Multi-objective optimization of external shading system using genetic algorithm based workflow to enhance energy efficiency of existing building envelope

By

Alkiviadis Oikonomidis

MSc Thesis

Master of Science
MSc Architecture, Urbanism and Building Sciences
Track: Building Technology

Graduation Thesis

How can a genetic algorithm based workflow be effectively employed in the multi-objective optimization of a shading system to improve the energy efficiency of an existing building envelope?

By

Alkiviadis Oikonomidis

Student Number: 5786746

in partial fulfilment of the requirements for the degree of

Master of Science
MSc Architecture, Urbanism and Building Sciences
Track: Building Technology

at the Delft University of Technology,
to be defended on Friday June 21, 2024

Supervisors/Mentors: Dr. S. (Simona) Bianchi,
Dr. C. (Charalampos) Andriotis

Thesis committee: Dr. S. (Simona) Bianchi
Dr. C. (Charalampos)
Andriotis Ir. M.J. de Haas

This report was developed for the purposes of the P5 presentation to be defended publicly on the 21st of June 2024 at 16.45.

Preface

In a period of escalating effects of climate change on the built environment, ensuring thermal resilience in buildings is of great importance. With the rise of extreme overheating events, there is critical need for robust strategies and designs to evaluate and enhance the performance of existing building envelopes. This research focuses on two main goals. The first one is to develop a workflow for supporting the design of a shading system as a measure to improve thermal resilience of a building against extreme overheating stresses by providing interdisciplinary feedback to a design team. The second one is to apply some of the state-of-the-art optimization methods for the design of this system with an integration to BIM. By integrating building performance analysis, data assessment, and BIM, this study seeks to support external shading systems design for retrofitting existing curtain wall systems.

This topic spans between different scientific disciplines including building physics, computational science, statistics, and building performance simulations. The main motivation of this research stems from a desire to evaluate and improve the thermal resilience of an existing building envelope and support the design of a retrofit solution during the preliminary design phase. The main goal is for the researcher to gain insights into the concepts of resilience, facade performance evaluation and to effectively communicate proposed designs for retrofitting an existing curtain wall system potentially improving the overall thermal resilence of a building.

Alkiviadis Oikonomidis
Delft, June 2024

Contents

Preface....4
Acknowledgements....6
1. Introduction....7
1.1 Background....7
1.2 Problem statement....8
1.2.1 Motivation....9
1.2.2 Research question and sub-questions....9
1.2.3 Objectives and Limitations....11
1.3 Research methodology....12
2. Literature Review....13
2.1 Background Research....13
2.1.1 Curtain wall and shading system types....13
2.1.2 Systems out of ETFE....20
2.1.3 Mechanical properties and main characteristics of ETFE systems....21
2.1.4 Thermal behavior and properties of ETFE systems....24
2.1.5 Part I concluding remarks....27
2.2 Resilience investigation....29
2.2.1 The term resilience....29
2.2.2 Resilience definition....30
2.2.3 Resilience quantification, phases and dimensions....31
2.2.4 Thermal resilience metrics....35
2.2.5 Part II concluding remarks....39
2.3 Computational methodology....40
2.3.1 Multi-Criteria Design Methods....41
2.3.2 Genetic algorithms....44
2.3.3 Part III concluding remarks....46
3. Case study Design – Scenario design....48
3.1 Location....48
3.1.1 Heatwaves in Europe and Athens....48
3.1.2 Weather data....50
3.2 Piraeus tower....54
3.2.1 Architectural and structural aspects....54
3.2.2 The proposed curtain wall system by Eckersley O' Callaghan....58
4. Digital Design Tool....65
4.1 BIM integration....65
4.2 Digital Design workflow....66
4.3 BIM workflow | Revit - Rhinoinside....68
4.4 Energy Simulation workflow....74
4.5 Shading System design and workflow....87
4.6 Static analysis workflow....93
4.7 Multi-Objective optimization & workflow....97
4.8 Results observation & their meaning....104
5. Discussion & Reflection....107
5.1 Summary....107
5.2 Discussion....109
5.2.1 Design proposal and energy aspects....109
5.2.2 Design proposal and structural aspects....117
5.3 Reflection....120
Bibliography....125
Appendix....128

Acknowledgements

Firstly, I would like to thank my mentors Simona Bianchi, and Charalampos Andriotis for their continuous and patient support throughout this research project. They both have heard my questions with patience and their guidance together with their valuable sub-questions and ideas helped me to develop this research. Moreover, I would like to express my sincere gratitude to my guest supervisor Maria Meizoso Aguilar. I am very grateful for her support to complete this thesis, the analysis concerning all the aspects of façade design and the valuable feedback she provided during this academic endeavour. Without the encouragement of my supervisors, I would never be able to complete this thesis as coherent and scientifically accurate as it managed to be.

I would like to thank Eckersley O Callaghan for granting me access to valuable drawings and information for such an important project as the Tower of Piraeus. The professionalism and quality of work shown by the material provided I hope that can also be seen through the output of this research. Particularly I am also grateful to Mrs. Anna Ioannidou-Kati for discussing together my master thesis and for additional feedback she provided especially in the beginning stages of this thesis.

Finally, I would like to thank my parents and my sister for their enormous and continuous help and support during the completion of my master studies in TU Delft. Without their support in almost all aspects I would never be able to realize things the way I do now. Their support and their constant motivation were an inspiration and gave me strength especially in periods of stress and disappointment. They have always been by my side and support me in every way. This research is the outcome of a combination of discussions, contributions, and support of all those mentioned above. For this reason, I am deeply grateful.

Delft, June 2024
Alkiviadis Oikonomidis

1. Introduction

1.1 Background

In an era of climate change energy crisis, interdisciplinary thinking is essential to developing innovative solutions to address these pressing global challenges. Thus, the building envelope is becoming more and more important in the built environment since it does not only divide the interior from the exterior conditions of a building, but it also becomes more technology oriented. Its performance in many aspects is reaching its limits. It becomes stronger, lighter, more adaptive, climate dependent and resistant. Even building envelopes that transfer data and behave based on this data are being investigated (adaptive systems). The design methodology of a curtain wall as well of its shading components are of great importance and a climate designer or façade engineer should be able to combine sustainability principles not only to form a design strategy (to consult design teams), but also to form feasible design solutions.

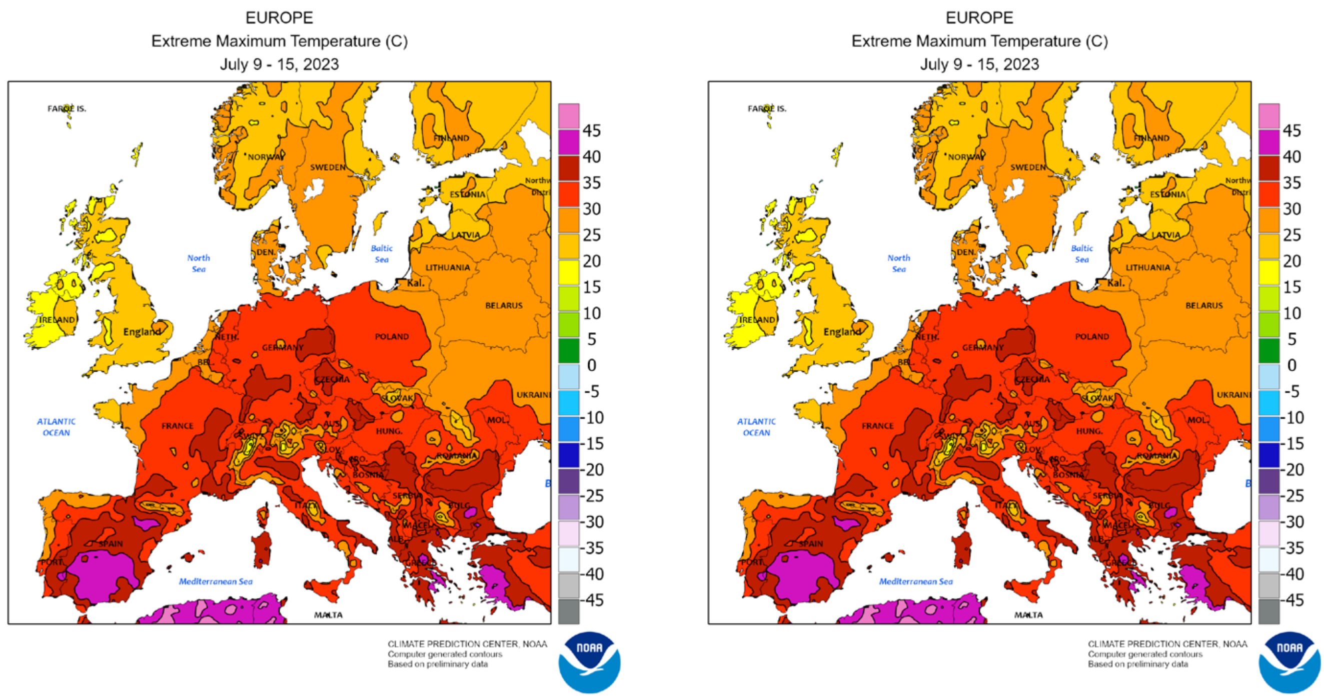


Figure. 1: Maximum air temperature maps of Europe
https://commons.wikimedia.org/wiki/Category:Maximum_air_temperature_maps_of_Europe

However, during a facade design or retrofit strategy definition, due to many different disciplines getting involved in the process, there is usually lack of communication concerning different aspects/criteria of facade design and of the relationships between them (see Figure 2). At the same time the need for retrofit design solutions that influence the behavior of existing building envelopes against rising temperatures is increasing, especially in hot climates where heatwaves and extreme hot temperatures occure with greater intensity and more often (see Figure 1).

Moreover, in the last couple of years computational design and AI have enabled new workflows and possibilities of design exploration, with respect to qualitive and quantitative criteria. Integration of generative computational tools usually in the early stages of design was a breakthrough for architects and engineers during the 2010's, allowing them to define parametric models and define optimal solutions where architectural concept, costs, sustainability, and efficiency goals are met.

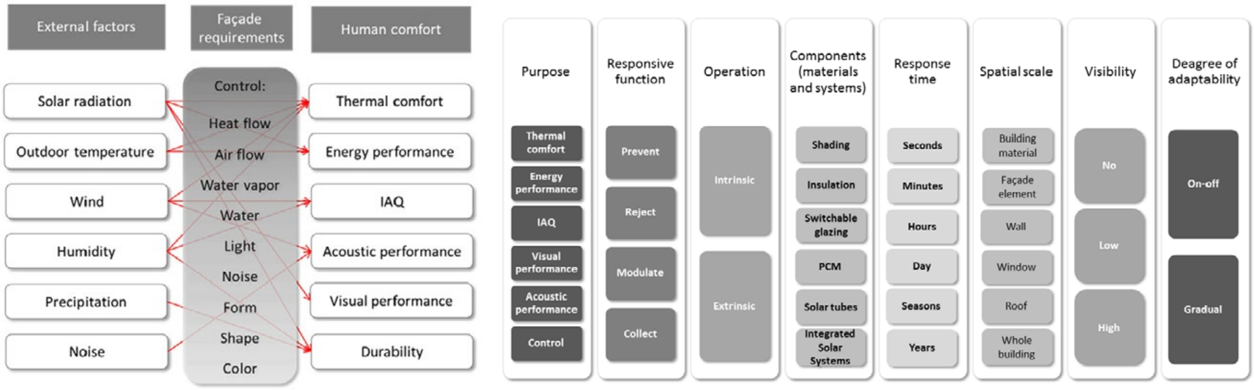


Figure. 2: Example of different façade properties in Façade design (Aelenei et al., 2016)

1.2 Problem statement

Considering the existing aging infrastructure left behind by previous generations and the increasingly hotter climates and hazardous phenomena, there seem to be two directions. The first one concerns new structures and building envelopes and their design. Engineers research and design new structures as efficient, durable, or adaptive as possible with the implementation of the sustainability goals and the R ladder in the design process (see Figure 3). The second direction concerns the existing infrastructure and the ways performance as well as carbon footprint of existing buildings can be improved.

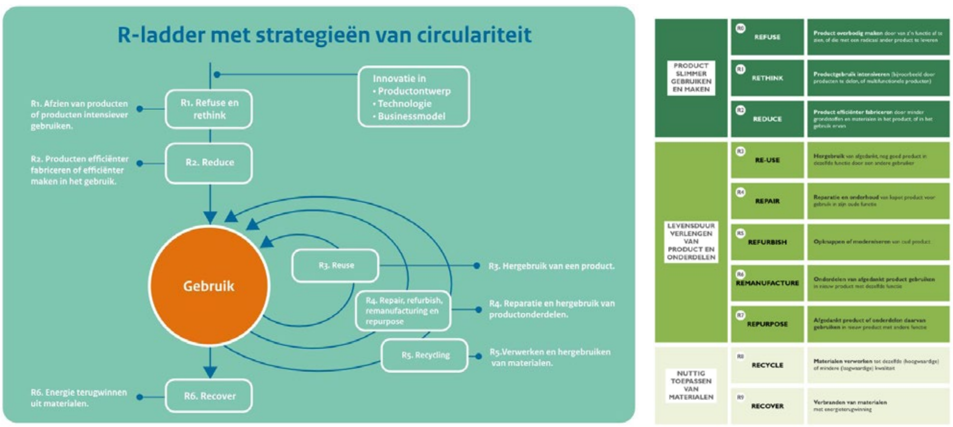


Figure. 3: R-Ladder
https://ikwilcirculairinkopen.nl/de-r-ladder-wat-is-het-en-wat-kun-je-ermee/

The design and optimization of a double skin façade was the original plan for this graduation topic. However, taking into consideration the fact that many buildings already exist and have a poor energy behavior, it is believed that a renovation and redesign of existing building envelopes is of much greater importance for the well-being of future generations and would thus contribute more to the EU sustainability goals. Goal number 11 states: "By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change, resilience to disasters, and develop and implement, in line with the Sendai Framework for Disaster Risk Reduction 2015-2030, holistic disaster risk management at all levels." ("The Sustainable Development Goals Report 2023: Special Edition," 2023)

Consequently, the appropriate design of new structures, if possible, out of recyclable materials to enhance the behavior of existing building envelopes not only combines the principles of climate design with architectural expression but can also contribute to ensure suitable conditions for future generations. Because these future generations will face problems that unfortunately cannot be resolved within a single generation.

A creation of a digital design tool for defining relationships between different properties of an existing building envelope and their conflicts and for supporting the preliminary design process of a retrofit shading system would contribute to these problems. A shading system as a structure could contribute to the improvement of an existing building's energy performance. At the same time communicating the various interrelations and conflicts between the envelope's properties would support a façade designer or façade design team to take the appropriate decisions for each unique project. An instant inter-discipline feedback during the design of a shading system could be possible with the integration of BIM and a designer would be able to generate the form and structure of a shading system based on pre-defined criteria and goals. Filtering out optimal solutions or families of solutions based on specific boundary conditions were also desired goals in this academic endeavor.

1.2.1 Motivation

Investigating state-of-the-art curtain wall and shading systems, the meaning of the term resilience as well as the impact of heatwaves on existing building envelopes, indoor thermal quality, and energy efficiency form the main motivation behind this research. Moreover, a desire to use current multi criteria optimization techniques and genetic algorithms based on building physics and structural engineering for preliminary design alternatives could be described as the second pilar of this investigation. Familiarizing with programming as well as applying energy simulation and optimization were also goals of this research.

1.2.2 Research question and sub-questions

In order for one to start a research, one needs to understand what he is about to investigate and the reasoning behind it. Part of the reasoning was presented in the previous two chapters. With the definition of a main research question, however, specific terms need to be used and connected in such a way in order for the end goals to be clear. In parallel the main question needs to be supported by sub-questions leading to a final answer or evaluation. While in previous chapters the goal was to answer the questions:

- What motivates this research?
- Who is the audience?
- What are the anticipated impacts and contributions?

In this part a more precise question is being defined which was formed during the preliminary literature review that was carried out from November 2023 until February 2024 and gradually evolved during this research. Therefore, the main research question is:

"How can a genetic algorithm based workflow be effectively employed in the multi-objective optimization of a shading system to improve the energy efficiency of an existing building envelope?"

Keywords: Genetic algorithm, multi-objective optimization, shading system, energy efficiency, thermal resilience, building envelope

In order for an answer to be formed a tree structure of research sub-questions is to be answered and separate literature research was carried out for each one of them. (See Figure 4)

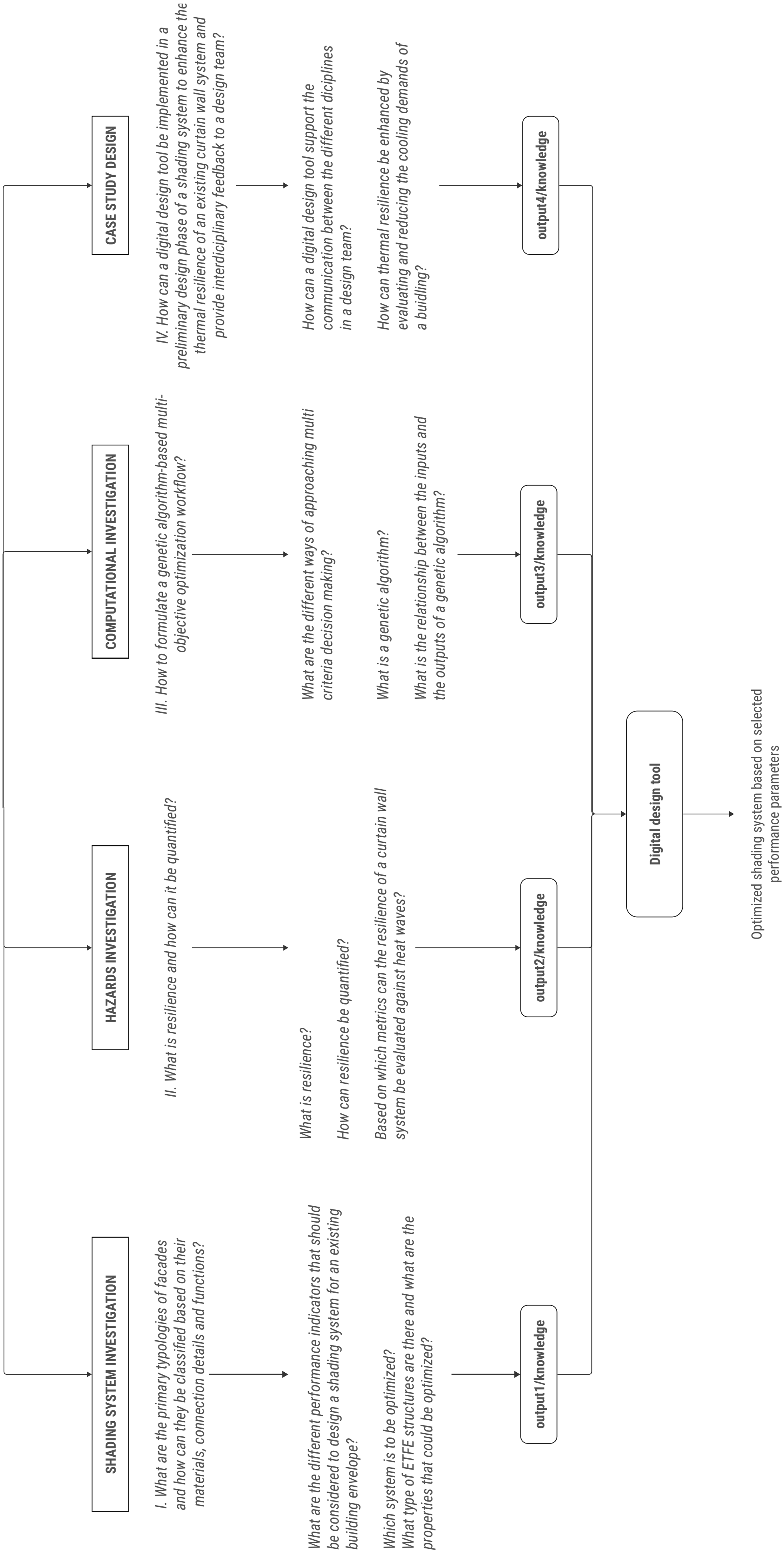


Figure. 4: Flowchart of research sub-questions

Sub-questions:

I. What are the primary typologies of facades and how can they be classified based on their materials, connection details and functions?

- *What are the different performance indicators that should be considered to design a shading system for an existing building envelope?*
- *Which system is to be optimized?*
- *What type of ETFE structures are there and what are the properties that could be optimized?*

II. What is resilience and how can it be quantified?

- *What is resilience?*
- *How can resilience be quantified?*
- *Based on which metrics can the resilience of a curtain wall system be evaluated against heat waves?*

III. How to formulate a genetic algorithm-based multi-objective optimization workflow?

- *What are the different ways of approaching multi criteria decision making?*
- *What is a genetic algorithm?*
- *What is the relationship between the inputs and the outputs of a genetic algorithm?*

IV. How can a digital design tool be implemented in a preliminary design phase of a shading system to enhance the thermal resilience of an existing curtain wall system and provide interdiciplinary feedback to a design team?

- *How can a digital design tool support the communication between the different diciplines in a design team?*
- *How can thermal resilience be enhanced by evaluating and reducing the cooling demands of a buidling?*

1.2.3 Objectives and Limitations

Objectives

The main goal of this research is to support a designer, either an architectural designer or a façade designer first to better understand the relationship between different properties (mechanical, geometrical, physical) of a shading system out of ETFE/PTFE elements, the properties of the building envelope and secondly to be able to produce design solutions for specific criteria. This research focuses on the behavior of an existing building envelope (Piraeus Tower) against current climate conditions. Energy consumption as well as the average daylight autonomy of the building are being calculated and evaluated through computer simulations in Grasshopper environment. Subsequently the design of the shading elements, their geometry and material properties are formed followed by further simulations and an multi-objective optimization. After the shading system's geometry is defined a structural analysis is carried out to assure the bearing structure of the system is stiff enough to resist self- and wind- loads.

The main objectives are for the researcher to get familiar with climate design and facade engineering and the development of a digital design tool for the preliminary design of such a shading system. It is envisioned as an assisting tool for evaluating a buildings' energy performance and further improve its behavior especially against heat stresses. The goal is to create a tool for this specific case study but also to be able to implement the same workflow to more buildings of different scales and heights in future projects.

Limitations

The research focuses on an office building in the port of Piraeus in Athens. Since it is not an existing study carried out for this building and this is an academic study, not all the criteria or calculations necessary for a proper construction are carried out. The properties and performance indicators chosen were selected for the purpose of a multi-objective optimization. An investigation of such a design approach and a formation of a digital workflow were the main goals. Design details such as corner panels of the tower and their various types (4 in total) were simplified since they would not contribute to the goals of this research. Therefore, typical non operable panels and values were chosen for the simulations and optimizations.

Moreover, although mechanical and natural ventilation are both present in the case study building, simplifications were made for reducing the computational time and burden. Thus, operable openings, although they could be represented, were not considered in the simulations. Furthermore, an investigation was carried out with various factors but many of them were considered as neglected. For example, the occupancy of the investigated spaces, the infiltration rates as well as air handling units and their efficiency were adjusted based on presets defined in the software used and were not further investigated since they are also not the main focus of this thesis. Other aspects that were neglected but could be subject of further investigation and implementation in future studies are the view factors, glare, the urban heat island effect, micro-urban climate as well as the exact type and mechanical properties of the brackets connecting the shading system to the beams and columns of the main bearing structure. The factors that were neglected are also mentioned as well as the reasoning behind this decision in the consecutive parts of the report. Finally, the study was focused mainly on the building scale and more specifically on the case study as presented in chapter 3.

1.3 Research methodology

The research presented in this work emerged from an extensive literature review addressing the various aspects and terminologies discussed herein, as well as from multiple energy and structural simulations and architectural design efforts. The primary research question and objectives were formulated to frame the research as a multifaceted design problem. The investigation and design processes, alongside the proposed solutions, served to define a series of sub-questions, prompting further inquiries and iterative experimentation. Therefore, this research was systematically carried out through distinct literature reviews for each aspect of the design problem. Detailed structural analysis of the selected case study provided a foundation for intervention and experimentation. Additionally, visual coding in the Grasshopper environment facilitated rapid measurement, comparison, and evaluation of performance indicators and design solutions. While the research hypothesis aligns with Horst Rittel's concept of a "wicked problem," the goal was to pursue research through design.

This thesis is split into four parts. The first part consists of chapters about the goals and limitations of this research as well as the methodologies used. The second part consists of the literature review as per the research question tree. This means that for each sub-question a separate literature review is presented as well as the conclusions for each one of them. The third part elaborates more on the selected case study, the materials used and the analysis of the existing curtain wall system. The fourth part is an in-depth analysis of the digital design tool that was formed from the conceptualization and flowcharts to the actual energy balance results and the optimization designs. Finally, in the fifth part the optimization outputs are discussed as well as the main conclusions concerning this investigation and the final workflow. For the literature review older MSc and PhD theses, structural engineering magazines and journals, papers and books were used to the extent they were needed for each aspect of this academic endeavor. The sources were mainly TU Delft library and its online repositories, Web of science, ResearchGate, ScienceDirect, Scopus, MIT Libraries and MDPI.

2. Literature Review

2.1 Background Research

The "background research" was carried out in order to better understand the state-of-the-art curtain wall systems, to understand the different goals, methodologies, stages, and disciplines involved in façade design and how these influence the design outcomes in every project. The main goal was to get in touch with all this information and pick a specific system that would fit better the defined case study's needs (in this case a shading system). Moreover, it was essential to complete this part in order to understand which of the several design phases of façade design this research should focus more on. This part is oriented around curtain wall system typologies and structures out of ETFE cushion panels which was the finally selected system.

2.1.1 Curtain wall and shading system types

In order to dive into solving a shading system, one first needs to understand the goals of facade design and of shading systems in total. What types of curtain walls are there and how are they being designed and manufactured? What type of shading system is to be designed? Which materials are to be used? In which stage of the façade design should the digital design tool be used? This chapter aims at answering the above questions and providing the basis for the case design. Thus, the first sub-question is to be answered:

I. What are the primary typologies of facades and how can they be classified based on their materials, connection details and functions?

Each system consists of different material families and is assembled based on each unique project's goals and of course based on the properties of the materials used. Therefore, in order for one to start investigating a shading system, firstly a preliminary study of the existing facade system types as well as the way they are being designed, produced, assembled, and delivered needs to be carried out. Professor Tilmann Klein, in his PhD carried out an investigation concerning the different stakeholders involved in the facade design process (see Figures 5 and 6) as well as the different phases of the facade design and the construction process. (Klein, 2013)

The relationship of the stakeholders in the façade construction process is being visualized in Figure 5. It is a structure almost identical to a project decision making hierarchy. At the top stands the client/investor, who made the decision to build and invest in his/her decision. Next to the client the architect trained to visualize needs and functions with sketches and diagrams supports the client in translating his ideas into a feasible built product. The architect in turn needs the support of several consultants and engineers since the building itself but also all its components are becoming more and more complex and specialized. Together client and architect define the architecture, and the performance goals of a building by taking the appropriate decisions. The goals set by these two roles are the ones that will eventually be translated into performance goals for the façade/ curtain wall. The general contractor takes over the project and guarantees to build it according to the given specifications and agreed goals. He subcontracts the façade design and delivery but maintains the responsibility for the overall process in terms of costs and time. The system suppliers on the other hand develop their products beforehand (usually without any project in mind) and try to get into the process by supplying various prefabricated elements or openings. According to Professor Klein façades are composed of "highly developed system products".

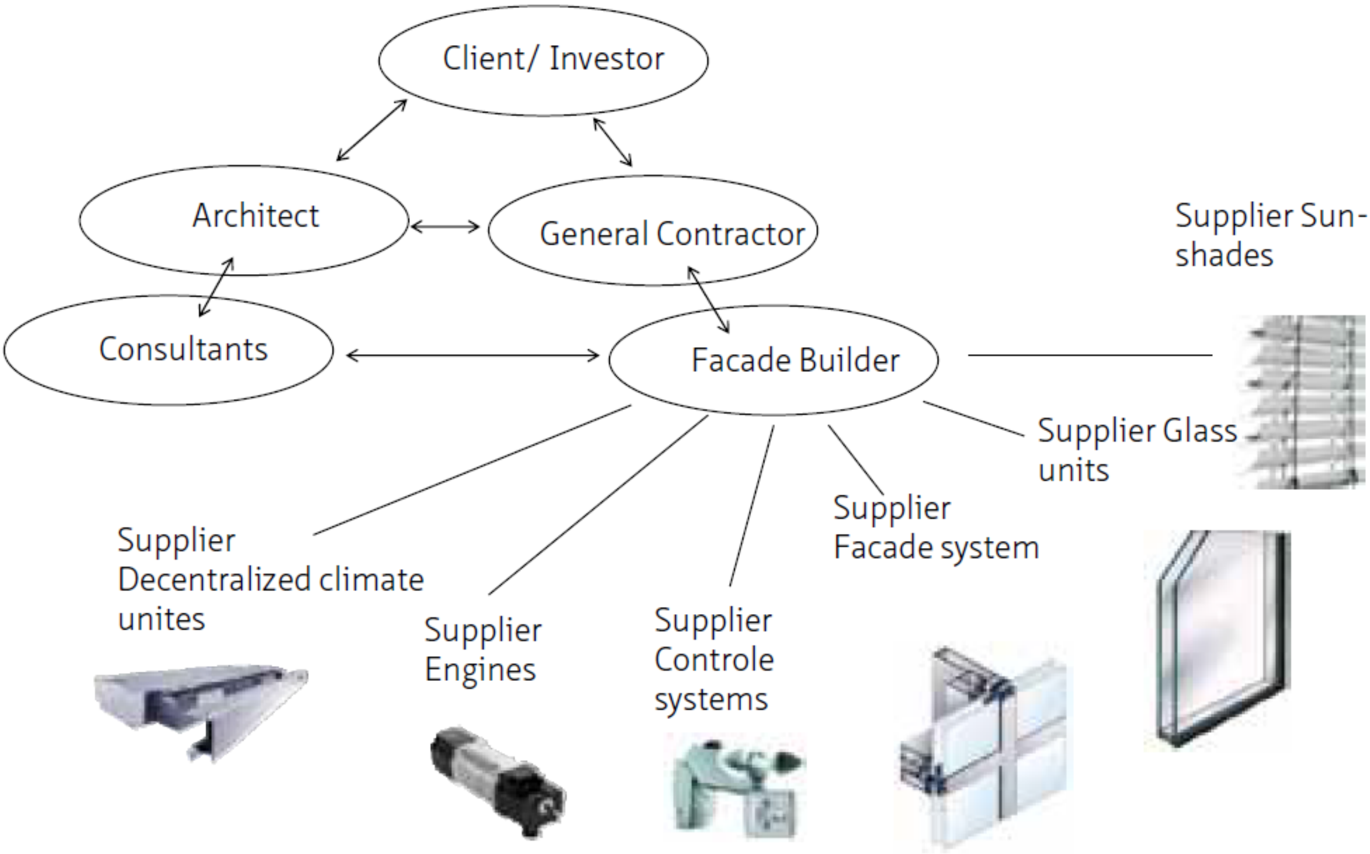


Figure. 5: Scheme of the relationship between different roles in façade design (Klein, 2013)

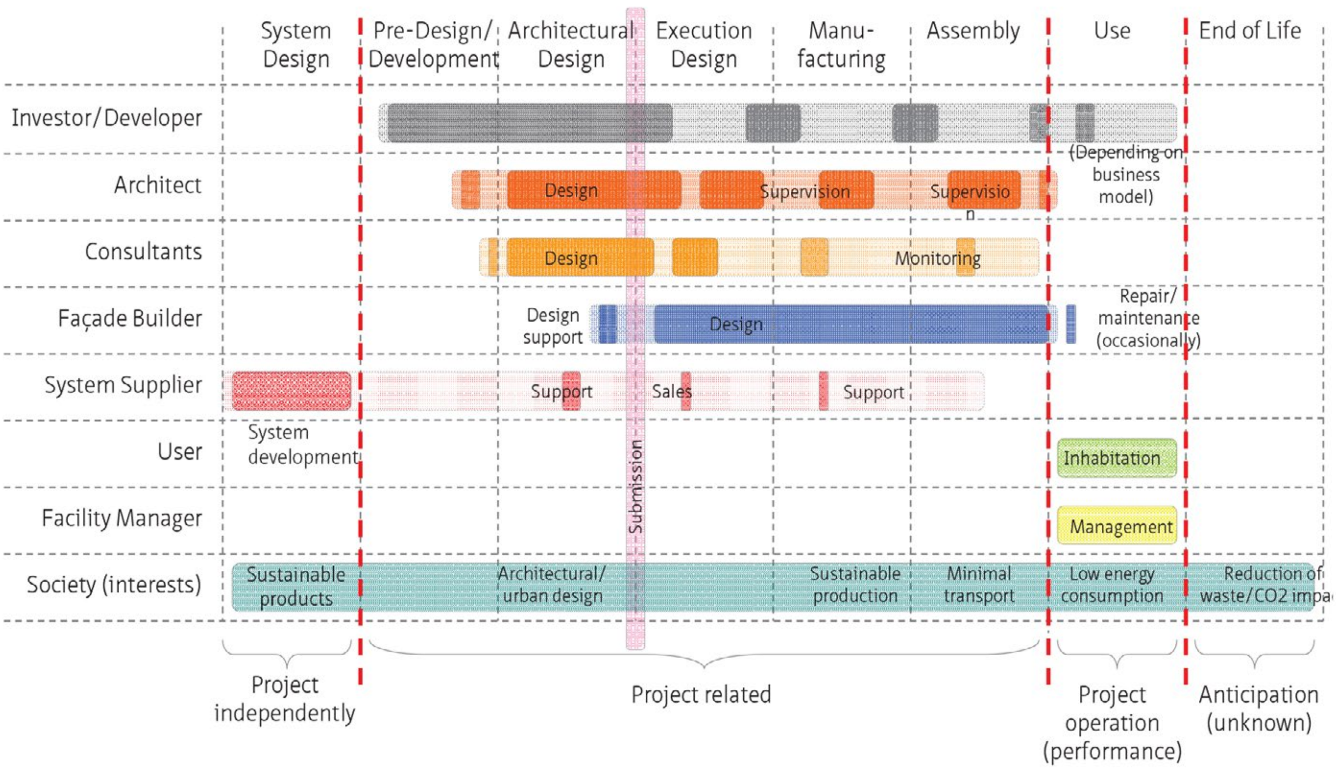


Figure. 6: The different disciplines and roles in façade design (Klein, 2013)

It is also suported that the number of system products will further increase with the trend to integrate adaptive and building services related components. Something that is worth mentioning here is that, according to Professor Klein, the architect typically is the one who decides about those components, but at the same time does not have full detailed knowledge of them. The architect is therefore dependent on his/her consultant's roles, knowledge, and experience.

These different roles and their relationships as well as their responsibilities are connected to a façade design timeline. The timeline depends on the facade's desired performance and the complexity of the design. It can be seen from this timeline that the design process is 25% before the submission of a proposal for a permit procedure (see Figure 6). This 25% is considered one of the most important phases of a façade design, and the decisions made here define the goals for the rest of the steps in the whole workflow, from an energy performance estimation to the production of the last screw. However, what is worth noting here is that as Professor Klein concludes in his analysis "…the design team needs reliable statements about the performance of products and their architectural quality and possibilities at an early stage. At the same time, product flexibility needs to be maintained in order to be able to react to changes in the design". This is the research gap that is intended to be filled with this research.

In his work Professor Klein also mentions the different functions of the building envelope. He metaphorically correlates a façade function to a programming function by saying that a façade is "converting the inputs into outputs". Since every function is assumed to be a set of functionalities for a specific outcome, he refers to Poelman for the different types of functions in order to form a façade function hierarchy or else a facade function tree. Professor Klein distinguishes facade functions from a broader context to a more specific one. He distinguishes primary, secondary, and supporting functions, positive and negative ones, functions for different users, technical and emotional functions.

The deeper one dives to the function tree (see Figure 8), the more he/she approaches the physical components and properties or otherwise known as Key Performance Indicators (KPI) that could fulfill certain functionalities in a façade system. In other words, a façade could be either classified based on their material or based on the specific goals they are aiming to reach. This façade function tree is considered to be a systematic way not only to classify existing façade systems, but also to set goals for designing a new one.

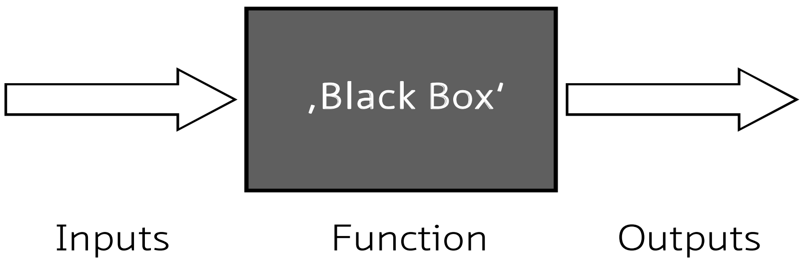


Figure. 7: "Blackbox" system model by Eekels and Cross for a function (Klein, 2013)

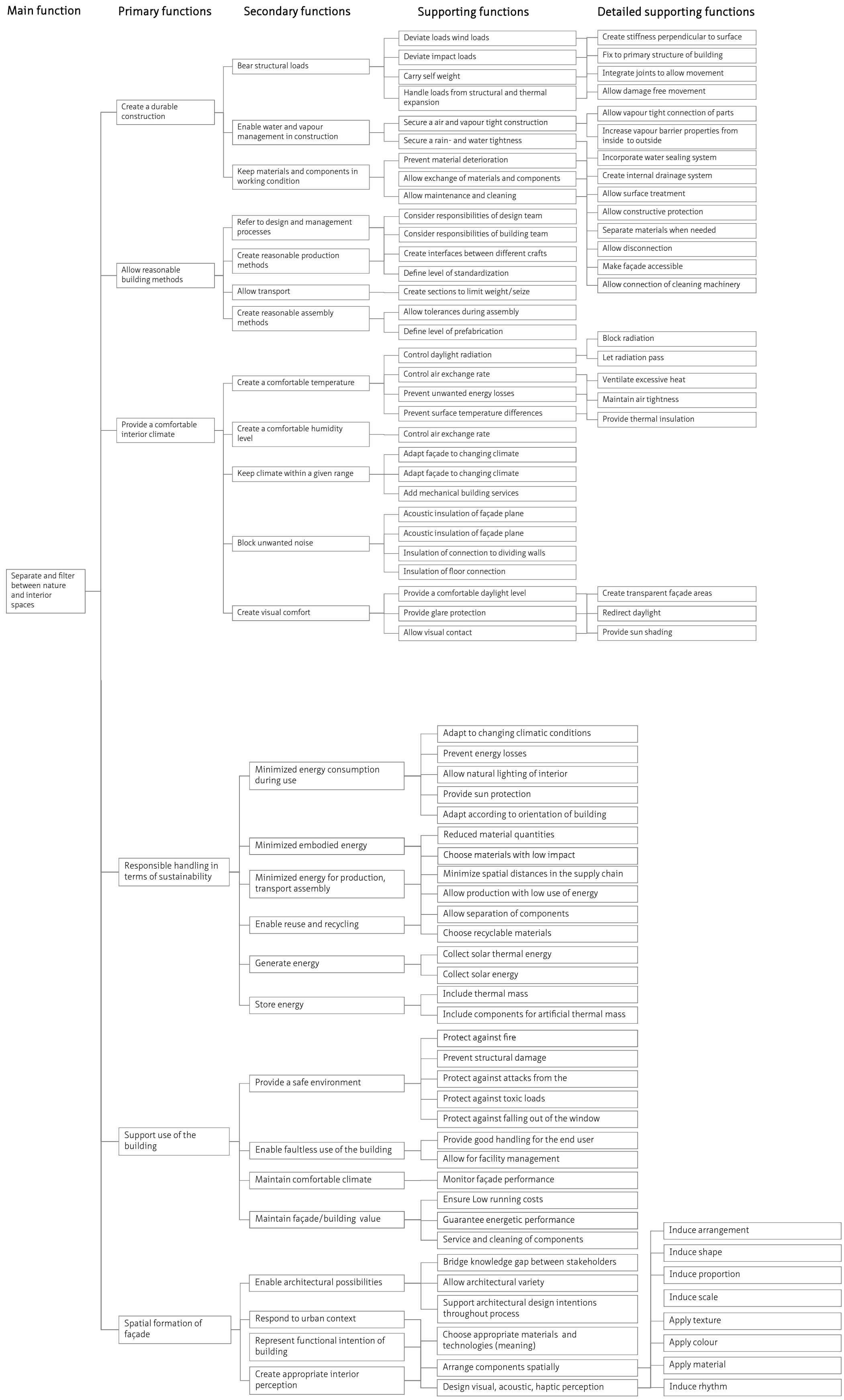


Figure. 8: The façade function tree. Mentioned in Mr.Klein's PhD and also developed on the basis of the graduation project of Joep Hoevels (Hoevels, 2007), (Klein, 2013)

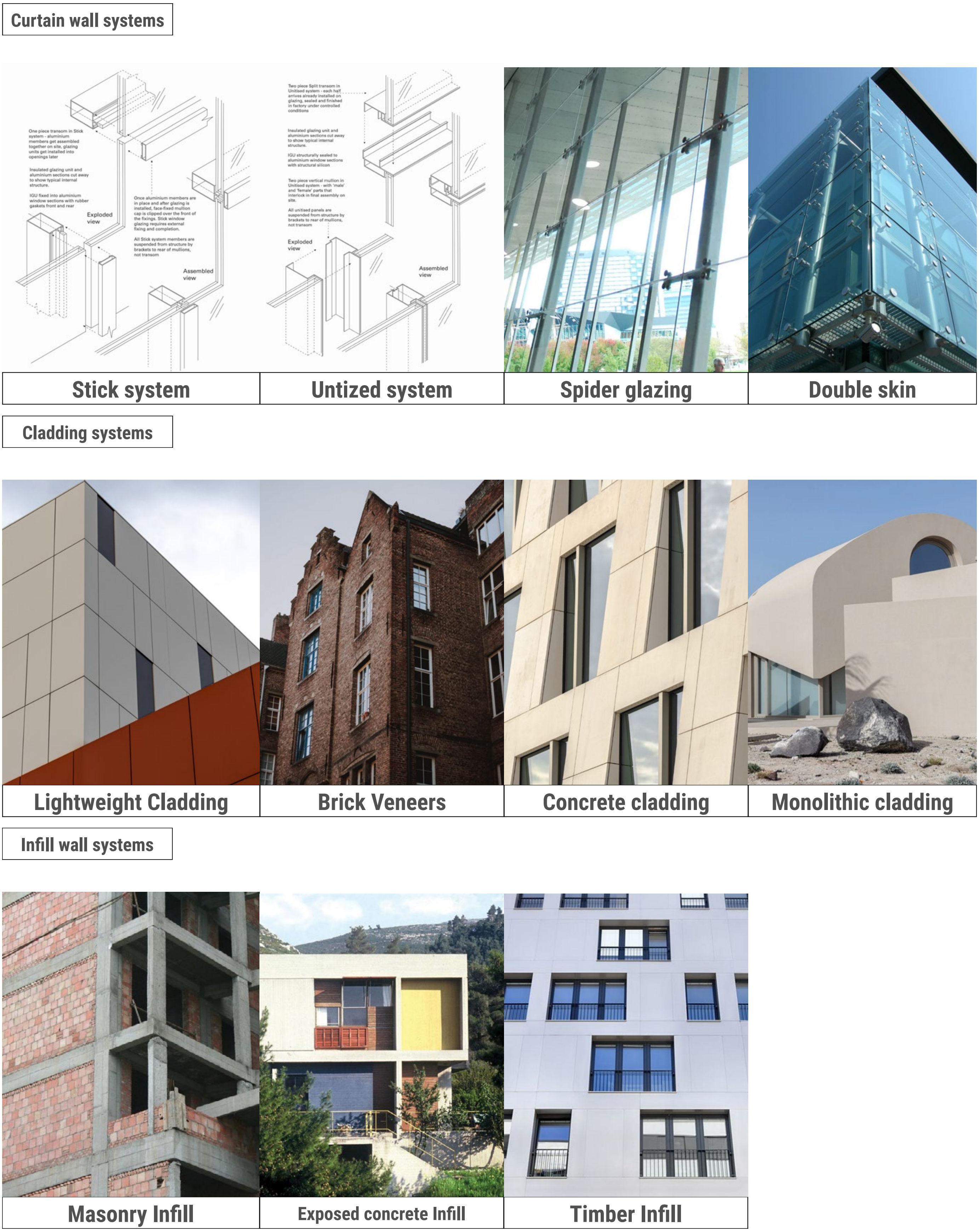


Figure. 9: Separation of facade systems based on material and structural aspects (Bianchi et al., 2024b)

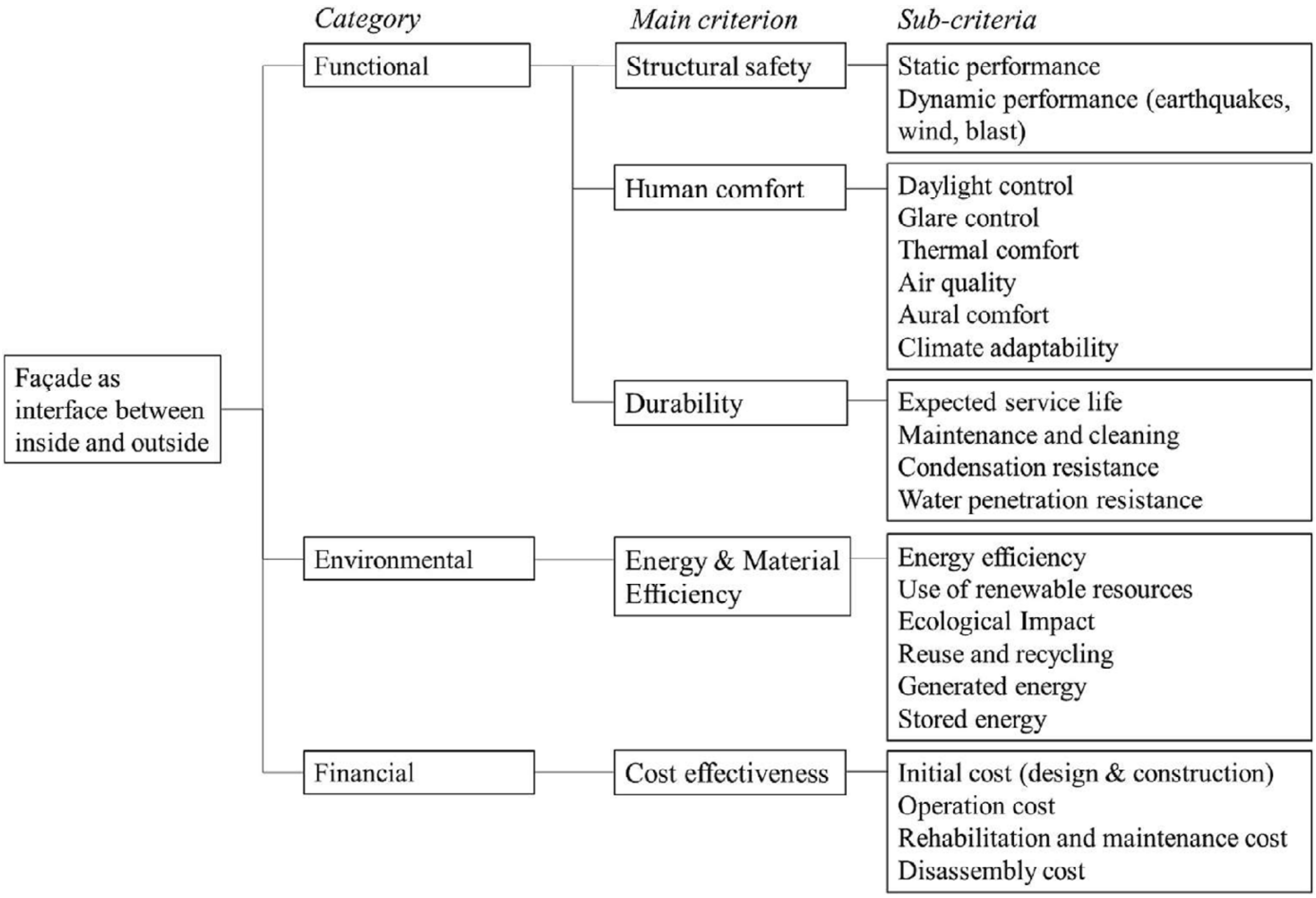


Figure. 10: Another approach to the facade function tree (Bianchi et al., 2024b)

In addition, in more recent literature a slightly different approach is discussed (Bianchi et al., 2024b), separating the facade systems based on material and structural aspects like the way the facade is supported or supports the main bearing structure. This is actually a common terminology in the vocabulary of stakeholders (see Figures 9,10). It seems that the original function tree of the earlier research has evolved and now focuses more to the structural aspects of the building envelope. Therefore, if one was to anwer the question:

- *What are the different performance indicators that should be considered to design a shading system for an existing building envelope?*

one should refer to the sources that thoroughly analyze these facade functions and categories.

Further research was carried out concerning the term adaptive façade, kinetic façade, and double skin façade. The research around these terms lead to investigating a series of magazines and journals with materiality and sustainability as the main topics. “The Future Envelope” series contains valuable information concerning glass alternatives and risky paths towards innovation. Professor Klein, Jan Cremers and Bert Lieverse among others discuss the importance of the building envelope, the various types of it as well as for the concept of the “Living Façade” which is one that refers more to the term adaptive facade. The third part of this series, although it is a bit outdated, provided interesting examples and inspiration about materials that transform the facade into a high-tech skin.

Among different materials, ETFE cushion panels and PDFE membrane structures were presented as two very promising materials for future envelopes (or retrofit solutions). These two are rated as B1 retardant (possible but hard to burn) in the German standard DIN4102 and this rating is not their only advantage.

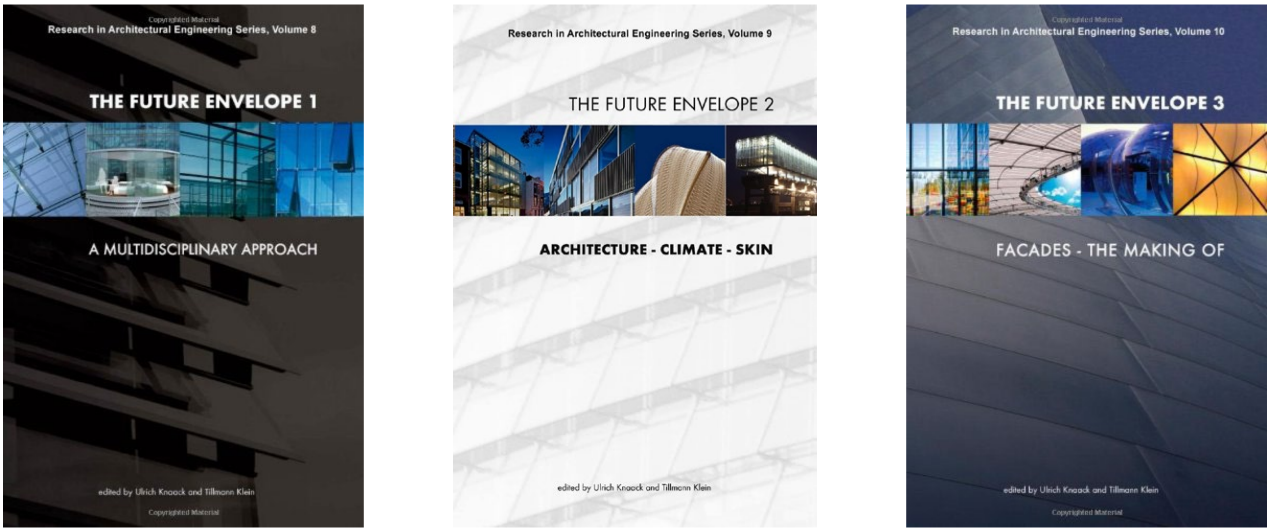


Figure. 11: The Future envelope magazine series

Figure. 12: Canary Wharf Crossall Station by Foster + Partners,
https://www.fosterandpartners.com/projects/crossrail-place-canary-wharf

Their life expectancy is aimed to be 20 years while as a material is close to maintenance-free as ETFE is a self-cleaning material. The biggest advantage, however, is that ETFE can be 100% recycled according to Jan Cremers which is something that makes this material a very promising one in terms of maintenance and sustainability. The material performance and durability would be able to protect other materials such as wood or aluminum in exterior conditions just like what happens in Canary Wharf Crossall Station designed by Foster+Partners. However, a very important drawback of these structures is their Co2 equivalent and emissions during production and building procedure. (Knaack & Klein, 2010) Therefore, for this research, an ETFE shading system is the answer to the sub-question:

- *Which system is to be optimized?*

2.1.2 Systems out of ETFE

This chapter focuses on answering the following reseach sub-question:

- *What type of ETFE structures are there and what are the properties that could be optimized?*

Polyethylene tetrafluoroethylene, commonly known as ETFE, is a copolymer comprising ethylene and fluoroethylene, finding utility across various applications, notably in structural cladding and façade engineering. This material is capable of extrusion into expansive thin sheets, commonly known as foils or films, adaptable for deployment in single or multi-layer cladding scenarios. In single-layer configurations, the foils are stretched over a structural framework, typically constructed from steel or aluminum, serving as a canopy in areas with moderate loading conditions. (Charbonneau et al., 2014b)

Multi-layer configurations, on the other hand, involve the combination of two or more layers of foil through clamping and sealing at the edges, with the intervening space between the foils inflated with air or gas (see Figure 13). These curved elements are known with the term cushion panels which in turn form cushion systems. Across almost all structural deployments, ETFE foils undergo tension, achieved either through pre-tensioning of the films or inflation if more than one layer is present. (Charbonneau et al., 2014b) This happens in order for the pillow shaped elements to facilitate the bearing of live loads and self-loads. ETFE cushions find prevalent usage in skylight and atria applications, where conventional glass could conventionally be employed, yet they also possess versatility to serve as integral components or even the primary elements of the building envelope (see Figure 14). The reasoning behind this will be further discussed later on.

Numerous studies in literature have explored the properties and applications of ETFE material, each approaching the subject from distinct angles. Some investigations delve into ETFE's mechanical characteristics (Charbonneau et al., 2014b), while others concentrate on aspects related to light transmission and insulation (Flor et al., 2022). Furthermore, certain authors analyze ETFE material through the lens of life cycle assessment (LCA) and environmental considerations. Conversely, existing literature also encompasses works that: 1. compare ETFE with glass, 2. address acoustic properties of ETFE structures, 3. investigate shading and thermal comfort aspects of ETFE structures, and 4. discuss issues pertinent to the inspection of ETFE foils. Concerning ETFE applications, a plethora of studies have been presented, encompassing diverse applications such as ETFE façades, roofs, atria as well as configurations integrating photovoltaic (PV) technology (Lamnatou et al., 2018).

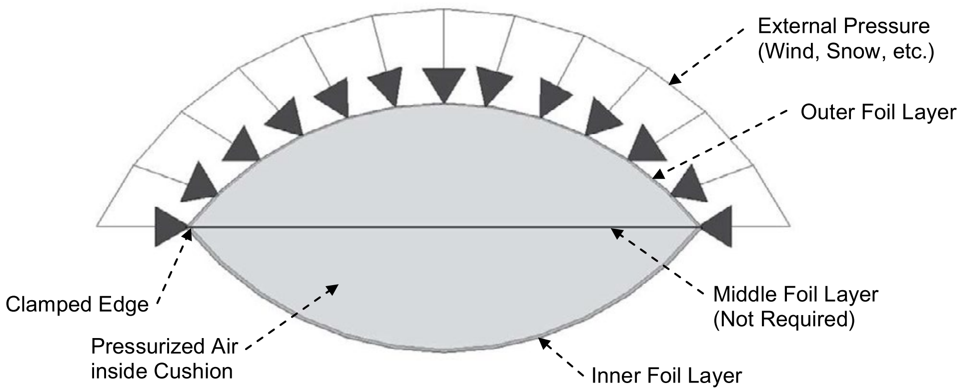


Figure. 13: Schematic ETFE cushion panel (Charbonneau et al., 2014b)

Figure. 14: Example of roof out of ETFE cushion panels (wikipedia)

2.1.3 Mechanical properties and main characteristics of ETFE systems

One reference focusing more on the comparison between ETFE, and glass is the article by Jan Cremers in the series “The Future Envelope”. Cremens considers the introduction of PTFE (poly tetra-fluoroethylene) and of transparent foils made of a copolymer of ethylene and tetrafluoroethylene (ETFE) as milestones in the search for appropriate materials for the building envelope. By mentioning built examples of ETFE structures like the Miroiterie Flon Lausanne, the Centre for Gerontology (GTZ) in Bad Tölz and Allianz-Arena in Munich (see Figure 15) he makes a brief introduction to the main properties and advantages of the new façade material.

Two of the most important advantages of ETFE are its recyclability and its behavior against fire (Knaack & Klein, 2010). ETFE is a recyclable material which means that damaged foils can be added to virgin resin to be reprocessed into new material. The same could happen in the end of life of any structure making this material compatible with the principles of circular economy. At the same time ETFE performance under fire conditions is unique. The material which is flame retardant (B1) according to DIN 4102 and other international standards as Cremens mentions. Moreover, due to its low mass (1750 kg/m^3) (Knaack & Klein, 2010) and thickness (50-300μm) (Lamnatou et al., 2018) it shrinks away, allowing smoke and fire to be vented to the exterior. There is therefore minimal chance of melting and dripping onto other elements or the occupants.

Another important characteristic that makes this material interesting for architectural interventions is its lightness. ETFE cushions are much lighter compared to glass panels, and therefore allow for a much lighter and thus less expensive support structure. Its lightness together with the minimal need for maintenance and cleaning makes this material an integral part of an architect’s vocabulary. An ETFE membrane boasts inherent self-cleaning properties owing to its chemical composition, ensuring sustained high translucency throughout its lifespan according to Cremens and (Lamnatou et al., 2018). Therefore, material maintenance is almost unnecessary. However, in literature periodic inspections are advised to detect and rectify any defects, such as damage from mechanical impacts by sharp objects, or failures at the clamping system or the primary structure.

As a material ETFE is flexible. This means that under dynamic loading it is less susceptible to failure than other materials. Compared to glass, ETFE poses lower risk of breakage, which means that it does not have the same structural limitations typically associated with overhead glazing installations. Even when an ETFE cushion does fail, the damage it causes will be minimal, and there is less chance of falling due to its ductile and lightweight nature. Literature suggests that the tensile

Figure. 15: Example of ETFE systems in buildings, Miroiterie Flon Lausanne at the top, Centre for Gerontology bottome left, Allianz-Arena bottom right

strength of ETFE is in the range 44-53 MPa, its yield strength is in the range 20-30 MPa, tear strength is in the range 400-450 MPa, tensile modulus (E) is in the range 300-1000 MPa whereas melt temperatures are within 265-278 °C for one layer foil structure (Charbonneau et al., 2014b).

Concerning radiation, ETFE foils present a notable contrast to architectural glass. Whereas glass exhibits near opacity in the infrared (IR) spectrum, transparent ETFE foils boast considerably greater transmission within this spectral domain (see Figure 16). The degree of transmission, including within the infrared (IR) spectrum, can be adjusted by printing on the ETFE foils. Thus, a higher density of printing diminishes transmission while concurrently augmenting reflection/absorption (Kersken et al., 2021). This material lets more infrared radiation pass through it than glass. An alternative way to reduce radiation except from printing a denser pattern on it is the integration of flexible PV modules on it with an increase of the foil thickness up to 0.1mm.

Concerning translucency it is a material that can typically reach 94-97% of visible light (380-780nm) and 83-88% of ultraviolet (UV) spectrum (300-380nm) which depends mainly on the foil layers count (1-4), the color and density of color dots printed on them (typically silver color), the foil thickness (50-300μm) (Lamnatou et al., 2018), which in turn depends on the actual strength the cushions need to have and thus their spans as well as their bearing structure spans. All these percentages seem to be much higher than the glass corresponding values.

ETFE cushions can be quite large with various dimension ratios. Along their longitudinal axis, the cushions can achieve almost unlimited spans, based on their ability to be folded or rolled for transportation to the installation site. However, opinions vary regarding the maximum spans achievable

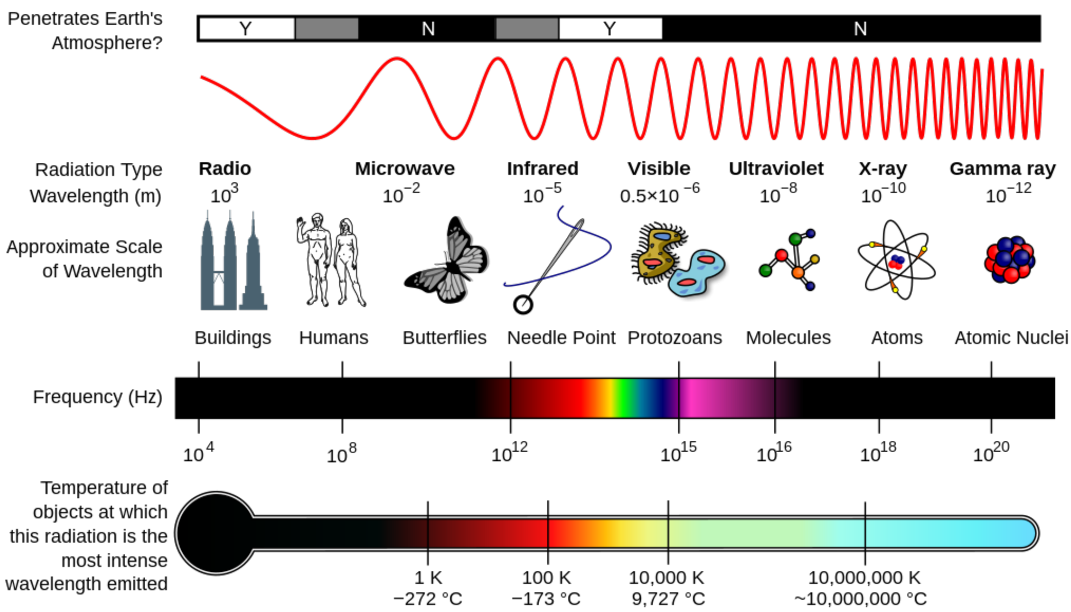


Figure. 16: Electromagnetic spectrum (wikipedia)

along their shorter direction. (Lamnatou et al., 2018) reference multiple studies by Tanno, suggesting a maximum span of 3.5 meters. Similarly, Architekten Landrel, as noted by Schöne, propose 4 meters as the largest practical span, while Moritz suggests a maximum span of 4.5 meters. Nonetheless, LeCruyer concludes that in practice, cushions as wide as 11-meter diameter hexagons and 5-meter by 17-meter rhombuses have been successfully constructed. It is also concluded that even greater spans can be attained through the implementation of secondary support systems such as cable nets. Moreover, the lower self-weight of ETFE cushions compared to glass panels enables the utilization of larger clear spans for supporting members.

Despite the numerous advantages attributed to ETFE systems, they also possess drawbacks, as is the case with any material. Particularly concerning its mechanical properties, the complexity inherent in these systems often complicates the precise determination of thermal transfer behavior or static characteristics. Another notable disadvantage lies in the acoustic performance of ETFE panels. Due to their thin composition and the air trapped between them, ETFE panels are susceptible to expansion, contractions, and vibrations. Consequently, these systems may emit sounds or reflect external sound waves into or out of the building, particularly affecting operations in environments such as football stadiums or train stations. However, in settings like libraries, residential complexes, or office buildings where quietude is paramount, the material's behavior, scale, and sound emissions during rainfall or external activities can adversely impact the functionality of the building. The thermal insulation properties of ETFE panels constitute another significant consideration for structures of this type. Existing literature suggests that ETFE panels offer superior performance in thermal insulation compared to traditional glazing materials. However, their determination is not always straightforward (Lamnatou et al., 2018).

Finally, one more notable drawback of ETFE is the ambiguity surrounding its energy requirements for production, transportation, and installation, namely its environmental footprint. Ultimately, despite its versatile applications, ETFE is a synthetic material, distinctly different from natural materials. As mentioned by (Lamnatou et al., 2018), while some studies clearly indicate that the energy required for ETFE production is significantly lower, approximately 27.0 MJ/m2, compared to glass, which demands around 300 MJ/m2, other research estimates for the carbon values vary widely, ranging from 26.5 MJ/kg to 210 MJ/kg. Specifically, the formation of the material necessitates approximately 173 MJ, with an additional 28 MJ allocated for pellet formation and another 9 MJ for the extrusion of pellets into the final films to be used.

2.1.4 Thermal behavior and properties of ETFE systems

As mentioned in chapter 2.1.3 ETFE constructions typically consist of a single layer or double layer foil in tension. Tension is the key here since the larger the loads the structure must withstand the greater the tension needed in order for the cushion panels firstly to not fail and secondly to not lose their form and aesthetic appearance.

(Lamnatou et al., 2018) mentions that single layer membrane configurations usually have a low mass and thickness but at the same time relatively high U-value. Therefore, single layer systems are mainly adopted for exterior structures such as sunscreens for sun, wind and rain protection or in order to adjust the visual barriers between indoors and outdoors. Multi-layer membrane configurations on the other hand show better thermal performance in terms of U-values and can be used as a layer or the main element of the building envelope's structure.

As mentioned in literature (Kersken, 2021) the installation conditions play an important role regarding convection. A distinction is made between horizontal heat flow (90, vertical façade) and vertical heat flow (0, horizontal elements, roof) in a cushion panel. There are also scenarios with 30 or 45 degrees of inclination and heat flow direction. However, it is clear that the U-value of cushion panels depends on the angle of inclination and the direction of the heat flow. The latter of course changes between different periods like summer and winter when the heat flow is reversed.

The single-chamber cushion positioned horizontally with upward heat flow, where cold is at the top and warmth at the bottom (see Figure 17a), exhibits a nearly uniform temperature distribution across most of its height. However, in this scenario significant temperature gradients are primarily observed near the boundary surfaces of the system. This means a chaotic turbulent flow in the air between the foils (see Figure 17b). Conversely, the vertical and inclined single-chamber cushions featuring sideways or upward heat flow, where the left side is cold and the right side is warm, exhibit nearly horizontal temperature stratifications, with warmth concentrated at the top and coldness at the bottom. This configuration encourages convection within the enclosed air volume, consequently resulting in a higher calculated heat flow.

It is therefore concluded that with the exception of the horizontal single-chamber system with downward heat flow (during the summer) all the other scenarios are systems with chaotic air flows in the cushion panel. For this reason, but also for maintaining the proper tension levels for structural behavior almost all cushion panel systems are equipped with ventilation systems for the renewal and regulation of the air between the different foil layers. Sensors can also be present for these adjustments making the system an adaptive façade system.

It is worth noting here that currently there is not a material specific standard for ETFE cushion systems. Therefore, the U-values used in order to determine the thermal behavior of a cushion system vary from manufacturer to manufacturer although they usually use the same standards. The methods to measure, transmission (τ), emission (ε) and reflection (ρ) are identical with the ones used for glass with the application of EN 673. Since ETFE foils allow light in the UV and IR spectrums to go through them, which does not happen in case of glass, these standards are often misinterpreted. Moreover, since the geometry of the cushions is usually complex, the varying distances between the foil layers and the air thickness between them as well as the uneven expansions that happen in reality are not considered with the standards used to define their U-values. The U-values therefore although they form a comparative value between systems, they do not reflect reality.

