



# GRADUATIONPROJECTREPORT

Student: Alvaro Rodriguez Garcia  
Student N°: 4628098  
A.G.RodriguezGarcia1@student.  
tudelft.nl

Program: Building Technology  
Mentors: Dr. Michela Turrin  
Dr. Wim van der Spoel

Date: 11/07/2018

# ABSTRACT

## COMPUTATIONAL DESIGN METHOD BASED ON MULTIDISCIPLINARY DESIGN OPTIMIZATION AND OPTIONEERING TECHNIQUES FOR ENERGY EFFICIENCY AND COST EFFECTIVENESS

### MASTER THESIS FINAL REPORT

#### STUDENT:

Alvaro Rodríguez García  
A.G.RodriguezGarcia-1@student.tudelft.com  
alvaro@pabellondearquitectura.com  
4628098

#### FIRST MENTOR:

Dr MSc Arch. Michela Turrin  
M.Turrin@tudelft.nl

#### SECOND MENTOR:

Dr Wim van der Spoel  
W.H.vanderSpoel@tudelft.nl

#### EXTERNAL SUPERVISOR:

Dr Darinka Czischke  
D.K.Czischke@tudelft.nl

11/07/2018

One of the cutting-edge interests gaining relevance among design offices, notably in the sphere of architecture firms, is computational design. With its inception embedded in the 60s and later reformed through the CAD revolution that boomed in the 80s, the use of the computer as a design tool has evolved to such lengths that it became indispensable to contemporary practices. Nowadays, under the bright prospect of a challenging future and considering the sustainability hypothesis - sophisticated computational approaches and parametric design can genuinely be considered a most promising alternative for exceeding outcomes in the fields of performance and efficiency.

Thus, under this spectrum, the following research focuses on investigating the evolution of the aforementioned tools, through understanding the currently user experience and interface in prevalent architectural offices. Consequently, through the use of existing computational tools - simulations, optimization and design exploration techniques - it will put forward a new method and use pattern that would also project the potential and the future of these technologies, specifically applied to a sustainable, energy-efficient and cost-effective vantage.

#### Keywords:

Computational design optimization, multi-objective optimization, multidisciplinary design optimization, building performance optimization, optioneering, conceptual architectural design, energy performance, building costs estimation, energy efficient sports design.



# ACKNOWLEDGMENTS

This document is the result of the final year of the Master in Building Technology at TU Delft University of technology. After a time-lapse of two large and complicated but enriching years, this period has represented a significant challenge in my life which I would not have been able to face without the support of the people that have been around me during all this process.

First of all, I am very grateful to my mentors, Dr March Michela Turrin for guiding me always from the beginning of the process to the end of it, sharing with me all her knowledge and passion about computational design and architecture. I am also very thankful to Dr Willem van der Spoel for his patience and for helping me understanding buildings from another perspective. Additionally, to Wang pan (Frank) and Ir Peter de Jong who although not being part of my graduation committee they took the time to help me with optimization and costs aspects respectively.

Secondly, I would like to thank my parents and my brothers, which have always been there supporting me and helping me in every step I have taken, without their support none of this would have been possible.

I express my deepest gratitude to CONACYT (Consejo Nacional de Ciencia y Tecnología) and SENER (Secretaría de energía ) for the financial support and the means that made studying this master a possibility.

Finally, I would like to thank all my Building Technology teachers and colleagues, especially to my friends Eve Farrugia, Lia Tramontini, Alexandra Farmazón, Akos Szabò, Tarik Alboustani and Michael Cobb for sharing with me all the good and the bad times during these years of studying.

# TABLE OF CONTENTS

## 1. RESEARCH FRAMEWORK

- 1.1 INTRODUCTION.....05
- 1.2 PROBLEM STATEMENT..... 06
- 1.3 RESEARCH OBJECTIVES.....07
- 1.4 RESEARCH QUESTIONS.....07
- 1.5 APPROACH AND METHODOLOGY.....08
- 1.6 RELEVANCE.....08
- 1.8 TIME PLANNING.....09

## 2. BACKGROUND RESEARCH

- 2.1 PRESENT ISSUES.....14
  - 2.1.1 Environmental conditions.....14
  - 2.1.2 Current architectural practice.....16
    - 2.1.2.1 Interviews .....19
- 2.2 COMPUTATIONAL DESIGN IN ARCHITECTURE.....27
  - 2.2.1 Antecedents - Performance based architecture .....27
  - 2.2.2 Generative design.....28
  - 2.2.3 Performance based generative design.....29
  - 2.2.4 Interviews.....32
- 2.3 SPORTS VENUES DESIGN .....36
  - 2.3.1 Performance requirements.....37
  - 2.3.2 Computational design in sports venues (Case studies).....44
  - 2.3.3 Interviews.....48
- 2.4 CONCLUSIONS.....49

## 3. LITERATURE REVIEW: OPTIMIZATION AND DESIGN EXPLORATION

- 3.1 BACKGROUND.....52
- 3.2 SIMULATION BASED OPTIMIZATION PROCESS.....54
  - 3.2.1 Pre-processing.....56
    - Algorithms and problem definition
    - The parametric model
  - 3.2.2 Processing.....61
    - Evaluation criteria and simulations.....61
      - Energy performance
      - Cost performance
    - Types of optimization.....89
      - Single-objective
      - Multi-objective
      - Multi-disciplinary
  - 3.2.3 Post-processing.....98
    - Design exploration.....98
    - Data managing and visualization.....101
  - 3.2.4 Interviews.....105
- 3.3 CONCLUSIONS.....108

## 4. PROPOSED WORKFLOW

- 4.1 WORKFLOW DEFINITION.....112
  - 4.1.1 Objectives & evaluation criteria.....118
  - 4.1.2 Decision variables & constraints.....119
  - 4.1.3 Design strategy selection.....122
  - 4.1.4 Tools definition.....124
  - 4.1.5 Costs database elaboration.....128
  - 4.1.6 Simulation modeling.....136
  - 4.1.7 Optimization process.....142
  - 4.1.8 Design Exploration process.....146

## 5. CASE STUDY

- 5.1 CASE STUDY.....151
  - 5.1.1 Location.....151
  - 5.1.2 Layout & requirements.....152
  - 5.1.3 Climate analysis.....156
- 5.2 IMPLEMENTATION.....163
  - 5.2.1 Costs database integration.....164
    - Cost database (Benchmarks).....165
    - Cost database (Detailed).....166
  - 5.2.2 Parametric model(Overall).....168
  - 5.2.3 Model calibration/ intercomparison.....172
  - 5.2.4 Computational workflow (Sequential strategy).....174
    - 5.2.4.1 Stage 1 - Massing.....176
      - Parametric model.....177
      - Simulation/optimization/exploration.....180
      - Results & observations.....184
    - 5.2.4.2 Stage 2 - Structure.....188
      - Parametric model.....189
      - Simulation/optimization/exploration.....194
      - Results & observations.....198
    - 5.2.4.3 Stage 3 - Envelope.....202
      - Parametric model.....203
      - Simulation/optimization/exploration.....206
      - Results & observations.....210
    - 5.2.4.4 Stage 4 - Systems.....214
      - Parametric model.....215
      - Simulation/optimization/exploration.....218
      - Results & observations.....222
  - 5.2.5 Computational workflow (Integrated strategy).....228
    - Parametric model.....230
    - Simulation/optimization/exploration.....234
    - Results & observations.....238
  - 5.2.6 Results and discussion.....240
- 5.3 WORKFLOW STRATEGIES COMPARISON.....242

## 6. FINAL RESULTS & DISCUSSION

- 7. CONCLUSIONS.....258
- 8. REFERENCES.....262

# 1. RESEARCH FRAMEWORK

# 1.1 INTRODUCTION

“Technology is the answer, but was what the question?”  
-Cedric Price 1965

Nowadays, according to the European Commission (2017), almost 40% of the energy consumption and CO<sub>2</sub> emissions are related to buildings. Environmental issues such as the excess of energy demand and the inefficient use of it is triggering the shortage of natural resources, climate change and the excess of polluted air in our surroundings. Inside this scenario, the architectural design process includes important choices that will significantly affect the energy performance of the buildings. Due to this, the complexity of regulations is continually rising having more and more ambitious requirements such as, the future 2020 European Union directive that will require every building to generate more energy that it will consume (Sartori et al 2012). In this scope, large and complex edifications such as sports venues are attractive typologies for deepening and analyze.

With the growing interest of associations like the International Olympic committee and the FIFA towards a more sustainable design approach comprehending environmental, social and economic factors. Each time is more necessary to accomplish with several rating systems such as LEED or BREAM among others. Together with this, cost optimization is one of the principal elements of the energy performance and with a future building stock moving towards more complicated forms and building systems, traditional costs estimation techniques become much more difficult to use. In this context, currently mainly large-scale architectural firms such as Norman Foster, BIG (Bjarke Ingels Group) and MVRDV utilize computational design applied to solve this issues and propose sustainable solutions based on real facts and environmental performance. However, there is still a lot to be done in this subject, since the majority of architectural firms continue working in an outdated way and with inefficient workflows. Applying computational design mainly at the latest stages of the design process while it is the conceptual/initial phase of the design which has the most critical impact when talking about energy, costs and environmental performance. This is principally true when it comes to middle scale and small scale offices in developing countries such as Mexico which does not have highly strict energy requirements yet but it is likely to change in the near future.

In this scope, Simulation-based multi-objective and multidisciplinary design optimization represents a viable solution towards the design exploration of sustainable and energy efficient alternatives. The aim of this document is to investigate how this new “computational approach” can represent a sustainable solution by changing the mindset of using the computer only as a tool to apply it as a decision supporter that can help designers to explore and propose more informed and environmentally conscious projects.

The following master thesis will start by giving an overview of the current environmental problems, regarding energy efficiency and costing analysis emphasizing on the direct responsibility that we have as architects and designers.

Together with a review about the way current architectural offices and educational institutions approach to the use of existing computational tools and new technologies, a computational methodology is proposed and later on tested. By using innovative software based on parametric design, performance simulations, optimization techniques and design exploration, this research combines a literature review with a research by design methodology to end up with a computational design method applied to a real case of a Sports hall located in Mexico City.



## 1.2 PROBLEM STATEMENT

The building sector is responsible for a significant amount of the global energy consumption, which causes the rise of CO2 emissions and the shortage of energy resources. Emerging tendencies towards energy efficient buildings address the objective of reducing operational energy and emissions in buildings. Therefore, architects and designers have the responsibility to propose energy efficient constructions, and this performance needs to be achieved for the lowest possible cost. In order to accomplish this, the computational design has proved to be a promising solution. However, most of the architectural offices keep on using traditional design workflows excluding engineering aspects from the beginning of the conceptual design, which is the stage that influences the most for energy consumption and overall cost. Due to the complexity of large-scale buildings and each time more strict regulation codes, it is complicated to find a balance between energy efficiency and cost-effectiveness together with an aesthetical (non-quantitative) evaluation. Several issues surround the answer that building design industry is providing to the environmental problems previously described. Some of them are listed below:

- Inefficient design processes
- Lack of computational (technological) background
- Lack of relevant theory
- Not enough research interest
- Retrograde building industry
- Non quantitative aspects when assessing aesthetic factors.

## 1.3 RESEARCH OBJECTIVES

To develop an interactive computational method for designing energy-efficient buildings based on energy and cost simulations, and multi-objective optimization techniques applied to the first phases of design.

- Review the existing computational tools for energy simulation cost estimation and multi-objective optimization together with design exploration.
- Determine the most influential parameters in the design towards energy neutrality and low-cost optimal performance.
- Define a tool that can achieve energy regulations, sustainable rankings and restricted budgets.
- Propose a tool that can be easily understandable and operable for possible future users

## 1.4 RESEARCH QUESTIONS

How architects and designers can benefit from the use of computational design techniques to integrate specific performative aspects in an energy and cost efficient conceptual design for complex buildings such as Sports halls.

- How can computer aided conceptual design support the generation of geometric design alternatives?
- To what extent can computer aided design support the designers learning process and be easily understandable and interactive for the future users?
- Can an automated performance-based computational design method be able to achieve an optimal balance between energy regulations, sustainable rankings, restricted budgets and the return of investments?

# 1.5 METHODOLOGY

This thesis consists of two main parts as described in Fig. [1]: Firstly, a literature research of theoretical information using books, scientific papers, journal articles and documentary videos focused in energy efficiency, costs estimation and sports venues design as a case study typology. Having also at each subsection, a set of interviews with specialists of each topic to analyze and conclude the chapters accordingly.

The second section of the document will be a practical research or “research by design” that consists on applying all the gathered knowledge from the first part of the study in the first place to define a computational design workflow. And secondly, to implement this methodology on an assigned case study of a sports hall located in the south of Mexico City.

At the end of the thesis, the computational design method will be tested, compared and evaluated to finish with a set of conclusions and discussions of the results and further research recommendations.

# 1.6 RELEVANCE

It is during the first stage of the design that decision making has the highest potential impact on the total building performance. Hence, it is important to take right choices once several design options are explored, compared and optimized.

Designing a Sports venue represents a significant challenge, due to the large-scale, complex geometries, multi-functional aspects and energy demands. Therefore, finding a rapid and efficient method that can take into account all these previous elements is an innovative and valuable input that later on can be applied to other typologies or building projects.

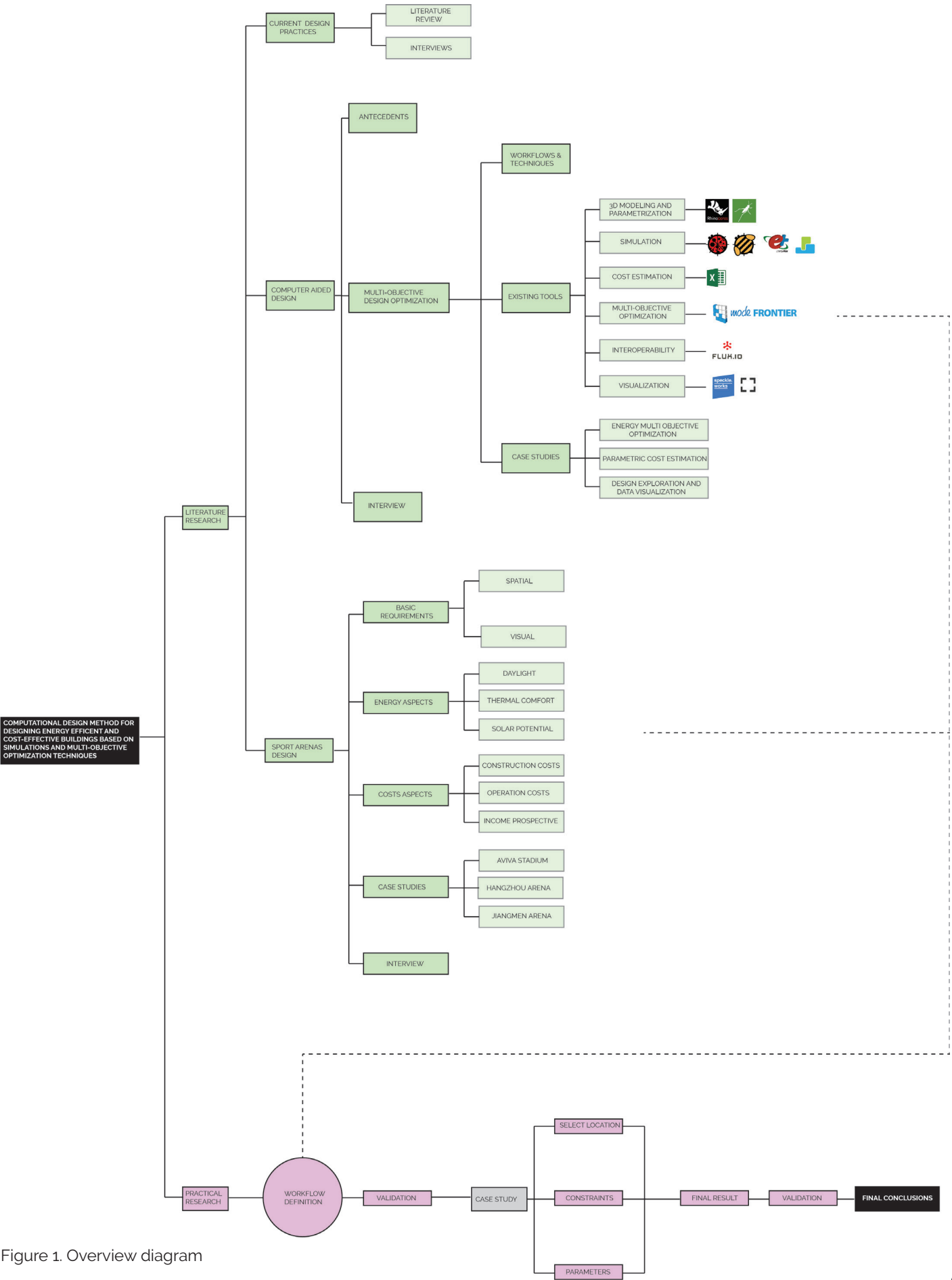


Figure 1. Overview diagram

1.7 TIMEPLANNING

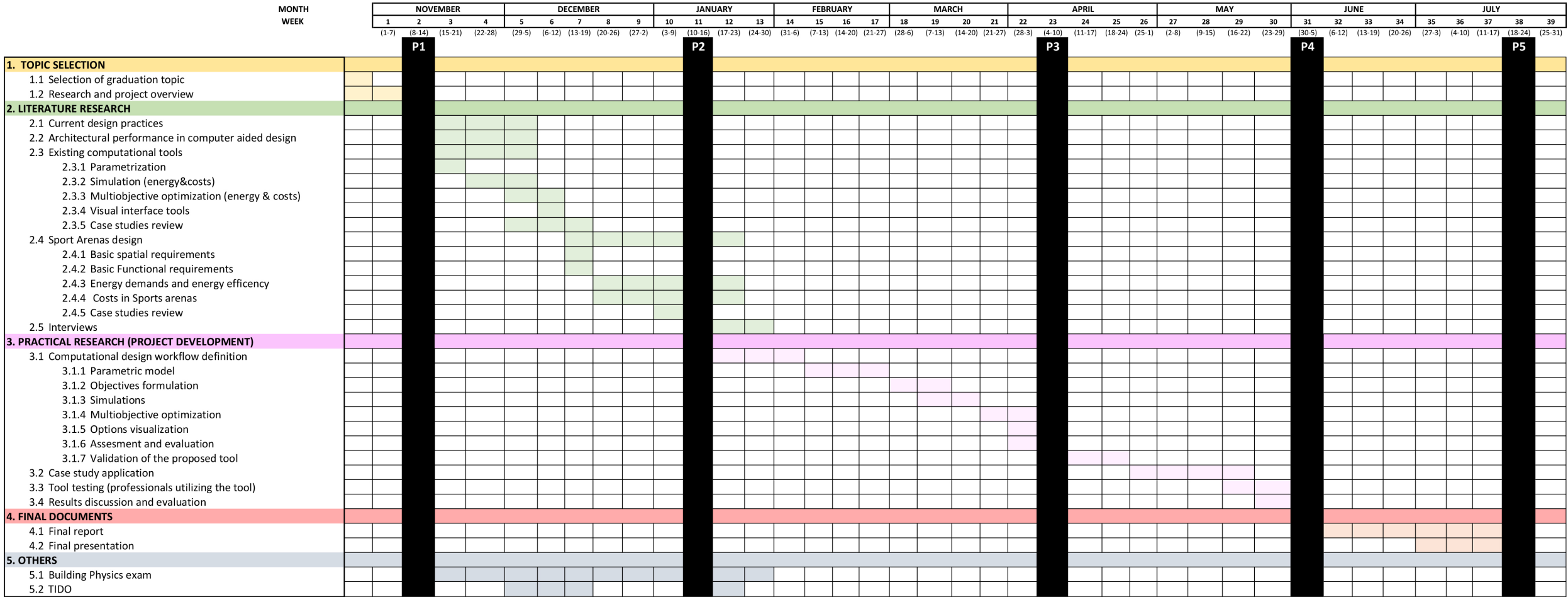


Figure 2. Planning Schedule

## 2.BACKGROUNDRESEARCH



# 2.1PRESENT ISSUES

## 2.1.1ENVIRONMENTAL CONDITIONS

As described before, we are facing serious problems regarding environmental aspects, such as climate change, bad air quality, global warming and global carbon emissions. On the top of this, according to Radwan & Osama (2016), since 1970, a major worldwide problem is the energy shortage along with the high consumption of energy in buildings as it could be seen in Fig.[3].

Shi & Zhichao (2016) describes that after the two oil crisis in the 1970’s the energy cost suddenly increased, leading to a change towards a more energy efficient way of thinking. Building energy efficient design started becoming a common practice among architects, engineers and even between governments and developers. However, as defined by the World Health Organization in 2014 the urban population accounted for 54% of the total global population, raising from 34% in the 1960s. With an expected growth of 1.84% per year between 2015 and 2020, , and 1.44% per year between 2025 and 2030.

Ergo, the increase in the number of people living in the cities and therefore the energy demand that this entails represents an immediate worry. If we also consider that as stated by Bluysen (2015) “people in the western world, in general, spend 80-90% of their time indoors”, we must approach to a performance-driven design of buildings based on energy efficiency and cost savings as primary considerations.

Nevertheless, this is not an easy job, as defined by to Shi & Tian et al. (2016) Building energy efficient design is by nature a multi-objective and a multivariable design task. Hamdy et al.(2011) also define that the building geometry, the envelope and many different building elements interact among them, requiring optimizing the combination of the building and systems rather than only the systems on an individual level. “It requires the collaboration of architects, heating, ventilation, and air conditioning engineers, energy consultants among others” (Tian & Zhang et al.(2017)

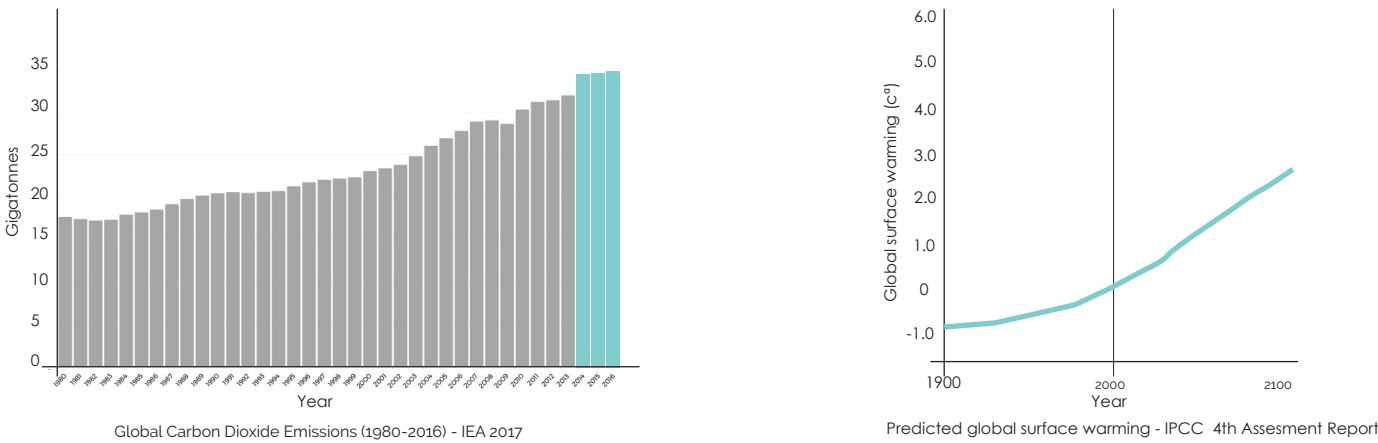


Figure 3. (Left) Global Carbon emissions graph, (Right) Global Warming increment graph

Due to this level of complexity involved in the building design industry, it is necessary to employ capable design exploration workflows to be able of making optimal decisions. Several problems are found in these previous aspects. Firstly, from an operational perspective, is during the first phases of the design that crucial decisions are taken in order to develop a selected idea or alternative. Despite the fact that there is a considerable number of software applications and plug-ins for energy and costs simulations and optimizations there is still a need for tools which are compatible and easy to understand by architects or clients that are not familiar with complex data managing and specialized software. On the other hand, energy and costs simulations typically require a considerable amount of computational work and time. This consideration has been worked out with BIM approaches mainly applied to regular buildings and simple shapes. However, with the modern complex shapes that are part of the new trends among the AEC industry and especially when talking about complex and “iconic” geometries such as sports venues, the inclusion of cost estimation and energy optimization is not yet fully developed. Proof of this is that at the moment there are not existing energy neutral stadiums at a worldwide level, besides, most of the sports venues end up with costs overrun both talking about construction costs and operational costs.

In fact, the process of simulation and optimization is incorporated individually at the later stage of the design when no more substantial changes can be done, excluding a significant number of design possibilities and alternatives away from the design process especially regarding massing and passive design strategies.

In developing countries, such as Mexico these previous considerations get worse. With the absence of strict energy regulations, normally the clients and constructors try to save the maximum amount of money by using the cheapest materials and energy systems or even by refusing to pay a proper project that considers the environment and the energy efficiency as a priority. In this sense, normally people without an environmental education and awareness, including architects, only think in solutions for a short period while in the long term an energy efficient building can save a significant amount of money while helping to improve the quality of life of the people and the environmental conditions.



Figure 4. (Left) Pollution in Mexico City, (Right) Resources shortage in La Paz Potosí Bolivia



2.1.2 CURRENT ARCHITECTURAL PRACTICE

“Architecture is the will of an epoch translated into space”  
-Ludwig Mies van der Rohe

Architecture and the building design practice has evolved with the time, answering to specific demands of diverse societies and epochs. Since the times when a building function was only meant to be a shelter space, to the building as an artistic monument passing through all the different artistic styles throughout the centuries. To finally arrive at an epoch in which environmental issues such as pollution, global warming and the shortage of natural resources imply that the architectural practice needs to deal and accomplish with several specific factors and building performances.



Figure 5. Physical model studies OMA

According Lin & Gerber (2014) nowadays buildings account for a major part of all the consumed energy, 48.7% in the United States and almost 40% of all energy consumption in the European Union. In this matter, Architects and mechanical engineers are probably the two professionals who take the most responsibility in the energy performance of a building, as defined by Shi & Zhichao (2016) who also states that “energy efficiency is a mandatory requirement and integral part of green and sustainable buildings”  
However, architectural discourse has over recent decades become increasingly diverse and shatter. Mainly due to the increasing number of necessities, energy requirements and economic factors.

Touloupaki & Thedodosiou (2017) defines that the currently used methods rely on simulation models to predict for example the thermal behavior of a future construction. However, because of their time consumption and specialized attributes, these are usually intended for the analysis of an already designed building or for the assessment of a short number of alternative options, instead of the synthesis of an optimal one.

With this each time more complex building stock in both overall form and building systems, traditional energy simulations and cost estimation techniques had become much more complicated to use, (Tucker, et al. 2011). Furthermore, developers and architects are rightly worried about the rising costs in the implementation of energy-efficient technologies and strategies into their designs and constructions. One of the main reasons for this, is that the AEC industry relies heavily on the belief that what worked on the last project will work for the next one. And it is by using unfounded assumptions and “rules of the thumb”, that most architects and engineers comply with the new energy codes by specifying the most expensive systems, wall types, windows, and control options. (Covetool,2017).  
Architects, as the majority of the designers, work with options and a versioning practice, as shown in Fig. [5]developing different alternatives mainly for exploring the shape of a project. Evaluating the implementation of design requirements relying on the judgment of the designer principally in a limited range of functionality and aesthetics. In the end, “design choices are mainly taken in a subjective unsustainable way”, as stated by Turrin, et al. (2011).  
The problem derives from one side in how to evaluate in a quantifiable and scientific way the performance of each one of the possible options to be able to make an optimal decision.

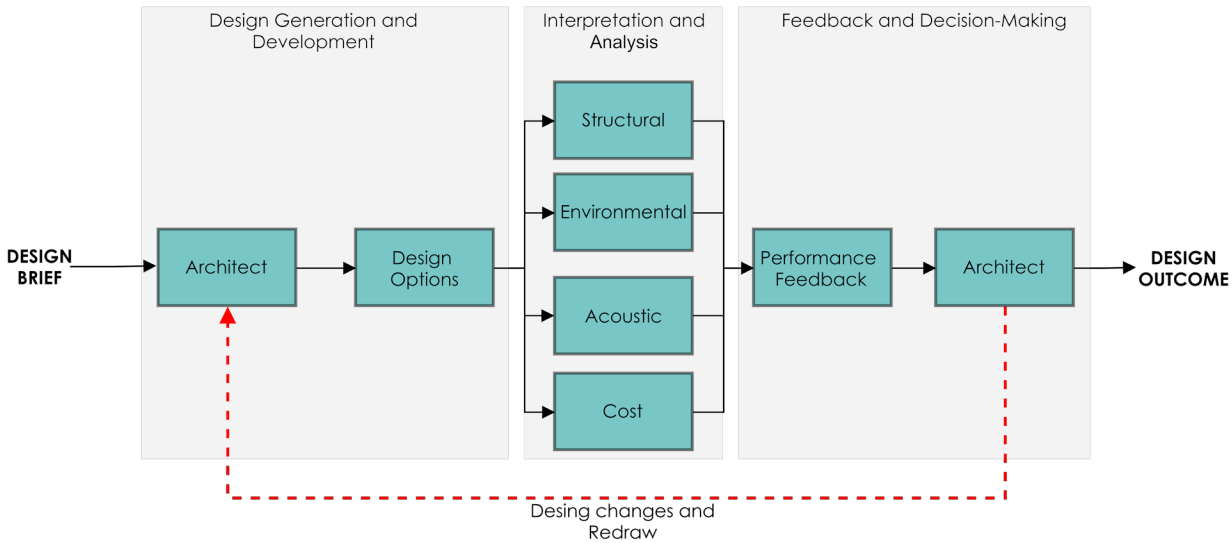


Figure 6. Typical architecture design workflow

And from the other, that as defined by Gerber & Lin (2014), design decisions are not usually made to satisfy a single objective, but are instead made to seek out a “ideal” balance between competing targets from the various expert fields. A clear actual example for this is, as mentioned before, the energy systems and passive design strategies that are now primary considerations in the building design, contrasting with costs and financial aspects, among other concerns.

In this scope, computer-aided simulations represent an excellent alternative to understand the behavior and performance of an intended design over specific engineering disciplines. However, two main problems exist, the first one is, as defined by Shi & Zichao et al. (2016), that many architects tackle the energy efficient design with traditional, obsolete, and inefficient techniques and workflows as illustrated in Fig.[6] One of the main reasons for this is that according to Marble (2012) quoting Eitan Grinspun “Architects have been hijacked” because the tools they are working with are written by programmers with a very scientific, engineering-based mindset.

And secondly, most of the design offices in the building AEC industry that use simulation software apply these types of analyses as post-design evaluation tools instead of as design aids. In other words, “a simulation tool helps to evaluate the performance of design but does not facilitate the exploration of different design options”. Lee, et al. (2016)

According to Holzer (2010) these traditional linear workflows result in a non-efficient design process because any significant change applied to the design project, results in complicated tasks for architects and in particular for the consultants involved. “The typical design workflows is to design then throw to the analyst. Redesign. And then keep playing catch. It’s inefficient “ Bradner et al. (2014).

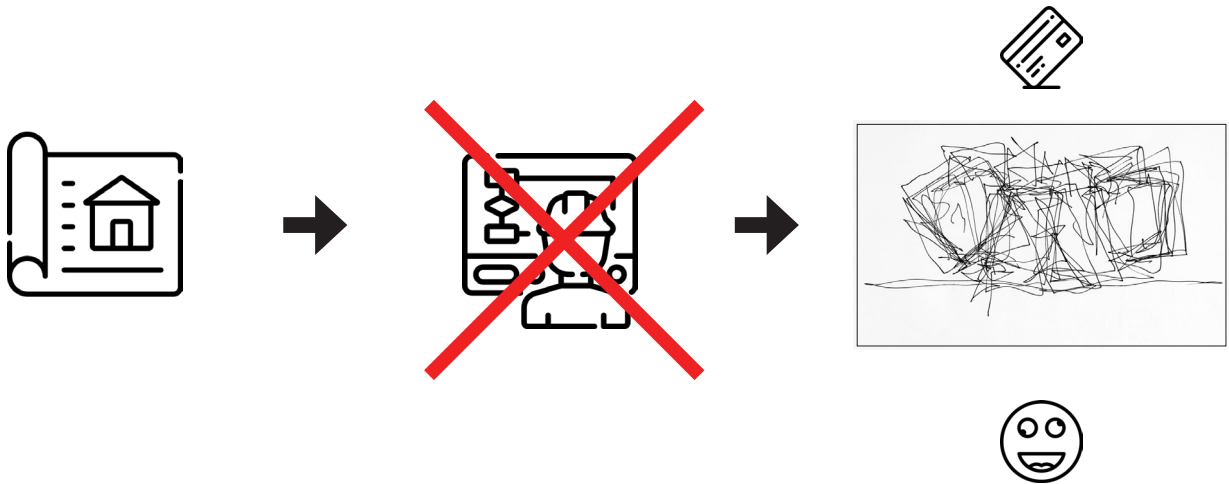


Figure 7. Uncertainty in the design process

Another important consideration, is that innovative techniques such as performance simulations and multi-objective optimization are used mainly for refurbishment projects. According to a literature study made by Shi & Tian, et al. (2016) among the real world buildings projects most of the cases are renovations, probably because of two reasons, the first one says Shi & Tian et al. (2016) is the actual significant need of renovation projects and the lowering of the carbon emissions. This is considerably true mainly in countries that have passed the urbanization stage and have an elevated percentage of existing buildings such as Mexico city for instance. In the second place, for renovation projects the shape and form of the building are normally fixed, leaving the opportunity to focus on intervening the building envelope and mechanical systems “making the energy efficient design optimization easier”. Being the most common typologies, residential buildings, office buildings, and educational buildings.

