, which used text to represent memory locations and instructions. Although this solved the problem partly, still, programming scripts had to be machine specific.

High level languages like FORTRAN, C and COBOL, solved in a great effect the problem of machine specific programming. These languages used compilers to translate to the machine the programming script. Since then, high level languages have evolved to allow programmers to use modules and libraries and thus not have to build a code from scratch.

**OBJECT ORIENTED PROGRAMMING**

In large programming projects the concept of an “object” was used, to improve the management of these modules. Objects, are concise parts of code, consisting of properties, to be filled in and procedures, to be carried out. The properties are usually called “Structure” and the procedures “Methods” or “Behaviour”.

Through object-oriented programming objects can inherit the “structure” and “methods” of a “parent object”. Then the designer can override any part of these attributes that he wishes to alter.
Annex C: Paris leisure centre case study additional information

In this annex additional insight will be given into the different massing defining parameters of the first case study presented in the application chapter. The multiplicity of parameters will be described, also to demonstrate possible future areas where similar research, to the one of this thesis, could aim towards.

According to the architect of the project and the visualization presented in the following figure, the articulation of the spaces was done in order to:

1. Raise the building through columns, in order to minimize the danger of flooding.
2. Distinguish two parts: active and passive.
3. Tilt the roof to collect and filter rain water through the green roof.
4. Mark the entrance.
5. Turn towards the river to guide the eye towards it.
6. Turn towards the bridge to lead the eye towards it.
7. Floating Part - extension of the program with the possibility of transportation.
8. Different tilting of facades in the active and the passive part:
   • a) Tilt downwards to block the summer sun, while keeping a large part of the solar gains to reduce heating demand in winter, while
   • b) Tilt upwards to maximize water evaporation in the “Lac of milles reflects”.

Future parametric tools could try to address also the objectives behind gestures 1 to 7, in order for the building design to achieve the efficiently in the maximum possible level.
Tilt inwards to block summer sun, let winter sun in

Tilt roof inwards to gather rainwater and infiltrate it through the green roof

Lift to avoid inundation danger

Rotate facade towards the bridge to guide the eye towards it

Split to active and passive part

Lift to avoid inundation danger

Rotate facade towards the river to guide the eye towards it

Tilt inwards to block summer sun, let winter sun in

Figure A.4. Massing gesture reasoning for the design of the Paris leisure centre.
Tilt facades to maximize benefits from solar energy

Tilt outwards to let winter sun in and also summer sun in to activate an evaporative cooling mechanism through the pool situated next to the facade

Tilt to mark the entrance

Floating part

Split to active and passive part

Rotate facade towards the bridge to guide the eye towards it

Lift to avoid inundation danger

Tilt roof inwards to gather through the green roof

Tilt facades to maximize benefits from solar energy
Annex D: Detailed results of validation, excel sheets of validation of the solar load component

This chapter will provide more insight on the calculations taking place within the script, showing in more detail how the results were validated through comparison with the ISO standard’s Annex J worked example.

The results below refer to the geometry presented in paragraph 4.1.2, where a less extensive demonstration of the validation process was provided. This worked example is concerning a west oriented room with facade area of 10.08m², glazing area of 7.0m², floor area of 19.8m² in Paris, France.

![Geometry of the worked example of the ISO13790 Annex](image)

First of all the facade and ventilation comparison of the ISO 13790 standard’s annex J worked example monthly results, to the results of the MEOtoolbox respective components will be presented.

On the facade heat transfer, as explained at the specific component’s description, the formula used, in order to calculate the monthly heat transfer, is the following:

\[
Q_{\text{fac.loss}} = \sum (U A) (T_i - T_e) h \quad \text{(Wh)} \quad (3.1)
\]

According to the example, the heat transfer coefficient by transmission, \(H_{n,adj}\), of the construction adjacent to the external environment is 18.2 W/K, which
corresponds to a U-value of 1.81W/m²K. The external facade area of the room is 10.08m². $T_i$ differs for heating and cooling which is why two different results are provided by the facade heat transfer component, one for heating and one for cooling demand calculation. $T_i$ for heating is set to 20°C and $T_i$ for cooling is set to 26°C. The monthly temperature file of Paris was provided by the worked example annex and was the following:

- January: 3.2°C,
- February: 4.8°C,
- March: 6.3°C,
- April: 7.8°C,
- May: 13.0°C,
- June: 15.4°C,
- July: 18.3°C,
- August: 17.0°C,
- September: 14.9°C,
- October: 10.1°C,
- November: 5.4°C,
- December: 4.2°C.