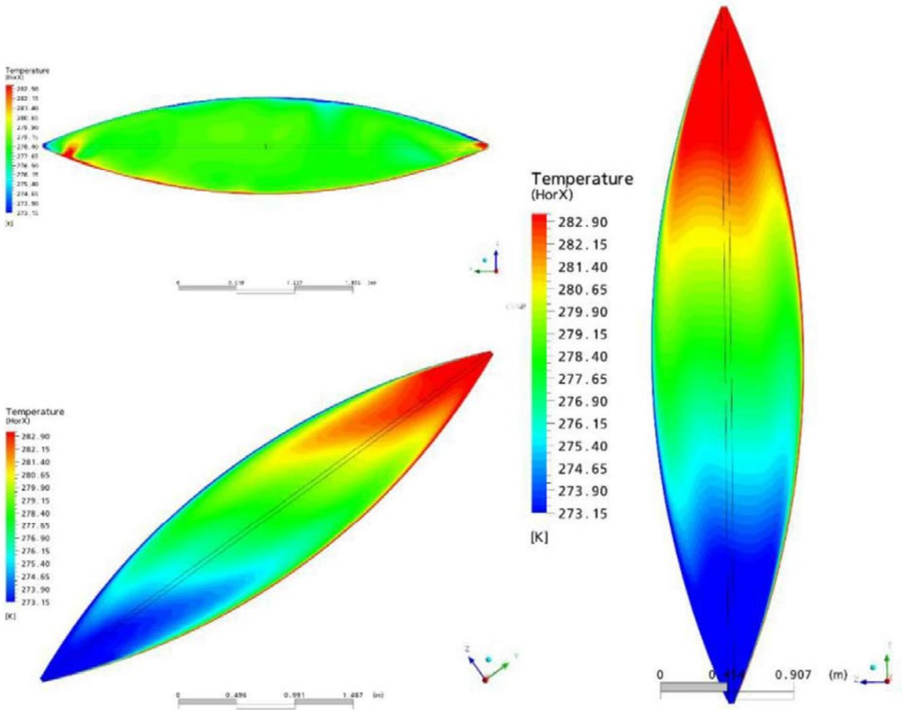


Figure. 17a: One-chamber-cushion different assembly situations and heat flow directions with temperatures Ti=20°C (inside) and To=-10°C (outside), (Kersken et al., 2021)

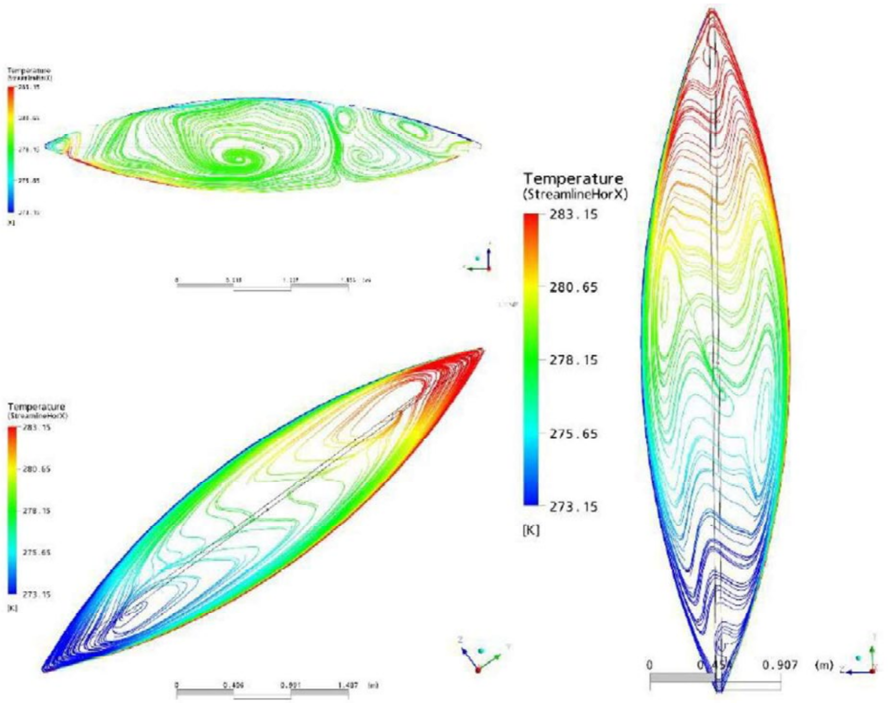


Figure. 17b: One-chamber-cushion different assembly situations and air flow inside the cushion panels with temperatures Ti=20°C (inside) and To=-10°C (outside) (Kersken et al., 2021)

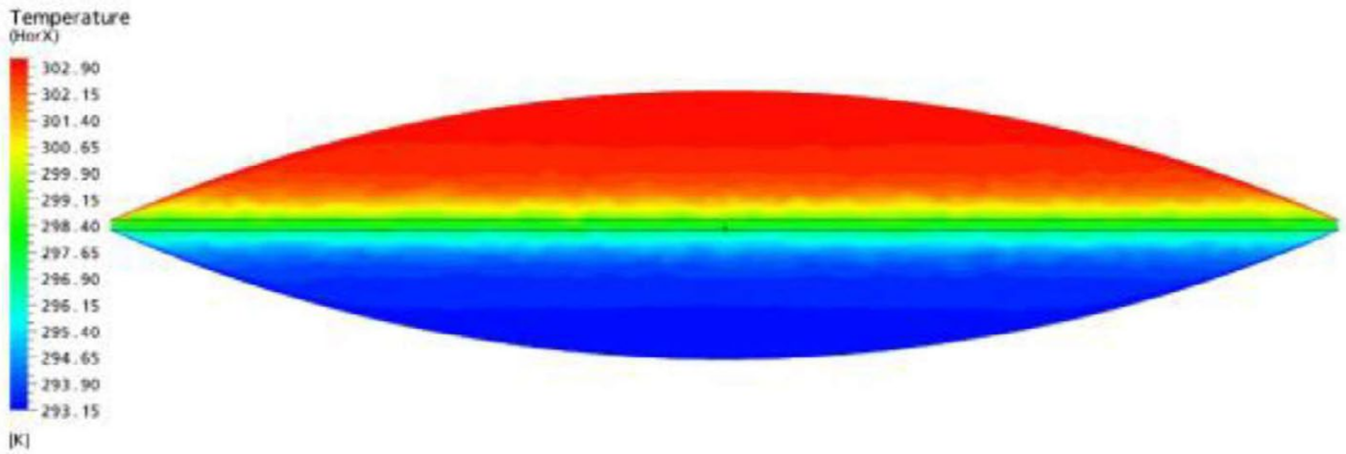


Figure. 18: One-chamber-cushion vertical heat flow (downward) with temperatures Ti=20°C (inside) and To=30°C (outside), (Kersken et al., 2021)

Standards like EN 673 and EN ISO 6946 also applied for cushion panels use the Kirchhoff's radiation law (simplified) for opaque components:

$$1 = \varepsilon + \rho \quad (1)$$

With ε: emission, ρ: reflection. But since they are used for glazing, transmission of UV IR waves is not considered. In order to take the transmitted radiation component for membrane cushions the following simplified formula is therefore applied:

$$1 = \varepsilon + \rho + \tau \quad (2)$$

With ε: emission, ρ: reflection, τ: transmission. In order for this formula to consider the emissivity of each foil layer εi on the opposite side of the incident radiation and the corrected emissivity considering the foil's IR transmission εi'* the following formula can be used for the nth layer of a cushion panel and then added to the Kirchoff's radiation law (Kersken, 2021):

$$\varepsilon'_n{}^* = \varepsilon'_n + \sum_{i=1}^{n} \varepsilon'_{n-1} \cdot \prod_{i=1}^{i} \tau_{n+1-j} \quad (3)$$

However, within the short boundaries of this research, which emphasizes the utilization of ETFE as an exterior shading system, the thermal insulation aspect of this material is not further explored or presented and only the basic geometrical properties of ETFE systems are used as shown in Figure 18.

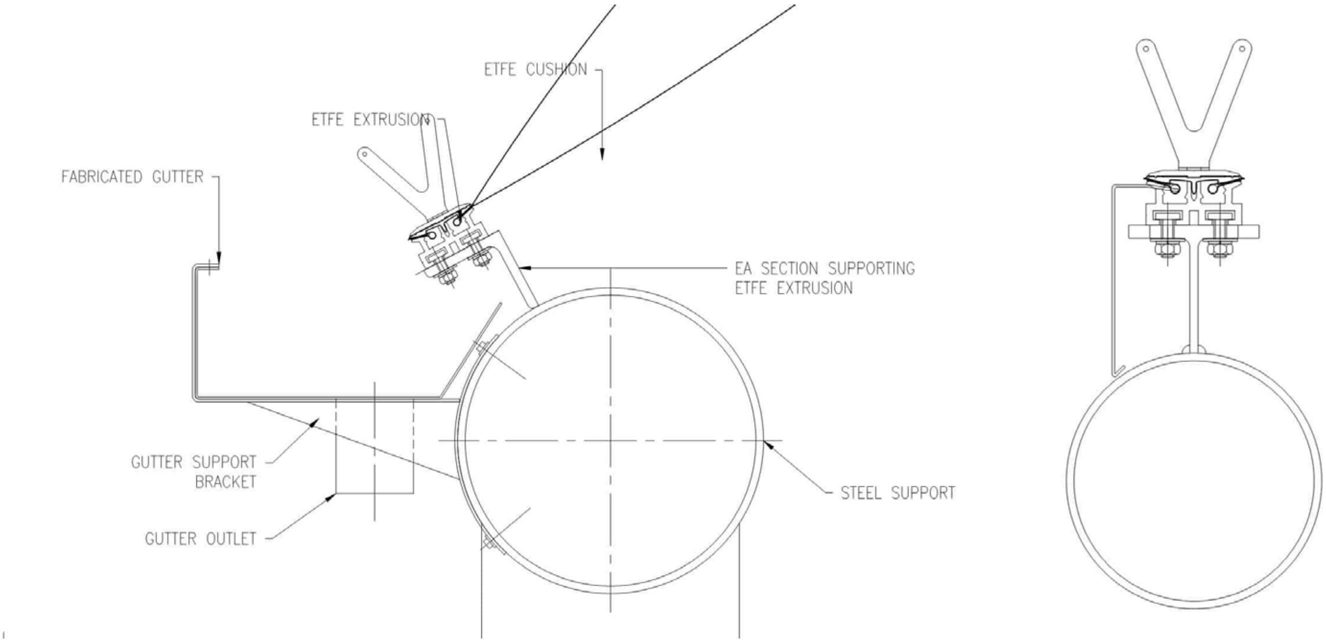


Figure. 19: Typical details for ETFE steel support frame structures, cushion frames and cushion panels

2.1.5 Part I concluding remarks

To sum up, the comprehensive "background research" conducted in this part aimed to elucidate the intricacies of contemporary curtain wall systems, shedding light on the multifaceted considerations in façade design and construction. The investigation delved into understanding various façade typologies, their design methodologies, and the roles of different stakeholders in the construction process always in parallel to the façade design timeline. Moreover, the realization that a façade is always connected with a goal was of great importance. It seems that the different façade types are either defined based on the needs they serve (the design goals set by the client and the architect) or based on the structural system needed to install them on the main structure of the building. The functional tree that Professor Klein developed in his research contributes to the recognition of these distinctions and supports either the analysis of an existing façade system or the goal setting procedure for designing a new one. This knowledge was very important in narrowing down and selecting a suitable system for the selected case study, ultimately leading to the adoption of ETFE cushion panels system as the focus of this research.

By exploring the realm of ETFE systems, the study has shown a wealth of literature highlighting the material's versatility and potential in architectural applications. ETFE's intrinsic qualities, such as its recyclability, fire resistance, and self-cleaning properties, set this material and systems as a promising candidate for sustainable building envelopes. Furthermore, its flexibility, lightweight nature, and superior thermal performance compared to traditional glazing materials underscore its suitability for a wide array of architectural interventions especially in retrofit strategies. The mechanical properties of ETFE foils and cushion panels as well their thermal properties and the uncertainties in their evaluation were presented. However, despite its numerous advantages, ETFE is not without limitations. Challenges concerning mechanical properties, acoustic performance, and environmental impact warrant careful consideration in architectural design. Additionally, the absence of standardized testing protocols specific to ETFE cushion systems complicates the assessment of their thermal behavior, highlighting the need for further research and development in this domain.

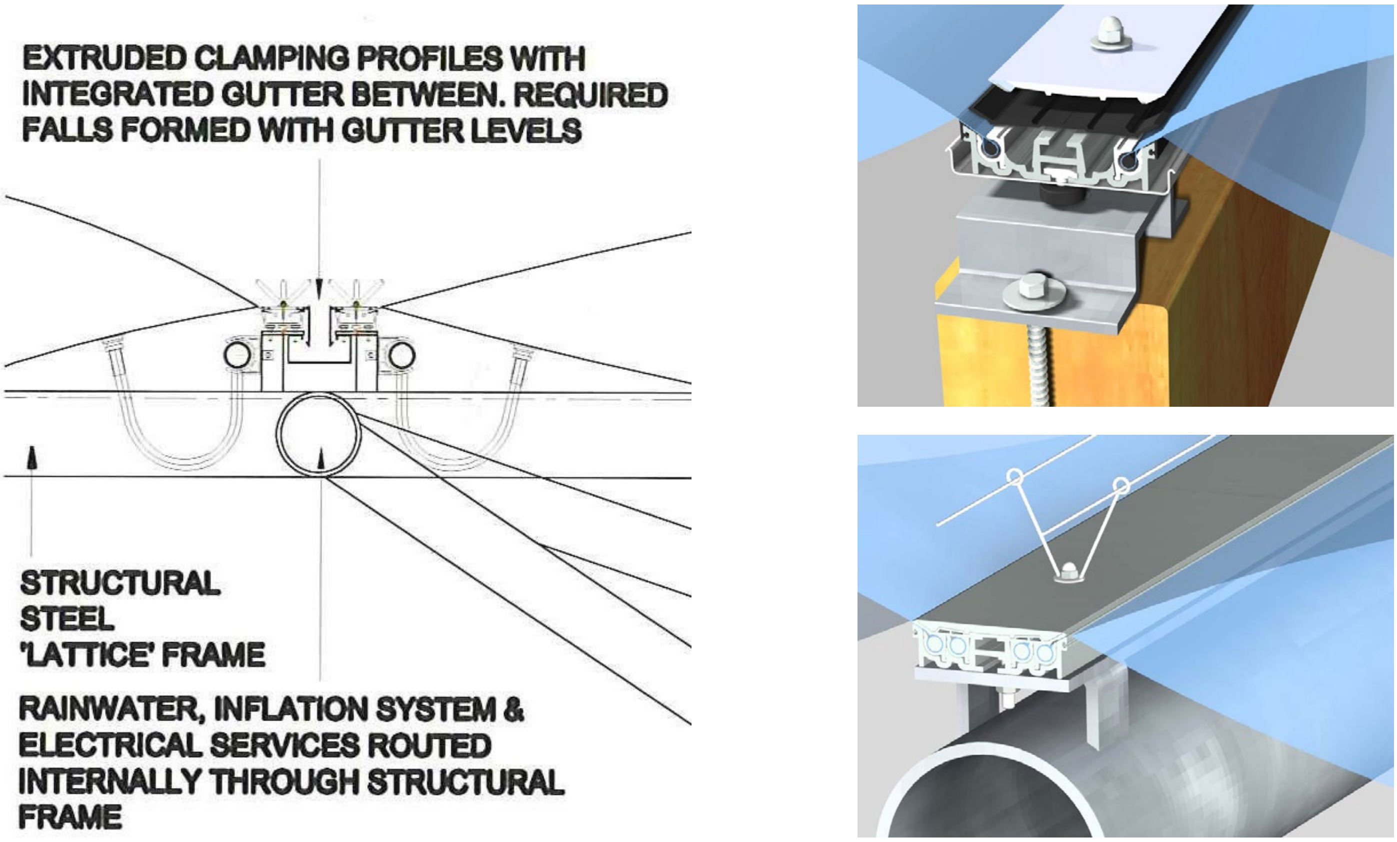


Figure. 20: Typical details for ETFE steel and wooden support frame structures, cushion frames, cushion panels as well as inflation system installation

Based on these findings, this study advocates for the informed integration of ETFE systems in architectural design, leveraging its strengths while addressing its shortcomings. Ultimately, the utilization of ETFE as an exterior shading system is considered to have tremendous potential to enhance the energy performance of the existing built environment, marrying functionality with aesthetic appeal in contemporary architectural discourse. Moreover, in the context of this research it is concluded that a typical ETFE structure consists of a main bearing structure either self-supported or attached to an existing structure. The system consists also of perimeter frames that hold the ETFE foil sheets in tension and finally the ETFE foils that are one to four in number that shape the cushion panels. The systems as presented, if they are multi-layered, they also have a system for regulating the air pressure inside the cushions, since their strength demands changes based on the temperature difference from one side of the panel to the other, but also with the live loads that they need to withstand, such as rain, snow and wind. All these elements can also be seen in typical details found (see Figure 20) and as such they are being defined in the digital design tool presented in chapter 4.

2.2 Resilience investigation

"Resilience investigation" is a title for describing the research concerning the terms resilience, resistance, robustness, recoverability, thermal comfort, thermal resilience, and their relation to the building environment and eventually to the building scale. Since the aim of this research is to improve an existing building envelope by improving its thermal resilience, an investigation for the metrics needed for evaluating a building envelope against heat was necessary. This part is oriented around the term resilience, its definitions and the indicators that have been used in literature in order to assess resilience. As noted by (Bruneau et al., 2003) it is very important when working with resilience to identify its dimensions and the way to measure these dimensions. Only then one is able to evaluate, classify and increase the resilience of a system. It's worth noting here that this research focuses more on thermal resilience and the building envelopes resilience against increasing temperatures.

2.2.1 The term resilience

In the context of this research the understanding of the term resilience, its definition as well as its connection with the properties of a building envelope were needed. Thus, scientific papers concerning resilience in a broader range at first and later on more closely to hazards like heatwaves were searched. Earlier academic endeavors about the meaning and significance of the term resilience were also investigated. The goal of this chapter is to answer the sub-question:

II. *What is resilience and with which metrics can it be quantified?*

Today, with the term "resilience" it is easy to think of either the endurance, the strength, the resistance of an element or system against an event or a situation. Indeed, it is a term related to various scales and to many different scientific fields including sociology, earthquake engineering, environmental research among others. The word resilience, however, stems from the Latin root "risilio" meaning "to spring back" and the first studies about it originated from the work of Holling in ecology during the 70s. Holling used resilience to describe the ability of an ecological system to maintain its function and structure by enduring shocks and absorbing disturbances. However, the term back then did not contain an extra meaning of a system remaining at the same pre-disturbance state after a shock, something it aquired later on (Homaei & Hamdy, 2021). This original meaning is today known as ecological resilience while in other scientific fields, like the ones mentioned above, the term apart from its original definition it gained new additional meanings.

One of the first introductions of the term resilience in engineering and more precisely in earthquake engineering was the work of Michael Bruneau and his team (Bruneau et al., 2003b). Since this introduction and basic framework for resilience evaluation of communities, many new frameworks as well as research concerning resilience took place. However, all later works almost always mention the work of Bruneau, and the research questions defined in his work.

Some papers focus on urban scale, CO_2 emissions and resilience (Naboni et al., 2019), (Sharifi & Yamagata, 2016) while other papers focus on infrastructure resilience (Panteli et al., 2017) or the development of a framework always related with a specific design problem. An example for earthquake is (Cimellaro et al., 2010) who develops a quantitative framework for analytical quantification of seismic resilience for healthcare facilities. There are, however, papers like (Attia et al., 2021) and academic research like (Tzoutzidis, 2023) and (Kim, 2023) that aim the assessment of energy performance of existing buildings and the thermal resilience of the building by evaluating its building

envelope. The latter research direction focuses more on the impact of climate change and more specifically the impact of heat waves and earthquakes on the building and its facade.
It is true that each and every word can have many different metaphorical or literal meanings, always depending on its use, user and time. It is therefore not uncommon for a term or expression to have a falsified meaning and to spread with a different meaning than the originally intended one. Typical examples are phrases like "Less is more" by the architect Mies van de Rohe and an even more misleading term "Brutalism" again in the field of architecture. Nevertheless, in this research an attempt was made to investigate the meaning of resilience and how this term is connected with the building envelope and its thermal performance. With a better understanding of resilience, one is able to set proper goals for improving it.

2.2.2 Resilience definition

The term resilience seems to be a term with different meanings and interpretations depending on the field in which it is used. Therefore, a good understanding of it is needed. In order to achieve that the answer to the following sub-question is to be answered:

- *What is resilience?*

Some of the definitions of resilience found in literature are the following:

I. " The ability of people or things to feel better after something unpleasant, such as a shock, injury etc.", (Oxford Advanced Dictionary)
II. "The ability of a substance to return to its original shape after it has been bent, stretched, or pressed", (Oxford Advanced Dictionary)
III. "The ability of a system to withstand stresses of environmental loading" (Horne and Orv 1998, p.31), (Bruneau et al., 2003)
IV. "The ability of an entity or system to return to normal condition after the occurrence of an event that disrupts its state", (Hosseini et al., 2016).
V. "The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform, and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management."(Attia et al., 2021)

It seems that the term implies the flexibility between a "normal" state with specific levels of stress and a sudden "shock" state with the level of stress or stresses are extraordinary. As Homaei and Hamdy mention "the concept of resilience is polysemic and its interpretation can be changed based on the context and objectives in different disciplines". In other words, the meanings that can be hidden behind the term resilience differ based on each unique system in combination with a unique hazard disturbing its balance. As mentioned above resilience refers to a system's capacity to recover from failure, handle unexpected threats, and return to its original functionality. Resilience therefore seems to be a widely explored concept across different fields of study, including environmental research, materials science, engineering, sociology, and economics, resulting in multiple definitions proposed by researchers.

(Bruneau et al., 2003) focused on Federal Emergency Management Agency's (FEMA) objectives for reducing future earthquake losses and the support of disaster-resilient communities. This need to evaluate a community on whether it is resilient against earthquake hazards or not, led to the development of a broader conceptual framework and a set of metrics-measures in order to determine which systems are resilient and which are not. Bruneau was also the one who defined the most representative broad-use resilience evaluation framework starting from earthquake resilience. The metrics for quantifying resilience will be further discussed in a later chapter.

Focusing more on the main concept of resilience, Homaei and Hamdy distinguish two phases that coexist with the term resilience. The first phase is the one when a building and its users respond during a hazardous event and the second phase is when a building and its users recover after such an event. Arup defines and adds another meaning to the term resilience. It is considered as the ability of a system to adapt to a disturbing condition, maintain its functionality as much as possible and in the face of stress or disturbance to even bounce back after the disruption. In the context of building technology and hazards like earthquake and heat waves, the concept can be thought of as prevent measures taken before and after a hazardous event (Homaei & Hamdy, 2021). In the first case these are measures that seek to prevent hazard-related damage and losses and in the second case they are post-event strategies designed to cope with and minimize a disaster's impact.

These phases and characteristics assigned to the term resilience led to a broader conceptualization of the term's meaning. Resilience can be understood as the ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance). More specifically, according to Bruneau's framework a resilient system is one that shows:

- Reduced failure probabilities
- Reduced consequences from failures, damage, and negative economic and social consequences
- Reduced time for recovery (restoration of a specific system or set of systems to their normal level of performance)

However, such definitions, typically address resilience within the broader context of the built environment and without specific indicators or properties. The latter are considered mandatory for the purposes of this research since an optimization and a design proposal are to be conducted. Therefore, specific performance indicators and properties are needed to evaluate design options.

2.2.3 Resilience quantification, phases and dimensions

In this chapter the goal is to answer the research sub-question:

- *How can resilience be quantified?*

Bruneau notes that it is very important when working with resilience to identify its dimensions and the way to measure these dimensions. In his research the performance curve was introduced (Bruneau et al., 2003). This curve presents the performance of a system in relation to time.

This methodology is based on the concept of a metric or indicator in relation to time, described by a function $Q(t)$. In Bruneau's case this indicator was a community's infrastructure quality. Specifically, the performance indicator's spectrum spans from 0% to 100%, where 100% means the probability of absence of system degradation, and 0% indicates a complete lack of system functionality. In case of a hazardous event (in Bruneau's case an earthquake) happening at time t_0 it may inflict significant damage upon the system resulting in an immediate reduction in performance (for instance, from 100% to 50%). The restoration process of the system is anticipated to unfold gradually over time (see Figure 21), culminating at time t_1 when complete restoration is achieved (performance rating of 100%).

$$R = \int_{t0}^{t1} [100 - Q(t)]dt \quad (4)$$

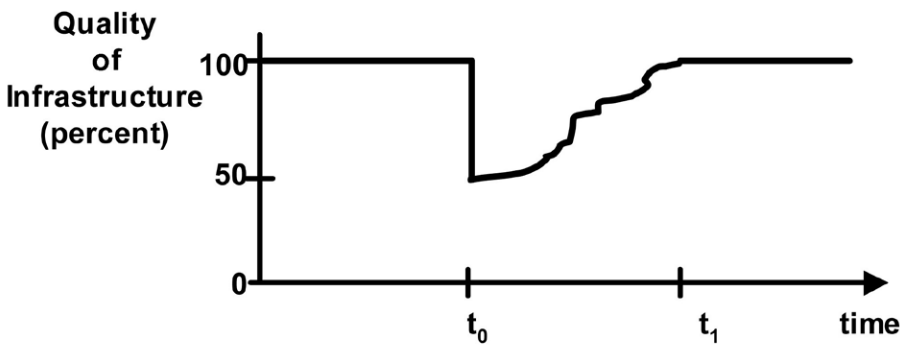


Figure. 21: Resilience quantification - Resilience curve (Bruneau et al., 2003b)

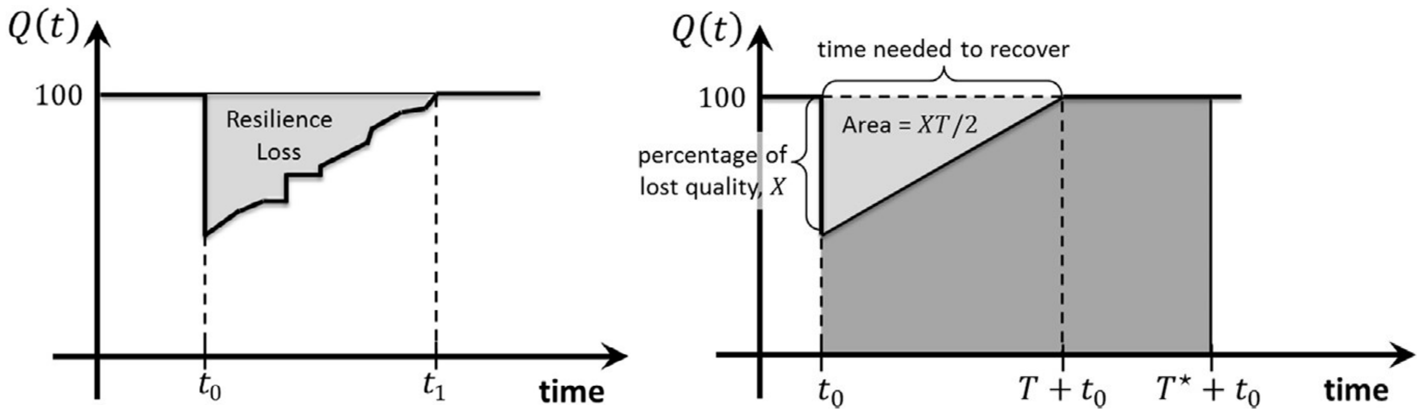


Figure. 22: Resilience loss - Resilience triangle (Hosseini et al., 2016)

The resilience loss R is then the area defined by the performance curve and is thus measured by the size of the expected degradation in performance (probability of failure), over time (time needed to recover). Depending on the performance indicator chosen for the definition of this resilience curve, and of course the nature of the system and its hazardous interruption, one is in position to assess the resilience of a system. The above presented methodology is widely known as the "Resilience triangle" (see Figures 21,22) and it was the first methodology for evaluating seismic resilience. Therefore, calculating the resilience loss of a system's property or performance indicator is a way to assess its resilience.

This method was further extended and investigated by Dr. Nikos Hatziargyriou and his team (Panteli et al., 2017) with the introduction of the resilience Trapezoid. This new conception of resilience was based on the fact that the resilience triangle cannot adequately describe hazardous events that last a longer period of time. While the triangle responds perfectly to a short-term hazard like an earthquake that may last from a few seconds to a few minutes, it is not an adequate performance metric for long-term hazards like a heatwave or a flood that can last from days to several weeks. A multi-phase resilience assessment was therefore introduced with the division of a hazardous event into five different phases. These are namely:

The original phase (Pre-disturbance resilient state): The phase when the system is functioning with a balance before a hazardous event occurs. In this phase a sufficient estimation of the event's location, severity and duration based on historical data would enable the application of preventive actions. Possible measures taken in this phase like design strategies or loss estimations would help calculate the system's ability to effectively deal with a potential hazardous event.

Disturbance progress phase (Phase I): The phase during which the system is under the influence of a hazardous event. High robustness and redundancy would help increase the system's resilience against the hazard and diminish the consequences of external shocks. Minimizing performance degradation would be the goal in this phase. Providing the appropriate flexibility with the proper sophisticated design of a system is particularly important as it would contribute in reducing the speed of performance degradation.

Post disturbance degraded phase (Phase II): Priority setting, disaster assessment and proper emergency preparedness and coordination would help the system operator to assess the damage by the event. Identifying the critical components contributing more to the recovery of the system to its original state and initiating as fast as possible the steps needed for restoring the damaged elements are mandatory in this phase. The main goal in this phase is to reduce its duration as much as possible. Usually, this phase is related to the economic loss of the system.

Restorative phase (Phase III): After the actions taken in Phase II, a resilient system should demonstrate high restorative capabilities in order to first preserve the occupant's thermal comfort (operational resilience) and secondly to restore the damaged system (system resilience). Several actions should take place in this phase according to (Panteli et al., 2017), such as replacing damaged elements of the system or adjusting all the components contributing to the desired indoor conditions.

Post restoration phase (post-disturbance resilient state): Following the event and the restoration of the infrastructure to a resilient state, the impact of the event, the performance of the system and its behavior in all the previous phases should be thoroughly analyzed to identify weaknesses or limitations. The outcome of this research and evaluation could be used for further improvements of the system in case of another hazard. Therefore, being adaptive and reflective are the key outcomes in this phase.

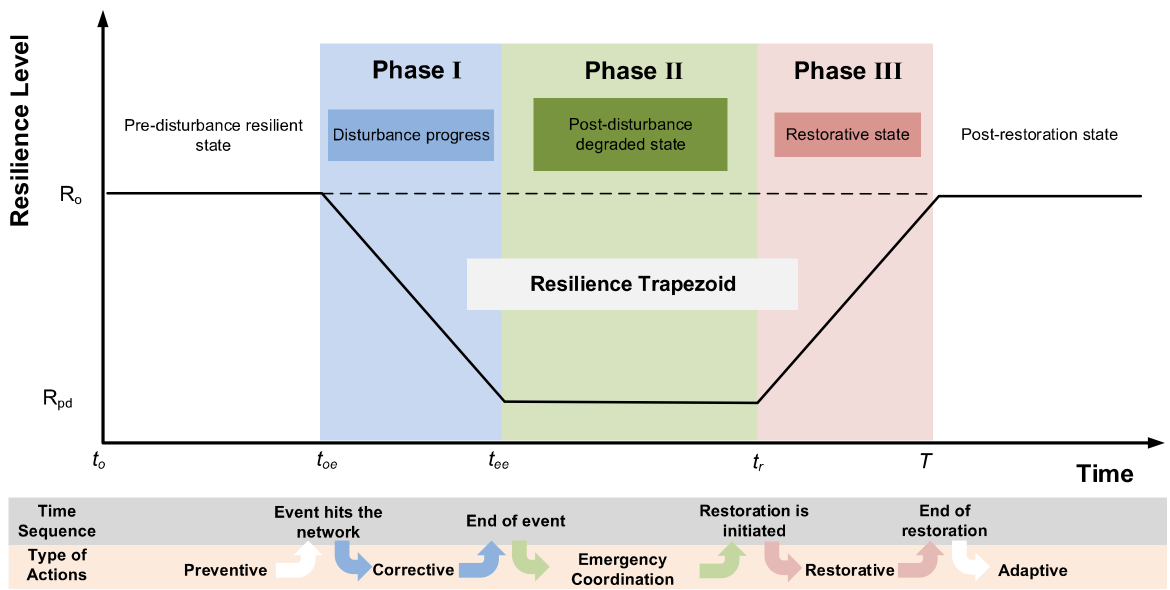


Figure. 23: Resilience loss - Resilience trapezoid (Panteli et al., 2017)

What resilience trapezoid does that the resilience triangle does not, is that it considers the degraded state that the system experiences when facing a hazardous event as well as the measures that can be taken during this phase.
Bruneau, once more in the context of seismic resilience defines the four dimensions of resilience which are the following:

- Robustness: It is the strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function.
- Redundancy: the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality.
- Resourcefulness: the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis.
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner to contain losses and a solid future disruption

(Homaei & Hamdy, 2021) on the other hand, when they discuss about a building's resilience, they define it based on building characteristics (e.g. building envelope, energy systems, storage, and backup systems, etc.) and the nature of its disruption. Moreover, they describe six components which form the fundamental abilities of a system to withstand or get over a hazardous event. These are namely: Preparation, Resistance, Absorbance, Response, Adaptation and Recover. Based on this context, a different combination of these abilities can be implemented for the definition and conceptualization of resilience for different systems and for different hazards. However as mentioned by the same authors, to achieve a comprehensive definition and assessment for building resilience, four main questions have been raised and should be answered in each unique scenario. These questions not only can help a designer understand the meaning of resilience, they can also support in setting design goals for a specific problem. These questions are the following:

Resilience of what?

This question indicates that to make research about resilience a system and a specific scale needs to be selected. Resilience can be evaluated in different ways and in different scales, from a single room/zone to a building or even a city scale. It is therefore very important to define this scale of analysis.

Resilience to what?

The second question relates to the hazardous event that influences the performance of a system or building. For example a building can be resilient to extreme hot weather but not necessarily to extreme cold weather or floods at the same time. It is thus very important to also decide against which hazard is the resilience going to be quantified. A whole new branch of research has been defined for classifying the different possible disturbances. Some approaches focus on the probabilities of a hazardous event to happen while others focus more on the impact and the duration of these events. Since this research field is a quite broad one, this research focuses more on thermal resilience of a building envelope.

Resilience in which phase?

As presented there are plenty of phases and stages in evaluating and measuring resilience. Homaei and Hamdy mention many different stages defined by other researchers in addition to their own defined ones. For example, (Sharifi & Yamagata, 2016) suggested abilities of preparation, absorption, recovery, and adaptation for a sustainable and resilient urban system. (Shandiz et al., 2020) counted preparation, withstanding, adaptation, and recovery as important abilities of the energy resilient communities. However, they all conclude that in order to be resilient, the building should be able to prepare, absorb, adapt to, and recover from the disruptive event for protecting building's occupant from health injuries due to the disruptive event like heatwaves.

Resilience based on what?

The last question to be answered is related to the metrics that are to be used to evaluate the resilience of a system. These metrics are usually related to the nature of resilience and its relationship with time. This question will be further discussed in the following section.

2.2.4 Thermal resilience metrics

When it comes to assessing resilience (Hosseini et al, 2016) identified two main types of resilience assessment methods: the qualitative and the quantitative methods. In the first category a system can be evaluated without numerical descriptive values while in the second category numerical calculations take place. These categories both consist of sub-categories. In case of the qualitative methods, conceptual frameworks and semi-quantitative indices can be found in literature. (Kim, 2023) developed a multi-hazard resilience framework for façade design focusing on seismic and thermal resilience. By quantifying seismic resilience and thermal resilience and with a multi-attribute analysis a multi-attribute decision-making workflow was proposed for evaluating and comparing different conventional façade systems.

(Hosseini et al, 2016) in his literature review mentions many more studies focusing on assessing resilience with a quantitative framework not only for (structural) systems in engineering but also for systems in other fields like social-economic systems, telecommunication networks. Broader uses of resilience are also mentioned like (Vugrin et al., 2010) that introduced resilience as a function of absorptive capacity. As will be discussed later on qualitative approaches seem to be closer to multi-attribute or else data-driven approaches in multi-criteria decision making.

At the same time, quantitative methods trying to evaluate the resilience of a system based on real measurements or simulation results and hybrid methods trying to bridge quantitative and qualitative methods for resilience assessment are also present in literature. (Tzoutzidis, 2023) through a sensitivity analysis among geometrical, material, ventilation, occupancy and temperature metrics properties and an uncertainty quantification, aimed to fill the gap between qualitative and quantitative methods for assessing thermal resilience in order to support decision making in the first stages of a new office building design. (Sun et al., 2020) developed a methodology for modelling and evaluating thermal resilience and energy-efficiency of buildings. The goal was to evaluate different retrofit strategies for improving thermal resilience, reducing cooling demands, and increasing energy efficiency. Other research like (Bennet et al.,2016) metrics like thermal autonomy and passive survivability were used to assess thermal resilience. In order to achieve this Energy plus performance simulations were used. The outcome of this particular research emphasizes the need for an approach that integrates adaptive functions within façade systems for making buildings dynamically respond to changing environmental conditions.

Diving a level deeper, according to World Meteorological Organization (WMO) (https://wmo.int/topics/heatwave) the metrics for assessing thermal comfort in buildings can be divided into two categories, biometeorological indices and heat-budget models. Biometeorological indices are based on simplified metrics of air temperature. In this category Heat Index (HI), Humidex (H), Wet-bulb globe temperature (WBT), Excess Heat Index (EHI) are only some of the indicators for assessing heat stress and each one of them has its own definition and use. Heat-budget models on the other hand are more complex indices based on multiple meteorological and physiological variables that

Heat index

Relative humidity \ Temperature	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	86 °F (30 °C)	88 °F (31 °C)	90 °F (32 °C)	92 °F (33 °C)	94 °F (34 °C)	96 °F (36 °C)	98 °F (37 °C)	100 °F (38 °C)	102 °F (39 °C)	104 °F (40 °C)	106 °F (41 °C)	108 °F (42 °C)	110 °F (43 °C)
40%	80 °F (27 °C)	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	94 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	105 °F (41 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	136 °F (58 °C)
45%	80 °F (27 °C)	82 °F (28 °C)	84 °F (29 °C)	87 °F (31 °C)	89 °F (32 °C)	93 °F (34 °C)	96 °F (36 °C)	100 °F (38 °C)	104 °F (40 °C)	109 °F (43 °C)	114 °F (46 °C)	119 °F (48 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)	
50%	81 °F (27 °C)	83 °F (28 °C)	85 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	99 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	113 °F (45 °C)	118 °F (48 °C)	124 °F (51 °C)	131 °F (55 °C)	137 °F (58 °C)		
55%	81 °F (27 °C)	84 °F (29 °C)	86 °F (30 °C)	89 °F (32 °C)	93 °F (34 °C)	97 °F (36 °C)	101 °F (38 °C)	106 °F (41 °C)	112 °F (44 °C)	117 °F (47 °C)	124 °F (51 °C)	130 °F (54 °C)	137 °F (58 °C)			
60%	82 °F (28 °C)	84 °F (29 °C)	88 °F (31 °C)	91 °F (33 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	110 °F (43 °C)	116 °F (47 °C)	123 °F (51 °C)	129 °F (54 °C)	137 °F (58 °C)				
65%	82 °F (28 °C)	85 °F (29 °C)	89 °F (32 °C)	93 °F (34 °C)	98 °F (37 °C)	103 °F (39 °C)	108 °F (42 °C)	114 °F (46 °C)	121 °F (49 °C)	128 °F (53 °C)	136 °F (58 °C)					
70%	83 °F (28 °C)	86 °F (30 °C)	90 °F (32 °C)	95 °F (35 °C)	100 °F (38 °C)	105 °F (41 °C)	112 °F (44 °C)	119 °F (48 °C)	126 °F (52 °C)	134 °F (57 °C)						
75%	84 °F (29 °C)	88 °F (31 °C)	92 °F (33 °C)	97 °F (36 °C)	103 °F (39 °C)	109 °F (43 °C)	116 °F (47 °C)	124 °F (51 °C)	132 °F (56 °C)							
80%	84 °F (29 °C)	89 °F (32 °C)	94 °F (34 °C)	100 °F (38 °C)	106 °F (41 °C)	113 °F (45 °C)	121 °F (49 °C)	129 °F (54 °C)								
85%	85 °F (29 °C)	90 °F (32 °C)	96 °F (36 °C)	102 °F (39 °C)	110 °F (43 °C)	117 °F (47 °C)	126 °F (52 °C)	135 °F (57 °C)								
90%	86 °F (30 °C)	91 °F (33 °C)	98 °F (37 °C)	105 °F (41 °C)	113 °F (45 °C)	122 °F (50 °C)	131 °F (55 °C)									
95%	86 °F (30 °C)	93 °F (34 °C)	100 °F (38 °C)	108 °F (42 °C)	117 °F (47 °C)	127 °F (53 °C)										
100%	87 °F (31 °C)	95 °F (35 °C)	103 °F (39 °C)	112 °F (44 °C)	121 °F (49 °C)	132 °F (56 °C)										

Key to colors: Caution, Extreme caution, Danger, Extreme danger

Humidex

Dew point (°C) \ Temperature (°C)	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
10	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
11	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
12	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
13	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
14	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
15	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
16		21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
17			22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
18				24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
19					26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
20						28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
21							29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
22								31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52
23									33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53
24										35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
25											37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55
26												39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
27													42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58
28														44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59

Figure. 24: Heat Index and humidex metrics for temperature perception and thermal comfort assessment
https://en.wikipedia.org/wiki/Heat_index
https://en.wikipedia.org/wiki/Humidex

aim to calculate the human body's heat gains and losses in mathematical terms. These indices are based on research conducted during the 70s that later became the basis for standards and guidelines and were gradually updated until today. In this category popular indices like Fanger's Predicted mean vote (PMV),

Universal Thermal Climate Index (UTCI), Standard Effective Temperature (SET), Perceived temperature (PT) and Physiological equivalent temperature (PET) among others can be found. Since thermal resilience of a building represents its response to a thermal hazard, like a heatwave, in all different phases as discussed in the previous chapters, indices defining thermal comfort indoors could also be considered as indices of thermal resilience of a building. According to the Energy Department of the United States the metrics needed for evaluating thermal resilience in the building scale are Heat Index (HI), Humidex (H), and Standard Effective Temperature (SET) and these are the ones that are considered in regulations and standards.

(Homaei & Hamdy, 2021b) in their research refer to metrics like overheating risk, heat index, passive survivability, and thermal autonomy as simplified metrics for evaluating thermal resilience based on simulation results. In an earlier study (Hamdy et al.2017) introduced three new metrics. The first one is indoor overheating degree (IOD) which is based on a more "traditional" metric Indoor overheating hours (IOH) and is considered a more accurate assessment of it. This metric was introduced in order to also consider different thermal comfort limits for each zone based on its function and at the same time the intensity and frequency of overheating occurrences. The second one is the ambient warmness degree (AWD) which describes the severity of global warming scenario and finally the third one is the overheating escalation factor (OEF) which is the ratio between IOD and AWD and represents the sensitivity of an indoor space with overheating and a climate change scenario.
IOD can be calculated by the equation:

$$IOD = \frac{\sum_{z=1}^{z} \sum_{i=1}^{Nocc(z)} [(T_{fr,i,z} - TL_{comf,i,z}) \cdot t_{i,z}]}{\sum_{z=1}^{z} \sum_{i=1}^{Nocc(z)} t_{i,z}} \quad (5)$$

Where $T_{fr,i,z}$ is the free running indoor operative temperature at the time step i in the z zone, $TL_{comf,i,z}$ is the comfort temperature limit at the time step *i* in the z zone, $Nocc(z)$ is the total occupied hours,

$t_{i,z}$ is the time step (typically 1h) and z is the total number of the building zones. In this equation, only positive values can be used for $(T_{fr,i,z} - TL_{comf,i,z})$. For thermal comfort temperature limits $TL_{comf,i,z}$ that are adaptive temperature limit Hamdy followed two directions.
One was to use CIBSE Guides and the other one was to use the Dutch adaptive assessment scheme. AWD can be determined with the equation:

$$AWD_{18^\circ C} = \frac{\sum_{i=1}^{N}[(T_{a,i} - T_b) \cdot t_i]}{\sum_{i=1}^{N} t_i} \quad (6)$$

Where $T_{a,i}$ is the outdoor dry-bulb air temperature, T_b is the base temperature (set at 18°C in Hamdy's research), N is the number of occupied hours so that $T_{a,i} >= T_b$ and *t* is the time step (typically 1h). T_b was chosen as 18°C by the researcher for practical reasons. Since the value is lower than every minimum summer comfort temperature limit this assures that AWD will always be higher than zero and therefore the overheating escalation factor can be calculated with the following equation in the next page.

$$\alpha_{IOD} = \frac{IOD}{AWD_{18^\circ C}} \quad (7)$$

Although these metrics are quite accurate and mathematically defined, Hamdy's research focuses on dwellings in the Netherlands. This is important since it has been examined that people feel warmer when they are at home compared to their work environments (an office). As Hamdy mentions "people feel warmer in their home than they do in their office even when the indoor climate is identical, they conduct the same activities and wear the same clothing". Therefore, the subjective nature of thermal comfort as well as the function for which these equations were formed (dwellings) make this methodology unsuitable for this research objectives.

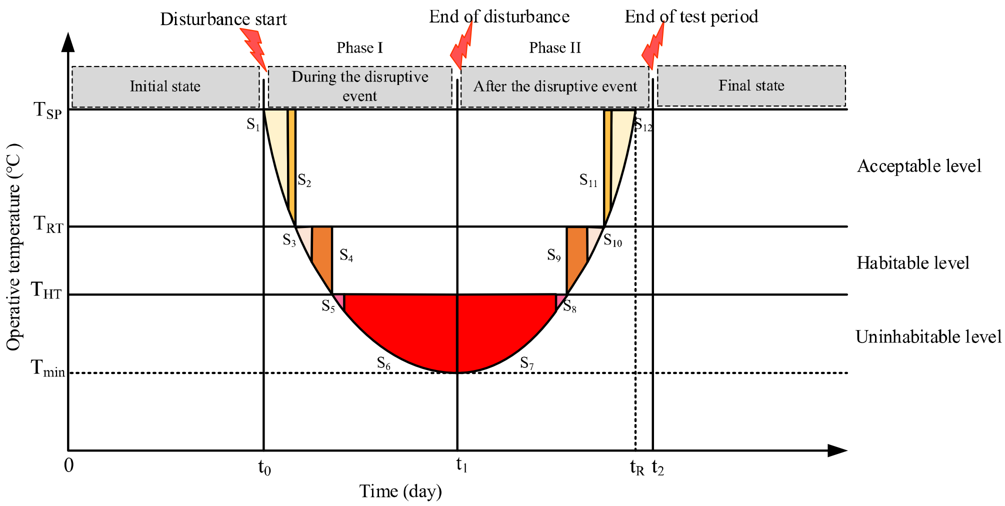


Fig. 3. Differentiation of 12 various segments in resilience test framework.

Figure. 25: WUMTP approach and differentiation of the 12 segments in the framework (Homaei & Hamdy, 2021)

As it is noted in literature most of the indices are focused on single zone areas and they cannot be used for evaluating a whole building. The latter is very important for a building and its resilience to be comparable with other cases. Thus, in order to define the "overall thermal resilience" of a building (Homaei & Hamdy, 2021b) introduced the weighted unmet thermal performance (WUMTP).

Weighted unmet thermal performance (WUMTP), which according to the author is the most precise metric currently in literature, is a determination of thermal performance deviation from the corresponding temperature targets for occupancy hours in case of a power failure. The calculation is based on four performance thresholds namely:

- the setpoint temperature Tsp
- the robustness threshold Trt
- the habitability threshold Tht
- the minimum expected performance/goal Tmin

Based on these performance thresholds and the two phases of a hazardous event similar to the resilience triangle but not similar to the resilience trapezoid (Phase I: disruptive event/event duration from t0 to t1, Phase II: recovery phase from t1 to t2) penalties can be determined based on the phase, the hazard type and the exposure time of a system to a hazard, in this case a thermal zone to a thermal hazard.

$$WUMTP = \sum_{i=1}^{12} S_i W_{P,i} W_{H,i} W_{E,i} \quad \text{[Degree hours]} \ (8)$$

The formula stated above where S_i is the area of a zone, the $W_{P,i}$, $W_{H,i}$, $W_{E,i}$ indicators represent the penalties as described of the ith zone describes mathematically the new metric introduced for a single zone. By dividing the sum of the weighted unmet thermal performance of all the zones in a building and dividing with the total area of the building an overall value very similar to energy intensity (division of the total energy demand of a space to the total area of the space) can be determined for evaluating the whole building. The lower the overall indicator is the greater the resilience of the building against the hazard. Thus, the lower this indicator is the more resilient the building.

$$WUMTP_{overall} = \frac{\sum_{z=1}^{z} WUMTP_z}{\sum_{z=1}^{z} A_z} \quad \text{[Degree hours/m2]} \quad (9)$$

Indeed (Homaei & Hamdy, 2021b) attempted to classify different design scenarios based on their overall WUMTP values in the same way buildings can get an energy label from A+ to G. The methodology, although it considers the conditions in all the building's zones and can be used to evaluate the whole building, is limited only to assessing resilience in a cold event and a specific type of building. As the researchers mention, the framework leaves space for improvements and adjustments when it comes to warm scenarios like heat waves and the definition of thermal comfort. Moreover, (Homaei & Hamdy, 2021b) conducted their research in order to investigate whether the implementation of PV panels and battery storage would contribute to the thermal performance of the building, mostly in phase II. The latter leads to the question: What happens with other measures like passive shading and ventilation system retrofit strategies? Perhaps these could be questions for further investigation.

2.2.5 Part II concluding remarks

Resilience, like any other term, has acquired different backgrounds and meanings since it was originally used. It started as a term in the field of ecology and through research mainly through earthquake engineering it managed to reach the field of climate design and thermal comfort. As it was analyzed, the term implies a flexibility of a system between a normal balanced state with specific performance indicators and values and a sudden shock state when the level of stress the system needs to withstand are extreme and its performance diminishes eventually leading to failure or an imbalanced state. The recovery of this imbalanced state and the speed of this recovery were meanings that were later added to the term's original meaning.

A fundamental property of resilience is that it is time dependent. This is because in all its definitions and dimensions assigned by researchers, it consists of the phase before and after a hazardous event occurs. Either by dividing these two phases into three phases: balance phase, hazard phase, recovery phase (resilience triangle) or by dividing them into more phases (resilience trapezoid) its other properties or else dimensions are always dependent on the time occurrence and the duration of the shock.

As discussed, resilience in engineering is usually based on Bruneau's performance curve and the way resilience loss of a performance indicator can be determined. Along with this broader conceptual framework the four dimensions of resilience were also given by Bruneau. These are robustness, redundancy, resourcefulness, and rapidity. Homaei and Hamdy on the other hand by being closer to resilience of a building system they connect resilience with terms and meanings like preparation, resistance, absorbance, response, adaptation and recover.

According to the aforementioned lterature review outputs, resilience definition as well as its properties for qualitative and quantitative evaluation always depends on the scientific field, the system to be investigated, the scale of this system, the hazardous event to be investigated, the hazard's nature and duration, but also the number and type of phases of a hazardous event. This means that a system may be resistant to one hazard but may not be resistant to another, as was shown in Hamdy's research. Therefore, the count of performance indicators to be evaluated as well as the complexity of a system's evaluation are based on the nature and scale of the system, the number of hazardous events, the probabilities that these events may affect the system simultaneously and finally the subjective perceptual analysis of the hazardous event by the researcher when it comes to hazard phases. It depends therefore on the nature of the investigation scenario (problem).

Homaei and Hamdy's questions contribute to this definition and determination of the scenario under investigation and an attempt was made to answer these questions for the purposes of the present research. In the context of this thesis and for the case study scale (resilience of what), thermal resilience is the ability of the building to maintain its indoor thermal comfort in case of extreme hot weather conditions (resilience to what). The phase in which this research focuses is the phase before the occurrence of a heat wave (the hazard under investigation). In case of Bruneau's resilience dimensions this research stands closer to the "robustness" of the building envelope against heatwaves while based on Homaei and Hamdy's components it stands between "preparation" and "resistance" (resilience in which phase). The last definition in order to define resilience are the metrics to be used (resilience based on what). The answer to this question emerged not during the literature review of this research but during the development of the digital design tool that is being presented in chapter 4.

Although in-depth research for resilience and thermal resilience was conducted, this research focuses more on the defined design goals and the development of a multi-objective optimization based framework. Thus, since the main objective of this research is to achieve a multi-objective optimization and deliver a design for an external ETFE shading system, it is aimed not to make a resilience quantification or classification, but to focus on the robustness of an existing building envelope against extreme hot weather. Therefore, the question to be answered is:

- *Based on which metrics can the resilience of a curtain wall system be evaluated against heat waves?*

Given all the analysis regarding resilience, it is assumed that the annual cooling demands of a building significantly influence its thermal resilience. Since nearly all metrics and indicators discussed are directly linked to a building's cooling strategies, cooling demands serve as a reliable indicator of the actual energy required to maintain a comfortable indoor temperature for occupants. Consequently, reducing a building's cooling demands offers dual benefits. Firstly, it positively impacts performance indicators related to thermal comfort during cooling periods, ensuring a more thermally comfortable indoor environment for occupants with reduced energy consumption. Secondly, decreasing cooling demands enhances the building's ability to withstand higher or extreme temperatures, which are expected to occur more frequently and with greater intensity due to climate change. This dual benefit not only improves thermal comfort but also contributes to the building's long-term thermal resilience.

2.3 Computational methodology

The "Computational Methodology" chapter begins by introducing the concept of multi criteria decision making and later on the significance of genetic algorithms. It then outlines the various techniques that have been employed in genetic algorithms, tracing their evolution to contemporary applications. The chapter concludes by identifying which techniques are most effective for this particular case study and workflow, explaining the reasons behind these choices. Consequently, the literature review in this section was conducted to support the development of an appropriate workflow for multi-objective optimization. Therefore,the research conducted in this part aimed answering the research sub-question:

III. *How to formulate a genetic algorithm-based multi-objective optimization workflow?*

As mentioned in the problem statement, the creation of a digital design tool would support on the one hand a designer to understand the relationships and conflicts of system properties and on the other hand it could provide instant inter-discipline feedback during the preliminary design process especially with a BIM integration. An architect and a client for example would be able to make changes to a BIM model and get instant feedback concerning the energy consumption of the building and the influence of their decisions on the design options. This way the balance between cost, aesthetics and energy consumption could be determined in an interactive way.

2.3.1 Multi-Criteria Design Methods

In order for a multi-objective optimization to be applied, basic knowledge of the different approaches available as well as a main understanding on genetic algorithms was needed. Therefore the research sub-question to be anwered is the following:

- *What are the different ways of approaching multi criteria decision making?*

Different approaches

In practice, there are two ways of approaching Building energy simulations and energy consumption predictions. These are Forward models (FM) and Data-driven models (DDM) (Olu-Ajayi et al., 2022)

Forward models (FM), also known as physics-based models, are models that usually require a large number of detailed inputs concerning the building and its environment. Inputs like HVAC system applied, insulation thickness, thermal properties, internal occupancy loads, solar heat gains and others are only some of them. In this approach, simulation programs like Energy Plus, Open Studio, TRNSYS and Doe-2 are used. Sometimes this method is considered inefficient based on literature due to the amount of information and the computational costs of such procedures. Despite its drawbacks, this method is closer to the actual design of a façade system, or a shading system and it is easier for a designer to visualize the outputs of potential decisions.

Data-driven models (DDM) on the other hand are usually based on mathematical models and machine learning techniques to calculate or estimate energy demands and consumptions based on existing data sets. The accuracy of the outputs, however, are highly dependent on the model selected and the quality and quantity of the data used. Another drawback of this method is that depending on the model used, sometimes no building geometry is used for applying calculations or to simulate energy or air flows in the building. Moreover, if the model does not fit the case or is improperly used then although a high accuracy is possible, logical mistakes can be made. This method is closer to statistics and has less to do with forms and design of façade elements. It is closer to the energy prediction and the climate design goals of a project rather than the actual design of a façade system. By comparing the two above mentioned approaches, it is easy to understand each case's pros and cons. However, not having an existing database or data set instantly directs a designer to compromise with one methodology over another.

Multi-Criteria Design Methods

At the same time there are two different ways for one to approach Multi-Criteria-Decision-Making (MCDM) concerning the building envelope of a building. These are Multi-Attribute decision making (MADM) and Multi-Objective decision making (MODM) techniques (see Figure 26). These two approaches depend mainly on the nature of façade design problem, the conflicting objectives of an optimization and the problem's variables.

As concluded in chapter 2.1.1 each façade is formed based on a specific place, specific weather conditions and specific goals defined with the guidance of an architect and his/her consultants. From literature, the design methodology usually used to design the building envelope consists of i. a façade preliminary design which begins after the end of the actual building's early design and of ii. the detailed design. The façade preliminary design is usually the most important step, since the decisions made in this phase define the complexity, the materials and the time needed to design

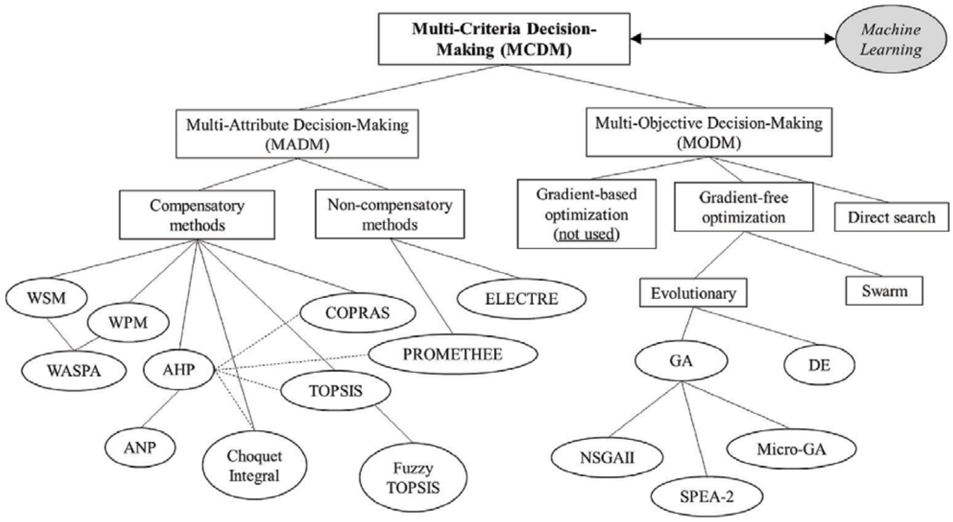


Figure. 26: Multi-Criteria Decision Making (MCDM approaches) (Bianchi et al., 2024)

properly, manufacture, produce, transfer, assemble and deliver the desired design. However, the detailed design is also very important, and, in many cases, this is also a phase when the façade materiality and architectural language tend to change based on a try and error procedure and based on mock tests in a construction site or in a factory.

The performance criteria based on which the different solutions and façade patterns of the preliminary design phase are being compared could be categorized based on the purpose, the structure and the concept. For example, functional criteria concerning the structural behavior of the system are of great importance, since the envelope needs to provide enough strenght and stiffness, tolerances, flexibility, and resilience to behave as a shelter from natural and manmade hazards. In this family of criteria, resistance against ULS (ultimate limit state: yielding, rupture, buckling and forming a mechanism) and SLS (serviceability limit state: Deflection, vibration, wind-induced oscillation and durability) loads, structural tolerances and the connection between elements are of great importance. (Cobb, 2014)

At the same time the building envelope and the basic conditions alone are not enough to distinguish the closed heated from the open unheated space. People who live and work within buildings are to live prosperously and not only in favor of the natural environment but also in favor of comfort and the balance between these two. This is when the functional criteria concerning human comfort are introduced. Providing the ideal conditions such as providing accurate daylight, visual connections between inside and outside, thermal comfort by achieving balance between heat gains, solar gains and heat losses create the appropriate circumstances for one to live healthy and work efficiently.

In literature, when façade performance indicators are being discussed, a distinction between functional, financial and environmental indicators is made. At the same time one can define variables in a multi-objective optimization by including façade-intrinsic variables (window to wall ratio, thermal properties of components, initial capital costs) or façade-extrinsic variables (building location, layout, orientation, functions-uses, HVAC system, control strategies). (Jin & Overend, 2014)

All the above-mentioned criteria are taken into account in both Multi-Attribute decision making and Multi-Objective decision making. In the first case MADM (see Figure 27), various complex decision problems can be handled based on the number of attributes-properties that need to be evaluated. Based on the population of attributes techniques like Analytic Hierarchy Process (AHP) or

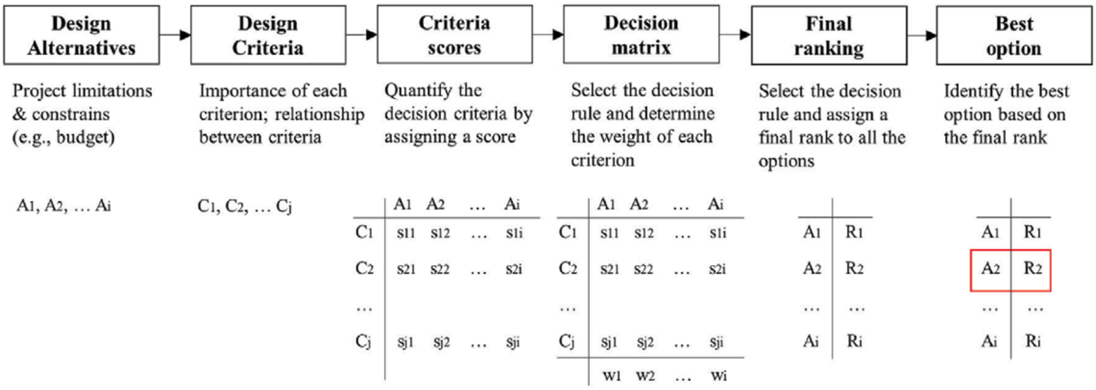


Figure. 27: Multi-Attribute Decision Making (MADM approaches) (Bianchi et al., 2024)

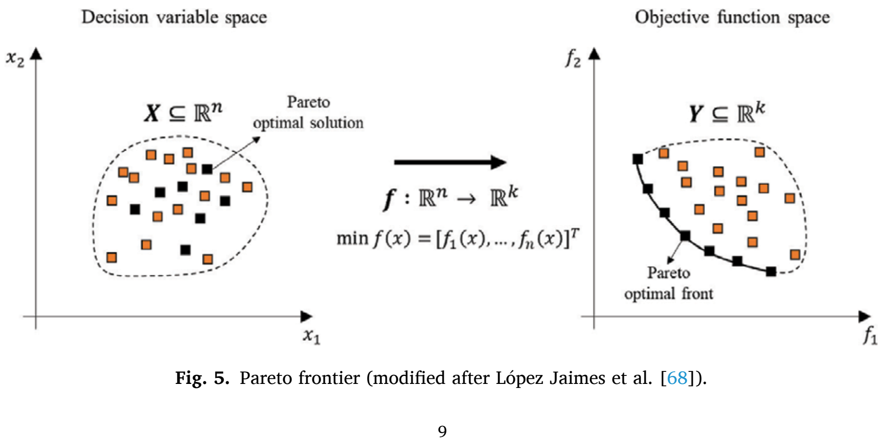


Figure. 28: Multi-Objective Decision Making and pareto front solutions (MODM approaches) (Bianchi et al., 2024)

Weighted Sum Method (WSM) as well as hybrid workflows investigating their compared predictions are usually being used. Both methods support the creation of hierarchies of façade design alternatives either by reducing the complexity of a problem or with the comparison of solution ratings. However, both methods with their sub-methods (TOPSIS-CORPA's) lack subjectivity and their results are sensitive to data variation and validation. Moreover, both methods do not account for correlations between different performance criteria. They do, however, require less computational burden and if they are used correctly, they can make accurate and precise evaluations and predictions.

In the second case MODM (see Figure 28) which is closer to forward models the problem is analyzed based on objectives. In this methodology the multi-objective optimization is based on optimization algorithms working together with numerical simulations in order for the designer to define a larger amount of design options and to evaluate them. After a simulation aiming a specific aspect of the design such as energy demands for heating and cooling, daylight, structural deflections of elements or CFD analysis is completed, all data is used to form in principle a true Pareto front curve. This curve is an optimal curve in the projection of a design space (solution space) that shows not which solution is the best but which solutions are the ones that are feasible, and it is impossible to improve one of their properties without deteriorating at least one other objective. These solutions are called non-dominated solutions. (Bianchi et al., 2024)

“A non-dominated solution is one in which no one objective function can be improved without a simultaneous detriment to at least one of the other objectives of the VMP.” (Nayak, 2020)

Multi-objective optimizations, which is the term used for these predictions, are usually performed with the use of genetic algorithms GA either directly or with their integration in simulation software. Hybrid algorithms are also present here. However, the former definition of parameters, the computation expense due to large number of simulations (each solution needs a simulation) to ensure optimal results, makes this methodology hard to implement in a workflow. The main advantage of this method, however, is that if a problem is described or designed properly then a very precise estimation of a performance criterion can be evaluated or predicted. Also, with the implementation of Machine learning techniques which is the trend in recent literature, the computational costs for the simulations could be reduced. (Bianchi et al., 2024)

In the context of resilience evaluation as it was discussed in previous chapters there are qualitative and quantitative approaches. Qualitative approaches that tend to assess a system’s resilience without numerical descriptions seem to be closer to multi-attribute decision making techniques (MADM) or else data driven models (DDM) while quantitative approaches that do need numerical descriptions tend to be closer to multi-objective decision-making techniques (MODM) or else forward models (FM). The latter approaches can be further analyzed into deterministic and stochastic approaches, dynamic and static ones. Deterministic-based approaches do not include uncertainties in their metrics while probabilistic-based approaches attempt to capture the stochasticity associated with a system behavior. On the other hand, a dynamic-based approach accounts for time-dependent behavior while a static-based approach is free of time constraints (Hosseini et al., 2016).

2.3.2 Genetic algorithms

As the title suggests, the research conducted in this part aimed answering the research sub-questions:

- *What is a genetic algorithm?*
- *What is the relationship between the inputs and the outputs of a genetic algorithm?*

The evolution and theory of Genetic algorithms

Genetic algorithms have been used for more than 30 years now and they are still being used to define large and complex design solution spaces and filter optimal solutions out of them. However, according to (Wang & Sobey, 2020) “the selection of the correct algorithm is not a simple problem by itself and can greatly affect the performance, it requires an in-depth knowledge of evolutionary computation and of the subject of optimization at the same time”. In optimization of composites for example the methodologies used are various and they are usually based on the input variables (Shape optimization SO) the objectives (weight, buckling, cost, deflection, mechanical properties MP, natural frequency NF) and the application (progressive failure PF) of the optimization. However, both in composite optimization as well as optimization for the building scale there is a lack of documentation of the genetic algorithm parameters in literature. This makes it hard to evaluate the validity and the consistency of the different genetic algorithms and the workflows in which they are used. Therefore, a broader analysis for the creation and development of genetic algorithms was conducted in order for the researcher to gain a more comprehensive understanding of the nature and reasoning behind genetic algorithms.

Genetic algorithms are inspired by Darwin's evolution theory and Maendel's inheritance theory. The main concept is that by mating the fittest individuals in a population the children of the next generation are on average fitter than the last generation. The first concept was introduced in 1950 by Turing (see Figure 29) who described the creation of a learning machine with the ability to mutate based on the "survival of the fittest". During the 1960s studies were focused on simulating and studying natural selection. The latter were the ones that inspired later in the 1970s and 1980s the development of optimization algorithms based on these theories. Elitism a mechanism developed in 1975 led to the first multi-objective genetic algorithm named Vector Evaluated Genetic algorithm (VEGA) that was created in 1985. It was a single objective genetic algorithm defining a pareto-optimal set and could divide its population in K subpopulations for its K objectives and each population was created for each specific objective. (Wang & Sobey, 2020)

After VEGA more genetic algorithms were developed like Weight-Based Genetic algorithms (WBGA), and Multi-Objective Genetic Algorithm (MOGA) in 1993. The latter was integrated in MATLAB with the MATLAB GA Toolbox. Later the more famous ones Self-Adaptive Genetic Algorithm (SAGA) in 1996, Strength Pareto Evolutionary Algorithm (SPEA) in 1999 and the first Non-dominated Sorting Genetic Algorithm (NSGA) in 1994 were developed. Micro-genetic algorithms were also developed in the 2000s with the main goal of reducing the number of function calls and were based on smaller population sizes with a function quite similar to modern machine learning techniques in which distinct populations are formed for the training and the evaluation of a model.

However, only the genetic algorithms that were developed after 2002 are considered as modern. The oldest among the modern genetic algorithms is the most famous genetic algorithm even today with the name Non-dominated Sorting Genetic Algorithm II (NSGA II) released in 2002 and it is the distinction between classic and modern genetic algorithms. Genetic algorithms that were developed in 2010s and 2020s like Indicator-based Evolutionary Algorithm (IBEA), Bi-Criterion Evolution (BCE), Multi-Objective Evolutionary Algorithm (MOEA/D) as well as Hybrid Evolutionary Immune Algorithm (HEIA) are all based on the classic algorithms with each case trying to overcome restrictions of the older versions making them more precise, less computationally expensive and more reliable, always in the context of the problem type that they are aimed to solve.