In this scope, deepening in the use of performance simulations and multi-objective and multi-disciplinary design optimization during the initial phase of the projects represents an idea that has not been fully explored and has an immense potential mainly when talking about new buildings with high energy demand.

The following section will consist of a series of interviews with various architectural offices with different backgrounds and approaches towards sustainability and computational design. Trying to assess the reasons they work as they do and what would imply to change their current design methods.

2.1.3 INTERVIEWS

ARCHITECT - STUDENT

JULIOENDARA  
MASTER STUDENT  
TUDELFT MASTER IN ARCHITECTURE

**1. What is your background?**

I am Julio Endara, a 30 year old student at TU Delft-Faculty of Architecture and the Built Environment. I am doing my master on the Architecture track and I am specializing on Dwelling. Before I came here I worked for 5 years at my home country (Ecuador)

**2. How do you use the computer for design purposes?**

I use the computer for most of the process. After I pass the sketching stage I rely on the computer for all the design work. I first create 2D basic drawings and after that I simultaneously combine the 2D and 3D explorations. When I finish my design drawings I make a post production process for my final product.

**3. What kind of software do you normally use for your projects?**

<input checked="" type="checkbox"/> OFFICE(Basic tools)	<input checked="" type="checkbox"/> 3D Modelling	<input type="checkbox"/> Structural (Specify)_____
<input checked="" type="checkbox"/> CAD	<input checked="" type="checkbox"/> 3D Visualization /VR	<input type="checkbox"/> Climate/Energy(Specify)_____
<input type="checkbox"/> BIM	<input type="checkbox"/> 3D Parametric Modelling	<input type="checkbox"/> Cost estimation(Specify)_____
		<input type="checkbox"/> Optimization(Specify)_____

**4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations, please clarify?**

<input checked="" type="checkbox"/> Conceptual (Early)	<input checked="" type="checkbox"/> Development	<input type="checkbox"/> Construction documentation(Late)
--	---	---

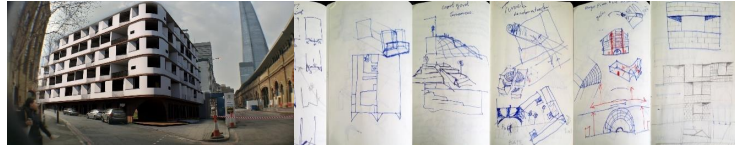
**5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies.?**

I feel that Performance-based architecture is an essential need for the future of the profession. Its really useful to rely on numerical data to organize your work an to have a solid backup for the decisions you take on the design and construction process. I also feel that Multidisciplinary design is efficient and should be more applied, specially on big offices.

**6. How do you see the future of the architect in a technological era?**

I wish that in the future I could learn more about these new techniques. At the moment I don't use them, but it is definitely imperative for the Architect to get involved with the technological solutions as the world in every sense is getting more involved with it. My plans are to learn about numerical assessment methods and programs and implement that knowledge into the development of myself as an architect.





### 1. What is your background?

Architecture diploma in Mexico City. I worked in different fields such as visual effects studio and furniture design office and different architectural offices like SUPERUSE Studios and Systems in Rotterdam

Main working experience in 3D modelling for Architecture and furniture design.

### 2. How do you use the computer for design purposes?

- To create 3D models of the study cases for analysis (Sketchup/Archicad/3dsMax)
- Creating diagrams to explain the analysis observations and proposals (Adobe Illustrator/Photoshop)
- Creating presentations and documents formats to share the process (Adobe InDesign)

### 3. What kind of software do you normally use for your projects?

- ☐ OFFICE (Basic tools)    ☒ 3D Modelling    ☐ Structural (Specify) \_\_\_\_\_
- ☒ CAD    ☐ 3D Visualization /VR    ☐ Climate/Energy (Specify) \_\_\_\_\_
- ☒ BIM    ☒ 3D Parametric Modelling    ☐ Cost estimation (Specify) \_\_\_\_\_
- ☐ Optimization (Specify) \_\_\_\_\_

### 4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations, please clarify?

- ☐ Conceptual (Early)    ☒ Development    ☐ Construction documentation (Late)

Normally when the idea of the project is clear and definitive we think in which ways we can reduce the costs of the building for the construction.

### 5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies?

It's a fascinating way of design but typically will be a task for the engineers to design that way. In a more pragmatic and solution-based method of design and I think that has to do more with engineering rather than architecture.

### 6. How do you see the future of the architect in a technological era?

Is hard to tell but I think with the technological tools that we have, and the ones to come will be more efficient solutions to solve complex problems. I still believe that the digital era is hardly going to compete with the human sensibility for design.



### 1. What is your background?

I am an architect with studies in Mexico City and in Milan Italy. I am also a painter and an overall artist. I have experience in a vast scale of projects from residential to cultural and commercial venues.

### 2. How do you use the computer for design purposes?

Honestly, I consider myself more as an old school – craft architect, however I am conscious about the importance of the technology not only in our lives but in our professions as well. When talking about the workflow in the office, the computer is used principally as a tool. Specially to communicate ideas, concepts and later on specifications.

### 3. What kind of software do you normally use for your projects?

- ☒ OFFICE (Basic tools)    ☒ 3D Modelling    ☐ Structural (Specify) \_\_\_\_\_
- ☒ CAD    ☐ 3D Visualization /VR    ☐ Climate/Energy (Specify) \_\_\_\_\_
- ☐ BIM    ☐ 3D Parametric Modelling    ☐ Cost estimation (Specify) \_\_\_\_\_
- ☐ Optimization (Specify) \_\_\_\_\_

### 4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations, please clarify?

- ☒ Conceptual (Early)    ☒ Development    ☒ Construction documentation (Late)

Sustainability aspects are considered from the beginning mainly with passive strategies such as the right orientation, location of the windows and the use of local materials and construction techniques. Later on, during the specification stage, together with the specialists, active systems are applied to the building, such as HVAC and Lighting systems

### 5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies?

Although the good performance of a building is essential, I consider more important the aspects that are "intangible" the ones that deal with the senses, such as the use of the light, the scale proportions and the experiences that an architectural piece can provide. In this sense I think we have two sheds, architects like Norman Foster or Zaha Hadid that use computational tools to support their designs. And from another we have for instance Peter Zumthor and Glenn Murcutt that have an architecture based more in the sensorial experience and the sensibility of the place.

### 6. How do you see the future of the architect in a technological era?

I use to think that from the Greeks and the Romans there was nothing to invent anymore, it was all a mere reinterpretation. However, from the last years with all this new parametric design and generative ideas in combination with the use of new materials and technologies we are starting to produce new shapes and new types of buildings. I also believe that the wise use of the technology can drive us to propose more intelligent and environmental friendly buildings so we should be more aware of these innovations.



SEBASTIAN NAVARRO  
ARCHITECT AND CEO  
PABELLON DE ARQUITECTURA

PABELLON de arquitectura



1. What is your background?

In the office we make a lot of things, from the conceptual to the construction with all the details, including furniture.

2. How do you use the computer for design purposes?

At the beginning we use the computer for general investigation like context, orientation, and some simple things, then the process starts with putting our ideas in a model to look at the 3D model, and then we develop the idea in SketchUp or AutoCAD to advance with the function, it's a two-way process.

Finally we use the model to make renders and a presentation, and then if the idea is approved we make a cost estimation in Excel or Neodata.

3. What kind of software do you normally use for your projects?

- |  |  |   |
|--|--|---|
| <input checked="" type="checkbox"/> OFFICE (Basic tools) | <input checked="" type="checkbox"/> 3D Modelling | <input type="checkbox"/> Structural (Specify) _____                               |
| <input checked="" type="checkbox"/> CAD                  | <input type="checkbox"/> 3D Visualization /VR    | <input type="checkbox"/> Climate/Energy (Specify) _____                           |
| <input type="checkbox"/> BIM                             | <input type="checkbox"/> 3D Parametric Modelling | <input checked="" type="checkbox"/> Cost estimation (Specify) _____ NEODATA _____ |
|  |  | <input type="checkbox"/> Optimization (Specify) _____                             |

4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations, please clarify?

- ☒ Conceptual (Early)      ☐ Development      ☒ Construction documentation (Late)

5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies?

It's an interesting idea but very complex for us, we really don't know first how to use it, and second the paper of the architect behind this technology, although we know it's the future. We think that it's a very useful tool for architects if they really know how to use it.

6. How do you see the future of the architect in a technological era?

The future of architecture will be different in several things, first in the materials, that doesn't mean that stone or wood won't be used any more, but will appear new elements to work, like already existing different types of concrete with nanotechnology or different chemical combinations.

In the process of design we know we aren't actualized in the BIM technology and we don't use Revit or other programs, but the environment with other firms is complicating.

And finally with the process of design we think that architects will have a lot of tools, **more easily** to work and make changes, where orientation, structure, cost will be integrated, but like a tool, not to replace the architect's role, maybe in little constructions will be more easy to supplant, but not totally.

THOMAS POND  
ARCHITECT  
POWERHOUSE COMPANY

POWERHOUSE COMPANY  
ARCHITECTURE / INTERIOR / DESIGN



1. What is your background?

I am an architect at Powerhouse Company, mostly involved with large-scale commercial & residential projects. I received my masters in architecture from TU Delft.

2. How do you use the computer for design purposes?

I use 3D modelling software such as Rhino for early design stages and competitions. Mass studies, quick facade tests, etc. In later design stages I use BIM software to make detailed design drawings and communicate 3D models with our advisers and collaborators. We don't use parametric software very much, only in few specific projects where the shape of the building asks for it.

3. What kind of software do you normally use for your projects?

- |  |  |  |
|--|--|--|
| <input checked="" type="checkbox"/> OFFICE (Basic tools) | <input checked="" type="checkbox"/> 3D Modelling         | <input type="checkbox"/> Structural (Specify) _____      |
| <input checked="" type="checkbox"/> CAD                  | <input checked="" type="checkbox"/> 3D Visualization /VR | <input type="checkbox"/> Climate/Energy (Specify) _____  |
| <input checked="" type="checkbox"/> BIM                  | <input type="checkbox"/> 3D Parametric Modelling         | <input type="checkbox"/> Cost estimation (Specify) _____ |
|  |  | <input type="checkbox"/> Optimization (Specify) _____    |

4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations? please clarify.

- ☒ Conceptual (Early)      ☐ Development      ☐ Construction documentation (Late)

We take these factors into account from the first sketches we do for projects. Both because competitions often have requirements regarding budget or energy efficiency, and also because it speeds up the process greatly if we have already incorporated for example efficient climate design in sketch design when we start detailed the buildings further. Many of our competitions are done in collaboration with a developer, who has to deliver a money offer next to the design. Therefore, building costs are often already a factor in the sketch design phase.

5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies?

I think BIM and new software developments have given us many new opportunities of optimizing and streamlining a design and design process. Especially our collaboration with for example structural engineers and climate advisers is a lot more smooth. However, it is also quite easy to fall into a too detailed/computer based design, or lose some of the design freedom.

6. How do you see the future of the architect in a technological era?

You can already see that some parts of our assignments can be quite easily automated (for example division of square meters or analyzing complicated programme of requirements). Furthermore, the conversion to BIM for building processes has given a great new way of collaborating in 3D with clients and advisers. In presentation aspects I can see that VR is proving to be a great new asset in communicating our design to clients, but also for ourselves to look at rooms/spatial layouts.

While buildings are becoming increasingly more complex, technology is a very necessary tool to aid designers and help make sense of complex processes and different disciplines working together in a building (e.g. Structural, climate, technical design).



### 1. What is your background?

Bsc. and Msc. Arch. from TU Berlin and TU Delft. I started with experimental computational design during my studies with The Why Factory at TU Delft.

### 2. How do you use the computer for design purposes?

Digital tools are part of the design process starting from the earliest design stages. From testing ideas in Photoshop and 3d modeling software to quantitative design evaluation (Grasshopper/Dynamo/Excel) and prototyping (CAM).

### 3. What kind of software do you normally use for your projects?

☒ OFFICE (Basic tools)    ☒ 3D Modelling    ☐ Structural (Specify) \_\_\_\_\_  
☒ CAD    ☒ 3D Visualization /VR    ☒ Climate/Energy: Grasshopper Ladybug/Honeybee  
☒ BIM    ☒ 3D Parametric Modelling    ☒ Cost estimation: Grasshopper/Dynamo + Excel  
☒ Optimization: Genetic Algorithms (GH),  
experimenting with Neural Network architectures

Although the software listed above covers most requirements for regular architectural and urban designs, some projects offer the opportunity to add tools from other industries or develop custom plug-ins and scripts (within BIM / 3D Modelling in particular).

The use of game engines (Unity, Unreal), video editing (After Effects, Premiere) and simulation software (Houdini) can help to develop a compelling narrative and develop a project from different angles.

### 4. How do you deal with sustainability, energy and costs aspects, at which stage of the design process, do you implement these considerations? please clarify.

☒ Conceptual (Early)    ☒ Development    ☒ Construction documentation (Late)

Clearly all of those aspects need to be considered from early sketch design onwards. However their relevance in each of the design phases depends on so many project characteristics (client, context, competition/commission/...) that it is difficult to answer the question in such a broad way.

### 5. What do you think about Performance -based architecture (Quantitative /numerical assessment of a design) and Multidisciplinary design optimization design strategies?

In general I am skeptical of the notion of optimization and much more interested in the use of algorithms to create design variations, effectively opening design space up rather than narrowing it down.

In addition the term optimization suggests that certain solutions are superior to other design variations although even multi-objective optimization algorithms can only optimize for a limited range of (usually) geometric constraints. The subjective definition of those constraints (it is still a designer, who defines the inputs of optimization algorithms) gets obscured behind the seeming neutrality of a computed, optimum state.

Having said that we quantify every design project in various ways and have used Genetic Algorithms to improve façade/cantilever configurations and occasionally even building envelopes.

### 6. How do you see the future of the architect in a technological era?

1. As digital tools become more sophisticated there is a risk of design bias and generalized assumptions being embedded in the way design software is constructed.

Thus the link between designing architectural program and software program becomes more urgent.

Though this idea is not new (e.g. MVRDV developed visions for tools since the early 2000's, see RegionMaker, VillageMaker, Spacefighter) recent events such as the acquisition of "The Living" through Autodesk and Sidewalk Labs operations in Toronto clearly hint towards stronger links between both programs.

2. While I strongly believe in the importance of intuitive design tools like sketching, model making and 3d modeling, the future of the architect's profession will most likely become much more data-driven.

This requires more sophisticated tools and understanding of big data, data mining, data cleaning, visualization and interpretation.

3. (A bit more speculative)

Rapidly increasing sophisticated tools will enable more and more people to design. This is neither a threat nor an opportunity in itself, but will need new protocols of evaluation and warranting agency to the architect by other means than academic degrees (simulated project briefs? A.I. design evaluation?).

## 2.2 COMPUTATIONAL DESIGN IN ARCHITECTURE

### 2.2.1 ANTECEDENTS - PERFORMANCE IN ARCHITECTURE

According to Kolarevic (2003), performative architecture can be defined as the one in which building performance, broadly understood, becomes a guiding design principle.

The notion of Performance in architecture emerged during the 1960's with the complex systems-engineering projects of the United States National Aeronautics and Space Administrations (NASA), Hensel( 2013) as shown in Fig.[8]

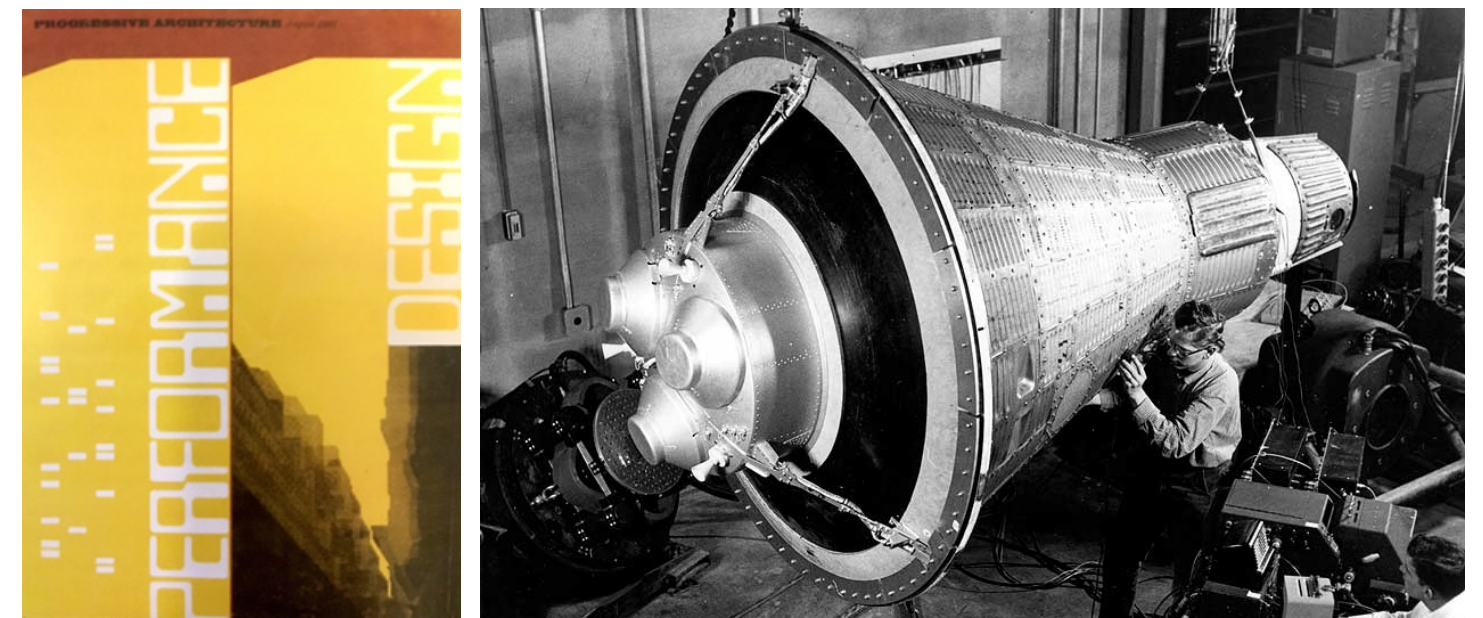


Figure 8. (Left) 1970 Performance design exhibition poster. (Right) NASA Performance inspection

Several years later, a number of architects and engineers began practicing design processes driven by performance. They initially focused on the minimal possible form deriving from structural performance and material properties, taking the building's relationship with its context as a minor role. Agkathidis,(2015).

Examples of this are the Vladimir Shukhov's steel tower, built for an industrial exhibition in Russia in 1896. This structure achieved a perfect combination of mathematical shape, optimized structure and material performance. Moreover, the Munich Olympic Stadium Roof designed by Frei Otto during the Olympics of 1972 aiming for minimum surface and therefore minimum weight. It worth mention that all these projects were made without computational techniques which were not developed until the 1960's to produce digital 2D blueprints being the first original (CAD) system the so called "Sketchpad" developed by Ivan Sutherland in 1963.(Aish in Peters & Peters 2013)



According to Culley & Pascoe (2009) Computerized design began to be used by the British construction industry during the complex engineering design of the Sydney Opera House in 1960. However, according to Parrish in Peters & Peters 2013, In 1975 most architects had not even heard of parametric design and actually 30 years later only few appreciated its potential and would have considered it the future of their profession.

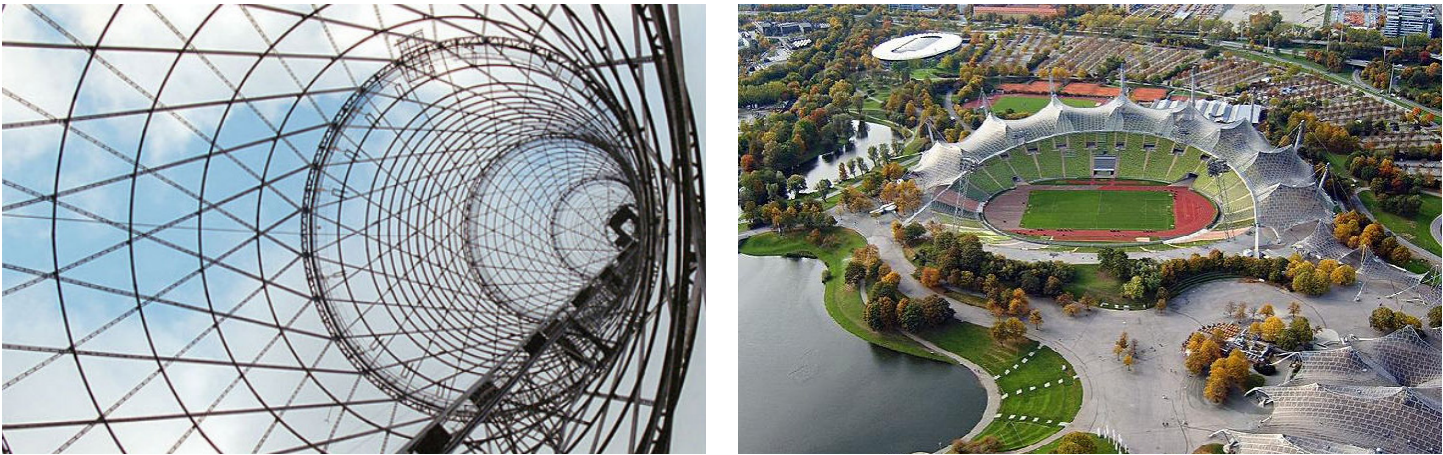


Figure 9. (Left) Shukhov Tower, Moscow, (Right) Munich Olympic stadium, Frei Otto

It was not until the 80’s that According to Aish in Peters & Peters 2013 that Objected- Oriented software emerged by Alan Borning. This software is based on the principle of linking real-world objects and computational objects. By mimicking some of the attributes and behaviour of real-world objects and reapplying them to the design of further real-world objects. The use of OO software is considered as the basis for computational design applications. In this way soon from drawing simple 2D geometries, there was a considerable step towards 3D modeling tools which lateron will become the so-called “Building Information Modeling” (BIM) which is a process of generating and managing data of a building’s design in a 3D model.

### 2.2.2 GENERATIVE DESIGN FROM - “FORM MAKING “TO “FORM FINDING”

“ The designer is no longer directly modeling the building: instead he develops a graph or script whose execution generates the model. This enables a completely different kind of architecture to be created” (Aisha in Peters & Peters 2013) Lately, computational tools have presented imaginative frame discovering methods, altering structural plans and generation. These techniques are frequently depicted by terms, for example, “generative outline” “parametric design” or “algorithmic design”, to give some examples. These offer new outline ways to engineers by breaking with unsurprising connections amongst shape and portrayal for computationally created complexities, in this manner empowering the improvement of new topologies. As indicated by Kolarevic (2003), they move the accentuation from “frame making” to “form finding” Laiserin (2008) also defines “form making” as a process of inspiration and refinement where form precedes the analysis of the functional program and design constraints having an emerging shape based on the previous analysis. According to Riccobono (2013) Generative Design is a design method in which the output is produced by a series of rules or by sets of algorithms.

As stated by Agkthidis (2015), as calculations and scripting turn out to be more available to modelers and creators, and advanced manufacture more moderate and parametric. Reproduction programming, improvement and generative calculations began to drive the new patterns in the design of the buildings. In this way, new different design workflows were established as shown in Fig. [10] It was with the development of Grasshopper, a visual programming language and environment developed by Daniel Rutten in 2007 that a new way for designing emerged among the modern architecture firms.

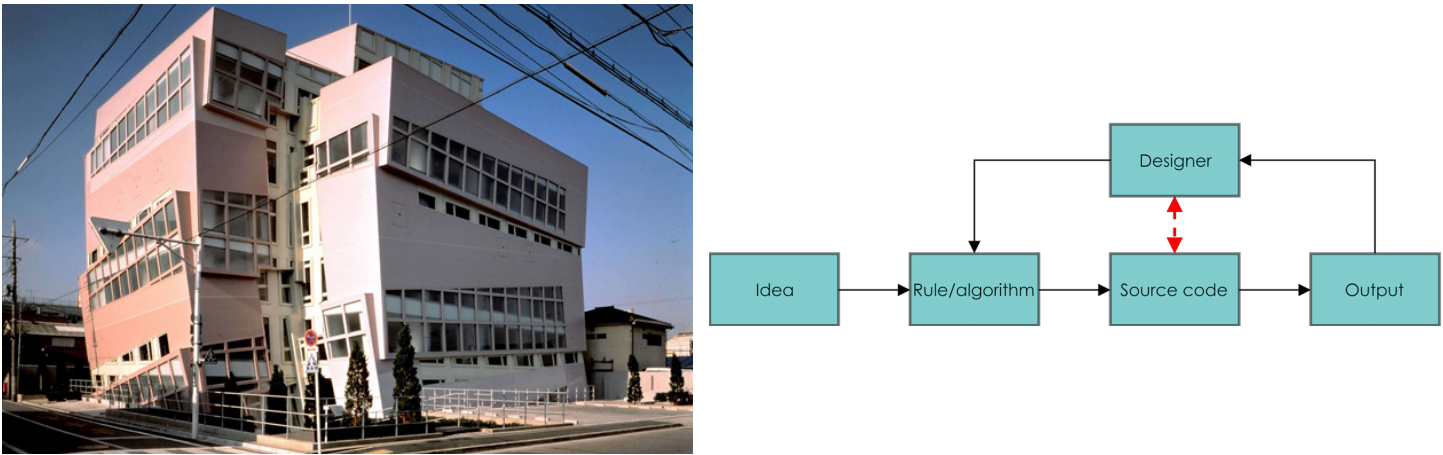


Figure 10. (Left) Nunotani Corporation P. Eisenman, (Right) Generative design process by Lazzeroni et al.

According to Riccobono (2013), the criterion of formal generation is inspired by nature (evolution of the species, synthesis of the best features, ability to adapt to the environment). The properties attributed to natural systems are, therefore, applied and also reported to digital systems:

- Ability to generate complexity
- The complex and interconnected relationship between organism and environment
- The ability to generate new structures, behaviors, results or reports

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

### 2.2.3 PERFORMANCE BASED GENERATIVE DESIGN

Initially, these processes were developed mainly with aesthetic and non-standard stylish intentions, as shown in Fig. [10] being this technological approach severely criticized by architects claiming that generative design methods disconnect architectural intentions from its context and its users, leading to a reduction in spatial quality and a buildings integration within the urban environment. Moreover, “arguing that this type of design also disconnects physical modeling and drafting techniques risking the loss of material qualities, effects and properties”. Agkthidis (2015).



According to Oxman (2008) Instead of being the outcome of already made decisions, performance-based generative design, takes the performance of a building as a driving factor for its design where the form and geometry generation, envelope materials, and HVAC systems are considered. The performance-based design is a new trend that has taken advantage of the new instruments developed in the last decade, putting them to serve the project. The general idea of this approach is that the project can arise from the consideration and the optimization of one or more parameters selected according to the final desired purpose. The parameters to be optimized may be from several disciplines, for instance from a technical point of view structural, to environmental or economic approaches. But also social aspects such as people flows, mobility and transport systems can be quantified. According to Riccobono (2013) Performance models are divided into two types:

- Performance-based formation: performative software intervene after a predefined shape.
- Performance-based generation: The project is born in a generative way from imposed parametric constraints and variations.

According to Shi & Zhichao, et al. (2016) It was not until the beginning of the 1990s and gaining significant momentum since 2000 that this innovative approach of generative design in architecture changed its focus towards sustainable design and energy efficiency approach with the emergence of the combination of energy simulation with optimization techniques. Being only the big firms especially the Hi-tech architects such as Foster & Partners, Renzo Piano and Nicholas Grimshaw the pioneers in involving the concept of performance in their projects. A couple of examples for this are the New London City Hall by Norman Foster & Partners. Were the solar radiation was taken as an environmental parameter reference to provide natural light and transparency into the building representing in energy savings. Another case is the Swiss Re Tower also by Norman Foster in which the concept was to minimize the wind loads on the building to reduce the size and the mass of the structure, rebounding in cost savings. Fig. [11].

A significant expansion for the performance-driven architectural design was the implementation of international green building standards such as LEED in the US or BREEAM in the UK , as stated by Shi & Yang (2013). These green building measures set up numerous quantifiable execution prerequisites that guide and control the design. Consequently, performance-driven design is encouraged and more rational thinking and scientific analysis are brought into the field of architectural design.



Figure 11. (Left) Gherkin tower. (Right) London City Hall, Norman Foster & Partners

As more and more green buildings had emerged, architects, (the leading professional of a building project team) are desperately in need to study and learn the new design philosophy and new supporting techniques to ensure the design quality while keeping the essence of the design. As shown in a study made by Shi & Zhichao, et al. (2016) where an incremental trend in the number of a core literature review about energy efficient design optimization can be clearly observed.

“Imagine automatically generating different design outcomes based on performance requirements while having instantaneous feedback from different perspectives, including the aesthetic, to produce the most optimized design solution available. In simple terms, the concept of generative design is like finding directions in Google Maps – it allows you to choose from different “routes” to your final (design) destination without compromising on where your planned arrival is, or how to get there.” (Fenestra Pro, 2016)

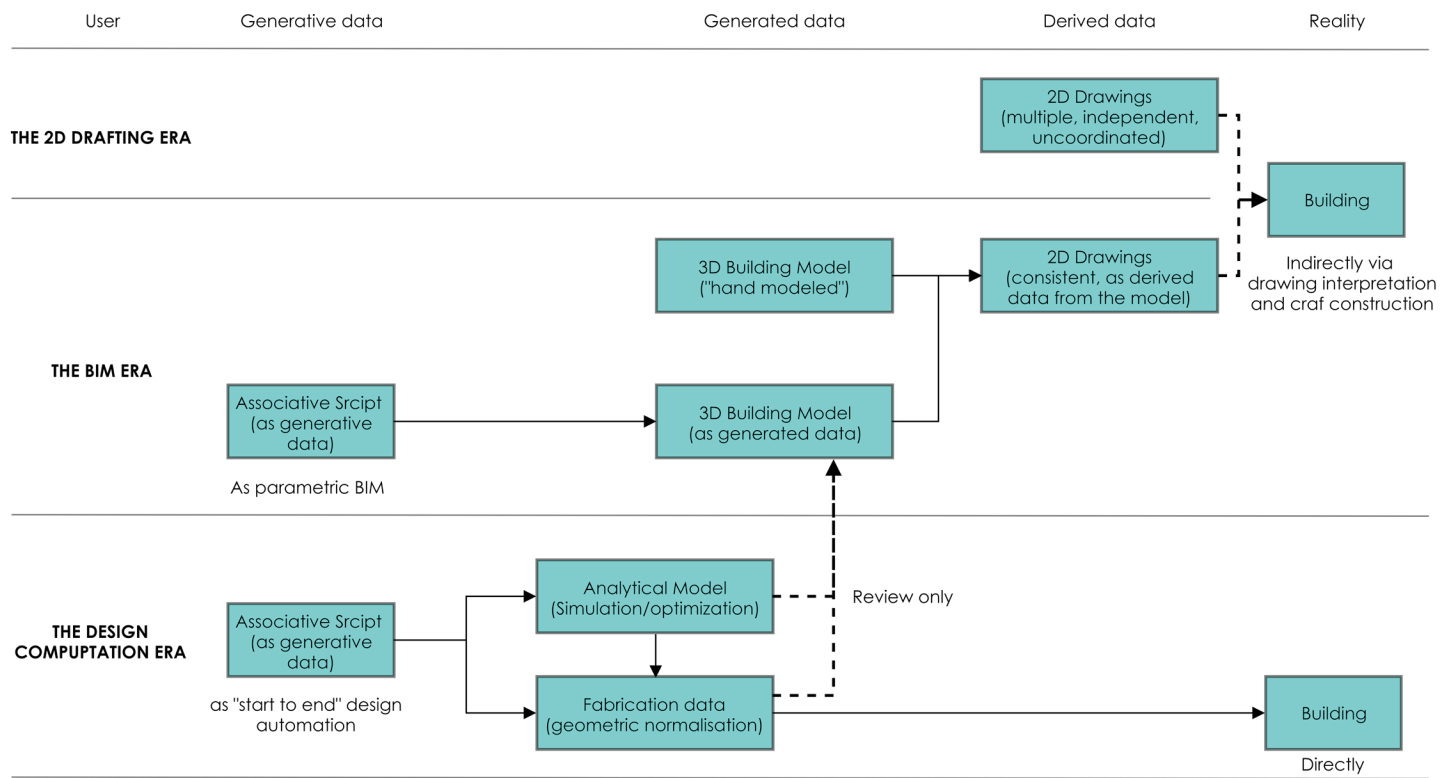
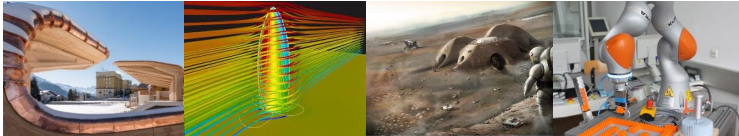


Figure 12. The three eras of CAD, Aish in Peters & Peters 2013

1

QUESTIONNAIRE (PERFORMANCE-BASED DESIGN SPECIALIST)  
JAN DIERCKX  
FOSTER AND PARTNERS - SPECIAL MODELLING GROUP

Foster + Partners



**1. What is your background?**

I did a double degree in civil engineering and architecture. I liked this because it combines the aesthetics of design with the efficiency of engineering. After that I did a year out in RWTH in Germany where I became very accustomed with compute aided tools and digital manufacturing. This lead to my postgraduate at the Bartlett in London which was very design oriented but backed by computational analysis.