These outdoor temperatures were input as a list in the facade heat transfer (as the $T_e$ of the above formula). The component calculates by itself the hours of each month (h in the above formula).

Doing the above calculation for the twelve different outdoor temperatures the results were the ones presented on the graph (blue bars) and the table below.

As it can be seen in the two graphs, most months give the same numeric result and the slight differences that occur in some months are less than 0.5%, probably having to do with the decimal number rounding up during the two calculations.
Figure A.6 Comparative bar charts and tables showing the results of the MEOtoolbox facade heat transfer component, in comparison to the ISO standard worked example monthly results.
The same procedure was repeated to compare the results of the MEOtoolbox ventilation heat transfer component. The formula as presented in the ventilation heat transfer description is the following:

\[ Q_{\text{ven.loss}} = \rho c_{\text{air}} Q (T_i - T_e) h \] (Wh) (3.2)

\( \rho c_{\text{air}} \) is set 1200J/m\(^3\)K and the ventilation rate is set to 0.417 h\(^{-1}\) to take into account that the ventilation rate of 1.0 h\(^{-1}\) is present at a fraction of 0.417 of the week hours.

\( T_i, T_e \) and \( h \) are set in identical ways to the facade heat transfer calculations presented before.

The resulting comparison of the ventilation heat transfer calculated through the components and the ISO annex worked example can be seen in the bar graphs and the tables below.

**MEO/ISO ventilation Heat Transfer comparison for Heating Demand Calculation (Paris)**

![Bar chart showing MEO and ISO ventilation heat transfer comparison](image)

<table>
<thead>
<tr>
<th>Total Monthly Ventilation Heat Transfer (KWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>MEO Heating (KWh)</td>
</tr>
<tr>
<td>ISO Heating (KWh)</td>
</tr>
</tbody>
</table>

Figure A.7 Comparative bar chart and table showing the results of the MEOtoolbox ventilation heat transfer component, in comparison to the ISO13790 standard’s annex J worked example monthly results for heating demand calculation.
As is visible in these tables the results are identical with the exception, of the April calculation featuring a 1KWh difference probably due to decimal rounding up differences in the two calculations.

Through the above methods it can be considered that the components produce valid results, calculating very precisely the values of the ISO standard annex worked example’s results.

The interior gains that are calculated by multiplying the function data component’s total interior gain output (which gives the standard design values for interior gains provided by the respective annex of the ISO13790), with the area of the room (19.8m²). The interior gains calculated in this way are compared to the ISO13790 worked example annex values in the bar graph and the table below.

![MEO/ISO ventilation heat transfer comparison for Cooling Demand Calculation (Paris)](chart.png)
Figure A.9 Comparative bar chart and table showing the results of the MEOtoolbox interior gains component, in comparison to the ISO13790 standard’s annex J worked example monthly results.

The solar gains on the other hand were calculated using different calculation methods in comparison to the ISO 13790, as the results for the radiation on a west facing facade were presented in the ISO’s Annex J, without explaining the way the results were produced. As stated in the report (paragraph 3.5.2.3), the formulas to calculate solar radiation are different to the ISO 13790 standard’s values, as these refer only to horizontal and vertical facades, thus not serving to the scope of this thesis to investigate the effect of various massing gestures like tilting etc.

The formulas through which this component produces its values were shown in the solar radiation and the solar load component paragraph (3.5.2.3) and are repeated below:

Direct radiation: \( B = I \left( \cos \beta \sin \gamma + \sin \beta \cos \gamma \cos(\alpha - \psi) \right) \)

Diffuse radiation: \( D = 0.5 \left( 1 + \cos \beta \right) D \)
Total radiation: $G_s = B_s + D_s$

All three produce results in Wh/m². The solar components produce results in Wh because they multiply also with the area of each input surface.

The results from the solar radiation component was also input to the solar load component, were the glass percentage ($(7.08 / 10.08) \times 100\%$) and the glass transmission value (0.2), as determined by the worked example.

As it can be understood from the equations above, the solar load does not only depend on the geometric position of the surface and the sun, but also on the hourly direct radiation at each sun position (symbolized with $I$ in the above equation). The weather data file for radiation thus plays an important role in the result, which is most probably the reason why the results differed for the two calculation methods.