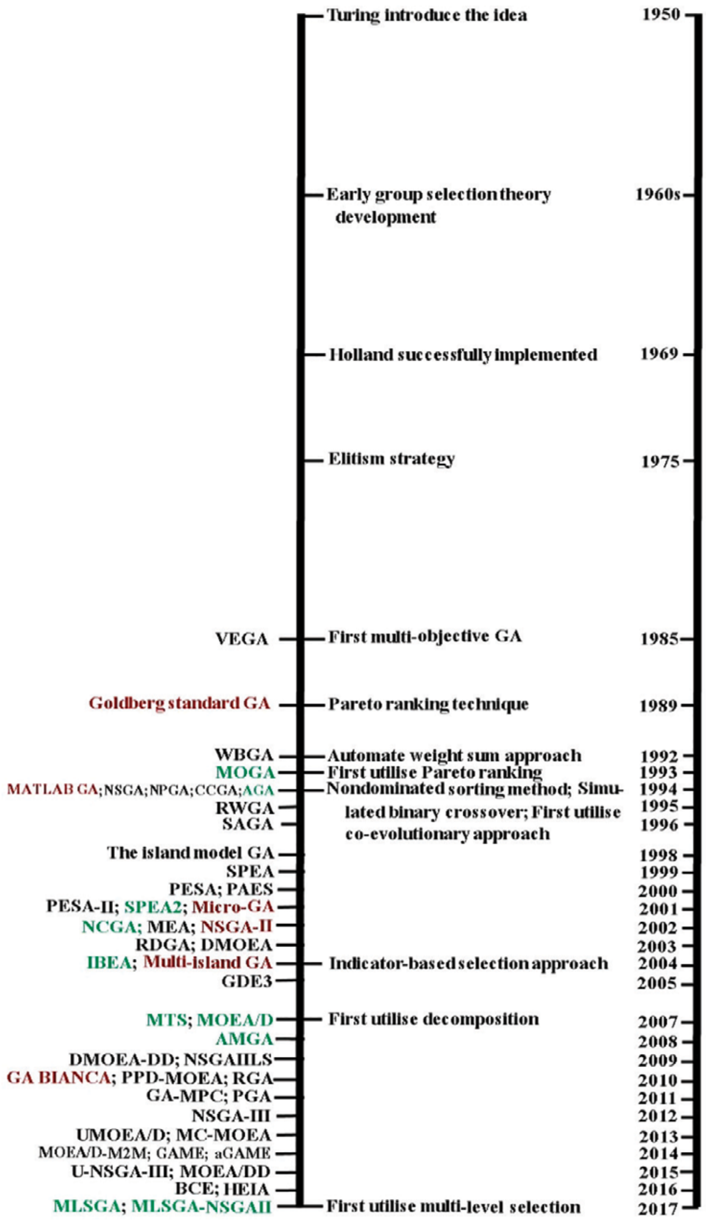


Figure. 29: Main genetic algorithm developments (Wang & Sobey, 2020)

With the evolution of genetic algorithms, different approaches to the main concept of defining the "true pareto front" were developed. Based on these methods the algorithms can be divided into four main categories. These are:

- Niching
- Decomposition
- Co-Evolution
- Multi-level selection, algorithms

More information about these techniques can be found here (Wang & Sobey, 2020), but in the boudnaries of this research niching will be investigated further.

Niching in Genetic algorithms

Although in ecology a niche is defined as the fit of a species living under specific environmental conditions, in the field of genetic algorithms and programming niching describes the formation of sub-populations in a population, where each sub-population responds to a specific sub-task of the optimization problem. The introduction of niching techniques increases the diversity of the population and helps genetic algorithms improve the ability of solving multi-objective optimization problems. The method was introduced in 1970 and is based on preselection. This means that the parent individuals can be replaced only when the new individuals and their properties are higher in terms of fitness based on the objectives of the problem, otherwise they are retained. The fitness of each individual (in case of this research a façade or shading system solution) is adjusted with the use of a sharing function that reflects the similarity between individuals in order to keep a broader diversity in the population. The algorithm is thus in position to perform selection operations by adjusting the fitness in later generations. This method of filtering solutions out and replacing them with new individuals is one of the most widely utilized niching techniques among the modern genetic algorithms. Based on this technique sequential niching as well as clearing based niching techniques which are improvements of the original niching technique were developed. Based on literature it seems that NSGA-II is the most popular Genetic Algorithm using niching as it is a robust general solver with few hyperparameters and good diversity of population based on the fast non-dominated ranking. This algorithm which has been implemented in many simulation and optimization problems in the last decade has been upgraded with versions NSGA III, UNSGA III with each specializing in many-objective optimization problem solving and mono- multi- and many-objective optimization problem solving respectively.

2.3.3 Part III concluding remarks

This chapter provided an in-depth exploration of the historical development and theoretical foundations of genetic algorithms. At the same time an examination of forward models (FM) and data-driven models (DDM), and multi-criteria decision-making (MCDM) approaches, including Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) were investigated.

The analysis highlighted the respective strengths and limitations of these approaches. Forward models, while detailed and precise, often require significant computational resources and extensive inputs. Conversely, data-driven models depend heavily on the quality and extent of pre-existing data, potentially lacking integration with building geometry an essential factor in design-oriented tasks such as the objectives of this research.

In the context of façade design and optimization, genetic algorithms have demonstrated substantial potential due to their capability to manage complex, multi-variable optimization problems. The progression of genetic algorithms, from the initial Vector Evaluated Genetic Algorithm (VEGA) to the more advanced Non-dominated Sorting Genetic Algorithm II (NSGA-II) and its newer versions (NSGA III, UNSGA II etc.), underscores their evolving efficiency and precision in addressing multi-objective optimization challenges. Modern advancements, including niching techniques, have further enhanced these algorithms' ability to maintain solution diversity and improve optimization outcomes.

However, the selection of the correct algorithm is not a simple problem. In order for one to pick or develop an algorithm one needs to have a better understanding of how a genetic algorithm works and in which way it would support a specific problem. According to (Wang & Sobey, 2020) in composite and building optimization there is a lack of documentation of the genetic algorithms and parameters that were used in literature. This makes it hard to evaluate the validity and the consistency of the different genetic algorithms and the workflows in which they are used. This means that all the algorithms that were analyzed share a common definition and goal (defining a pareto front curve of solutions) but in each unique scenario and in every unique application usually adjustments are made that unfortunately are not documented or shared with the public.

Some of the approaches, however, that are being shared. Among them are niching, decomposition, co-evolution and multi-level selection algorithms. Niching, particularly as implemented in NSGA-II and its subsequent iterations, has emerged as a critical technique for sustaining diversity and effectively solving multi-objective optimization problems. This approach allows for the creation of sub-populations within the overall population, each targeting different facets of the optimization problem. Consequently, this technique facilitates a more comprehensive exploration of potential solutions and the establishment of a true Pareto front, identifying non-dominated solutions where no single objective can be improved without degrading another.

Wallacei , as a sophisticated tool built upon these principles, seamlessly integrates with design environments such as Rhino and Grasshopper, offering a user-friendly interface for conducting complex multi-objective optimizations. Its capabilities align with the objectives of this research, providing robust analytical tools and visualizations that enhance understanding and decision-making within the design process. This tool's integration of a genetic algorithm (NSGA II), including a niching technique, along with its practical applicability within the design workflow, rendered it the optimal choice for this research. By leveraging Wallacei, this research aims to develop a digital workflow that assists designers in balancing conflicting objectives like cooling demands, daylight autonomy, total structure mass and displacement. This workflow not only aims in understanding the interrelationships and conflicts among system properties but also provides immediate interdisciplinary feedback, particularly beneficial when integrated with Building Information Modeling (BIM).

In conclusion, the selection of Wallacei and NSGA II for the multi-objective optimization was driven by its alignment with the project's objectives and its practical applicability within the workflow in Grasshopper environment.

3. Case study Design – Scenario design

3.1 Location

In order to answer the question: Resilience of what? The Pireaus Tower located in Athens was chosen as a case study for this research. Currently standing as the second tallest tower in Athens at 84 meters in height and with 22 floors, the tower was initially conceived by greek architects I. Vikelas, G. Molfesis, and A. Loizou. Constructed in 1972 in place of the old market of Piraeus ("old agora"), the tower's main purpose was to replace its predecessor functions and to be an indication of speedy development and progress. However, despite its grand ambitions and due to political reasons, the tower remained dormant and abandoned until its eventual completion and transformation into an office building in 2022.

Today the tower is finally completed and beyond its primary function as office spaces features two basements, retail spaces, restaurants, cafes, auxiliary areas, and a green roof, adding to its multifaceted appeal. Notably, the renovation of its façade played a pivotal role in Revitalizing the tower and its surroundings and significantly altering their character. The façade was designed by PILA, a renown architectural studio in Athens. PILA, in collaboration with Eckersley O'Callaghan specializing in facade design and construction, designed and successfully executed the innovative redesign of the tower's exterior delivered in the end of 2023.

This ambitious project, not only changed the tower aesthetics and image, but also Revitalized the entire port of Piraeus, leaving an indelible mark on the architectural landscape of the region.

3.1.1 Heatwaves in Europe and Athens

The Port of Piraeus is a major commercial port located in Athens. Like the center of Athens, Piraeus is often subject to heatwaves. However, what is a heatwave and how would this influence the case study building?

Heatwaves or else known as extreme heat is a period of extreme hot weather compared to the normal standards of a specific region and for a specific period during the year. The intergovernmental Panel of Climate Change (IPCC) defines a heatwave as "a period of abnormally hot weather, often defined with reference to a relative temperature threshold, lasting from two days to months". Another definition by the World Meteorological Organization (WMO) is that "a heat wave occurs when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5 °C, the normal period being 1961–1990".

In Europe it seems that the definition of a heatwave varies based on the position the term is used. The difference of course depends on the different temperatures people are used to. Temperatures that humans from a hotter climate consider normal, can be regarded as a heat wave in a cooler area. For example, in Denmark a heatwave is considered as a period of at least 3 consecutive days in which the average temperature across more than 50% of the country is over 28°C. In the Netherlands a heatwave is a period of at least 5 consecutive days in which the temperature in De Bild exceeds 25°C and during that period the temperature in De Bild has to exceed 30°C for at least 3days. In Greece the National Meteorological Service defines the heatwave as 3 consecutive days at 39°C or more when the same period normal minimum temperature is lower and there are weak or no winds at all (source). However, in literature when a heatwave is mentioned its meaning is based on the above-mentioned definitions of IPCC and WMO.

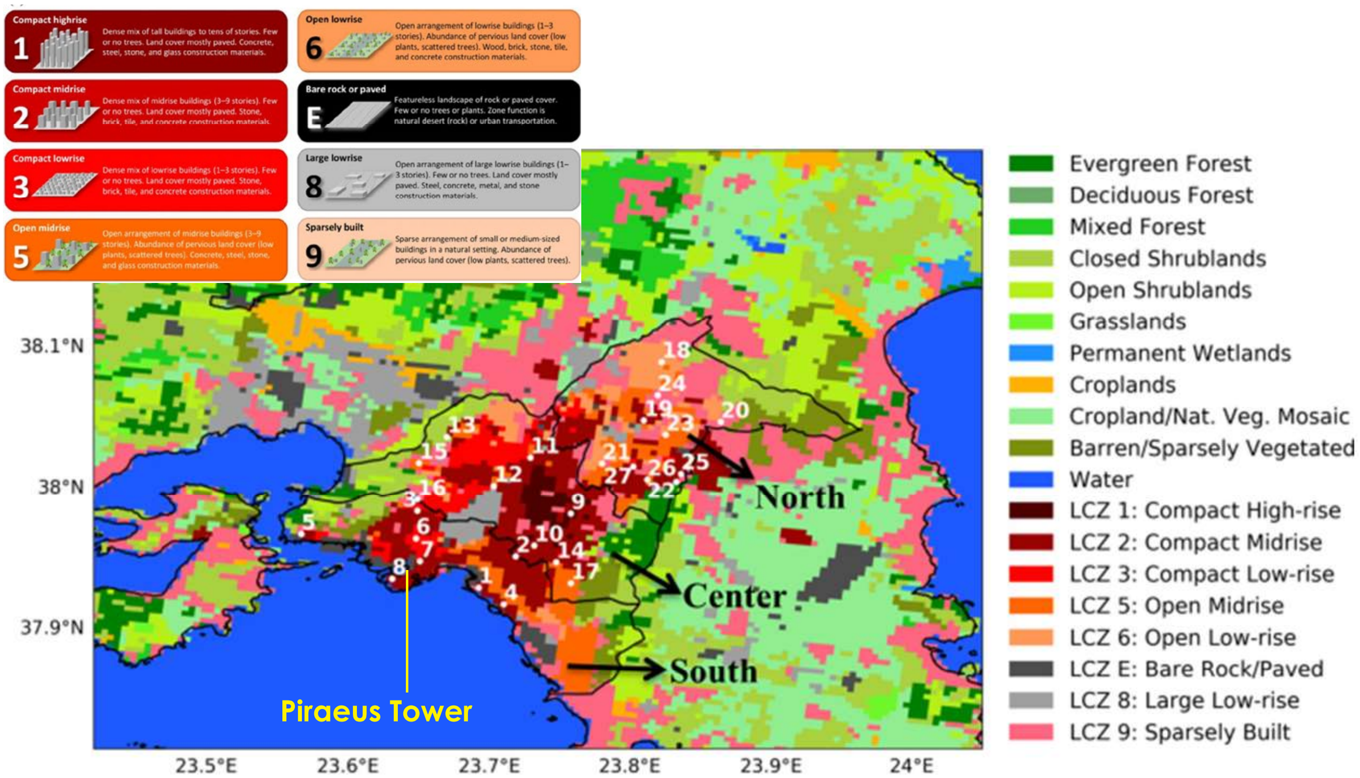


Figure. 30: District urban area types, Climate classification sectors and position of case study building (Giannaros et al., 2023)

According to (Giannaros et al., 2023) heat waves are a common feature in the summer months in countries characterized by Mediterranean climate like Greece. The heatwaves intensity and duration seem to have increased significantly in the last decades, especially after 1990. Furthermore, it is mentioned that based on future climate projections the heat waves that were observed during the early 21st century and were characterized as extreme weather events are likely to be the norm in the coming years. Based on RCP 8.5 scenario for future climate conditions super- and ultra- extreme heatwaves are expected. These extreme heatwaves and their stresses to occupants are based on Urban heat island effect (UHI) that is of course present in Athens and is based on local climate challenges due to urbanization.

It is noted that not every individual in a given city is equally exposed to increased heat stress levels. In order to quantify this a local climate zone (LCZ) framework was introduced (Giannaros et al., 2023) to classify and divide Athens into 10 distinct urban area types (see Figure 30). This framework provides a standard characterization method of both meteorological and human biometeorological environment at local urban scale. According to (Giannaros et al., 2023) Athens urban area that spans 415 km2 within the Attica region in Greece has a hot-summer Mediterranean (Csa) climate base on the Köppen-Geiger climate classification (Beck et al., 2018) and can be split into three sectors. These are: a. the south sector, b. the center sector, c. the north sector. Almost all sectors are governed by dense compact built-up areas with narrow streets, flat roof structures and light grey colored buildings.

Heatwaves that occured in the summers of 1987 and 2007 were considered as the most intense and deadly in Athens. However the summer of 2021 (see Figure 31) was one with exceptional high temperatures. Typically the highest temperatures occure during July and August as observed in literature and the weather data collected. (Giannaros et al., 2023)

In the boundaries of this research however, the Greek temperature threshold of 39°C and a duration of 7 days will be considered as a heatwave and techniques to represent these temperatures in simulations will be used.

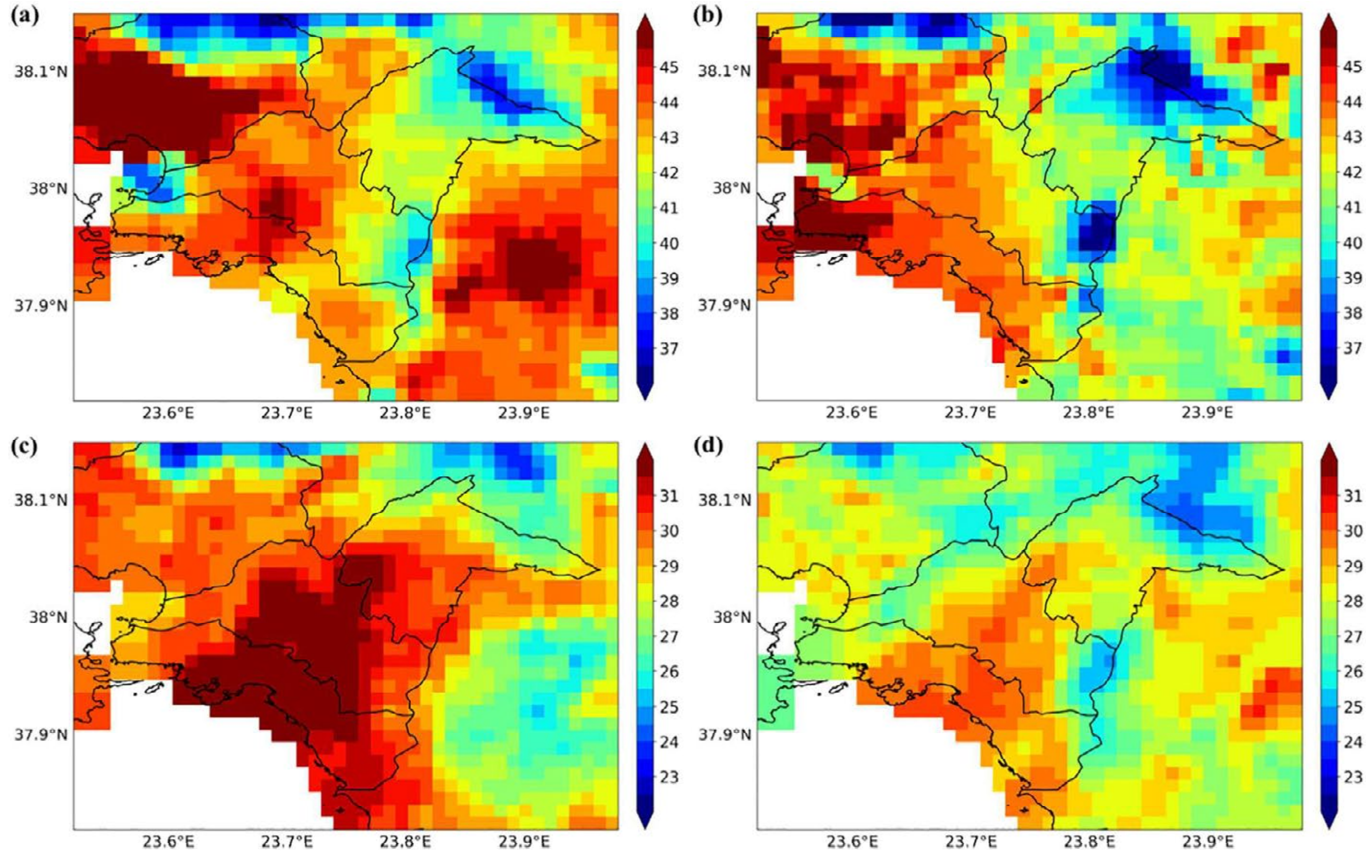


Figure. 31: Satellite-based (a, c) andWRF-BEP/BEM modeled (b, d) spatial variation of the land surface temperature on July 29, 2021, at 0800 UTC (a, b) and 2000 UTC (c, d). (Giannaros et al., 2023)

3.1.2 Weather data

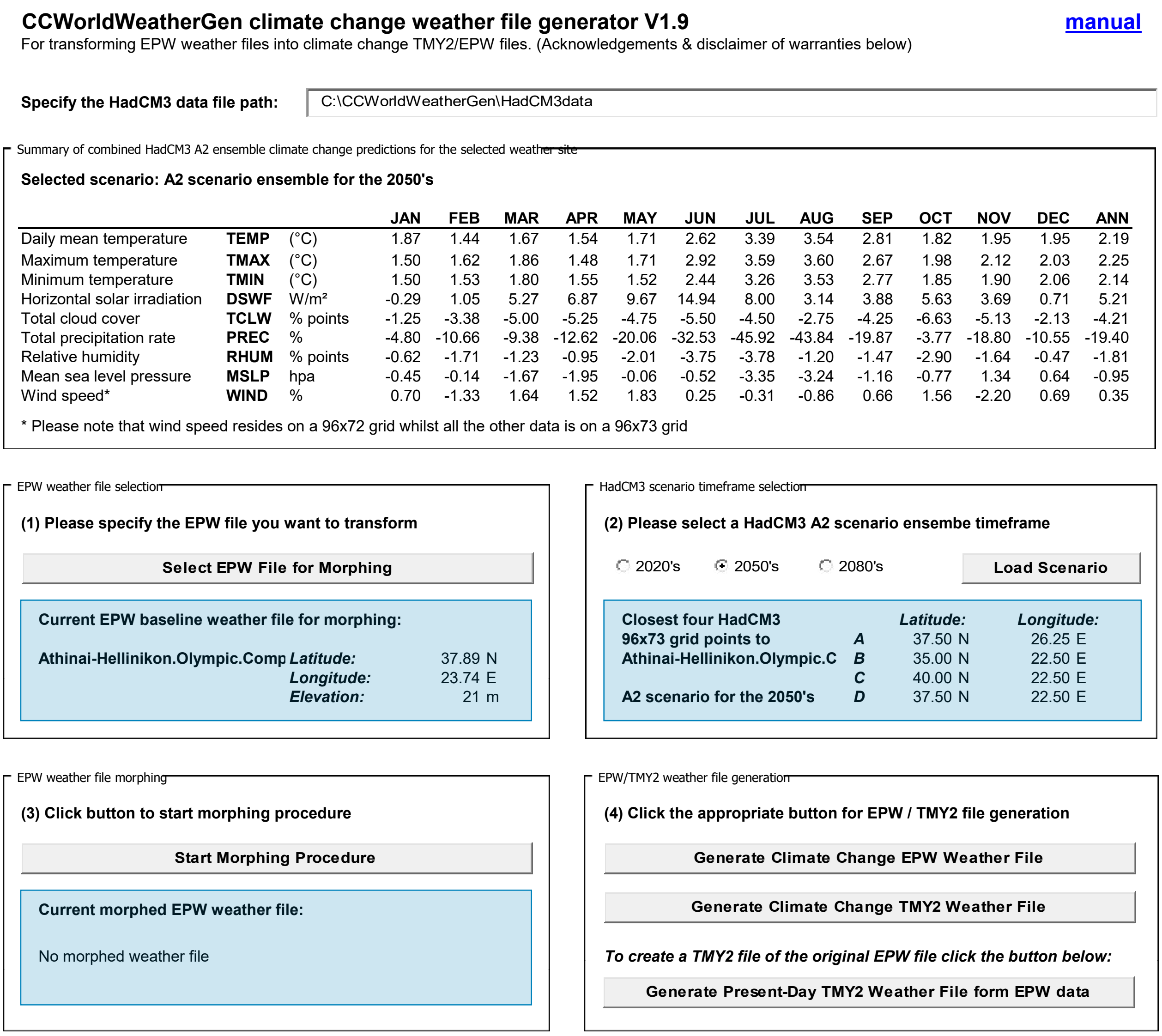
In order to represent a heat wave during a year there are plenty of approaches possible. One of them is to rely on historical data and try to determine when a heatwave occurred in the past, what its intensity and duration and base on these properties to assume that this period of the year the building is more vulnerable to heat waves. By considering a bigger amount of data a better estimation is possible and machine learning techniques would support such predictions for future weather analysis. This analysis is possible with data stored in a TMY file. TMY files are files that contain data for measurements taken during each hour of the year in a weather station and are usually translated into EPW files that are compatible with energy simulation software like EnergyPlus.

Another approach is to rely on future weather data. Future weather data are predictions about future weather trends based on climate change research and climate change scenarios published by the Intergovernmental Panel of Climate Change (IPCC). For example, Representative Concentration Pathways (RCP) are used to describe the concentration of greenhouse gas emissions in the coming years and their impact in rising temperatures. Originally there were four scenarios RCP2.6, RCP4.5, RCP6 and RCP8, but currently there are more describing the possible scenarios from now until the years 2030, 2050 and 2100.

With the help of tools like CCWorldweathergenerator, Weathershift and Meteonorm as well as new open-source tools in python environment like MEWs package, it is possible to adjust existing data and measurements (usually historical data) to make accurate predictions about future weather conditions. This procedure would help a designer to consider rising temperatures due to greenhouse gas emissions in their designs.

Online databases with historical data like OneBuilding.org, Ladybug EPW map among others were considered and the following files were found for the case study location:
GRC_AT_Athinai.Venizelos.Intl.AP.167410_TMYx.2004-2018
GRC_AT_Athinai.Venizelos.Intl.AP.167410_TMYx.2007-2021
GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx
GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx.2004-2018
GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx.2007-2021
GRC_AT_Elefsis.AP.167180_TMYx.2007-2021
GRC_Athens.167160_IWEC (sources)

From all these weather files, by focusing more on dry-bulb temperatures and after visualizations of the data in Grasshopper environment, file GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx.2007-2021 was selected because firstly it contains historical data for a more recent time period, secondly its weather station in Hellinikon Olympic complex (former international airport) is trustworthy and close to the case study building. Finally the observed peak temperatures after comparison with the rest of the files seemed to be much closer to the values discussed and analyzed by (Giannaros et. al.2023).



			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
Daily mean temperature	**TEMP**	(°C)	1.87	1.44	1.67	1.54	1.71	2.62	3.39	3.54	2.81	1.82	1.95	1.95	2.19
Maximum temperature	**TMAX**	(°C)	1.50	1.62	1.86	1.48	1.71	2.92	3.59	3.60	2.67	1.98	2.12	2.03	2.25
Minimum temperature	**TMIN**	(°C)	1.50	1.53	1.80	1.55	1.52	2.44	3.26	3.53	2.77	1.85	1.90	2.06	2.14
Horizontal solar irradiation	**DSWF**	W/m²	-0.29	1.05	5.27	6.87	9.67	14.94	8.00	3.14	3.88	5.63	3.69	0.71	5.21
Total cloud cover	**TCLW**	% points	-1.25	-3.38	-5.00	-5.25	-4.75	-5.50	-4.50	-2.75	-4.25	-6.63	-5.13	-2.13	-4.21
Total precipitation rate	**PREC**	%	-4.80	-10.66	-9.38	-12.62	-20.06	-32.53	-45.92	-43.84	-19.87	-3.77	-18.80	-10.55	-19.40
Relative humidity	**RHUM**	% points	-0.62	-1.71	-1.23	-0.95	-2.01	-3.75	-3.78	-1.20	-1.47	-2.90	-1.64	-0.47	-1.81
Mean sea level pressure	**MSLP**	hpa	-0.45	-0.14	-1.67	-1.95	-0.06	-0.52	-3.35	-3.24	-1.16	-0.77	1.34	0.64	-0.95
Wind speed*	**WIND**	%	0.70	-1.33	1.64	1.52	1.83	0.25	-0.31	-0.86	0.66	1.56	-2.20	0.69	0.35

Figure. 32: CCWorldweathergenerator tool and the four steps of generating future weather data

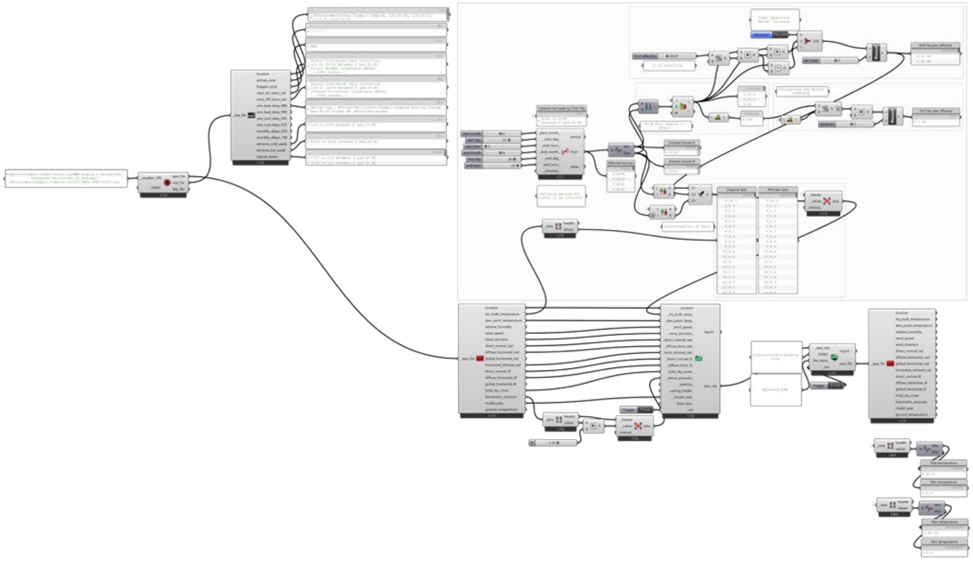


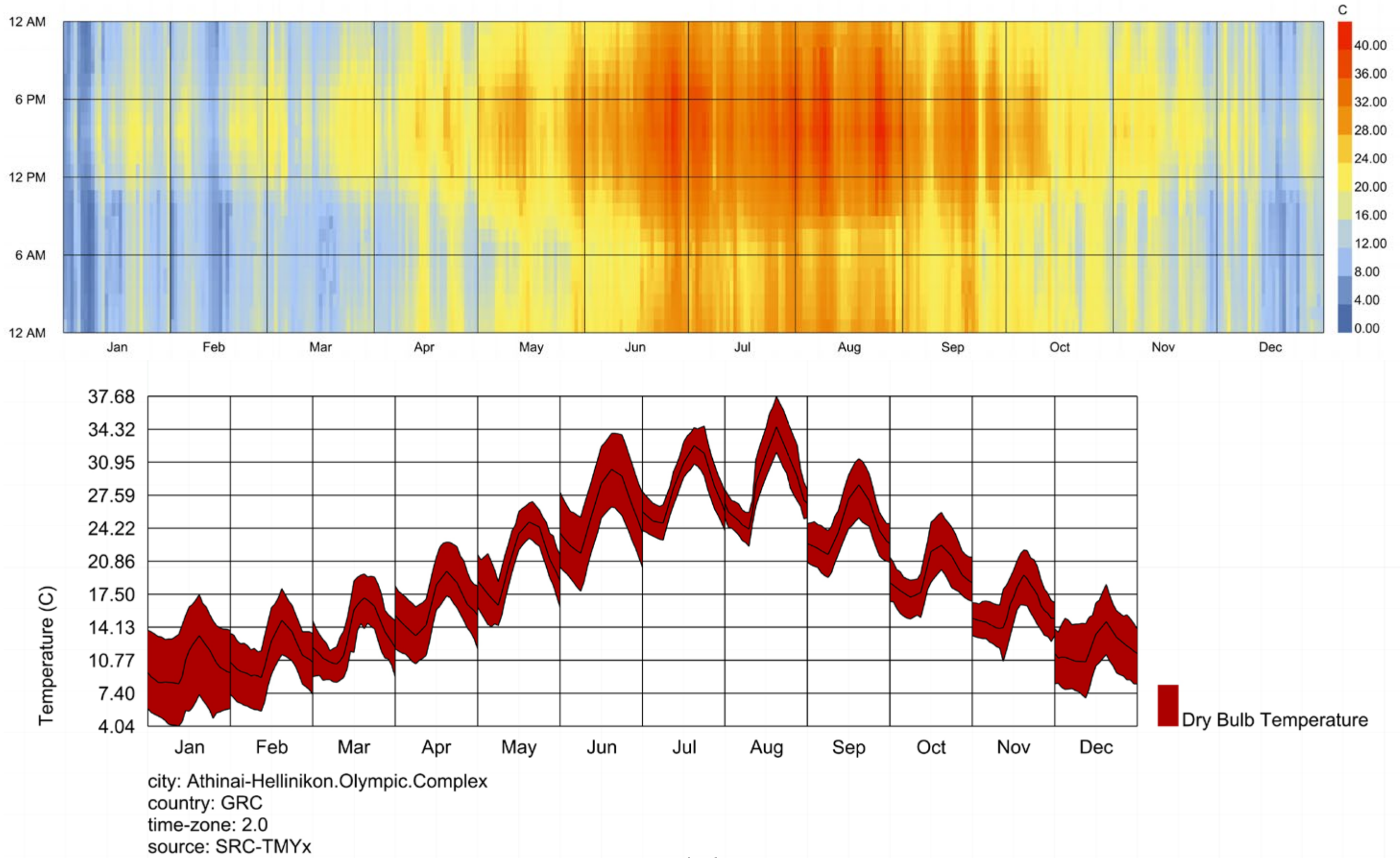
Figure. 33: Ladybug-Dragonfly workflow to affect EPW file and create a new adjusted one.

Indeed, an attempt was made (see Figure 32) to use the open source CCWorldweathergenerator by the University of Southampton to process the existing weather data available for Athens. This tool uses IPCC databases with measurements based on specific standards for evaluation and documentation of greenhouse gas emissions. Based on these data and the position they were created the tool is able to automatically find the data that was gathered for the closest weather station to the weather station the user's data were collected. By applying a climate change scenario prediction period between 2020,2050 and 2080 a morphing procedure is possible for an existing EPW file. However, due to some technical issues concerning the methodology and the time schedule of the existing EPW files a morphing procedure was not possible with this tool. Furthermore, with the morphing procedure a uniform increase in the weather data is possible, which is not considered as something accurate enough for future predictions.

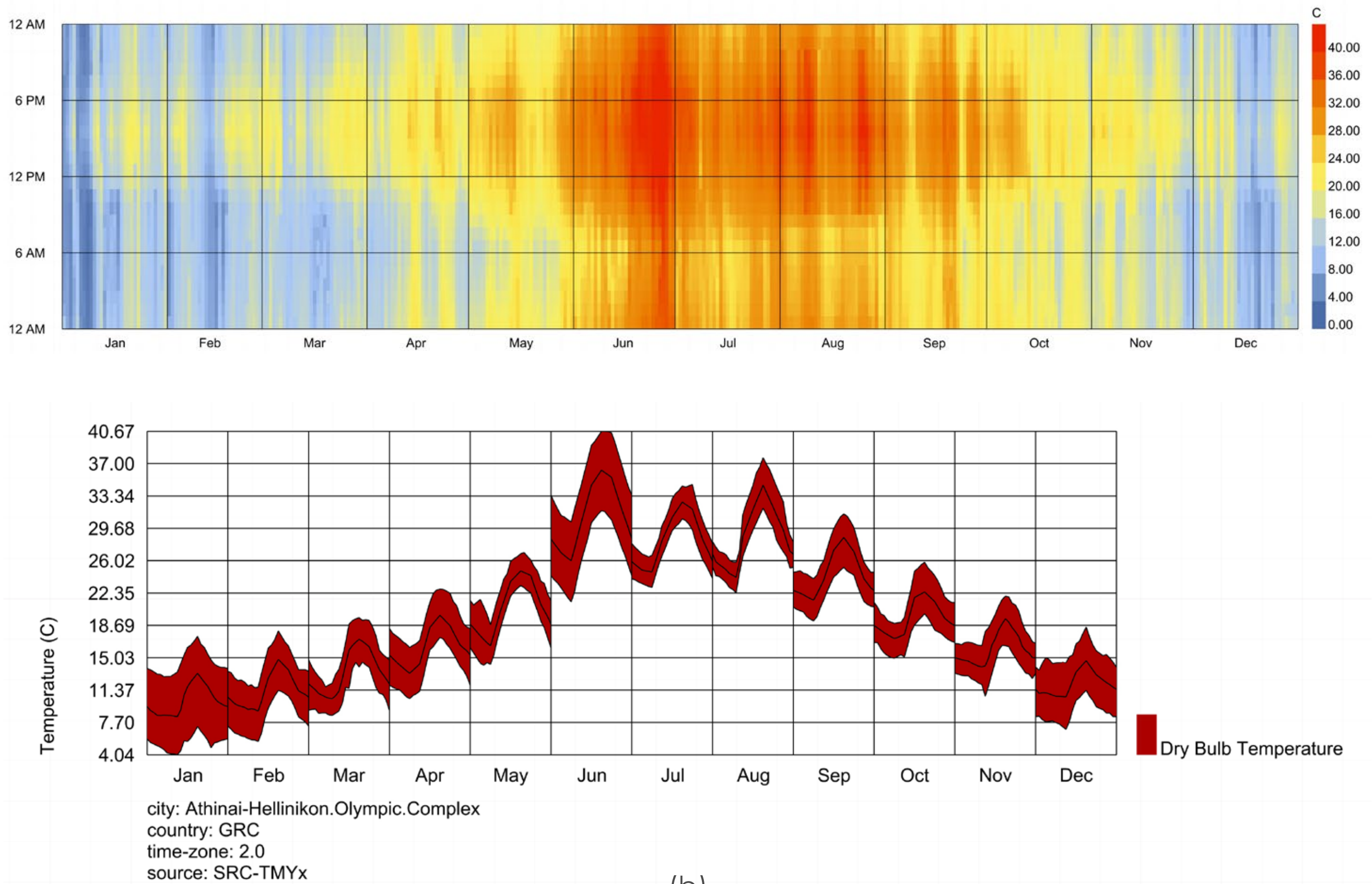
A second attempt was made (see Figures 33,34) to affect the weather data manually in Grasshopper environment with the help of dragonfly plugin in Ladybug tools. The algorithm gets weather data from an EPW file and visualizes them. Afterwards by adjusting an influence period, the percentage of influence and if the temperature is increased or decreased one is able to affect and create a new EPW weather file. Furthermore, by also considering the given STAT file from the weather station data and by adjusting the influence period to the extreme hot week calculated by a ladybug component one is able to influence the week or the month when a heatwave occurred.

Of course, such a way of processing the data does not correspond to reality since a heat wave can appear at different times during the summer months and it is unlikely that it would affect the weather conditions preceding and following it uniformly. Therefore, such a technique can only be considered as a programming exercise can not considered as accurate to represent a heatwave. MEWs package for python was also investigated but it only has morphing techniques for specific locations mainly in the US when tools like Weathershift and Meteonorm are not open source and therefore were excluded from this research.

As a conclusion, due to the sophisticated nature of morphing procedures and the uncertainties depending on the validity of the weather data and the future weather data predictions, it was decided to remain a step backwards and use the latest historical data for the purposes of this research just by adjusting the analysis period for the simulations that follow in chapter 4. Of course, further research and proper investigations should be undertaken in this step but would be easily integrated into the existing workflow.



(a)



(b)

Figure. 34: Weather data and dry Bulb Temperatures of a. the original EPW file, b. the one adjusted for a month period of 20% increase

3.2 Piraeus tower

3.2.1 Architectural and structural aspects

Piraeus tower consists of two volumes. Volume A is from the ground level +2.31m to the 3rd floor +17.15 while volume B is from the 4th floor to the 21st floor +79.18m (basements excluded).
(see Figures 35,36,37)

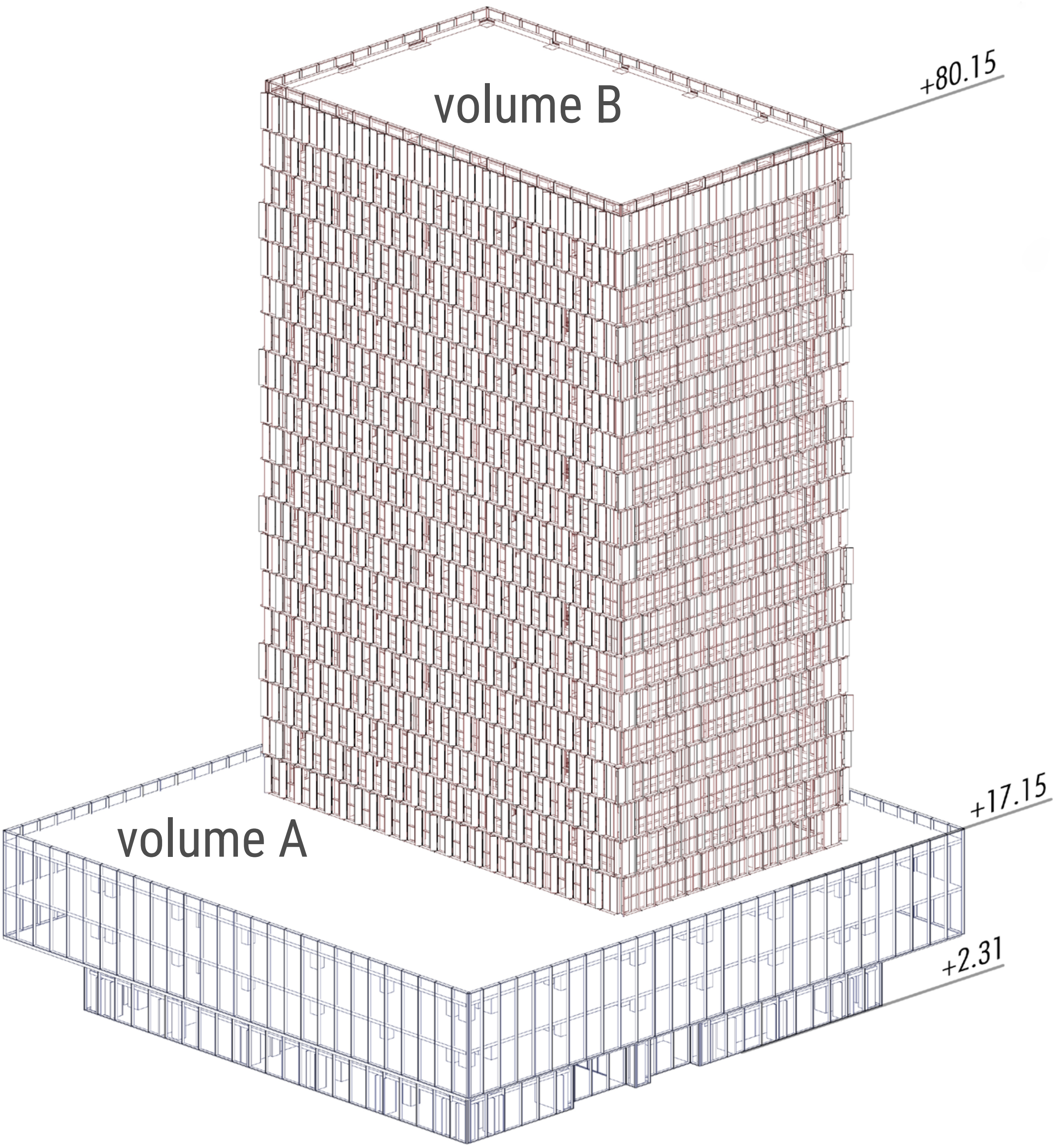


Figure. 35: Piraeus Tower and its main volumes. Design by Alkiviadis Oikonomidis based on the protoype drawings provided by Eckersley O'Callaghan

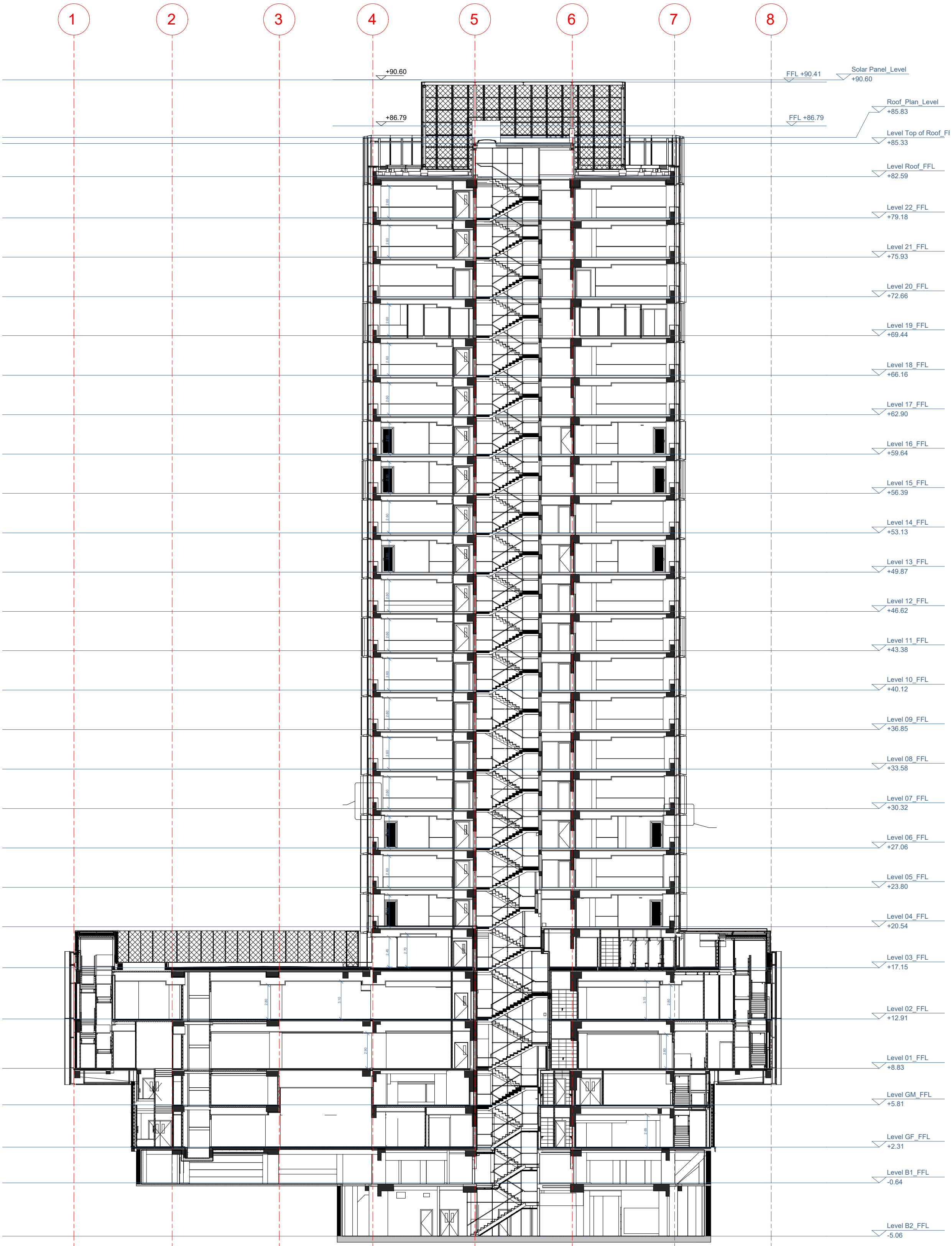


Figure. 36: Piraeus Tower Section. Drawing provided by Eckersley O'Callaghan

The first volume, which hosts functions of more public nature, houses reception areas, shopping and retail areas. The second volume, which is the main part of the tower, consists of office spaces with two typical floor plans. A typical plan of either type A or type B consists of a main part in the center of the plan, or otherwise the core of the building, and the perimeter spaces.

The core from an architectural point of view consists of the elevator areas and waiting areas, stairwell areas, server areas, mechanical areas, but also sanitary areas and break areas. This choice has been made so that the vertical and horizontal movements are as close as possible to each other to save movement time. In addition, that way the main office areas are developed around the perimeter and have access to natural light and the sun.

From a structural perspective, the core consists of concrete walls that start from the foundations of the building in the basement, penetrate all the floors and end up at the roof level. Around the core, a series of concrete wall-columns with dimensions from 2150x820mm to 1000x1000mm define the spaces and with inverted L-beams of dimensions 650x340x350x980x300x1320mm (see Figure 38) that span between them hold the concrete slabs of 250mm thickness. However, it is worth noting here that for the purpose of this research, some of the above dimensions have been rounded and simplified.

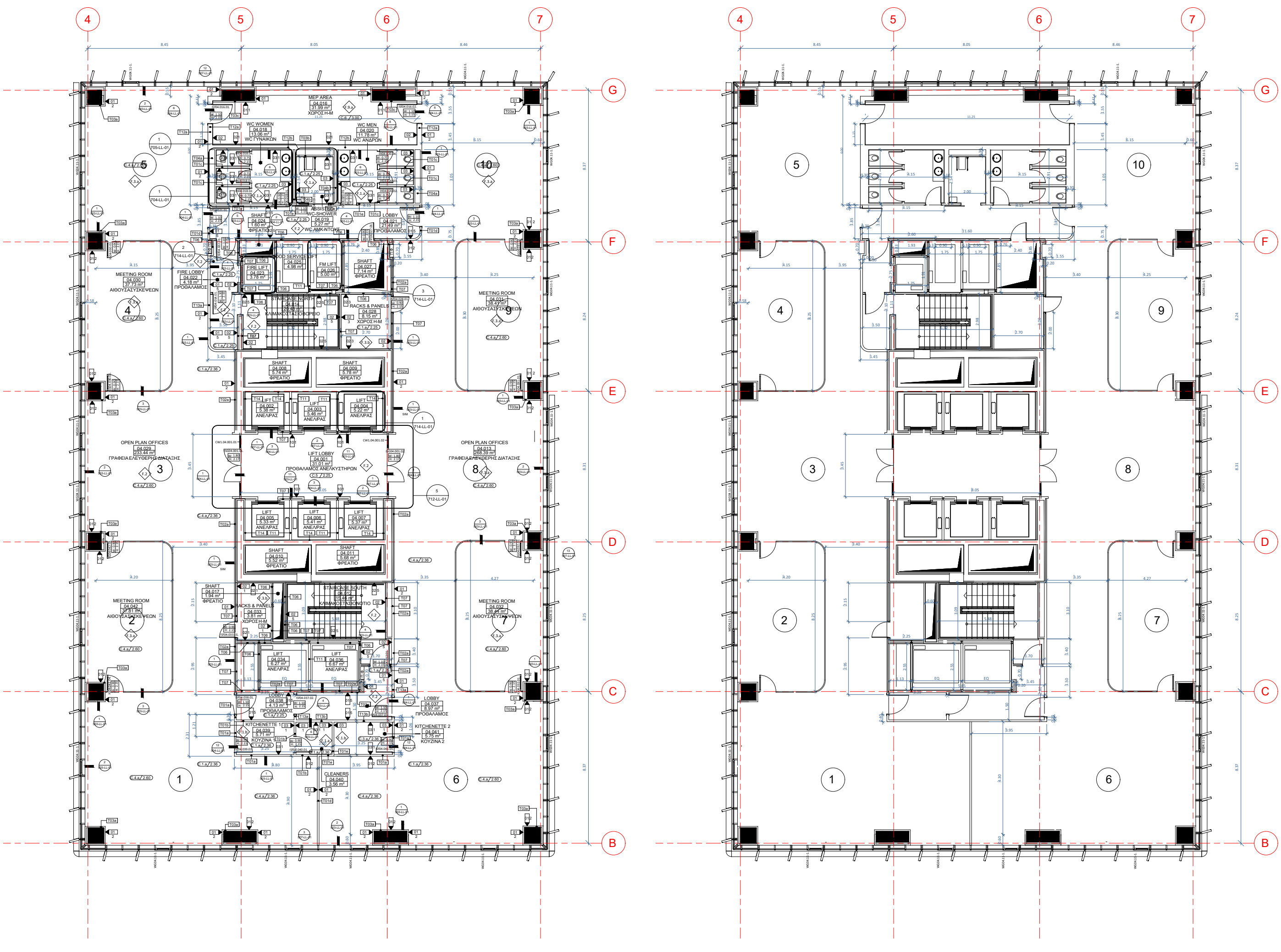


Figure. 37: Piraeus Tower typical plan A (left) and B (right)

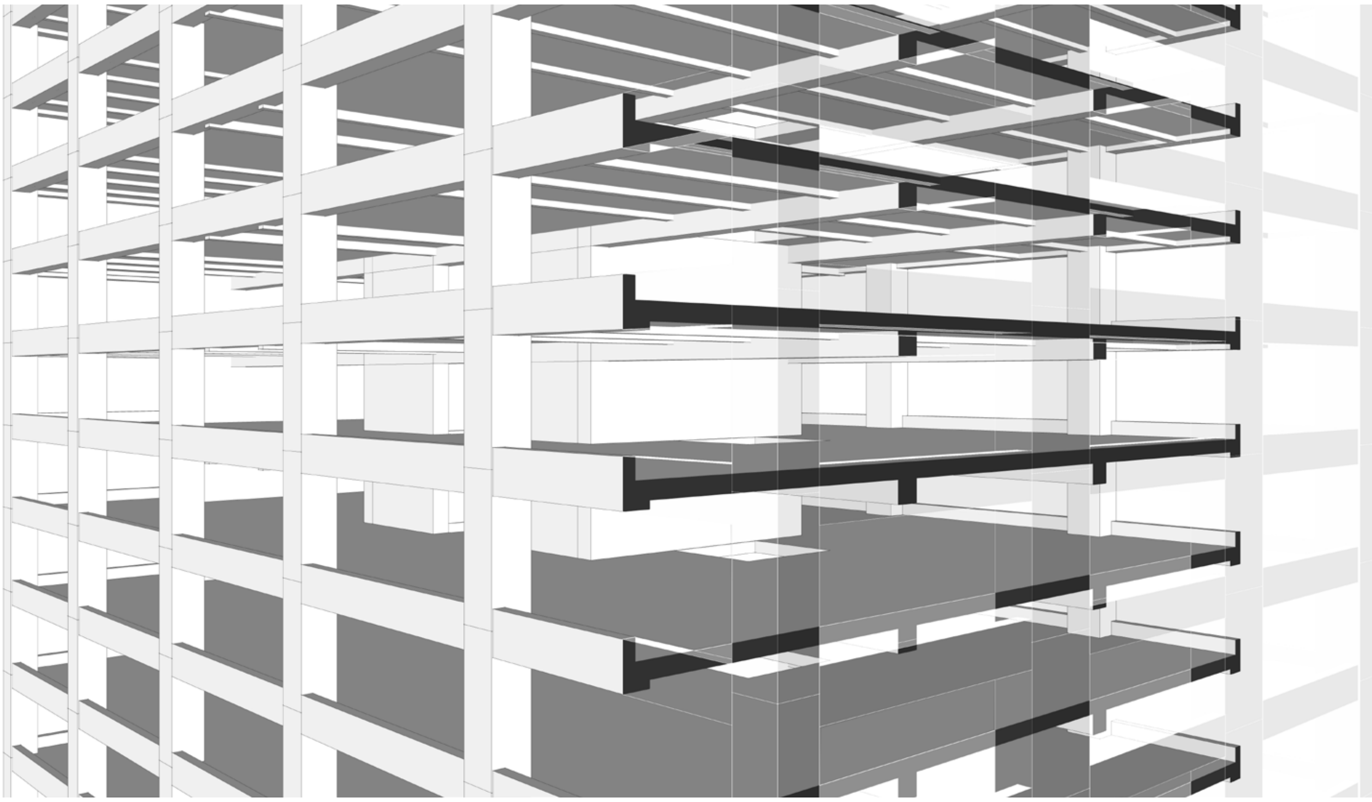
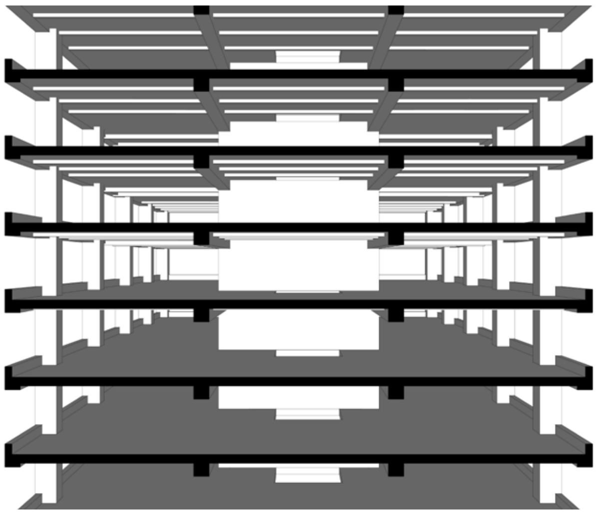


Figure. 38: Piraeus Tower main bearing structure out of reinforced concrete. Drawing by Alkiviadis Oikonomidis based on provided drawings by Eckersley O'Callaghan



While the space around the core could be a single space (see Figure 39), in both standard floor plans internal glass curtain walls that define meeting areas and closed work areas are present. In this way space gives diversity and interest but in parallel complexity as will be discussed later on.

Finally, in all spaces except the staircases there is a ceiling offset for ventilation, cooling and heating of the spaces with corresponding systems inside the floor. Again, at this point, simplifications and certain assumptions were made since there was no access to the mechanical engineering study of the building. Regarding the energy assessment model, ceilings were not included in the calculations, keeping the analysis at a simpler level.

As mentioned above, the tower was built in 1970, therefore its main load-bearing structure out of reinforced concrete was present long before the installation of the new facade. Consequently, the elevation line was defined by the researchers as the exterior line aligned with the existing columns and beams that also define the slab boundaries. This exterior line in the plan is for volume A 44.9x47.9m while for volume B 41.6x25m. However, because of some simplifications and adjustments in the BIM model this outline for the present research was set for volume B as 41.9x25.24m.

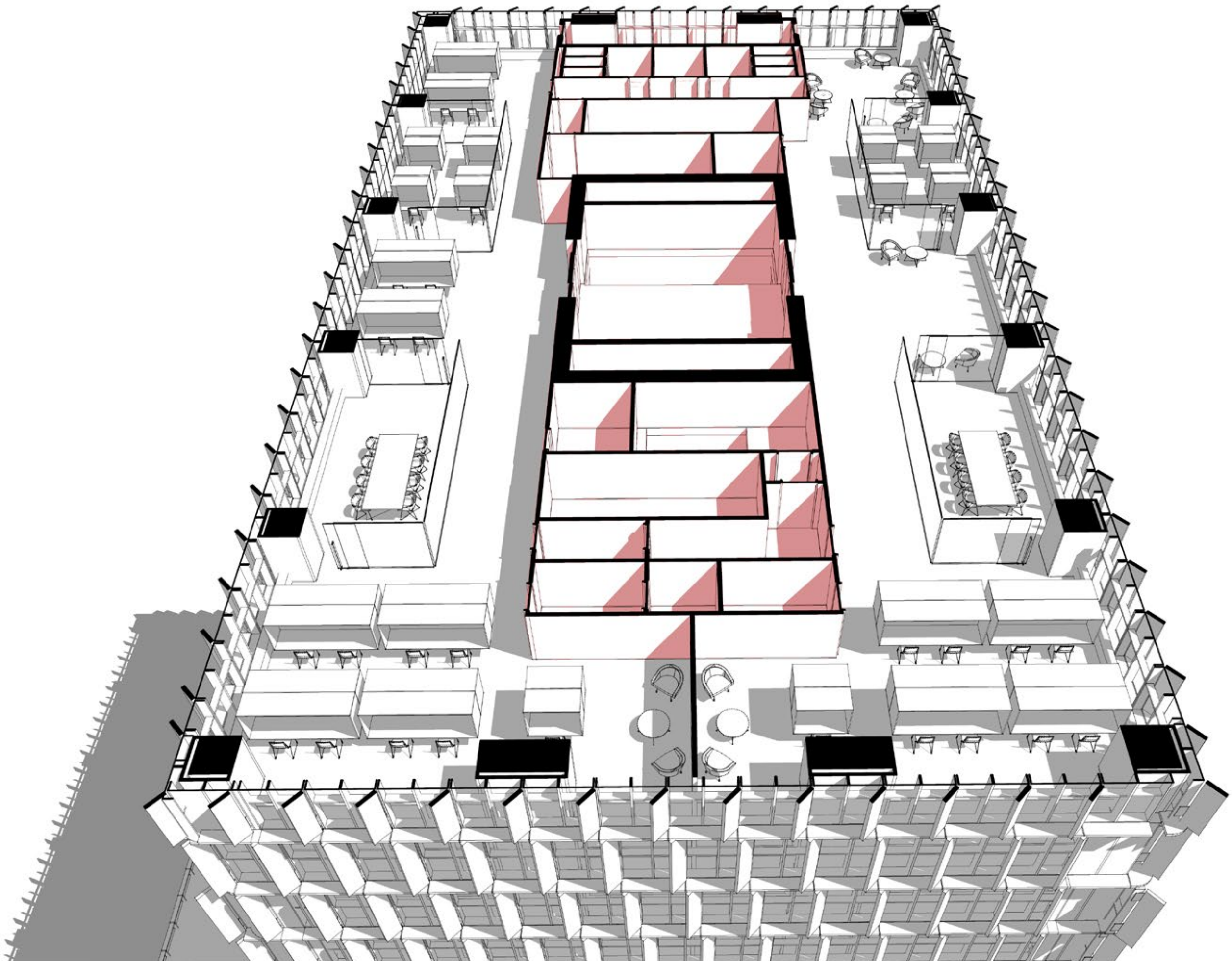


Figure. 39: The core and the perimeter functions of the tower.

3.2.2 The proposed curtain wall system by Eckersley O' Callaghan

The tower consists of 14 different types of external walls (see Figure 40). The building envelope, however, could be divided into two main parts, which are also the main types of facade types present on the tower. These are a unitized curtain wall system in the main tower (volume A and B) and a stick curtain wall system at ground level between volume A and the ground floor. This research was focused to volume B, its spaces, its energy performance and of course its shading elements.

In order to better understand the design and function of the outer envelope of the building, a series of 2D and 3D drawings for the details of the unitized curtain wall system were redesigned and analyzed based on the prototypes provided by Eckersley O' Callaghan. In addition, while the tower has four characteristic panels and more specifically the following (see Figure 41)

a. Panel with fixed glazing
b. Panel with operable window
c. Panel with fixed window
d. Metal mesh MEP panel

only the fixed glazing panel was analyzed and redesigned in detail with the assumption that it does not have a shading box.

Reference code	Legend	System description	Thermal / Weather tightness			Acoustic		Fire		Security		
			U-value requirement [W/m²K]	System air leakage	Water tightness	Sound Transmission Rw [dB]	Sound flanking Dn,f,w [dB]	Fire compartmentation	Fire Rated components	Manual intrusion	Ballistic	Blast
EWS-101		Glazed unitised curtain wall	<= 1.5 (TBC)	Class AE 900 to EN 12152 (TBC with wind tunnel test)	Class RE 900 to EN 12154 (TBC with wind tunnel test)	>= 46 (most onerous)	> 50	EI 90	n/a	n/a	Not required	Not required
EWS-102		Opaque unitised curtain wall at MEP rooms	n/a	Class AE 900 to EN 12152 (TBC with wind tunnel test)	Class RE 900 to EN 12154 (TBC with wind tunnel test)	not available (TBC)	> 50	EI 90	n/a	n/a	Not required	Not required
EWS-103		Glazed unitised curtain wall at crown	n/a	n/a	n/a	n/a	> 50	EI 90	n/a	n/a	Not required	Not required
EWS-104		Opaque unitised curtain wall at level 03	<= 1.5 (TBC)	Class AE 900 to EN 12152 (TBC with wind tunnel test)	Class RE 900 to EN 12154 (TBC with wind tunnel test)	>= 46	> 50	EI 90	n/a	n/a	Not required	Not required
EWS-201		Podium unitised curtain wall	TBC	Class AE 900 to EN 12152 (TBC with wind tunnel test)	Class RE 900 to EN 12154 (TBC with wind tunnel test)	>= 46 (most onerous)	> 50 (TBC)	EI 90	n/a	n/a	Not required	Not required
EWS-202		Inclined feature canopies	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Not required	Not required
EWS-301		Stick curtain wall system	TBC	TBC with wind tunnel test	TBC with wind tunnel test	>= 44 (most onerous)	Not available (TBC)	EI 90	n/a	TBC	Not required	Not required
EWS-401		MEP box screen	<= 0.30 (TBC)	n/a	n/a	TBC	n/a	n/a	n/a	n/a	Not required	Not required
EWS-501		Unitised glazed elevator shaft	n/a	n/a	Class RE 900 to EN 12154 (TBC with wind tunnel test)	n/a	n/a	n/a	n/a	n/a	Not required	Not required
EWS-502		Unitised window wall system at elevator	TBC	Class AE 900 to EN 12152 (TBC with wind tunnel test)	Class RE 900 to EN 12154 (TBC with wind tunnel test)	>= 41 (most onerous)	> 50	EI 90	Required (TBC)	n/a	Not required	Not required
EWS-503		Restairant entrance at elevator shaft	TBC	TBC with wind tunnel test	TBC with wind tunnel test	>= 36	> 50 (TBC)	EI 90	Required (TBC)	n/a	Not required	Not required
EWS-601		Metal rain-screen system	<= 0.30 (TBC)	3.0 m³/h/m² @ 50Pa	All weather joints shall be watertight at the pressure indicated in the air permeability criteria	>= 41 (most onerous)	> 50	EI 90	n/a	n/a	Not required	Not required
EWS-701		Glazed staircase box	TBC	TBC with wind tunnel test	TBC with wind tunnel test	TBC	TBC	EI 90 (TBC)	TBC	n/a	Not required	Not required
SOF-801		External soffit	TBC	n/a	All weather joints shall be watertight at the pressure indicated in the air permeability criteria	TBC	n/a	n/a	n/a	n/a	Not required	Not required

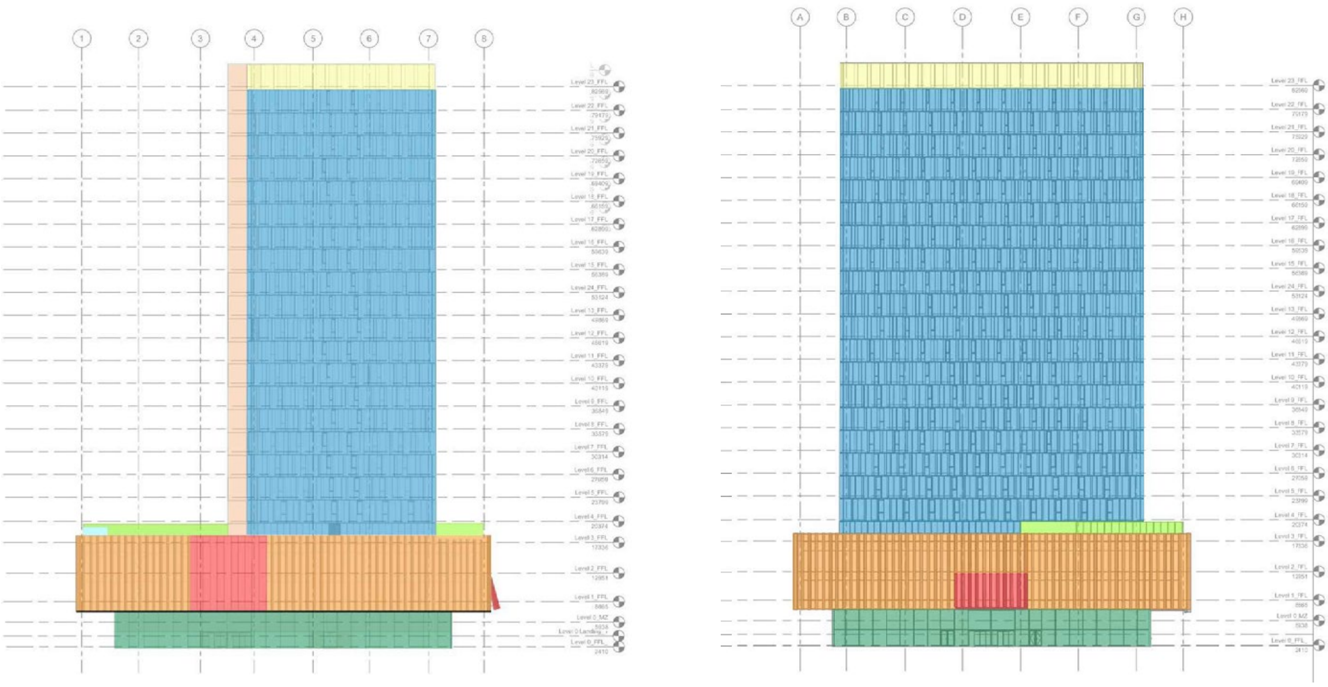
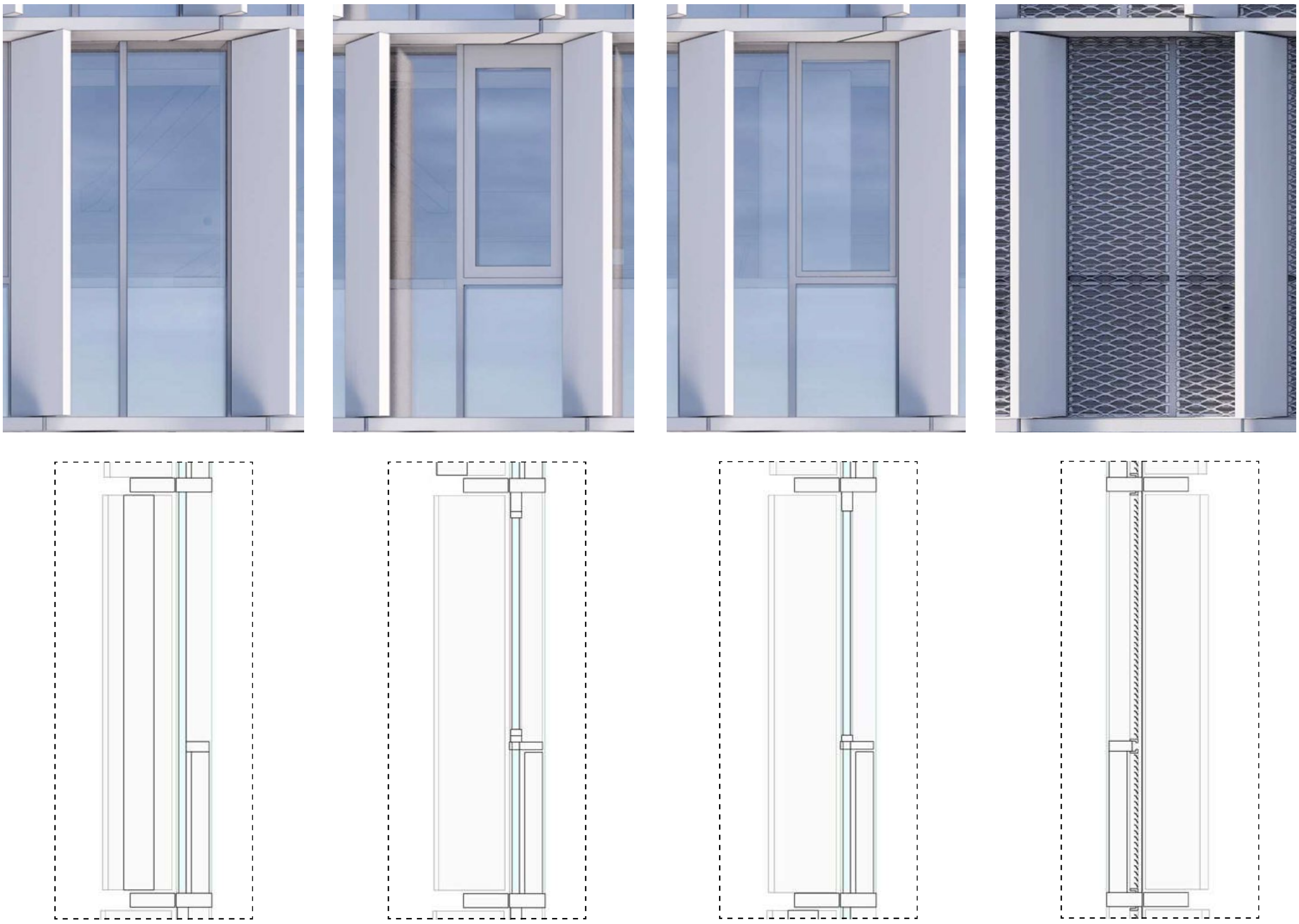


Figure. 40: The tower's different skin types, drawings provided by Eckersley O'Callaghan

In other words, it was considered that the unitized panels were 100% transparent and without operable windows. However, their actual dimensions were kept the same in this research for all the static reasons analyzed in the previous chapter. Consequently, 3.2 x1.8m panels were designed and used for this research.