**2. How do you use Computational design in your office?**

We use computational design for almost everything. The design philosophy of Foster + Partners is one of integrated design, where things don't only look beautiful but also are performative. We use a lot of solar, shading, view analysis to optimize facades which usually directly influence parametrically designed options.

**3. Which are the most common aspects or disciplines that you normally apply performance simulations and optimization strategies?**

The two most common aspects are structural efficiency and energy efficiency. We look at making the best possible use out of the materials we choose and vary geometry and buildup to make this possible

**4. What kind of software do you use for energy and cost simulation and which one for optimization purposes?**

We use a multitude of tools to achieve an optimal design and are always looking to expand and improve our knowledge. Our team uses a lot of Grasshopper and Dynamo which we usually augment with our own custom tools.

**5. Why do you think Performance-based generative design (Quantitative /numerical assessment of a design) and design optimization procedures are still a not that common practice in most of the architectural firms?**

Architecture and especially construction is a slow-moving field, not adjusting as quick as product and industrial design. Although many of the new generation of architects has some knowledge of performance-based design, it will take some time for this to become mainstream. For now it is limited to very large projects in big practices, where there is scope to hire specialist, and budget to look into optimization.

**6. How do you see the future of the architect from a technological point of view?**


I feel an architect will increasingly be enabled to make informed decisions to design in a more performative way. Creativity will always come from the human mind, but computers can assist a great deal in helping us to see things from a different perspective and open up solutions we might not have thought of ourselves

PERFORMANCE BASED DESIGN SPECIALIST

2

KARIMDADA  
SENIOR MECHANICAL ENGINEER  
ARUP

ARUP



**1. What is your background?**

8 years of Building Physics, Design and Optimisation. I have worked on varied projects from football stadiums, hospitals, residential-office towers and laboratories

**2. How do you use Computational design in your office?**

Computational tools are used by everyone in the office. Varying expertise provide an excellent mix of skills. We set minimal skills for all engineers and push the bar every year.

**3. Which are the most common aspects or disciplines that you normally apply performance simulations and optimization strategies?**

a. Weather analysis

b. Environmental Analysis

c. Renewable Energy

d. Orientation-Shading-Façade Analysis

e. Visual-Thermal Comfort analysis

f. Energy modelling

g. Cost and life cycle analysis

h. System selection, operation and control simulations

i. Multi-Physics (disciplinary) challenges

**4. What kind of software do you use for energy and cost simulation and which ones for optimization purposes?**

a. IES-Excel: Energy, Cost

b. Rhino, Grasshopper, Excel and add ins (E+, OpenStudio, OpenFoam, Radiance, Therm, Own code): Optimisation

**5. At which stage of the design process, do you normally implement these strategies?**

Different computational tools play a major role at each design stage. At the early stages of the design I tend to use graphical programming, parametric, optimization and visualization tools to assess different options and converge towards a set of possible solutions that fit the design criteria and use graphical tools to output the results. During the later phases of the design, I move towards more detailed computational tools which have advanced system, control and physics engines.

**6. Could you give an example of a project in which simulation and optimization techniques were applied, how did they affect the design process and the final result?**

Luxembourg Dubai Expo: We had an incredible opportunity to influence the design of the pavilion. Through a weather and environmental analysis, we changed the orientation and shape of the building to optimize self shading, thermal comfort, natural ventilation. We then focused on the specification of the external envelope to minimise the internal surface temperature (heat transfer). The envelope had to be simple, efficient and thin so we used a combination of CFD and solid-thermal transfer and conduction simulations to eliminate thermal bridges, optimize an air gap based on velocity and turbulence and minimise insulation. We finally focused on the internal thermal and visual comfort. We modified some of the geometry and worked closely with the mechanical engineers to devise our design and distribute limited conditioning at the right locations.

**7. How do you see the future of the designers from a technological point of view?**

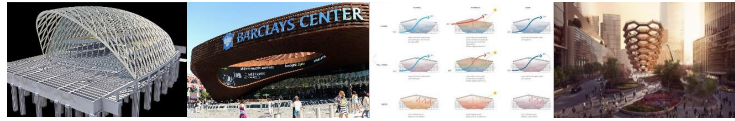
There is no doubt that in order for the industry to catch up on the performance and technological front, we need to leverage technology for our benefit. It is of essence that designers start engaging with graphical coding as a strict minimum in order to:

a. As projects become more complicated they require customized engineering solutions.

b. Solve multi-physics (discipline) optimization problems

c. Automate our processes and use computational tools as a virtual workforce

PERFORMANCE BASED DESIGN SPECIALIST



#### 1. What is your background?

BS-Civil Engineering (concentration on structures)

MS-Building Engineering (TU Delft, interest in special structures and façade structures)

Professional-Glass (stairs, structural fins, facades). Cable and membranes (shading structures, bicycle wheel stadia) Grid shells(steel, domes and shells, small and large). EFTE cushion facades and structures. Façade engineering (mullions, system selection, glass sizing). Forensic (Glass breakages). Field inspections (anchorage, splices, etc.) Pneumatic/inflatable structures.

#### 2. How do you use Computational design in your office?

The office is quite large and uses computational design to varying degrees between groups and projects. Generally: Parametric design is used to aid the architect in formal and structural exploration as well as a way to produce drawings, this involves many computer programs (grasshopper, dynamo, Catia, excel and others) At the early stages of design computational design is used as a way to open up formal/geometric options to architect, at mid stages these tools are used to evaluate design options and narrow the design space, at later stages these tools are used to adjust and improve the design, towards the end of a project these tools are used to finalize engineering design and eventually produce drawings.

#### 3. Which are the most common aspects or disciplines that you normally apply performance simulations and optimization?

These concepts are used in very many different degrees based on topic. For thermal and energy aspects the results of simulations are used more generally to assess massing and façade properties. These optimizations can lead to glass frit pattern variation to reduce solar heat gain or glare. Commonly optimization is done for lateral design of tall buildings, for example setting drift targets can lead to the design of a core to the level of wall thickness, outrigger location, and guidance on core penetration percentages. For grid shells, tensile structures, and other structurally driven forms simulation/optimization could be called "form finding" which we apply at very early stages of a project to set certain criteria (such as rise/span ratio and boundary conditions) which must be architecturally suitable but however we also perform this for inflatable structures and bending structures(see images above)

#### 4. What kind of software do you use for structural design, energy and costs simulations and which one for optimization procedures?

MS Excel works very well for everything, tying into it with python and other scripts allows us to impose optimization and other techniques into most other software. Within my group in the office we typically use grasshopper to narrow down formal aspects with architects early on. Then we move on to SOFiSTiK for more complicated form finding/force finding, and preliminary sizing, global buckling checks and eigen mode analysis are also checked here for confirmation with the wind consultant, to understand the structure from a stiffness standpoint, from there we move on to SAP, EASY, Strand7 and other software to validate our previous analysis, check against code, and to proceed with detail design.

#### 5. What do you think about Performance-based generative design (based on numerical assessment) and design optimization procedures as strategies for designing sustainable buildings?

I'm not sure what you mean here maybe this is something like form finding or a way to determine regional cladding characteristics, etc. I think it is a good idea, but I feel it is often not well implemented. I think about sustainability in the building industry in terms of operation energy and embodied energy. The first has to do more with the massing, orientation and fenestration. The second has to do with structural design and material selection. The third part is people, psychology and lifespan (but I typically don't address that part) Unless these tools (or simpler versions of these tools) are available to architects at an early stage their results will not be deeply integrated into the design of a building. Certain grasshopper tools are excellent examples of how this can go correctly when applied to grid shell atria. Kangaroo for structural form (embed energy) and honeybee for solar orientation, shading and massing (operational energy).

When these tools are used later in the design process I generally consider performance-based generative design/optimization, as a way to design beautiful buildings/structures with less material. While very important and effective, I see operational energy optimization as more of a bandage than a solution. Often it seems architects determine a massing and cladding material then hand it over to sustainability consultant who's job is to change the properties slightly instead of addressing the issues head on.

The question of sustainability must be addressed at a higher societal, philosophical level. It would be a mistake to call a building truly sustainable if it lacks sustainability from the onset. Approachable generative/optimization tools should be available to architects before engineers get involved, engineers can offer guidance, and carry those "baked-in" sustainable strategies further after concept.

#### 6. How do you see the future of the building design industry from a technological point of view?

Building design is too technological, too much of a gap exists between engineers and architects, each having a fairly separate skill set and set of objectives. Technology such as increased architectural possibilities (forms and cladding) to a point where engineers as consultants are expected to apply technologies to solve problems left open by formal/cladding decisions. For example, low-e coatings have enabled larger transparent facades by reducing solar heat gain coefficients of the glazing.

Hopefully technological tools for generative designs to meet performance goals, will bring engineers and architects closer, perhaps because the tools begin to change how authorship/ownership of the design is seen and felt.

Thornton Tomasetti is working on some tools that will help to bridge this gap between architects and engineers to create better buildings, such as this tool called asterisk: <https://asterik.thorntontomasetti.com/>



# 2.3 SPORTS VENUES DESIGN

“Sports facilities reflect the times in which they are built . They are a measure of civilization because they indicate refinement in interests and tastes. It is said that today’s stadiums are the equivalent of Europe’s medieval cathedrals in terms of the wonderment they inspire.”

-Culley & Pascoe, 2015

The same author, emphasizes that it is a good moment to invest in this kind of buildings since they represent a good business opportunity combining imagination and technology among other considerations.

For the research purpose of this thesis, the Sports hall typology will be considered and analyzed. Culley & Pascoe (2015) defines a Sports hall as an enclosure capable of containing a designated indoor sport or permutation of indoor sports. The size of it must be determined by balancing the aspiration (the intended sports and future users).

Due to the fact that sports is considered a fast changing business these facilities have to consider flexibility in use and possible future extendibility. According to the same author, the principal indoor court sports are basketball and volleyball; nevertheless it can also be possible to held tennis, badminton and soccer events. The typical “standard” size of a sports hall is approximately 33m long by 18 wide x 7.6m high.

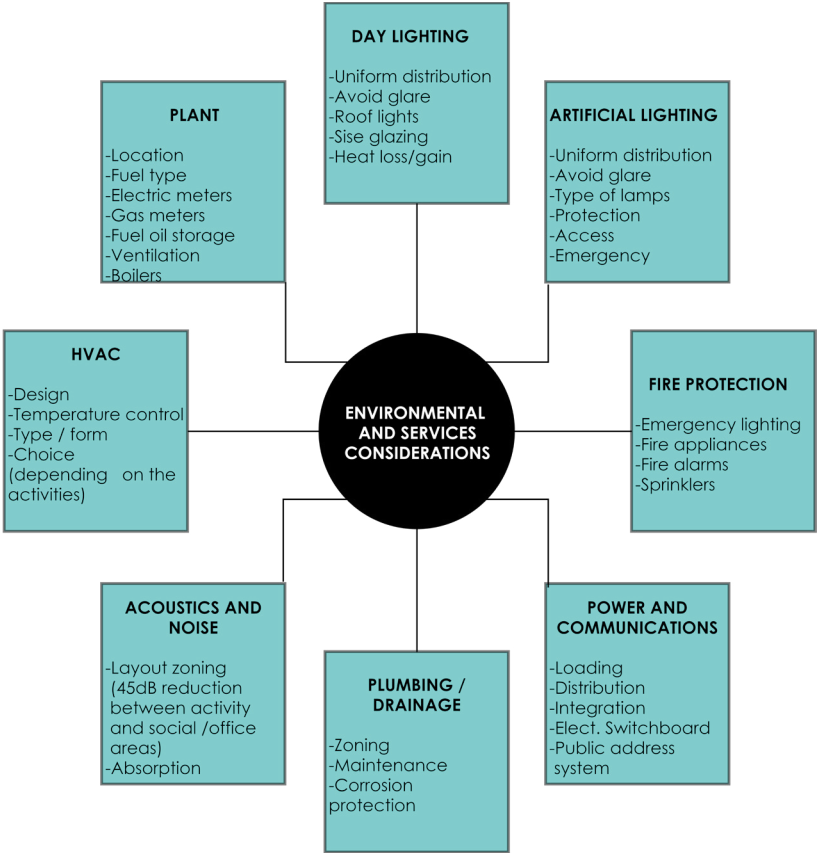


Figure 13. Environmental and services aspects in Sports buildings

## 2.3.1 PERFORMANCE REQUIREMENTS

### 2.3.1.1 Illumination requirements

Daylighting of sports facilities is a natural and energy efficient matter. In this scope, it is important to consider the counter effects of a high amount of light can produce for visual comfort problems such as glare when the building is not well designed.

According to Culley & Pascoe (2009) Recommendations for the illumination of sports activities include 50 lux(skating, dance), 10lux (swimming) 107 lux (bowling, volleyball) 322 lux(badminton, gymnasium, exhibitions, handball, squash) 538 lux (basketball, ice hockey) 2152 lux (professional boxing). Today the required illumination levels for sports activities are normally within the range of 300-1600 lux.

There are several ways to illuminate a Sports hall naturally, as defined by Dixon & Crane (1991) it can be by using side windows on the facade or more commonly with skylights on the roof as showed in the image below Fig.[14]:

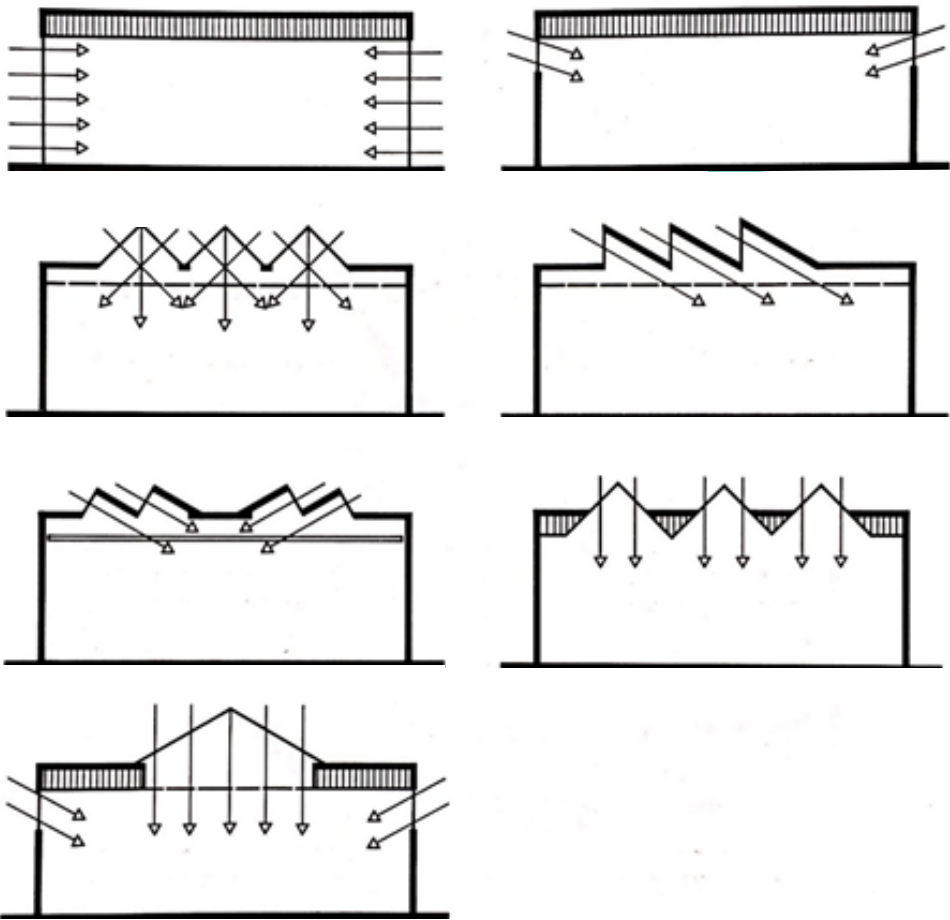


Figure 14. Natural daylight strategies for Sports halls.

Perrin (1980) states that levels of illumination vary for individual requirements. For general use, 250 lux with a glare index of 19 is a common design objective. Different conditions are: training 200 lux, competition 400 lux, ends of the pool and over diving boards 500 lux, underwater lighting 600 lux, colour television 1200 lux. Lightning design for sports facilities is a matter of enhancing good visibility. Natural light has to be considered from the initial design stages. Sizing and locating correctly the position of the windows to avoid, unwanted solar gains, glare and reflections.). During these stages, devices such as screening (blinds, planting), protection to low level glazing. External shading devices such as vertical overhangs, vertical sun-screen, rotating panels, roller shades, awnings, sliding or light shelves, trees, shrubs and vines can be also considered.

### 2.3.1.2 Temperature range & Ventilation rates

According to Perrin (1980) To satisfy the environmental conditions of games, Sports halls are generally developed as windowless boxes of large span construction, requiring two to three air changes per hour, heating to 12°C and average lighting intensities of between 300-350 lux, in order to satisfy most playing conditions. Culley & Pascoe (2015) defines that thermal comfort depends on the temperature of the air surrounding the human body, the temperature of adjacent surfaces, the relative humidity of the air and the movement by the wind. In this complex matter, users need to be considered by the design.

When having more than one activity in a single space (which is the case for multi-purpose buildings), an additional complication is added to the intention of providing an appropriate thermal comfort.

According to Culley & Pascoe (2015), the American College of Sports Medicine (ACSM) recommends a temperature of 15.5-20°C for court sports with a relative humidity of 60% or less and 8-12 air changes per hour for enclosed courts. Furthermore, according to the Sports England Organization (2012), The CIBSE (Chartered Institution of Building Services Engineers) guide defines a value of 8-12 l/s of fresh air per person with air velocities generally kept below 0.1 m/s with the sports activity volume. Regarding air-tightness, the leakage allowance is 10 m<sup>3</sup>/h/m<sup>2</sup> at 50 Pa. and an optimal indoor relative humidity (RH) 40-60%.

### 2.3.1.3 Heating, ventilating and air-conditioning systems

Yastrebov (2015) describes that for the good being of Sports halls users, an optimal indoor climate will give an opportunity to develop sports effectively. In this sense, ventilation can solve problems such as the lack of fresh air, and excess of exhaust air. The optimal conditions of the indoor climate in a sports hall or a gymnasium are basically the following:

- Good removal of exhaust air
- Necessary amount of supply air
- Absence of draught

There are many ventilation strategy options available from totally natural, entirely mechanical and a mixture of the two previous ones. For the aim of this thesis, only mechanical ventilation will be considered due to the fact that a maximum ventilation speed is allowed and therefore

the ambient must be controlled.

In a mechanical ventilation system, the air is moved in and out of the building with several fans. It is normally divided into central and local mechanical ventilation. Central provides all the volume with fresh air. It can be supply, exhausts or combined (supply-exhaust) while local is used for a specific zone inside the building. The mechanical ventilation in a sports hall can be proposed with airflow going from the top and downwards or the other way around, applying a displacement ventilation strategy as defined by Culley & Pascoe (2015). Who also states that the height and the shape of the roof of this type of buildings affect directly to the heat demand. Therefore, "the larger the span of the roof, the lower should be the pitch of it". The heating and cooling systems must be based on the characteristics of the building fabric, the building orientation, temperature variations, solar conditions and internal sources of heat gain and loss as defined in previous chapters.

Improved efficiency targets for ventilation includes heat recovery devices and the setting of a maximum specific fan power, for central systems providing heating and cooling with 2.5 W/litre/sec for new buildings.

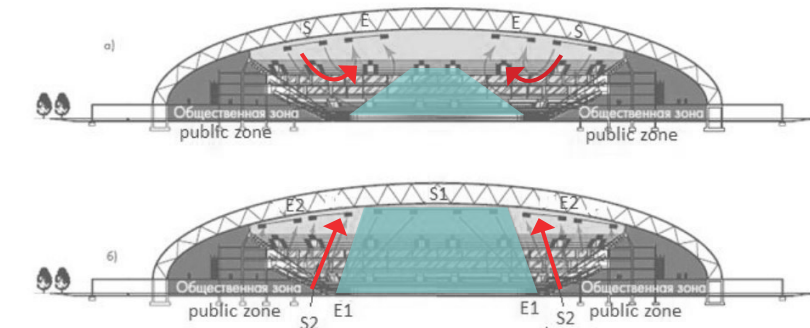


Figure 15. Air exchange strategies. (Up) "Up to top" (Down) "Down to top"

Culley & Pascoe (2015) defines as a good overall option to use the "displacement ventilation" strategy in this kind of buildings, it works by introducing conditioned air at low velocity through the floor, as it goes up the heat sources lift it up to be exhausted at the high level displacing the airborne pollutants benefiting people's health.

According to Yastrebov (2015) for small gyms and fitness halls, a duct air conditioning system is used, consisting of duct fans, a heater and a filter which is typically located on the ceiling or in a technical room. These systems also include an air handling unit that supplies and exhausts air ducts. For heating the most commonly used systems are:

- Infrared emitters (gas or electric)
- Radiant panels
- Convectors
- Water radiators
- Underfloor heating (water and electric)
- Electric and water
- Warm air heating (Air handling unit system)



2.3.1.4 Structure & materials

“Sport is a great driver of materials technology “Culley & Pascoe (2015). Due to the activities that are held inside this typology of buildings, long-span roofs column-free spaces are required. Representing a challenge from an engineering point of view, however, there are many alternatives of structural systems each one of them will, of course, have different performances not only structurally speaking but energy and environmentally speaking aswell.

There are several structural systems to consider when designing a Sports hall. Configurations include, space frames, rigid frames, beams and trusses, folded plates, shells arches, vaults and domes, cable structures and other types of lightweight structures as it can be seen in the figure below:

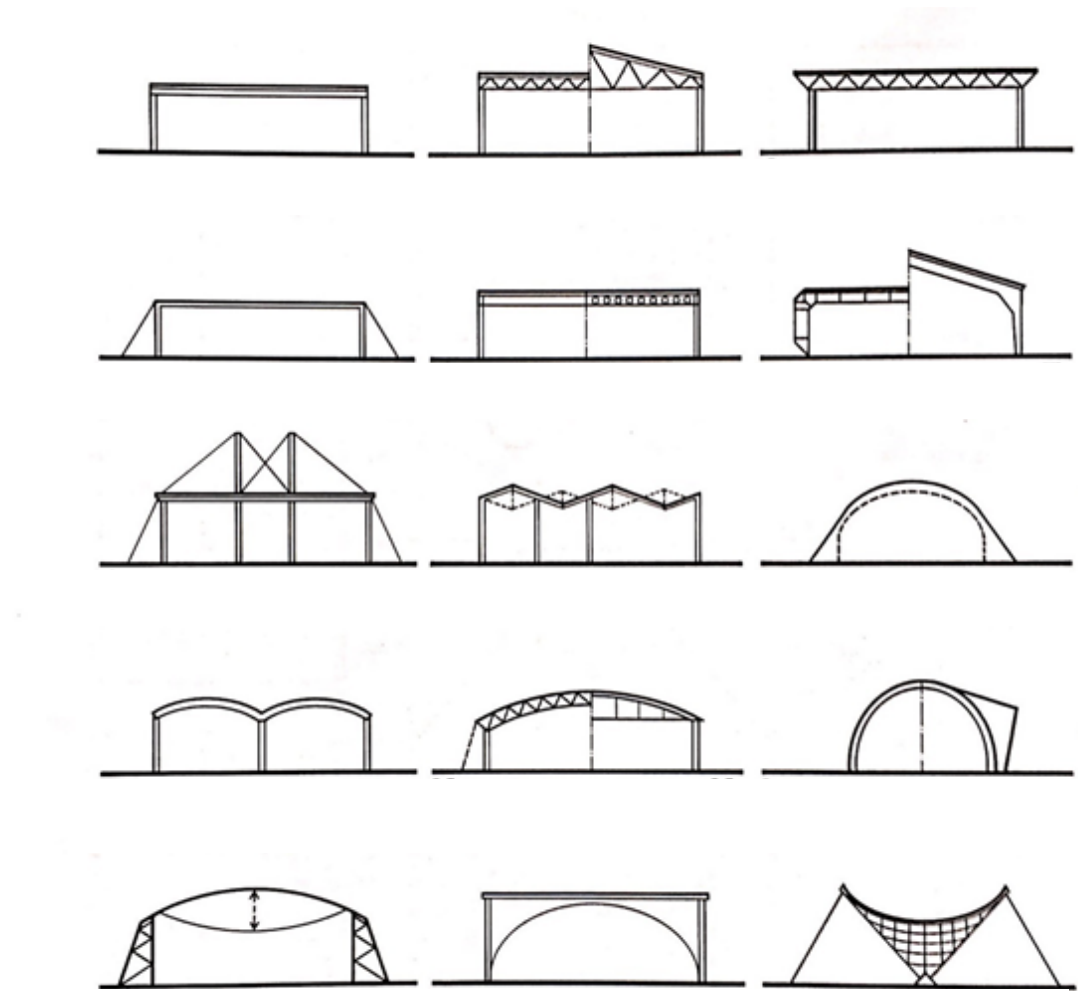


Figure 16. Structural systems types for Sports halls.

According to Culley & Pascoe (2015), these facilities are typically designed using flat, pitched or curved forms. Nevertheless, while arches and domes are appropriate for stadiums and arenas, a rectangular shape is likely to be more efficient for accommodating activities of a rectangular and square plan playing area because of its regular height and flexibility. In this scope, Sports buildings have demonstrated the potential of space frame construction better than any other building type. While these can be made out of several materials,

structural steel has been more commonly used for over the past 40 years especially applying the steel structural hollow section, because these tubular sections are more easily joined at any angle and their higher performance in compression produces lighter structures. For the facade and division elements the most common materials are the following

- Bricks
- Concrete
- Timber
- Membranes
- Glass
- Iron and steel
- Stainless steels
- Aluminium
- Titanium
- Lead
- Copper
- Zinc

2.3.1.5 Finances

In order for a Sports hall to be a successful venue, the action of choosing the right size of the building is a crucial matter. According to Sports England Organization (2012), there are seven main steps to consider when taking this decision, listed as follows:

1. Supply and demand issues
2. Strategies considerations
3. Type of activity/Level of play category
4. How much use
5. Developing the project brief
6. The business case
7. The decision

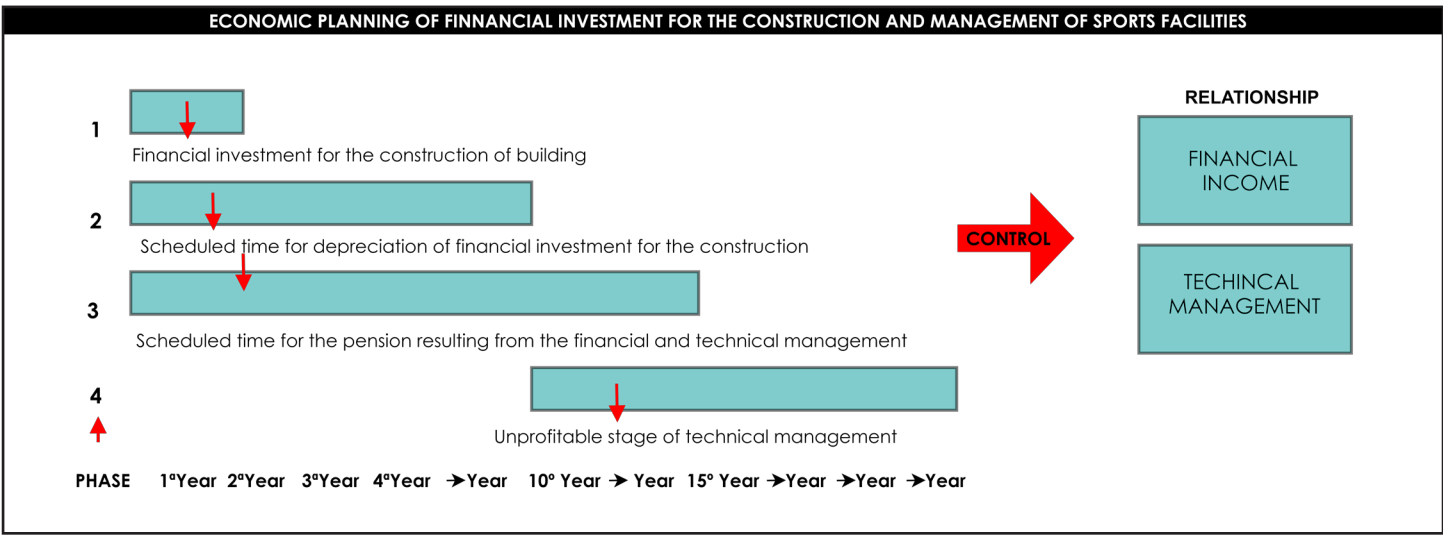


Figure 17. Economic planning of investment in a Sportshall, FIBA (2009)

According to Culley & Pascoe (2015), the main factors affecting the costs of a Sports hall are shape, size and standard of finishes. Consequently, large halls cost more because they have greater height and wider spans, and therefore use more construction materials. However, the selection of the materials is especially important. For instance, the consideration of high strength materials can be a good choice.

In this kind of buildings where there is the need for large spans and column-free spaces, the structural system and the materials represent an important part of the general cost. According to Culley & Pascoe (2015) around 20% of the total overall cost of a Sports building is spent in the structure so a special focus in the efficient design of it should be considered.