**MEO/ISO solar gain comparison (Paris)**

![Graph showing MEO/ISO solar gain comparison](image)

Figure A.10 Comparative bar chart and table showing the results of the MEOtoolbox solar radiation + solar load component, in comparison to the ISO13790 standard’s annex J worked example monthly solar load results.

As stated also in the validation chapter the result of this difference in the an-
Annual heating demand is less than 3% difference. (571KWh if calculated through the MEOtoolbox’s component in comparison to 586KWh heating demand calculated in the ISO13790 annex J).

Figure A.11 Comparative bar chart and table showing the results of the MEOtoolbox heating demand component (using solar input from the ISO and from the MEOtoolbox components), in comparison to the ISO13790 standard’s annex J worked example monthly solar load results.

Beyond showing the effect of taking different solar loads in the total heating demand the above graph validates the results of the Heating demand component, showing that the calculation of heating demand is the same for the ISO and the MEOtoolbox if the solar load of the ISO annex J is used as input.

The only difference occurs in the months of April May and October, because the annex example did not include the calculation of the heating season percentage, according to the ISO 13790 paragraph 7.4, describing how to correct values according to the fraction of the month that should be included in the heating season. This...
was verified because the results for these months were identical before the inclusion of this paragraph to the C# script of the heating demand component.

The formulas through which the heating demand is calculated within the heating demand component were presented in the heating demand component. The heating demand is calculated through subtracting from the heat losses a percentage of the heat gains: \( Q = Q_L - \eta Q_G \). The utilization factor’s calculation is a complex process taking into account also the width and the area of the heat capacity components.

In the heating demand calculation component, the inputs apart from the gains and losses shown in the previous steps where, the internal capacity per area 355,000 J/m²K as in the annex J and the intermittency percentage of 0.3, also same as in the annex.

The \( H_t \) and \( H_v \) outputs are provided already from the Facade and Ventilation Heat Transfer components.

The same procedure took place for the cooling demand, only inputting the cooling demand outputs of the facade and ventilation heat transfer components, and that the intermittency percentage for cooling was 0.7, same as in the annex J of the ISO13790 standard.

The ISO results and the results of the MEOtoolbox, by taking for solar load a) the results from the ISO annex J example and b) the results from the MEOtoolbox solar load, are shown in the following figure. This comparison shows that the cooling demand component is again calculating very close results to the ISO results, with the differences being due to the inclusion of paragraph 7.4 of the ISO 13790 standard. (As was verified in the same way as for the heating demand component.)

The difference of calculating the cooling demand by inputting the values of the MEOtoolbox and the ISO solar radiation results of annex J is larger mainly on the month of August, resulting in a total difference of 8%. 211KWh total cooling demand according to the ISO standard’s worked example, 194KWh total cooling demand by using the MEOtoolbox’s solar load component.
Based on these results, the user can decide if he will consider them satisfactory. For the initial uses of the tools, the user is advised to cross-reference the results with other available tools. In case there is another available tool that according to his own judgement is more reliable in the solar load calculation, he can easily input the monthly solar gains calculated through the other component to the heating and cooling demand components of the MEOtoolbox.
Annex E: Detailed results of typology studies

In this annex, more insight will be given to the results presented on the applications chapter of the report. Since this thesis was dealing with the initial design phase, the results were provided mainly in graphs, as the exact values are not so much of interest, and might be misleading with regards to the analysis’ precision, since it is featuring rules of thumbs and standard conservative design values (for example, for the calculation of interior gains).

For the reproductability of the typology study’s research, the exact values given by this thesis’ Grasshopper script, are provided in this annex. It should be noted that the precision of the values should be considered, as for example the standard design values for internal loads or appliances demand cannot be considered to be very precise, based only on the programmatic function that is taking place there.

The script through which the results are provided is shown in the end of the development chapter (paragraph 3.8), while the steps through which the script calculates the results were explained on the previous annex.