(a) (b) (c) (d)

Figure. 41: The tower's different panel types, a. Panel with fixed glazing, b. Panel with operable window, c. Panel with fixed window, d. Metal mesh MEP panel, drawings provided by Eckersley O'Callaghan

Structural support system

Each aluminum panel consists of prefabricated interlocking profile sections out of extruded aluminum. These profiles are then filled with glass and insulation where needed. Additionally, each panel has its own shading elements. Each panel has a horizontal and a vertical fin also made of extruded aluminum, while each panel, both in the normal and in its shadow box section, has triple glazing. Finally, the insulation neglected in this research is actually out of mineral wool and is hidden inside an aluminum casing suspended by the panel frame.

When it comes to the support method, each panel spans from slab to slab and is usually hung from the slab above it with the help of two hung hooks and pre-placed brackets on the main bearing structure (L shape beams). Each panel snaps to the one below and next to it, holding itself as well as the adjacent panels in plane. Despite the offset of 400mm per floor carried out for aesthetic reasons, in each vertical connection between two panels there is a longitudinal "shear block" connection that allows the adjustable vertical and horizontal movement of the panels.

According to Eckersley O' Callaghan's study and after the analysis of the plan and section drawings, the slabs of the reinforced concrete building showed large variations in their boundaries. These variations are of the order +- 50mm and they are much larger than what is typically expected in new buildings.

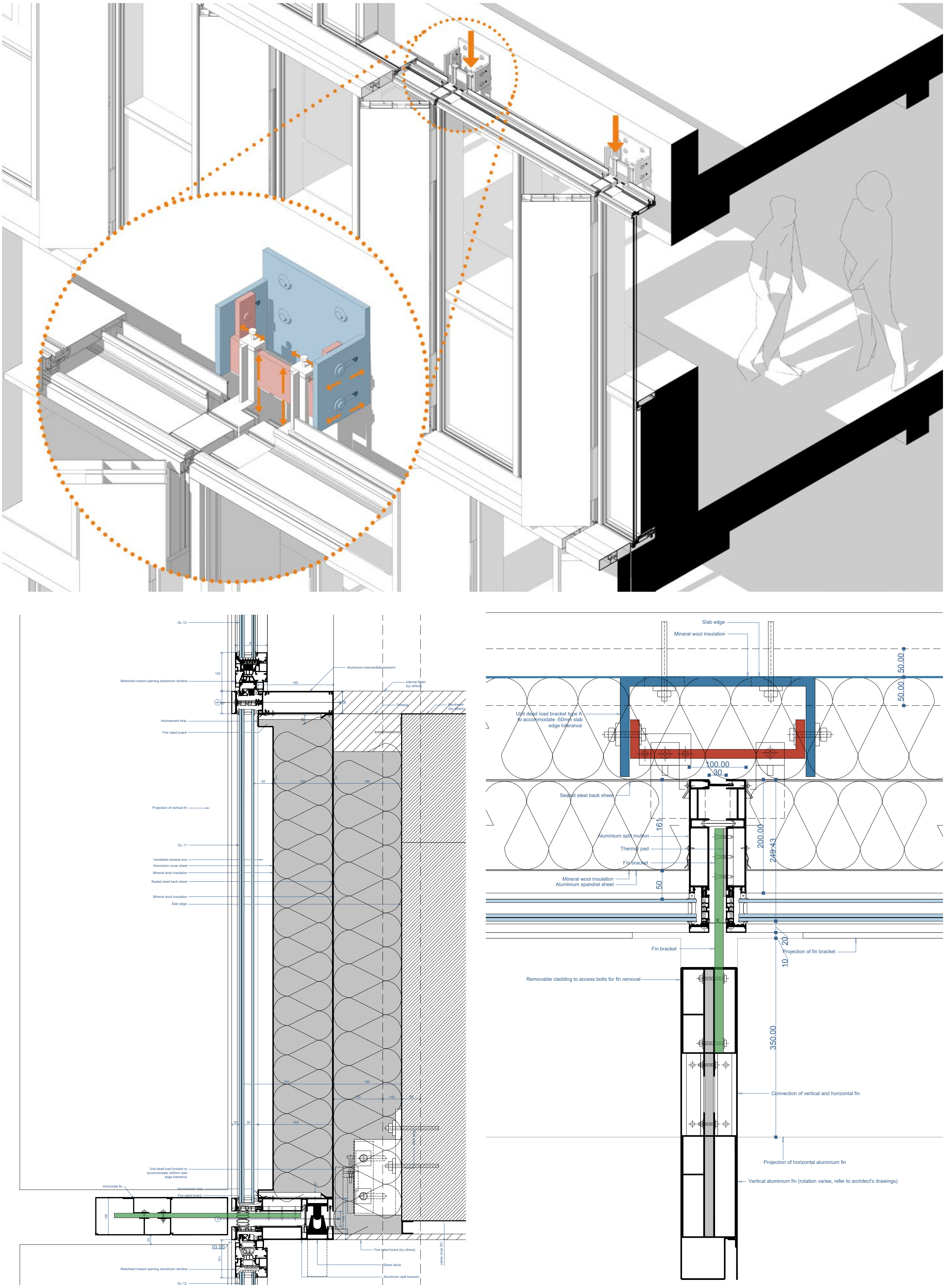


Figure. 42: The panels structural details. Movement accomodation at the top, typical details and connection with horixontal and vertical fins at the bottom. Drawings by Alkiviadis Oikonomidis based on provided drawings by Eckersley O'Callaghan

Of course, these are due to old construction methods and the exposure of the load bearing structure to external weather conditions. To deal with this problem, however, as well as with the horizontal and vertical tolerances, two C-Shaped brackets were used per panel joint, one inside the other (see Figure 42). One bracket is nailed on the inverted beams which are also the limits of the slab, while the other allows the hung hooks to be supported. One bracket will handle the variations from -50mm to 0mm, while the other one will handle the variations from 0mm to +50mm.

Movement accomodation

The building moves as a whole as well as locally due to deformations because of the dead and live loads it carries and because of inter-storey drift due to horizontal loads such as wind and earthquakes. For this reason, the panels have a "stopper" element in their lower part (see Figure 43) in order for it to rotate around it in case of such movements of the main bearing structure. Creep is also a factor in panel movements. However, according to Eckersley O' Callaghan study, since the building is relatively old, the creep has already appeared in the structural elements and is unlikely to increase significantly in the future.

According to Eckersley O' Callaghan, the differential movement between adjacent panels must be less than or equal to 10mm, with preferred values of 5-7mm, in order for the face to be airtight and waterproof. This means that the wider a panel is, the smaller this limit of differential movements should be. (see Figure 44)

Shading elements

The panels feature an external shading system with vertical and horizontal fins. The rotation of the vertical fins changes on each floor and can be adjusted with brackets set at different angles.

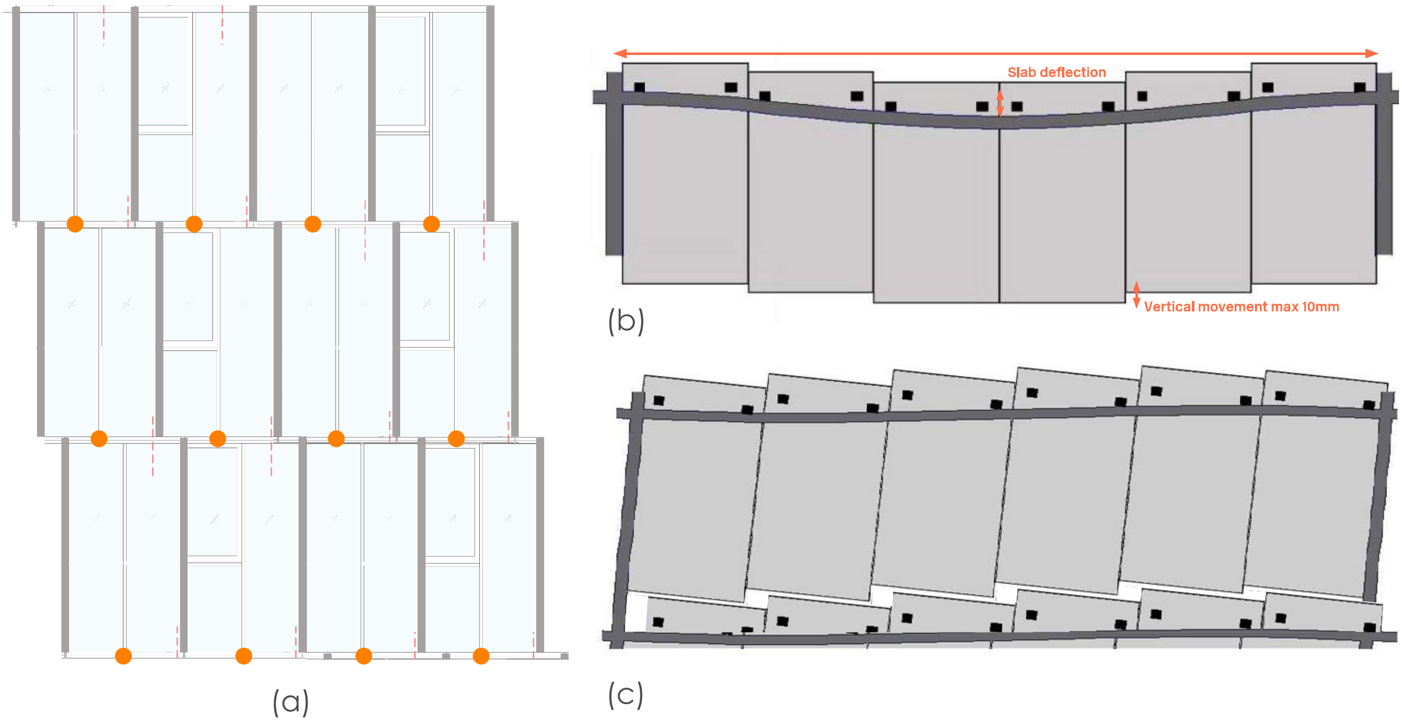
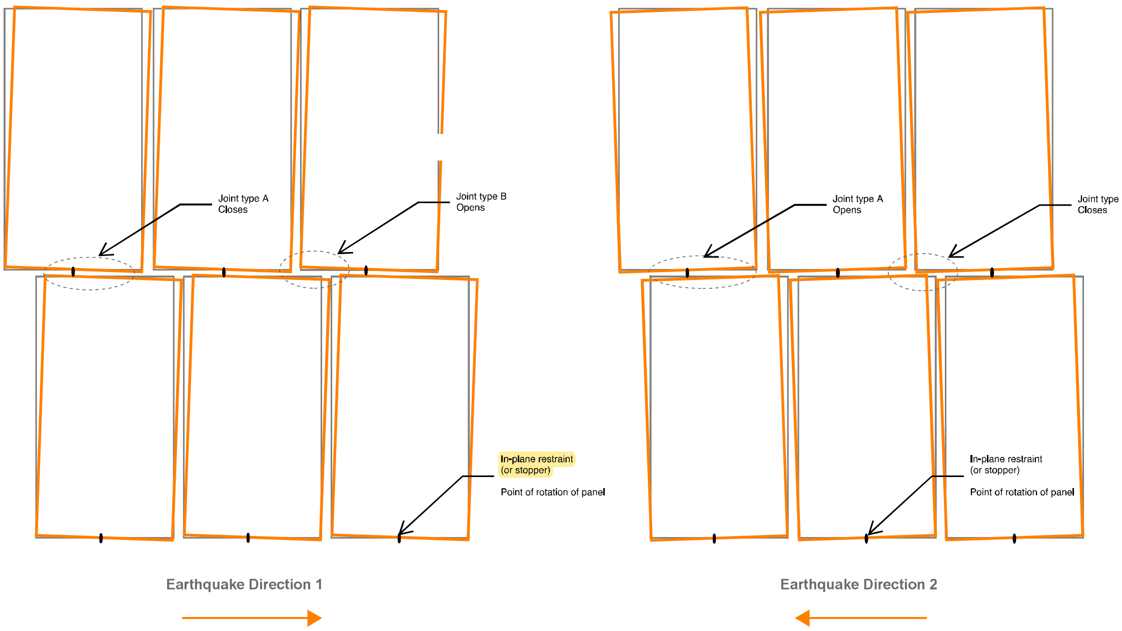


Figure. 43: Panel a. stopper elements and movements due to local deformations, b. creep and c. interstorey drift Drawings provided by Eckersley O'Callaghan



Sizing	Horizontal joint	Vertical joint
Total movement - joint closing	-18mm	-8mm
Total movement - joint opening	+13mm	+6mm
Saddle gasket min thickness	2mm	n/a
Fin bracket thickness	12mm	12mm
Thermal break thickness at fin connection	5mm	5mm
Nominal joint size	**40mm**	**25mm**
Minimum allowable size joint	22mm	17mm
Maximum allowable size joint	53mm	31mm

Movements/ tolerances	Joint opening (+) Joint closing (-)	Notes
Thermal expansion	+4.9mm (vertically) + 2.7mm (horizontally)	Based on aluminium thermal coefficient of expansion and temperature change of +65°C for expansion
Thermal contraction	-1.5mm (vertically) -0.8mm (horizontally)	Based on aluminium thermal coefficient of expansion and temperature change of -20°C for expansion
Column shortening	0mm	Based on column shortening 0.15mm/m as advised by DENCO
Cladding fabrication tolerances	+ - 2mm	
Cladding installation tolerances	+ - 3mm	
Differential slab deflection	7.2mm	

Earthquake direction	Type A Horizontal joint size	Type B Horizontal joint size
Earthquake Direction 1	32 mm joint closes	49mm joint opens
Earthquake Direction 2	44mm joint opens	31mm joint closes

Figure. 44: Panel movements in case of an earthquake top, Movements and tolerances taken into account bottom. Drawings provided by Eckersley O'Callaghan

However for this research a simplification was made and this angle has been adjusted to a common 45° angle for all vertical fins. Horizontal fins are placed above the glazing to maximize shading efficiency. Each panel includes one horizontal and one vertical fin arranged in an L-shaped formation (see Figure 45)

Unitized systems usually have two layers of protection against water infiltration one at the front and two or more at the back of the profile. The first layer offers initial defense, while the second layer provides the main watertight protection. The fin brackets should not breach the gasket that forms the primary waterproofing defense (second layer). The detailed design for the tower's facade shows that the bracket does not compromise the main waterproofing line (second layer of defense). Additionally, a thermal pad separates the fin bracket from the aluminum frame to reduce localized thermal losses caused by the bracket fixings (see Figure 46).

The vertical fins are too large to be produced as a single extrusion. Therefore, the fins are constructed from multiple extrusions joined together using interlocking mechanisms and screws.

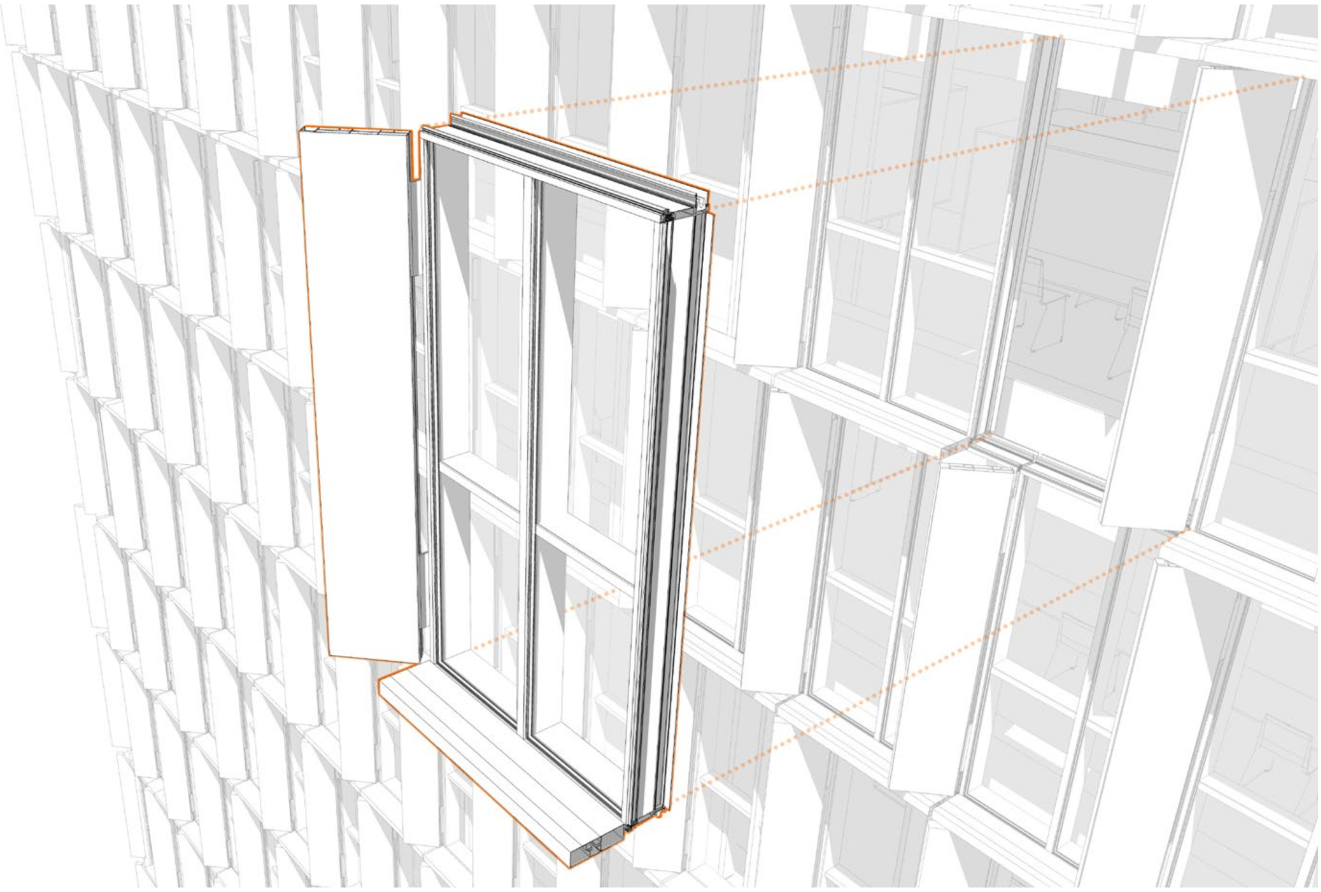


Figure. 45: Typical panel with its horizontal and vertical fins. Drawings by Alkiviadis Oikonomdis based on provided drawings by Eckersley O'Callaghan

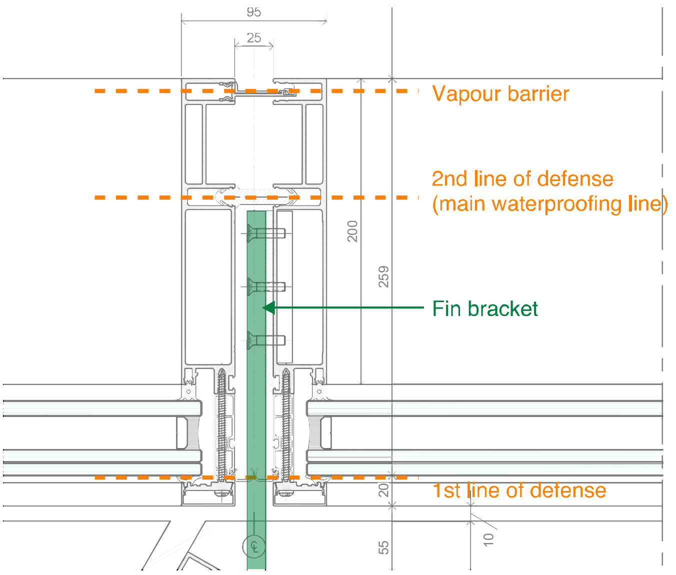


Figure 18: Fin connection at mullions

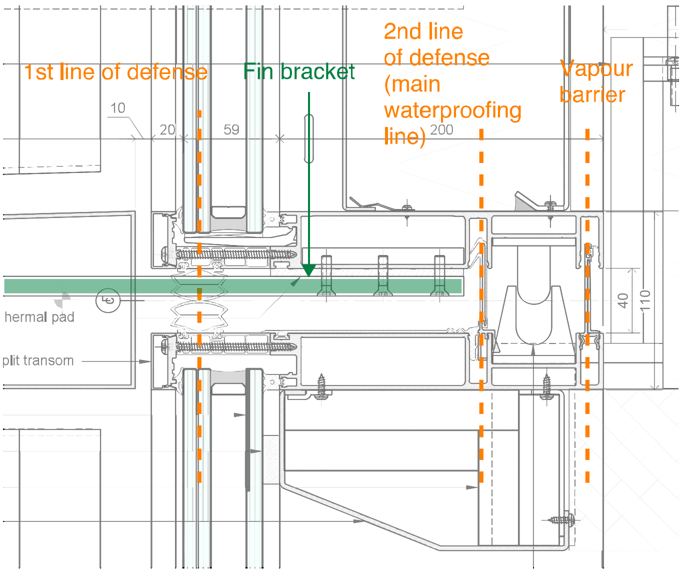


Figure 19: Fin connection at transoms

Figure. 46: Panel watertight barriers and connections wit horizontal and vertical fins. Drwaings provided by Eckersley O'Callaghan

4. Digital Design Tool

4.1 BIM integration

As discussed in the first chapter a shading system as a structure could contribute to the improvement of an existing building energy performance. The creation of a digital design tool for defining relationships between different facade and space properties as well as identifying their conflicts would contribute into taking appropriate desicions early in the design phase. At the same time communicating the various interrelations and conflicts between the envelope's properties to many different roles in a design team would increase the teams efficiency and consequently the final design performance. The research conducted in this part aimed answering the research sub-question:

- *How can a digital design tool support the communication between the different diciplines in a design team?*

ISO 19650-1:2018 defines BIM as:
"Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions"

Building Information modeling (BIM) is an attempt to create a common platform for every specialty in the building industry. Each dicipline can work in parallel on the same BIM model creating entities that represent a building or a system as a whole. The architect can define spaces and communicate them with a structural engineer while a structural engineer can design preliminary versions of the main bearing structure of a design. More diciplines can be involved like mechanical engineers (MEP), light engineers, climate engineers (CD) and facade engineers (FD) with the continous update and evolution of popular BIM software like Autodesk Revit and Graphisoft ArchiCAD. While the concept of BIM and the parametric definition of a building elements with properties was first developed during the 1970s it started being implemented in the industry workflow during the 2010s and the 2020s finally reaching today with the implementation of visual coding and machine learning techniques in this workflow.

Therefore, since BIM offers a an inter-discipline feedback during the design of a new or a retrofit structure it could also be used by a designer to generate the form and structure of a shading system based on energy performance criteria and goals. This way the developed workflow would support a team in the architectural, execution and manufacturing phases as discussed in chapter 2.1.

For the above reasons Autodesk Revit 2023 for the communication with an architecture team and Rhino 7- Grasshopper for communication with a climate or/and facade design team were chosen as the software more suitable for this research. The latter stems from the fact that visual prorgramming environments like Grasshopper with the implementation of simulation programs like EnergyPlus and Openstudio as well as static analysis software like Karamba3D can be an efficient interface to visualizing and gathering numerical quantitative values that could be later on used in a multi-objective optimization.

Furthermore, in Grasshopper interface it is easier to visualize a system's performance indicator values, compare them and apply boudnary conditions to them either by using native pre-programmed components or by integrating packages with languages like C# or python.

4.2 Digital Design workflow

Based on the analysis in the previous chapters, a digital design tool for the evaluation of an existing case study and the optimization of a shading system out of ETFE cushion panels was developed. The workflow consists of five parts.

The first part is the creation of a BIM model representing the case study and the integration of the BIM model into Grasshoper visual programming interface. With the use of Rhino.Inside®.Revit plug in this integration is possible. Technically speaking, Rhino.Inside is an add-on for Revit that loads Rhino and its plugins (Grasshopper) into Revit's memory. However, the way of importing geometry and entities from Revit to Rhino as well as their properties is not a simple task since every transition depends on the end goal and the purpose of this transition.

The second part consists of an energy simulation workflow commonly known as Ladybug tools. Ladybug tools started in 2012 with the work of Mostapha Sadeghipour Roudsari graduate from University of Pennsylvania and later on combined with the work of Chris Mackey a 2015 graduate in building technology from MIT. This workflow consists of Ladybug and Honeybee plugins for Grasshopper whose goal was initially to visualize weather data (Ladybug) and later on to implement energy simulation software (EnergyPlus, Radiance, Daysim, THERM, UrbanOpt, OpenStudio) into Grasshopper environment (Honeybee) for easier visualization and communication of energy simulation data between design teams and decision making roles in a team. The workflow started with the development of the legacy version of the plugins (Ladybug v0.0.69, Honeybee v0.0.66) with their last update on 27August 2020 and continued with the current version namely Ladybug Tools v1.8.32. (last checked 16 June 2024). The differences and the similarities of the older and newer versions were investigated during this research. However for compatibility issues and computational resources version 1.7.68 was chosen for this workflow.

The main objective of this part is to define a proper energy model for applying an energy balance and daylight simulation based on the imported rooms/zones geometries from Revit. The steps and parameters needed, the material properties, the analysis period, the occupancy schedules as well as the HVAC, cooling and heating systems needed for the simulations will be discussed in depth in chapter 4.4.

The third part is the definition of the shading system based on the case study facade type and scale and the analysis undertaken in chapter 2.1. The definition of a pattern, its scale and the offset from the existing curtain wall system, as well as its main bearing structure are being defined in this part. In parallel with the parametric model the geometric parameters that can be used for optimization are being presented.

The fourth part is the application of a linear static analysis for the structural parts of the shading system with the help of Karamba 3D plug in for Grasshopper. Karamba3D originaly developed by Clemens Preisinger is an easy to use software that enables the analysis of simple shell or truss structures based on custom written components that will be discussed later in chapter 4.6.

Finally, the last part is the introduction of Wallacei a multi-objective optimization plug-in for Grasshopper developed by Mohammed Makki, Milad Showkatbakhsh and Yutao Song. As discussed in chapter 2.3 this plug in with the introduction of NSGA II genetic algorithm and a niching approach is apporpriate for optimizations with multiple objectives. It is however important to note here that the more the objectives, the less efficient the generations are and thus the end result (design solutions).

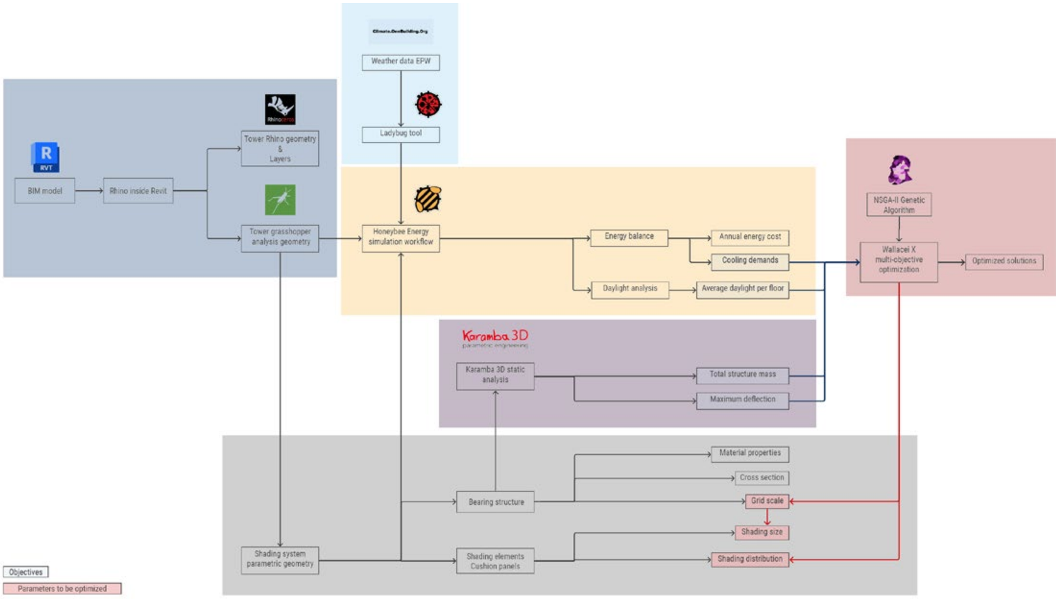


Figure. 47: Schematic flowcart of the proposed workflow

Figure. 48: Overview of the workflow in Grasshopper environment

Since all the above mentioned plug-ins are all under development and with some limitations, the calculations and the end results are not guaranteed and can only be used as estimations for the actual energy demands in case of enrgy simulation, stresses and deflections for the static analysis simulations.

4.3 BIM workflow | Revit - Rhinoinside

Revit model

In order to move into an integration between the aforementioned software the creation of an accurate representation of the case study building was mandatory. Therefore the first step was to create a BIM model representing the Tower of Piraeus the unitized curtain wall system included.

As mentioned in chapter 3.2 some of the given dimentions of the building and the building's main bearing structure were adjusted for the purposes of this research. Despite these assumptions concerning mostly the columns dimentions, all the room dimentions were kept the same as well as most of the typical floor uses (see Figures 49,50).

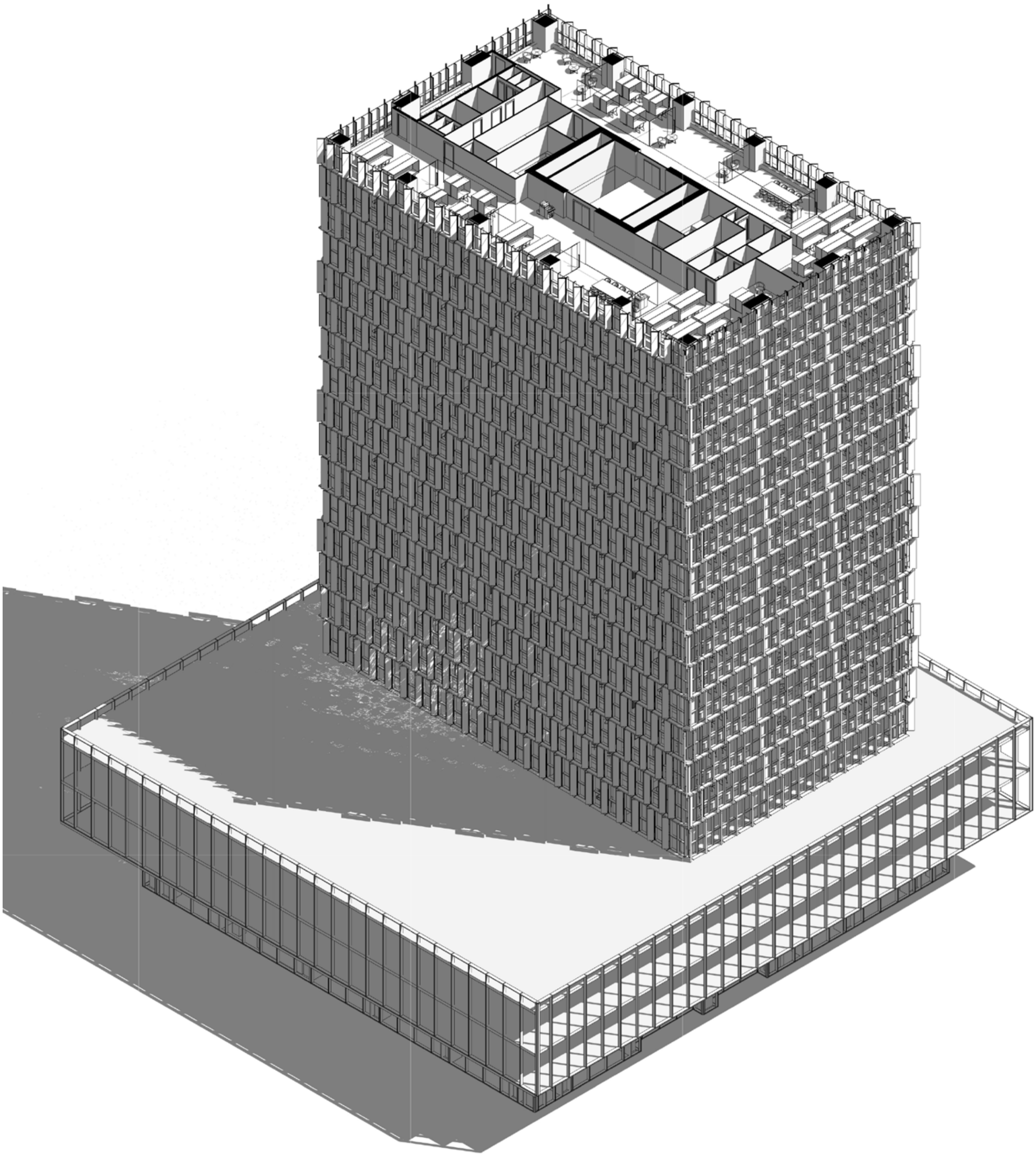


Figure. 49: Revit model axonometric diagram of the tower

Figure. 50: Typical plan in Revit environment

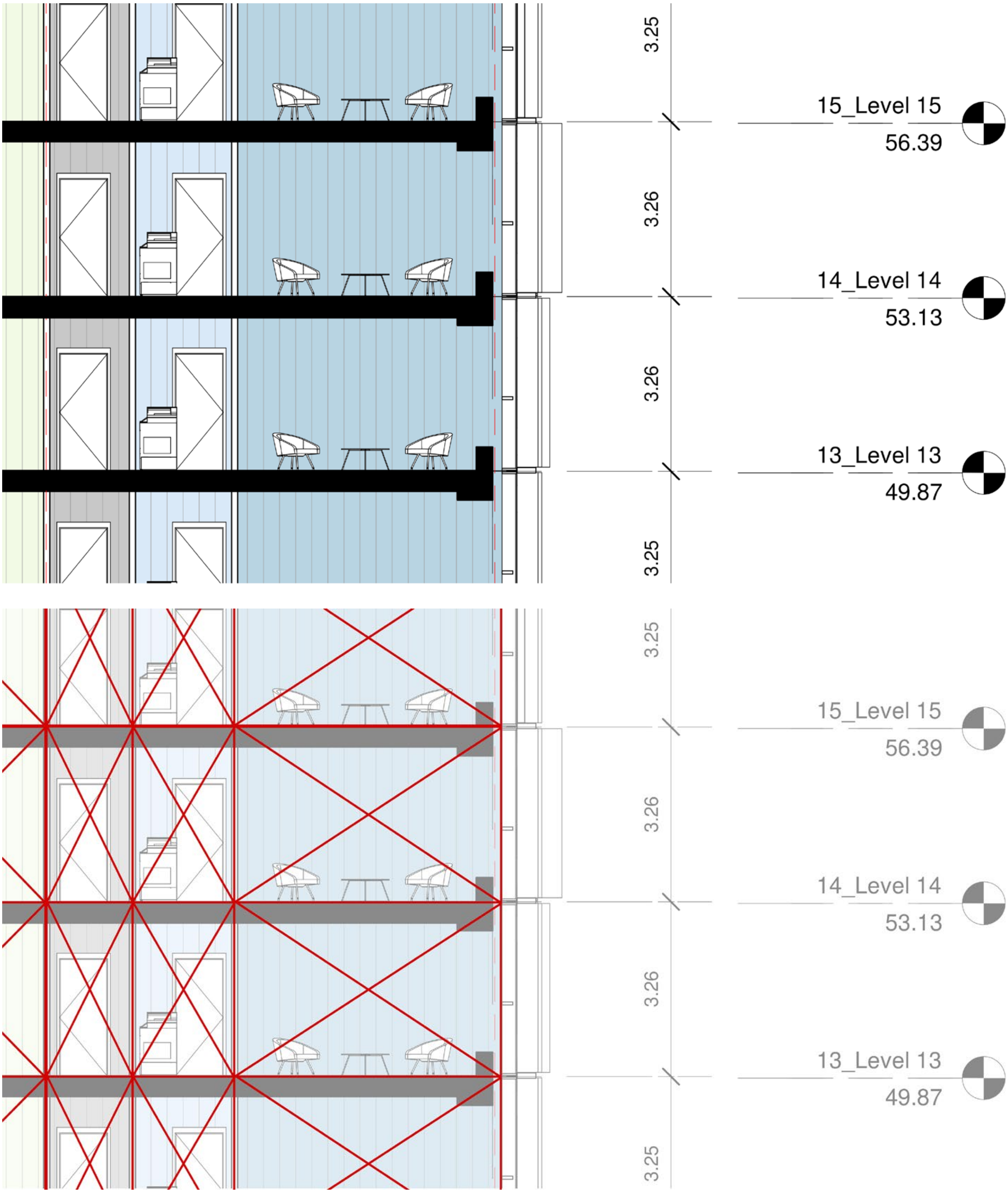


Figure. 51: Revit section and definition of rooms

It was important however to not only define walls, openings and the facade panels to represent spaces but to also define room entities in the model. Room entities in Revit are properties definitions for each space based on its boundaries. What Revit does is that it automatically finds the walls that represent spaces and instantly gives the user the ability to assign a tag-name to these spaces. Based on these tags the spaces funtions can be previewed in plan views and a hidden solid is created to represent the room/zone.

Although the room definition in plan view is being done automatically, the height defintiion of each room is not an automatic procedure and has to be defined manually by the user in a section view. For the purposes of this research and the integration with Honeybee workflow, the rooms were defined by the centerlines of the walls in plan and by the final floor level of each slab in section view (see Figure 51). This way each solid representing one room/zone could have an identical intersecting surface with the neighbouring room/zone. This overlap can be adjusted later on in Honeybee environment and this is the way OpenStudio and Energy plus need the rooms/zones defined in order to apply energy simulations.

Rhino Inside workflow

The workflow consists of nine steps split into two parts. The first part "Revit-Rhino integration" focuses more on translating geometry from Revit to Rhinoceros in a practical way. The goal of this part was to define layers based on the different families and entities present in the Revit file under investigation. The second part "Revit-Grasshopper integration" , focuses on the translation of the rooms/zones and functions present in the Revit file into Grasshopper and then into Honeybee geometries. These geometries and their data are being used later on for the energy simulation in Openstudio/Energyplus.

The first step was to filter out the levels to be analyzed. By picking these levels, the script automaticlly informs all of its parts to gather information for these levels only. For the purposes of this research, although an analysis of the whole building or of a different combination of levels could be possible, only typical levels 16 and 17 were filtered out for investigation. Since these floor plans are typical floorplans, an estimation for the whole building is possible. (see Figures 52,55)

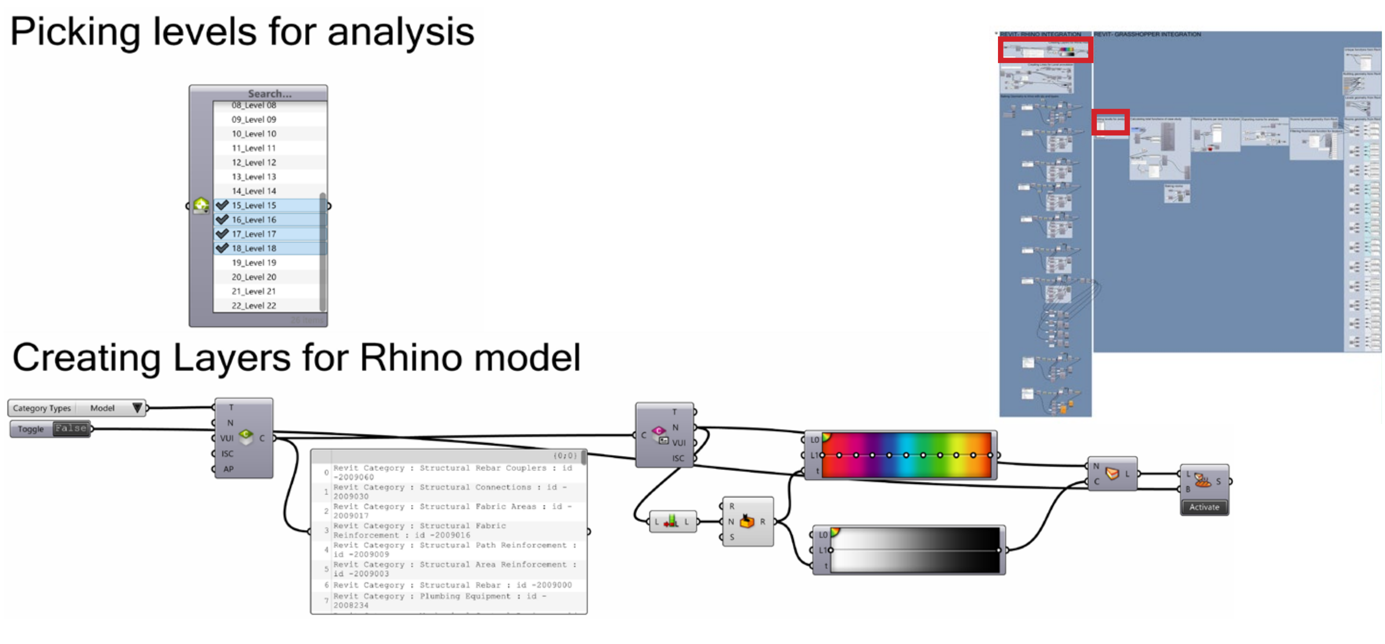


Figure. 52: Picking Levels and creating layers for rhino integration

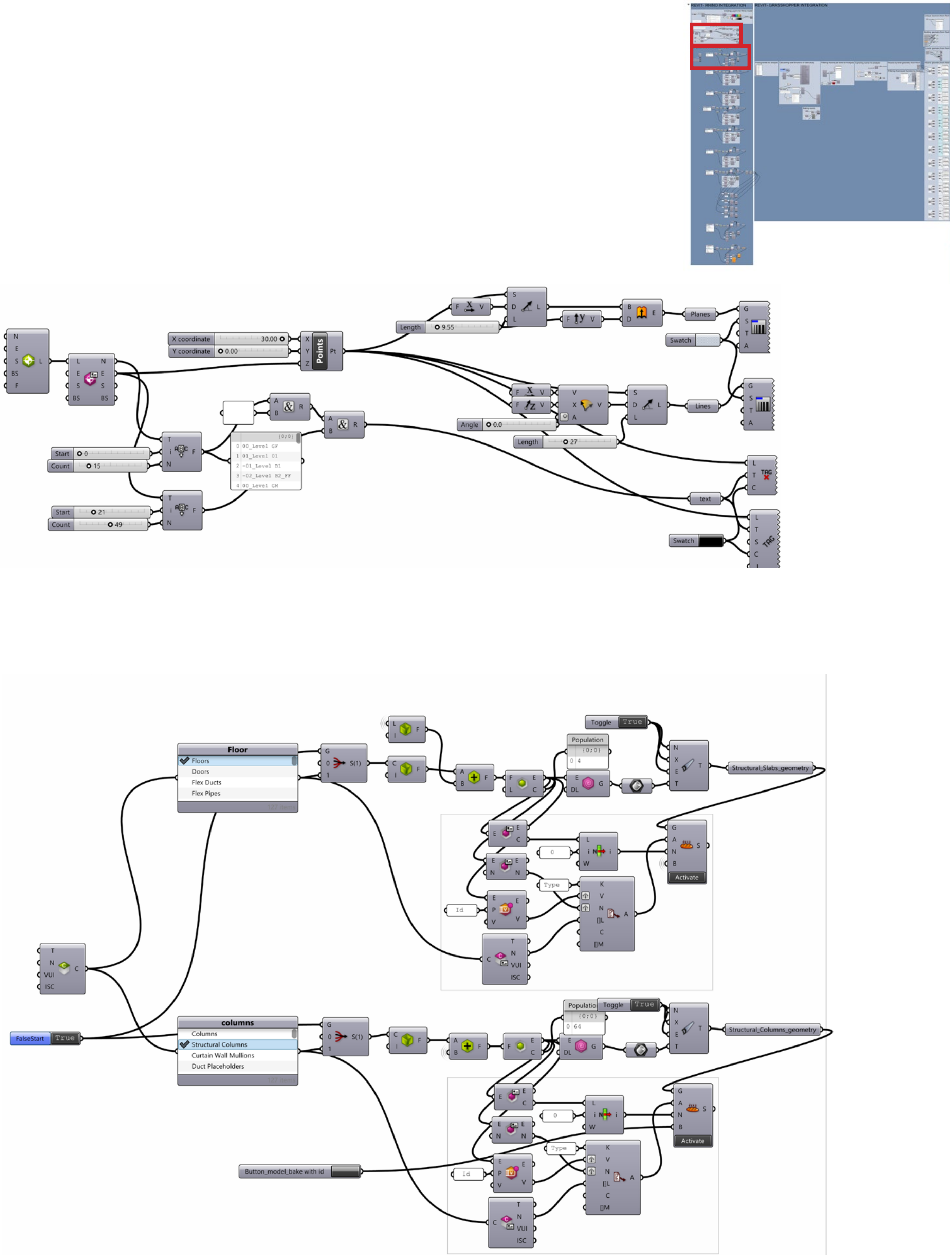


Figure. 53: top filtering and visualizing levels from Revit to grasshopper, bottom filtering specific elements and baking them into the predefined layers

The next steps were the definitions for level annotation and their transition from Revit to Rhino and Grasshopper environment. This way a quicker communication between the architect, the client and the facade engineer is possible, since the CAD model in Rhino can be efficiently used for visualization purposes. (see Figure 53)

At the same time geometries needed for the shading and glazing of the tower were filtered out ready to be used in Grasshopper. The same procedure was used for filtering floors, columns, walls, structural beams, doors, ceilings, interior glazing as well as exterior curtan wall systems.

In order for the data transfer between Revit and Honeybee to be smoother, some extra steps for filtering rooms, their geometry and their names were mandatory. This way all the data could be structured in a proper way for setting each space ventilation type, occupancy heating sytem and temperature setpoints. In order to achieve this, the unique functions of the BIM model were calculated and then used for filtering out the corresponding rooms. For example if the rooms/zones with a specific function were to be filtered out (for example "closed meeting spaces" or "rest rooms") from the BIM model, this was considered to be the most efficient way. (see Figure 54)

Assuming the BIM model is properly designed and in the final stages of the design phase or in its final versions then the functions are to be filtered out correctly and automatically.

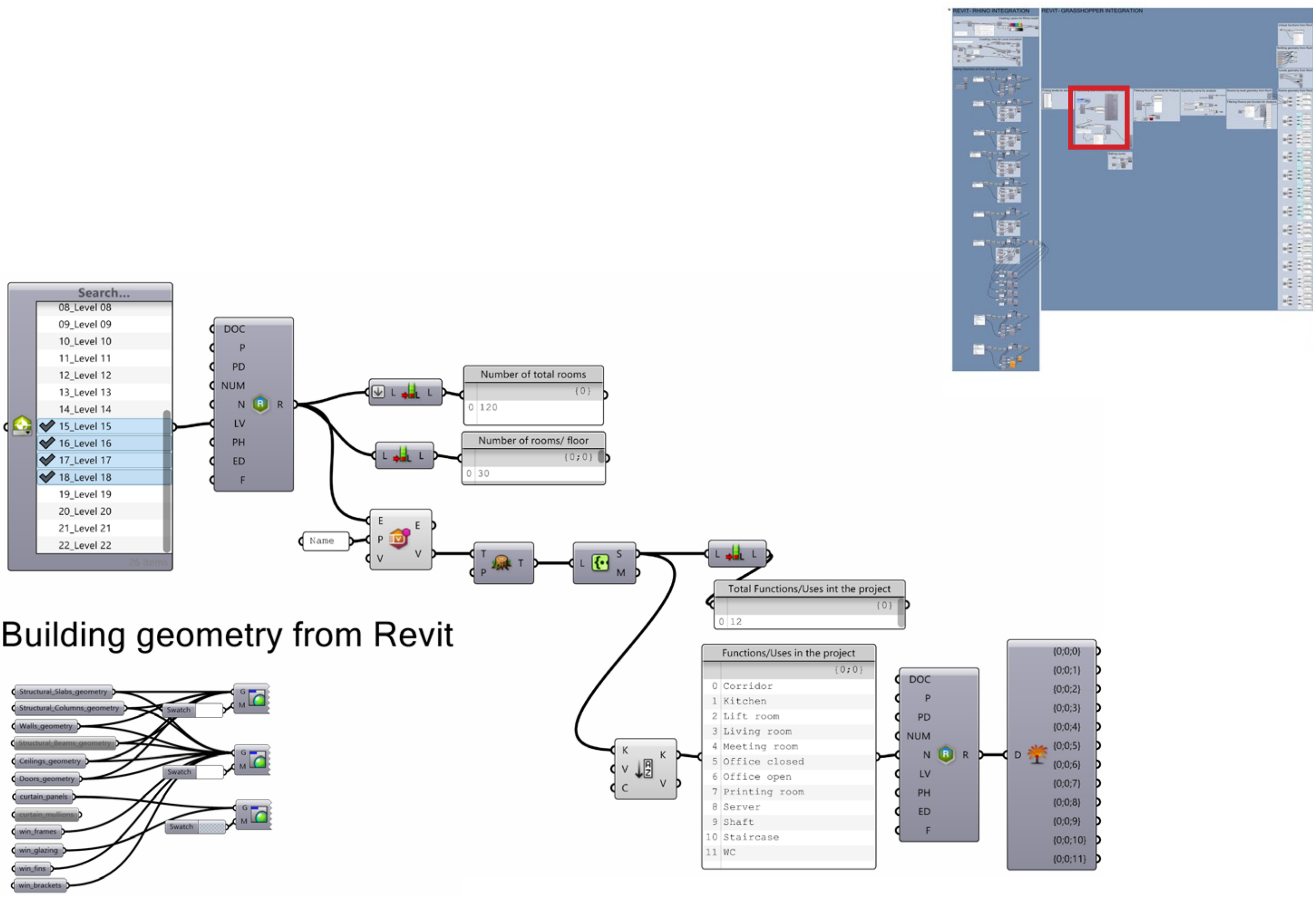


Figure. 54: Unique function calculation and filtering rooms based on these unique functions.

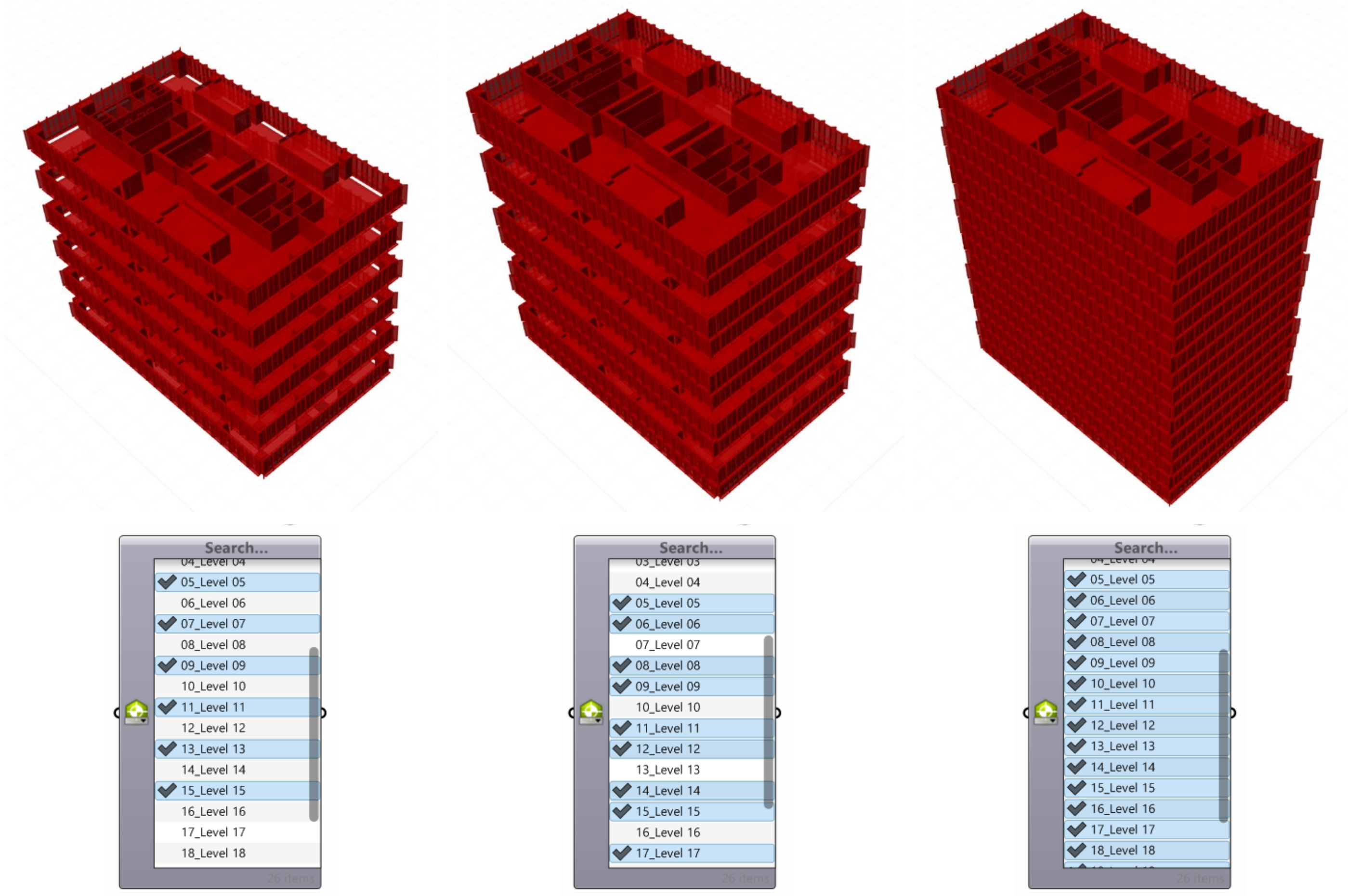


Figure. 55: Different level filtering outputs, by picking different level combiantions

4.4 Energy Simulation workflow

The energy simulation workflow was based on the one developed by Chris Mackey and Mostapha Sadeghipour Roudsari in the last decade with the development of Ladybug and Honeybee. The workflow integrates OpenStudio and Energy Plus in order to run simulations in these two programs and then return and visualize the results in Grasshopper and Rhino environments.

The workflow is split into three parts. The energy model definition, the simulation and the simulation results part. Each part consists of sub parts depending on the components hierarchies as they were defined by the developers and the end result goals. For example, it is different to apply a broader analysis to a case study without defining a specific HVAC system for the building and when specific heating, cooling and air exchange systems are defined. At the same time a distinction is being made in all the sources available for Ladybug tools concerning whether the building has natural or mechanical ventilation. The decision of these two critical questions (if the case study building has mechanical ventilation and if there is a specific HVAC system to be simulated) determine the depth of analysis to be applied. If a specific HVAC system is defined then the energy demands returned after the energy balance is applied with Honeybee instead of being expressed in KWh (energy) or KWh/m^2 (energy intensity) they are expressed based on electricity, gas or net energy demands depending on the system under investigation. At the same time the efficiency of every HVAC system is greatly influenced if operable openings are present in the building under investigation. For this research, however, the main geometry and the room geometries for a typical floor were filtered out. (see Figure 56)

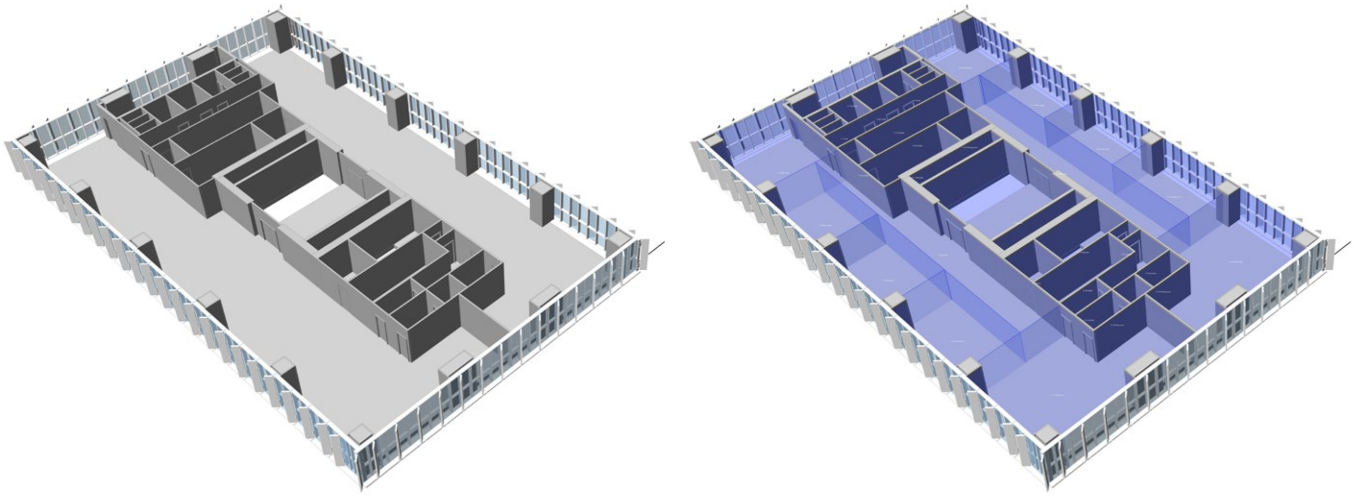


Figure. 56: Main geometry and rooms filtered out from Revit

Energy model definition

Following the final step of the Revit-Grasshopper integretion, the rooms/zones were translated into Honeybee rooms. Honeybee rooms is a way to translate a closed solid element in Rhino-Grasshopper environment into an Opestudio-EnergyPlus thermal zone. The two different ways of applying this translation are to either use a series of solids that represent the thermal zones to be investigated or to define each zone or each complex of zones out of their surfaces. In the second approach, after the definition of surfaces geometries, materials as well as custom properties like the reflection factor, the U values among others can be adjusted. The surface to zone assembly method focuses in a deeper detail level in terms of daylight and radiance simulations while the solid to room method focuses on broader energy simulations when the preliminary design of a building or facade is to be evaluated.

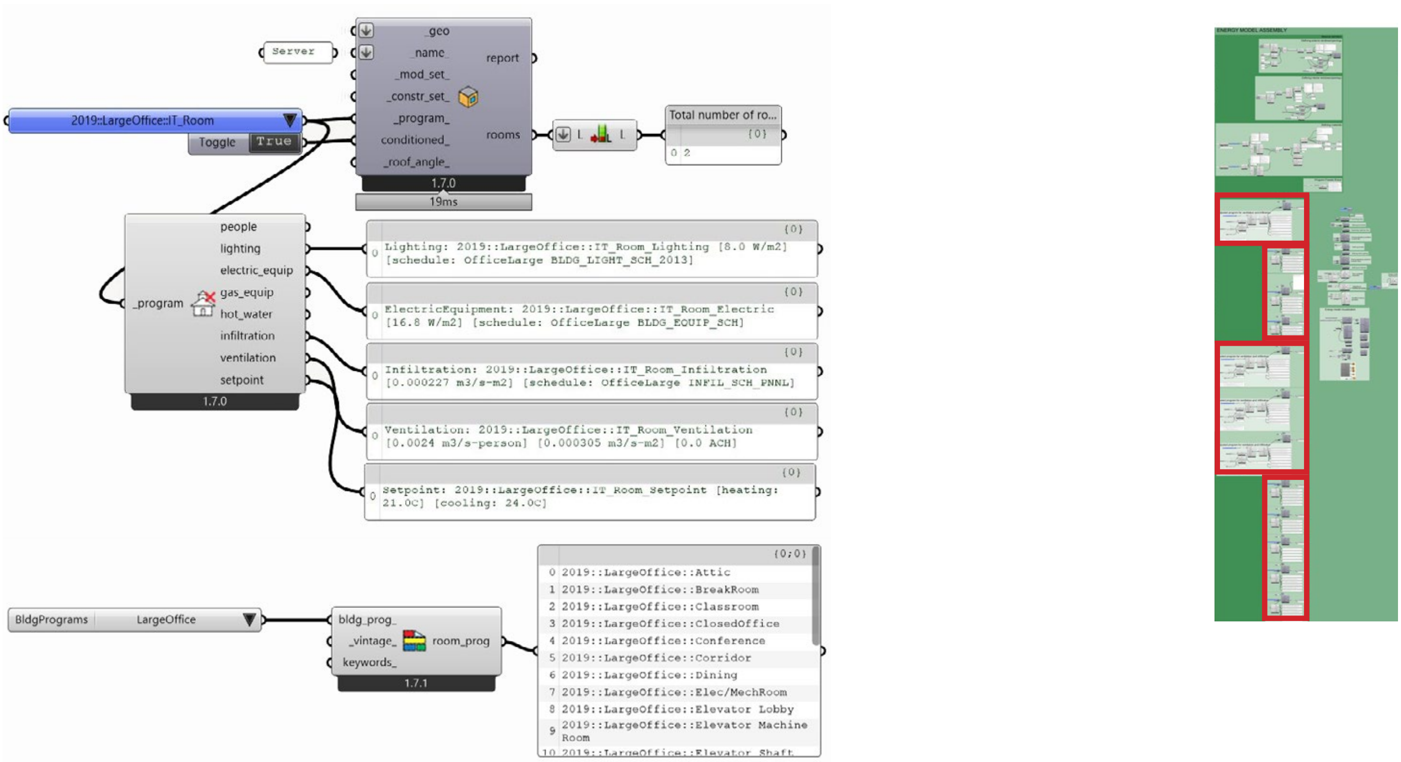


Figure. 57: Translation of rooms from simple solids imported from Revit to Honeybee rooms(thermal zones)

After the rooms/zones are defined, a name, a construction set as well as the occupancy programm for each zone has to be defined (see Figure 57). Concerning the construction set, Honeybee provides a library with pre-defined materials which can be easily used together with specific components to analyze the construction set into materials and then into material properties. It is worth noting here that the workflow is different for transparent and non-traparent (opaque) materials (see Figures 58,59). Based on all the above, exterior and interior walls, interior glazing as well as the material and layers for the unitized curtain wall system were defined.

The values used to define the exterior glazing were the values that were provided by Eckersley O' Callaghan for the typical panels that are consisted mainly by triple glazing. A new custom material was defined with the name GL-11_PTOWER consisting of simple glazing layers and two types of air gaps (see Figure 60). This material was then applied on all exterior openings surfaces to be considered in the optimization. These window surfaces were automaticaly generated by the unitized curtain wall system's geometry from Revit. Respectively, for interior and exterior walls typical knauf plasterboard walls and plaster boards were used. For the columns present in this model only their cover was used, since taking the columns geometry into account would increase the computational burden.

Concerning the occupancy program for each room/zone, Honeybee offers the flexibility of defining custom occupancy programms with the HB ProgramType component. This component can be used to define custom name, custom people occupancy, custom lighting type, electric equipment, hot water use as well as custom infiltration, heating and cooling setpoints as well as mechanical or natural ventilation. Of course this flexibility is provided for the workflow to be easily adjusted to each project's goals. Since the aim of this research is not to optimize a ventilation or heating system but to investigate the influence of an optimized exterior system to an existing building envelope, some assumptions and default values were selected in this step and were kept as constants both during the tower's evaluation phase as well as the optimiziation phase.

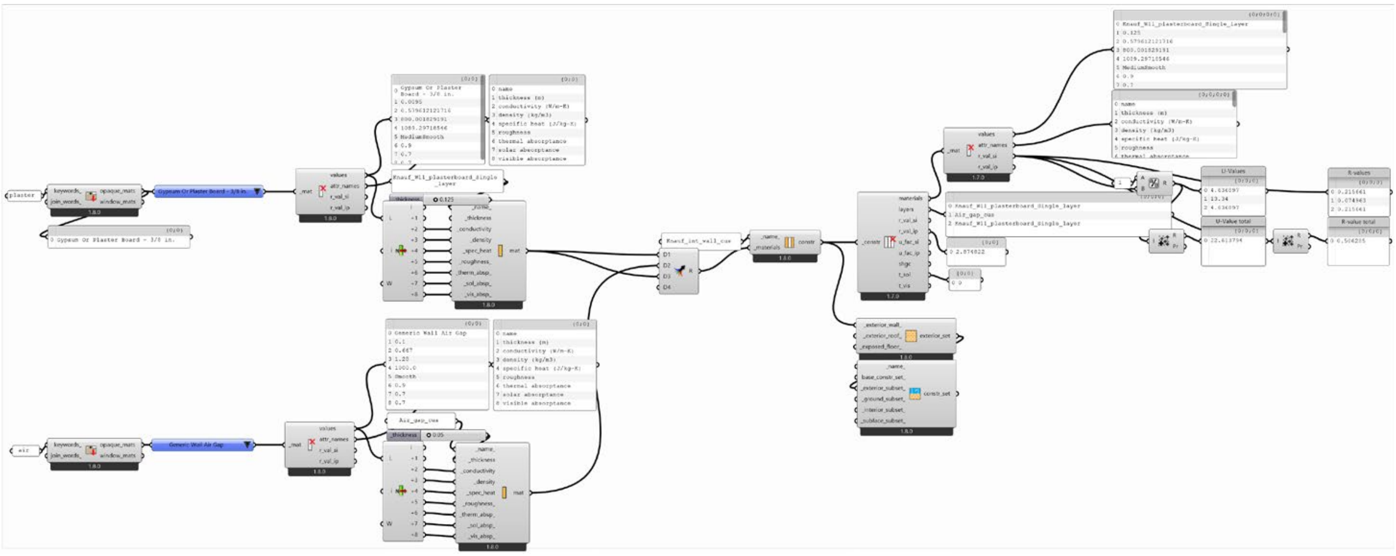


Figure. 58: Definition typical plasterboard walls for the indoor walls. Knauf W11 system was selected since no access to construction details was possible.