When talking of a Sports hall as a business case, there are several ways to make money out of a building of this typology, however, this, of course, goes in parallel with an in-depth and complex urban analysis and a market analysis that takes into account the context and the possible future users. (Which will not be considered for the aim of this thesis). With this in mind, Perrin (1980) States that there are several ways to get profits from a Sports venue:

- Membership fees (Personal, team)
- Rental of the space (By court, by hour, events)
- Ticket sales
- Sponsorships (Branding)

2.3.1.6 Energy

As described before, nowadays there is an each time more high demand for recreative spaces such as Sports venues. In this matter, Sports halls and Gymnasiums, are large spaces with a specific energy demand profile, which is defined by a high level of heat and electricity demand. According to Artuso & Santangeli (2008), the energy consumption is directly related to the activity, the schedules, and the site-specific climate conditions. Fig. [18] shows a benchmark study of this type of buildings and the energy use breakdown according to the CIBSE (Standard Energy Efficiency in buildings, 2004):

BUILDING TYPE	ENERGY CONSUMPTION BENCHMARKS FOR EXISTING BUILDINGS / (kW.hm-2)PER YEAR				BASIS OF BENCHMARK	
	Good practice		Typical practice			
	Fossil fuels	Electricity	Fossil fuels	Electricity		
Retail						
- High street agencies	150	55	230	75	Sales floor area	
- High street agencies all electric)	-	90	-	160	Sales floor area	
- Meat buthcers (all electric)	-	475	-	577	Sales floor area	
- Off licences (all electric)	-	475	-	562	Sales floor area	
- Supermarket (all electric)	-	1034	-	1155	Sales floor area	
Post offices	140	45	210	70	Sales floor area	
- Post offices (all electric)	-	80	-	140	Sales floor area	
- Shoe shops (all electric)	-	197	-	279	Sales floor area	
- Small food shops	80	400	100	500	Sales floor area	
- Small food shops (all electric)	-	440	-	550	Sales floor area	
- Supermarket	200	915	261	1026	Sales floor area	
Sports and recreation						
- Combined centre	264	96	598	152	Treated floor area	
- Dry sports centre (local)	158	64	343	105	Treated floor area	
- Fitness centre	201	127	449	194	Treated floor area	
- Ice rink	100	167	217	255	Treated floor area	
- Leisure pool centre	573	164	1321	258	Treated floor area	
- Sports ground changing facility	141	93	216	164	Treated floor area	
- Swimming pool (25m) centre	573	152	1336	237	Treated floor area	

Figure 18. Overall benchmark of energy consumption by typology. CIBSE (2004)

ZONE	LOCAL ELECTRICITY USE BY STATED SYSTEM* / kWh.m-2					LOCAL HEATING FUEL USED BY STATED SYSTEM* / kWh.m-2			
	Lighting	Ventilation	Pumps	Other	Total	Fabric	Ventilation	Pool/Other	Total
- Leisure pool hall	49.9	104.6	148.9	15	318.4	361.1	866.9	1097.6	2325.6
- Conventional pool hall	49.9	104.6	148.9	15	318.4	294.6	707.2	934.9	1936.7
- Sports hall	49.9	9.1	7	100	69	107.1	83.4	33.9	224.3
- Bowls hall	49.9	1.8	4.7	2.5	51.9	107.1	16.7	6.8	130.5
- Ice rink hall	49.9	49.3	8.5	200	307.7	0	83.4	75.4	158.8
- Fitness/health suites	61.3	49	9.7	10	130	170.6	294.8	16.9	482.3
- Internal courts	60	9.1	7	10	86.2	107.1	83.4	0	190.5
- Wet changing and showers	46	97.9	13.1	10	167.1	284.3	982.7	0	1267
- Dry changing and showers	46	84	9.7	10	149.6	170.6	505.4	0	676
- Spectator areas	46	36.7	9.7	10	102.4	170.6	184.3	0	354.8
- Common areas:									
- - Mechanical ventilation	61.3	36.7	9.7	10	10	170.6	1843.3	0	354.8
- - Natural ventilation	61.3	2.9	9.7	7	7	170.6	14.7	0	185.3
- Plant rooms	61.3	36.7	9.7	10	10	170.6	184.3	0	354.8
- Stores	61.3	2.9	9.7	7	7	170.6	14.7	0	185.3

Figure 19. Detailed energy breakdown by service systems. CIBSE (2004)

In this kind of buildings, as explained by John, et al. (2013), the envelope plays a significant role in the energy strategies and performance, as it could affect until the 80% of the overall climate and energy strategy as shown in Fig. [93]. Besides this, energy savings can also be achieved regarding active systems. According to Culley & Pascoe (2015), heat recovery (thermal wheels, plate heat exchangers and run- around coil systems) and automated control systems for cooling, heating and lighting are employed to optimize the energy use. More in detail, for instance, the use of time switches connected to internal and external temperature sensors which determine the appropriate time for the building systems so switch on. Another example is the use of a “humidistat” that measures the humidity of the air, activating the ventilation when the humidity exceeds a predetermined threshold.

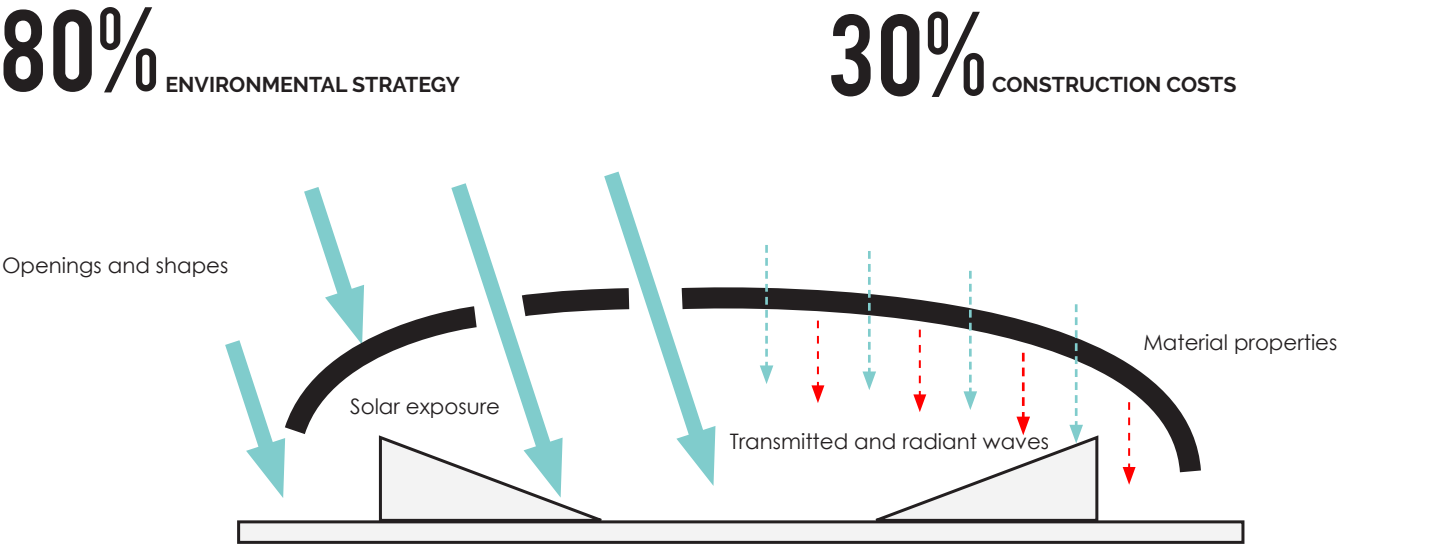


Figure 20. Effect of the shape, openings and material properties of the building fabric



2.3.2 COMPUTATIONAL DESIGN IN SPORTS VENUES - CASE STUDIES

2.3.2.1 Aviva Stadium

Location: Dublin Ireland  
Designer: POPULOUS  
Year: 2010

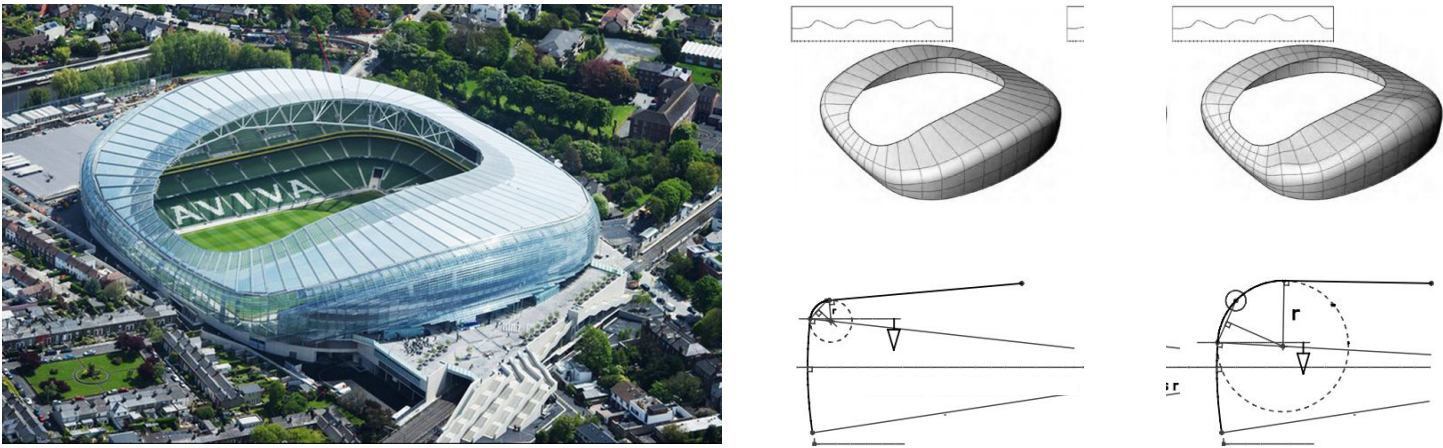


Figure 21. (Left) Aviva stadium overview. (Right) Parametric design strategies. Hudson & Hines (2011)

The Aviva Stadium is the first building to be designed from start to finish using specialized parametric modeling Software by developing an integrated multidisciplinary parametric model as shown in Fig. [22]  
This method is defined by Chandrasekaran (1990) as a sequence of “propose-critique-modify” where the design development takes place cyclically getting continuous feedback from the diverse specialists involved.  
In this sequential workflow, a single parametric model across a multidisciplinary team, sharing data with engineering analysis and manufacturing processes led to an efficient design.  
This model was developed in different scales of detail, a structural one which objective was to optimize the structural performance of the roof to withstand the extra forces induced by snow, wind and self-weight. According to Hudson & Hines (2011), the roof steelwork is clearly a major part of the overall stadium design and had huge implications in terms of aesthetic, sightliness and cost.

From another side, mechanical engineers could also interact to fulfill the ventilation requirements of the building while ensuring that the aesthetic concepts were not compromised.

In addition to this, the cladding designers and contractors also had their own parametric model to optimize the standardization of the elements, and balance three conflicting criteria; facade ventilation, ingress of windblown rain, and the aesthetic concept.  
Also, a script to generate the seating bowl and optimize the C-Value was developed.  
Finally, 3D detailed fabrication models were produced for documentation and fabrication documentation during all the construction process numbering panel sequencing and bar coding the pieces.

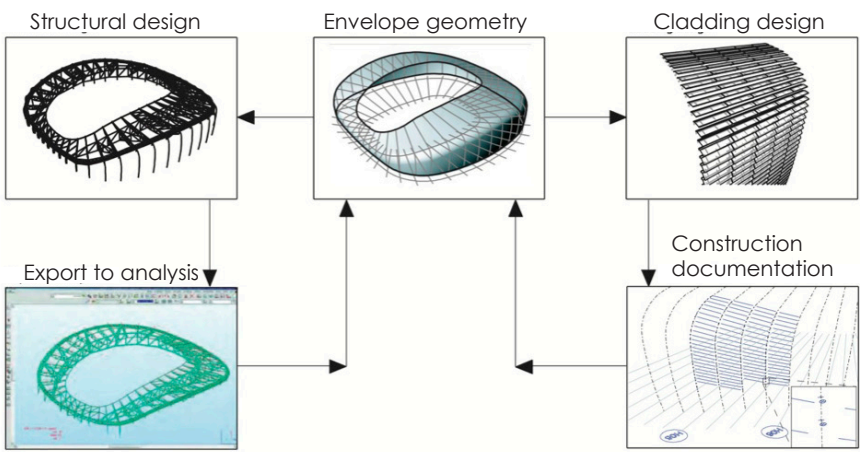


Figure 22. Collaborative design process. Hudson & Hines (2011)

This interactive model was developed , taking place at various levels of detail simultaneously . This form of visual optimization provided the architects with the ability and freedom to fine-tune geometry based on input from across the architectural team. Nevertheless, in a controlled way since the structural model could only be modified by the structural engineering team and so on.

According to Hudson & Hynes (2011), the parametric model was configured to enable aesthetic implications based on geometry to be analyzed together with quantitative performance data which was used to inform about the design changes as shown in Fig. [22]

The utilized software was Bentley Generative Components(GC) to generate the geometry, Microsoft Excel Spreadsheets containing the defining parameters. Static geometry references were made on CAD files and Robot Millennium was intended for structural analysis.

2.3.2.2 Hangzhou tennis arena

Location: Hangzhou  
Designer: NBBJ  
Year: 2010

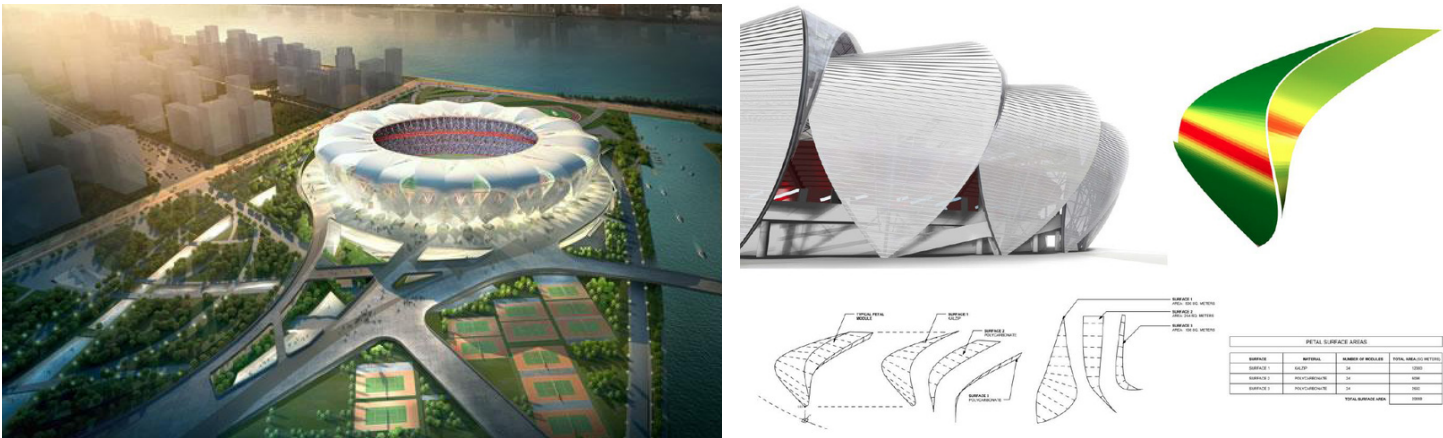


Figure 23. (Left) Overview of the Hangzhou arena. (Right) Parametric and fabrication design strategies. Miller (2011)



“A parametrically-driven process was implemented”  
-Miller, 2011

For this venue, a parametrically-driven process was performed with the aim of integrating several considerations of the design using parametric software such as Grasshopper and Kangaroo and integrating a BIM strategy for a later stage of the design process.

For the geometry, a set of modules composed by trusses was arrayed in a circular arc trying to provide shade and rain protection for the spectators. Using this parametric model to have diverse variations of the design within the conceptual constraints. In the evaluation of this alternatives, several factors were analyzed, for instance, shade, drainage, structural performance and technical systems.

According to Miller (2011). Because of the symmetric shape of the building, computational time and effort were successfully saved by only computing a single quadrant of the entire geometry and repeating it among the general shape.

For this project, the structural collaboration was a driver during the entire design process, to facilitate this, algorithms were developed in order to automate the generation of a structural wireframe which was compatible with the specific software for structural simulations by using a so-called “centerline model.” This structural model was also used to optimize the structural sections and the overall structural system saving around 67% of steel in comparison to similar Sports arenas, as described by Miller (2011).

In a later stage, a surface analysis was applied to the parametric model to explore and assess the performance of possible double curved shapes of the cladding system. These curvatures were rationalized to later on being panelized accordingly with an optimized fabrication approach.

Finally, the model was exported to Revit for the documentation and construction drawings merging the parametric model with a BIM approach in an automated manner.

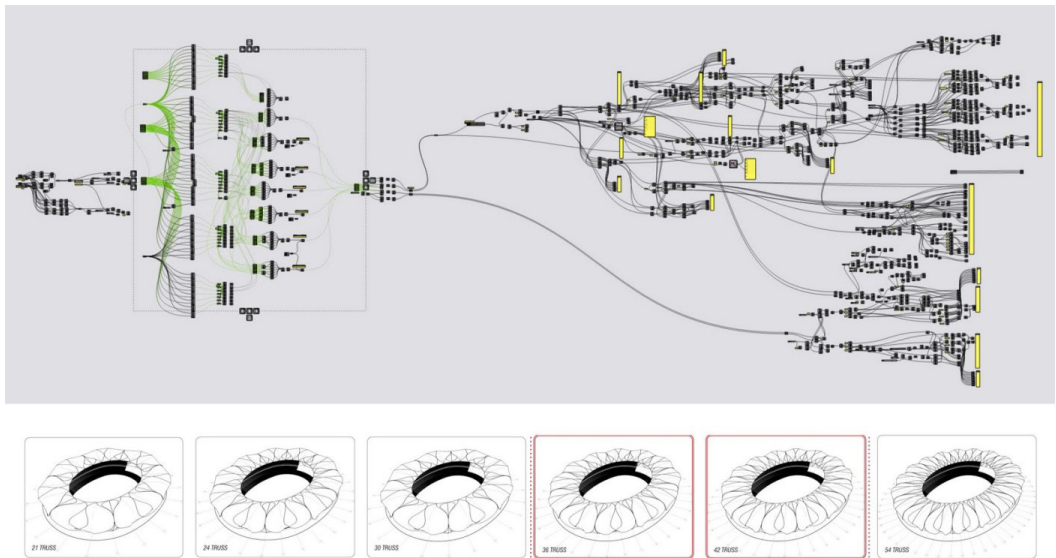


Figure 24. Grasshopper definition of the Hangzhou Tennis Stadium. Miller (2011)

2.3.2.3 National Arena Scotland

Location: Glasgow, UK  
Designer: Foster & Partners  
Year: 2008

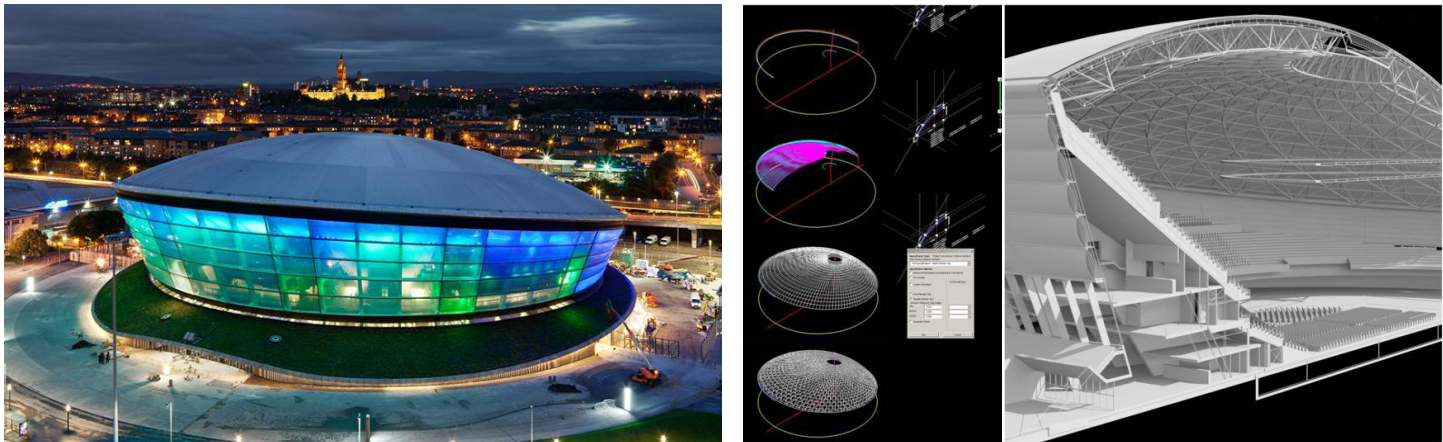


Figure 25. (Left) Overview of the National arena. (Right) Parametric modeling. Peters /Foster & Partners (2008)

This building provides a new indoor space for concerts and performances in the cultural and event complex of the Glasgow's Scottish Exhibition and Conference Center. Being a venue designed with the intention of having a highly flexible building and accommodate a wide range of events.

For the shape concept, the angle of the roof was intended to give a low profile facing towards the adjacent freeway. While at the other side of the building the facade has a 40-meter high front elevation. The roof of the auditorium is designed to be an impressive 120 m circular spaceframe with exposed diagonal structural elements.

Brady Peters, (Foster & partners, Special Modelling Group 2008) describes that computational design tools were mainly used for the design process and rationalization of the seating bowl, roof structure and the facade as shown in Fig. [25]. The seating bowl was designed using parametric software in Microstation. The facade was proposed as a series of cones/ rotational surfaces referenced to the seating bowl so that the facade could be easily constructed from simple planar elements. Several different designs for the roof structure and the space frame system were explored and analyzed using a custom written computer program developed by Peters that linked a parametric model of the surface of the roof and the facade.




Figure 26. Parametric structural roof. Peters /Foster & Partners (2008)



2.3.3 INTERVIEWS

1

IR. ROBERT FRANSEN  
SPORTS VENUES DESIGN SPECIALIST



**1. What is your background?**

As a soccerplayer myself I have always been fascinated about stadiums. During my graduation thesis at the TU Delft I worked on the design of a multipurpose, demountable, transportable and floating stadium. After my study I started working at Zwarts & Jansma Architects ZJA, who are specialized in sport facilities. They are responsible for the design of many stadiums, such as Feyenoord stadium De Kuip, the renovation of ice stadium Thialf, ADO Den Haag stadium and many more. Currently I'm working at Alphaplan, which did the construction site management for Sportcampus Zuiderpark, a multipurpose sportfacility in Den Haag.

**2. How do you use Computational design in your office?**

In my opinion, a sport facility should always be 'about sports'. Every aspect in designing a sport venue should be considered from a sports point of view. For players it should be the perfect stadium for optimal results. For spectators it should be the perfect stadium to attend and even for the stadium owners it should be the perfect stadium to host. In that case, the revamp of Thialf Ice Stadium is one of the best examples.

**3. Which are the most common aspects or disciplines that you normally apply performance simulations and optimization strategies?**

In my current office, computational design is not used at all. Most of project are in (nearly) building phase, when the design is already finished. During my graduation thesis I used it through the whole process of designing the stadium.

**4. What kind of software do you use for energy and cost simulation and which ones for optimization purposes?**

In all designing phases the use of computational design is very helpful for optimization of the design.

**5. At which stage of the design process, do you normally implement these strategies?**

During my graduation project, computational design was used in nearly every discipline.

- Grandstand design to provide optimal sight for all spectators
- Shape of stadium for optimizing transportation and floating abilities
- Structural analysis for an ideal structure without harming the design
- Façade design in combination with structural changes
- Solar studies to design an optimal roof

For all the above optimizations, Rhino and Grasshopper were used and in case of structural design a calculation program GSA was linked to Grasshopper.

**6. Could you give an example of a project in which simulation and optimization techniques were applied, how did they affect the design process and the final result?**

I think all recently build stadiums and sport venues are optimizing the grandstand design to provide a perfect view for all spectators. Parabolic shaped grandstands are ideal for sightlines but at the same time very expensive.

**7. How do you see the future of the designers from a technological point of view?**

In my opinion, sport venues should have the optimal design for a variety of sports and events. In that way, the building can be used as much as possible which makes it a lot more feasible. The combination of an optimal stadium and a wide variety of usage is very difficult because each event, type of sport or game demands different requirements. To fit all these requirements in one building, allowing it to adapt to different events will be the future of Stadium Design.

SPORTS VENUES DESIGN SPECIALIST

2.4 CONCLUSIONS

During this first part of the research, it could be seen that architecture is imperatively needing for integrative approaches that begin to combine specialist domains with the aim of joining efforts towards improving the buildings and its direct impact on the natural environment. Considering this, the capacity of including the energy efficiency in combination with costs factors as important drivers for a building's design represents a highly complicated task.

This is specially true when talking about complex buildings such as Sports venues , where different specific performance aspects such as high energy demands, elevated and special Daylight values, large span (column free) structures, in combination with particular cost and quality requirements represent a big challenge for the designers. This of course needs also to be compiled with the fact that this kind of buildings have an important focus on the shape / formal expressiveness of the project.

Architectural performance computer-aided design, has proved to be a promising approach towards energy-efficient building design. Nowadays, there is an important growing interest towards this topic and a vast amount of literature and on going research projects mainly inside the scientific field. However, most of the architects, who have the primary responsibility for a building's design, continue using traditional and inefficient methods particularly when talking about small - medium scale offices and when speaking about the still traditional architecture educational approaches as it could be observed from one side in the reviewed literature and from another in the diverse realized interviews.

The main reasons for these considerations are the following:

- The available commercial tools are not user-friendly enough for architects
- Complications with the Interoperability between different software
- Long amount of times required for complex systems
- High amount of computational work (specialized hardware)

The previous section defined the necessity of a user-friendly methodology in which designers can set up a design workflow, defining optimization design objectives, choosing among multi optimization strategies, use performance-based simulation programs, and being able to explore and compare the results in an understandable manner.

The next section will focus on Multi-disciplinary design optimization and optioneering techniques as emerging alternatives for performance-based energy efficient and cost-effective building design.

# **3.LITERATURE REVIEW**

## **MULTIDISCIPLINARY DESIGN OPTIMIZATION & DESIGN EXPLORATION TECHNIQUES**

# 3.1BACKGROUND

Optimization is basically the selection of the best element from several available alternatives with a predefined criteria. It can be applied to many different fields such as mathematics, computer science and general operations. According to Baños, et al. (2011) Optimization algorithms refer to the field of computational optimization, as the process of designing, implementing and testing computational procedures for solving optimization problems.

An optimization problem consists of minimizing or maximizing a real function by systematically choosing input values from a determined group of options and computing the value of the previously defined function. Normally, optimization includes finding “best available” values of some objective function given a defined set of objectives and constraints,

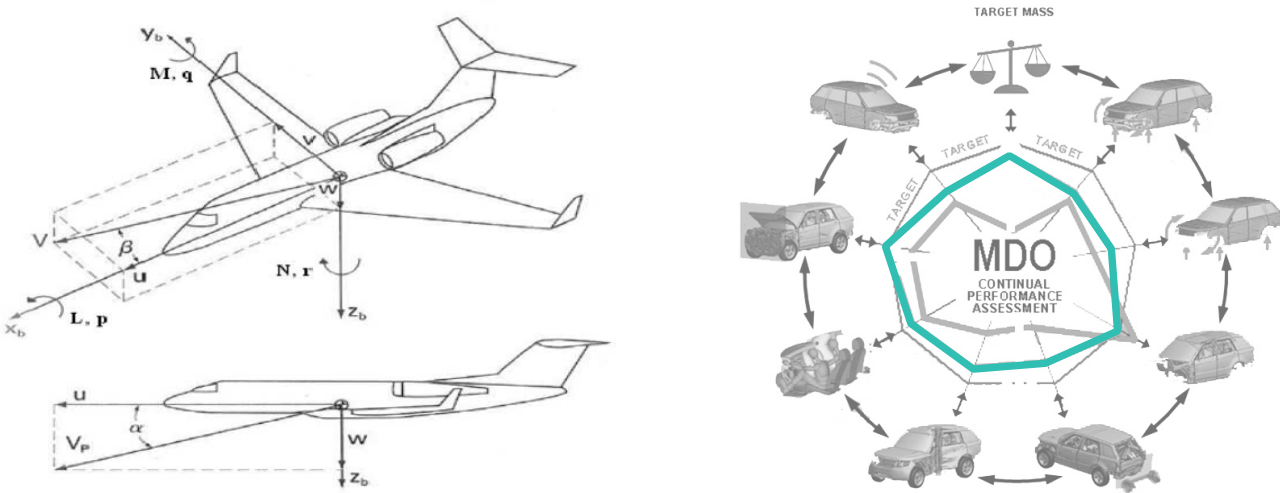


Figure 27. Optimization techniques in aerospace and automotive industries

Conforming to Ashour & Kolarevic (2015) these techniques are not new, they started to appear when the Genetic Algorithms were introduced in the 1970’s by John Holland as a method inspired by a biological mechanism using it for solution generation in Multi-Objective optimization. Since then, these algorithms have been used mainly for the aerospace and automotive fields  
It was not until the late 1980’s and early 1990 that according to Kim et al. (2012)they became to be introduced into the architecture practice by John Frazer in optimizing performance criteria.

“Software is moving beyond optimizing mechanical aspects to understanding something much more complex; the needs of the people”

-Erin Bradner ,Autodesk conference 2017

As shown by FIG [28] Optimization techniques can be applied to solve a vast and diverse types of problems. This methods have investigaded and applied in diverse scientific fields such as mathematics, computer science, engineering, operations research, among other disciplines. According to Ipam(UCLA)(2010) the optimization topics have experienced an important growth since the last 20 years, specially when talking about mathematical disciplines.

Optimization strategies and techniques, change according to the circumstances in addition to the scale and the nature of the problem itself. For the aim of this thesis and after reviewing several research papers and scientific articles, the simulation based optimization process will be reviewed in detail to later on apply it to solve the real problem of designing an energy efficient and cost effective Sports hall.

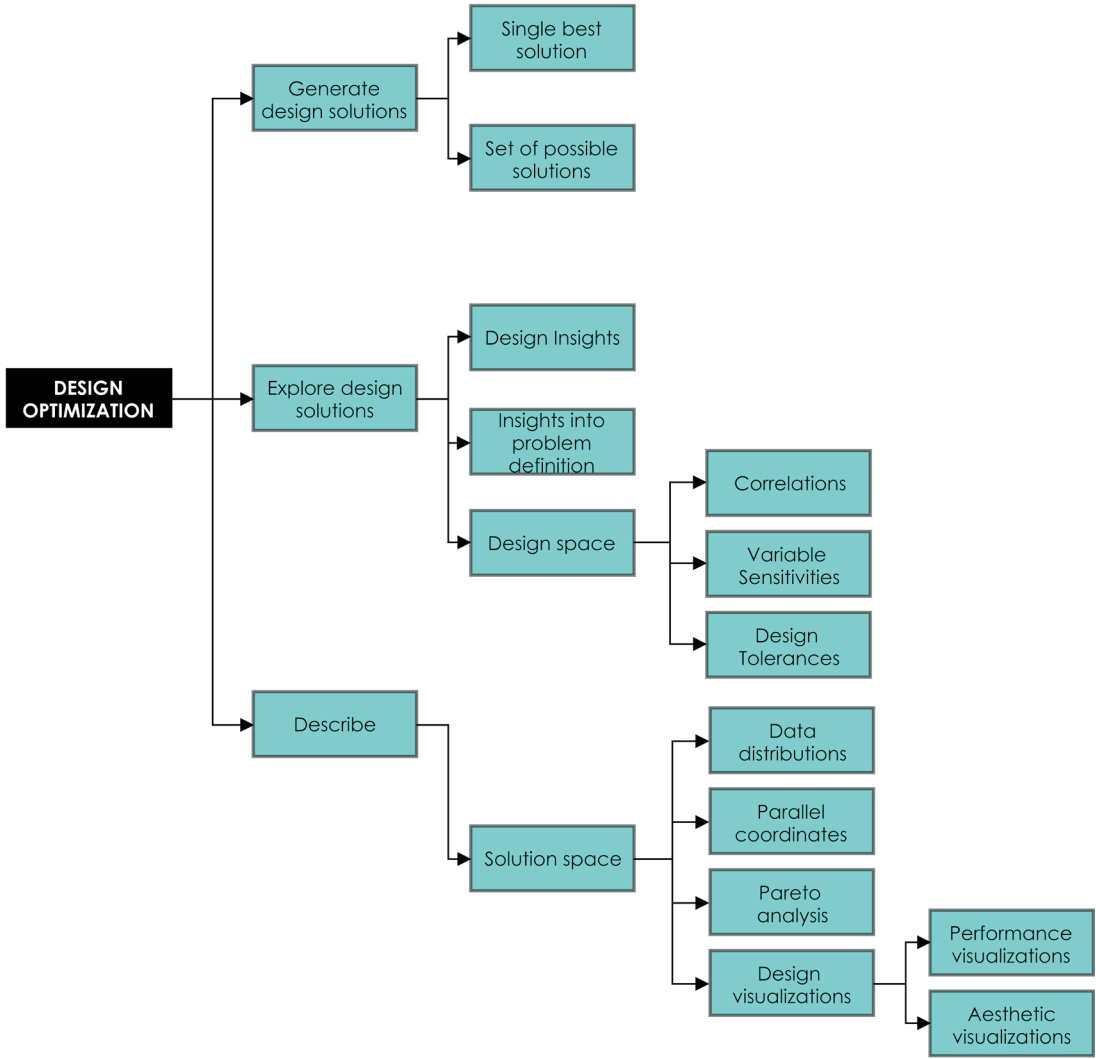


Figure 28. Uses of design optimization, Bradner et al. (2014)

# 3.2 SIMULATION BASED OPTIMIZATION PROCESS

Once stating the growing interest and the basic definition of design by performance applied to energy efficiency and costs savings. Modern architectural offices are nowadays using simulations and optimization tools. However, as stated before, they are applying them individually, and during the later stages of the design, while is during the conceptual design phase that the most impressionable decisions are taken. As stated by Wang (2001) 75% of the product life-cycle cost is determined during the conceptual design stage, and according to Duffy et al. (1993) 80% of the cost of a product is defined by its conceptual design, being highly difficult to compensate this later on.