Thus in this chapter only the extra assumptions used at each case, along with the numerical results that the script provided, will be presented. The initial input values for the system

1. Climate data for Amsterdam,
2. U-value for the whole building envelope: 0.69W/m²K
3. Office function
4. $\text{COP}_{\text{heating}} = 4$
5. $\text{COP}_{\text{cooling}} = 2$
6. Normal weight construction: 165.000J/m²K
7. No intermittence for heating and cooling
8. Glass percentage on roof: 0%
9. Glass percentage on facades: 80%

In the initial step of the typology study the solar transmission through the facade (in the solar load component) was changed from 0% (in order not to have solar loads, as was the case for Andy van den Dobbelsteen’s study) to 61%. The addition of heating and cooling demand for each typology can be seen in the graph
In the graph it is obvious that the Cooling demand increase, increases very much the expected heating and cooling demand. Of course it has to be noted that, the scenario of no solar gains is not possible and it is just a simplification, that is proved not to be always a conservative approach.

The second step of the research was the change from a uniform U-value for all the building envelope to a different U-value for the roof and base (0.14 W/m²K) and for the facade (depending on the glass percentage). The absolute values of the results that were presented and discussed in the applications chapter are shown in
the graph and table below.

![Comparative bar graphs showing the effect of facade U-value variation in the thermal analysis' results for the different typologies.](image)

<table>
<thead>
<tr>
<th></th>
<th>Heating and Cooling demand with Uniform U-value (MWh)</th>
<th>Heating and Cooling demand with different U-value for Roof and Base (MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse</td>
<td>301</td>
<td>249</td>
</tr>
<tr>
<td>Cube</td>
<td>344</td>
<td>336</td>
</tr>
<tr>
<td>Tower</td>
<td>681</td>
<td>687</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>361</td>
<td>354</td>
</tr>
<tr>
<td>Fence</td>
<td>402</td>
<td>385</td>
</tr>
<tr>
<td>Slab</td>
<td>481</td>
<td>483</td>
</tr>
</tbody>
</table>

Figure A.14 Comparative bar graphs showing the effect of facade U-value variation in the thermal analysis' results for the different typologies.

The absolute values for the rest of the cases can be found on the graphs below, giving the total energy demand per GFA (the first one) and per NFA (the second graph). The specifications of each case presented are the following:

**Case 1:**
- Climate: Amsterdam, Netherlands
- Glass percentage: 30%
- U-value roof and basement: 0.14W/m²K
• U-value facade: 0.3
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office

Case 2:
• Climate: Amsterdam, Netherlands
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office

Case 3:
• Climate: Amsterdam, Netherlands
• Glass percentage: 80%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.59
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office

Case 4:
• Climate: Amsterdam, Netherlands
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Residential

Case 5:
• Climate: Amsterdam, Netherlands
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to south-north axis
• Program function: Office

Case 6:
• Climate: Athens, Greece
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office

Case 7:
• Climate: Quebec, Canada
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office

Case 7:
• Climate: Abu Dhabi, United Arab Emirates
• Glass percentage: 50%
• U-value roof and basement: 0.14W/m²K
• U-value facade: 0.42
• Glass transmittance: 0.61
• Orientation: Long facade parallel to east-west axis
• Program function: Office
Figure A.15 Point graph showing the energy demand per GFA (in kWh/m²) for the different typologies and the different analysis cases.
Figure A.16 Point graph showing the energy demand per NFA (in kWh/m²) for the different typologies and the different analysis cases.
After analysing these cases, the study proceeded to a calculation of the embodied energy of the typologies with the following specifications:

- floor height: 20 cm
- floor material: concrete
- roof height: 30 cm
- roof material: concrete
- basement height: 30 cm
- basement material: concrete
- CO₂ per m² of wall with U-value of 0.15: 70kgCO₂/m²
- glass percentage: 50% glass
- GFA: 3456 m²

For the embodied CO₂ of glass and concrete per square meter, the values were taken from the material data component, which uses the values from the inventory of Carbon Energy of the University of Bath\(^\text{95}\).

The calculation for floors roof and basement used the following formula:

\[
(\text{Embodied CO}_2 \text{ of floors + roof + basement}) = (\text{Embodied CO}_2 \text{ concrete per kg}) \times (\text{Density}) \times [(\text{GFA}) \times (\text{Floor width}) + (\text{basement square meters}) \times (\text{basement width}) + (\text{roof square meters}) \times (\text{roof width})]
\]

with the Embodied CO₂ per kg being 0.202kgCO₂/kg and the density of reinforced concrete 2300kg/m³.