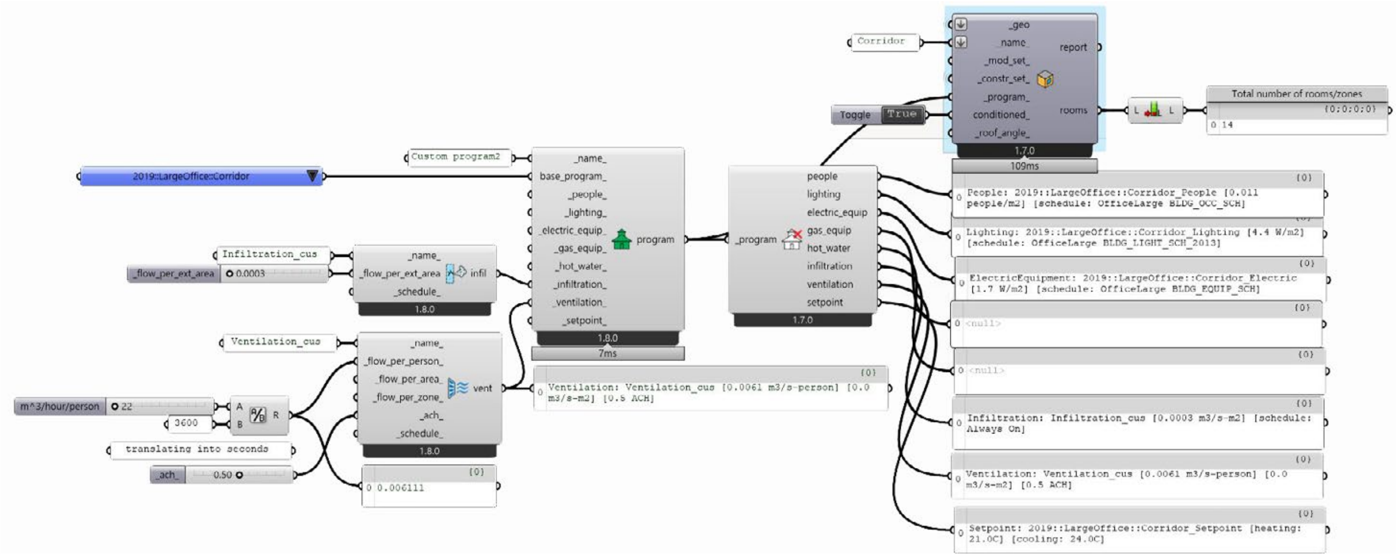


Figure. 59: Translation of rooms from simple solids imported from Revit to Honeybee rooms and making the appropriate adjustments to the ventilation type and the inflitration between the spaces

Glass schedule

Ref.	Performance		Build-up[2,3]	Coatings[1]	Remarks
GL-11 TOWER FACADE Fixed clear glazing	U-value[5]	≤ 1.1	66.2 HS 20 Argon 6 FT (HST)	High performance coating on face #4	Low-iron: Yes Frit: Solid ceramic frit or silicone skim at spacer bar and to conceal fittings as required. Edges: Smooth ground, arrised Form: Flat Interlayer: acoustic PVB (clear) Manual intrusion: n/a
	U-factor[7]	≤ 1.45			
	G-value[6]	≤ 0.35			
	SHGC[8]	≤ 0.32			
	LT	≥ 65%			
	LR_{ext}	≤ 16%			
	Rw	≥44dB			
	CRI	< 93%			

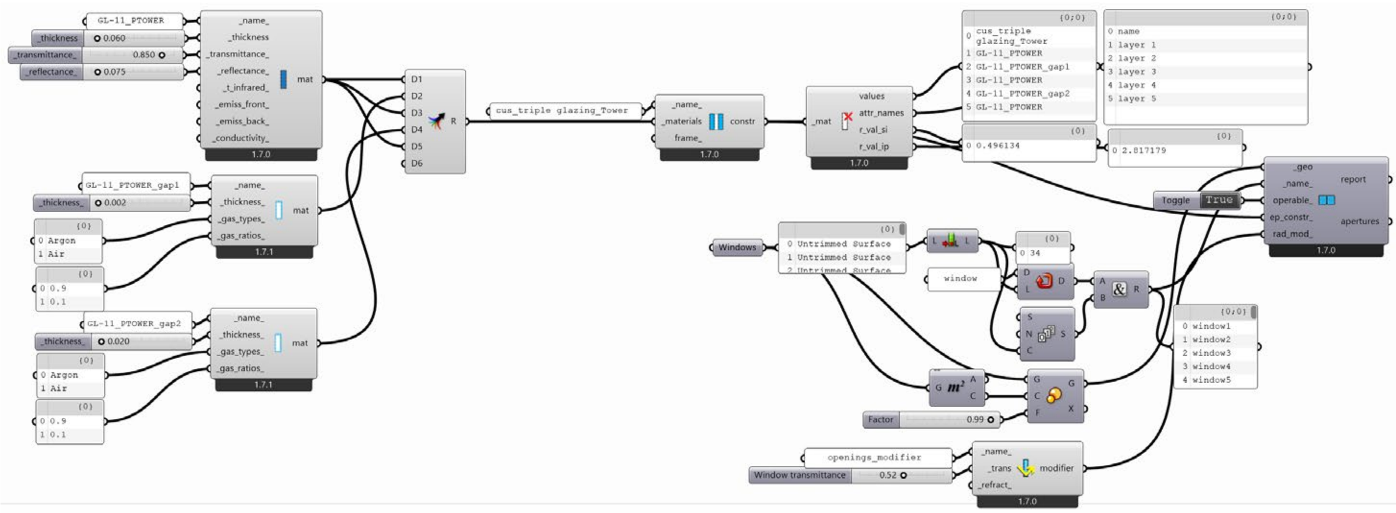


Figure. 60: Definition of triple glazing GL-11 based on the material provided by Eckersley O'Callaghan and exterior openings definition

Furthermore, Honeybee provides default program presets with predefined values based on building uses and space functions. For example presets about the occupancy, lighting, electric equipment, infiltration, ventilation and temperatures can be found in the local Honeybee repositories. Therefore, for the purposes of this research focus, most of the zones were assigned with the corresponding program preset with some exceptions like the open office, meeting room, closed office and the corridor spaces that were assigned the custom values of 0.0061 m^3/s/person for ventilation and 0.0003 m^3/s/m^2 for infiltration based on Peter J.W. van den Engel's Hybrid ventilation guide.

After the definition of all rooms/zones and their materials, some additional Honeybee components were used in order to solve any inaccuracies between the geometries by removing duplicate surfaces where the zones boundaries overlap with each other, for spliting the total zones of the building model into levels, for assigning the defined interior and exterior glazing to the corresponding walls of the model and finally to define global thermal set points for the heating and cooling of the spaces (see Figure 61). Normaly these setpoints should be adjusted based on the architect's and the clients goals and decisions but always in correlation with the regulations applicable to the building plot. In this case study 19°C for heating and 27°C for cooling were used as setpoints as per the greek regulations for building energy performance (Technical Instructions TEE for the Energy Performance of Buildings Nov 2017, KENAK)

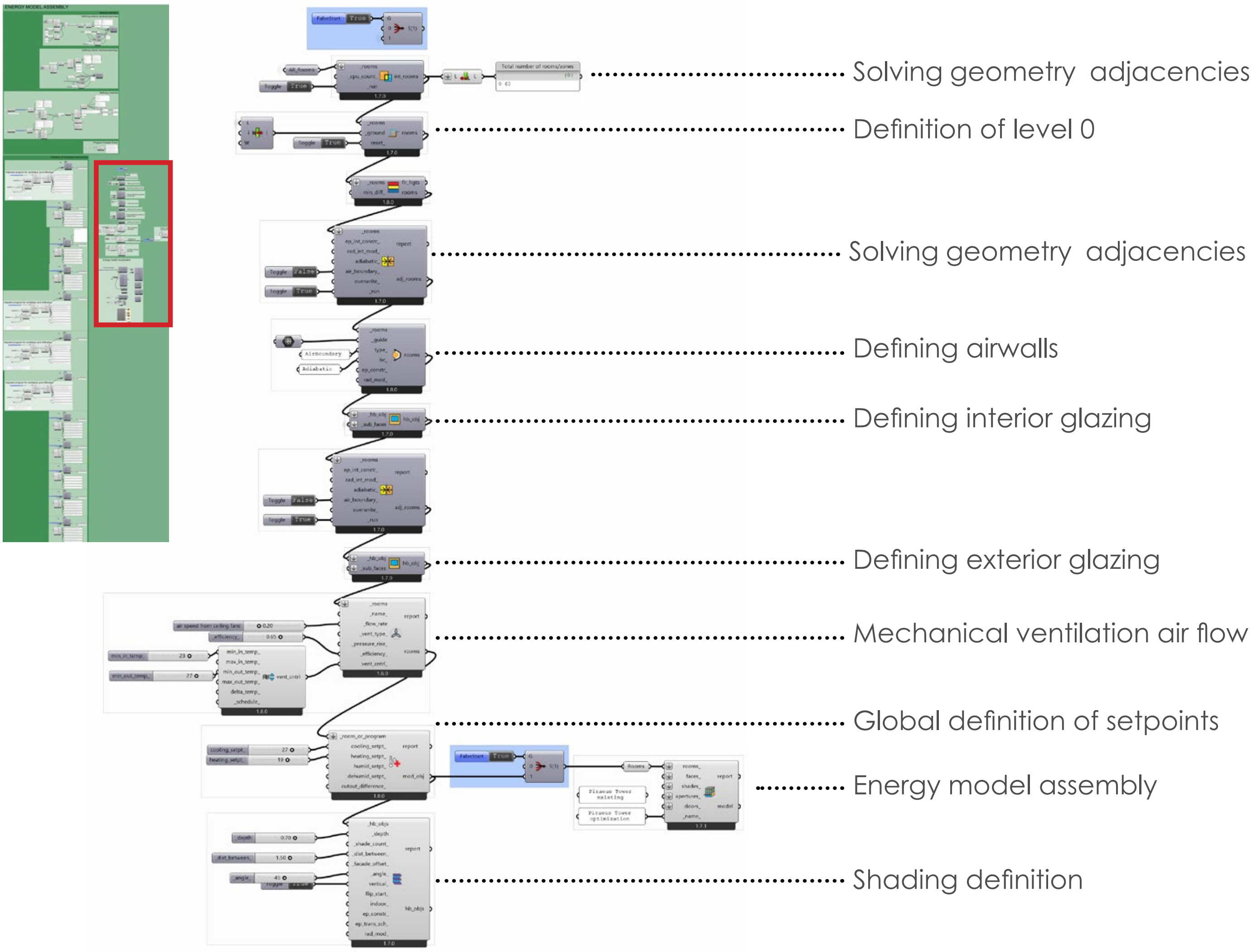
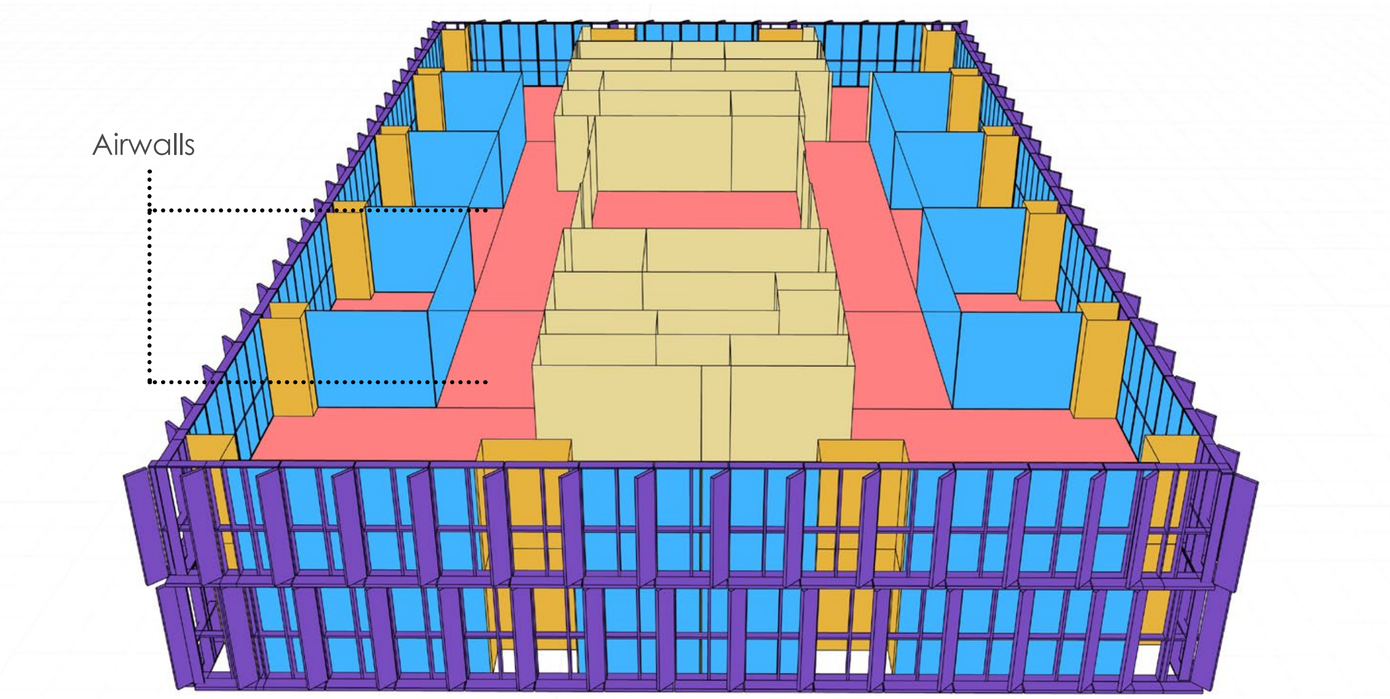


Figure. 61: Additional honeybee components for resolving any geometry inaccuracies



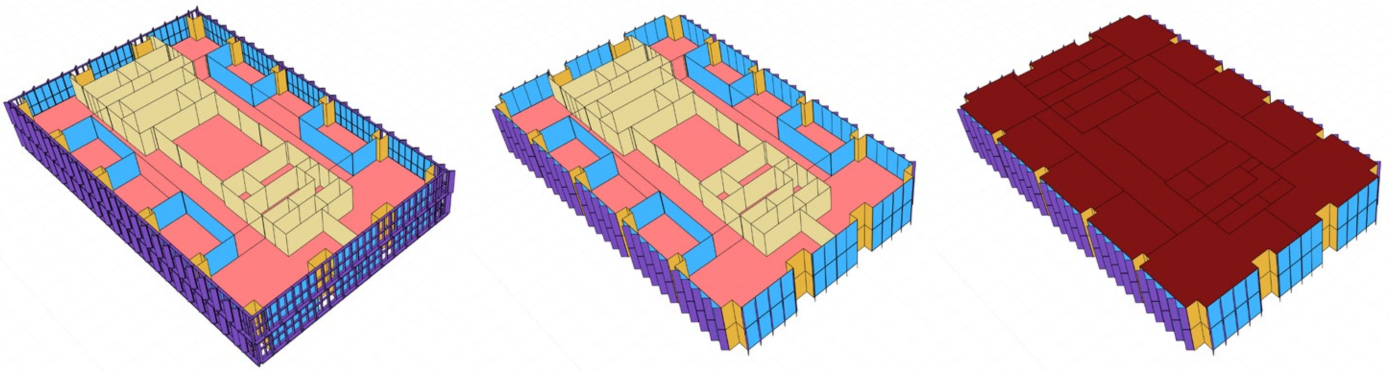


Figure. 62: Final energy model preview a. with original unitized panels and fins, b. with simplified fins and c. with top and bottom floor of the segment to be investigated.

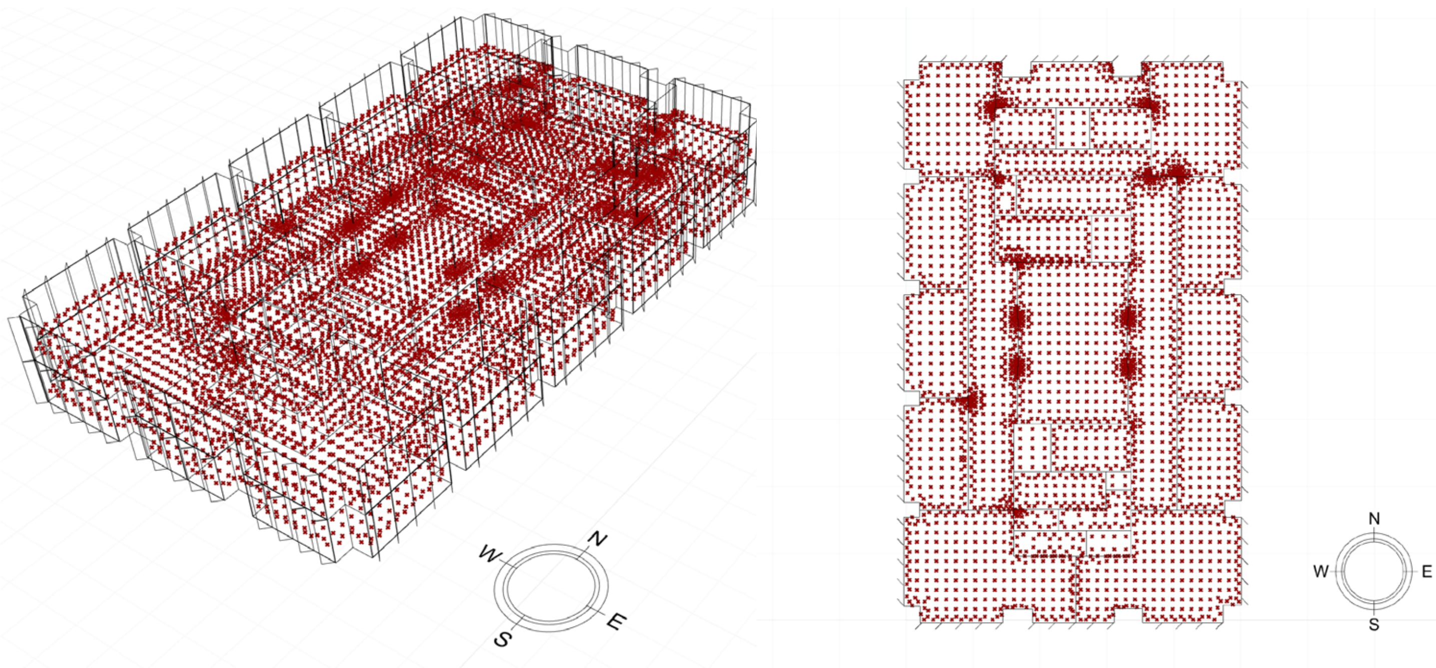


Figure. 63: Distribution of grid points for Daylight simulation for the two typical floors

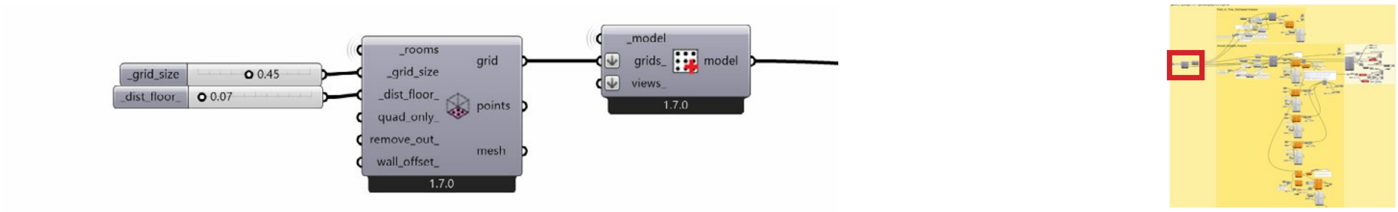


Figure. 64: Rooms/zones grid points size and their distace from floor level definition

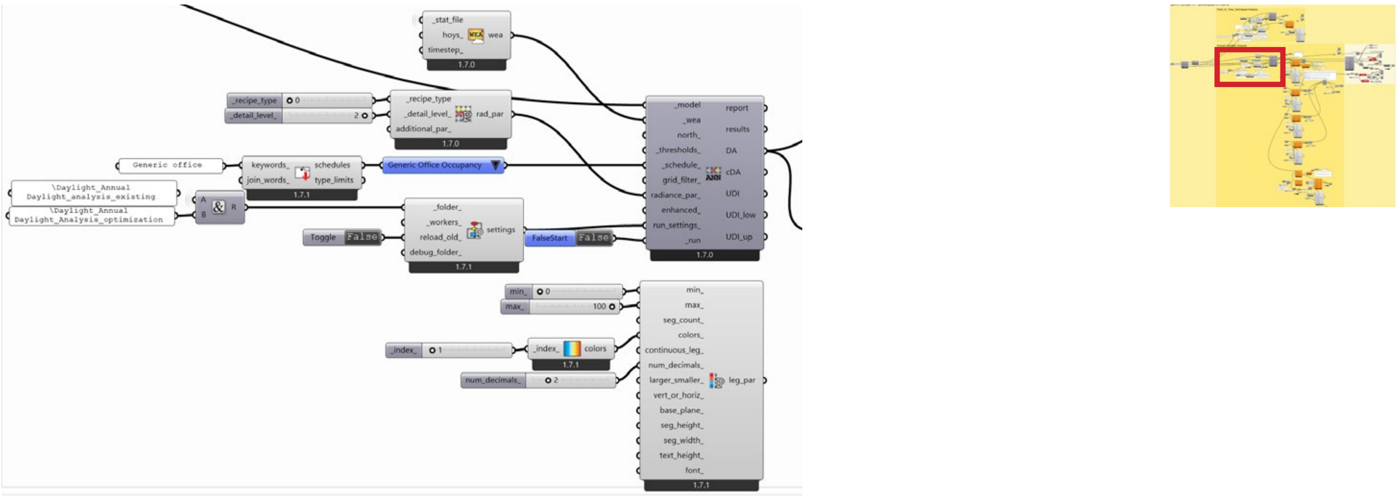


Figure. 65: Daylight receipe and Radiance imulation settings definition

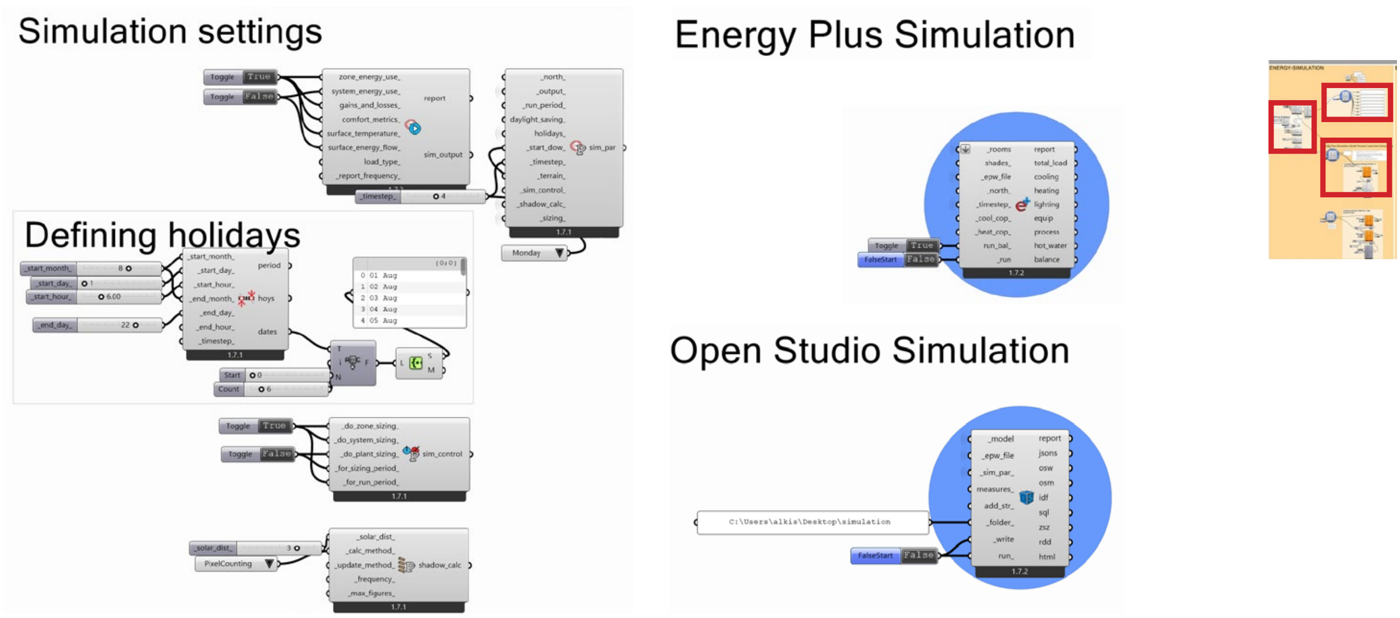


Figure. 66: Simulation settings defined at the left and simulation run components at the right

Concerning the daylight simulation workflow, the spaces definition in Honeybee are almost identical with the defintiion of the rooms/zones as presented already for the energy simulation (see Figure 62). In case of daylight simulations Honeybee implements Radiance into Grasshopper environment in order to apply its raytracing algorithms to Grasshopper geometries. The only difference between energy simulation and daylight simulations is that a daylight simulation, or else daylight recipe as it is called in Honeybee environment, in order to make calculations and visualizations a level of investigation as well as a series of points (grid) needs to be defined in the spaces to be analyzed. Indeed this was defined with a square grid of 450mm at a height of 70mm from the floor level of each room (see Figures 63,64).

Simulation

Based on the reasoning discussed in chapter 3.1.3, with the use of weather file GRC_AT_Athinai-Hellinikon.Olympic.Complex.167160_TMYx.2007-2021, after the defintion of a holidays period (since this is an office building) and the definition of the repository for the simulation files to be saved, a simulation was applied.

As discussed in chapter 2.2 about resilience, it is important to define a situation before and after a hazard as well as the dimentions of resilience in order to assess it. However, since this research objective is the application of a multi-objective optimization for a proposed design instead of a resilience assessment, instead of defining the simulation analysis based on resilience phases (before,during, after a hazard) an annual analysis period was chosen for the state of the tower before the design of a shading system and the situation afterwards.

At the same time, since historical weather data are not considered reliable in literature for predicting a short term event hazard like a heatwave for future scenarios (at least without post-processing and coding techniques) it was considered that an annual energy and daylight analysis would be closer to real situation scenarios. Thus, based on the TMY weather file data used and its reliability in longer time period analysis an annual analysis period was decided for the simulations and the optimization. This way the shading system would be optimized not only to be efficient against hotter periods of the year (including heatwaves) but for the whole year too.

Simulation results for annual analysis period

As can be seen from the simulation outputs, not all spaces have the same cooling demands. Spaces oriented towards the south seem to be more susceptible to heat with higher cooling demands reaching 7149.49 KWhs (see Figure 67). This result is quite normal since the southern facades always receive more sunlight hours and absorb more radiation during the year in the case study location. In total, however, for the typical floors analyzed and for the heating and cooling systems and the ventilation type used for this simulation it seems that 159264 KWhs are needed annually for cooling these two typical floors (see Figure 74).

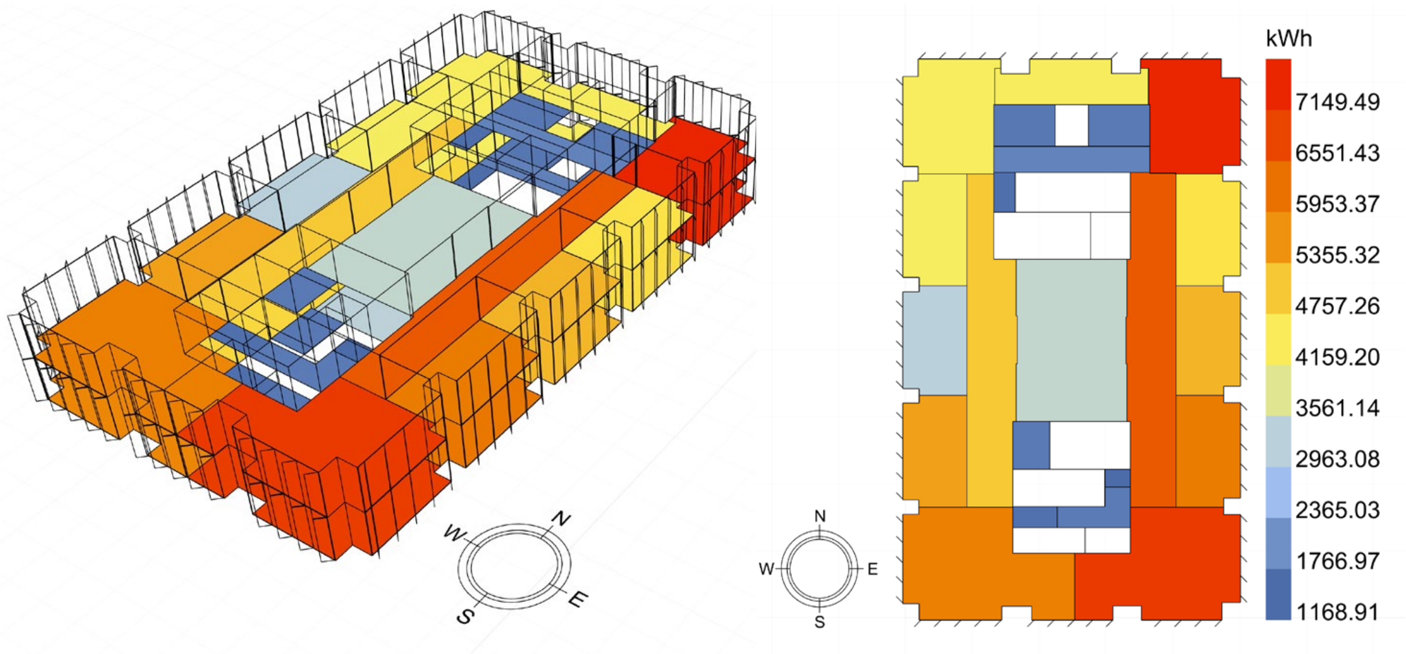


Figure. 67: Total zone Ideal Loads supply air Total cooling energy 1 Jan to 31 Dec from 0.00 to 23.00

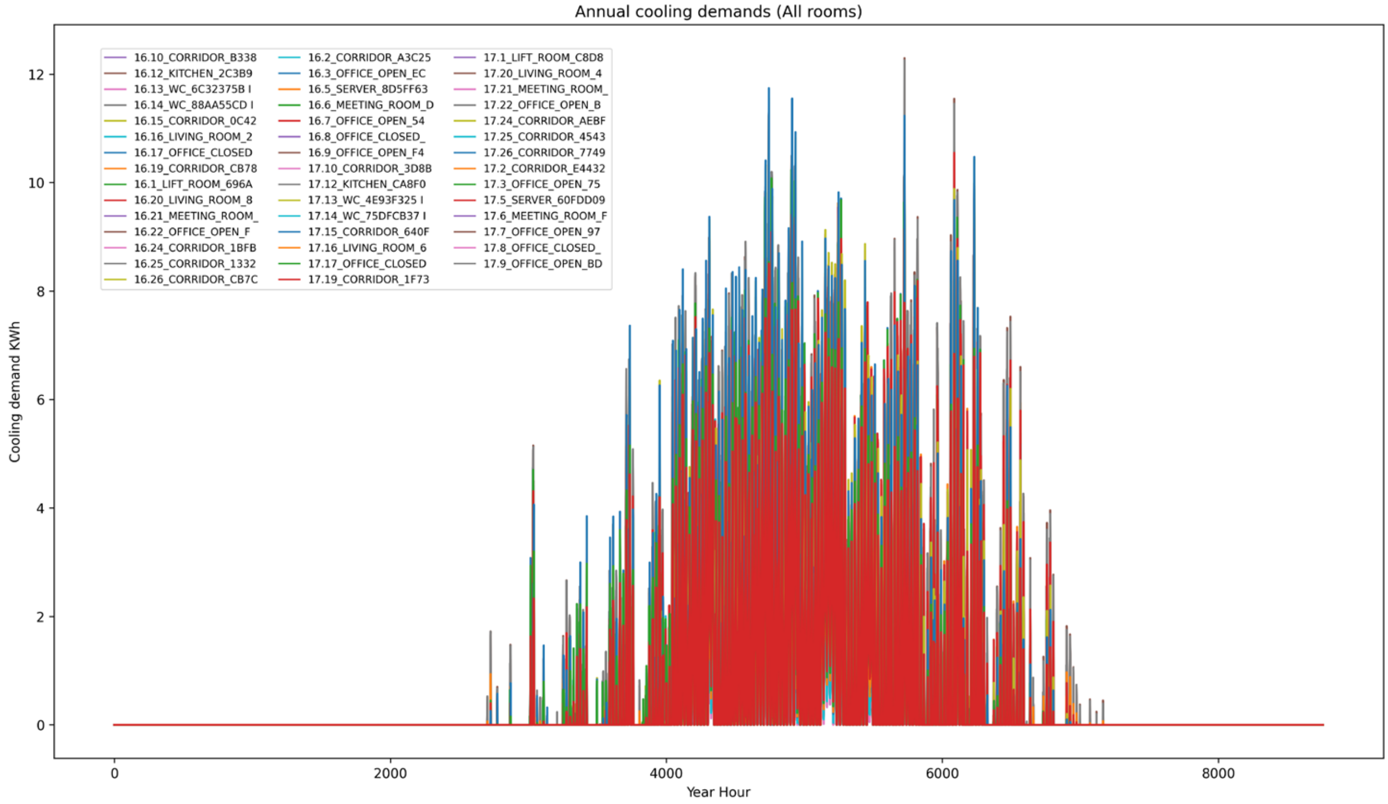


Figure. 68: Grapgh with all rooms annual cooling demands

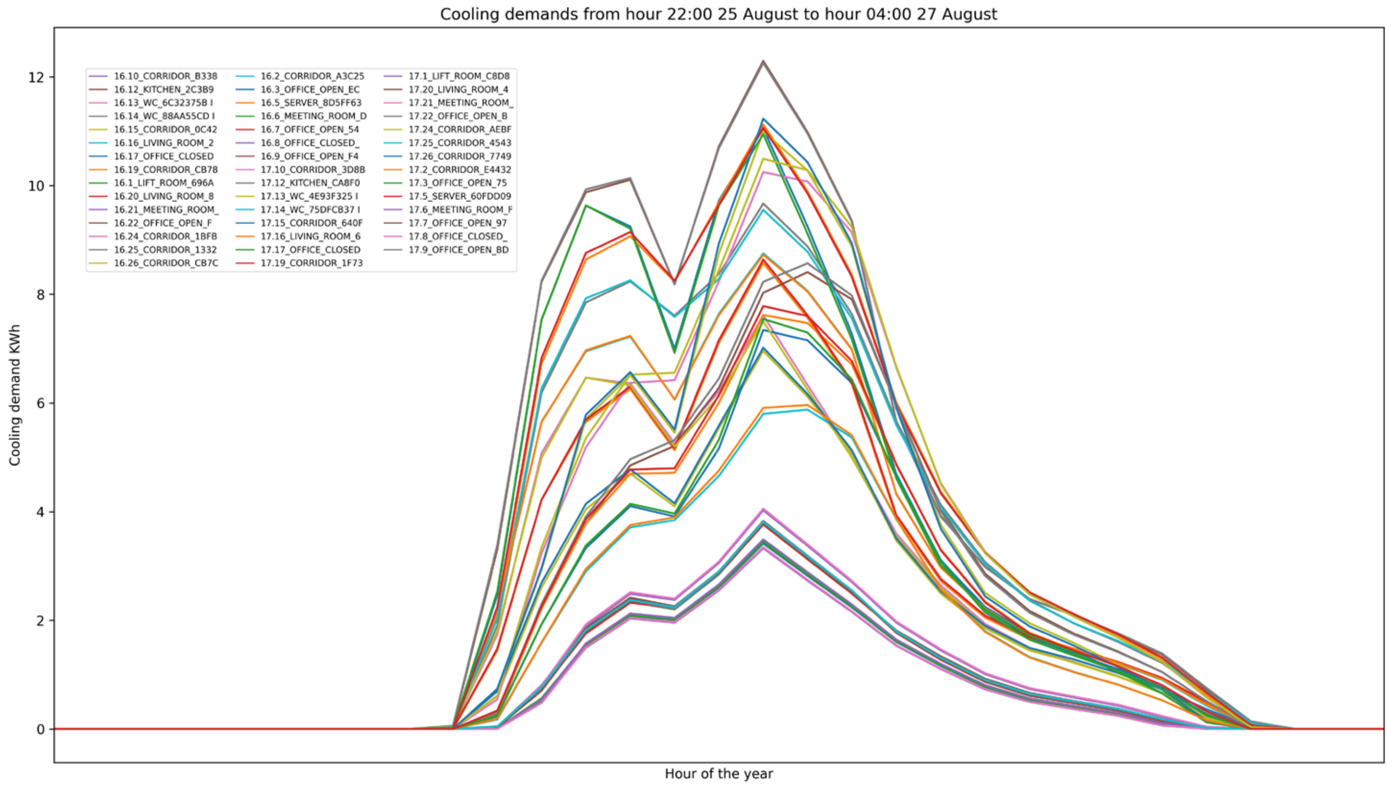


Figure. 69: Graph previewing each room/zone's cooling demands in a shorter period during a year

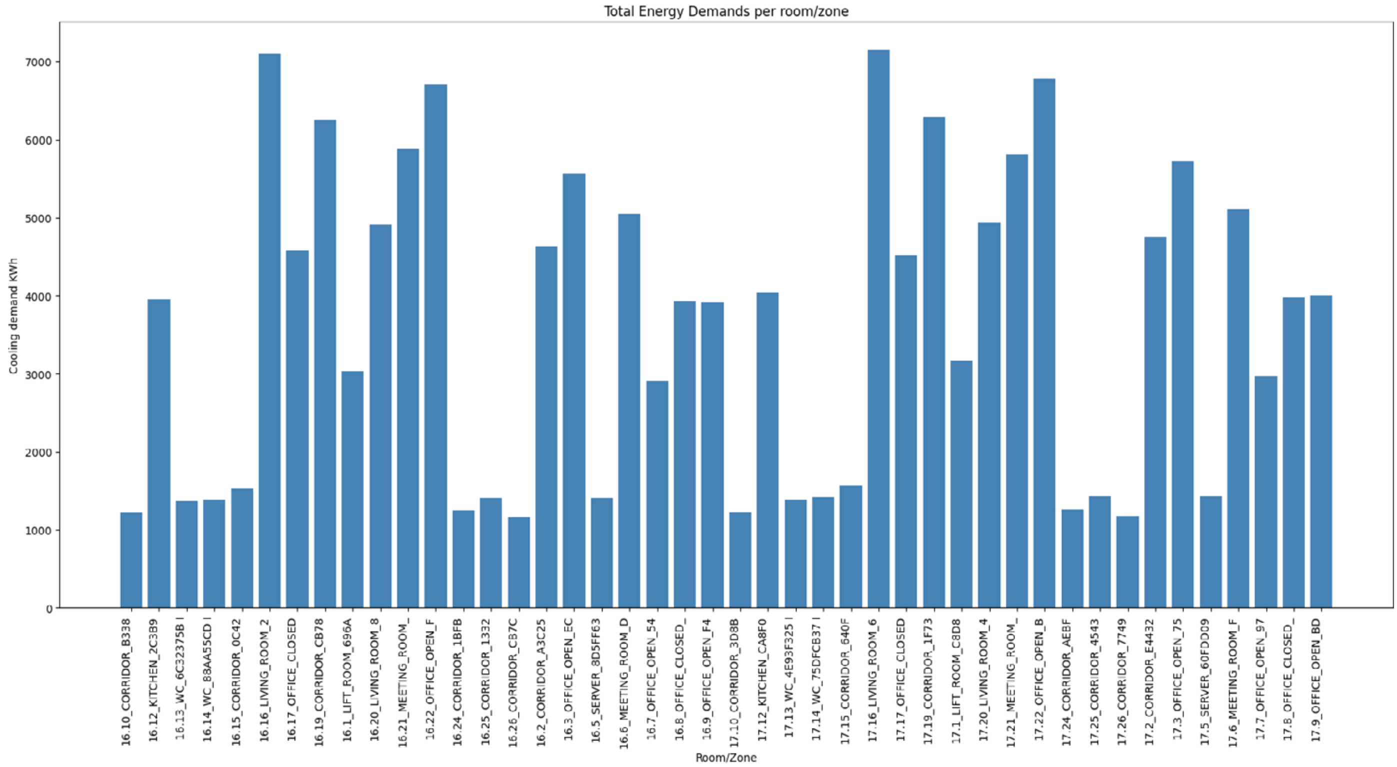


Figure. 70: Total cooling demands for each room/zone in the typical floors under investigation

It is worth mentioning here that although in the rooms/zones visualization the maximum cooling demands reach a value of 7149.90 KWhs, in the energy balance outputs as well as the simple visualization of the results in Honeybee envirnoment the maximum values barely reach 6000 KWhs (see Figures 72,73). This deviation may occur due to further processes in the Honeybee components. The simulation data was therefore exported into a csv file for python post-processing. Through post-processing the maximum cooling demands of the rooms were calculated based on the simulation output data (see Figure 70) and indeed the maximum cooling demands of the rooms is 7149.90 KWhs. Therefore these values were used in the multi - optimization workflow.

When it comes to Daylight autonomy most spaces in the perimeter of the core reach a maximum DA autonomy of 50% in annual basis. This means that with the assumptions made for the curtain wall system panels (100% transparency) and their horizontal and vertical fins the surrounding spaces have not ideal daylight conditions (see Figure 71). These results show mainly that the ratio between the spaces area and the openings area (Window to wall ratio,WWR) would be quite problematic if they were dependent on daylight only. The spaces are quite enormous for the defined opening heights which also happen to be the level heights. On the one hand, this could be based on the age of the pre-existed main bearing structure of the building or the different regulations during that period. On the other hand, it is quite common for high rises with similar floor plans to rely more on artificial lighting and thus energy. The latter can be confirmed by the 0% DA autonomy observed in the closed spaces at the core of the typical plan. This means that these spaces rely mostly to artificial lighting.

Therefore, it is quite important to note here that in terms of daylight the case study is already in an intermediate state and a potential shading element or shape blocking the daylight entering the spaces would only make the situation worse. Nevertheless, in order to stick to the original research scenario, the average daylight autonomy of the the average autonomy of each floor was taken into account as an objective to maximize in the different generated solutions to a solid excessive covering of the openings. This was decided with the awareness of the researcher that this would partly increase the electricity demands for artificial lighting something that was indeed observed in the simulation results.

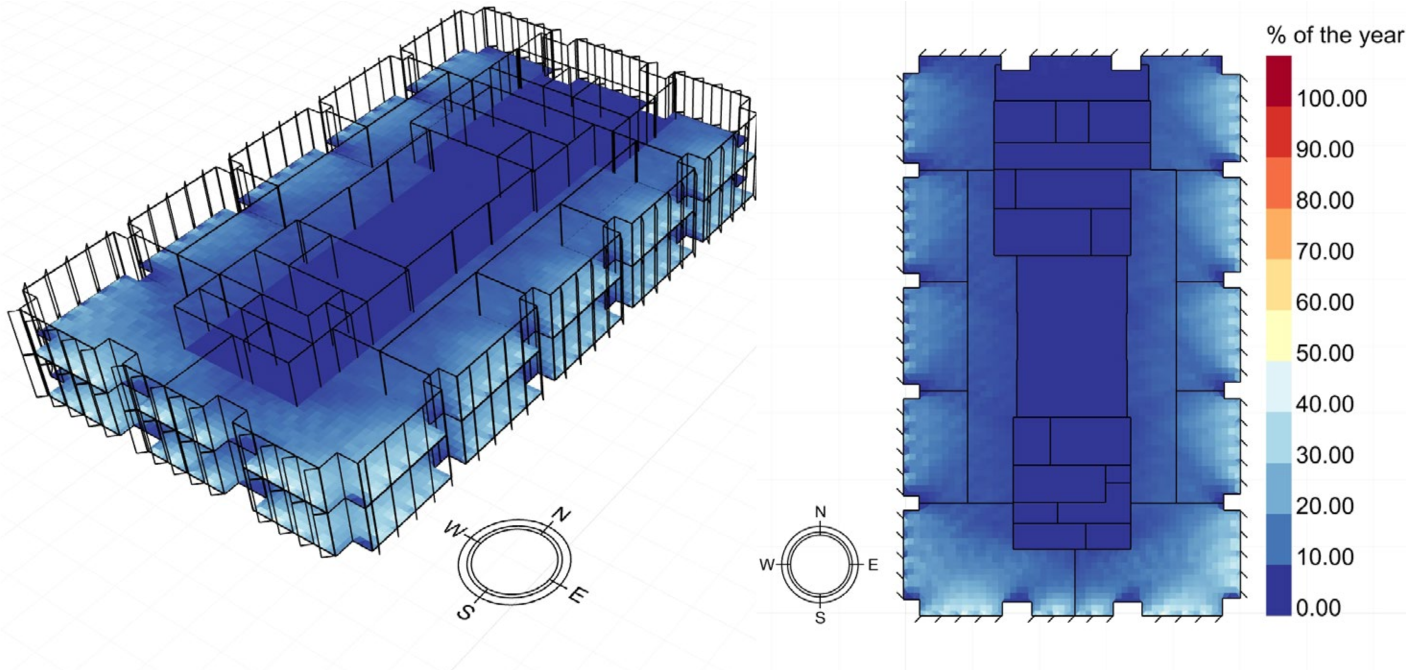


Figure. 71: Daylight autonomy study results for typical floors 16 and 17

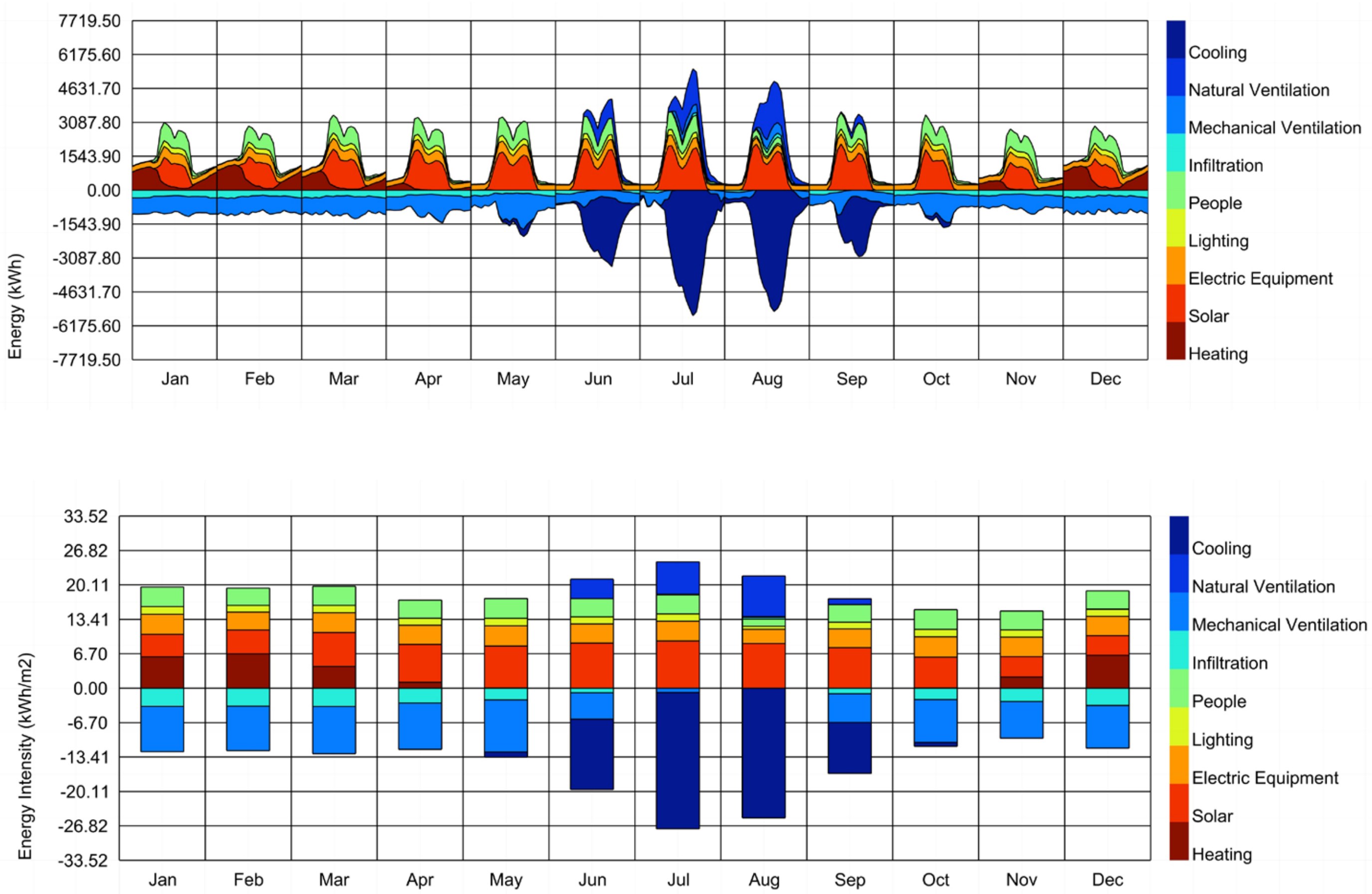


Figure. 72: Energy and energy intensity balance outputs by Honeybee balance components

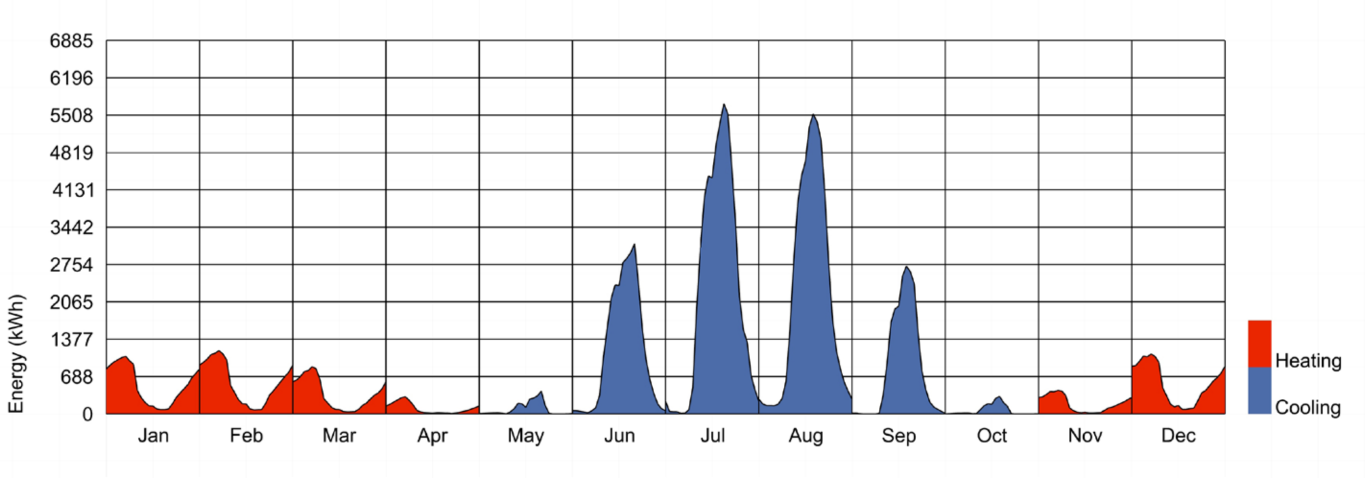


Figure. 73: Heating and cooling demands outputs by Honeybee components

With the same workflow more energy demand types can be calculated as well as the energy balance of these rooms/zones. For example it is possible to make estimations for heating demands, lighting demands, electric equipment, gas equipment as well as internal gains like solar gains, people gains and the energy intensity of all the above (see Figure 72). Moreover, in Honeybee environment, it is possible to connect the simulated data with each room's/zone's area. This way the energy intensity (which is the energy demand (KWh) divided by the room'sarea (sqm)) can be estimated for each room/zone or for each floor of the building. In this case the total end use intensity of the two floors under investigation can be calculated. This calculation is possible with components provided for this purpose, but can also be applied manually(see Figure 74).

Reaching a step further, by applying factors to each energy intensity value an annual utility cost estimation is possible (EUR/sqm). The factors used in this example, however, are indicative (see Figure 74). The reason this extra workflow was developed was that although this research focuses more on the energy performance and static parameters of this system to be optimized, the actual energy cost could also constitute a parameter or an optimization factor of the proposed solution. Moreover, with this part of the workflow it is clear that a relationship between cost, energy demands and later on defined geometrical properties (of the shading system) are possible. At the same time, many new research questions could arise from this step onwards especially if a machine learning technique was to be implemented here. For example which parameter has more influence in the final cooling demands.

Although all the above mentioned metrics could be calculated and more computational techniques could be implemented in this part of the workflow, this research focused more on cooling demands and average daylight autonomy of the selected typical floors. Therefore, only these two values were considered as objectives in the multi-objective optimization.

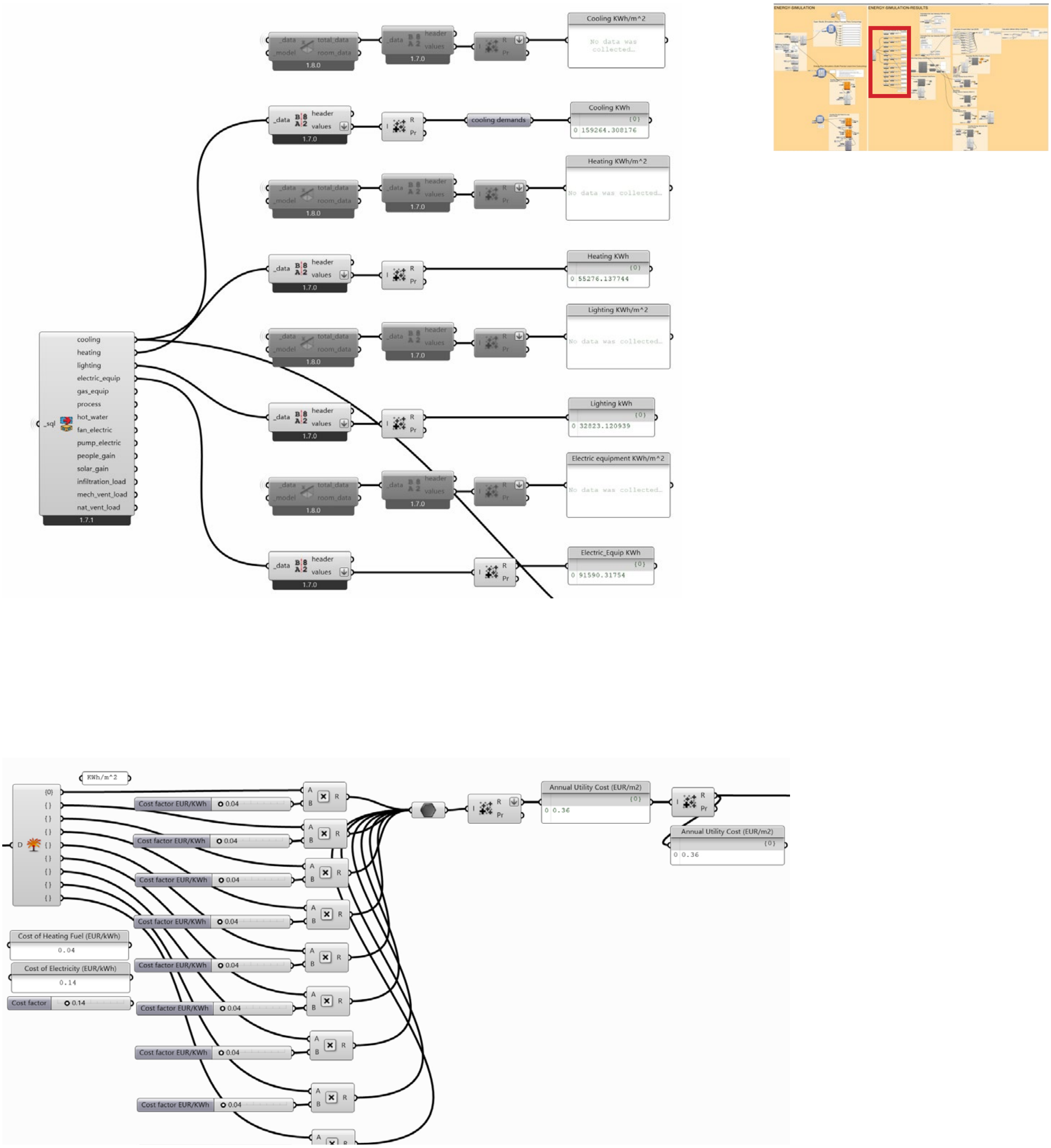


Figure. 74: top energy demands estimations, bottom Annual utility cost estimation in EUR with indicative cost factors

4.5 Shading System design and workflow

The first investigations concerning the shading system shape and bearing geometries aimed in connecting the newly defined elements to the existing unitized curtain wall system. Based on this intention an attempt was made to design a shape that would take advantage of the existing brackets connecting the unitized system's frame with its horizontal and vertical fins out of aluminium. The intention was to make a self standing shading system which would carry its own weight and live loads vertically and transfer it to volume A (base volume). Moreover, the system would take advantage of the unitized system brackets to withstand wind pressure loads in the horizontal direction. In every scenario however, the vertical and horizontal fins were to be removed.

At the same time, since only two of the typical floors were modeled for energy demands estimations, the design and optimization of the shading system was also constrained for the two typical floors under investigation. It was therefore assumed for the short boundaries of this research that an optimal solution for these two typical floors could also be proportionally optimal for the whole building. However, this could also be a research question for another approach or another workflow as it will be discussed later on.

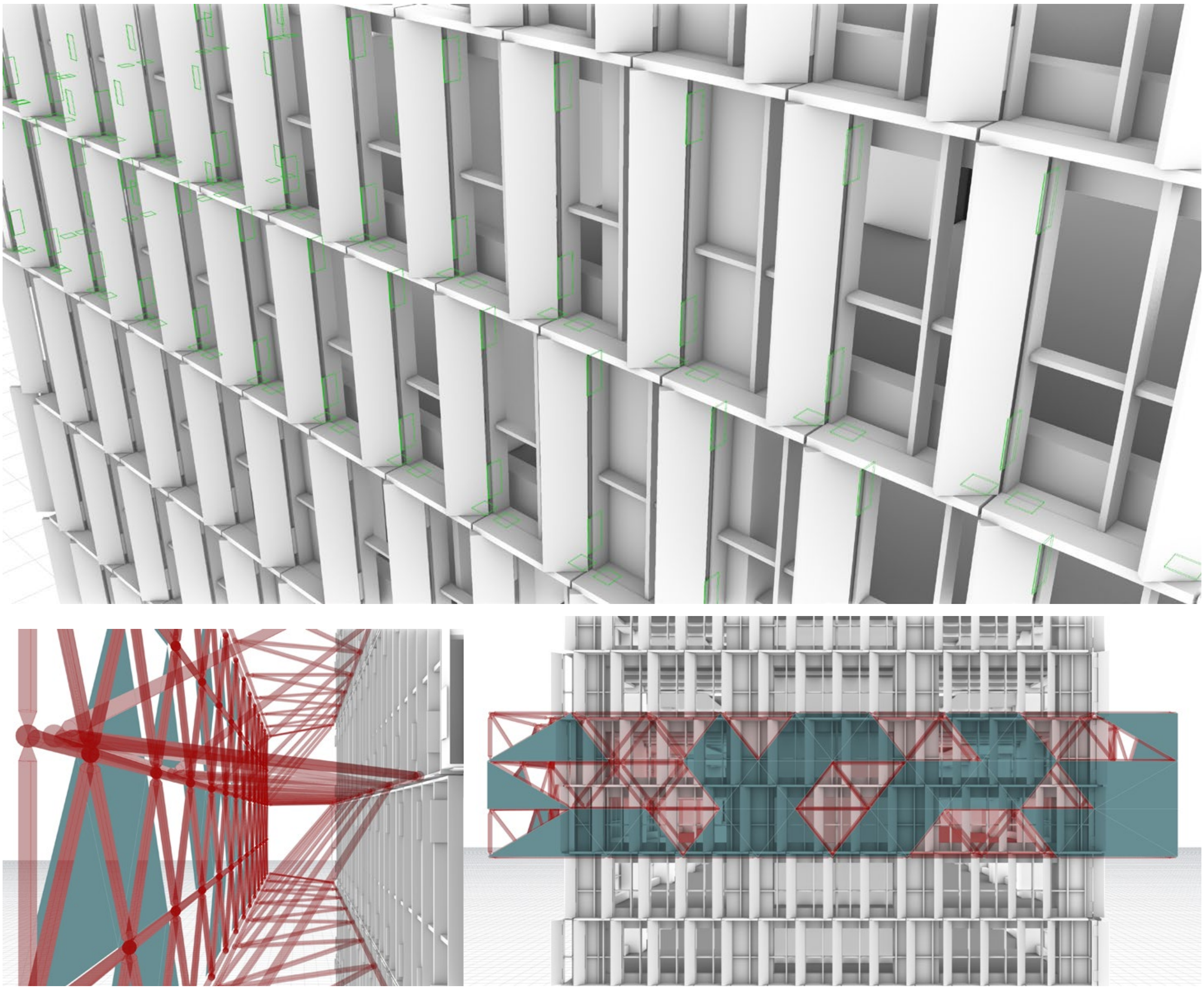


Figure. 75: Brackets connecting the horizontal and vertical fins and first approaches for the shading system.

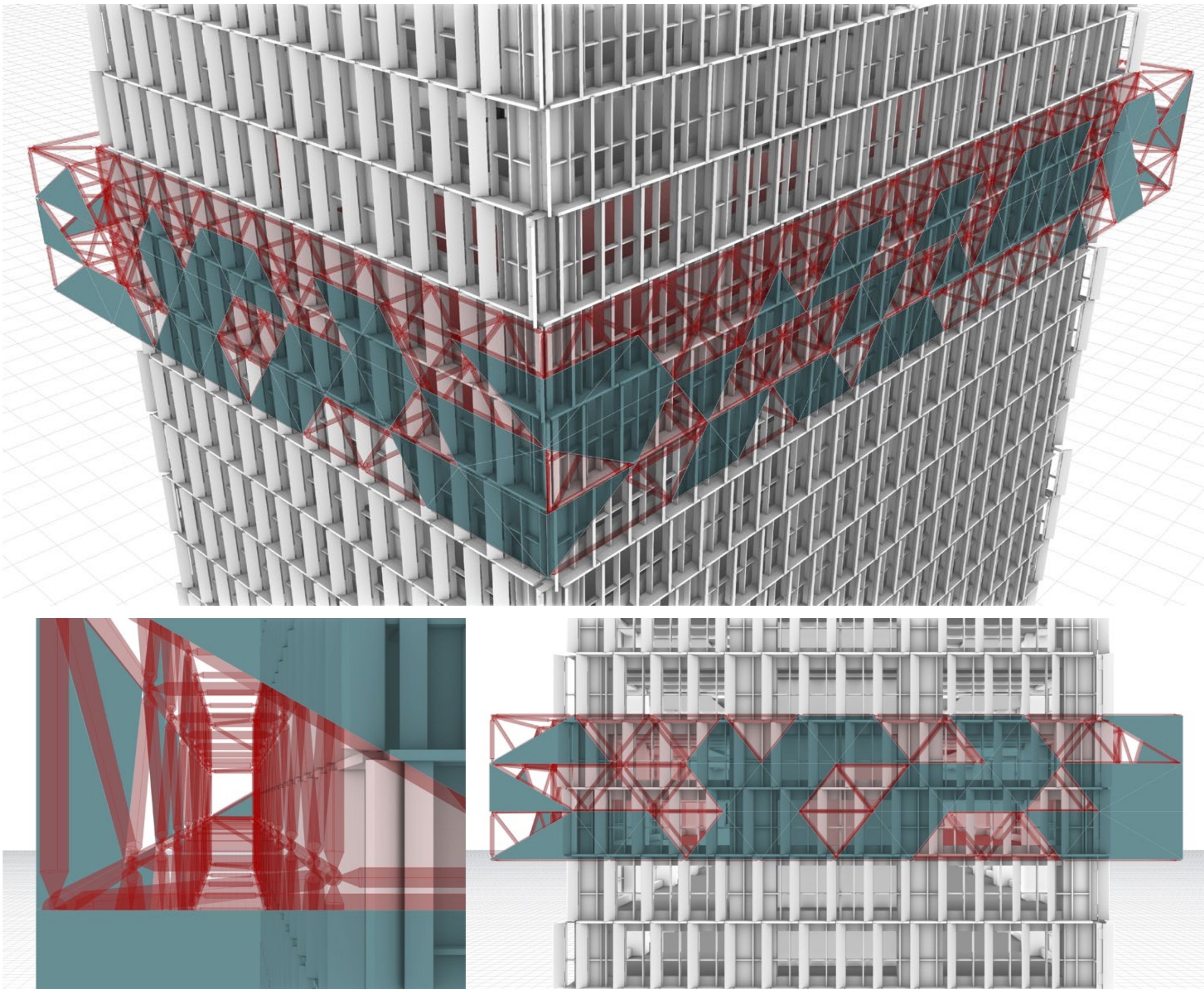


Figure. 76: Shading system approach with self standing bearing structure

Although the original intention is promising in terms of sustainability and circularity, the panels' 400mm offset per floor as was discussed in chapter 3.2, as well as the data structure limitations from Revit to Grasshopper made this attempt a tricky challenge. Some designs were indeed defined based on the list and tree data structures available in Grasshopper environment, however the design lacked basic principles of structural design. In other approaches, it was attempted to solve the problem with the implementation and parameterization of an external spatial network completely independent of the external envelope of the tower (see Figures 75,76). However, in the latter an enormous amount of material was to be used dismissing the solution as it would be completely inappropriate for an intervention of such scale.

Moving to the proposed shape, it is worth noting that in this stage the main goal of the design changed. From the initial goal of connecting the new shading system to the existing curtain wall system, its connection with the main bearing structure of the building was instead attempted. Although from an architectural perspective this is partly a failure, at least for the author, in the narrow time frame of this research a significant simplification of the design problem was made to ensure the completion of a workflow and of multi-objective optimization.

The workflow begins by isolating the slabs of the typical floors under investigation. After the slabs were isolated, a diagrid pattern was defined based on the slabs final floor distances. It was essential to adjust the diagrid height devisions in such a way, to ensure the presence of nodes in the floor planes. This way a connection of the shading system with the slabs would be possible regardless of the number and scale of the cushion panels. (see Figures 77,78)

From the defined diagrid, the points were used to define vectors pointing outwards. This way an off-set of the diagrid points was possible and in this way an offset diagrid was created. The lines defined by the second diagrid were the ones used to define the main bearing structure of the exoskeleton shading structure. With the connection of the offset points with the originally defined points aligned with the slap edges the horizontal beams were defined.

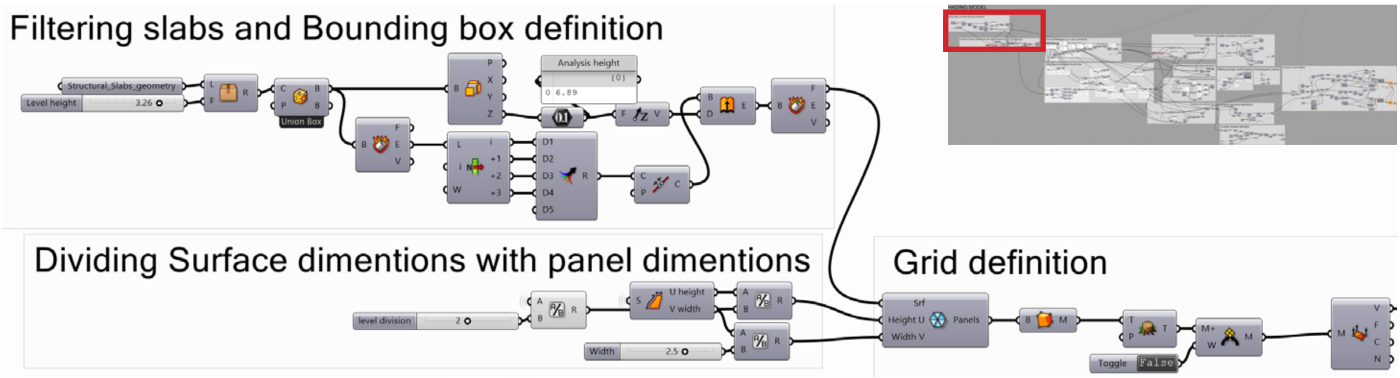


Figure. 77: Isolation of slabs and grid definition

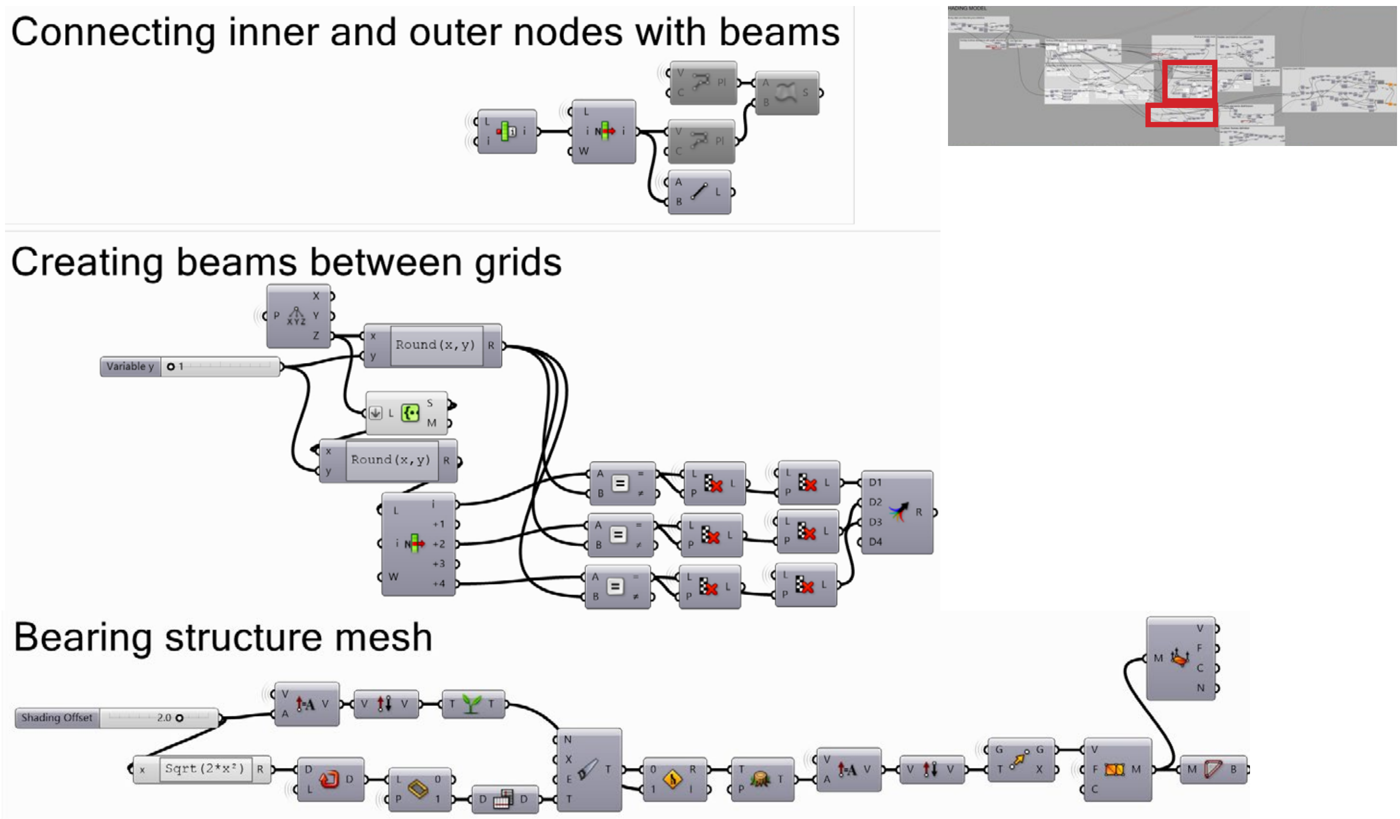


Figure. 78: Definition of diagrid patterns and of the in-between beams based on slab heights

Subsequently, based on the diagrid frames, triangular surfaces were defined to represent the shading elements. Although an accurate design of a cushion panel could be achieved using physics simulation in Grasshopper environment, simpler surfaces were employed at this stage to streamline the geometry for multi-objective optimization and to reduce computational load. Furthermore, to ensure sufficient daylight and views from and to the office areas, adjustments were made to the number of shades around the entire perimeter of the typical plan. Finally, by assigning a hollow cross section to the beams and a spherical node at the points of the outer and inner diagrid a visualization of the bearing structure was possible. The hollow section diameter and thickness, as well as the nodes will be further discussed in a later chapter. (see Figures 79-82)

The last step after this parametric model definition was to translate the shading surfaces into Honeybee shading elements and to implement this geometry into the energy model as it was defined and simulated in the previous chapter. After a new energy model was defined, the cooling demands and the average dalight autonomy of the spaces could be evaluated.