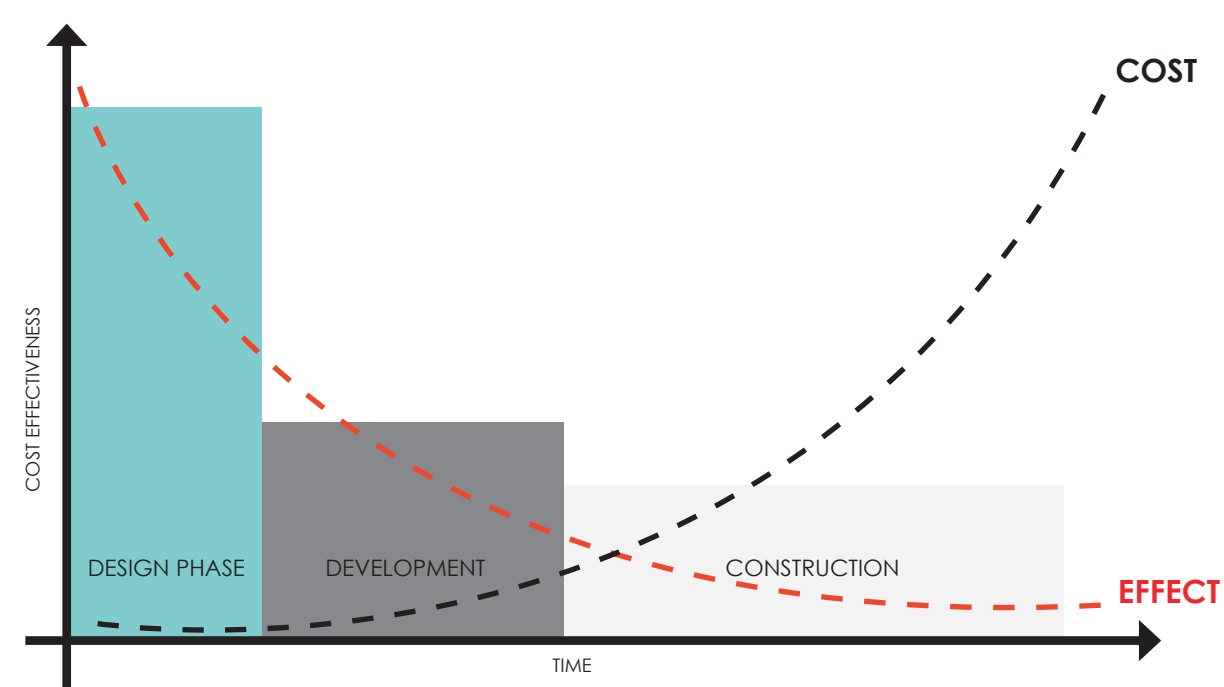


Figure 29. The influence of the initial phases of the design

The need for computer software in building planning processes to calculate the performance of a project is evident nowadays. Building simulation programs are used to calculate the energy demand, the structural load or even the cost of a building. In this scope, Building design and renovation projects are multi-variable parameter problems that combine a large number of possible variations of parameters settings. One way to find a global optimal solution is to use enumerative search methods where all possible parameter settings are combined with each other. However, sometimes due to the large number of possible combinations, this optimization process can take long times and computational efforts. A more suitable solution is to use an automated building optimization algorithm coupled with a simulation program to find an optimal solution.

According to Bernal, et al. (2015) computational design approaches support many designer actions in four focus areas:

- Solution generation
- Solution evaluation
- Decision making
- Integration

Lin & Gerber (2014) establish that multiple efforts have been made to solve these previous issues, including research about improved interoperability, design automation, platform integrations and multi-objective optimization strategies. Encompassed by these efforts, multi-disciplinary design optimization which is the combination of multi-objective optimization algorithms with parametric design (Lin & Gerber 2014) coupled with simulation tools demonstrates a great potential as a design exploration methodology that is able of providing rapid visual and analytical feedback for early-stage design decision making.

As stated by Ostegard et al. (2016), building optimization procedures typically consist of six distinct steps that can be repeated in an iterative manner:

1. Identification of design variables and constraints
2. Selection of simulation tool and creation of a baseline model
3. Selection of objective function(s)
4. Selection of optimization algorithm
5. Running of the simulations until optimization convergence is achieved
6. Interpretation and presentation of the produced data

The following chapter will review the general basic components of this innovative method based on a broad Building Energy Simulation and Optimization (BESO) technique. Which according to Tian, et al. (2017) is an emerging innovative technique that shows a great potential in the architectural field. This chapter will focus first on energy efficiency and cost-effective performance aspects as they are the disciplines of recent relevant interest, secondly in multidisciplinary optimization techniques and finally in data visualization and design exploration.

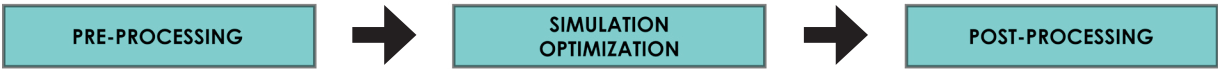


Figure 30. Simulation-based optimization process



3.2.1 PRE-PROCESSING

“Our ability to do great things with data will make a real difference in every aspect of our lives.”  
- Jennifer Pahlka

According to Tedeschi (2016), the concept of Parametric architecture was invented by the Italian Luigi Moretti in 1939 when he started developing his innovative models for stadiums linking viewing angles with economic feasibility: the final shape was generated by calculating isocurves, that aimed to optimize views from every position in the stadium. Fig [31]

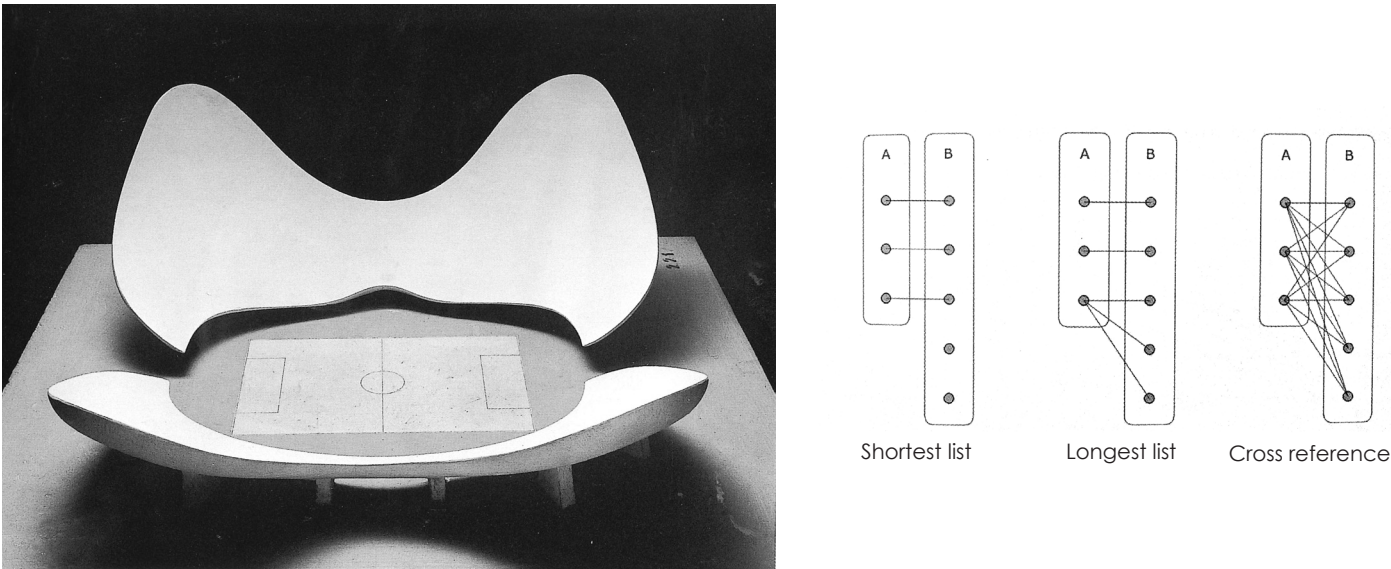


Figure 31. (Left) Luigi Moretti parametric based Stadium, Milan 1960. (Right) Grasshopper parametric data managing

Parametric design in architecture is a practice of an algorithmic modeling based on logic relying on the ability to establish conceptual associations between geometry and mathematics. In other words, data is manipulated instead of digital objects. Tedeschi (2016). In this scope, According to Mayne (2012), Parametric modeling results in an acceleration in the design process, allowing to produce a design and continuously shift it in response to any number of generative influences, being able to experience more iterations and exercising more options. As defined by Riccobono (2013):

“The parametric tools are an effective way of controlling the various parameters and their correlation. Meaning that changing a parameter automatically will involve others, because their relationship does not change, providing the designer with a total control of the project and all changes that take place...”,  
“Parametric approaches represent the symbol of changes” , Patrick Schumacher, Manifesto of Parametricism (2008)

For the generation of quick feedback for different massing, a software has to acquire information on the diverse shapes systematically. Contemporary parametric design tools, provide immediate update on input parameters, making the vision of fast design feedback, possible.

3.2.1.1 Algorithms

“An algorithm is both a description of the problem and the solution”  
-Scheurer in Peters & Peters, 2013

In mathematics and computer science, an algorithm is defined as an explicit specification of how to solve a determined class of problems. Algorithms can perform data processing, calculations and automated operations.

An algorithm is an effective method that can be expressed within a finite amount of space and time and in a well-defined formal language for calculating a function. Starting from an

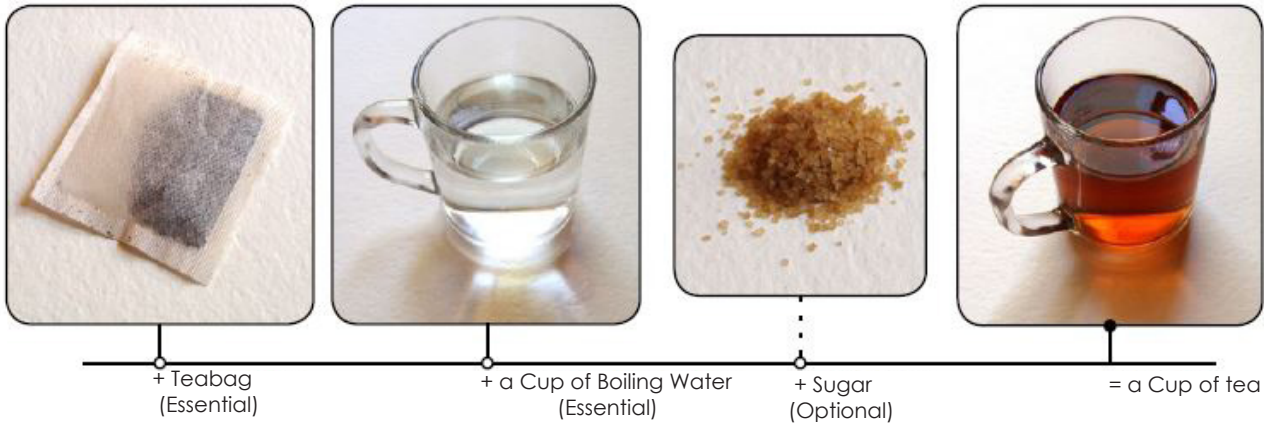


Figure 32. Algorithm to elaborate a tea cup

initial input the instructions describe an operation that, proceeds through a number successive states, producing an output as a final result. For this process there are several types of algorithms from the deterministic ones, to the ones that include random operations inside their definitions.

Algorithms could integrate many of the desired features of the final design, and the creativity of the design process would involve designing objectives and designing experiments rather than input designing solutions. In other words, the role of the architect would involve designing the problem. Rather than focusing on form and performance in an alternating sequence, the architect will focus on creating the potential design space. Marble (2012). As defined by Oxman (2008) The designer should become a digital “tool maker”

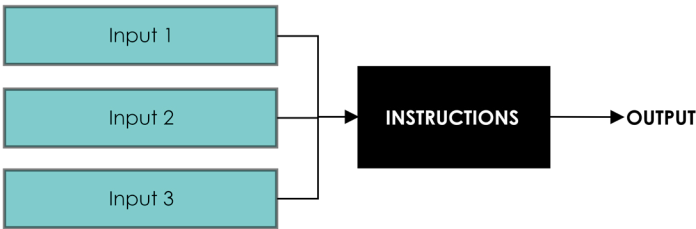


Figure 33. Algorithmic process, Tedeschi (2014)

3.2.1.1.1 Optimization algorithms

There is an infinite amount of algorithms and algorithm types, however, according to Terzidis K. (2006) the most generally used algorithms in building energy efficient design optimization are:

- 1. Evolutionary algorithms
- 2. Derivative-free search algorithms
- 3. Hybrid algorithms

3.2.1.2 Evolutionary algorithms

Evolutionary algorithms are used most frequently in building optimization because of their optimal performance. They are defined by Evins (2013) as common meta-heuristic optimization algorithms. They apply the Darwinian principle of survival of the fittest by maintaining a population of solutions of which the poorest are eliminated on each generation. According to Riccobono (2013) the structure of an evolutionary algorithm is constituted by:

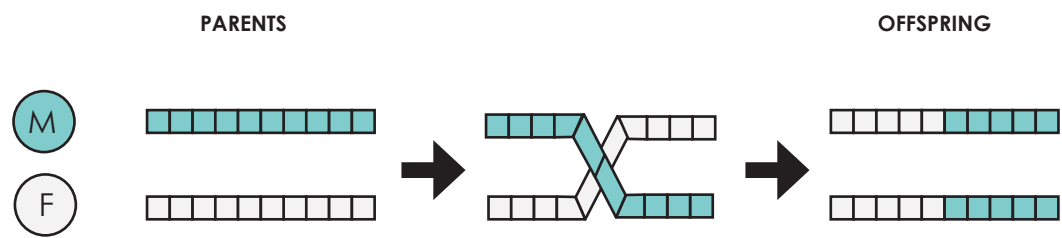


Figure 34. Crossing over process, Domingos (2013)

- Population of individuals, that represent the candidate solutions, identified as a set of random parameters, avoiding local minima.
- Display of individual parameters by the designer, who can choose from a variety of visual solutions among those offered.
- Operators of transformation, which produce a new population from the original parameters, implementing the concept of inheritance.
- Selection of the optimal configuration, which will be the best possible since it is the one obtained by the selection of the best starting features

3.2.1.3 Genetic algorithms

Junghans in Andia & Spiegelhalter (2015) classifies the most common optimization strategies applied to the Building Optimization practice, concluding that Genetic Algorithms are the most successful approach since building optimization projects have a combination of discrete and continuous parameters. Genetic Algorithms are cyclic search techniques which operate on generations of large sets of design solutions defined as populations. Including operations such as, crossover, mutation and selection, shifting progressively successive generations toward s solutions which perform better concerning a previously given criteria.

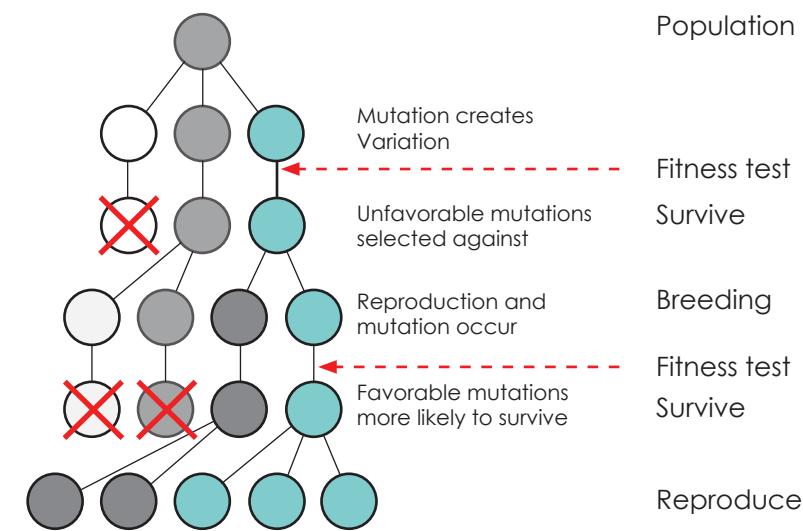


Figure 35. Mutation process , Zhao (2015)

According to Frazer, et al. (2015) Genetic operations include crossover, mutation and selection. These operations are described as follows:

1. Crossover. It is the first operation of the process, which purpose is to create two new trees that contain genetic information about the problem solution retrieved from two successful parents. A crossover node is randomly selected in each parent tree. The tree below this node in the first parent tree is then swapped with the sub-tree below the crossover node in the other parent, creating two new offspring as a result.
2. Mutation. The mutation operation is used to increase the diversity of trees in the new generation opening new possibilities in the solution space. It selects a random node in a single parent and removes the sub-tree below it. Later, a randomly generated sub-tree replaces the previously removed sub-tree.
3. Selection. The requirements are given from the designer and transfered it into the objective function. After this, the fitness value is obtained by calculating the similarity degree between the objective and the particular individual by a specified formula.

When talking about optimization techniques and genetic algorithms, it is also essential to define two important concepts:

- Objectives: Are the performance indicators that are being minimized or maximized during the optimization, for instance, the weight of a structure that needs to be minimized.
- Fitness function: Is defined as a particular type of objective function that states how close a given design solution is to achieve a single or multiple aims.

Examples of these kinds of algorithms are; Non-dominated Sorting Genetic Algorithm II (NSGA-II) Objective Genetic Algorithm (MOGA), Multi-Objective Genetic Algorithm II (MOGA-II), Particle swarm optimization (PSO), simulated annealing (SA), ant colony optimization, among other evolutionary algorithms that are rarely found in research works that focus on the optimization of building design. capabilities towards building design practices.



According to Junghans in Andia & Spiegelhalter (2015) The optimization tools that are available and based on the GA are mostly based on computer language codes like Java, C++, or Python.

3.2.1.2 The parametric model

As defined by Hudson (2010) the term “parametric is used to describe digital representations relating parameters as any measurable factor that can define a system or determine its limits”.

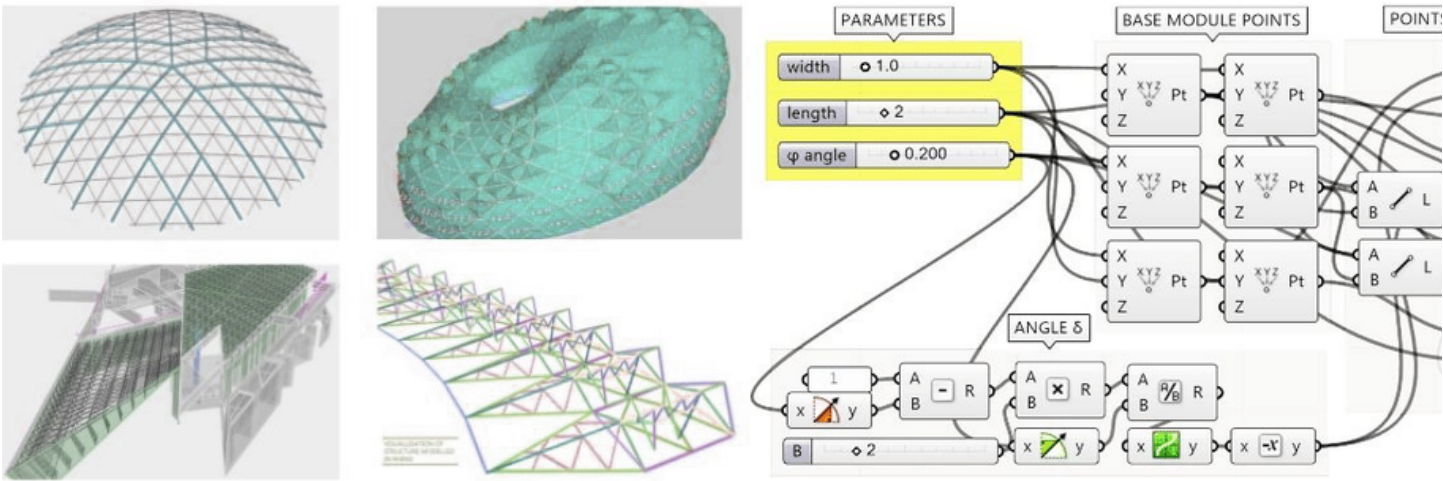


Figure 36. Different parts and types of a parametric model

Hudson(2010) also states that a parametric model can be described as the relationship of a set of parameters with a design, in other words, it can be understood as the description of the problem, generating and searching different alternatives to find a solution that satisfies the problem. This, of course, represents an important amount of new possibilities for the designers. A parametric model is composed by different elements, in the first place, there are the parameters, also called “design variables” which are according to AlphaOpt (2017) the values that the user or the future optimizer application can change. This parameters can be related among each other to produce various combinations defining what is known as “the solution space” or “design space”.

Junghans in Andia & Spiegelhalter (2015) states that mainly there are three types of parameters that can be classified as follows:

- Discrete: Mostly used for building optimization. For instance, a finite number of available construction types and thicknesses are available when adding insulation to a wall. Specific values. For instance number of holes, pipe diameter, etc...
- Continuous: These methods do not use fixed numbers, they utilize ranges of values like 5mph-10mph. For example, window to wall ratio, building orientation, etc...

- Binary: Yes or no, on / off

In second place the parametric model its also defined by constraints which contrary to the parameters are the boundaries that the user or the optimizer cannot modify. There are several types of possible constraints, some of them are enlisted below:

- Physical constraints (Max size, min size)
- Normative constraints (Sustainability)
- Client needs (Budget)
- Technical aspects
- Design aspects
- Computational aspects

3.2.2 PROCESSING

3.2.2.1 Evaluation criteria and simulations

In Generative Performative Design, the object is generated by simulating its performance. The design is defined and characterized by applying digital simulations of external forces to drive form generation. (Oxman, 2008). Hence, these techniques are becoming a trend in the modern building design specially applied to energy and cost related aspects, this is also due to the significant increasing computational power that is nowadays available which allows to solve problems that were impossible in the past. (Attia et al. 2013)

To define how well or how badly a design alternative performs, performance indicators are needed, also called “performance criteria” or “design requirements”. Depending on these requirements, different performance indicators might be more or less important for each different architectural project.

These simulation tools as defined before, work evaluating the performance of a determined option which later on will be evaluated by a Fitness function also defined in the previous chapter.

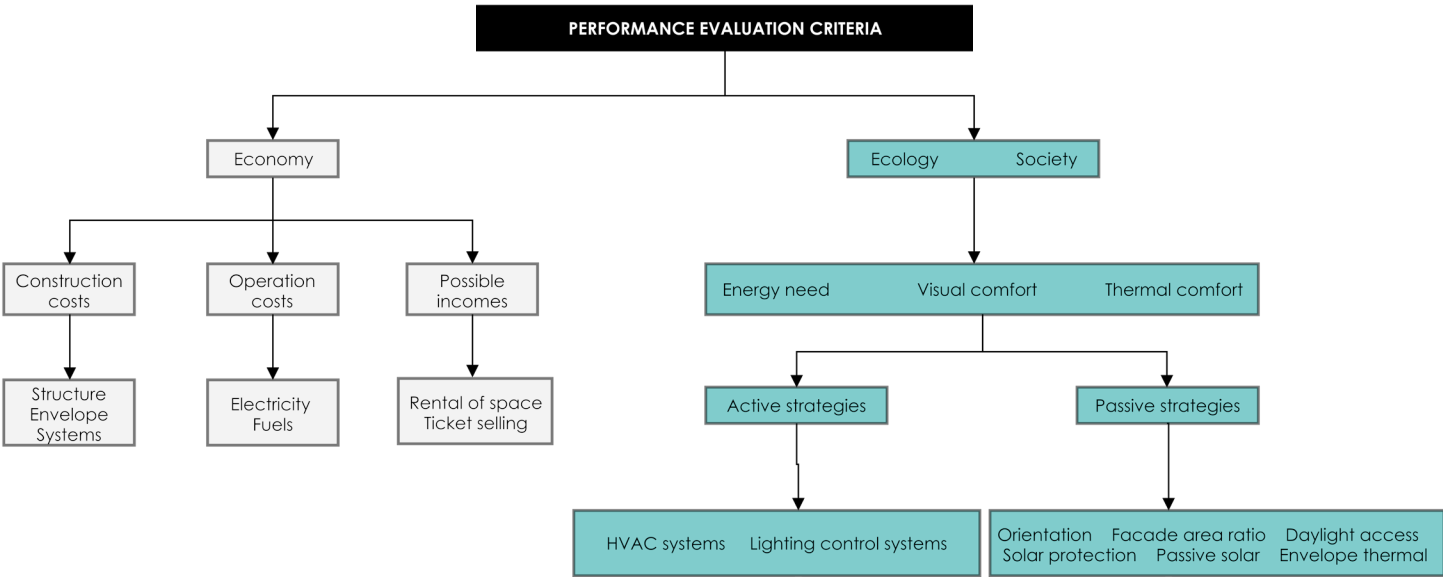
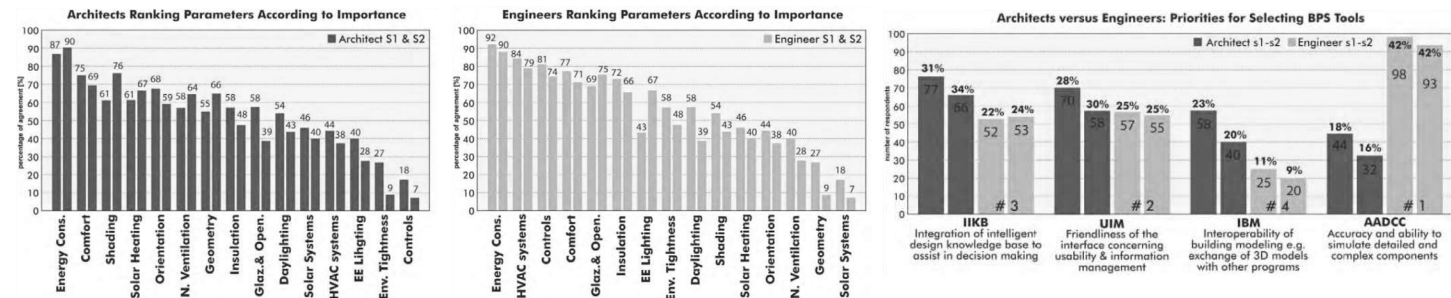


Figure 37. Performance evaluation criteria overview



Figure 38. Ranking of the most important features of simulation tools and areas of interest, Attia, et al (2012)



### 3.2.2.2 Energy performance

-Perkins+Will 2014

- Selecting an energy-efficient installation system, for instance, selecting among a distribution water-based system for heating such as a radiator or cooling ceilings.
- Limiting the amount of glass in the outer walls, because of heat transmission. Also applying high-efficiency glazing, with a low heat transmission coefficient could be a good option.
- Limiting heat transmission in large buildings by building compactly. Depending on the circumstances. Using atria between spaces can also be an effective measure in reducing heat losses.

- According to Linden et al.(2013) a good quality indoor climate and high-quality lighting should be the starting point for calculating energy performance.

Building simulation is an essential element that tackles critical building performance issues such as human comfort, energy efficiency, and compliance with building codes and norms. It allows assessing complex interactions between use scenarios, climate data and building geometry by representing “real life” conditions in approximated models. As shown in Fig. [39] Linden et al.(2013) defines referring to NEN 2916 that the total energy consumption is calculated from heating cooling, ventilating, lighting, hot tap water, humidifying and pumping.

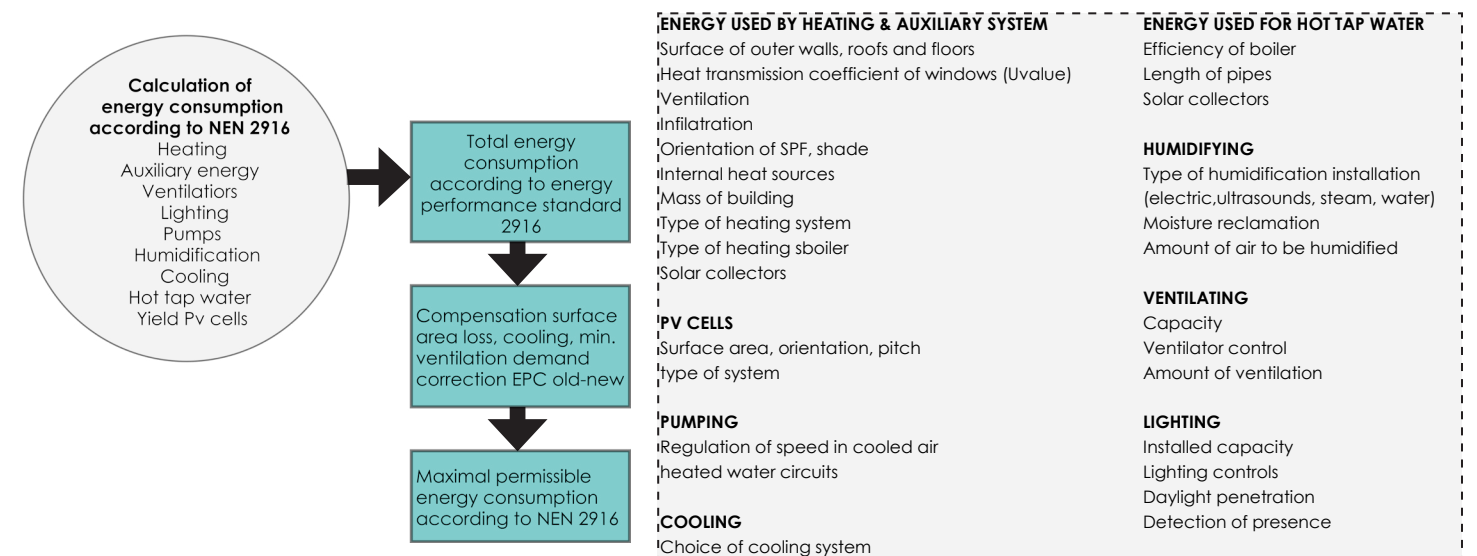


Figure 39. Calculation of energy consumption scheme, Linden et al (2013)

Whilst ventilation energy could be also significant, for the purpose of this thesis, only heating, cooling and lighting energy use will be assessed due to the fact that these three aspects are the more determinative aspects during a building’s operation when talking about non-residential buildings. (Linden et al. 2013). Therefore the operational energy demand will be calculated as the sum of energy expenses for heating, cooling and artificial lighting.

$$Q_{tot} = \sum_{m=1}^{12} N_t (Q_{aux} + \sum_{t=1}^{wh} Q_{dem}) * t \text{ [Wh]}$$

Figure 40. Equation 1- Total energy consumption. Heidegger (2013)

### Thermal analysis and the energy used for heating & Cooling

According to the ANSI/ASHRAE Standard 55-2010, thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.” It is a matter of high importance in energy efficient buildings because if there is no thermal comfort, mechanical systems will need to be introduced involving more energy costs and therefore economical affectations. According to Linden et al. (2013) one of the things that designers of buildings aim at is a comfortable indoor climate for the people who will be working or living in them. To achieve this, a method is needed to work out from measurable, physical variables how people asses their indoor climate. However, thermal comfort is difficult to measure because it is highly subjective. It depends on aspects like the following (Autodesk Sustainability W. 2017):

- Air temperature: Temperature of the air surrounding the occupant
- Metabolic rate: The energy generated from the human body
- Clothing insulation: The amount of thermal insulation the person is wearing
- Radiant temperature: The weighted average of all the temperatures from surfaces surrounding an occupant
- Air velocity: Rate of air movement given distance over time
- Relative humidity: Percentage of water vapour in the air

In the book “Building Physics” Linden et al. (2013) describes two primary methods to measure thermal comfort:

- Predicted Mean Vote (PMV)  
Based on the Fanger’s thermal model (1970), this model assumes an energy balance for people in a stationary situation, in which the energy released by the body's metabolism is

equal to the energy removed from the area, as shown in Fig. [41]. This heat balance can be affected by changing the amount of clothing being worn. By making comparisons using a comfort scale, Fanger arrived to the PMV method. Concluding that there are several factors that do not influence how an in interior climate is appreciated, such as age, gender or even race. The limitations of this model, are that it only applies within the comfort range, and it assumes a stationary situation, therefore is not possible to give a valuation for the climate during activities that las only a short time. An advantage of Fanger’s model is that is easy to use with a computer or a pocket calculator.

- Adaptive Thermal Comfort (ATC)  
According to Linden et al. (2013), There is a distinction between building and climate types, alpha and beta. Alpha is used for buildings in which windows can be opened and the users can influence the indoor thermal climate, while beta are the buildings with sealed facades and centrally controlled air conditioning. For buildings in which the windows can be operated and where the occupants can influence the indoor climate, the “comfort temperature” as stated by the building’s users and is not the same as the “neutral thermal simulation” defined in the PMV model. The comfort temperature in the adaptive model is related to the “average outdoor temperature” Linden et al (2013) points out several points when talking about this method:
  - The clothing resistance should be separated
  - The metabolism varies according to the activity
  - It takes into account the effect of the dynamic character of thermal conditions
  - Non-thermal factors also play a role particularly in the affectation and influence of the surroundings by the users or the expectations with regard to the thermal indoor climate.

According to Linden et al. (2013) when talking about local discomfort, the level of relative humidity hardly matters in terms of thermal comfort. An upper limit of 70% or a moisture content of 12g/kg is often maintained. The author also defines several aspects that need to be taken into account when analyzing a thermal model such as vertical temperature gradient, asymmetric thermal radiation, floor temperature and air velocity, however for the intention of this master thesis these will not be considered.