For the amount of CO₂ for structural elements, the equation (3.9) is used, as presented on chapter 3, which gives the amount of steel in kilograms depending on the amount GFA and the amount of floors. These are 3 for the warehouse and the caterpillar typologies, 6 for the cube and the fence, 12 for the slab and 24 for the tower. This equation does take into account the increased steel needed for bracing depending on the height of the building. The amount of embodied energy for columns, beams and bracing is then multiplied by the Embodied CO₂ per kilogram (1.77 kgCO₂/kg).

\(^{95}\) Available at: http://web.mit.edu/2.813/www/readings/ICE.pdf
For the amount of embodied CO$_2$ in the facade the glass percentage is multiplied to the total facade area and then to the embodied CO$_2$ per square per kg (0.85kgCO$_2$/kg) and the density of glass (2600kg/m$^3$). The rest of the facade ($(1$-$\text{glass percentage})$ of facade area) is multiplied to the embodied CO$_2$ per m$^2$ of wall with U-value of 0.15: 70kgCO$_2$/m$^2$. This value is taken of the Environmental design pocketbook of Pelsmakers, S$^{96}$.

The results using the values above, are shown in the graph and the table below:

![Embodied CO2 emissions graph](image)

<table>
<thead>
<tr>
<th></th>
<th>Embodied CO2 emissions (Tonnes CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steel Structure</strong></td>
<td>251 322 215 483</td>
</tr>
<tr>
<td><strong>Floor</strong></td>
<td>260 322 287 242</td>
</tr>
<tr>
<td><strong>Façade</strong></td>
<td>389 322 574 60</td>
</tr>
<tr>
<td><strong>Roof + Basement</strong></td>
<td>251 322 323 483</td>
</tr>
</tbody>
</table>

Figure A.17 Embodied CO$_2$ calculation for structure, floors, facade, roof and base of the typologies.

In the last step of the typology study, the sum of the embodied energy for each typology, is compared to the total operational CO$_2$ for 1, 10 and 50 years, for the typologies (using the resulting values of the case 2 presented above). The conversion of the total Energy demand to the total operational CO$_2$ is done using

the Energy Data component. The heating demand and the hot water demand are multiplied with the embodied energy per KWh of gas for non-industrial use (0.198 kgCO₂/KWh), while the cooling and the appliances electricity demand is multiplied to the embodied energy per KWh of electricity for non-industrial use (0.517 kgCO₂/KWh)

The 10 years total energy CO₂ is the multiplication of the above sum by 10, while the 50 years total energy CO₂ equals the multiplication of the above sum by 50. The resulting values can be seen in graph and the table below:

![Figure A.18 Comparison of embodied and operational energy for the typologies of this research.](image)

<table>
<thead>
<tr>
<th></th>
<th>Embodied Energy (tonnes CO2)</th>
<th>Annual Energy (tonnes CO2)</th>
<th>10 years Energy (tonnes CO2)</th>
<th>50 years Energy (tonnes CO2)</th>
<th>100 years Energy (tonnes CO2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warehouse</td>
<td>1271</td>
<td>84</td>
<td>838</td>
<td>4188</td>
<td>8376</td>
</tr>
<tr>
<td>Cube</td>
<td>1111</td>
<td>97</td>
<td>969</td>
<td>4843</td>
<td>9685</td>
</tr>
<tr>
<td>Tower</td>
<td>1345</td>
<td>150</td>
<td>1505</td>
<td>7524</td>
<td>15048</td>
</tr>
<tr>
<td>Caterpillar</td>
<td>1379</td>
<td>98</td>
<td>977</td>
<td>4887</td>
<td>9773</td>
</tr>
<tr>
<td>Fence</td>
<td>1182</td>
<td>106</td>
<td>1062</td>
<td>5309</td>
<td>10618</td>
</tr>
<tr>
<td>Slab</td>
<td>1240</td>
<td>122</td>
<td>1218</td>
<td>6091</td>
<td>12182</td>
</tr>
</tbody>
</table>

This thesis hopes to contribute to the process of making the future computational massing design an intuitive, fluent and hands-on procedure, through using the rapid innovation in the area of informatics and currently booming technologies like touch-pads and holograms. It is a strong personal belief that parametric assessment feedback can enhance the traditional processes and help in making better “informed”, more efficient and more exciting design choices possible.

Alex Christodoulou
MSc Building Engineering, TU Delft
S: AlexChristodoulou.tumblr.com
L: linkedin.com/in/achristodoulou
M: ChristodoulouAlexandros@gmail.com
T: +31615609173