Since the multi-objective optimization purpose was to investigate the different solutions available with this parametric model and eventually select the most promising solutions, some parameters of the geometry's definition were used for the multi-obective optimization. These parameters were considered the ones affecting more the energy and static simulations and would give more value to a generation of solutions. These parameters are namely: the shading system's offset from the slabs, the scale and ratio of the diagrid defined for the structure and finally the shading coverage percentage, to adjust how many filled triangles are needed on this diagrid structure.

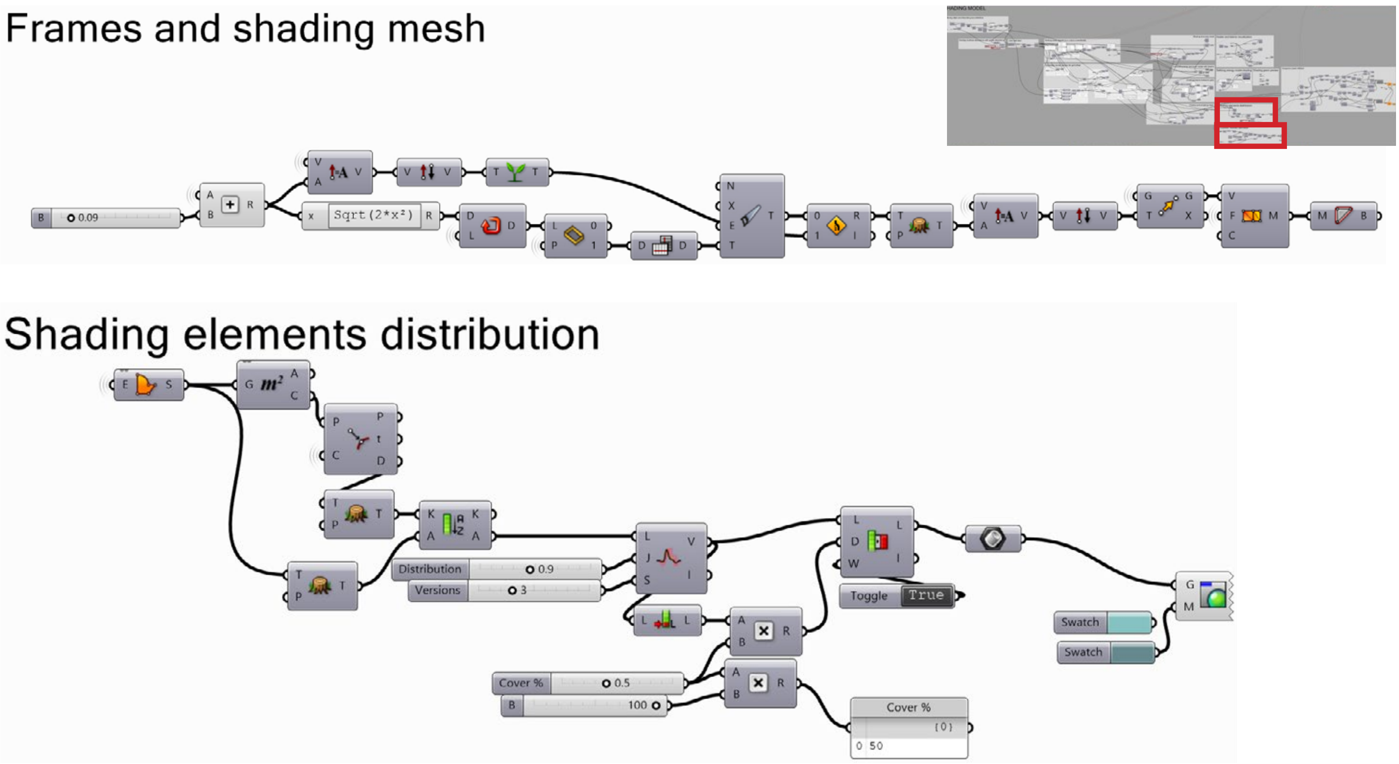


Figure. 79: Brackets connecting the horizontal and vertical fins and first approaches for the shading system.

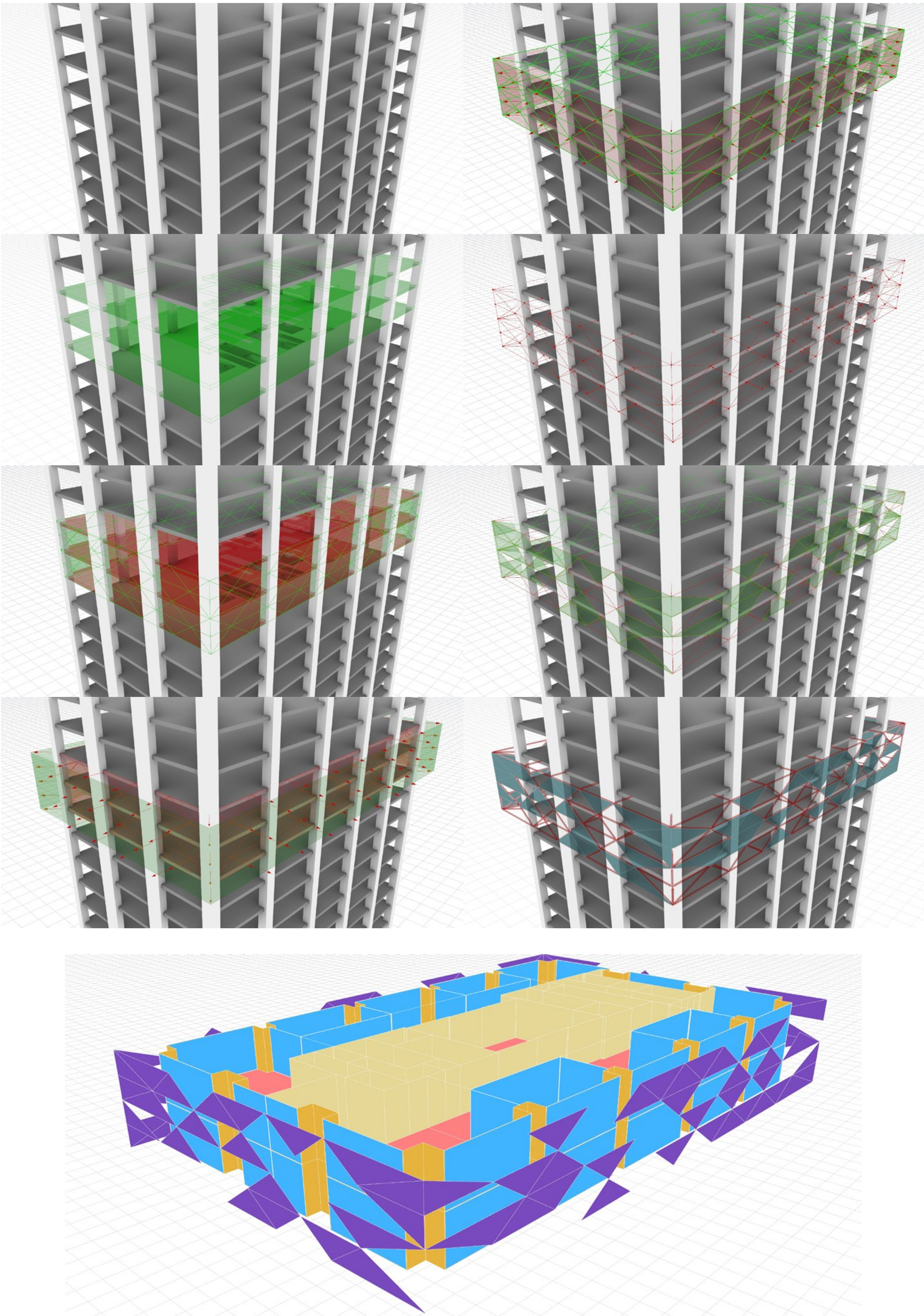


Figure. 80: Consecutive steps for defining the exoskeleton shading system in relation to the tower 's main bearing structure and the end resault energy model

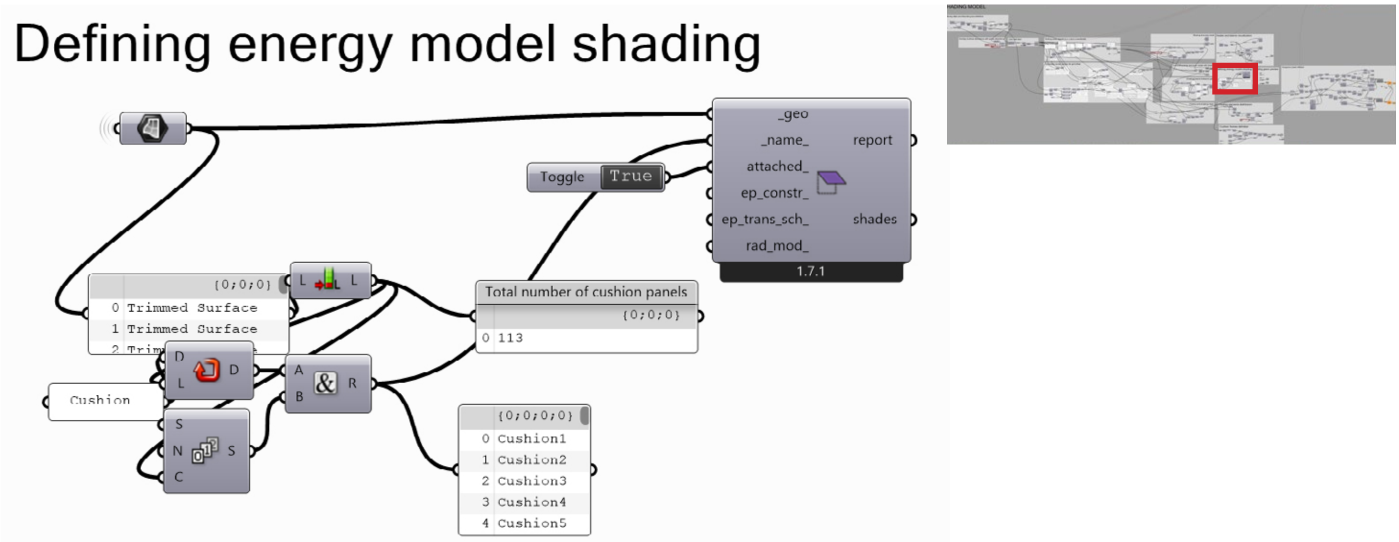


Figure. 81: Translating the newly defined shading system into honeybee shading elements

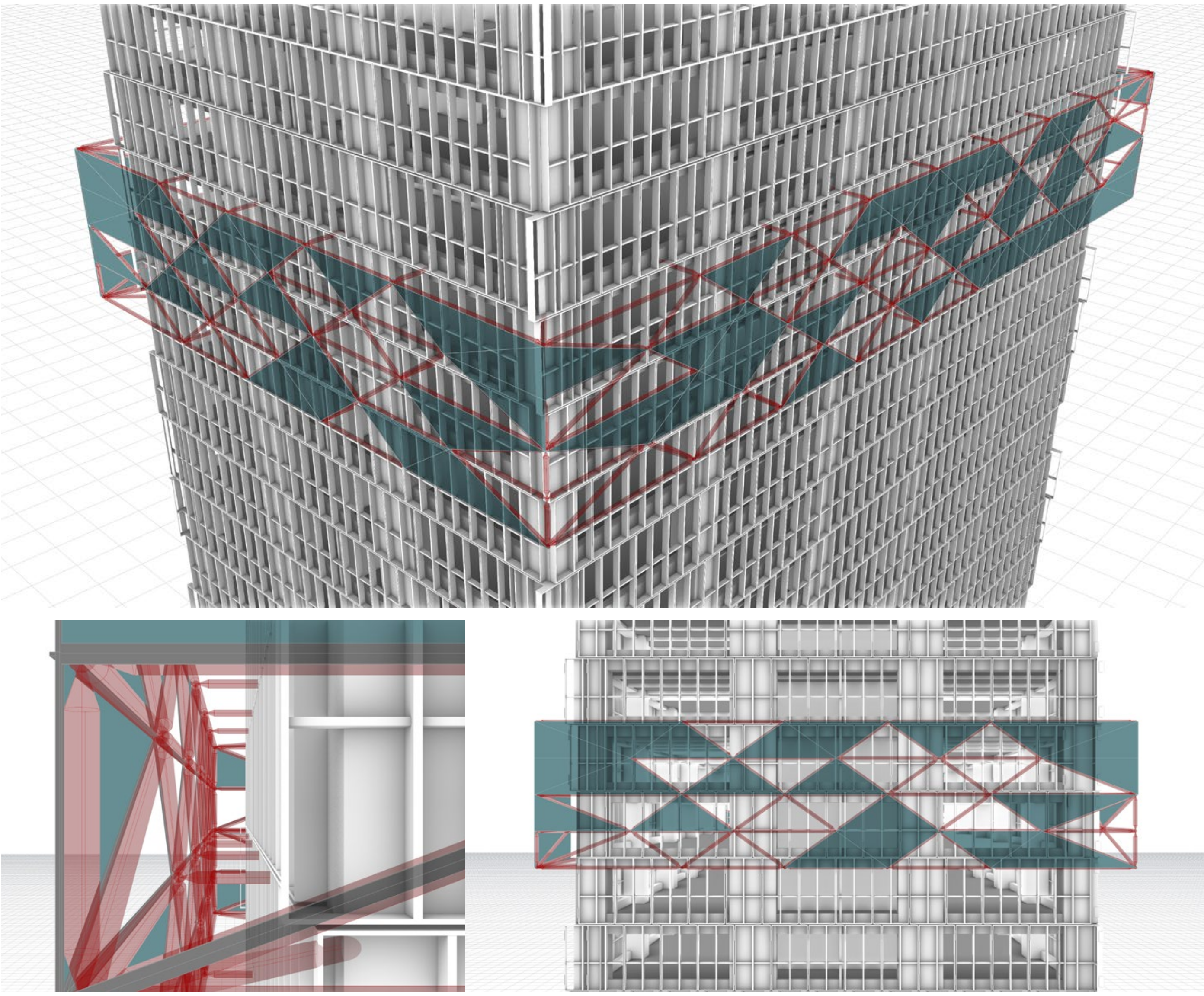


Figure. 82: Shading system approach with self standing bearing structure

4.6 Static analysis workflow

Structural elements definition

Following the shading system shape definition, the inner and outer diagrid points, the lines connecting them as well as the outer diagrid lines were used to define a static model for analysis. As discussed in chapter 4.2, Karamba 3D was used in this part of the workflow.

Cross section selection

For the linear static analysis of the bearing structure, a rule of thumb was used for a correlation between a steel hollow section and the height of each floor of the tower (CTB2320-Quick Reference Guide, 2022, prof. ir L.A.G. Wagemans). For a multi storey building with a given height x and 2m<x<4m we have:

$$\min = \frac{x}{28} \quad \max = \frac{x}{7} \quad (10)$$

In this case study where x=3.25m, we get the minimum and maximum of the hollow sections in meters (see Figure 83). Based on the calculated values a typical hollow section based on EN 10210 properties with a diameter of 177.8mm and a thickness of 12.5mm were chosen for this analysis.

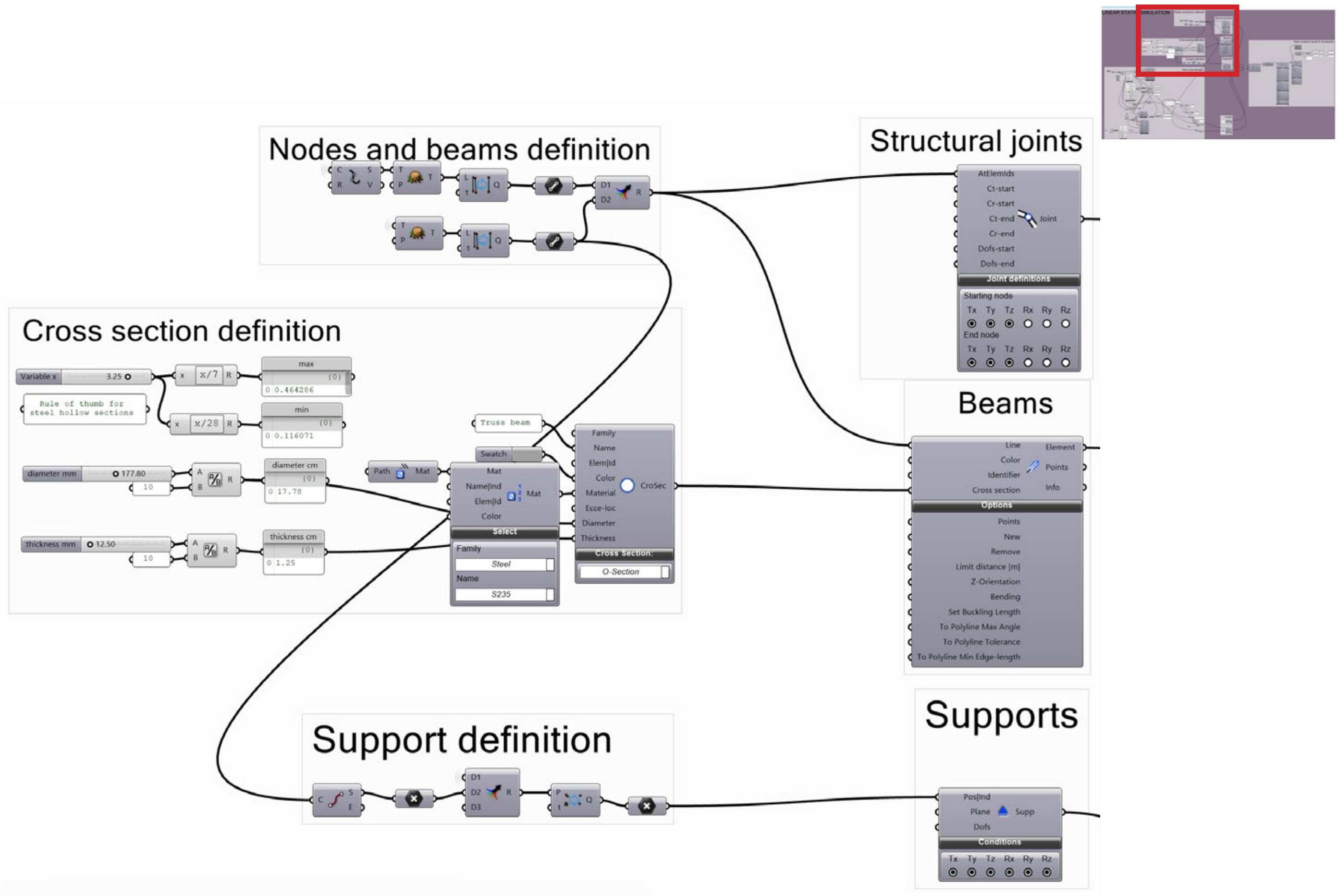


Figure. 83: Translating the already defined geometry of the shading system into Karamba Beams, Supports and Joints. Source for EN 10210 cross section: (http://www.b2bmetal.eu/en/pages/index/index/id/105/)

The selection of a cross section affects the costs, the mass, as well as the carbon footprint of the structure. These properties as well as a potential cross section database implementation in the workflow would enable the use of these properties either as parameters or as objectives in the multi-objective optimization. These properties as well as their correlation could, however, be subject of further investigation with the form of new research questions. Such investigations would be, the hierarchy of criteria used in such a multi-objective optimization procedure, or an investigation concerning the correlation between these criteria and their inbetween relationship.

Supports

In order to adequately analyze the shading system, the connections of the load bearing structure to the slabs were considered as fixed supports with zero degrees of freedom in both axial forces and moments. In parallel, in the lowest part of the external diagrid's plane, it was considered that at its base there are also fixed supports, so that the shading system can transfer its self loads to the main bearing structure. With these assumptions, however, it is as if the supporting body is standing on solid ground or on the concrete slab of the tower (volume A), which is not true in reality since the floors under invesitgation are at 50m height from the pedestrian level. In fact, to adequately solve the load-bearing structure of such a shading system, it should first be designed for the entire tower. This way the appropriate wind and self loads would be automatically applied to the structure.

For the purposes of this multi-objective optimization, however, and mainly for computational feasability reasons, the structure was analyzed as a two storey structure with members as discussed above and loads as discussed later on in the first place and later on it was designed for the whole building.

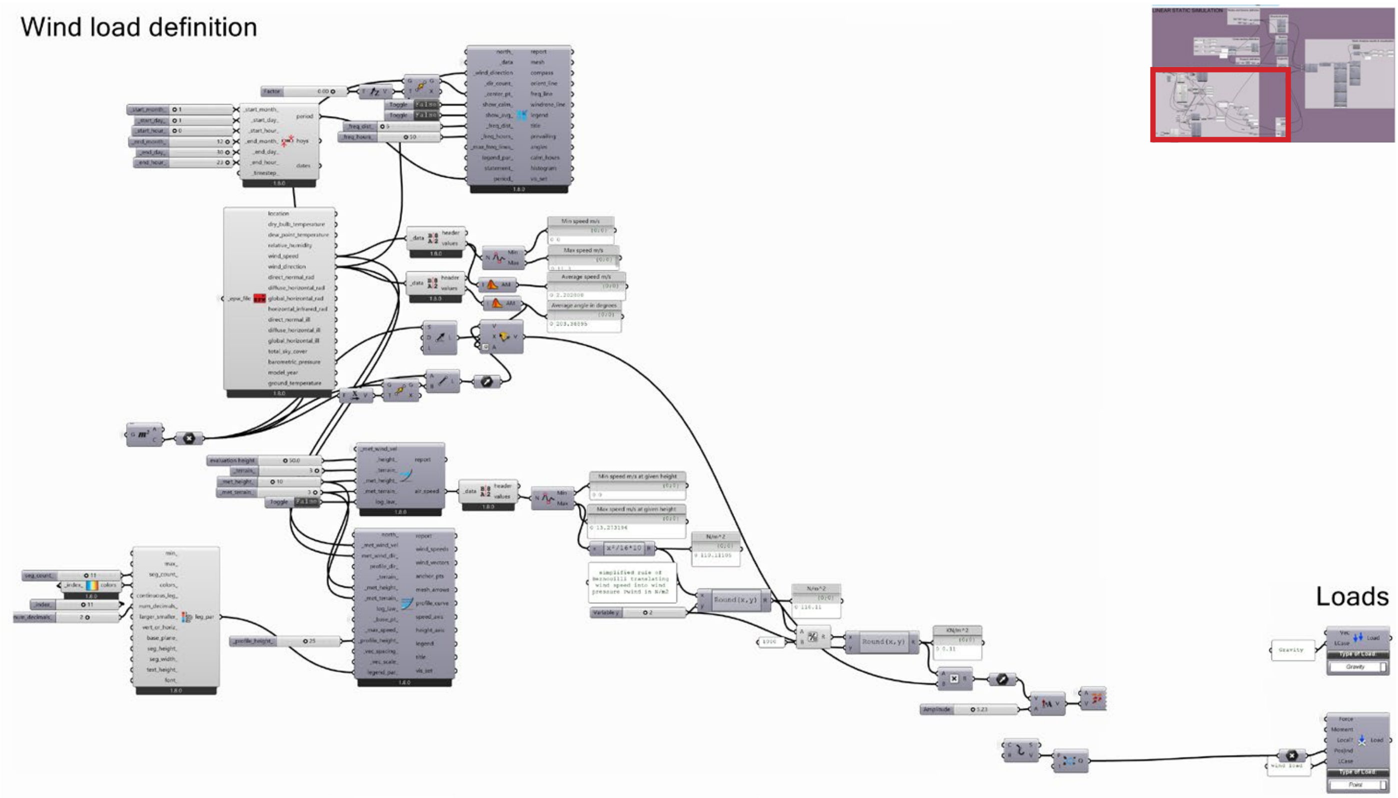


Figure. 84: Extraction of wind direction and speed and translation of wind speed into wind pressure

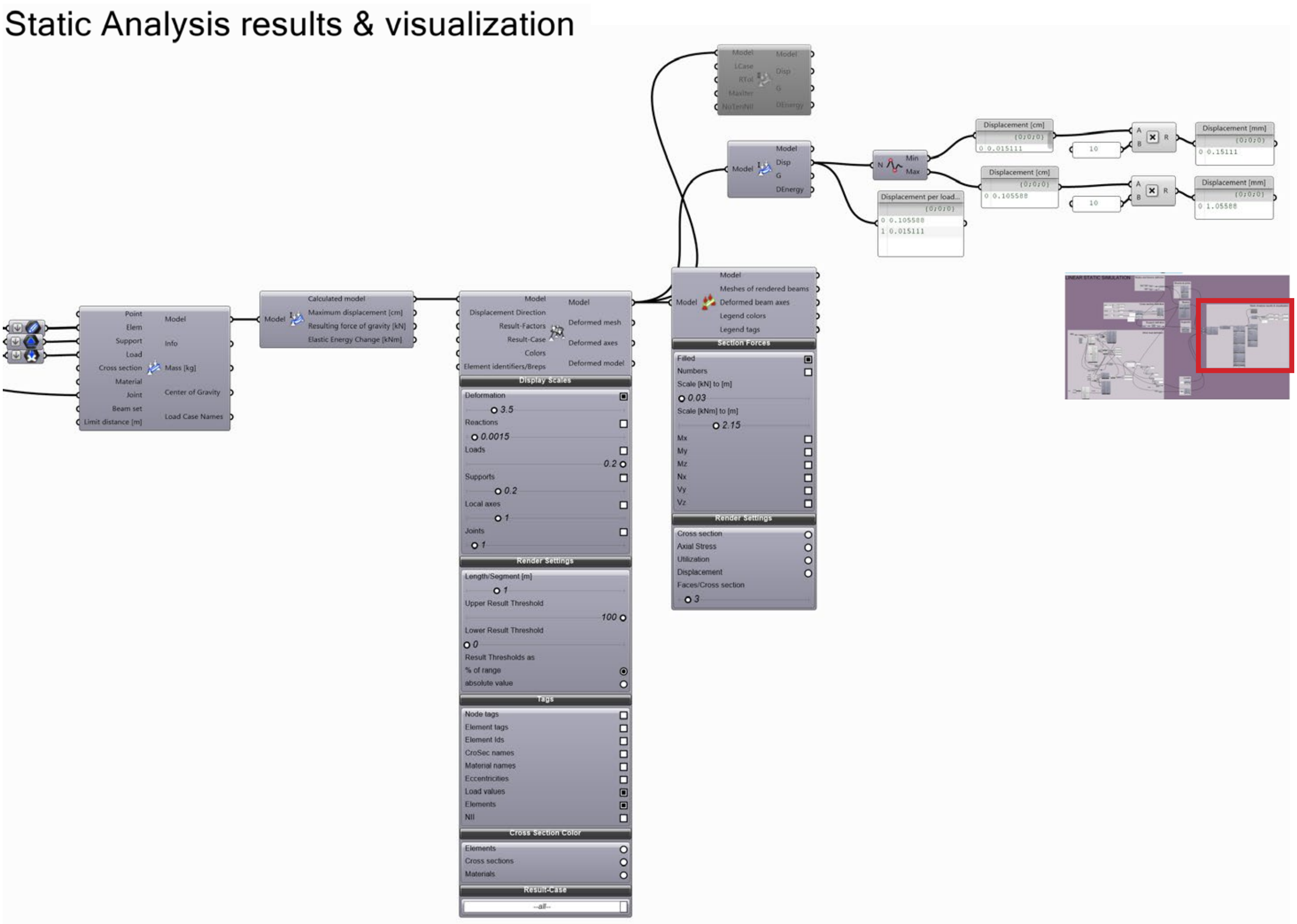


Figure. 85: Linear Static Analysis with Karamba 3D and results visualization

Loads definition

The data needed in order to design a structure concerning ULS (ultimate limit state) and SLS (serviceability limit state) is the total loads applied. Therefore, for the structural simulation, the self-load of the structure, as well as the wind loads are the first things that should be defined. For self weight Karamba 3D automatically applies automatically the structure's self weight based on its mass and automatically the corresponding loads are applied. For the windloads however, a rule of thumb was used. (see Figures 84,85)

With the calculation of the mean wind direction vector, based on all the measured wind directions from the EPW file and with the wind maximum speed in the height of investigation, an estimation for the windloads was possible. In order for this translation, from air speed to air pressure to be possible a simplified rule of Bernulli was used. Based on this rule of thumb:

$$P_{wind} = \frac{V^2}{16 \cdot 10} \quad (11)$$

where: V is the air speed measured in m/s and P_{wind} is the air pressure measured in Pa or N/m^2. The calculated maximum pressure was then applied to all the nodes of the structure independent of their position. This means that the structure was solved without taking into account the tower's shape and the way it affects the wind flows arround it. (see Figure 86)

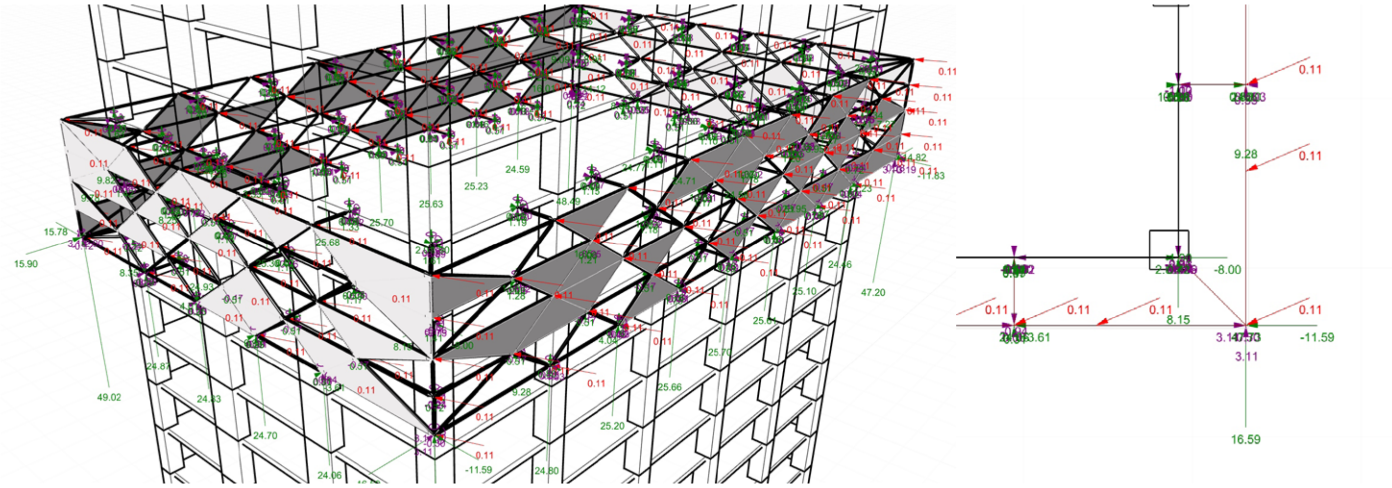


Figure. 86: Translation of shape into a static model, application of loads, supports and reactions calculation

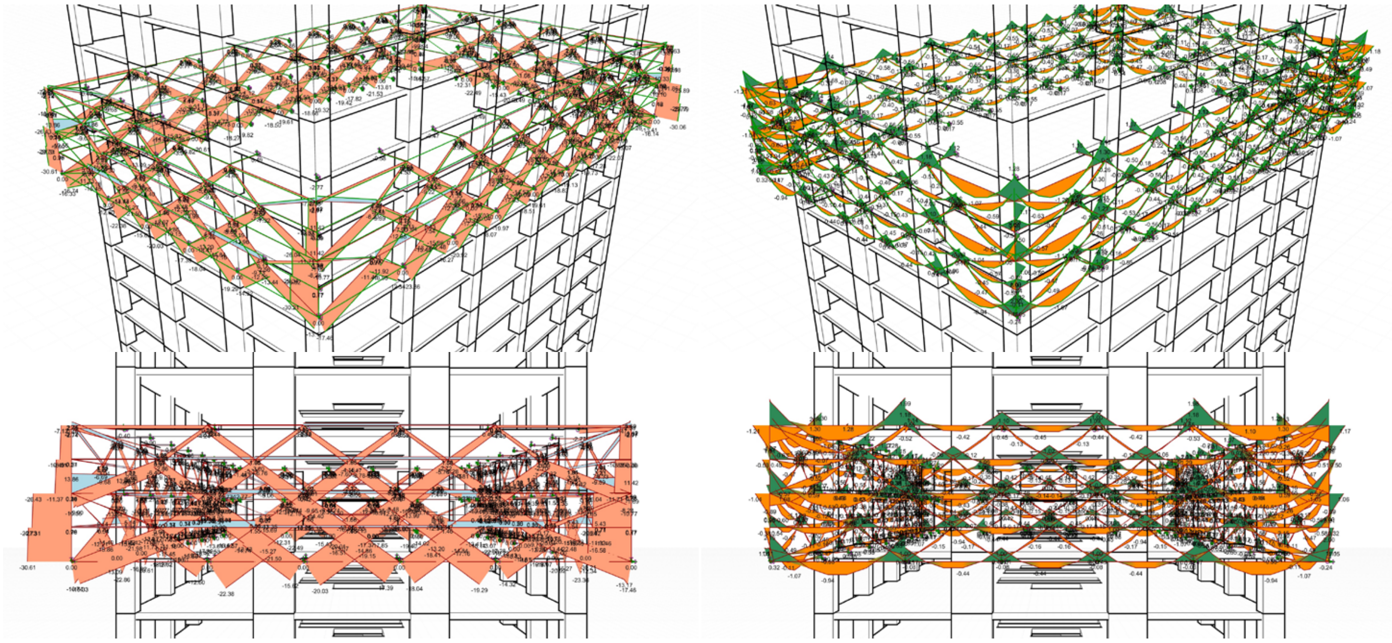


Figure. 87: Axial forces and bending moments calculations with Karamba 3D

In order to make a calculation with more precise estimations, sophisticated CFD simulations should be applied for taking windward and eleward pressures into account. The maximum pressures from these calculations should be used together with norms and standards boundary conditions and methodologies for the proper design of the bearing structure. Moreover, when applying loads on this structure two dimentional loads should be applied to the cushion panel surfaces and then transferred as linear loads on the frames and nodes of the structure.

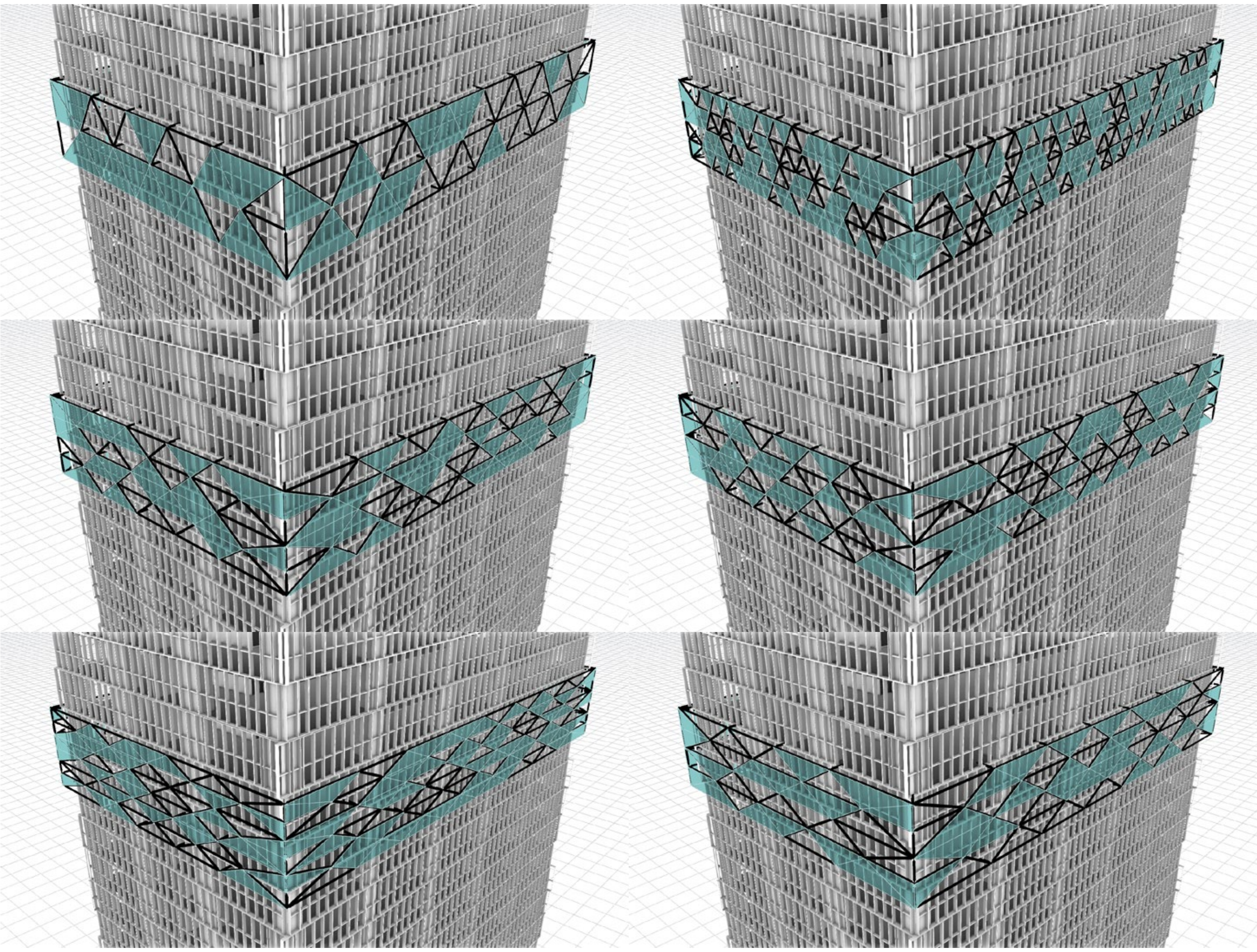
Linear loads should also be applied on the beams of the structure not for one but for many directions. A proper estimation for the deflections in midspan of the beams as well as for the supports (nodes) under investigation would be possible only with a rough hand calculation and later on with in depth FEM analysis with static analysis software like Robot, Strusoft, Dlubal, Ansis and others. However, once more, since this direction would be a whole new research topic, and this work only focuses on a preliminary design proposal, for the purposes of a multi-objective optimization a simplified analysis with the application of point loads was used.

For these reasons, the total mass of the designed structure as well as the maximum displacement among all the above investigated structural members were used as objectives to minimize in the multi-objective optimization.

4.7 Multi-Objective optimization & workflow

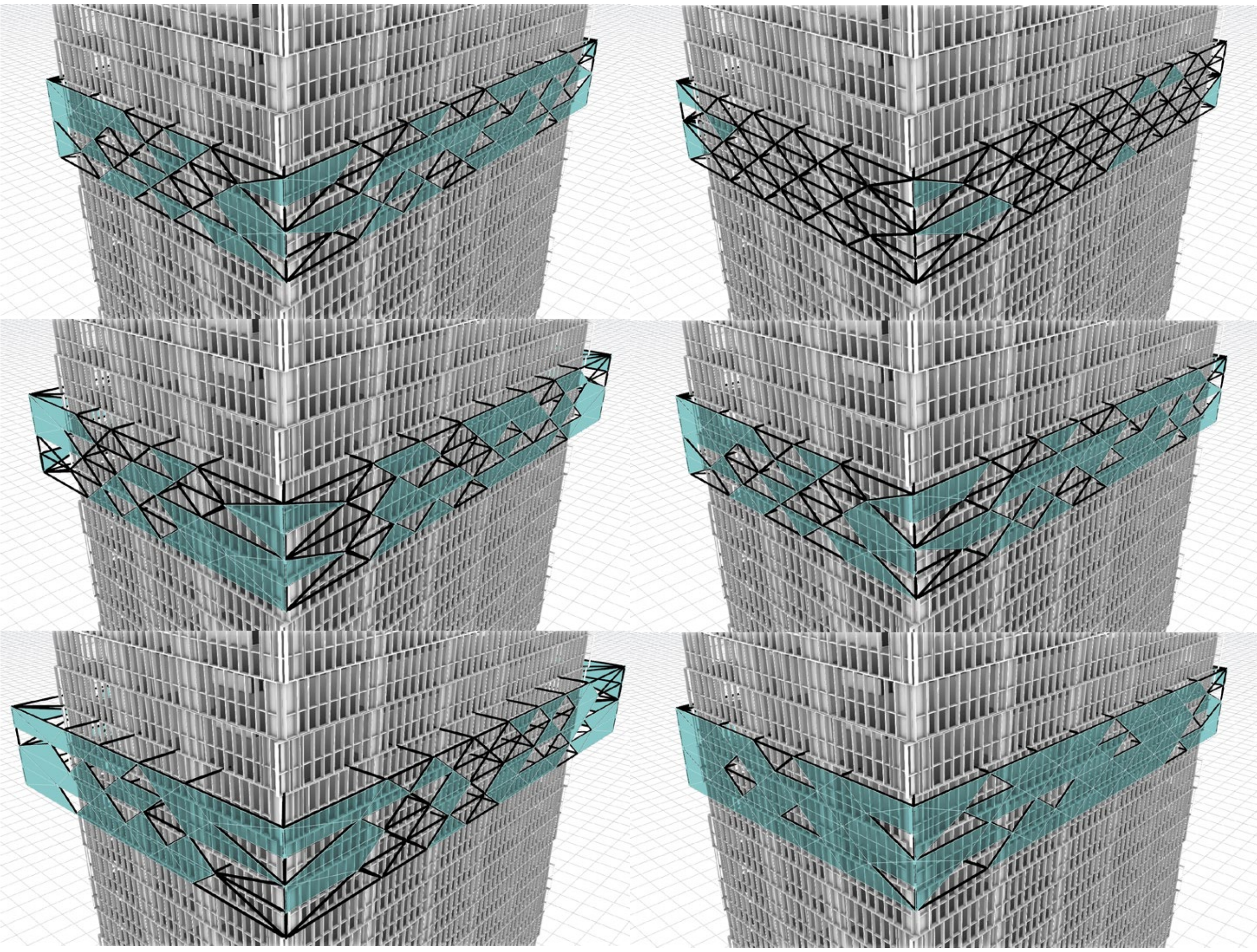
As mentioned in the previous chapters, only a subset of the numerous parameters of the workflow were considered in the optimization, although more could have been included. It is, however, crucial to distinguish between parameters and objectives in this stage to clarify what is being compared and what the final outputs of a multi-objective optimization are.

The shading system's pattern scale (P1), its width-height ratio (P2), and its offset (P3) as well as the amount of shading (P4) were the parameters that were used from the parametric model for the optimization (see Figures 88,89). These parameters were the ones affecting the different versions of this parametric design. In parallel, the calculated total mass (O1) of the shading system's



(a) (b)

Figure. 88: a. pattern scale (P1), b. the width-height ratio (P2)



(c) (d)

Figure. 89: c. diagrid offset (P3), d. shading coverage (P4)

structure as well as its maximum displacement estimation (O2) were used as the fitness objectives for the optimization from a structural perspective. From the energy efficiency perspective the cooling demands (O3) and the average daylight (O4) outputs of the energy and daylight simulations were used as fitness objectives. (see Figure 90)

Wallacei, utilizing the provided parameters (Genes) and the specified objectives (Fitness values), employs the NSGA II algorithm to generate solutions based on preceding iterations. This process involves iterating through all possible combinations of the four defined parameters. For each new generation, following a niching approach as discussed, new individuals (undefined solutions) and a pareto front curve are produced for each generation. The fitness of the solutions produced in each generation, based on the given objectives, depends on the generation size (the number of individuals in a single generation), the generation count (the number of generations produced) as well as the total possible values of the parameters.

The larger these values, the closer the solutions are to the true Pareto front solutions, and thus, the best solutions for the given objectives. At the same time, however, the more time is needed for the optimization to be completed. (see Figures 91,92) It is worth noting here that for each parameter specific bounds were defined based on literature review and on the design nature. For example the diagrid pattern's width-height ratio scale was defined based on the maximum possible cush-

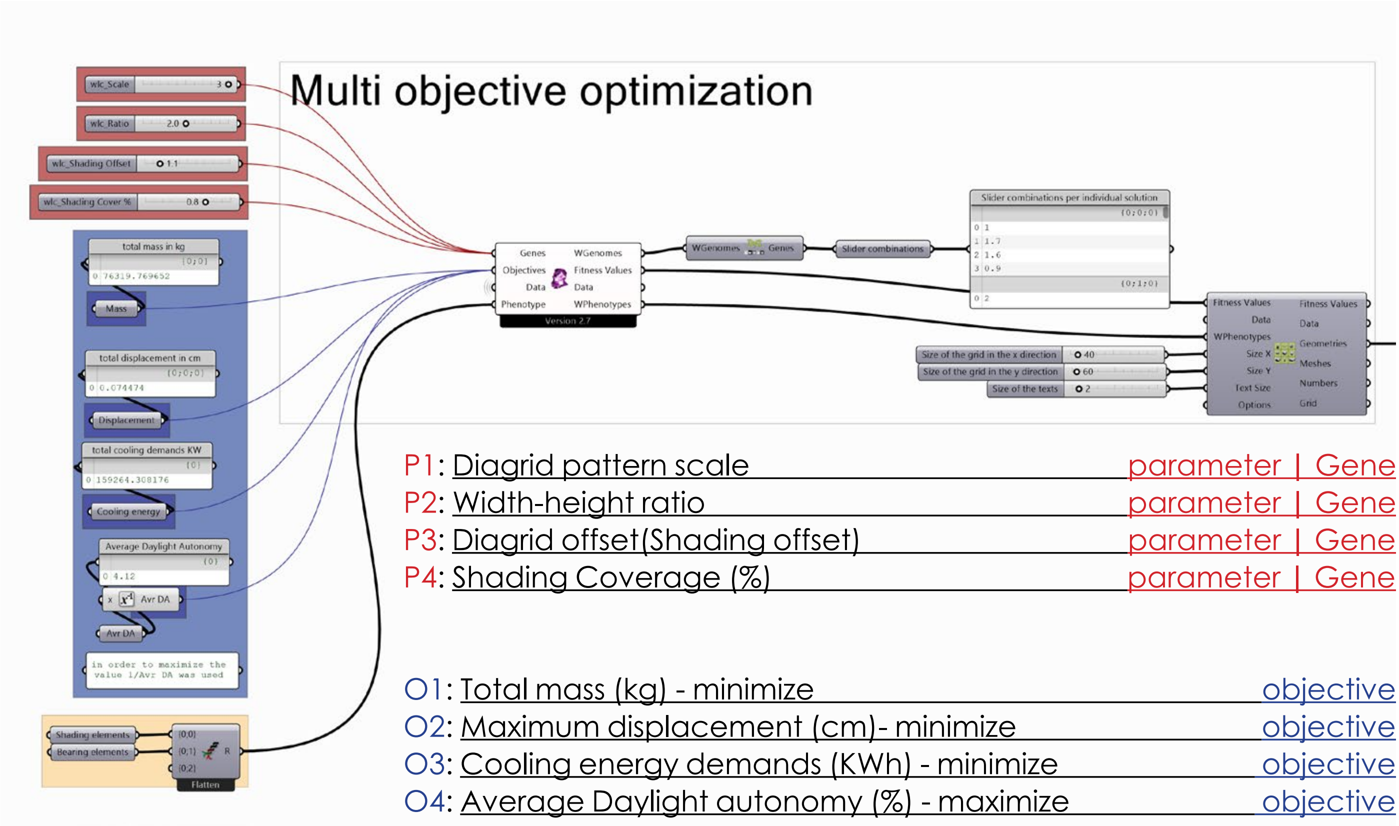


Figure. 90: Walacei workflow, input parameters, objectives and geometries to be generated

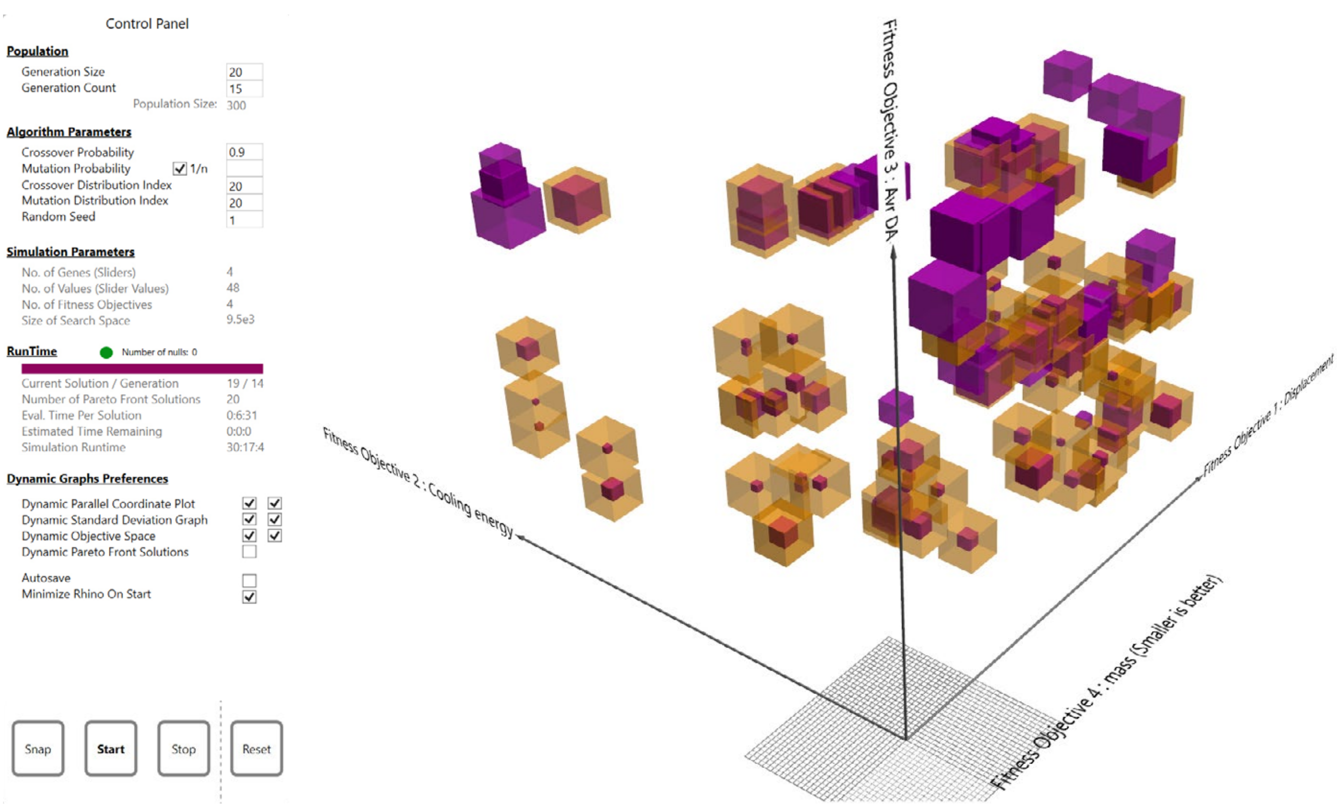


Figure. 91: Optimization settings and all the solutions ploted in the solution space as boxes

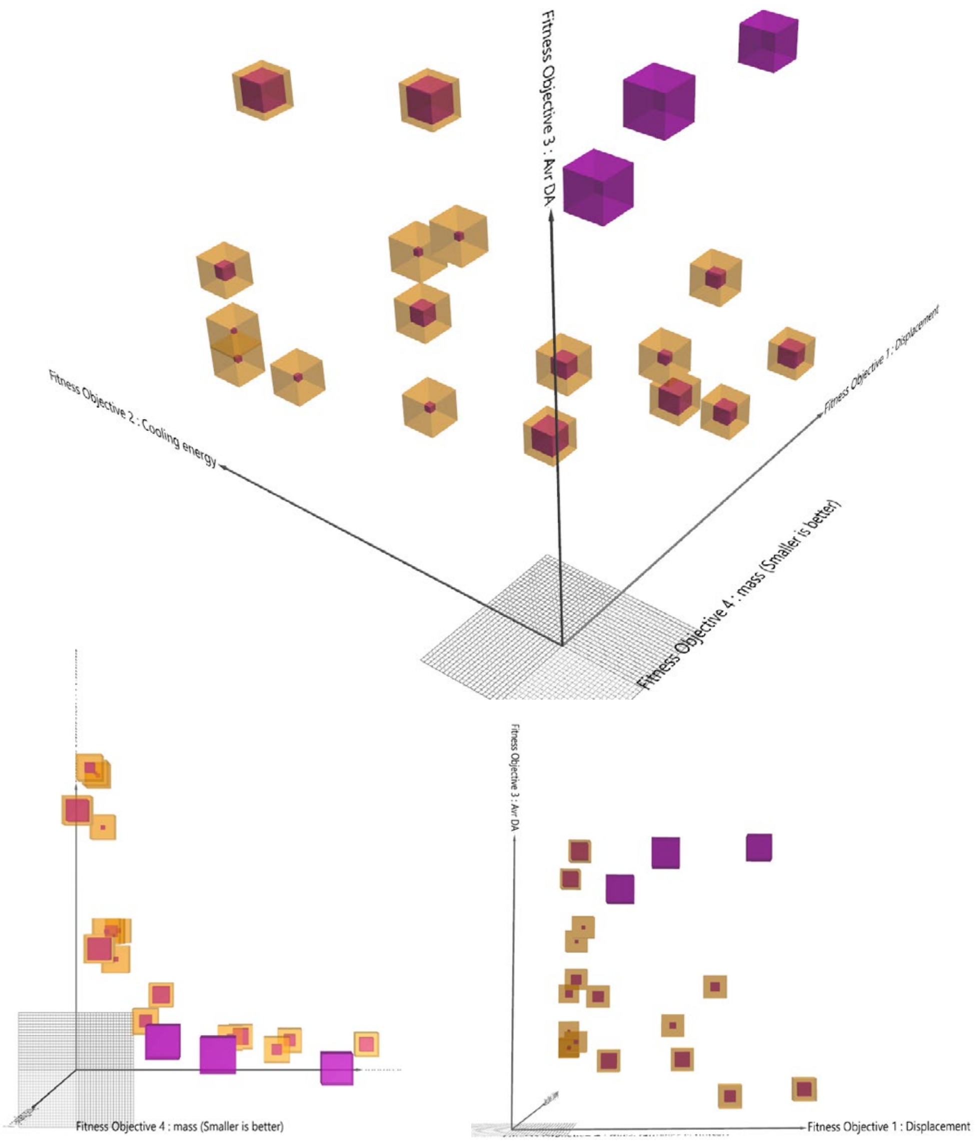


Figure. 92: Projection of last generation solutions in solution space with pareto front solutions for pair of objectives

ion panels spans invesitgated in chapter 2.1. The diagrid pattern scale was limited in such a way so that the nodes and the corresponding beams connecting the shading system to the slabs are always in tha same plane. The diagrid offset was limited above the minimum 800mm offset needed for maintainance and cleaning of a double skin facade. Finally, only the shading coverage was a parameter without bounds.

In this workflow, since all of the objectives are outputs from Karamba 3D and Honeybee simulations, during the optimization procedure the corresponding simulations needed to be carried out. This means that one simulation for the cooling demands, one simulation for average daylight and one for the linear static analysis of the shading system was applied for each individual of every solution generation.

In the optimization settings for an annual period and for two typical floors with a generation size of 20 solutions, 15 generations were produced. Thus, for computational feasability a population size of 300 solutions was defined based on the four parameters and the four objectives discussed.

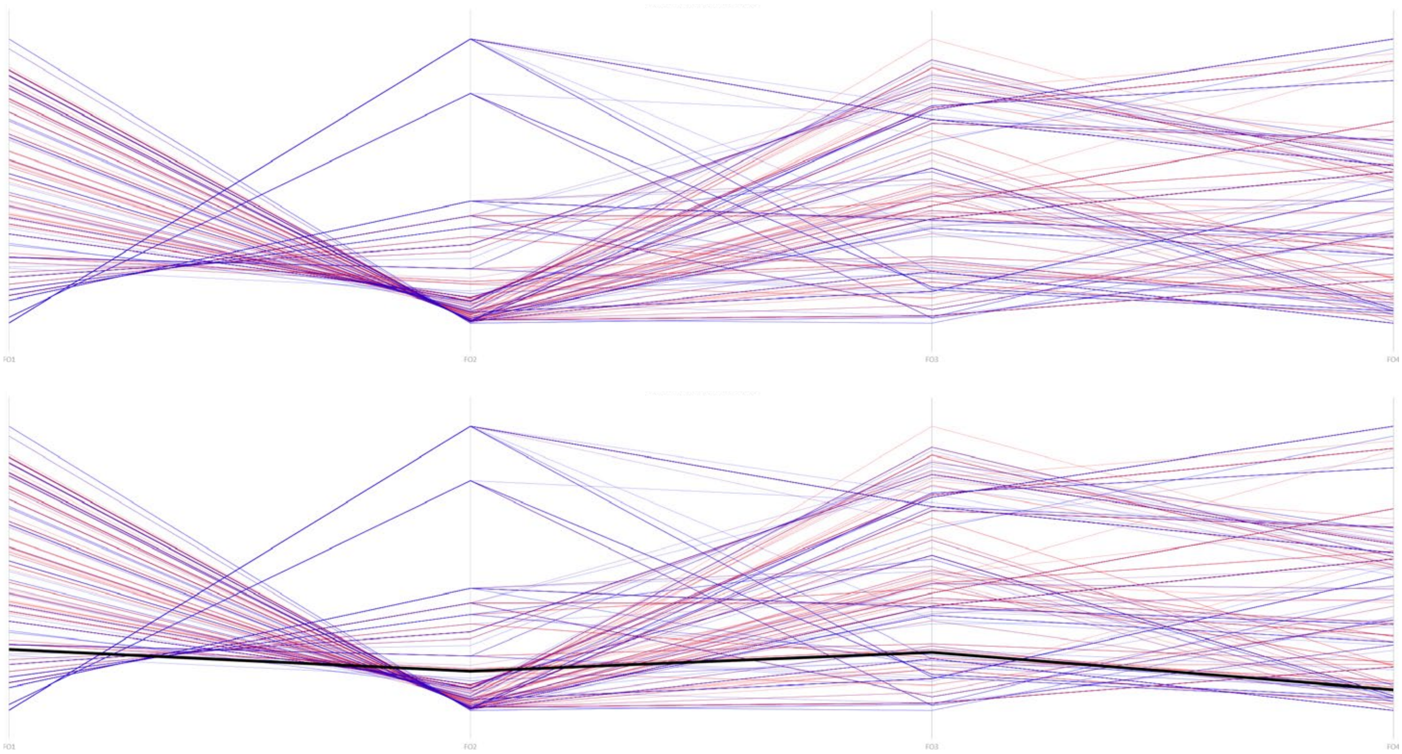


Figure. 93: top fitness objectives parallel coordinate plot where FO1=O1 is the total mass, FO2=O2 is the maximum displacement , FO3=O3 are the cooling demands, FO4=O4 is the average daylight, bottom the highlight of the average fitness ranked solution (the one that is not perfect nor worse for all objectives at the same time)

Since every energy simulation needed 4,2 minutes and every daylight simulation 2 minutes in Honeybee environment a total of 6 minutes were needed for every iteration. Therefore for the total 300 individual solutions to be produced an optimization of 30 hours took place.

These 300 solutions were then plotted on the solution space as boxes with each axis representing one objective. (see Figure 92) For the fourth objective the size of each box represents its fitness. The smaller the size of the box the fitter the solution to the objective. In this case the size of the boxes represents the total mass of the shading system's main bearing structure. Moreover, the yellow boxes containing some of the solutions represent the pareto front solutions. In case all the populated solutions are visible in the graph then all the pareto front solutions for each generation are shown (see Figure 93). When only the last generation is visible then only the pareto front of the last generation is visible. The last generation's pareto front solutions, are the solutions that could not be improved without downgrading another objective and based on the above could contain the optimal solutions for the population size given.

With the workflow presented, it is possible to generate all the corresponding geometies to every solution of the population. Wallacei's component WGenomes output automatically saves parameter values while WPhenotypes output generates the geometries needed. However, a filtering procedure is possible in Wallacei interface. This filtering procedure is partly dependent on the plug-in's composition and interface. Within Wallacei interface various analysis methods are provided.

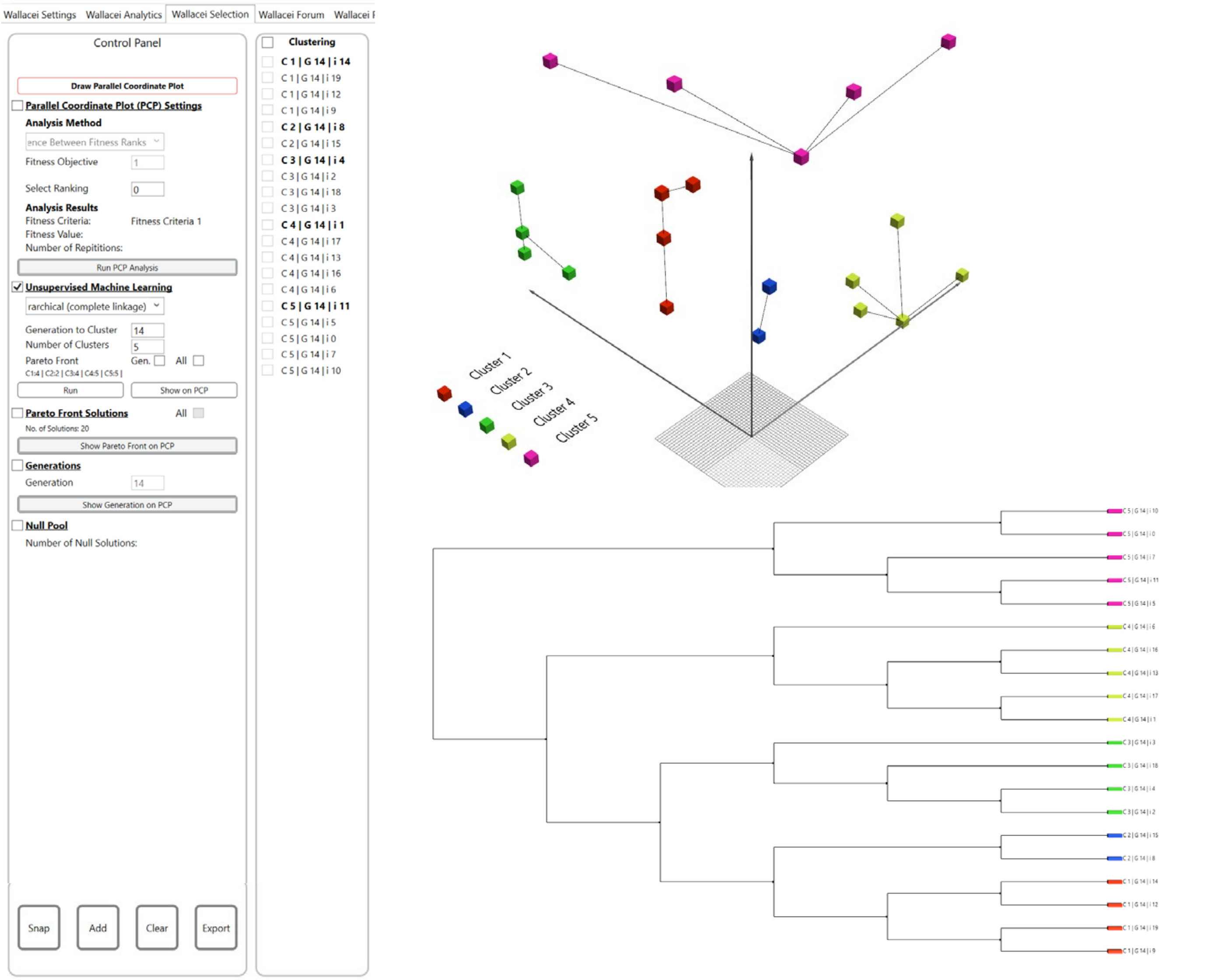


Figure. 94: left Wallacei analysis tab, right Hierarchical solution grouping (complete linkage) with visualiziation in solution space (top) and with a dendrogram (bottom)

Wallacei Analytics tab enables options like selecting idividuals based on a selected generation and a selected id or selecting individuals based on objectives and ranks. This method is important and was used to define the extreme solutions, meaning the optimal solutions for each objective as well as the solution that is not perfect but not bad for every objective (see Figure 93). Wallacei Selection tab on the other hand which is the main way of exporting geometries offers a list of different ways of analyzing a solution space. A parallel coordinate plot can be created showing all the solutions. Red lines represent solutions closest or in the first generation and blue lines represent solutions closest or in the last generation. This way a better observation and udnerstanding of the evolutionary solver progress is possible.

Moreover, unsuprvised machine learning methods like K-means and Hierarchical solution grouping is possible. This way a better understanding of correlations between individual solutions in a single generation or the entire population is possible. These analytic methods are very handy in case a brief insight of the solution space and a specific data or geometry for each individual solution are desired. However, this filtering procedure could be subject for further research and development with post processing techniques in python environment.

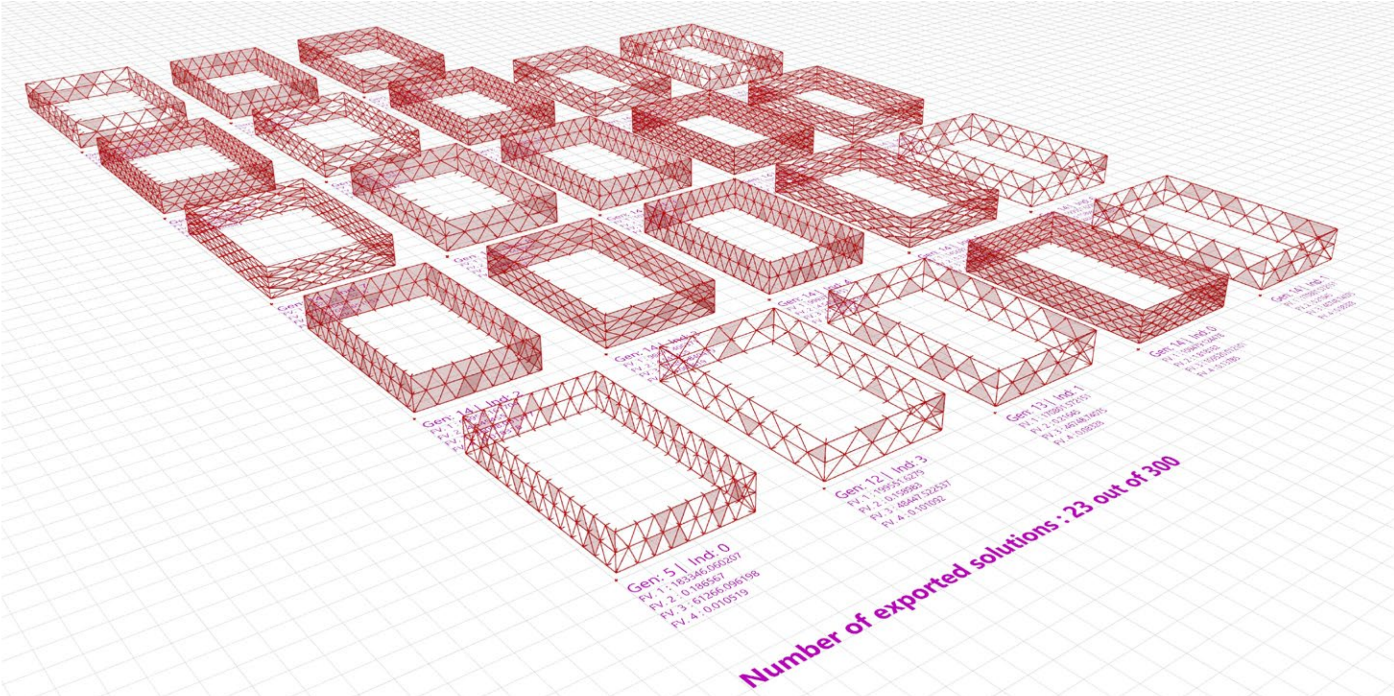


Figure. 95: Export of 23 solutions out of the 300 generated. Out of these solutions 4 of them 4 are the extreme solutions, meaning the fittest for each one of the four objectives and the rest are the last generation solutions. They are 23 in total and not 24 because individual id0 of the G14 (14th generation) happens to also be the fittest in terms of fitness objective 4 which in this case is the one with the minimum, maximum displacement.