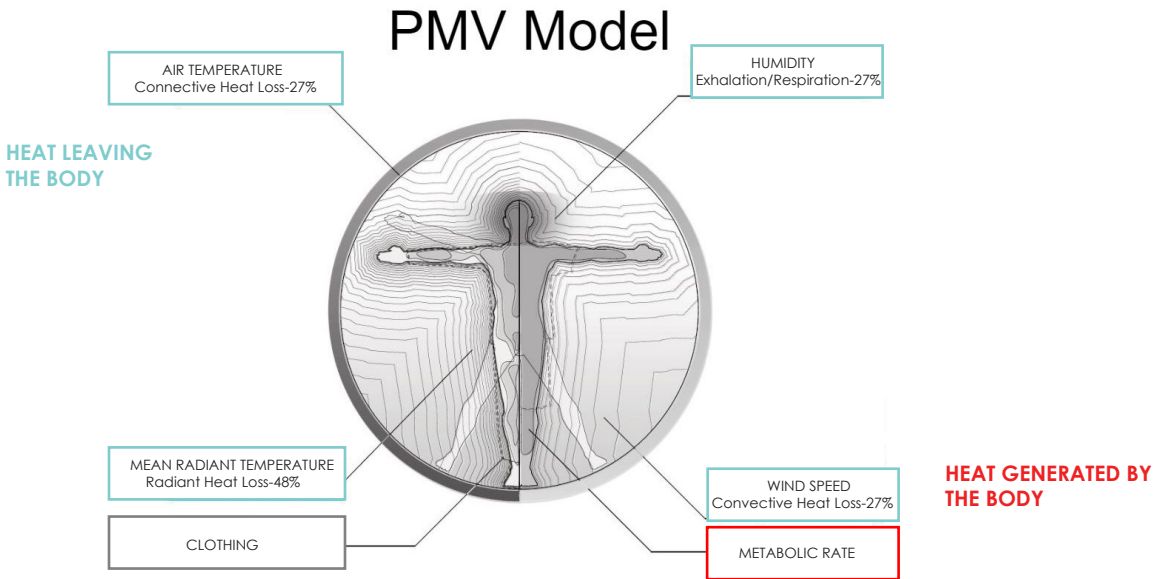
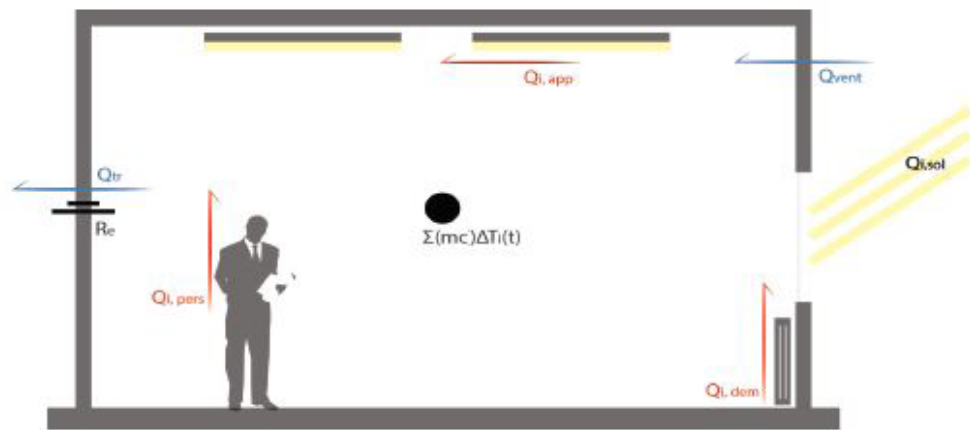


Figure 41. Overview of the Predicted Mean Vote method, Ladybug tools LLC (2018)



$T_i$	inside temperature [°C]
$T_e$	outside temperature [°C]
$H_v$	specific ventilation heat loss to the outside [ $\frac{W}{K}$ ]
$H_{tr}$	specific transmission heat loss to the outside [ $\frac{W}{K}$ ]
$Q_{int}$	internal heat loads [W]
$Q_{sol}$	incoming solar radiation [W]
$U_e$	heat transmission coefficient of the external closure [ $\frac{W}{m^2K}$ ]
$A_e$	Area of the external closure [m²]
$c$	specific heat capacity [ $\frac{J}{kgK}$ ]
$m$	mass being heated [kg]
$q_v$	room ventilation flow with outside air [ $\frac{m^3}{s}$ ]
$q_{pers}$	internal heat production by persons (Table 10.1 in NEN 7120) [ $\frac{W}{m^2}$ ]
$q_{app}$	internal heat production by appliances (Table 10.2 in NEN 7120) [ $\frac{W}{m^2}$ ]
$\rho c_a$	volumetric heat capacity of air : 1200 [ $\frac{J}{m^3K}$ ]
$g_{gl}$	solar energy transmittance of glass, sometimes also called heat gain coefficient

Figure 42. Single node thermal model, Heidegger (2013)

Hensen & Lamberts (2011) defines the thermal load of a building as the amount of heat that must be removed or added to maintain a constant indoor air temperature. Normally, the building is divided into zones, portions of the volume that are assumed to have approximately the same air temperature. This division is, as defined in the Energy Plus Users manual (2015) based on a “thermal” and not in a “geometric” concept as shown in Fig. [43] Hence, a “zone” is defined as “an air volume at a uniform temperature plus all the heat transfer and heat storage surfaces bounding or inside of that air volume.” (Energy Plus Users manual, 2015) This analysis involves the three types of heat transfer mechanisms; convection, conduction and radiation within the building envelope (walls, roofs, floors) and its surroundings. Since this three mechanisms occur simultaneously, a heat balance model as shown in Fig. [33] has to be



Figure 43. Thermal zone division, (Left) Single zone, (Right) Detailed zone, Energy Plus manual (2015)

elaborated to simulate the temperature fluctuations inside the zone or zones of the analyzed building.

According to Linden et al. (2013) the energy used for heating a public building is calculated from the following items:

- Demand for heat. As defined above, a heat balance should be elaborated (heat lost minus heat gained). Being the heat loss the sum of the heat transmission through windows, outer walls, roof and ground-level floor (surface area, U value), infiltration and ventilation- The amount of air that needs to be heated depends on the amount of air that is supplied via either natural or with a mechanical ventilation system. In this scope, as stated before, the use of a heat recovery system can produce considerable savings. The heat gained is the total heat gained from solar penetration and the presence of people, lighting and machines.
- System efficiency of the boiler of the heating system, the greater the level of the efficiency, the lower the amount of primary energy is used for heating. For instance, a high efficiency 107 boiler has an efficiency rate of 90% while an improved efficiency one about 70%
- The yield from solar energy systems.

Energy used by cooling is determined on the basis of a calculation of the need for cooling. This is according to Linden et al. (2013) comparable to a heating energy calculation; only that is the other way round. Contrary to the winter, the indoor temperature in the summer will often have to be lower than the temperature outside.

$$T_i(t + \Delta t) = T_i(t) + \frac{Q_{s,tot} + Q_{dem} + H_{tot} * (T_e(t) - T_i(t))}{H_{tot}} * [1 - \exp(-\frac{H_{tot}}{C}(\Delta t))]$$

Figure 44. Equation 2- Energy use for heating and cooling. Heidegger (2013)



Examples

In the paper “Simulating natural ventilation in large sports buildings. Prediction of temperature and airflow patterns in the early design stages”. Turrin, et al. (2016) Developed an example of the analysis of a Sports hall thermal performance using a rapid feedback methodology by coupling airflow simulations with thermal analysis until convergence was reached, being both disciplines correlated affecting one to each other.

The research paper starts defining that in buildings with such large envelopes temperature measures depend highly on the shape, construction and ventilation openings.

In this experiment, with the aim to reduce computation times, due to the fact that according to Turrin, et al. (2016) CFD analysis requires long times and computational work. The 3d model was first simplified and then divided into two systems; the first one was the airflow analysis using the software CONTAM 3.1 for calculating the airflow rates and the second one the thermal simulation using Energy Plus and Honeybee as shown in Fig. [45]

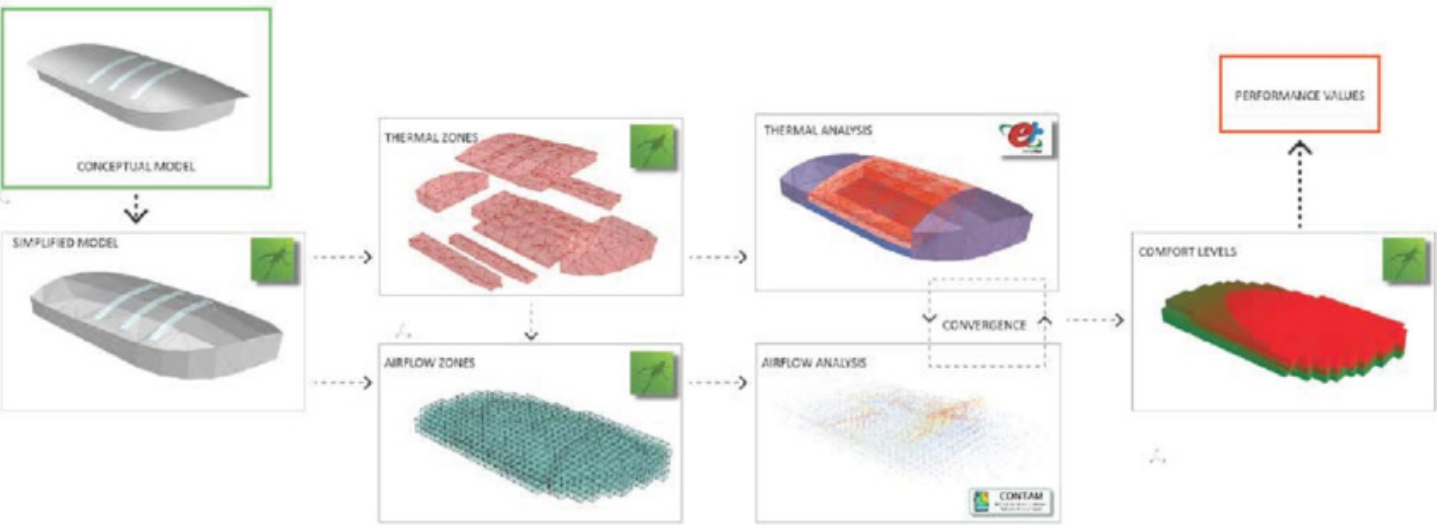


Figure 45. Computational workflow using temperature and airflow simulations, Turrin, et al. (2016)

Some strategies were later proposed, in the first place, because for a sports building, the requirements for air changes per hour between the area where the athletes perform and the spectators zone are different. The model was divided into two called “thermal zones” as it can be seen in Fig. [46] Then the simplified model also was assigned with material properties, including glazed surfaces and at the end, an average temperature was provided. Simultaneously airflow analysis were simulated, and results interpreted. Finally, both systems were coupled and analyzed simultaneously.

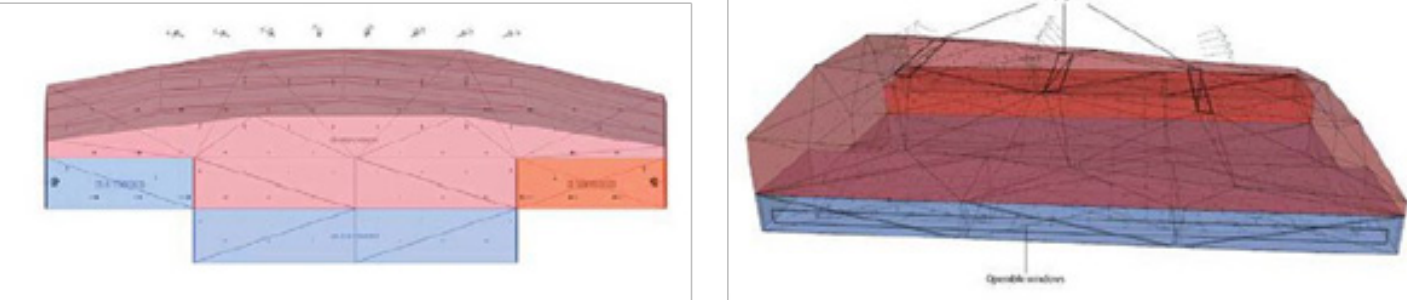


Figure 46. (Left) Elevation showing thermal and airflow patterns. (Right) View of the building openings Turrin, et al.(2016)

Later on, the methodology was tested with two different design concepts by comparing the indoor thermal comfort results. At the end of the paper to test the accuracy of the computational approach, an application on a simple design case was performed and compared to the results from the same case modeled in a different software called Design-BUILDER which according to Baharvand (2013) is a reliable tool for design performance assessment. But that nevertheless as stated by Ianni & de León (2013) does not have the necessary flexibility to develop or change a model of the building, and its feedback is not immediate.

In the paper “Energy systems in cost-optimized design of nearly zero-energy buildings.” Ferrara et al. (2016), developed a methodology to reduce the energy consumption and operation costs of a residential building located in France. It consists of two main parts; the first one attempted to minimize the energy demand of the building by modifying a building's envelope geometry and construction and secondly by using high-efficiency energy systems. Via an automated search strategy dynamic simulations and optimization algorithms were combined in order to

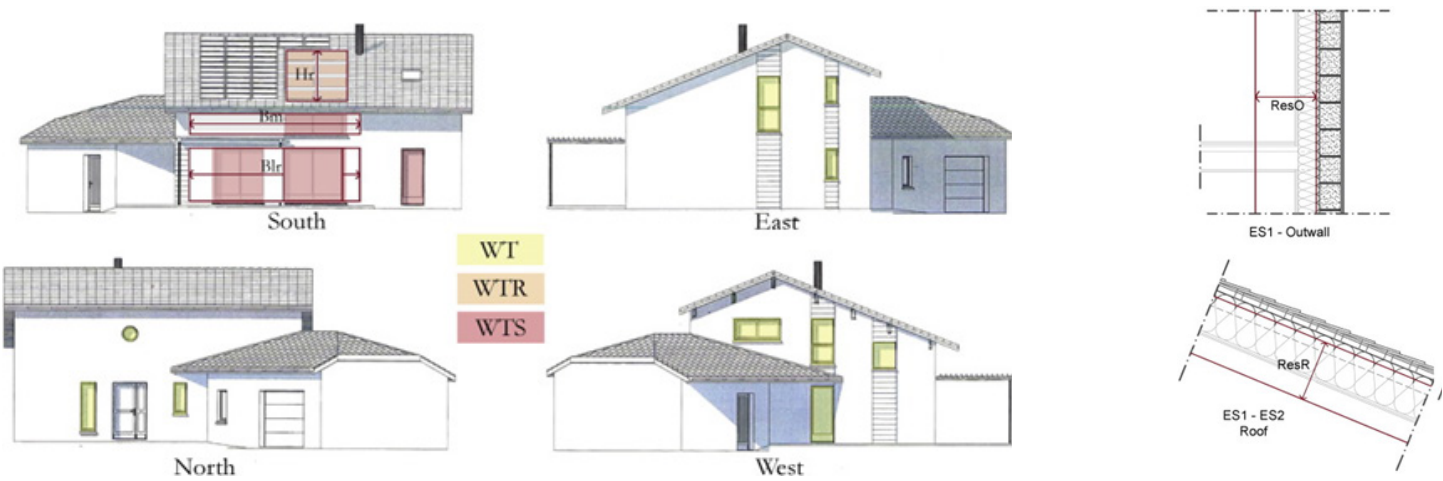


Figure 47. (Left) transparent envelope parameters, (Right) opaque envelope parameters, Ferrara, et al (2016)

evaluate a great number of design options and perform a deep optimization research. The first part consisted in modifying the thickness and the materials of different envelope options, roof and walls together with the size of the windows as shown in Fig. [47]. The second one explored four different energy systems that were selected among those that are currently more commonly used in France. To assess the energy performance of the diverse options, a thermodynamic model was developed taking into account local conditions and regulations. Later on, in order to reduce the computational times and being able to explore a significant number of alternatives, a simulation-based optimization process was proposed, coupling the simulation engine with optimization algorithms. Furthermore, a financial model was also developed to compare the savings and expenses that each of the options represented.

At the end of the paper, Ferrara et al. (2016), drew a series of charts and graphs to make some conclusions about the influence of the energy systems in combination with the envelope variables described above. Finding a balance between the investment costs and the operational costs achieved satisfactorily by the simultaneous optimization of the many involved design variables.

For this study, the utilized software was TRNSYS a building dynamic simulation program together with a GenOpt a Generic Optimization program.

3.2.2.3 Daylight analysis and the energy used for artificial lighting

“Daylight is the most appreciated source of illumination for exteriors and interiors of buildings for human beings. Therefore, strongly influences the physiological and psychological well being of people” De Luca & Voll (2017). It is a topic that has been largely investigated lately; because of its potential for energy savings since almost 20% of the total energy electrical consumption in Europe is caused by artificial lighting, Orme (2011). This means that the indoor environment must fulfill the visual needs of its occupants, according to the task they are performing in it.

Regulating the lighting can help to reduce the number of hours during which it is on. Also the presence of daylight -sensitive controls. Whereby the level of lighting capacity that is actually used falls when the level of daylight penetration is sufficient. Automatic lighting control systems that switch off the lighting centrally at defined times of the day for instance at the end of a working day can help by decreasing the energy used by 30% as defined by Linden et al. (2013)

Visual comfort can generally be achieved by providing a sufficient level of illuminance (lux). However, there might be glare sources causing visual discomfort and reduced performance. Besides, a good view outside of the building could help to increase the visual comfort and to create a healthy and productive environment. Furthermore, from an architectural point of view light has a highly significant role in the overall design of a building. As stated by the Swiss architect LeCorbusier “Architecture is the masterly, correct and magnificent play of masses brought together in light...” though, this aspect will not be covered in this study.

According to Eltaweel &Su (2017) Daylight is influenced by a wide list of criteria such as, latitude, longitude, sun path, solstice, equinox, sky type, wind speed, solar radiation, humidity,etc... He divides the study of this discipline into the following aspects:

- Louvers design
- Skylight design
- Mass and shadow study
- Fenestration design
- Windows design
- Photovoltaics design

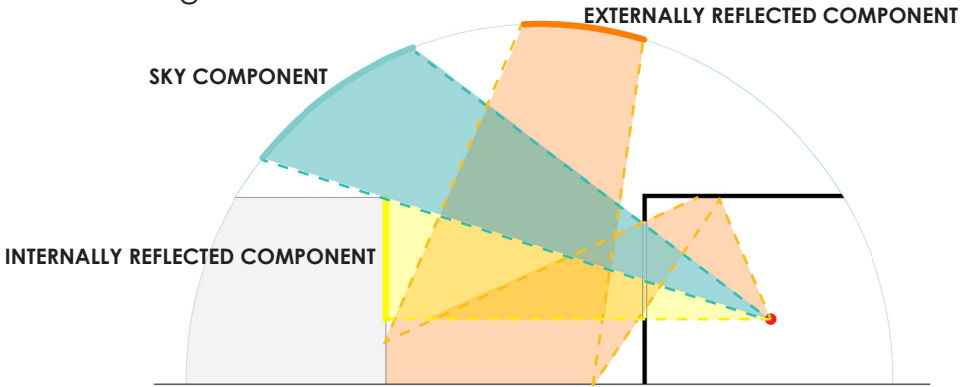


Figure 48. Sources of natural daylight

According to Linden, et al. (2013) there are several indicators for Daylighting analysis among which for the sake of this investigation only the most common will be studied:

- Illuminance (I)  
Illuminance E, is the amount of captured luminous flux  $\Phi$  per unit of surface area A:
- Daylight Factor (DF)  
The daylight factor is defined as the relationship between the illuminance indoors and the illuminance outdoors in an open space, at the same time. If the former is 150 lux and the latter 5000 lux, the daylight factor would be as follows:

$$E = \frac{\Phi}{A} \text{ [Lumen /m2 or lux (lux)]}$$

$$150/ 5000 * 100\% = 3\%$$

To achieve a given daylight factor, various matters have to be taken into consideration; including the size of windows, the interception of light by the geometry of the building or context buildings. The transparency of the glass, the blinds, the dirt of the windows, the reflection of light by the interior walls, floors and ceilings in the room, besides, the colors of the surface will also influence this. According to Linden et al.(2013), the calculations for determining the daylight factor assume a cloudy sky, as the string of the sun is too changeable as a source of light. Inside the daylight factor calculation, there is also the shy component aspect which is the direct light from the sky reaching the point under consideration after it passes through a window opening.

- Spatial Daylight autonomy (SDA)  
According to Yang, et al. (2015) it is stated in LEED v4 and describes how much of a space receives sufficient daylight, Specifically, it represents the percentage of floor area that receives a minimum of 300 lux for at least 50% of the annual occupied hours.
- Annual Sun Exposure (ASE)  
According to Zhao (2015), it describes how much space receives “too much” direct sunlight, which can cause visual discomfort (glare) or increase the cooling loads. It measures the percentage of floor area that receives at least 1000 lux for at least 250 working hours per year.
- Useful daylight Illuminance (UDI),  
Is described by Han et al. (2017) as a dynamic daylighting evaluation index developed by Nabil and Mardaljevic in 2005 defined as the percentage of the occupied hours of the year across the work plane when all illuminance is between 100-2000 lux. The lower illuminance value is 100 lux, under which the daylight level is considered insufficient. Whereas the values higher than 2000 lux are considered to produce glare. Therefore generally 100-2000 is defined as a satisfactory range for the daylight calculation of UDI, and is represented like  $UDI_{100-2000}$ .



- Daylight autonomy (DA)  
It is defined as the percentage of the occupied hours of the year during which a minimum illuminance level can be maintained by daylight, Carlucci, et al. (2015).  
According to Han et al. (2017) the concept of DA was proposed by the Association Suisse des Electriciens in 1989 and later on refined by Reinhart and Walkenhorst in 2001. It uses a climate-based daylighting dynamic evaluation metric.

According to Linden et al. (2013) Energy used by lighting can be obtained in two different ways.

- The standard method is based on a fixed amount of electricity consumption for every m2 of usable surface area which varies according to user function.
- The other method is based on multiplying the total of the installed lighting capacity by the number of hours the lighting is switched on. This previous number is determined according to the user function. It is important to mention that this strategy is not applicable during the first stages of the design.

After calculating the natural daylight conditions, the daily energy consumption for lighting can be expressed as:

$$Q_{art,l} = \sum_{h=1}^{wh} \sum_{n=1}^P f * A_n [Wh]$$

$$\text{with } f = 0 \quad \text{if } (E_{art} - E_n) \leq 0$$

$$f = \frac{(E_{art} - E_n)}{\eta_l * K_l} \quad \text{if } (E_{art} - E_n) > 0$$

where  $E_{art}$  = minimum required level of illumination [lux]  
 $E_p$  = hourly level of illumination on analysis point [lux]  
 $\eta_l$  = efficiency of lighting system [%]  
 $K_l$  = visual efficacy of lighting system  $\left[ \frac{lm}{W} \right]$   
 $wh$  = number of working hours  
 $P$  = number of sub surfaces (analysis points)  
 $A_n$  = area of sub surfaces  $[m^2]$

Figure 49. -Equation 3-Energy for artificial lighting calculation. Heidegger (2013)

## Examples

In the paper "Bio-inspired parametric design for adaptive Stadium facades." Park & Dave (2014) developed a project based on a biological adaptation taking as inspiration the compound eyes of the crustaceans to develop an adaptive stadium facade.  
In this research, several simulations regarding daylight were made. The amount of total daylight reaching in the pitch area is the fundamental factor that guides the performance criteria and according to the authors it can be quantified by:

- Solar insolation (Wh/m2)
- Illuminance levels (Lux)
- Daylight factor (Percentage)

According to the IESNA (Illuminating Engineering Society of North America) Lighting handbook, the minimum illuminance level for a gymnasium is 300x lux for general exercising and recreation and 1,000 lux for sports matches. Therefore, an envelope that traces the light of the sun was developed and in order to do that, several simulations were required. The utilized software was Grasshopper to model the geometry, Geco as a plug-in link and Autodesk Ecotect for the daylight analysis. The methodology was to parametrize and translate the optical structure of the "eye" into architectural geometries and secondly to link the kinetic mechanism of each component module responding to the sun movement to redirect sunlight based on either functional demands or environmental conditions.

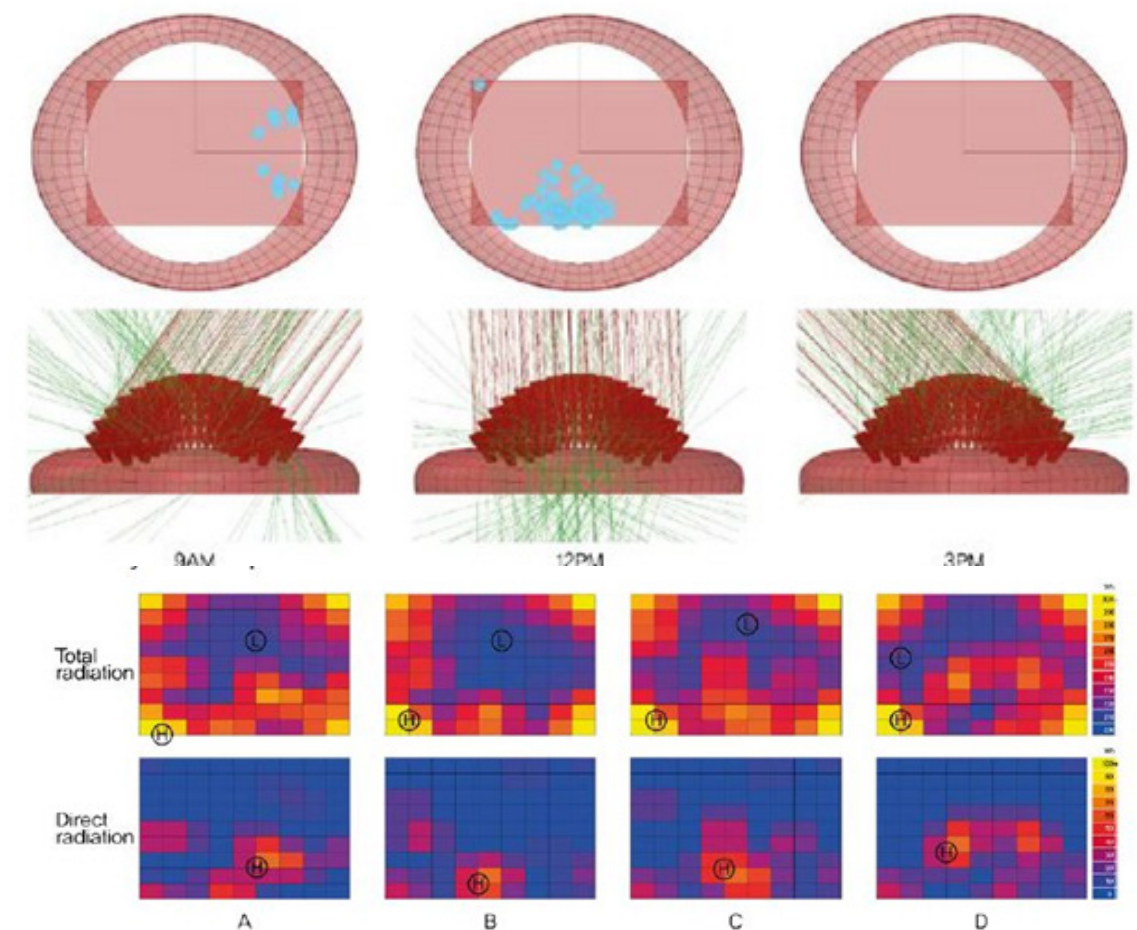


Figure 50. (Up) Reflection of sunlight rays simulation. (Down) Solar insolation simulations Park & Dave, et al. (2016)



In “Simulation-based Multi-objective optimization of timber-glass residential buildings in severe Cold Regions” Han, et al. (2017) conducted a research paper with the aim of proposing a method to improve the, energy efficiency, economic performance and daylight quality of timber- glass buildings in cold regions. By setting a methodology based in the use of simulation tools together with parametric and optimization software the authors proposed as variables of the design firstly the building form, varying the building width, roof height and orientation. And secondly, the window variables controlling the size of the windows, the window height and the window to wall ratio independently. The envelope materials were defined as fixed values together with the occupancy settings of the building.

After defining a parametric model with constraints and variables, simulations and optimization procedures were developed gathering some conclusions about the influence of the building form and the windows variables in the final energy demand of the building. To evaluate the daylight aspect two indicators previously described were selected namely Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI). These two indexes were selected because according to Han, et al. (2017) it is not only about increasing the amount of daylight in the inside but the quality and of it is important as well. Once gathering the information of this daylight performance, the energy need for artificial daylight was calculated and later on combined with the heating and cooling demand to calculate the final energy use of the design option. In order to evaluate and compare the energy efficiency of the diverse options an indicator defined as EUI (Energy Use Intensity) was employed. It is described by Konis et al. (2016) as the energy consumed during the year per unit area, which is measured in KWh divided by the square meters of the building, representing a good indicator for comparing several design options. Finally, the total cost was also defined from one side the construction costs and from another the operation (energy costs) that were related directly to the results from the simulations.

At the end of the paper, several negative and positive correlations among the variables and the objectives were found, such as for example in order to increase the DA values, the window area must be enlarged, leading to an increase of the cost of glazing reducing from another side the energy consumption for artificial lighting. Or that building width was the largest influencing factor, followed by window to wall ratio at the north. The authors utilized Rhino and Grasshopper for the geometric modeling, Diva for daylight performance and Archsim together with Energy Plus for energy calculations. Finally, for the multi-objective optimization process Octopus was applied.

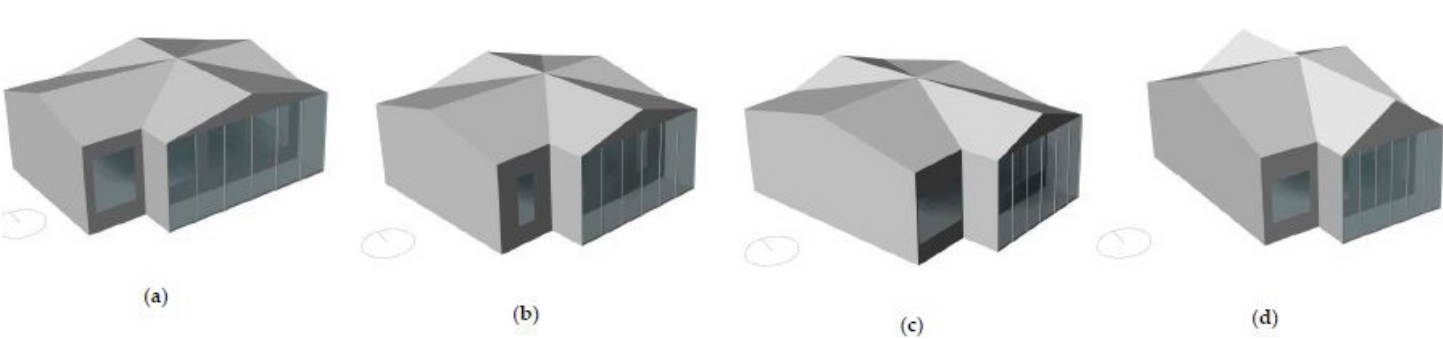


Figure 51. Models of different building solutions, Han, et al. (2017)

Solar design can is defined as a process that involves the simulation of natural light sources, (sun and sky). It is used in different fields whether for scientific and artistic purposes in the form of qualitative or quantitative analyses of spaces and surfaces considering various spatial and temporal resolution and accuracies, Jakica (2018) Solar energy production relies principally on the so-called “Solar envelope” which according to Chi, Moreno & Navarro (2016), when talking about daylight, the building envelope plays an essential role in controlling and or admitting the various elements of the external environment. Being capable of achieving about 80% of an environmental solution. Therefore, the shape of the overall envelope is a fundamental aspect to consider. According to Alkadri (2017), three main important parameters affect the solar envelope climate, urban rules or zone regulation, and the surrounding environment. As illustrated in Fig. [52] In the paper “Computational method for variable objectives and context-aware solar envelopes generation” De Luca & Voll (2017), developed an exercise for the computation

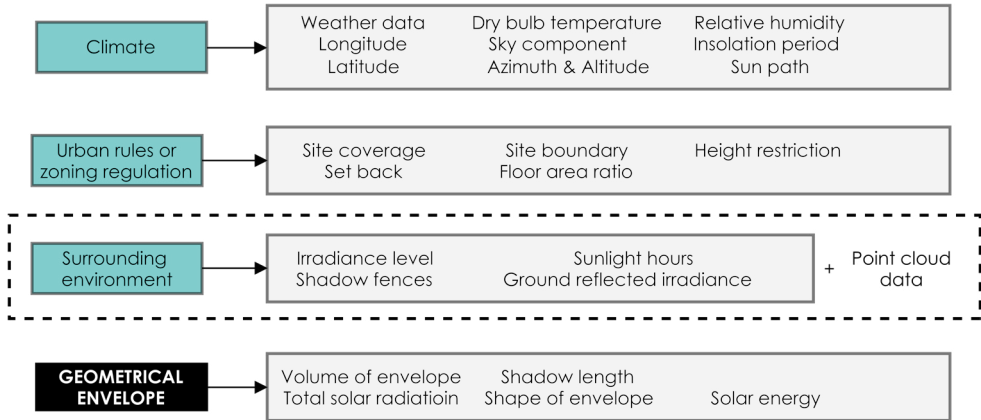


Figure 52. Parameters of solar envelope, Alkadri, et al. (2017)

of the maximum buildable volumes to allow specific quantities of direct sunlight on the neighboring building facades in Estonia. Stating that the surrounding buildings of the project need to receive at least 50% of the direct sunlight for each day according to local regulations. They achieve this with a series of simulations together with a designed recursive algorithm that includes the context and surrounding buildings in the calculations. As shown in Fig. [43], the sun path and the sunlight hours analysis were utilized to assess the possible maximum size of the intended envelope while at the same time respecting the right to light of the surrounding buildings. The method applied Grasshopper and the environmental analysis suite Ladybug.

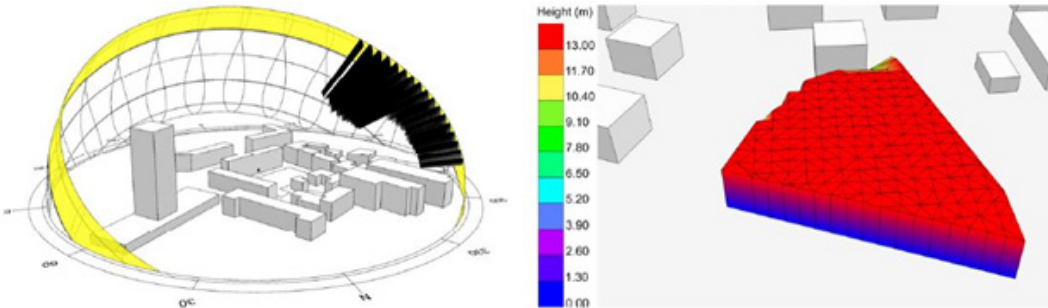


Figure 53. Solar sun path and sun light hours analysis, De Luca & Voll (2017)

3.2.2.4 Cost performance

“Architect should be a bridge between the creative and the achivable”  
-Garcia & Furtado, 2015

According to Linden et al. (2013), to create a balanced building, it is often necessary to carefully weigh up the various possible measures that need to be taken. It will not only be energy, climate and architecture-related considerations that will play a role. Economic interests will also feature in the overall decision-making process.

“The whole field of qualities finds expression in form, which is the designers, domain”. The designer is by definition the one who maintains an overview of the whole range of qualities that concern the building as a product. The designer is responsible for coherence. “ (Gerritse, 2008). Because of the increasing degree of specialization in all fields connected with buildings, the designer must usually cooperate with specialists, each of whom has only part of the total quality field and usually concentrates on the “hard” quantifiable qualities. Consequently, the designer continually operates in a difficult situation where “soft”, non-quantifiable qualities are at risk of being dismissed by hard, quantifiable ones.

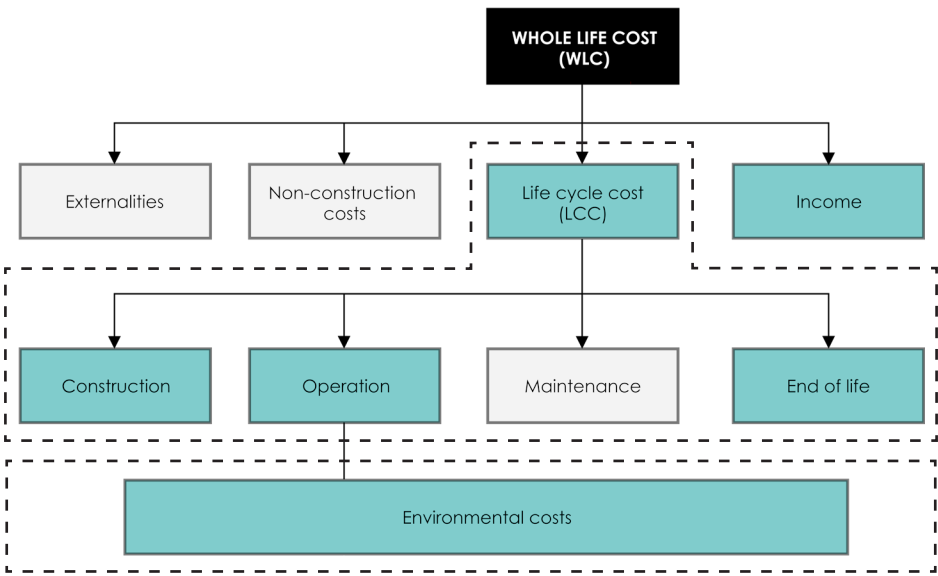


Figure 54. LLC Analysis overview, NEN-ISO 15686-5 (2017)

Gerritse (2008), defines that it is a mistake to try to control costs and quality by means of indices, references or cost/quality models without any insight into architectural relations. Inexpert application of what are in themselves fantastic tools yields deceptive results and generally leads to disappointment in the subsequent course of the process, for example in the form of quality decrease caused by insufficient budgets ( Geeritse, 2008).

Nowadays cost estimators develop the cost information that business owners or managers, professional design team members, and construction contractors need in order to make budgets and feasibility decisions. For example, from an Owner’s point of view, the cost estimate may be used to determine the project scope or whether the project should proceed.

Conforming to Sherif, et al. (2011) Traditionally cost estimators used architects design intent drawings to generate datasets for the estimates. In their assessment, they relied on manual take off using 2D drawings, on screen take off from PDFs or CAD drawings, or custom-built spreadsheets. This process proved to be exhaustively time-consuming, susceptible to errors and mostly inaccurate. In architectural practice, this meant a feedback process not prompt enough for design decision-making, where estimates were generated in an isolated way near to the end of the design process. As stated by Wong, et al. (2005) there is a lack of correlating development economics and objectives into the design process. According to Miller (1993), the costs of the design process usually consist of 5-8% of the overall costs, while the 60-80% is destined to the construction costs. Although, the most significant impact on life-cycle performance comes from the choices made during the conceptual phase (Ellis, 2008)

Life cycle costing is defined by NEN-ISO 15686-5:2017 as “a valuable technique that is used for predicting and assessing the cost performance of a constructed asset.” It is one form of analysis for determining whether a project meets a client’s performance requirements. Life cycle costing compares alternatives and estimate of future costs, project or component level. Life cycle costing is performed with an agreed period of analysis, clearly identifying whether the analysis is for only part of or for the entire lifecycle of the building. The purpose of life cycle costing should be to quantify the life cycle cost (LCC) for input into a decision-making or evaluation process, and should usually also include inputs from other evaluations like environmental assessment, design assessment, among others. The quantification should be to the level of detail that is required for the key project stages.

According to Holm et al. (2005) there are broadly three types of construction cost estimating methods as shown in Fig. [45]. NEN-ISO 15686-5:2017 describes that Life Cycle Cost is compounded by several elements, construction is only a small part of the cost associated

TYPE OF ESTIMATE	CONSTRUCTION DEVELOPMENT	EXPECTED PERCENT ERROR
Conceptual	Programming and schematic design	+/- 10-20%
Semi-Detailed	Design development	+/- 5-10%
Detailed	Plans and specification	+/- 2-4%

Figure 55. Three types of construction cost estimating methods. Holm, et al. (2005)

with a built asset. There may be land acquisition costs, fees, taxes and so on incurred before construction begins, and management, maintenance and other costs once the project is completed. These may be categorized as capital costs and operational costs. For the scope of this thesis only construction costs regarding building materials, operation costs referring to energy consumption and finally prospective income as a possibility to manage the building as a business model will be reviewed. Fig.[44] Describes the different types of costs according to NEN-ISO 15686-5:2017, as it could be seen a life cycle cost analysis is compounded by several components, however for the scope of this thesis only the following three costs will be reviewed:



Construction costs (material costs)

Construction costs form part of the overall costs incurred during the development of a built asset such as a building. Broadly, construction costs are those costs incurred by the actual construction works themselves.

According to Bielefeld (2013), there are different methods to calculate costs. The choice of the method depends on the project phase and the depth of planning achieved. He defines that the fundamental principle of them is that costing figures are always multiplied by a unit of quantity in order to be able to make a statement about the cost to be expected. Bielefeld (2013), describes the following costing methods and their application potential as follows:

- Gross cubic capacity

Is derived from the area of the building and its height, from the foundation of the floor slab to the top edge of the roof covering. It is a very flexible planning instrument for early project phases without a definitive building design. But the results must be treated critically and system-related fluctuations should be pointed out. Cost figures can be obtained from national building cost information services or from setting up an individual costing system, based on a large number of projects of the same type, similar size and finishing standard. It is essential to ensure that uniform references are made to cost values and quantities.

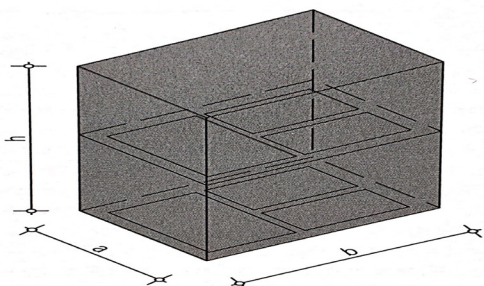


Figure 56. Gross cubic capacity method. Bielefeld (2013)

- Floor area and usable area

This method involves simple calculation methods as the previous method. However, in this method, the height is ignored, hence it is imperative to use costings for comparable properties with similar absolute storey heights. It is advised to compare cubic gross capacity with floor area costing to check the results and aim for a realistic approximation to the actual building costs. There is no direct connection between costing figures and the actual costs factors. This method is quick and easy to use and generally well known by architects and clients. But is imprecise because the use of space and ground plan arrangements could differ. Hence, it is important to select comparable properties correctly.

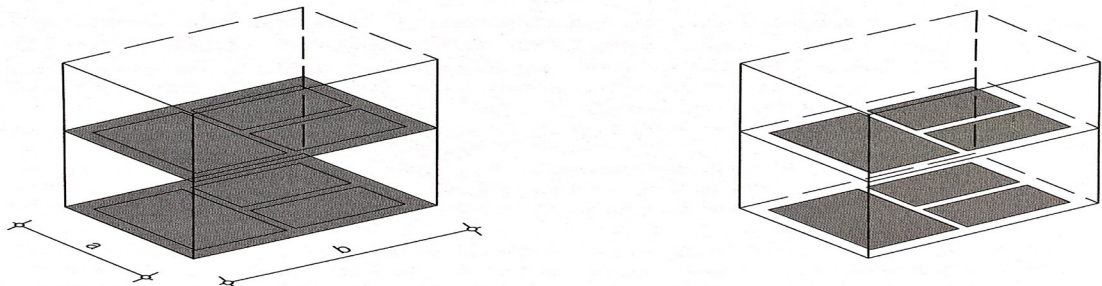


Figure 57. Floor area and usable area method. Bielefeld (2013)

- Component elements

It is used during later planning stages when a more detailed calculation method is needed. A definitive building design is essential for this, as quantities have to be calculated for the individual structural buildings components needed for the planned buildings. A uniform procedure must be followed to establish the quantities of the individual components elements such as an exterior wall or a ceiling. The cost figures relate to a specific part of the building rather than a building type creating a direct connection between cost figures and cost factors. The costings for the individual components are multiplied by the quantities and it can be used by cost generators. This method can be highly precise but it can be time-consuming and complex because different specialists and craftsmen are mixed when costing for a component element.

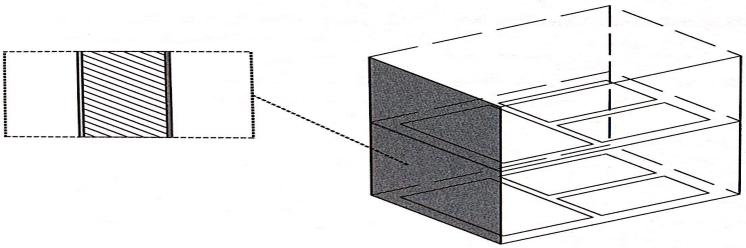


Figure 58. Component elements method. Bielefeld (2013)

- Construction and system elements

A construction element is a part of a building that can be designated as a component and also assigned to a particular construction skill. This method is based on a building description, which must contain all the construction elements in the planned building. When using this method, it is necessary to go through the individual cost groups for a building and note all the relevant construction elements. In this, way a "catalogue" is realized establishing in a table all the quantities to later on calculate the overall construction element by multiplying the quantities by the costs figures. The main advantage lies in the additional use that can be made of the calculated costs by reallocating them in budgets for tendering units for individual craft skills. Despite the high level of detail it remains flexible, as each construction element can be allocated precisely to a cost group.

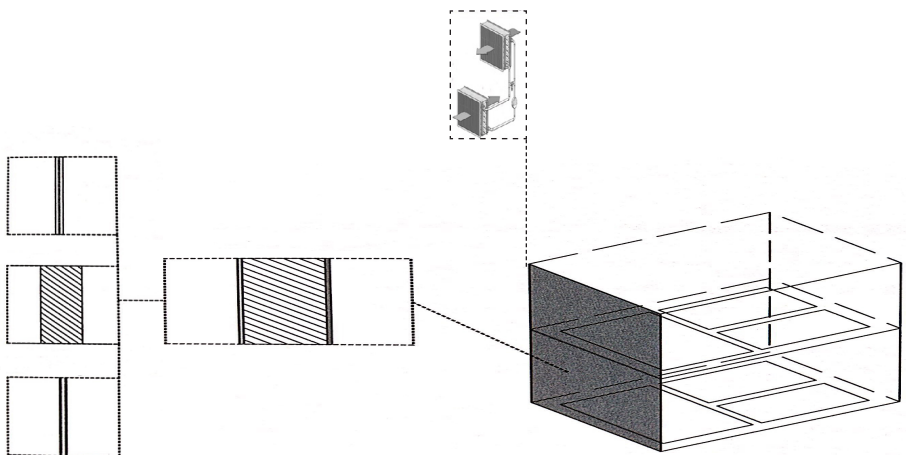


Figure 59. Construction and systems elements. Bielefeld (2013)



Operational costs (energy costs)

According to NEN-ISO 15686-5:2017 when an analysis is made for energy costs, present-day supply costs should be considered unless it is foreseeable that the relative costs can change between alternative energy sources. Where an investment judgment is assessing energy-efficient technology, energy savings should be treated as a future income stream (or negative cost) for comparison purposes. According to Lin & Gerber (2013), operation costs are calculated by combining the expected fuel and electricity usages from the energy simulation results multiplying them by the units costs provided by the user or the defaults in the system.

In EN 15459-1:2017, a calculation method called “Global cost” is defined. It consists of summing the present value of the initial investments costs, annual running costs and replacement costs (referred to the starting year) as well as disposal costs if applicable. In other words, is aggregating the past, present and future costs over a period of calculation as shown in Fig. [60]. It can be calculated on a yearly or a monthly basis.

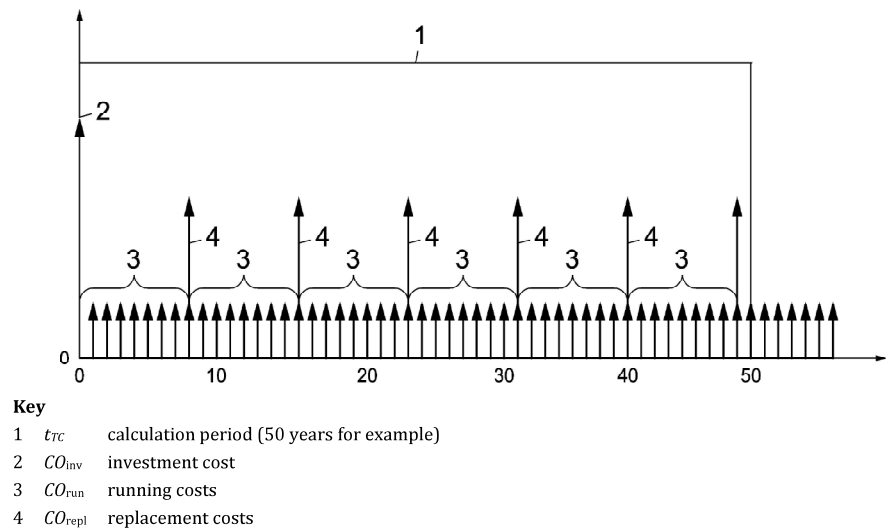


Figure 60. Global cost method. NEN-EN 15459 (2017)

For the aim of this thesis, only energy costs and payback periods will be reviewed. According to EN 15459-1:2017 the calculation of the energy cost during the operation stage is calculated by coupling the energy consumption with the tariff for the energy considered.

The energy is calculated or metered depending on the data availability (existing building, or building in construction or at the design stage).

In the same standard, it is explained that the systems related to energy are divided into several types. Fig. [60] proposes a presentation of the energy costs calculation. The following will be analyzed according to the research interests:

- Building thermal envelope and building construction  
This includes part of the structure, which is related to energy efficiency or energy consumption, more generally all the building envelope elements that have an impact on the thermal transmittance.
  - Roofing and roof insulation
  - Wall
  - Glazings and openings
  - Ground floors and basement ceilings

- Space heating
  - Generation
  - Storage
  - Distribution
  - Emission
  - Control
  - Connection to energy
- Space cooling
  - Generation
  - Storage
  - Distribution
  - Emission
  - Control
  - Connection to energy
- Lighting
  - Type of lighting and associated control systems

In some cases, the energy consumption should be calculated according to the flexibility or the tariffs of the utility. These tariffs (mainly for electricity) may vary during the day and specific periods of the year. Renewable energy sources or energy sales can be considered either as a financial income or as a way to reduce the energy cost of the building. It is fundamentally important to consider this aspect during the early stages of the design. In NEN-ISO 15686-5:2017 it is stated that the planning and the design phase offers the greatest potential to influence the post-construction life-cycle cost since the opportunity to lead the design and construction becomes increasingly limited as the acquisition phase proceeds beyond the commitment to invest in purchase or construction of the asset. In this scope, up to 80% of the operation, maintenance and replacement cost of a building can be influenced in the first 20% of the design process.

	CONVERSION FACTOR FOR PRIMARY ENERGY <sup>a</sup>	UNITARY COSTS <sup>b</sup>	CO2 CONTENT	HEATING	COOLING	VENTILATION	DOMESTIC HOT WATER	LIGHTING	TOTAL (\$)
Energy 1									
Energy 2									
Energy exported									

<sup>a</sup> For information, as the energy cost is base on the delivered energy.

<sup>b</sup> Unitary cost per kWh could include a fixed and proportional part dependig of the energy carrier and commercial conditions of the supplier; different values...

Figure 61. Global cost calculation method. NEN-EN 15459 (2017)

- Prospective incomes.

According to Lin & Gerber (2013) there are two possible ways to calculate the potential revenues of diverse building design options. The first method has to do with a business model that changes according to the use of the building and the context conditions. Gerritse (2008), analyses the case of office buildings, the rental or selling of the space is considered as a Cash flow defining the amount of revenue that a design option could recover and this is used later on to compare design alternatives. To calculate this generally the Net Present Value (NPV) technique is applied. It is defined by Lin & Gerber as a technique utilized to provide financial performances of design alternatives through an estimate of the expected, operation costs, construction costs and generated revenue values. According to NEN-ISO 15686-5:2017 is described as the sum of the discounted benefit of an alternative less the sum of the discounted costs, and it is calculated with the following formula:

$$X_{NPV} = \sum (Cn \times q) = \sum_{n=1}^p \frac{Cn}{(1+d)^n}$$

where

- $C$  is the cost in year,  $n$ ;
- $q$  is the discount factor;
- $d$  is the expected real discount rate per annum;
- $n$  is the number of years between the base date and the occurrence of the cost;
- $p$  is the period of analysis.

Figure 62. Equation 4- NPV cost calculation method. NEN-ISO 15686-5:2017

Secondly, the payback period is defined by EN 15459-1:2017 as a methodology used to compare the cost efficacy of two or more different solutions. Usually, the selected option is compared to a reference. The payback is considered when the global cost of the option is lower than the global cost of the reference for the same period of calculation. For new buildings, the reference could be a building that satisfies the minimum requirements of the national regulation. The payback period is the time when the difference between the initial investment cost for the optimal and reference case are balanced with the cumulative annual costs difference in each individual year:

$$\sum_{t=1}^{TPB} CF_t \cdot \left( \frac{1}{1 + RAT_{disc}} \right)^t - CO_{INIT} + CO_{INITref} = 0 \tag{8}$$

where

- $CF_t$  is the difference of annual costs (cash flow difference) between the optional case and the reference case in year  $t$ ;
- $TPB$  is the last year for payback period (time when the sum is stopped when the formula becomes negative or equal to 0);
- $RAT_{disc}$  is the discount rate;
- $CO_{INIT}$  is the initial investment costs;
- $CO_{INIT,ref}$  is the initial investment costs for reference case (is 0 for option doing nothing).

Figure 63. Equation 5-Payback calculation method, NEN-ISO 15686-5:2017

### Examples

In the paper “Optimizing creatively in multi-objective optimization” Ashour & Kolarevic (2015) developed an exercise to optimize the De Rotterdam office building in the Netherlands, in this approach two aspects were selected to improve, the following elements were analyzed; area ratio (FAR) financial profit, average daylight factor and views. Chosen because according to the author nowadays the main aim is efficiency and maximum profit and also because they are easy to quantify. The author also mentions that this multi-objective optimization together with automation of performance feedback are well explored using Revit in combination with Green Building Studio. Nonetheless, the application of MOO with an automated performance feedback loop has not been fully developed in Grasshopper (Ashour & Kolarevic, 2015). For this research project the constraints such as height restrictions and plot dimensions , building information, data such as program areas ( hotel,residential, office & retail), profit calculations and geometry definitions were established Grasshopper. Daylight and views simulations were done in Diva.

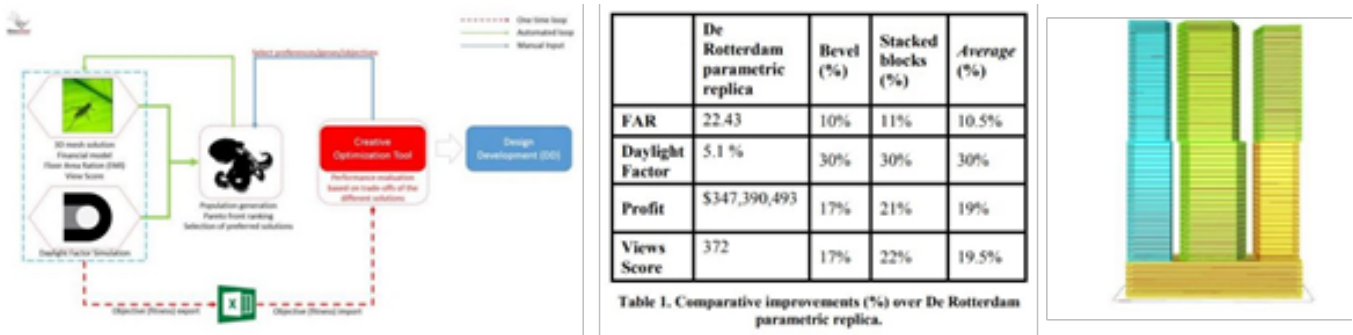


Figure 64. Optimization workflow for the volume and daylight. Ashour & Kolarevic (2015)

Octopus was utilized for the optimization process and Microsoft Excel as a quantitative database with the costs linked to Grasshopper by the Plug-in called “LunchBox”. The general workflow is shown in Fig. [64].

For the cost analysis, local market prices and construction cost databases were reviewed according to the case study location selection. The objective was to model a financial system in combination with programming and massing design studies as stated by Flager, et al. (2009). In the paper “Cost estimating and material takeoffs with parametric tools” Tucker, et al. (2015) suggests that parametric information supports the continuity in the development of a design. Analyzing the case study of the San Francisco Museum of modern art expansion. He suggests that a parametric infused cost estimation and material take-off strategy can influence the design and that an optimization sequence can investigate how to reduce cost of a project by pushing design options through Grasshopper with design constraints and cost evaluation for each configuration. In this way he states that time can be used for refining designs rather than manually looking over 2D drawings and re-calculating elements.

In the paper “Cost analysis and data-based design for supporting programmatic phase”, Marin et al. (2015), proposes a parametric cost estimation strategy based in associative modeling. This parametric process was based on the definition of parameters that influence the shape.

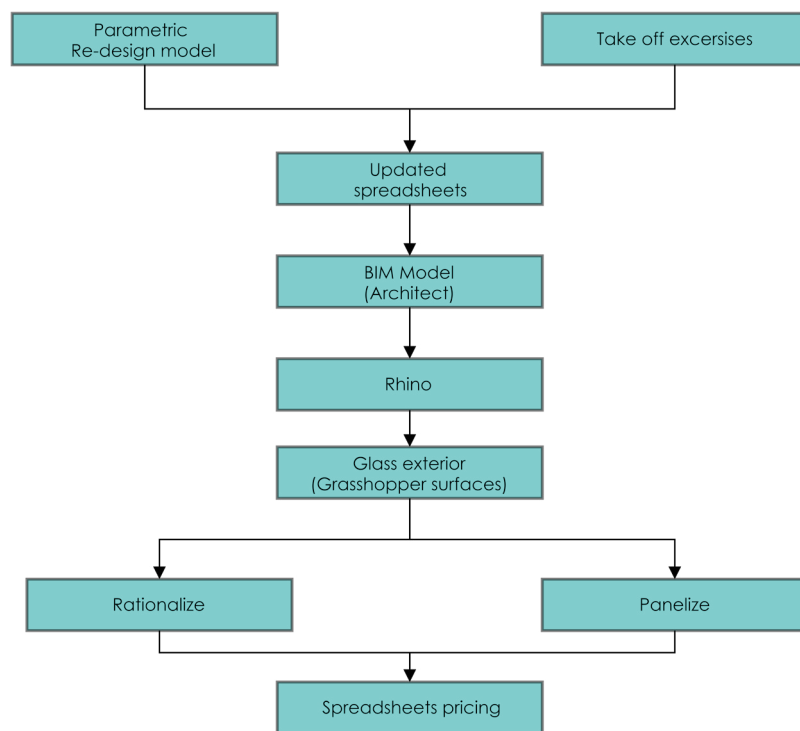


Figure 65. Cost estimation method. Marin, et al. (2015)

In this article, it is mentioned that commonly there are three main costs evaluation methods based on the project development stage:

1. Design estimate. During the Project development (estimates based on plans and specifications)- Engineer
2. Bid estimate: During the negotiation (Direct construction costs + manpower+quantities and construction procedures)- Contractor
3. Control estimate: During the construction (Added value) Owner + design team

The objective of this research was to find a method to make cost approximation a design parameter, providing rapid direct feedback of diverse alternatives.

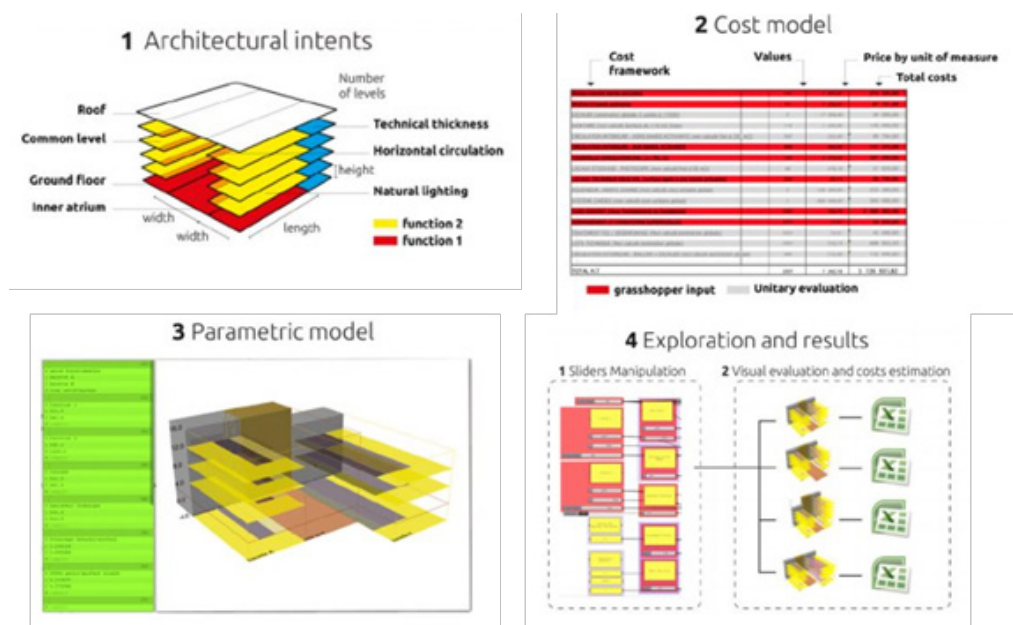


Figure 66. Cost estimation method overview. Marin, et al. (2015)

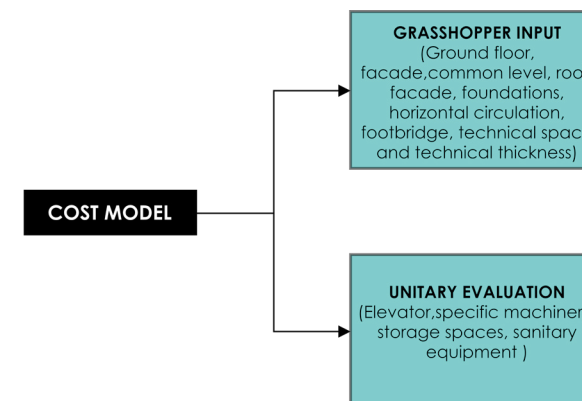


Figure 67. Cost estimation method overview. Jrade (2004)

In the end, the user is able to understand the project through a 3D representation, a list of surfaces to compare with the needs and a spreadsheet with the cost calculation. Fig. [67].

Jrade(2004), developed a parametric costing estimating method. A tool for preparing early conceptual estimates when there is only a little technical description.

The input parameters of the model were: Floor area, floor height, number of floors, percentage of area as office, percentage of area as wet lab, percentage of area as dry lab, percentage of area heated, percentage of area cooled, number of corners, interior construction finish quality, mechanical services quality, electrical services quality, escalation factor, location factor and local productivity factor.

The method uses a cost accounting system that refers to a database and operates statistical evaluation to provide a global cost evaluation divided into ten criteria:

- Foundations
- Substructures
- Superstructures
- Exterior closures
- Roofing
- Interior construction
- Elevators
- Mechanical
- Electrical

The method however according to Marin et al. (2015) Does not provide rapid feedback to evaluate and support design decision making. So it does not become a design parameter and architects cannot operate tests, hypotheses and make choices based on tactical strategies.

Abelmoshen, et al. (2011), proposes an automated costs analysis of a conceptual design based on a BIM model using an IFC data description to extract quantity take-off data and generates an XML file, which is then used by a software called PACES for cost estimating.

Another example is proposed by Gerber, et al.(2012) in the paper "Associative parametric design and financial optimization "Cash Back 1.0." A Genetic algorithm is applied to optimize the geometric model in function of financial criteria and offers automated generated



alternatives that are displayed visually and that contribute to the preliminary design decisions. The parametric and associative tools support the design process and engage at the same time visual interaction and wider exploration of spatial solutions.