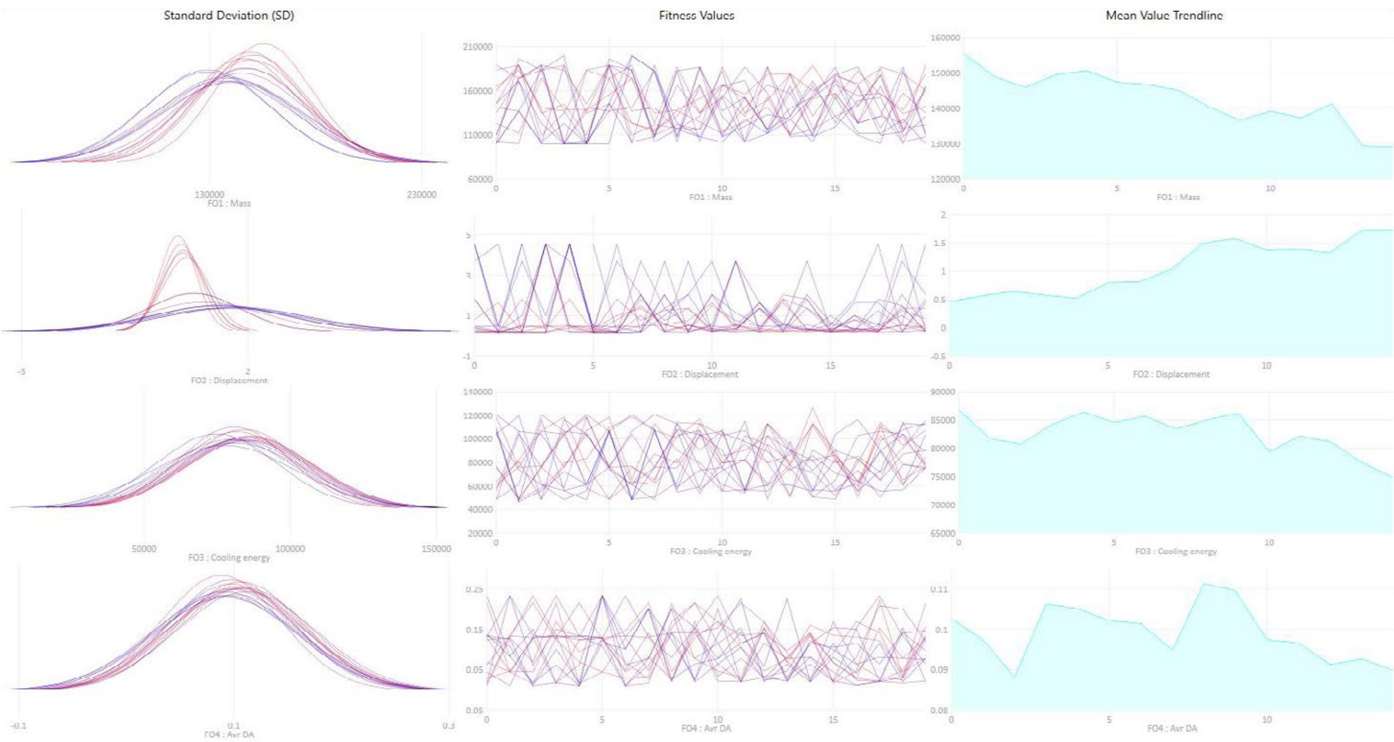


Figure. 96: Standard deviation, fitness values and Mean value Treadline during the evolutonary solver.

For the goals of this research, the four extreme solutions were generated as well as some of the last generation's pareto fron solutions. With the term "extreme" solutions, it is meant the optimal solutions that excel in minimizing total mass (O1), minimizing maximum displacement (O2), minimizing cooling energy demands (O3), and maximizing average daylight autonomy (O4). In order for these solutions to be compared apart from comparing their geometries and fitness values a manual seperate rerun of the simulation was conducted.

By observing the mean value trendline (see Figure 96), it is evident that during the optimization, with each new generation the solutions tend to exhibit a lower cooling energy demand and a higher average daylight autonomy. Additionally, there is a slight decrease in mass and a relatively unsteady evolution of displacement. The latter is not a cause for concern, as the displacement of the members due to static loads remains minimal, on the order of millimeters, even in the worst-case scenario.

4.8 Results observation & their meaning

Multi-objective optimization results for two typical floors and annual analysis period

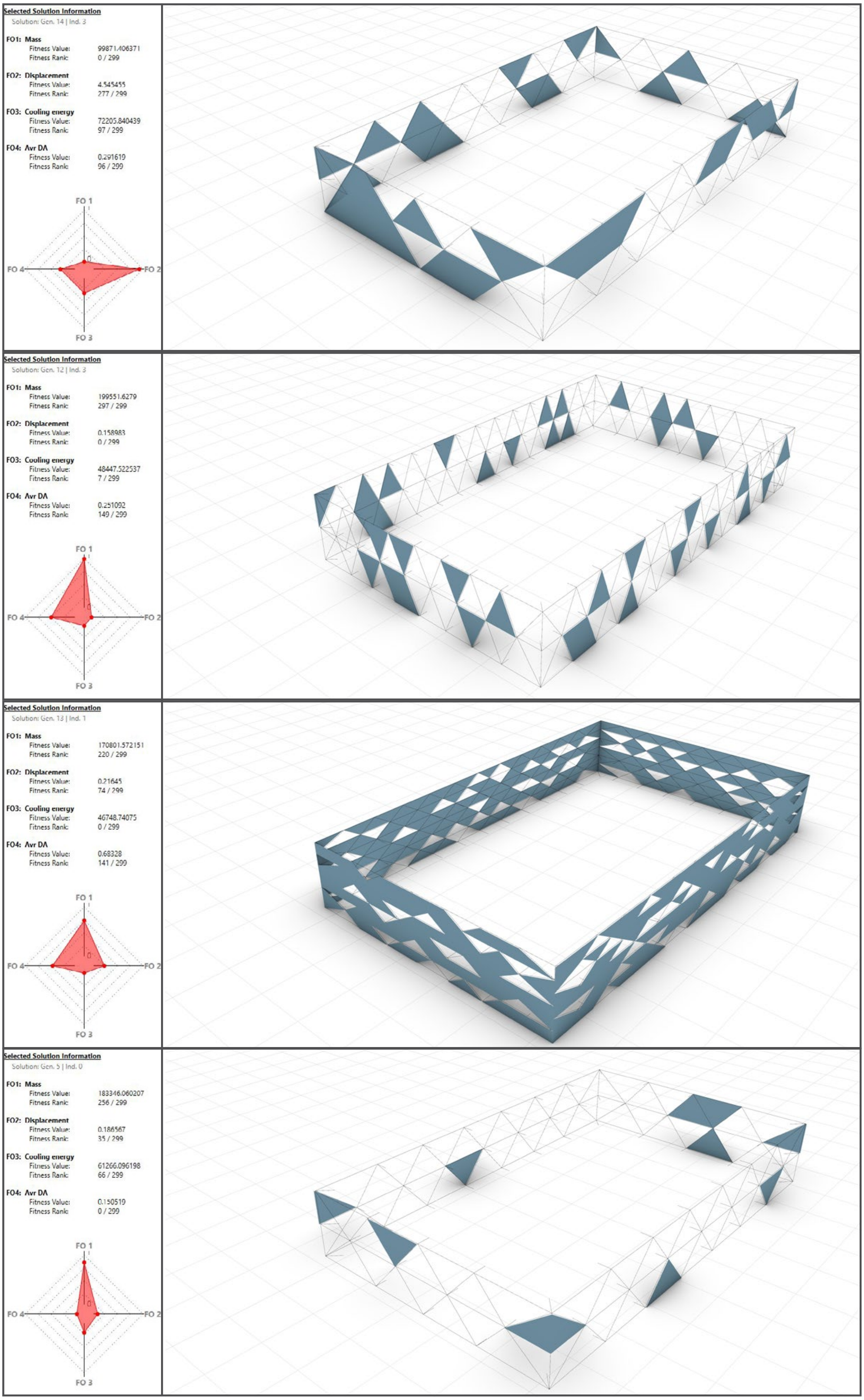
To get a better understanding of the results, the four extreme solutions were exported alongside the last generation. The extreme solutions are a way to confirm weather the optimization was a successful one or not, while the last generation is considered, as per the literature review, as the one closest to the true paretofront solutions. The fitness diamonds that come together with the solutions are a good indicator for where each solutions stands in terms of their objective fitness. The closer the solution's dot to the center of the fitness diamond the fitter the solution is for this specific objective.

By comparing Wallacei's output values for each objective and the generated geometries the results seem to be quite accurate (see Figure 97). The solution with the denser distribution of panels was the one that resulted in the lowest annual cooling demands with a minimum value of 46748.74 KWh among all the rest of the solutions. This however means that in terms of daylight autonomy the solution is not one of the strongest.

The solution with the least panels distribution was the one with the highest average daylight autonomy score of 6.67 % for all spaces. However as can be seen, most of the bearing structure in this scenario is useless, since it is not carrying any panels. Therefore in this scenario more criteria that were not considered in the multi-objective optimization emerge. For example the embodied carbon of the bearing structure and the total cost of the construction in this extreme solution are considered as inappropriate.

The structure with the least amount of material mass with a minimum value of 99871.40 kg or else 99,8 tonnes is located somewhere in-between the two previous extremes with relatively more shading than the daylight best and certainly less shading than the best solution in terms of cooling demands. Again however

Finally, the solution with the least displacement possible is the one with the smallest offset from the slabs. It may be worse than the best solution concerning mass but it still is better in terms of displacement in its parts with a minimum displacement of 0.1 cm! In terms of shading however it seems to be much better than one of the other extreme solutions.



(a)

(b)

(c)

(d)

Figure. 97: Extreme solutions: a. best solution for minimal cooling demands, b. best solution for average daylight autonomy of the spaces, c. best solution for minimal mass, d. best solution for minimal displacement

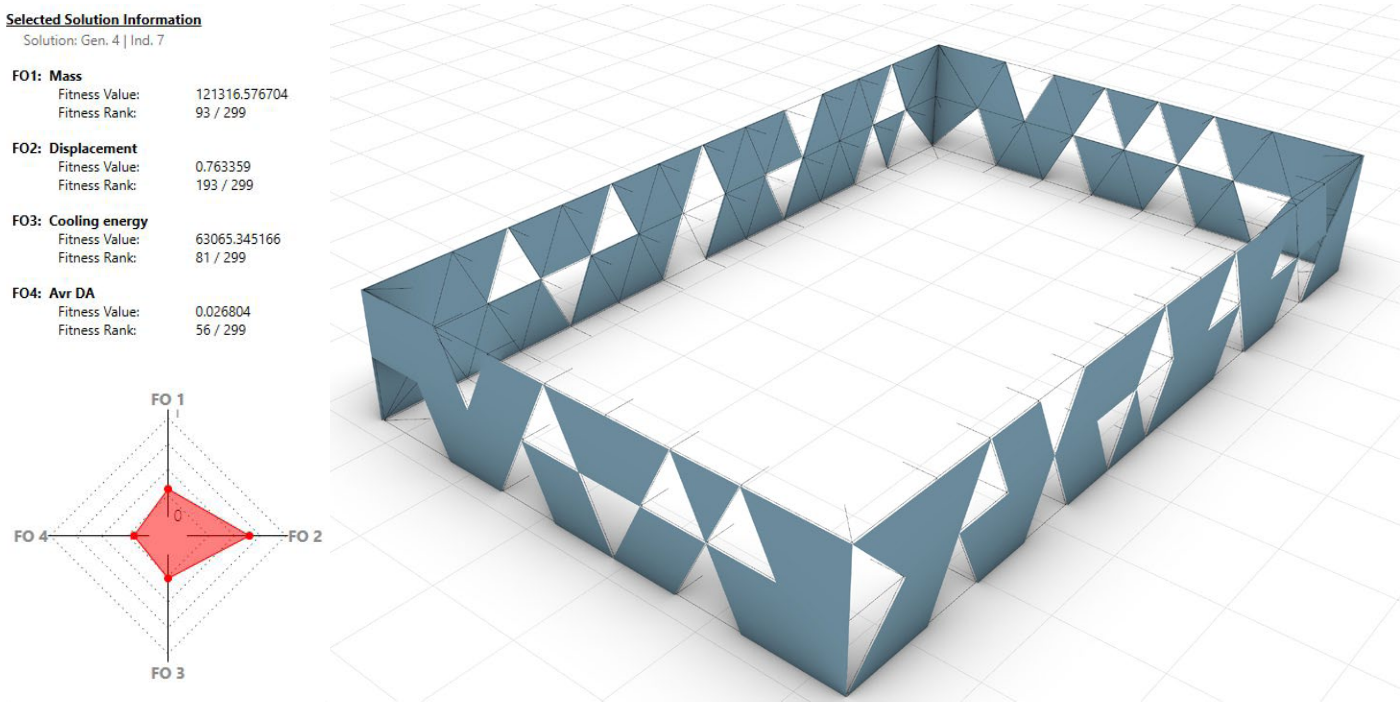


Figure. 98: Solution with first rank in terms of average fitness ranks. This means that this solution is considered average for all the defined objectives, it is not the best for neither of them and its projection is the highlighted projection in the parallel coordinate plot in page 101 (see Figure 93)

Through observation, it was concluded that the selected typical hollow section effectively prevented significant deviations in terms of member deformation and movement. This indicates that the selection was highly appropriate, resulting in minimal movements. However, it also implies that as an optimization criterion, it did not significantly influence the final solutions generated.

The shading percentage parameter appears to significantly impact the daylight performance of the generated solutions, while remaining independent of other parameters. However, post-optimization observations revealed that some solutions in the final generation, as well as on the Pareto front, exhibited a total coverage of 100%. This discrepancy suggests either a logical error in the algorithm or the dominance of other criteria during the optimization process. A potential solution would be to conduct a single-criteria optimization in a subsequent phase or to constrain the parameter value range with logical operations prior to the optimization. It was also observed that with the offset change, the randomness of the covered panels varies, which is normal given that the dimensions of the offset surfaces of the external diagrid also change.

In addition, the total surface area of the panels could serve as another criterion for optimization. The latter, combined with the calculation of the total mass, could facilitate the estimation of the overall cost and carbon footprint of the shading system.

Finally, the shading coverage percentage can be determined based on the facade orientation, as the effectiveness of shading varies with the building's orientation. Therefore, orientation factors can be utilized to avoid shading areas that do not require it. For example, shading is generally unnecessary on the north side.

5. Discussion & Reflection

5.1 Summary

As mentioned in the first chapters this research was developed to investigate how a genetic algorithm based workflow could be integrated in a design problem. More accurately, the design problem concerned the design and optimization of a passive fixed shading system out of ETFE cushion panels for enhancing the thermal resilience of an existing building envelope. For this reason the research question was defined:

*"**How can a genetic algorithm based workflow be effectively employed in the multi-objective optimization of a shading system to improve the energy efficiency of an existing building envelope?**"*

In order to answer this question, a broader research was conducted in four seperate fields that are all connected with this design problem. These are ETFE double skin structures investigation, resilience quantification, multi criteria decision making approaches with genetic algorithms and finally the case study building facade analysis.

If a shading system of such type and scale were to be designed, an extensive research in all these fields and an in depth knowledge for all these fields should have been aquired even in a Phd level, maybe in much greater detail and depth than this research has managed to reach. However, by answering the sub- question:

I. What are the primary typologies of facades and how can they be classified based on their materials, connection details and functions?

and after a literature review concerning the different functions of facades and the different ways of analyzing and classifying them based on their performance, goals and materials, a facade design timeline as well as its various phases were found and discussed. Thus, in order for this research and its output to be scientifically accurate it was decided to focus mainly on the shading system's preliminary design phase for it to act as a retrofit design.

To start a design development, however, one needs to understand and define why, what and for whom he/she designs. Since rising temperatures is a contemporary problem and minimal effort has been made to improve existing infrastructure in terms of energy efficiency and standardization an attempt was made to ensure these structures will not lose their energy efficiency and viability. For this reason, the term resilience emerged as a term in question and a second research question was defined:

II. What is resilience and how can it be quantified?

As discussed (chapter 2.2), resilience is a time dependend measurable assessment of a system against a balance disturbance. Always based on each researcher's perspective, resilience can be connected with a system's performance degradation due to one or multiple hazards. This degradation can be analyzed based on time with two or multiple phases (before, during, after the hazard occurance). In case of a heat wave, however, thermal resilience was under the microscope and a definition of a heatwave in the case study location was necessary.

In this resilience context, it was assumed that by influencing the cooling demands of the building with a retrofit strategy like a shading system, the thermal resilience of the building would be enhanced.

Towards the what of this research, a material of great debate and controversy was chosen for the design proposal. ETFE a completely unnatural material, which, however, has great mechanical properties and enormous endurance to most weather conditions was invesitgated and used for defining the boundary conditions and shapes of the shading system. Although this material is not considered as a very promising one anymore, due to its chemical composition and its relative high costs (moslty due to its need for continuous air pressure maintainance), it was chosen as a reference point material and of course this materiality could be subject for further investigation.

The next sub-question to be asnwered was:

III. How to formulate a genetic algorithm-based multi-objective optimization workflow?

In order to answer this question, a research concering the different multi criteria decision making approaches was conducted. Between the two main approaches that were discussed (chapter 2.3), Multi-attribute decision making (MADM) and Multi-objective decision making (MODM), the second approach was closer to an actual design proposal. Therefore, despite its computational limitations and burden, this approach was chosen. At the same time, an investigation about genetic algorithms and the way they generate solutions as well as the relationship between these solutions was also conducted. This way among the various optimization tools available (Tunny, Opossum, Galapagos, modeFRONTIER, Optimus, Octopus and others) Wallacei was rendered as the most promissing one together with the niching methodology that was analytically discussed.

Finally, since this research was aiming to improve a building against thermal hazards and support a design team of different diciplines to have more efficient communication the last sub-research question was defined:

IV. How can a digital design tool be implemented in a preliminary design phase of a shading system to enhance the thermal resilience of an existing curtain wall system and provide interdiciplinary feedback to a design team?

In order to reach the answer to this question the Tower of Piraeus, in the port of Athens was chosen as a case study for this research. The building under investigation is often exposed to heatwaves during the summer months and also to earthquakes which was also one of the initial sub-topics of this research. With the generous support of Eckersley O' Callaghan and PILA architecture office that provided part of their material, a thorough analysis of the new existing look was carried out to start making design decisions.

The digital design workflow aimed firstly to support an interdiciplinary working method between the various roles by integrating BIM into the workflow and seconfly to enhance the building's thermal resilience with a multi-objective optimization.

5.2 Discussion

5.2.1 Design proposal and energy aspects

Multi-objective optimization results for two typical floors and extreme hot week analysis period

After the workflow was set and the optimization was evaluated it was considered that this workflow is accurate to start evaluating more specific time periods like a heatwave period. By narrowing down the analysis period, the energy demands of the two typical floors is possible for shorter periods. In this step in order to evaluate the building's thermal resilience with the addition of the shading system an energy simulation for the situation prior and an energy simulation after the addition of the shading system was necessary.

As can be seen in the simulation results and the post processing of the data, the maximum cooling demand appears again in the southern side of the typical plan in the open office spaces and reaches a maximum value of 599.83 KWh for the extreme hot week of the year (see Figures 99,100). The extreme hot week of the year was considered as the period of a potential heat wave and based on the weather data used it was defined from the 3rd of August to the 9th of August. In order to evaluate the resilience of the indoor spaces, normally the operative temperature and other indicators affecting the indoor comfort levels should be evaluated and a comfort simulation would be appropriate for this step. However, due to time constraints and based on the analysis discussed in this research, the cooling demands were used as a metric for thermal resilience.

Concerning the structural design of the solution, in a later stage the bearing structure of the shading system was indeed designed for the whole tower by using the same cross section in order to have a better understanding of its structural behaviour (see Figures 101,102). However, due to the large computational costs of the multi objective optimization method selected only the isolated part of the two typical floors was used once more for the heat wave period optimization.

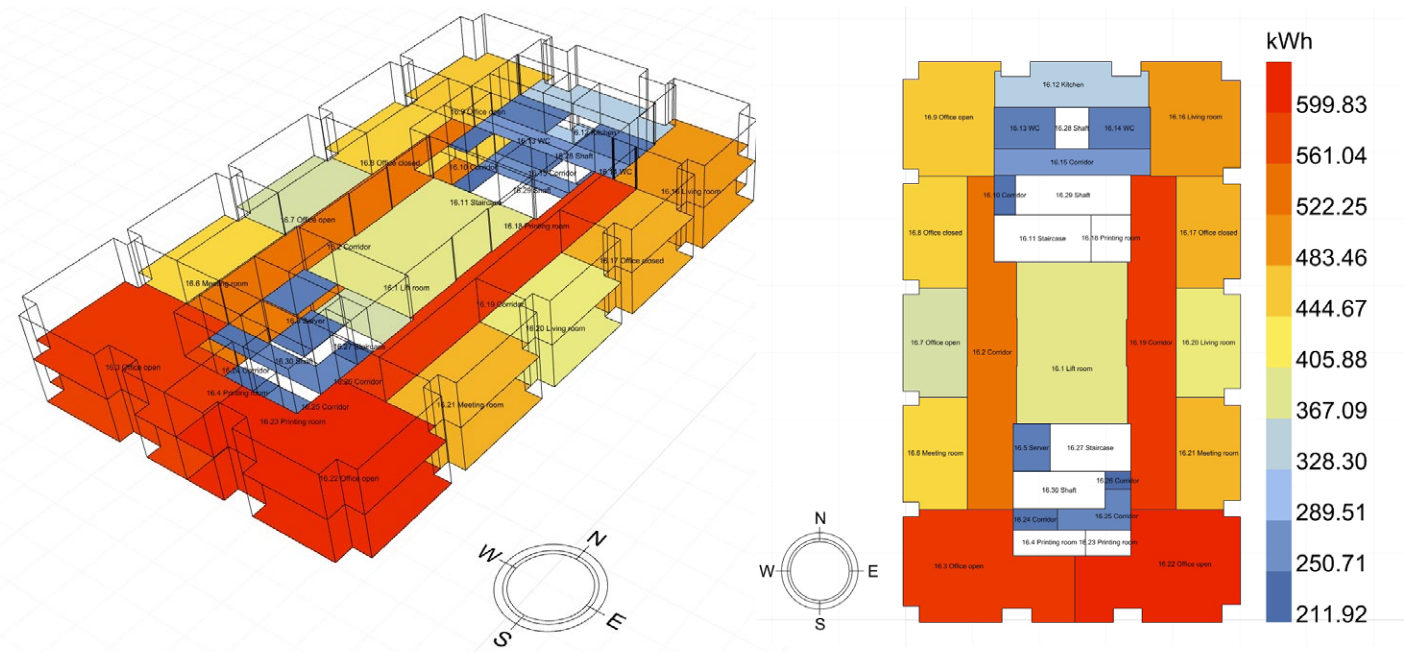


Figure. 99: Total zone Ideal Loads supply air Total cooling energy 3 Aug to 9 Aug from 0.00 to 23.00

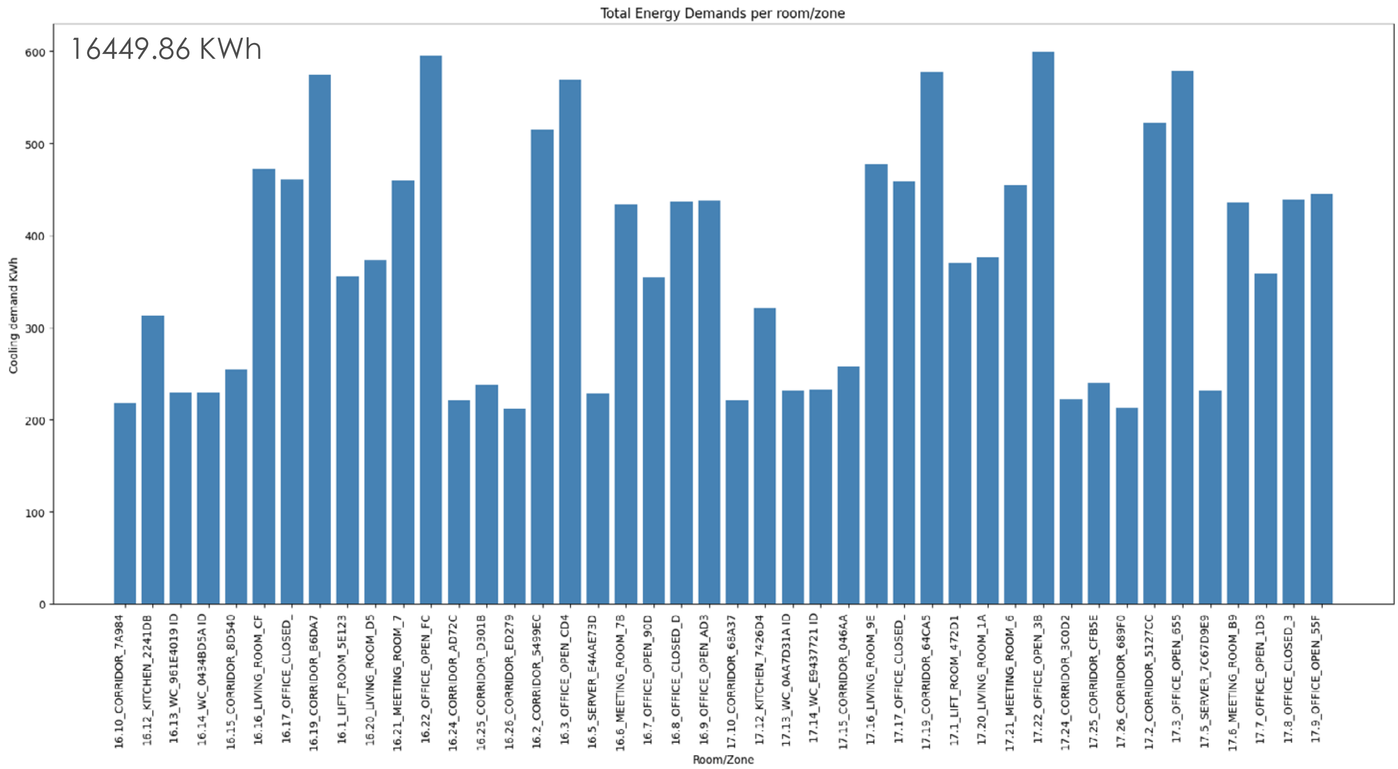


Figure. 100: Total cooling demands for each room/zone in the typical floors under investigation in the original situation for an extreme hot week meaning 3-9 August

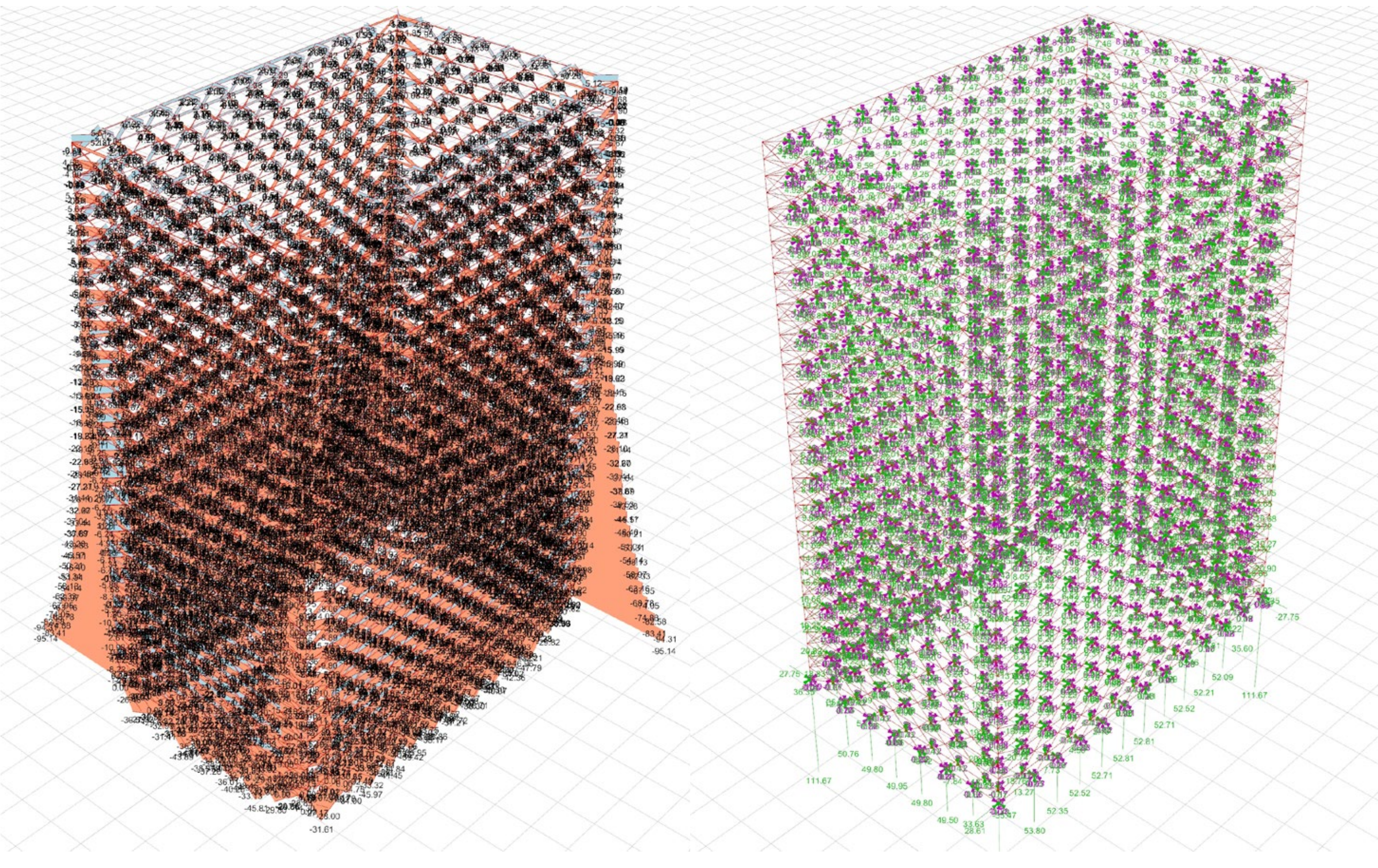


Figure. 101: Static analysis for the whole bearing structure of the shading system

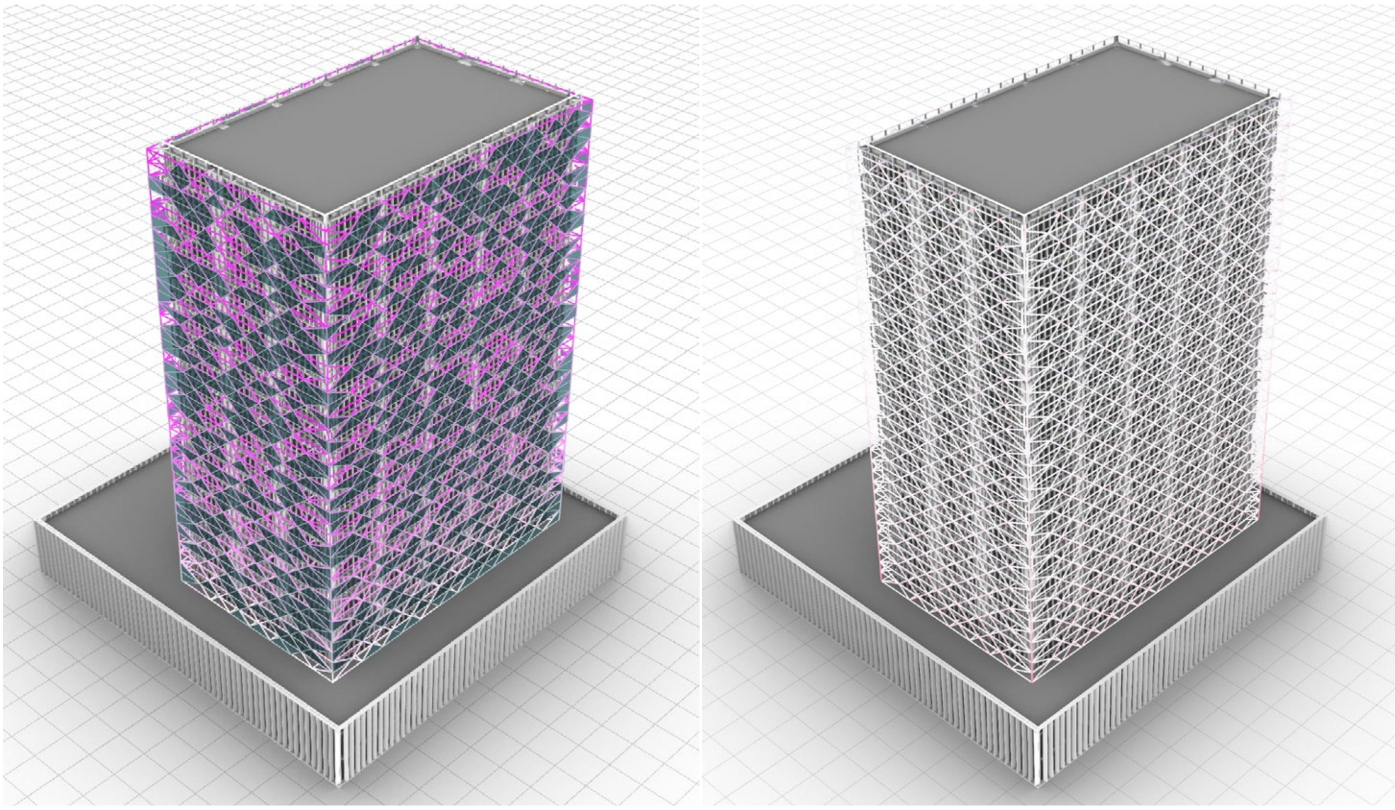


Figure. 102: Displacement diagram left, Axial stress diagram right

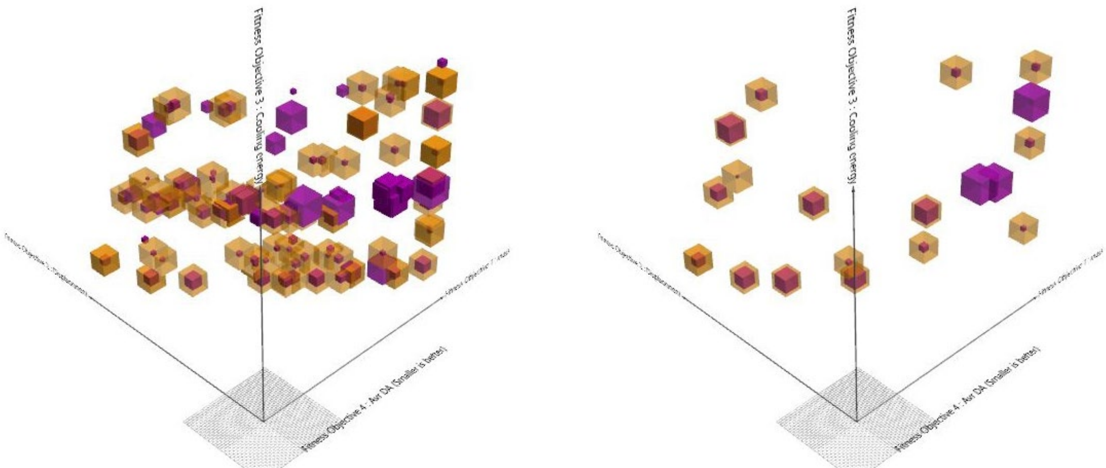


Figure. 103: Projection of all the generations and the last generation of solutions

Once again in the optimization settings for an extreme hot week period and for two typical floors with a generation size of 20 solutions, 15 generations were produced. Although bigger populations were attempted of 500 or 1000 solutions, the computational burden only led to unfortunate crashes. Thus, for computational feasability a population size of 300 solutions was defined again.

Since every energy simulation needed 2 minutes and every daylight simulation 1.2 minutes in Honeybee environment a total of 3.2 minutes were needed for every iteration. Therefore for the total 300 individual solutions to be produced an optimization of 16 hours hours took place.

The solutions were projected again (see Figure 103) in a solution space and the extreme solutions were filtered out. In order to evaluate the enrgy demands of the generated solutions seperate simulations run for the extreme solutions and the solution average for all the objectives.

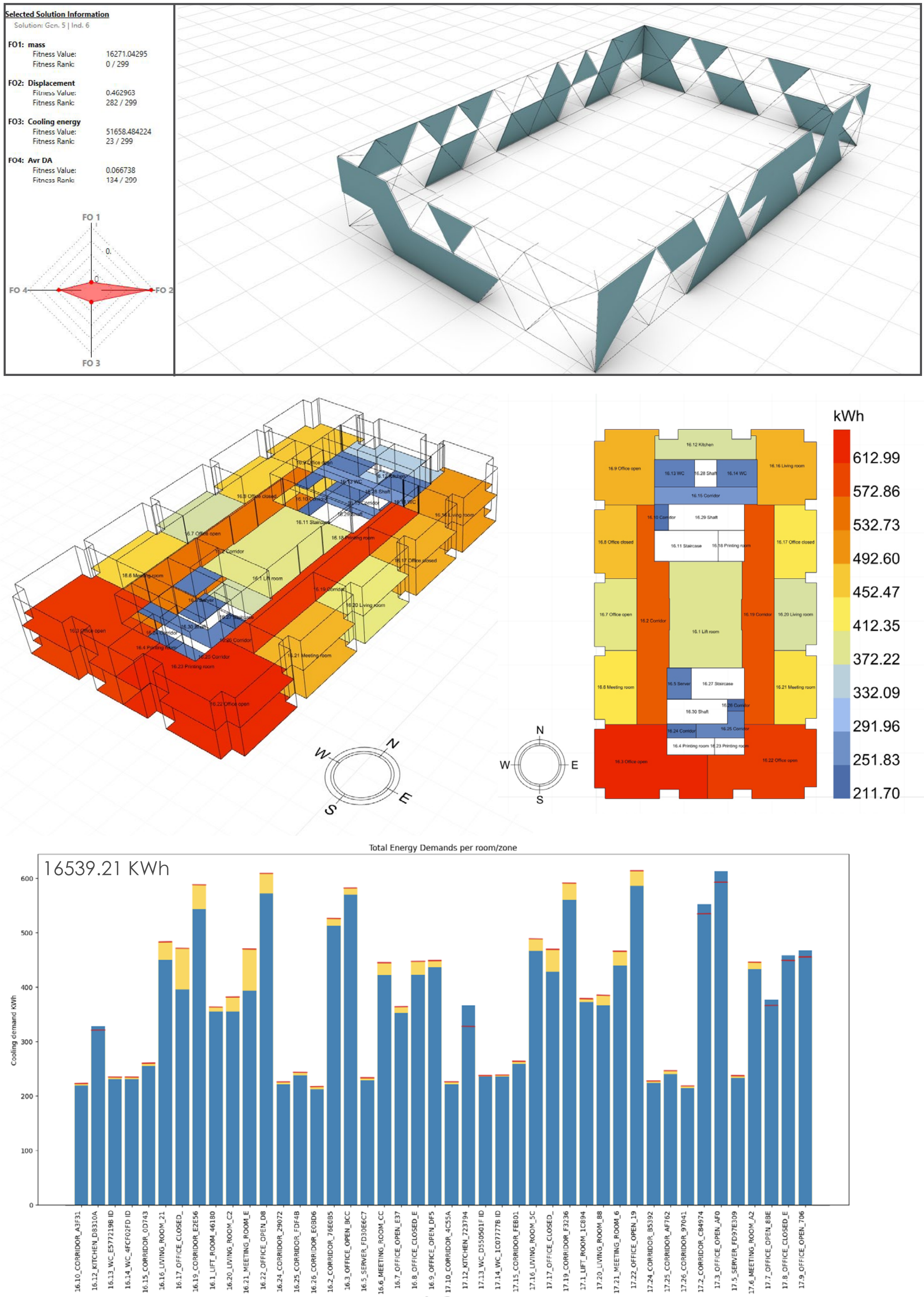


Figure. 104: Best solution for minimum mass
cooling energy demands 3 Aug to 9 Aug 0.00 to 23.00

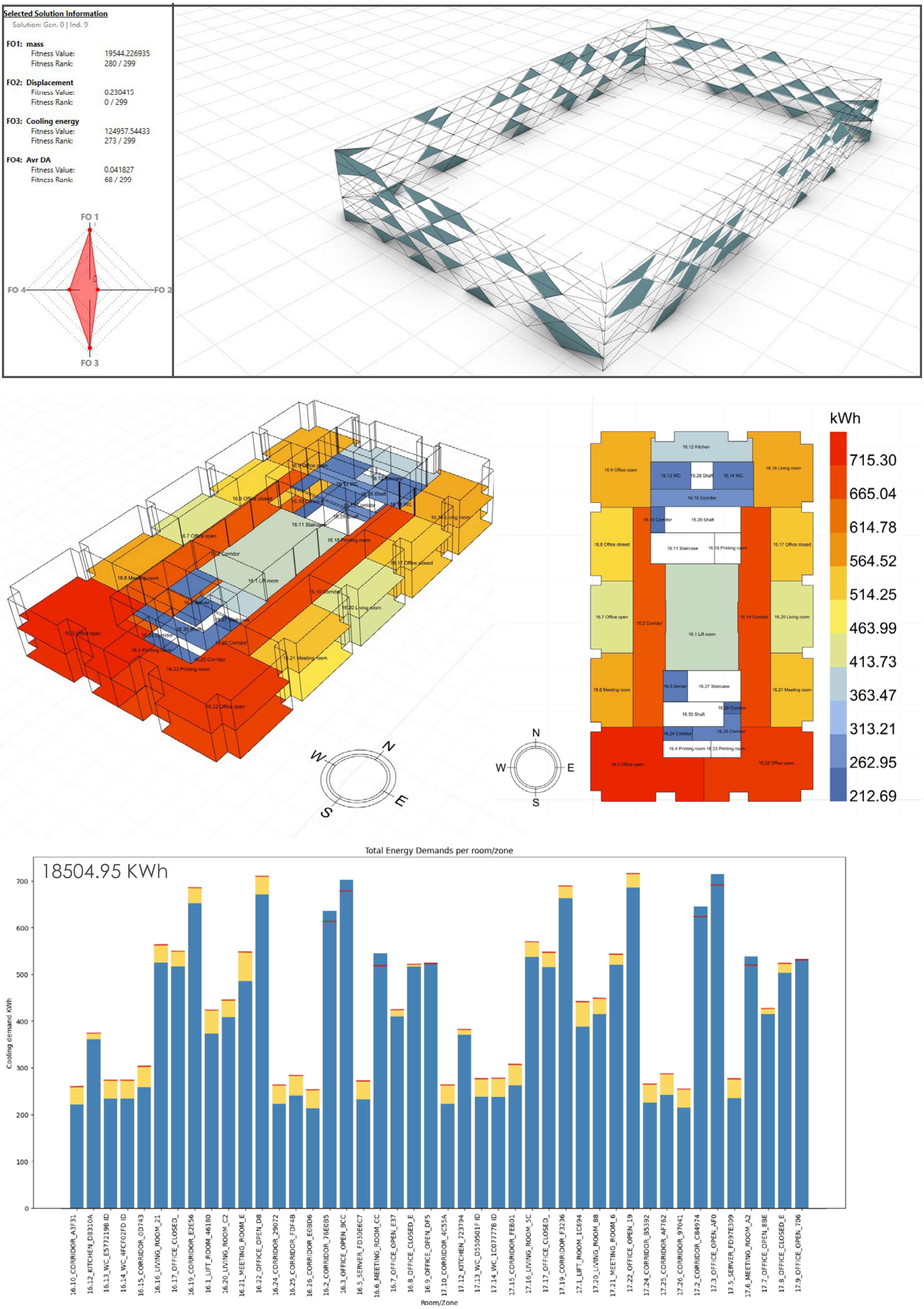


Figure. 105: Best solution for minimum displacement cooling energy demands 3 Aug to 9 Aug 0.00 to 23.00

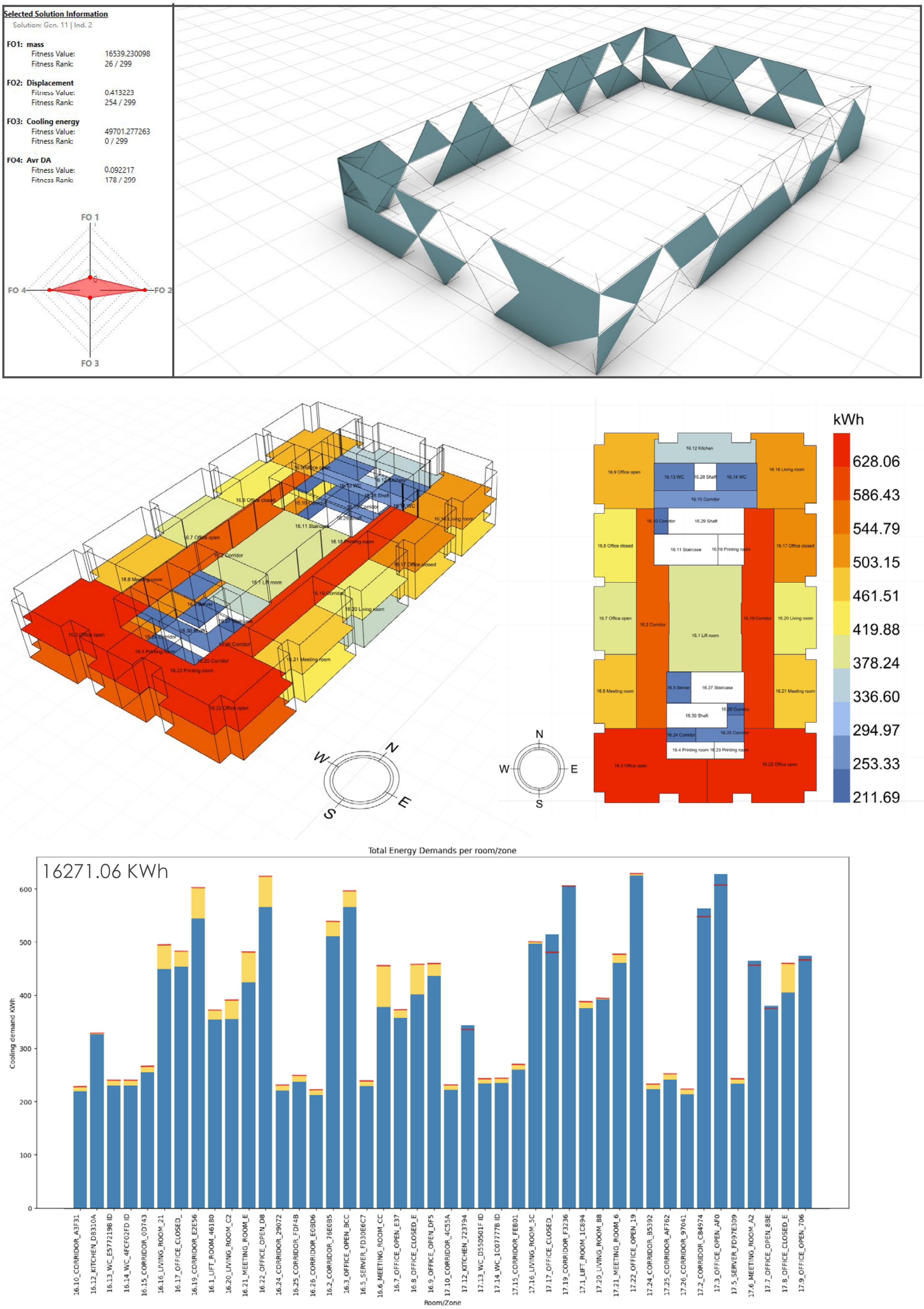


Figure. 106: Best solution for minimum cooling demands
cooling energy demands 3 Aug to 9 Aug 0.00 to 23.00

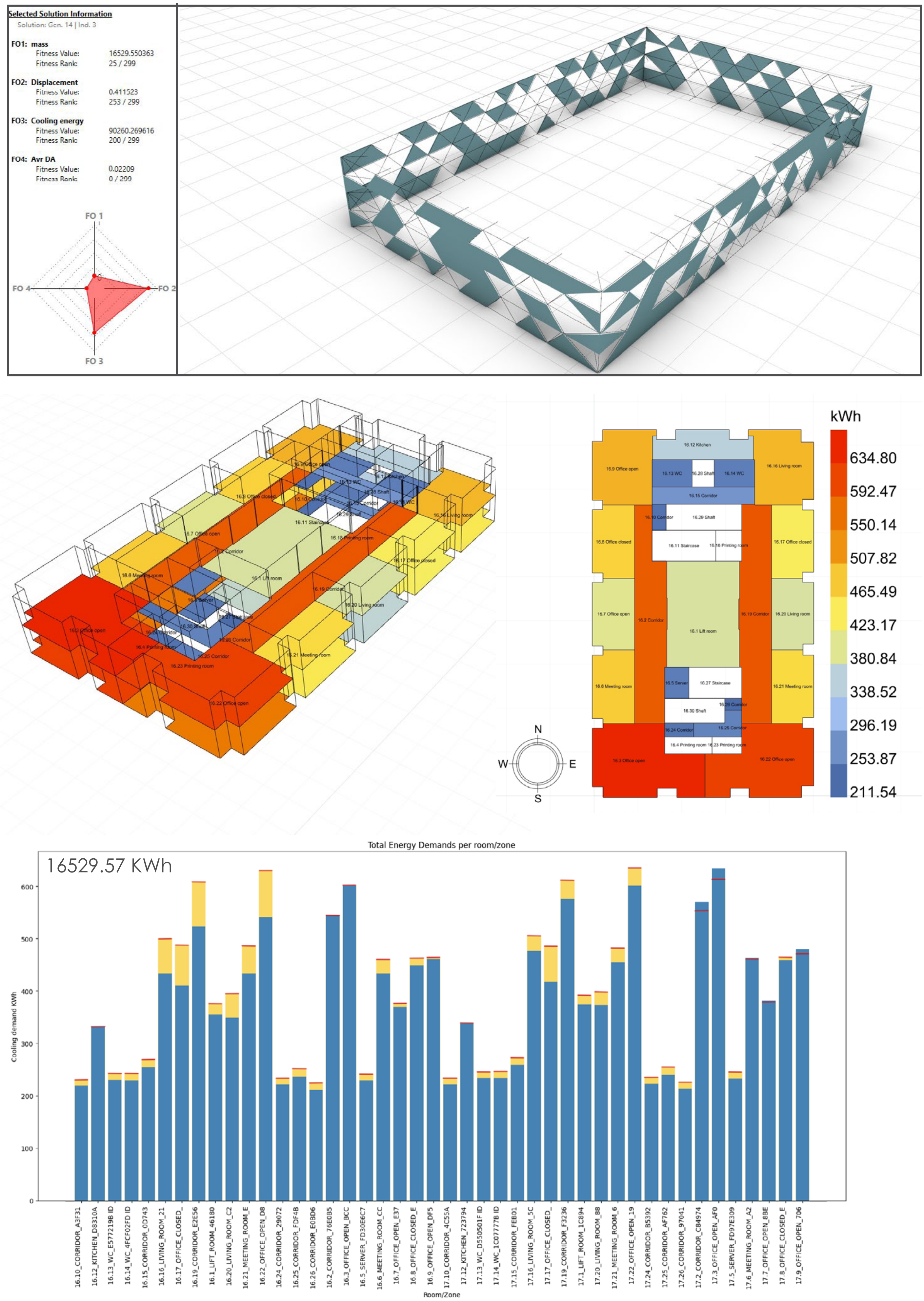


Figure. 107: Best solution for maximum avarage daylight autonomy cooling energy demands 3 Aug to 9 Aug 0.00 to 23.00

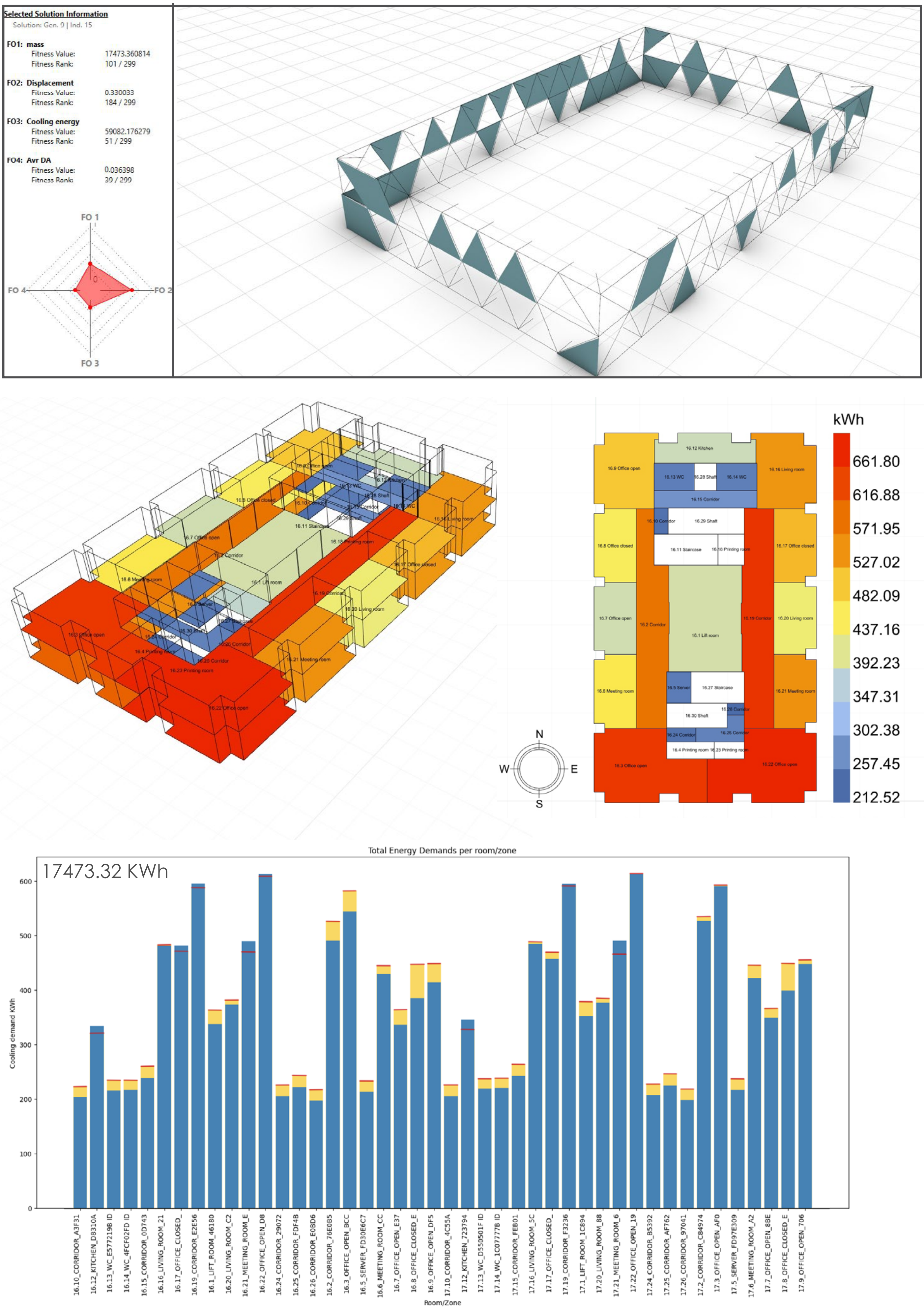


Figure. 108: Not the best solution for all objectives
cooling energy demands 3 Aug to 9 Aug 0.00 to 23.00

As it can be observed by the optimization and simulation results (see Figures 103-108) the cooling demands in each schenario vary. From the 5 solutions that were filitered out not in a single solution the cooling demands are reduced in all the spaces. In some solutions some spaces have a reduced cooling demand for the analysis period while others have a higher demand.

It is, however, worth noting that although in some solutions the maximum cooling demand among the rooms may be lower than the respective maximum cooling demand for the original state of the building, the total cooling demands may be higher. Among the filtered solutions it is clear that the extreme solution concering the cooling demands is more efficient than the original scenario.

The next step from here concerning the design problem would be to keep running simulations for all the pareto front solutions. However, since the extreme solution concerning cooling demands is more efficient only for 178 KWhs, the pareto front solutions are assumed to have a worse energy efficiency in terms of cooling demands.

In conclusion, the workflow effectively generates and filters optimal solutions with improved thermal resilience. However, it requires adjustments to better manage the parameters and objectives used for optimization. The computational demands of this workflow make it impractical for professional use, as it depends on multi-hour simulations and occupying a computational unit that could be otherwise be used for other purposes. Nevertheless, if sufficient computational power is available, the workflow performs adequately, with noted areas for improvement discussed in the reflections.

5.2.2 Design proposal and structural aspects

Initially the shading system was intended to also act as a seismic retrofit strategy for the building under investigation. Based on literature (Takeda et al,2013) the three types of seismic retrofitting technology are:

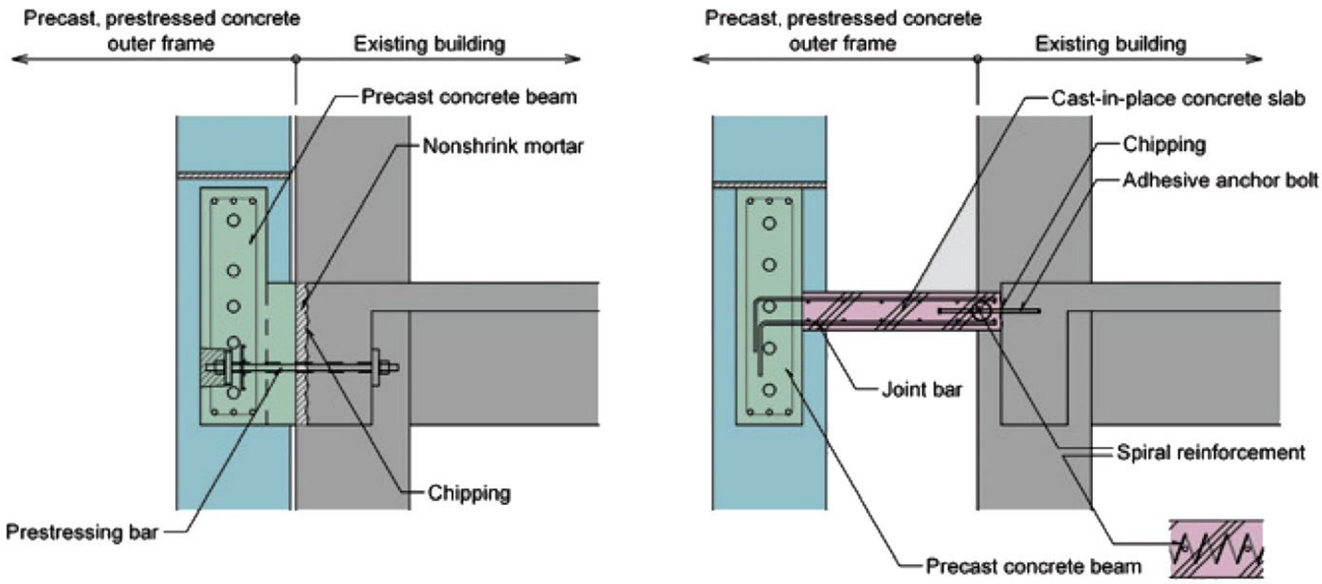
- strength improving
- ductility improving
- seismic dissipation

Within these main categories when one focuses more to external retrofitting sub-structures which is the case of this shading system under investigation three more sub-categories emerge (Cao et al., 2022):

- external frame sub-structures
- external frame-base sub-structures
- external wall sub-structures

From these categories the two first take the main load-bearing members of structures as energy-dissipating members, while the last one adopts the non-load-bearing components or additional components for energy dissipation or isolation in order to protect the main bearing structures. The shading system under investigation would fit in the seismic dissipation retrofit type and among the external frame types it stands next to the frame-base sub-structures that aim to increase the strength of the main bearing structure. However, the design as presented is not considered appropriate for this function for the reasons that will be discussed here.

External frame-base structures contribute to achieve larger lateral stiffness and improvement in bearing capacity after retrofitting. Moreover, an exoskeleton of such type can provide sufficient lateral stiffness in the elastic stage of the building and can be designed and calculated in a way to dissipate earthquake energy in the plastic stage. Since conventional braces are subject to compressive buckling, new methodologies with multiple novel external braces are recently developed



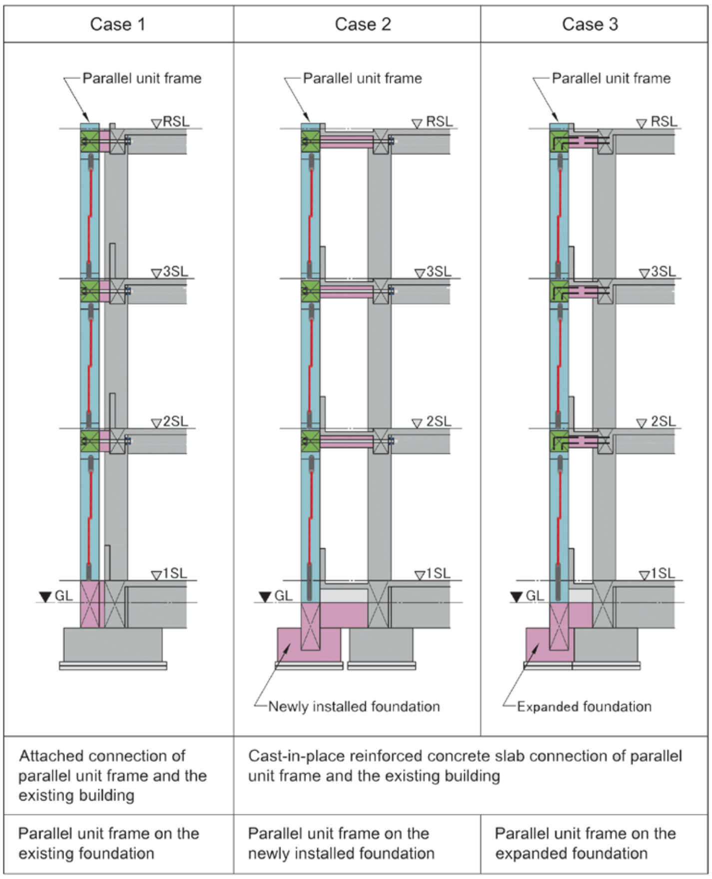


Figure. 109: Different ways of connecting exoskeleton structures on reinforced concrete (Takeda et al,2013)

(buckling-restrained braces BRB, self-centering braces SCB, variable stiffness braces VSB). The same principles an approaches used for these braces should ideally also be integrated in the design of this shading system if it was to act as a seismic retrofit. Although this was part of the initial intentions for this reseach only a preliminary study was possible with the computational methods discussed.

According to (Cao et al., 2022) the ultimate goal of seismic retrofitting is to improve the overall seismic performance of an existing structure. Thus, a broader understanding of the impact of the shading system on the original building is needed. Since the shading system is an extra addition of elements and mass (seismic dissipitation type) although its original purpose is to increase the shear strength of the building, with the extra mass added an increase in the interstorey drift is expected. Despite external retrofitting sub-structures commonly do not carry vertical loads, this solution was designed to carry its self weight vertically and only to transfer windloads and earthquake lateral loads horizontally to the slabs of the case study. Since the new structure is not fixed to the existing structural frames but only with point connections, instead of hanging from the supports on the beams, the new added mass may support the existing bearing structure in case of an earthquake by transfering point loads. These loads, however, depend on the connections used between the two systems. Thus, in order to properly solve the system, the connections types should be defined first.

The latter structural aspect, which was briefly invesitgated in this research, is very important and together with the joint types are the most critical regions of such a structure. The connections influence the structural behaviour of the whole exoskeleton. (Cao et al., 2022) mentions that research concerning structural failure patterns has shown that these patterns highly depend on the type of connections and the joint properties. Indeed if these connections were properly designed and different types of supports or different degrees of freedom were used in the static analysis, completely different solutions would be generated after the multi-objective optimization.

Research has shown that in prestressed concrete frames behaving as exoskeletons the connections between the original bearing structure out of reinfrorced concrete and the prestressed external frame is possible either with prestressed bars and local compactions between the frames, or with cast-in place conrete elements like slabs or beams (see Figure 109).

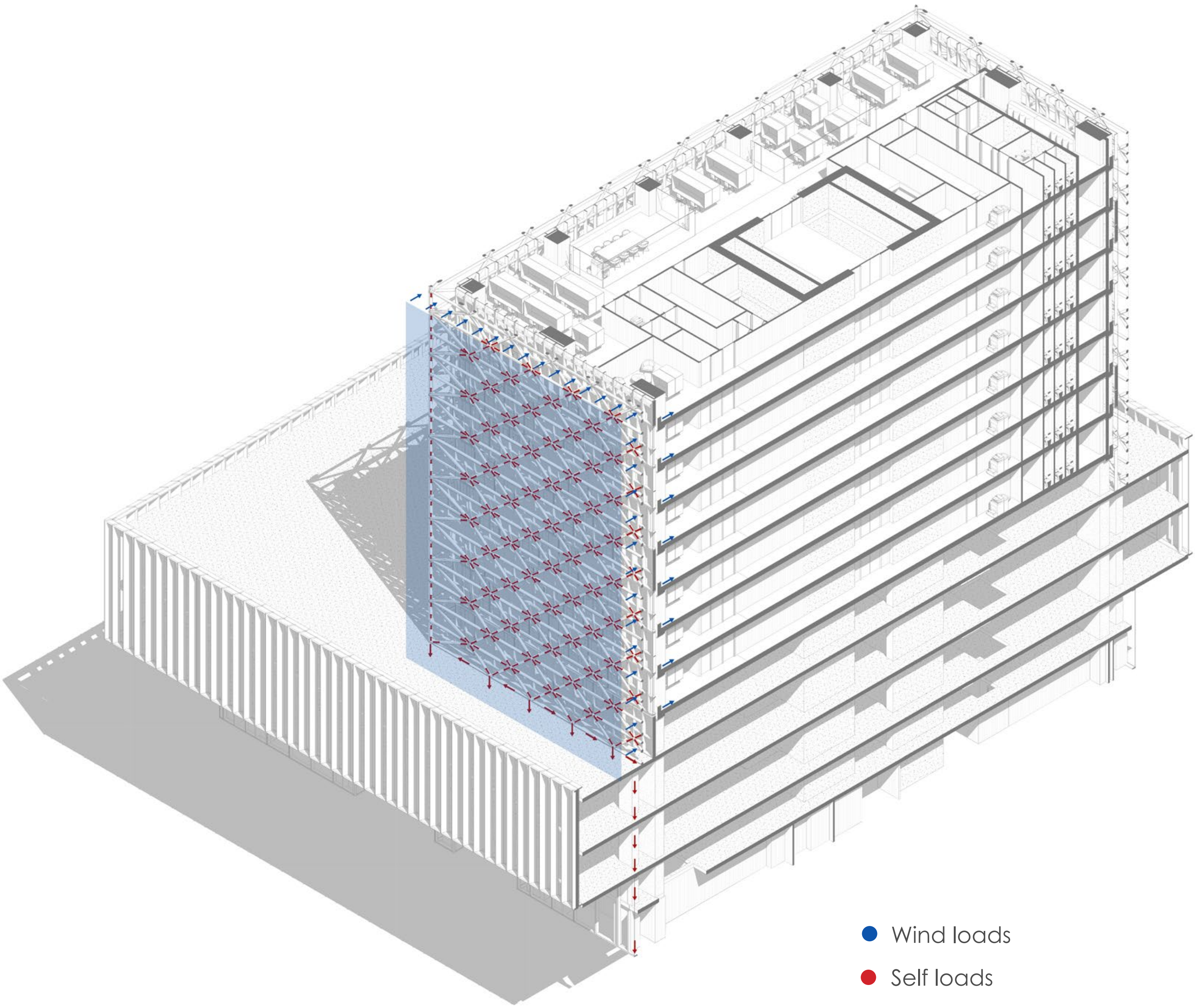


Figure. 110: Vertical and horizontal load transfer

Although this methodology is the stat of the art, its not compatible with the material and the design decisions made in this reseach. In order to implement these connection methods, however, a hybrid connection could be developed. The solution for the shading-beams connection could be the use of fiber reinforced plastic (FRP) or rebar prestressed bars located in the positions of the original points of the diagrid on the beams-slabs. Thus, a combination of these bars and the structural joints-nodes used in the frame could be developed. Alternatively, anchor connections could be placed in a manner that the reactions are closed to the fixed supports assumed in the optimization.

Finally for the connections of the shading system to the slab at the base, although initially it was considered necessary to create new walls and columns directly beneath the structure so that the vertical loads could be transformed to the existing foundations, the existing columns could serve for this purpose (see Figure 110). It is, however, considered necessary to apply the appropriate buckling and shear strength checks for the columns as well as the foundations in case further strengthening of these structural elements is needed.

The specialized methods of solving and designing both the connecting elements between the exoskeleton and the main bearing structure (beams-slabs), as well as between the exoskeleton and the base slab of volume A, led to these structural aspects to only be investigated in a superficial manner without the elaboration of analytical calculations about the total capacity of the case study building. No access to the static study of the building also contributed to this.

Nevertheless, Eurocode 8 provides detailed instructions and regulations concerning the proper and safe design of such structures which, however, are not within the scope of this research. Like more aspects of this work, such an investigation could be the subject of a new research.

5.3 Reflection

Societal Impact

The escalating temperatures and increasingly intense heatwaves constituted the primary focus of this research, around which the design scenario was formed. To address this issue for an existing building, the study explored thermal resilience through a design proposal for a fixed shading system as a retrofit strategy. Additionally, the research aimed to aid architectural and façade design teams by offering a BIM-integrated workflow for building energy simulation and visualization. This workflow is designed to be versatile, allowing for improvements in various aspects, yet remains easily adaptable for projects tackling contemporary sustainability and energy challenges. The methodology proposed combines structural and climate design approaches, provides insights and supports a multi-criteria design approach for a façade retrofit strategy. The research aimed not only to assess and evaluate but also to deliver impactful designs that enhance thermal resilience.

Graduation process

What is the relation between your graduation project topic, your master track (Building Technology), and your master program (MSc AUBS)?

As a sub-topic of the Re-Struct Research group, the design of such a structure aligns with the principles and knowledge imparted in the Building Technology track at TU Delft. This track encompasses both architectural and engineering design topics, encouraging students from diverse backgrounds to engage with structural engineering, façade engineering, climate design, and computational design, as well as understanding their interrelationships and impacts on projects and the environment. The emphasis on interdisciplinary thinking, crucial for innovative solutions, is a key aspect of these studies.

This research aims to apply the information and knowledge acquired during this academic track to the author's primary field of expertise, architecture. From the author's perspective, architecture reflects the values and uncertainties of its era, made possible through technological advancements. Consequently, the study focuses on addressing uncertainties concerning rising temperatures and the conflicts between design roles.

The inherently interdisciplinary nature of this topic attracts various disciplines into one workflow, making it imperfect. Structural and climate design form the core pillars, integrated with computational approaches. The computational methods employed enable further development and investigation of each aspect of the workflow, inviting more expertise to be involved based on each project's requirements. Utilizing this workflow facilitates faster and more efficient communication between decision-makers and engineers within a design team, an essential factor for achieving sustainability goals and mitigating the environmental impacts of previous generations decisions.

How did your research influence your design/recommendations and how did the design/recommendations influence your research?

The main goal of this research was instead of only assessing a building in terms of thermal resilience to take a risk and propose a design for facing the aforementioned problems.

The research started with a broader overview of the façade types and design stages in order to resolve the stage and depth of analysis it should focus on. With the selection of a fixed shading system the boundaries of this research were defined. The research focused on the optimization of structural and geometrical properties of the proposed shading system in order to influence the thermal resilience of the building mostly by influencing all the metrics that affect indoor thermal comfort. This was possible with the use of cooling demands as a performance indicator for the building's thermal resilience.

From a theoretical standpoint, resilience investigation, its dimensions, and metrics contributed to understanding the connection between thermal resilience and building performance. The ETFE structures investigation was conducted to ensure that the proposed solutions were realistic retrofit options, while the exploration of genetic algorithms and multi-criteria decision-making approaches ensured the workflow's feasibility.

As outlined in the objectives chapter, the aim was to implement a trial-and-error process, characteristic of both architectural design and structural engineering, to achieve research through design. The belief that innovative solutions can be realized only through continuous revision and learning from errors was a driving principle for this research, and it is believed that it has been accomplished.

How do you assess the value of the proposed approach, the used methods and methodology?

The main goals of this research were:

- To be able to evaluate the energy performance of existing buildings.
- To provide instant interdisciplinary feedback in a design team.
- To enhance an existing building envelope's thermal resilience/energy performance by reducing its cooling demands (with an optimized design).

As discussed in previous chapters an energy performance evaluation as well as interdisciplinary feedback were possible just by using the developed workflow. However, concerning the optimization of the shading system more conclusions were drawn. For example:

With the current workflow although an "optimization" is possible, with the discussed methodology no solution is perfect. Some solutions outweigh others based on one or more objectives-criteria but defining a best solution is subjective based on the criteria that are "more important". Therefore, the option of adding more criteria and applying weights for their importance in the optimization as well as more flexible solution filtering and visualization could be some steps for further improvement.

Many of the boundary conditions concerning the shading geometry definition were based on literature concerning ETFE cushion system dimensions and rules of thumb concerning their cross sections and weight. Other metrics like the deflections of the bearing structure, thermal comfort metrics like the operable temperature of indoor spaces or the indoor overheating degree introduced by Homaei&Hamdy should be further investigated to connect the final design with standards like LEED or BREEAM. This stricter boundary condition definition could , however, be easily integrated into the existing workflow.

Additional areas for investogation include the material of the shading surfaces, the type and size of HVAC systems used, potential natural ventilation , sensitivity analysis between energy demands, cost and mass of the added structure, cross section parametrization, solution filtering, criteria hierarchies and decision trees. All the aforementioned aspects are only some of the possible research branches that could be developed following this workflow.

When it comes to the impact of the proposed shading system to the existing building, a deeper investigation concerning the structural performance of the latter after the installation of the shading system should be carried out to ensure structural safety against Ultimate limit state (ULS), Serviceability limit state (SLS) loads as well as loads against earthquake.

The connections of the shading system to the main bearing structure of the tower were determined not by specific regulations or standards, but rather by employing some rules of thumb. However, the reactions were calculated based on the assumption that the supports-connections were fixed supports. This output can be utilized either within the same workflow or by a structural engineer involved in the project or in the development of this workflow.

Machine Learning techniques could also be implemented in the workflow. Unsupervised machine learning techniques could be used to filter out solutions and to create families of solutions. A visualization of these families of solutions would then be the means for the decision makers to compare outputs and pick objectives or solutions based on specific needs of a project. Another approach would be to use Convolutional Neural Networks (CNNs) to analyze the outputs of the energy simulation.

Regarding the proposed parametric design, the one developed in this research is just one approach to the existing facade. Alternative parametric approaches could potentially replace this part of the workflow, allowing for more preliminary parametric design models and thus enabling more estimations and comparisons.

In conclusion, based on the initially set goals, when energy evaluation and interdisciplinary feedback have been successfully achieved, there is considerable potential for adjustments and improvements in the optimization and solution filtering phase. Consequently, the third goal of the thesis could be a subject for further research and development. Enhancements could focus on the methodology of setting weighted objectives for optimization, on using future weather data, on improving the workflow's efficiency, and on providing more effective communication of the generated solutions to the user. These aspects are areas that could certainly be refined in future studies.

How does your project contribute to the existing body of knowledge in your field?

Although this research did not result in the creation of a standalone program or a prediction model, it did develop a cutting-edge workflow suitable for use within the Grasshopper environment. This research pushed the existing software to its limits, revealing the constraints of the plug-ins utilized. Consequently, by examining this report, one can efficiently review the detailed computational methods employed and gain a fundamental understanding of BIM-CAD integration, energy model definition, and linear static analysis within Grasshopper. Additionally, a basic comprehension of genetic algorithms, their iterative processes, and the principles of multi-criteria decision-making is provided, all within the context of the specific environmental challenge addressed by this research.

Unlike previous literature that primarily focuses on the results of workflows, this research offers a comprehensive analysis of all stages, aiming to share the experience and knowledge acquired. It is anticipated that by studying this report, readers will gain foundational knowledge of energy simulation workflows and be equipped to further develop one of the various research directions identified in this research. When this research may be something extraordinary for a discipline like a designer or an architect, for a programmer, a structural or mechanical engineer it may be just a simple exercise. This, however, takes us back to the conclusion of this research that no perfect solution exists and if it does, it is only connected to a single criterion.

What were the major challenges you encountered during your project and how did you address them?

One of the most challenging aspects of this research was the frequent emphasis on the term "multi" as seen in terms like multi-objective, multi-criterion, and multi-attribute. This term encompasses a broad range of goals and objectives that the researcher could address. However, the research aimed to maintain the workflow at a sufficient sophisticated level across all design aspects while preserving coherence. This approach led to certain components, such as energy evaluation, being explored in greater depth, while others, like static analysis, were kept simpler or earmarked for future research. For instance, the initial goal of studying the seismic response of the shading system could not be achieved due to time constraints. Nevertheless, the workflow was designed to potentially allow for an in-depth analysis of this aspect in the future.

Another significant obstacle encountered was the lack of step-by-step documentation for many methods used in similar research with different algorithms, as highlighted by the literature review. This gap made understanding and applying these programs challenging. The process required extensive time watching lengthy instructional videos and experimenting with various predefined commands in the mentioned plug-ins, which detracted from the time available for final code development. The code had to be rewritten multiple times for comprehension and then redefined to suit the design problem.

Additionally, the research concluded that the workflow to a great extent relies on ready-made plug-ins. While these plug-ins automate certain tasks, they often limited and obscure the capabilities of external programs, such as pure simulation software. Therefore, further post processing of the data possible with programming languages like Python or C++ is highly recommended for future research for the workflow to become more independent of these plug-ins.

Transferability

As mentioned, the workflow initially aims to deliver interdisciplinary feedback in a design team and to be able to provide optimizations for more resilient buildings. Although as is the workflow can automatically transfer the data needed from a BIM model (different than the case study one) to Energy Plus and apply energy simulations, some further adjustments mostly in case of materiality definition of indoor and outdoor surfaces as well as adjustments of occupant's schedules and ventilation systems used are needed. As discussed, presets were used to define constants parameters for the optimization, but they could easily be adjusted for a future project scenario.

Another aspect of transferability is the knowledge needed to use this workflow. Depending on each project and its focus in order for the user to effectively use the workflow a prerequisite is to get familiar with Grasshopper environment and the plug-ins used in the workflow, namely: Ladybug tools, Karamba 3D and Wallacei. Custom components in python environment with packages like eppy, tensorflow, pytorch, scipy for direct control of Energy Plus and further post processing of the analysis conducted in Grasshopper are possible and highly recommended. In any case, however, for the workflow as is, basic knowledge of the aforementioned software is needed.

Bibliography

Aelenei, D., Aelenei, L., & Vieira, C. P. (2016). Adaptive Façade: concept, applications, research questions. Energy Procedia, 91, 269–275. https://doi.org/10.1016/j.egypro.2016.06.218

Afrin, S. (2017). Thermal performance analysis of ETFE-foil panels and spaces enclosed with ETFE-foil cushion envelope. ResearchGate. https://www.researchgate.net/publication/321794686_Thermal_performance_analysis_of_ETFE-foil_panels_and_spaces_enclosed_with_ETFE-foil_cushion_envelope

Attia, S., Levinson, R., Ndongo, E., Holzer, P. J., Kazanci, O. B., Homaei, S., Zhang, C., Olesen, B. W., Qi, D., Hamdy, M., & Heiselberg, P. (2021). Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. Energy and Buildings, 239, 110869. https://doi.org/10.1016/j.enbuild.2021.110869

"Bennet, I. (2016). Simulation-based evaluation of high-rise residential building thermal resilience. ASHRAE Transactions, 122."

Bianchi, S., Andriotis, C. P., Klein, T., & Overend, M. (2024b). Multi-criteria design methods in façade engineering: State-of-the-art and future trends. Building and Environment, 250, 111184. https://doi.org/10.1016/j.buildenv.2024.111184

Bilow, M. (2012). International façades: CROFT - Climate Related Optimized Façade Technologies. TU Delft.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K. J., Wallace, W. A., & Von Winterfeldt, D. (2003b). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 19(4), 733–752. https://doi.org/10.1193/1.1623497

Cao, X., Shen, D., Feng, D., Wang, C., Qu, Z., & Wu, G. (2022). Seismic retrofitting of existing frame buildings through externally attached sub-structures: State of the art review and future perspectives. Journal of Building Engineering, 57, 104904. https://doi.org/10.1016/j.jobe.2022.104904

Charbonneau, L., Polak, M. A., & Penlidis, A. (2014). Mechanical properties of ETFE foils: Testing and modelling. Construction & Building Materials, 60, 63–72. https://doi.org/10.1016/j.conbuildmat.2014.02.048

Charbonneau, L., Polak, M. A., & Penlidis, A. (2014b). Mechanical properties of ETFE foils: Testing and modelling. Construction & Building Materials, 60, 63–72. https://doi.org/10.1016/j.conbuildmat.2014.02.048

Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010, November 1). Framework for analytical quantification of disaster resilience. Engineering Structures/Engineering Structures (Online). https://doi.org/10.1016/j.engstruct.2010.08.008

Cobb, F. (2014). Structural Engineer's pocket book: Eurocodes. CRC Press.

Engineers, A. S. O. C. (2010). Tensile membrane structures. Amer Society of Civil Engineers.

Eurocode 8: Design of structures for earthquake resistance | Eurocodes: Building the future. (2023, January 31). https://eurocodes.jrc.ec.europa.eu/EN-Eurocodes/eurocode-8-design-structures-earthquake-resistance

Fan, Z., Liu, M., & Tang, S. (2022). A multi-objective optimization design method for gymnasium facade shading ratio integrating energy load and daylight comfort. Building and Environment, 207, 108527. https://doi.org/10.1016/j.buildenv.2021.108527

Flor, J., Liu, X., Sun, Y., Beccarelli, P., Chilton, J., & Wu, Y. (2022). Switching daylight: Performance prediction of climate adaptive ETFE foil façades. Building and Environment, 209, 108650. https://doi.org/10.1016/j.buildenv.2021.108650

Giannaros, C., Agathangelidis, I., Papavasileiou, G., Galanaki, E., Kotroni, V., Lagouvardos, K., Giannaros, T. M., Cartalis, C., & Matzarakis, A. (2023). The extreme heat wave of July–August 2021 in the Athens urban area (Greece): Atmospheric and human-biometeorological analysis exploiting ultra-high resolution numerical modeling and the local climate zone framework. Science of the Total Environment, 857, 159300. https://doi.org/10.1016/j.scitotenv.2022.159300

Graham, L. T., Parkinson, T., & Schiavon, S. (2021). Lessons learned from 20 years of CBE's occupant surveys. Buildings & Cities, 2(1), 166–184. https://doi.org/10.5334/bc.76

Hamdy, M., Carlucci, S., Hoes, P., & Hensen, J. L. (2017). The impact of climate change on the overheating risk in dwellings—A Dutch case study. Building and Environment, 122, 307–323. https://doi.org/10.1016/j.buildenv.2017.06.031

Homaei, S., & Hamdy, M. (2021a). Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric. Building and Environment, 201, 108022. https://doi.org/10.1016/j.buildenv.2021.108022

Homaei, S., & Hamdy, M. S. (2021). Developing a test framework for assessing building thermal resilience. Building Simulation Conference Proceedings. https://doi.org/10.26868/25222708.2021.30252

Hosseini, S., Barker, K., & Ramirez-Marquez, J. E. (2016). A review of definitions and measures of system resilience. Reliability Engineering & Systems Safety, 145, 47–61. https://doi.org/10.1016/j.ress.2015.08.006

Institute for Building Technology and Safety. (2015). REDi™ Rating System for Earthquake-Resilient Design: Version 1.0.

Jin, Q., & Overend, M. (2014). Sensitivity of façade performance on early-stage design variables. Energy and Buildings, 77, 457–466. https://doi.org/10.1016/j.enbuild.2014.03.038

Kazemi, P., Entezami, A., & Ghisi, A. (2024). Machine learning techniques for diagrid building design: Architectural-Structural correlations with feature selection and data augmentation. Journal of Building Engineering, 108766. https://doi.org/10.1016/j.jobe.2024.108766

Kersken, M. (2021). Method for the climate-independent determination of the solar heat gain coefficient (SHGC; g-value) of transparent façade and membrane constructions from in situ measurements. Energy and Buildings, 239, 110866. https://doi.org/10.1016/j.enbuild.2021.110866

Kersken, M., Moritz, K., Krah, W., & Goecke, F. (2021). Building Physics of ETFE-Film Systems. INTERNATIONAL CONFERENCE ON TEXTILE COMPOSITES AND INFLATABLE STRUCTURES – STRUCTURAL MEMBRANES 2021. https://doi.org/10.23967/membranes.2021.050

Kim, K. (2023). Resilience-based Facade Design Framework: A case study on facade systems under seismic and heat hazard. https://repository.tudelft.nl/islandora/object/uuid%3A5195b2b6-daf5-463f-ad57-fa9ae41603fe

Klein, T. (2013). Integral Facade Construction: Towards a new product architecture for curtain walls. TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid:f90c1c7e-b6b3-42de-8f17-22cc23981de7?collection=research

Knaack, U., & Klein, T. (2008). The Future Envelope 1: A Multidisciplinary Approach. IOS Press.

Knaack, U., & Klein, T. (2009). The Future Envelope 2: Architecture, Climate, Skin. IOS Press.

Knaack, U., & Klein, T. (2010). The Future Envelope 3: Facades - the Making of. IOS Press.

Lamnatou, C., Moreno, Á., Chemisana, D., Reitsma, F., & Clarià, F. (2018). Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis on buildings. Renewable & Sustainable Energy Reviews, 82, 2186–2201. https://doi.org/10.1016/j.rser.2017.08.072

Loonen, R., Rico-Martinez, J., Favoino, F., Brzezicki, M., Menezo, C., La Ferla, G., & Aelenei, L. (2015, November 1). Design for façade adaptability: Towards a unified and systematic characterization. Eindhoven University of Technology Research Portal. https://research.tue.nl/en/publications/design-for-fa%C3%A7ade-adaptability-towards-a-unified-and-systematic-c

Marini, A., Passoni, C., Belleri, A., Feroldi, F., Preti, M., Metelli, G., Riva, P., Giuriani, E., & Plizzari, G. (2017). Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC buildings: a proof of concept. European Journal of Environmental and Civil Engineering, 26(7), 2475–2495. https://doi.org/10.1080/19648189.2017.1363665

Monticelli, C., Campioli, A., & Zanelli, A. (2015). Environmental load of EFTE cushions and future ways for their self-sufficient performances. ResearchGate. https://www.researchgate.net/publication/50838810_Environmental_load_of_EFTE_cushions_and_future_ways_for_their_self-sufficient_performances

Naboni, E., Natanian, J., Brizzi, G., Florio, P., Chokhachian, A., Galanos, T., & Rastogi, P. (2019, October 1). A digital workflow to quantify regenerative urban design in the context of a changing climate. Renewable & Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2019.109255

Nayak, S. (2020). Fundamentals of Optimization Techniques with Algorithms. Academic Press.

Olu-Ajayi, R., Alaka, H., Sulaimon, I., Sunmola, F., & Ajayi, S. (2022). Building energy consumption prediction for residential buildings using deep learning and other machine learning techniques. Journal of Building Engineering, 45, 103406. https://doi.org/10.1016/j.jobe.2021.103406

Panteli, M., Trakas, D. N., Mancarella, P., & Hatziargyriou, N. (2017, July 1). Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement Strategies. Proceedings of the IEEE. https://doi.org/10.1109/jproc.2017.2691357

Pouniou, D. (2019). Computational optimization for the facade design of a nearly zero-energy high-rise office building in the temperate climate. TU Delft Repositories. https://repository.tudelft.nl/islandora/object/uuid%3A990911ae-7a8a-4407-84da-e1feebf14265

Seismic retrofit of reinforced concrete buildings in Japan using external precast, prestressed concr. (n.d.). https://www.pci.org/PCI/Publications/PCI_Journal/Issues/2013/Summer/Seismic_retrofit_of_reinforced_concrete_buildings_in_Japan_using_external_precast__prestressed_concr.aspx

Selvan, S. U., Saroglou, S. T., Joschinski, J., Calbi, M., Vogler, V., Barath, S., & Grobman, Y. J. (2023). Toward multi-species building envelopes: A critical literature review of multi-criteria decision-making for design support. Building and Environment, 231, 110006. https://doi.org/10.1016/j.buildenv.2023.110006

Shandiz, S. C., Foliente, G., Rismanchi, B., Wachtel, A., & Jeffers, R. F. (2020). Resilience framework and metrics for energy master planning of communities. Energy, 203, 117856. https://doi.org/10.1016/j.energy.2020.117856

Sharifi, A., & Yamagata, Y. (2016, January 1). Urban Resilience Assessment: Multiple Dimensions, Criteria, and Indicators. Advanced Sciences and Technologies for Security Applications. https://doi.org/10.1007/978-3-319-39812-9_13

Sun, K., Specian, M., & Hong, T. (2020). Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. Building and Environment, 177, 106842. https://doi.org/10.1016/j.buildenv.2020.106842

The Sustainable Development Goals Report 2023: Special Edition. (2023). The Sustainable development goals report. https://doi.org/10.18356/9789210024914

Tzoutzidis, N. (2023). Quantification of thermal resilience in buildings: Evaluation of Building Envelope Performance and Operational Parameters. https://repository.tudelft.nl/islandora/object/uuid%3Ac5bfbee8-76fa-48a9-866a-52ec01ecc5d9

Vugrin, E. D., Warren, D. E., Ehlen, M. A., & Camphouse, R. C. (2010). A framework for assessing the resilience of infrastructure and economic systems. In Springer eBooks (pp. 77–116). https://doi.org/10.1007/978-3-642-11405-2_3

Wang, Z., & Sobey, A. (2020). A comparative review between Genetic Algorithm use in composite optimisation and the state-of-the-art in evolutionary computation. Composite Structures, 233, 111739. https://doi.org/10.1016/j.compstruct.2019.111739

Appendix

A. Graduation timeline

February

Concerning the timeline of this research, a preliminary agenda was formed and presented during the P2 presentation (see Figure 111). The goal was by the end of February everything concerning the background research for curtain walls and shading systems would have been completed but with a greater focus in shading systems out of ETFE/PTFE. In parallel all the preparation needed for the analysis of the case study before the design of the shading system was also to be completed by the end of February. This eventually happened in mid-March however. The key parameters that had already been found in relative papers were filtered out and the ones needed for the optimization were defined in this phase. A complete BIM model for the tower of Piraeus as well as its energy simulation model, the necessary assumptions for the uses, the ventilation systems used, the materials, the U, R values, as well as the main properties of the existing unitized system were defined and translated in Grasshopper interface in this period. Rhino Inside tutorials were used for this purpose in order to define more precise zones for analysis and to be a step closer to an actual building, its complexities and imperfections. Finally, in the same period a literature review was carried out for genetic algorithms and how the suitability of them is defined based on each problem.

March

During March, material provided by Eckersley O'Callaghan and PILA was investigated, in order to understand the energy and structural goals of the existing building envelope. This was possible with the material that was kindly provided by Eckersley O'Callaghan concerning the final design stage of the tower's facade. The redesign of the unitized system as well as the scanning of the building envelope's report contributed to that. Moreover, the first simulations for one to four stories of the tower were to be completed by the end of March. This way the relationships between daylight, cooling demands and the geometrical and structural properties of the shading system could be more clear. The goals until the P3 presentation were for all the above-mentioned results concerning the existing building envelope to have been completed for a more efficient feedback by the mentors.

April and May

April and May were the months during which the shape of the shading system as well as the muti objective optimization were to be carried out. During this period the investigation concerning the shading system shape and its bearing structure was completed. Any python programming in Grasshopper environment was completed in this period. Feedback by the mentors as well as preparation of the P4 and P5 reports and presentations were also to take place in this period. For a more detailed schedule please see Figure 111.

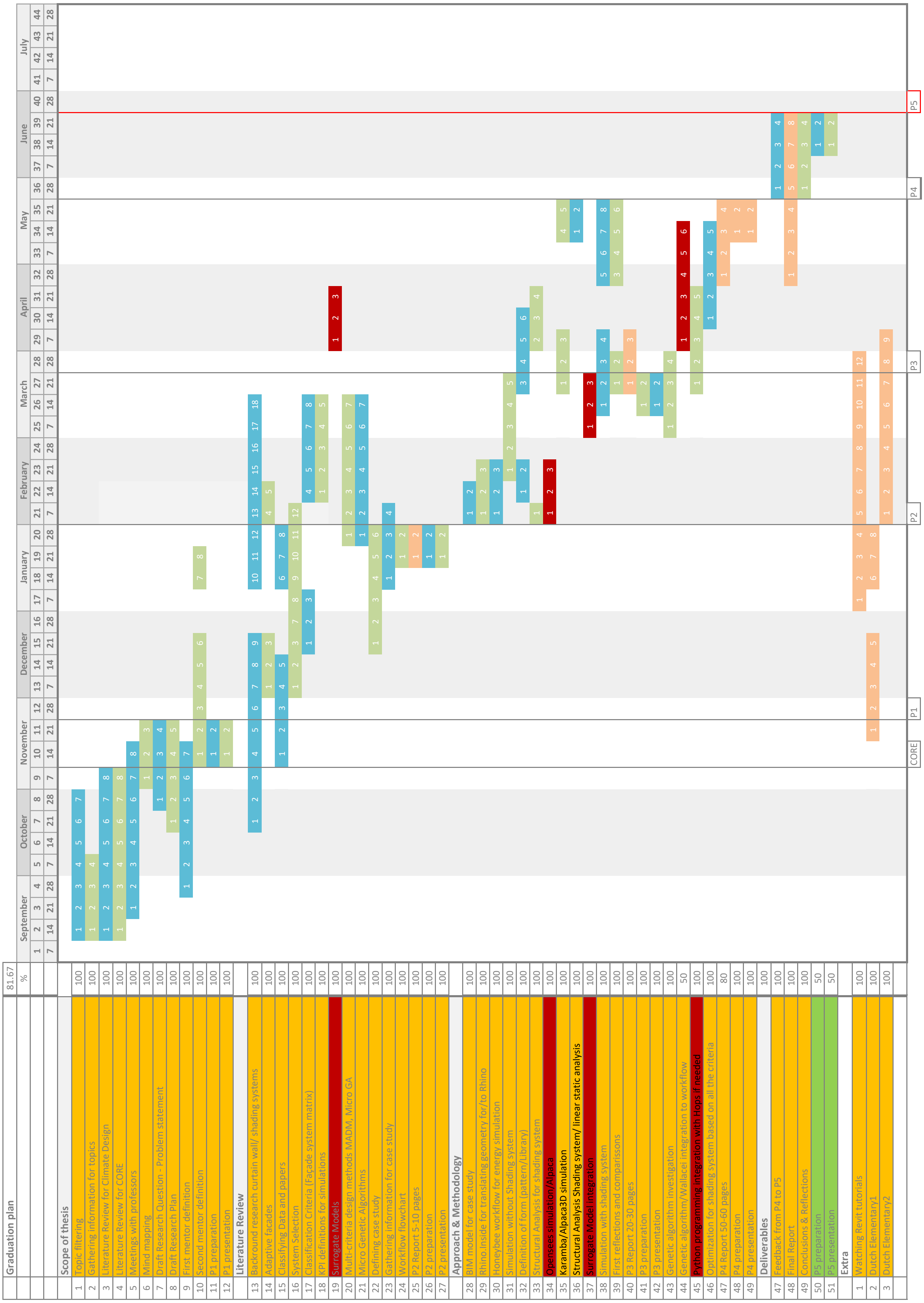


Figure. 111: Graduation timeline-agenda

B. Earthquakes and Regulations

Since one of the initial aims of this research was also to include earthquake engineering in the workflow the following information was gathered although finally not used in the proposed workflow.

The Port of Piraeus is the largest port in Greece and the Mediterranean Sea, and the third-largest container port in Europe. The port is located on the Saronic Gulf, which is a tectonically active region with earthquakes happening almost every month with relatively small magnitudes. There are however cases when earthquakes of bigger scale occur and influence the port. The port is located on a fault line that is part of the Hellenic Arc, a system of active faults that runs along the southern coast of Greece. The Hellenic Arc is a result of the collision of the African and Eurasian plates.

In the past the port has been affected by a number of earthquakes. One of the most influential earthquake in modern times to hit the port was the earthquake in September 1999 in Eleusis, which had a magnitude of 5.9 on the Richter scale. However, earthquakes occur quite often with much smaller magnitudes around 4 on the Richter scale. (source: GHEAD) Therefore, earthquakes are relatively common in the town of Piraeus. The Hellenic Arc is a seismically active region, and earthquakes of magnitude 6 or greater occur in the region every few decades. To mitigate the risk of earthquake damage, new buildings in the Port of Piraeus are constructed in such a way to meet strict seismic safety standards. These standards are either based on the Eurocode 8 regulations or based on the native Greek regulations for earthquake resistance.

In 2014, a law was signed requiring engineers in Greece to use either the Greek Earthquake Regulations (E.A.K. 2000) exclusively or Eurocode 8 exclusively. While the Greek regulations aim to incorporate Eurocode 8 into their chapters, civil engineers must still choose one or the other set of standards. This decision has been met with some controversy, as both sets of regulations have their own strengths and weaknesses. The Greek Earthquake Regulations are more specific to the Greek context and consider local seismic data and building practices. Eurocode 8, on the other hand, is a more comprehensive and up-to-date set of standards, but its application in Greece may require some adjustments. Ultimately, the decision of which set of standards to use should be made on a case-by-case basis, considering the specific characteristics of the project and the expertise of the engineering team. In the short boundaries of this research however, and for the goals that have been set only Eurocode8 will be considered.

C. Earthquake data

Regarding valid sources of information regarding earthquake recording, the sources investigated were the department of Geophysics-Geothermics databases as well as the Faculty of Geology databases in the University of Athens. Databases of the Institute of Engineering Seismology and Earthquake Engineering in Athens and the GIS Hellenic Accelerograms Database GHEAD v1.0 were also investigated. All these sources have information on historical earthquake records as well as platforms with live earthquake records. Especially the GHEAD data base can be used to search both an earthquake epicenter and data for the location of the case study. If one was to investigate a project in Athens, then these sources might be the best places to start concerning earthquake data bases.

D. Complete schematic workflow

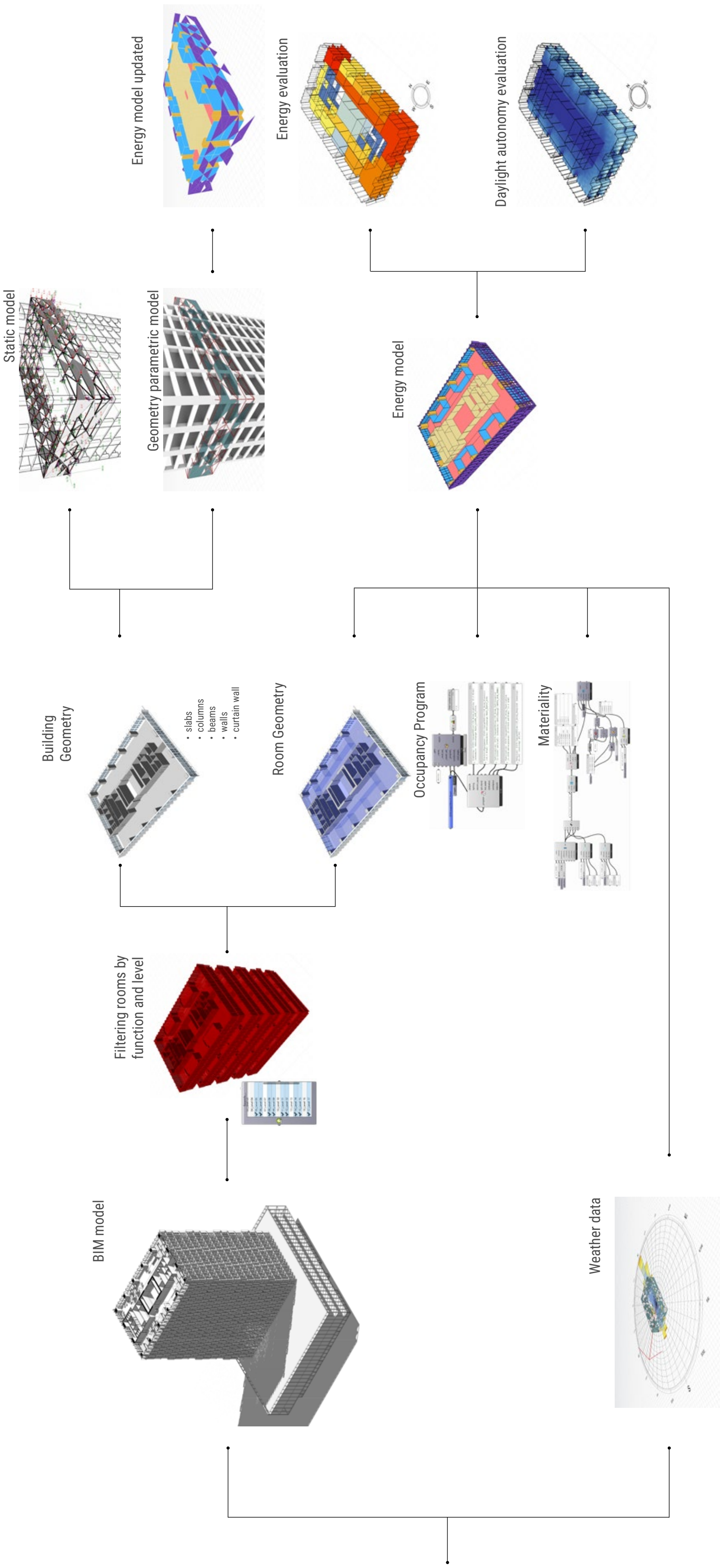


Figure. 112: Workflow Part A

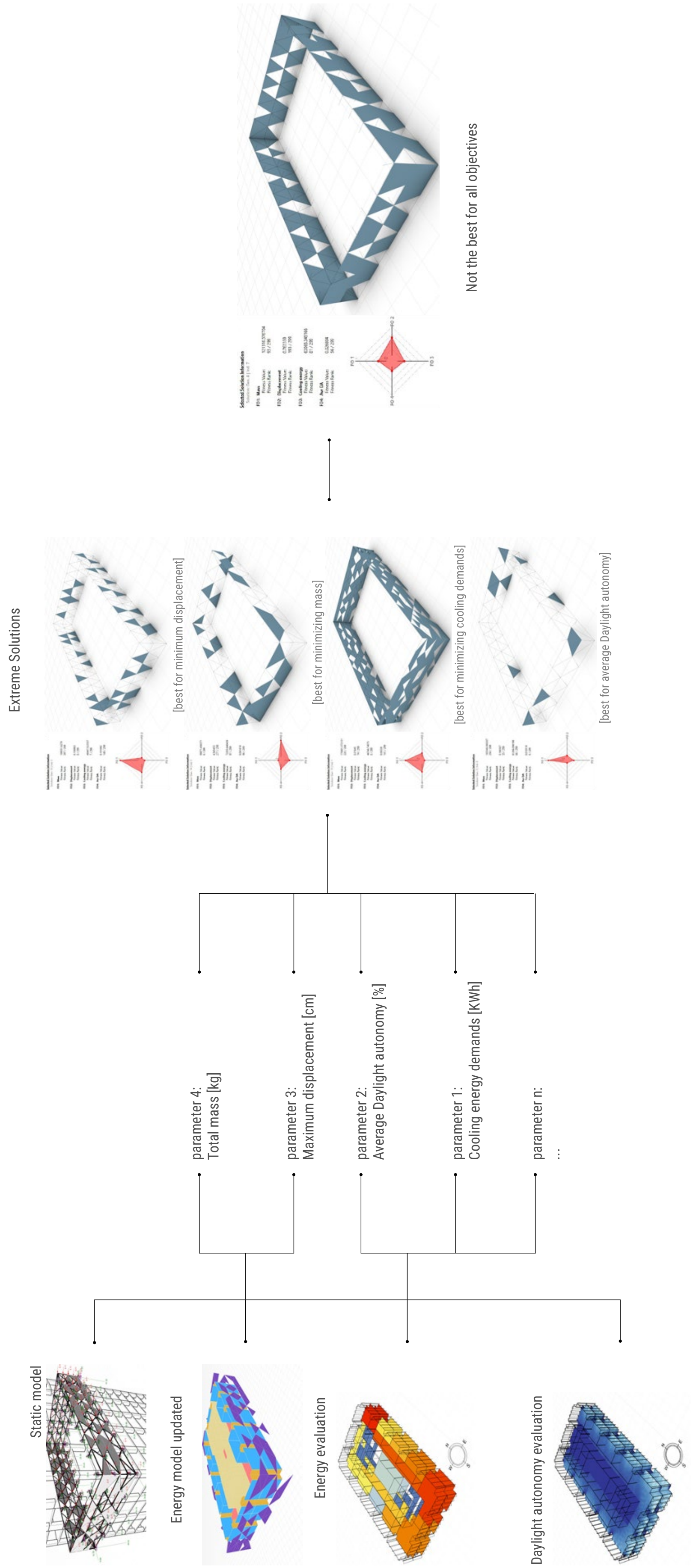


Figure. 113: Workflow Part B

E. Bibliography data base

		Literature Review						
		N/N	Author APA	Author APA Short	Title	Pub.Year	Name in data base	Source
PART_I_Background research		1	Knaack, U., & Klein, T. (2010). Th	(Knaack & Klein, 2010)	The Future Envelope 3 Facades - The Making of	2010	01_U. Knaack_ T. Klein - The	TUDelft library
		2	Knaack, U., & Klein, T. (2009). Th	(Knaack & Klein, 2009)	The Future Envelope 2: Architecture, Climate,Skin	2009	02_U. Knaack and T. Klein - The	TUDelft library
		3	Knaack, U., & Klein, T. (2008). Th	(Knaack & Klein, 2008)	The Future Envelope 1: A Multidisciplinary Approach	2008	03_U. Knaack_ T. Klein - The	TUDelft library
		4	Bilow, M. (2012). International fa	(Bilow, M. (2012)	CROFT - Climate Related Optimized Façade Technologies	2012	02_CROFT_MARCEL	TUDelft repository
		5	Klein, T. (2013). Integral Facade (	(Klein, 2013)	Integral Facade Construction: Towards a new product architecture for curtain walls	2013	02_INTEGRAL_FACADE_CONSTF	TUDelft repository
		6	Aelenei, D., Aelenei, L., & Vieira, (	(Aelenei et al., 2016)	Adaptive Façade: concept, applications, research questions	2016	01_Adaptive Façade concept, ap	ScienceDirect
		7	Loonen, R., Rico-Martinez, J., Fav	(Loonen et al., 2015)	Design for façade adaptability: Towards a unified and systematic characterization.	2015	02_Design for façade adaptabilit	ScienceDirect
	ETFE	8	Afrin, S. (2017). Thermal perform	(Afrin, 2017)	Thermal Performance Analysis of ETFE-foil Panels and Spaces Enclosed with ETFE-foil Cushior	2017	00_Phd_Thermal Performance A	ResearchGate
		9	Kersken, M., Moritz, K., Krah, W.,	(Kersken et al., 2021)	Building physics of ETFE systems	2021	01_notes_KERSKEN_KAUFMANN	ResearchGate
		10	Charbonneau, L., Polak, M. A., &	(Charbonneau et al., 2014b)	Mechanical properties of ETFE foils: Testing and modelling	2014	02_notes_Mechanical-properties	ScienceDirect
		11	Engineers, A. S. O. C. (2010). Ten	(Engineers, 2010)	Tensile membrane structures	2010	03_notes_American Society of C	ASCE American
		12	Lamnatou, C., Moreno, Á., Chem	(Lamnatou et al., 2018)	Ethylene tetrafluoroethylene (ETFE) material: Critical issues and applications with emphasis o	2018	04_Ethylene tetrafluoroethylene	ScienceDirect
		13	Flor, J., Liu, X., Sun, Y., Beccarelli	(Flor et al., 2022)	Switching daylight: Performance prediction of climate adaptive ETFE foil façades	2022	05_Switching daylight Performan	ScienceDirect
		14	Kersken, M. (2021). Method for tl	(Kersken, 2021)	Method for the climate-independent determination of the solar heat gain coefficient	2021	06_Method for the determinatio	ScienceDirect
		15	Charbonneau, L., Polak, M. A., &	(Charbonneau et al., 2014)	Mechanical properties of ETFE foils: Testing and modelling	2014	02_Mechanical-properties-of-	ScienceDirect
		16	Monticelli, C., Campioli, A., & Zar	(Monticelli et al., 2015)	Environmental load of EFTE cushions and future ways for their self-sufficient performances	2015	07_Environmental load of ETFE c	ResearchGate
PART_II_Hazards Investigation	Thermal_Resilience	17	Kim, K. (2023). Resilience-based	(Kim, 2023)	Resilience-based Facade Design Framwework - Master Thesis	2023	00_Master_Thesis_P5_Kyujin_Ki	TUDelft repository
		18	Tzoutzidis, N. (2023). Quantificat	(Tzoutzidis, 2023)	Quantification of thermal resilience in buildings - Master Thesis	2023	01_5611725_NATHANAIL_TZOU	TUDelft repository
		19	Bruneau, M., Chang, S. E., Eguch	(Bruneau et al., 2003b)	A framework to quantitatively assess and enhance the seismic resilience of communities	2003	00_Bruneau_notes_A Framework	ResearchGate
		20	Attia, S., Levinson, R., Ndongo, E.	(Attia et al., 2021)	Resilient cooling of buildings to protect against heat waves and power outages: Key concepts a	2021	01_Attia_Resilient cooling of buil	ScienceDirect
		21	Homaei, S., & Hamdy, M. S. (202	(Homaei & Hamdy, 2021)	Developing a test framework for assessing building thermal resilience.	2021	02_Homaei_Hamdy_a_Developir	IBPSA
		22	Homaei, S., & Hamdy, M. (2021a	(Homaei & Hamdy, 2021a)	Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labell	2021	03_Homaei_Hamdy_b_Thermal r	ScienceDirect
		23	Hosseini, S., Barker, K., & Ramire	(Hosseini et al., 2016)	A review of definitions and measures of system resilience	2016	05_Hosseini_A review of definitic	ScienceDirect
		24	Hamdy, M., Carlucci, S., Hoes, P.	(Hamdy et al., 2017)	The impact of climate change on the overheating risk in dwellings—A Dutch case study	2017	06_Hamdy_IOD_The impact of cl	ScienceDirect
		25	Panteli, M., Trakas, D. N., Mancai	(Panteli et al., 2017)	Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement	2017	07_Panteli_Matheos_Power_Sys	ResearchGate
		26	Graham, L. T., Parkinson, T., & Sc	(Graham et al., 2021)	Lessons learned from 20 years of CBE's occupant surveys	2021	04_Graham_Lessons learned fro	Building&Cities
		27	Naboni, E., Natanian, J., Brizzi, G.	(Naboni et al., 2019)	A digital workflow to quantify regenerative urban design in the	2019	09_Naboni_A digital workflow to	ScienceDirect
		28	Sharifi, A., & Yamagata, Y. (2016,	(Sharifi & Yamagata, 2016)	Urban Resilience Assessment: Multiple Dimensions, Criteria, and Indicators	2016	10_Sharifi_Urbal Resilience Asse	ResearchGate
		29	Cimellaro, G. P., Reinhorn, A. M.,	(Cimellaro et al., 2010)	Framework for analytical quantification of disaster resilience	2010	11_Cimellaro_Framework for an	ScienceDirect
		30	Giannaros, C., Agathangelidis, I.,	(Giannaros et al., 2023)	The extreme heat wave of July–August 2021 in the Athens urban area	2023	01_The extreme heat wave of July	ScienceDirect
		31	Vugrin, E. D., Warren, D. E., Ehler	(Vugrin et al., 2010)	A framework for assessing the resilience of infrastructure and economic systems	2010	12_Vugrin_A Framework for Asse	ScienceDirect
		32	Sun, K., Specian, M., & Hong, T. (:	(Sun et al., 2020)	Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home.	2020	13_Sun_ thermal resilience and e	ScienceDirect
		33	Bennet, I. (2016). Simulation-	(Bennet et al.,2016)	Simulation-based evaluation of high-rise residential building thermal resilience	2016	15_Bennet_Simulation highrise	ResearchGate
		34	Shandiz, S. C., Foliente, G., Rism	(Shandiz et al., 2020)	Resilience framework and metrics for energy master planning of communities	2020	14_Shandiz_Resilience framewo	ScienceDirect
		35	Eurocode 8: Design of structures	(Eurocode 8: Design of structure	Design of structures for earthquake resistance	2004	EN 1998-1_ 2004 Eurocode 8_ D	European
		36	Institute for Building Technology	(REDi Rating System)	Rating System for Earthquake-Resilient Design	2013	Resilience-based Earthquake De	Arup.com
		37	The Sustainable Development Go	("The Sustainable Development	The Sustainable development goals report	2023		
PART_III_Computational Methodology		38	Pouniou, D. (2019). Computatior	(Pouniou, 2019)	Computational optimization for the facade design of a nearly zero-energy high-rise office build	2019	00_P5_Report_DespoinaPounio	TUDelft repository
		39	Bianchi, S., Andriotis, C. P., Klein	(Bianchi et al., 2024)	Multi-criteria design methods in façade engineering: State-of-the-art and future trends	2024	01_Ment_Multi-criteria	ScienceDirect
		40	Selvan, S. U., Saroglou, S. T., Jos	(Selvan et al., 2023)	Toward multi-species building envelopes: A critical literature review of	2023	02_SOS_Toward multi-species	ScienceDirect
		41	Fan, Z., Liu, M., & Tang, S. (2022)	(Fan et al., 2022)	A multi-objective optimization design method for gymnasium facade	2022	03_SOS_simona_A multi-	
		42	Jin, Q., & Overend, M. (2014). Sei	(Jin & Overend, 2014)	Sensitivity of façade performance on early-stage design variables	2014	03_SOS_simona_Sensitivity of	ResearchGate
		43	Cobb, F. (2014). Structural Engin	(Cobb, 2014)	Structural Engineer's pocket book: Eurocodes	2014		Book
		44	Nayak, S. (2020). Fundamentals	(Nayak, 2020)	Fundamentals of Optimization Techniques with Algorithms	2020	05_Sukanta Nayak -	Book
		45	Kazemi, P., Entezami, A., & Ghisi,	(Kazemi et al., 2024)	Machine learning techniques for diagrid building design:	2024	04_Machine learning	ScienceDirect
		46	Wang, Z., & Sobey, A. (2020). A c	(Wang & Sobey, 2020)	A comparative review between Genetic Algorithm use in composite	2020	04_SOS_A comparative review	ScienceDirect
		47	Olu-Ajayi, R., Alaka, H., Sulaimor	(Olu-Ajayi et al., 2022)	Building energy consumption prediction for residential buildings using	2022	00_Building energy	ScienceDirect
	Exo-skeltons	48	Marini, A., Passoni, C., Belleri, A.	(Marini et al., 2017)	Combining seismic retrofit with energy refurbishment for the sustainable renovation of RC bui	2017	01_Marini_Combining seismic re	ResearchGate
		49	Seismic retrofit of reinforced cor	(Takeda et al,2013)	Seismic Retrofit of Reinforced Concrete Buildings in Japan Using External Precast, Prestressec	2013	02_Takeda_Seismic retrofit of rei	ScienceDirect
		50	Cao, X., Shen, D., Feng, D., Wang	(Cao et al., 2022)	Seismic retrofitting of existing frame buildings through externally attached sub-structures: Sta	2022	03_Cao, Seismic retrofitting of ex	ScienceDirect

Figure. 114: Bibliography data base

F. Architectural visualizations

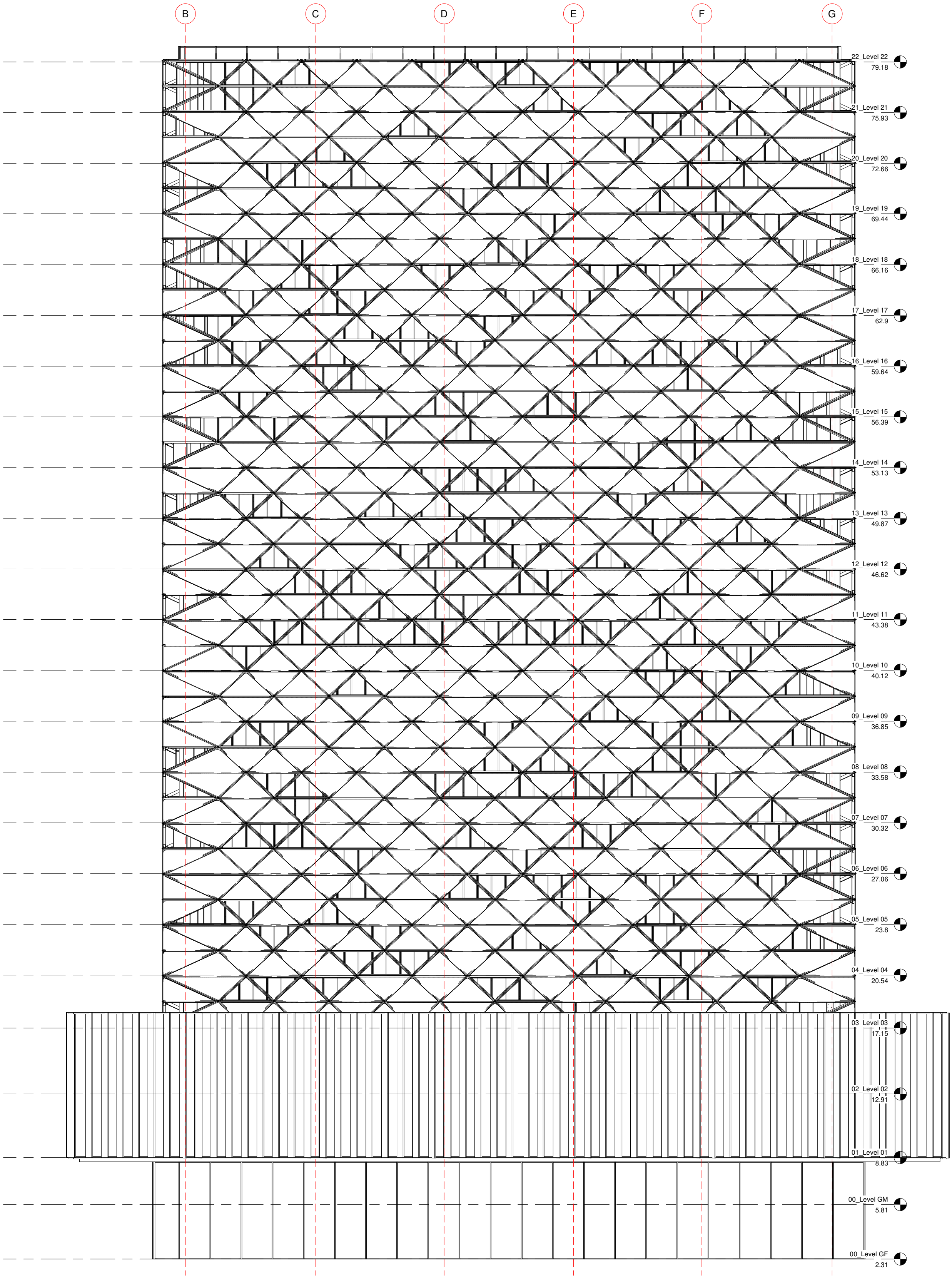


Figure. 115: East facade with proposed shading system

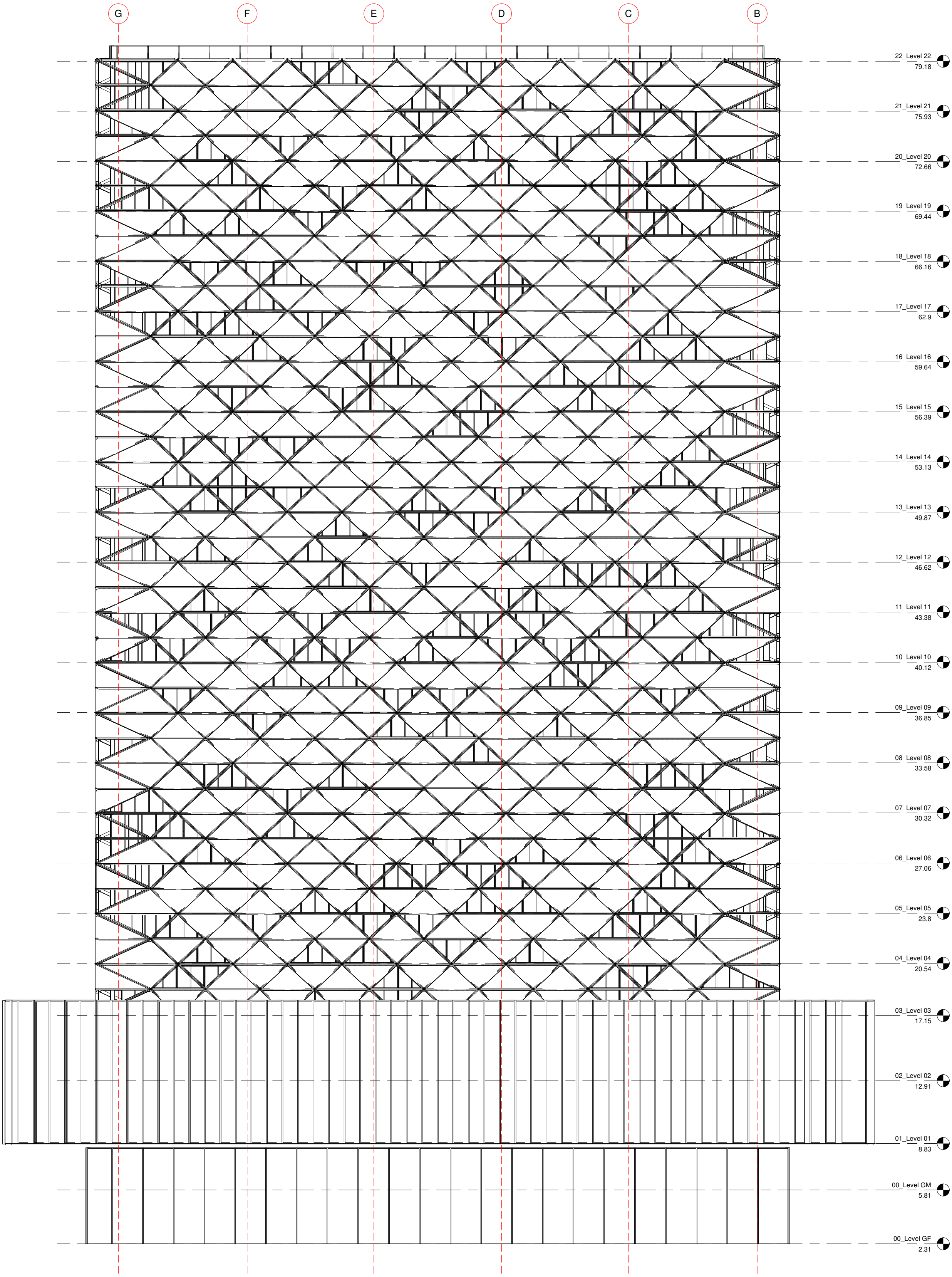


Figure. 116: West facade with proposed shading system

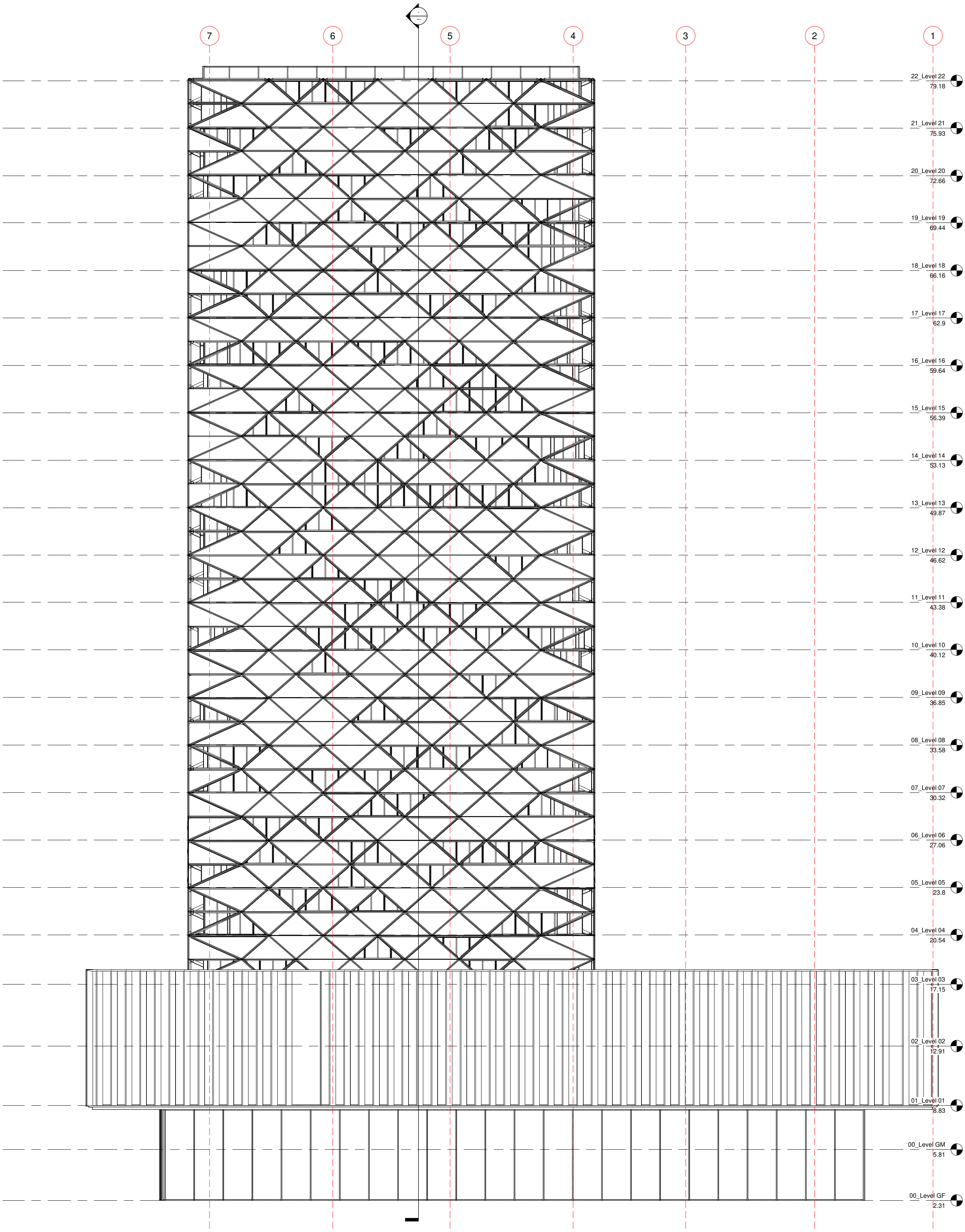


Figure. 117: North facade with proposed shading system

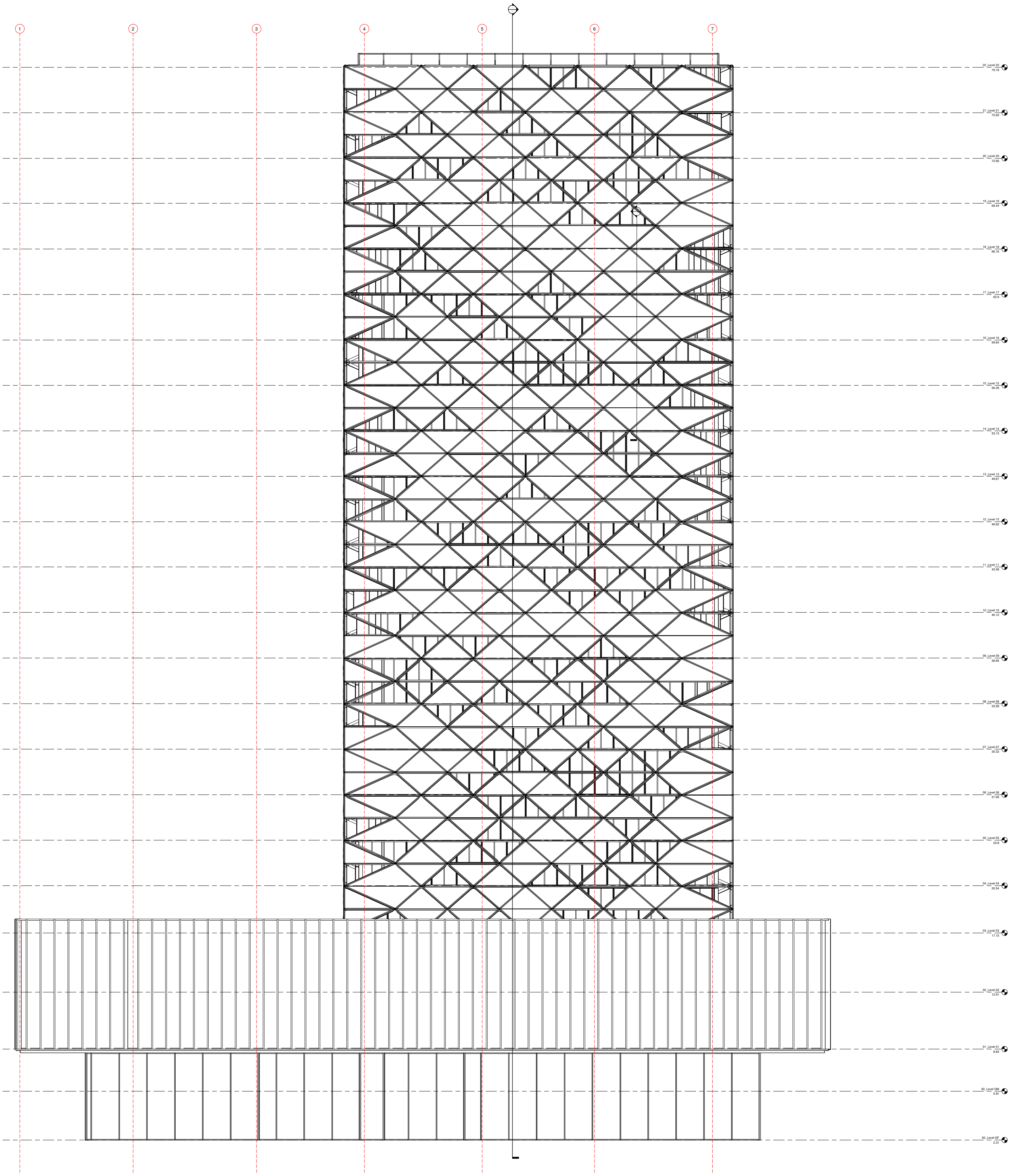


Figure. 118: South facade with proposed shading system

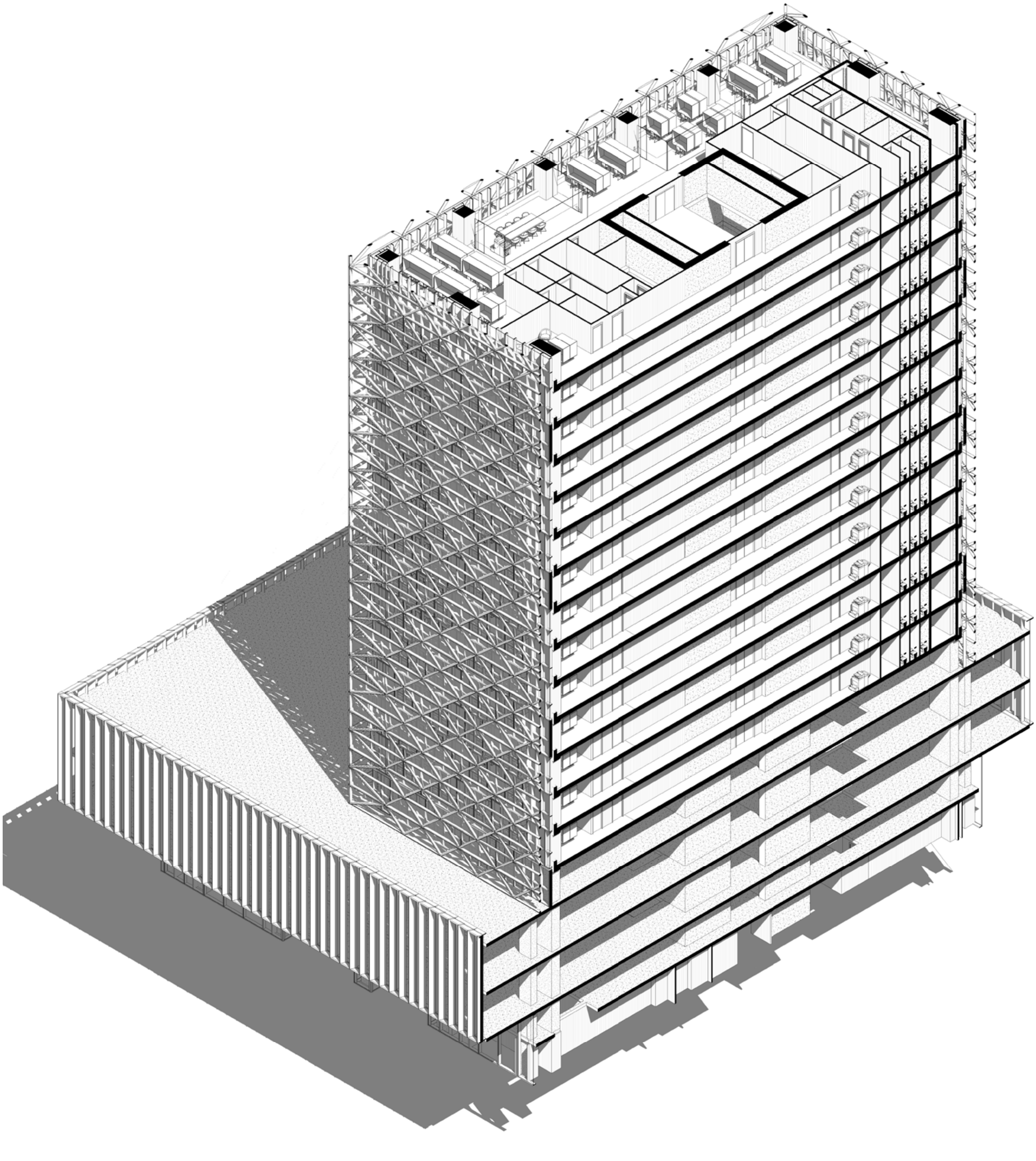


Figure. 119: Axonometric section of case study with proposed shading system

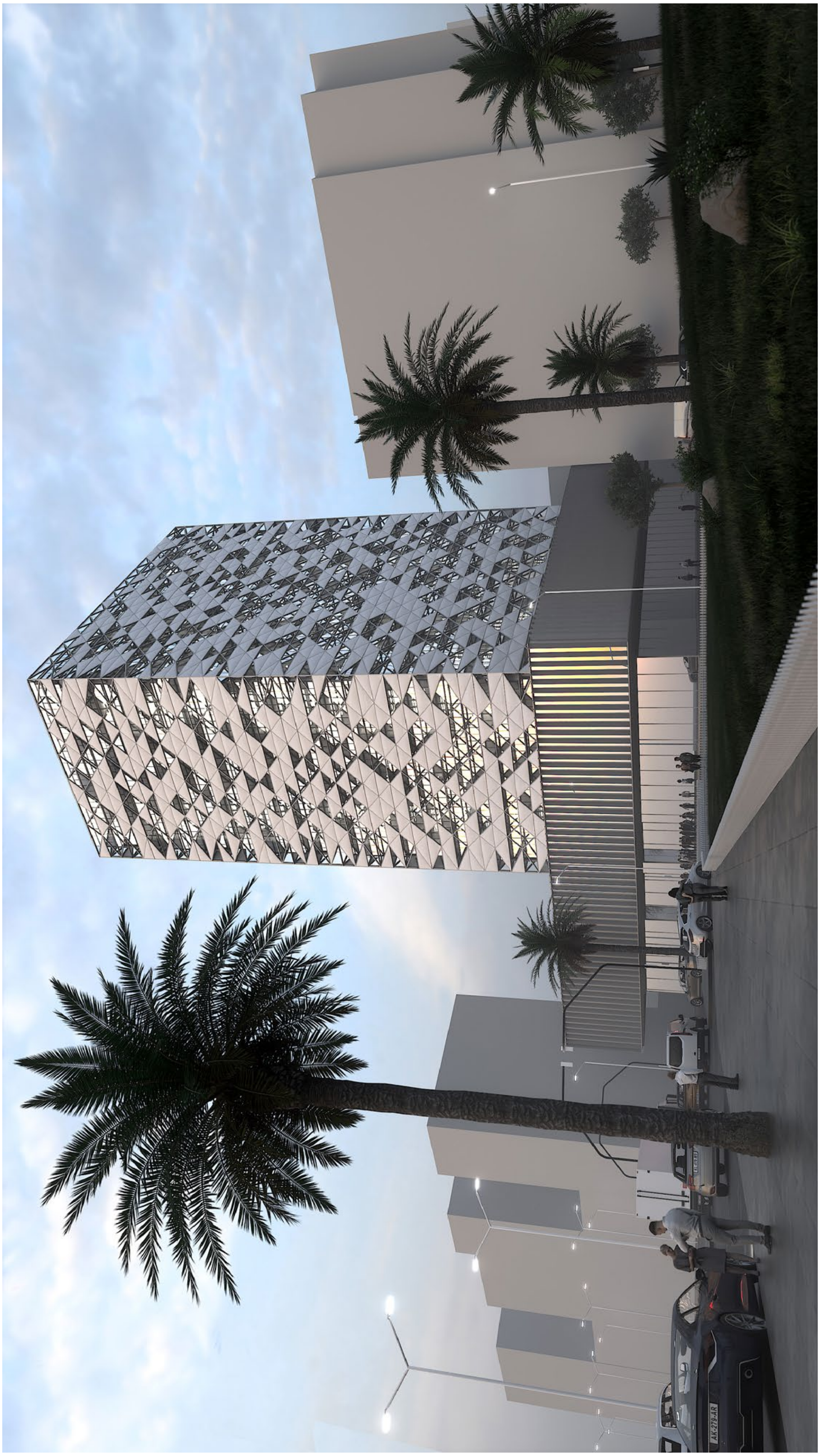


Figure. 120: Street view of the case study building with proposed shading system