- 1. Process integration
- 2. Design exploration
- 3. Optimization

The designed Genetic algorithm definition followed the following strategy:

- 1. Site constraints
- 2. Program ratio
- 3. Program geometry
- 4. Continuous geometry
- 5. Cost and revenue
- 6. Profit calculation
- 7. Galapagos
- 8. Excel exporter

The fitness criteria was to optimize the programmatic mix for profitability, therefore ,Galapagos (an evolutionary optimization tool) removes the worst combinations and breeds the most fit ones:

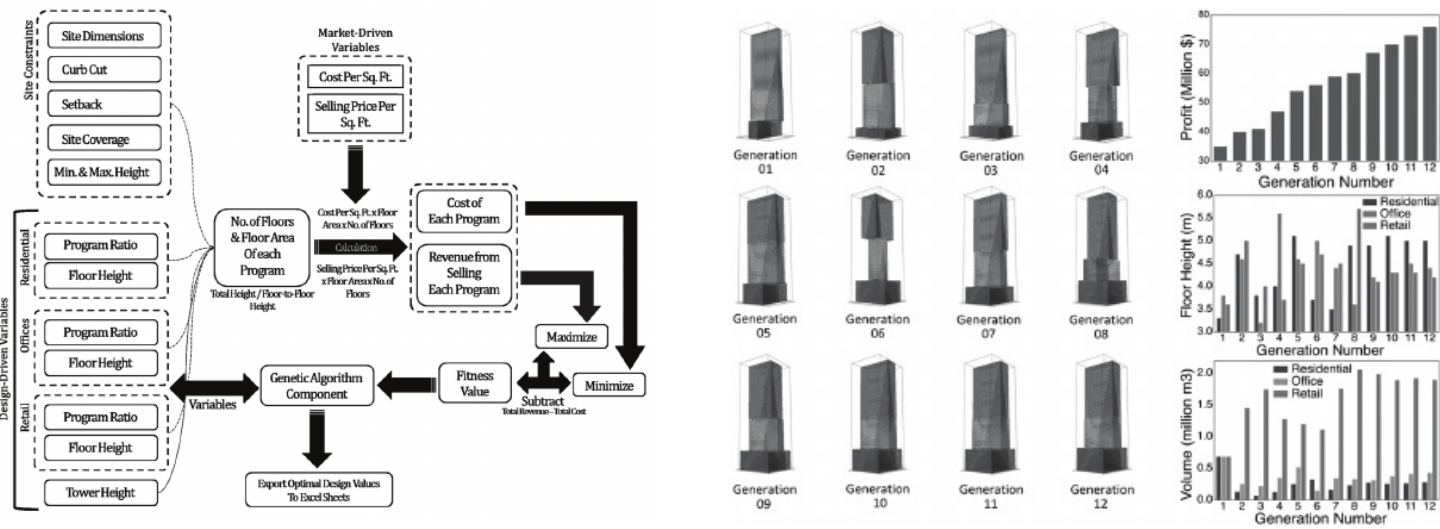


Figure 68. (Left)Associative parametric workflow.(Right)Results and design options visualization. Gerber,et al .(2012)

Garcia & Furtado (2015), developed a case study focusing in cost performance in the conceptual design phase, proposing a feedback loop in the process where every time there is additional information this can be included in the sequence of decisions. They have focused in program, sunlight, and ventilation as criteria. Dividing the process into 7 steps in where they talk about a division between a more general approach called Macro BIM to a more detailed phase defined as Micro scale:

- 1. Conceptual design
- 2. Automated
- 3. Semi automated



Figure 69. Overview of costs calculation method. Gerber, et al. (2012)

- 4. Digital process
- 5. Number of evaluations
- 6. Macro BIM
- 7. Micro BIM

cost performance of each analyzed option for decision support. However, as stated by Garcia & Furtado (2015) in this performance-based approach, the proportion of authorship can lower when compared to a conventional design. In this project they propose a strategy to explore options according to a specific budget or fixed constraint, reversing the traditional approach when working with consequential costs as illustrated in Fig. [70]. “Putting the architect in the position not only of creator and organizer, but also of construction facilitator.” (Garcia & Furtado, 2015)

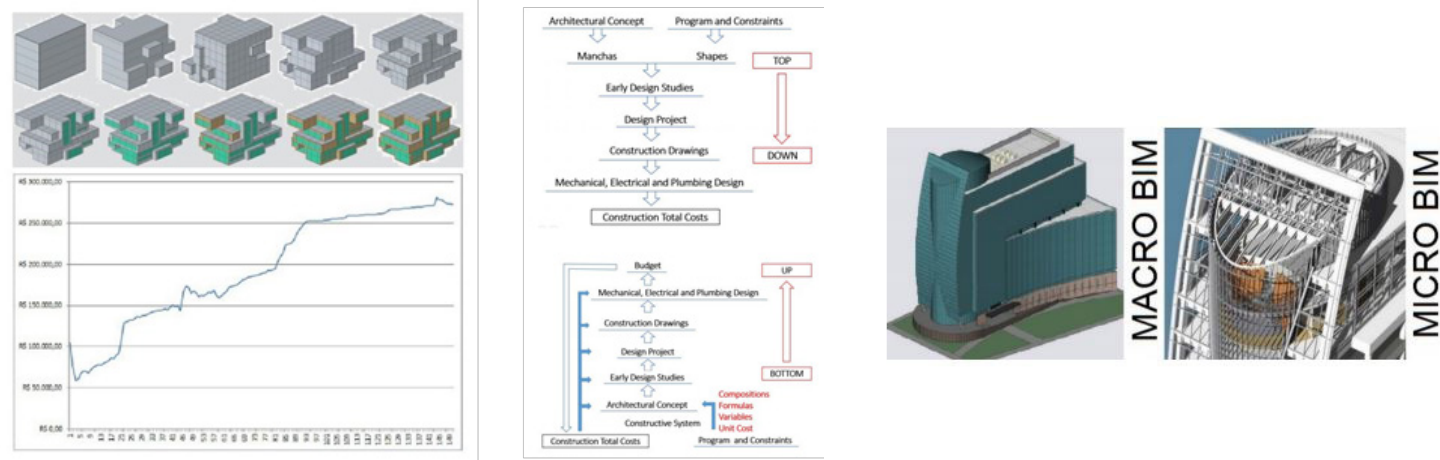


Figure 70. (Left) Different results visualizations. (Middle) Top down and Bottom up diagrams. (Right) Macro and Micro strategies description. Marin, et al. (2015)

Being the structure an essential part of the building, it represents a significant percentage of the final cost of a building specially in large spans buildings such as sports venues.(Culley & Pascoe (2009). Therefore, it is an aspect that should be taken into account when thinking about energy and cost-effectiveness and will be also analyzed in this thesis.

In the article “Multidisciplinary process integration and design optimization of a classroom building”, John Haymaker (2008) applies the so-called “PIDO” technique defined by the author as Process Integration and Design Optimization, to optimize the structural and energy performance of an educational building. After analyzing several existing tools and strategies he set up the objectives consisting as follows:

- Minimize the capital cost of the buildings steel frame
- Minimize life cycle cost for the buildings operation

The design constraints in this exercise were:

- Structural safety: meeting building code requirements for strength
- Daylight performance : maximum annual average lighting power multiplier of .6
- Space: fixed 960sq ft area in a single-story building.

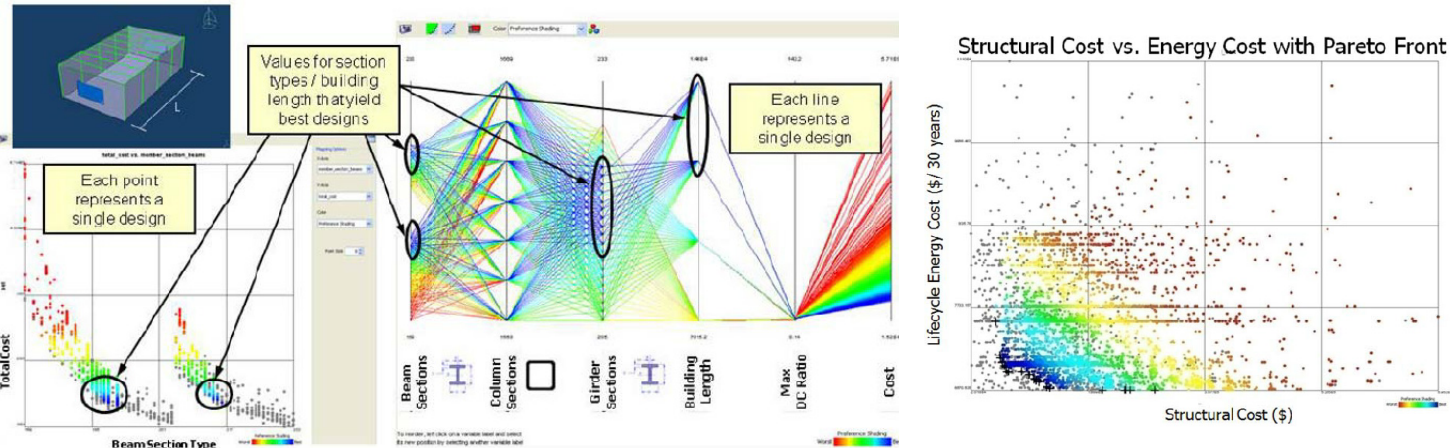


Figure 71. Design alternatives visualization and comparison. Haymaker (2008)

As part of the applied methodology, Haymaker (2008) also analyzed the cost of the structure, by using a cost calculator component that calculates the total cost of the building's steel frame based on the sum of the weight of each structural member multiplied by an assumed price of steel per unit weight defined by local market fees.

By having as variables the type of sections of the steel frames, the size of the windows (Window to wall ratio) the building orientation and the building length, it was possible to get a significant number of design alternatives to compare.

As one of the main conclusions, as it can be seen in Fig. [71] there is an important trade-off between structural costs and energy (operating) costs. More precisely, the best designs from an energy point of view have a relatively high capital cost and vice versa.

For this research, the utilized software were Digital Project (Ghery technologies), Excel spreadsheets to manage the information, Energy Plus as a simulation engine for energy and thermal calculations, GSA for structural simulations and Model Center as a genetic optimizer platform.

### 3.2.2.5 Types of optimization

The following chapter will review the three different optimization techniques that work essentially with the same performance simulation-based logic as explained before but varying in the type and number of objectives and in the disciplines involved in their processes. Fig. [72] shows an overview of the main objective relevant aspects in building design.

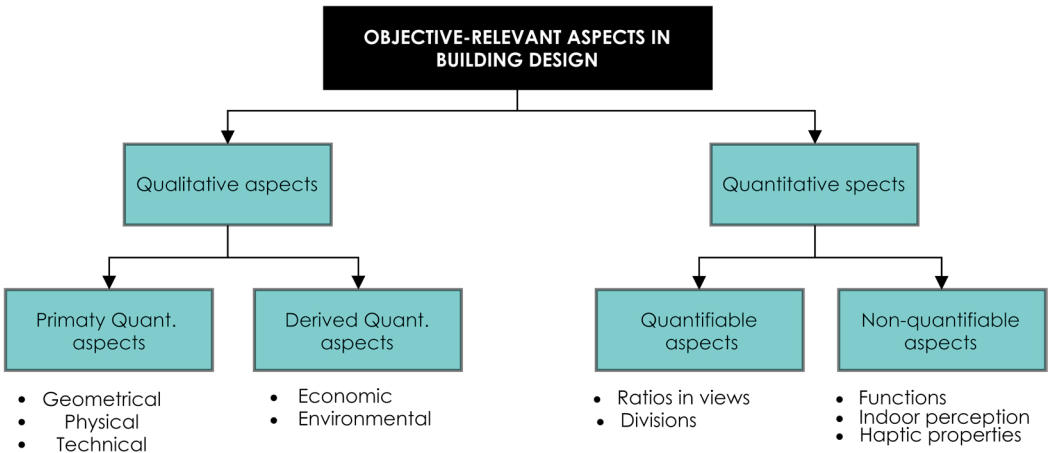


Figure 72. Relevant objectives in Building design, Geyer & Beucke (2010)

#### 3.2.2.5.1 Single objective optimization

In a single-objective optimization, an optimum solution of the problem could be its global minimum or maximum. (Attia, et al. 2013). According to Albright (2005) most real-world optimization problems are best represented as constrained optimization problems. Formulated as follows:

$$\begin{aligned} &\text{Optimize } f(\mathbf{X}) \\ &\text{Subject to:} \\ &\quad \mathbf{C}(\mathbf{X}) (=, \leq, \geq) 0.0 \\ &\quad \mathbf{X} \in \Omega \end{aligned}$$

Figure 73. Single objective optimization problem definition. Albright (2015)

where:

f is the objective function  
X is the vector of decision variables,  
C is the set of general constraints, and  
n is variable space.

3.2.2.5.2 Multi-objective optimization

In many real problems like building design, it is required to address more than one objective function simultaneously. Such problems are multi-objective optimization problems. Rather than achieving a solution as maximum or minimum for a single objective function as described before, in the multi-objective optimization, a balanced result should be attained between two or more conflicting objective functions. Therefore, the aim of a multi-objective optimization problem, also called Pareto optimization (Evins, 2013) is to find the trade-off in satisfying all the individual objective functions.

According to Mueller, et al, in Peters & Peters 2013, there are two principal approaches to resolving conflicting goals. One approach priorities goals and computes a single optimum while the other looks for the ones that relatively performance better for each goal compared to the others.

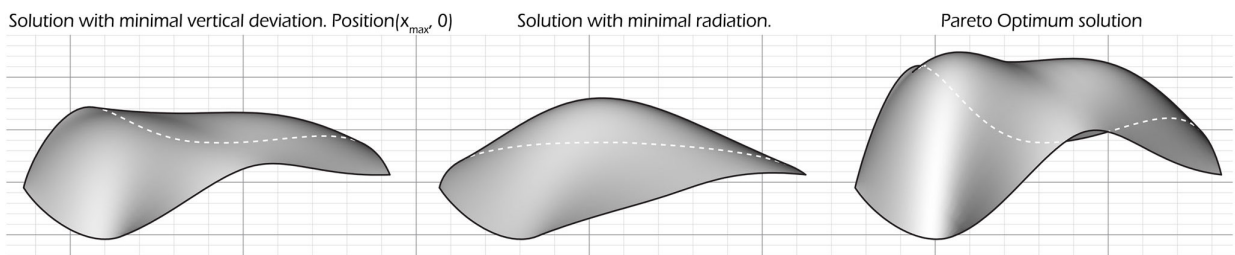


Figure 74. Multi-objective optimization example

3.2.2.5.3.1The Pareto front.

” Selecting a single design from the set of all Pareto efficient designs could be understood as the exact location where computation meets design”

- Scott Marble ,2012

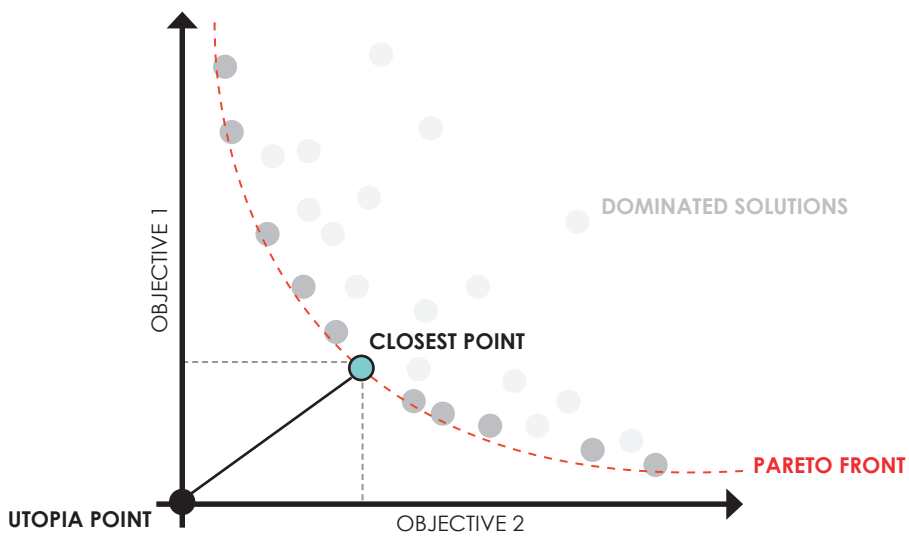


Figure 75. Pareto Front description

As shown in Fig. [75], the Pareto front consists of a series of equally optimal solutions, from which a single design solution must be chosen. The aim is to find the Pareto optimal trade-off among conflicting design objectives such as for example maximizing thermal comfort and minimizing energy consumption. Or improving energy efficiency and reducing the investment costs. According to Radford & Gero, (1988), in their book titled “Design Optimization in Architecture, Building, and Construction, study the application of Pareto efficiency for architectural design.” Compared to other optimization techniques, the Pareto optimization “is more realistic and useful for design” because “ it allows subjective criteria to be taken into account”

Conforming (Attia, et al. 2013) The most commonly used methods for multi-objective optimization can be classified into three categories: enumerative algorithms, deterministic algorithms, and stochastic algorithms.

The enumerative methods search in a discrete space. These algorithms are computationally expensive and hence not appropriate for applications that demand several solutions.

The deterministic algorithms require the evaluation functions to have continuity and derivability. Therefore, this makes them not suitable for handling discontinuous building and HVAC problems with constrained parameters.

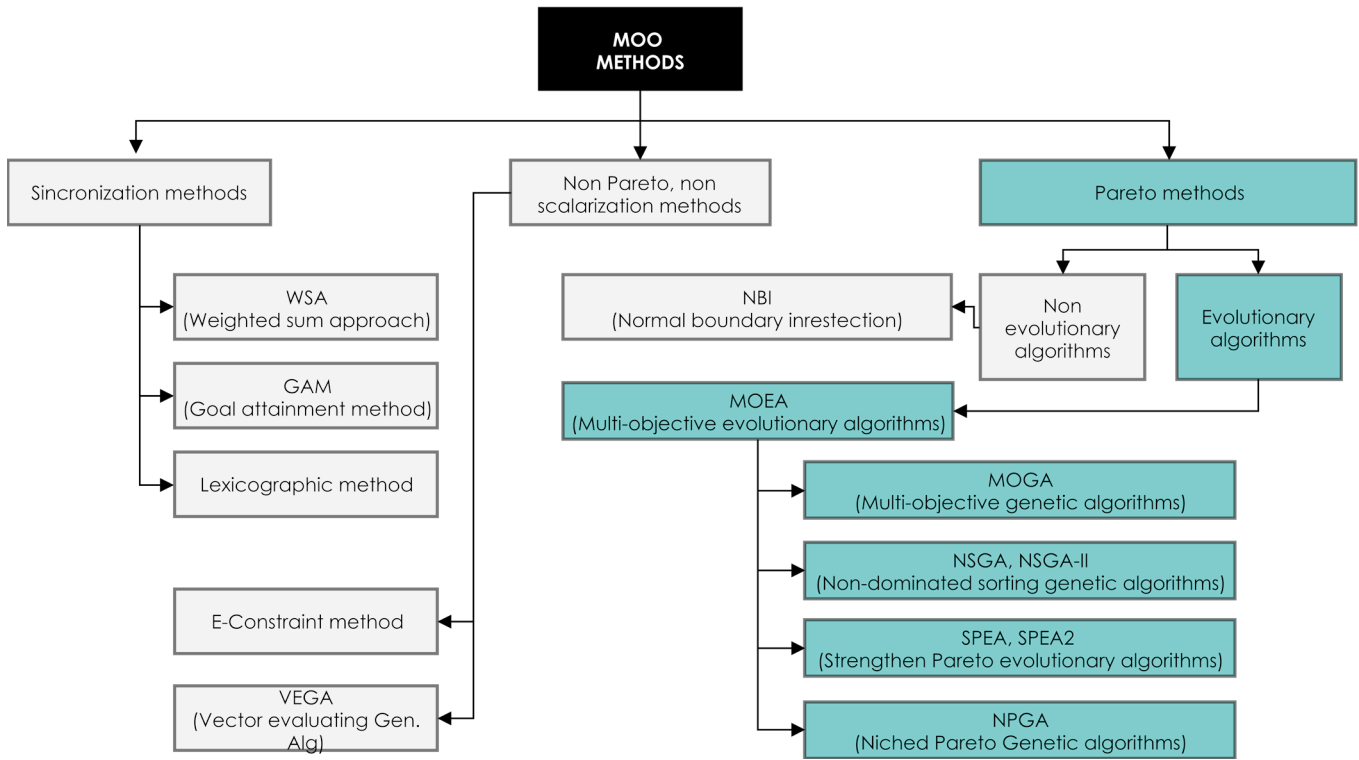


Figure 76. General classification of MOO solving methods , Chouraqui & Benzater (2013)

Contrarily, the advantage of the stochastic algorithms compared to the previous examples is the limited mathematical requirements for driving the optimization processes (Attia, et al., 2013) . Being Genetic algorithms combined with the Pareto concept widely used in recent years for optimization of building and HVAC systems.

Among this type of algorithms, according to several studies and reviews, The NSGA-II (Non-Dominated Sorting Genetic Algorithm II).is a widely used optimization algorithm that handles multi-objective building and energy efficient design problems with several variables, (Shi, 2016)



According to Brown & Mueller (2016), This algorithm starts with a population of design options, then it does an evaluation of their performance, and breeds the next generation through crossover and mutation between the highest performing designs. This employs a diversity preservation mechanism to ensure a representative spread along the entire Pareto front and it also uses the concept of elitism to speed the computation.

In the paper “Designing-in performance: A framework for evolutionary energy performance feedback in early stage design”, Lin & Gerber (2014), developed a workflow based in what they defined as Evolutionary Energy Performance Feedback for Design (EPPFD) in where they start stating that a computational design tool not only requires a user-friendly environment but also to have the ability to provide the following aspects:

- Rapid generation of design alternatives
- Fast evaluation of design alternatives
- Trade-off analysis of competing criteria
- A search method to identify design alternatives with better performance.

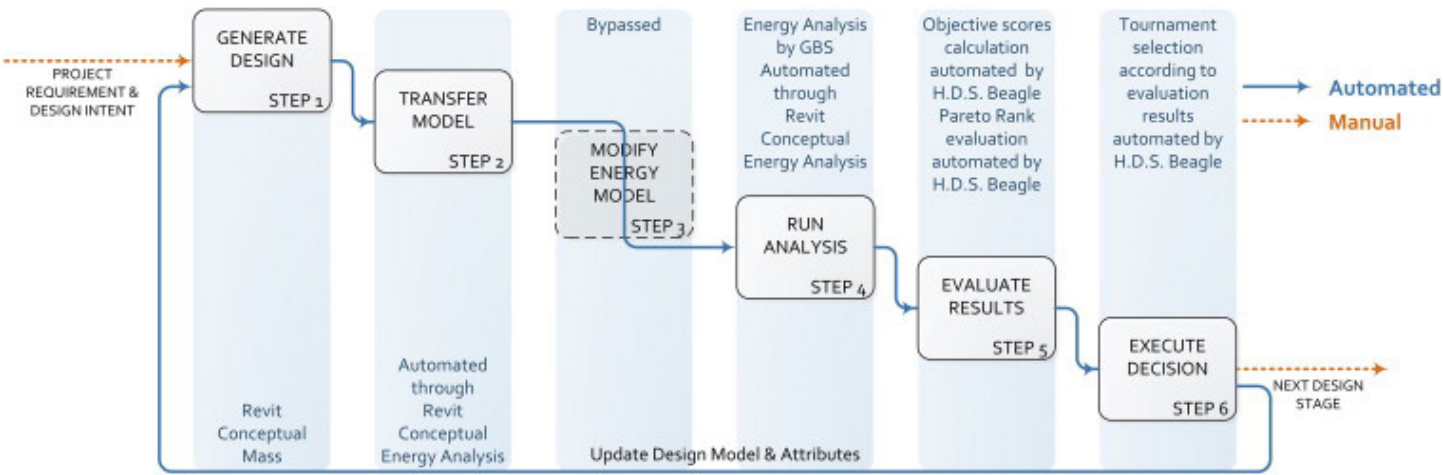


Figure 77. Six steps strategy for integrating design and energy simulation. Lin & Gerber (2014)

In this scope, the intention was to implement performance evaluation in the early stage of the design providing feedback to influence design exploration and future design decisions. By putting particular attention on the importance and impact of the form exploration in the energy use. The methodology consisted of a combination of parametric design and multi-objective optimization as shown in Fig. [77].

In essence, an initial geometry model was input into an automated system which is a cycled process until the automation loop is interrupted either by the user or by the meeting of the systems termination criteria.

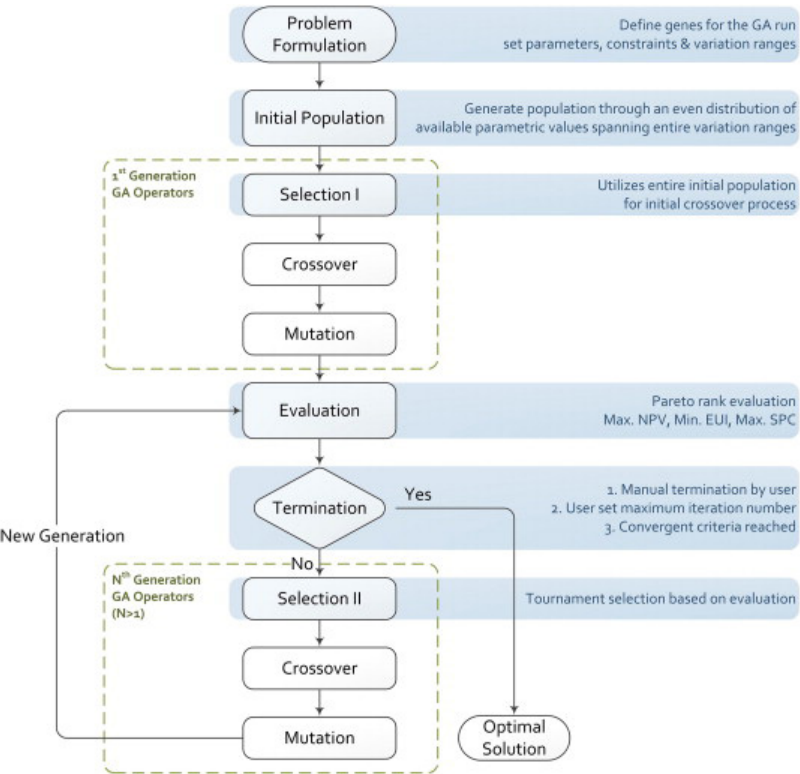
After this, as shown in Fig. [78] there are two ways to proceed; either one design alternative is chosen, and it proceeds to the next stage of development, or the user manually implements changes in the initial design or constraints file and starts the automate process again.

The selected objective functions were divided into:

- Spatial programming compliance, The spatial programming compliance score evaluates the meeting of the project defined program requirement by a generated design option.
- Energy performance. The energy use intensity (EUI) Value evaluates the estimated energy performance of the generated design options. Electricity and fossil fuel local costs were considered inside the calculations.
- Financial performance (NPV). This value was calculated according to the definition of a financial case for each generated design option. Construction costs Fig. [78] were derived from combining the calculated material quantities from the generated geometry with their respective user provided unit prices or the default cost settings. The cost calculation was divided in:

- Construction costs
- Operation Costs
- Generated revenue values

For the formulation of the design problem the authors Shin & Gerber (2013) developed the following strategy:



**Table 2**  
Financial settings, parameters, and formula in the Beagle Financial Model (NPV).

Cost category	Financial param name	Formula
Construction cost	Land Acquisition	$\text{Unit Land Acquisition Cost} \times \text{Lot Size}$
	Structure	$\text{Unit Structure Cost} \times \text{Gross Volume}$
	Floor Construction	$\text{Unit Floor Construction Type Cost} \times \text{Mass Floor Area}$
	Slab Construction	$\text{Unit Slab Construction Type Cost} \times \text{Mass Slab Area}$
	Exterior Wall Construction	$\text{Unit Exterior Wall Construction Cost} \times \text{Mass Exterior Wall Area}$
	Exterior Wall-Underground Construction	$\text{Unit Exterior Wall-Underground Construction Cost} \times \text{Mass Exterior Wall-Underground Area}$
	Interior Wall Construction	$\text{Unit Interior Wall Construction Cost} \times \text{Mass Interior Wall Area}$
	Glazing Construction	$\text{Unit Glazing Type Cost} \times \text{Mass Glazing Area}$
	Roof Construction	$\text{Unit Roof Construction Cost} \times \text{Mass Roof Area}$
	Skylight Construction	$\text{Unit Skylight Construction Cost} \times \text{Mass Skylight Area}$
Operation cost	Shade Construction	$\text{Unit Shade Construction Cost} \times \text{Mass Shade Area}$
	Circulation Cost	$\text{Unit Circulation Cost} \times \text{Gross Floor Area}$
	HVAC System Cost	$\text{Unit HVAC System Cost} \times \text{Gross Volume}$
	Annual Electricity Cost	$\text{Electricity EUI} \times \text{Electrical Cost} \times \text{Gross Floor Area}$
Revenue	Annual Fuel Cost	$\text{Fuel EUI} \times \text{Fuel Cost} \times \text{Gross Floor Area}$
	Annual Operating Cost	$\text{Unit Operation Cost} \times \text{Gross Floor Area}$
	Annual Lease Payment	$\text{Unit Lease Payment} \times \text{Gross Floor Area}$
	Cash Flow	$\text{Fixed User Defined Value}$
Cash flow	Cash Flow Time Span	$\text{Fixed User Defined Value}$
	Discount Rate	$\text{Fixed User Defined Value}$
Financial score		$\text{NPV} = \left( \sum_{t=1}^T \frac{C_t}{1+r} \right) - C_0$ <p>where <math>T</math> = Cash Flow Time Span <math>r</math> = Annual Rate of Return <math>C_0</math> = Construction Cost <math>C_t</math> = Revenue - Operation Cost</p>

Note:  
*Italic text* – Value retrieved from user modifiable template.  
Underlined text – Value retrieved from the conceptual mass building (.rvt).  
*Underlined bold text* – Value retrieved from the energy analysis results.

Figure 78. Multi-objective optimization workflow. Lin & Gerber (2014)

1. Design problem formulation

- Parameters possessing a range of values:
- Design parameters (geometric configurations)
- Energy setting parameters (energy consumption)
- Parameters possessing a given value
- Spatial program parameters
- Financial parameters

2. Genetic Algorithm encoding

3. Population methods

4. GA operators

- Crossover
- Mutation

5. Evaluation

6. Termination criteria

7. Trade off analysis for design decision support.

In this method, as illustrated in Fig. [79] the evolutionary generations were defined by crossover and mutation operators selecting the options with the higher rankings to be the parents of the next generation and so on.  
The applied tools were Autodesk Revit, Excel and Green Building Studio utilizing Beagle as a prototype plug-in link.

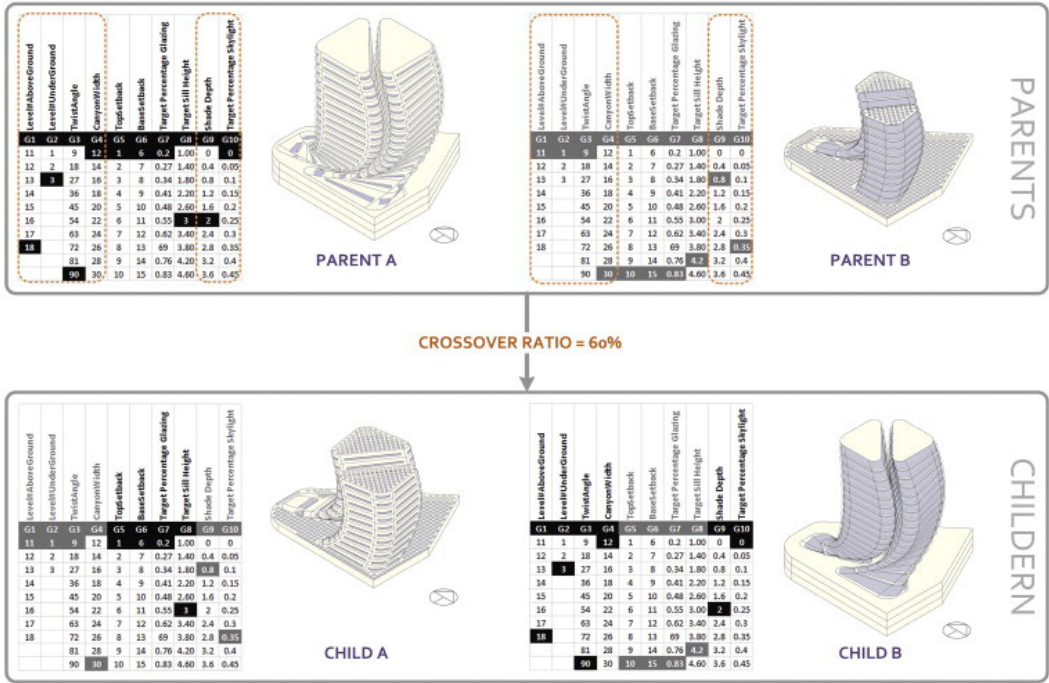


Figure 79. Crossover results optioneering results. Lin & Gerber (2014)

3.2.2.5.3 Multi-disciplinary optimization

Due to the fact of the increasing complexity of systems, nowadays MOO may involve different disciplines simultaneously, instead of being constrained in one specific discipline as illustrated in Fig. [80]

Multi-objective and multidisciplinary optimization (MMDO) is a powerful tool that takes into consideration of multiple disciplines at the same time instead of optimizing each discipline individually. According to Yang, et al.(2015) The most significant advantage of MDO lies in its abilities of “decomposition” and “coordination”. Allowing the decomposition of complex systems into smaller subsystems (solved separately) Fig [81] and for coordinating the subsystem solutions between different disciplines, towards an optimal system design that fulfills with defined objectives, being the primary challenge distributing the analysis and optimization,

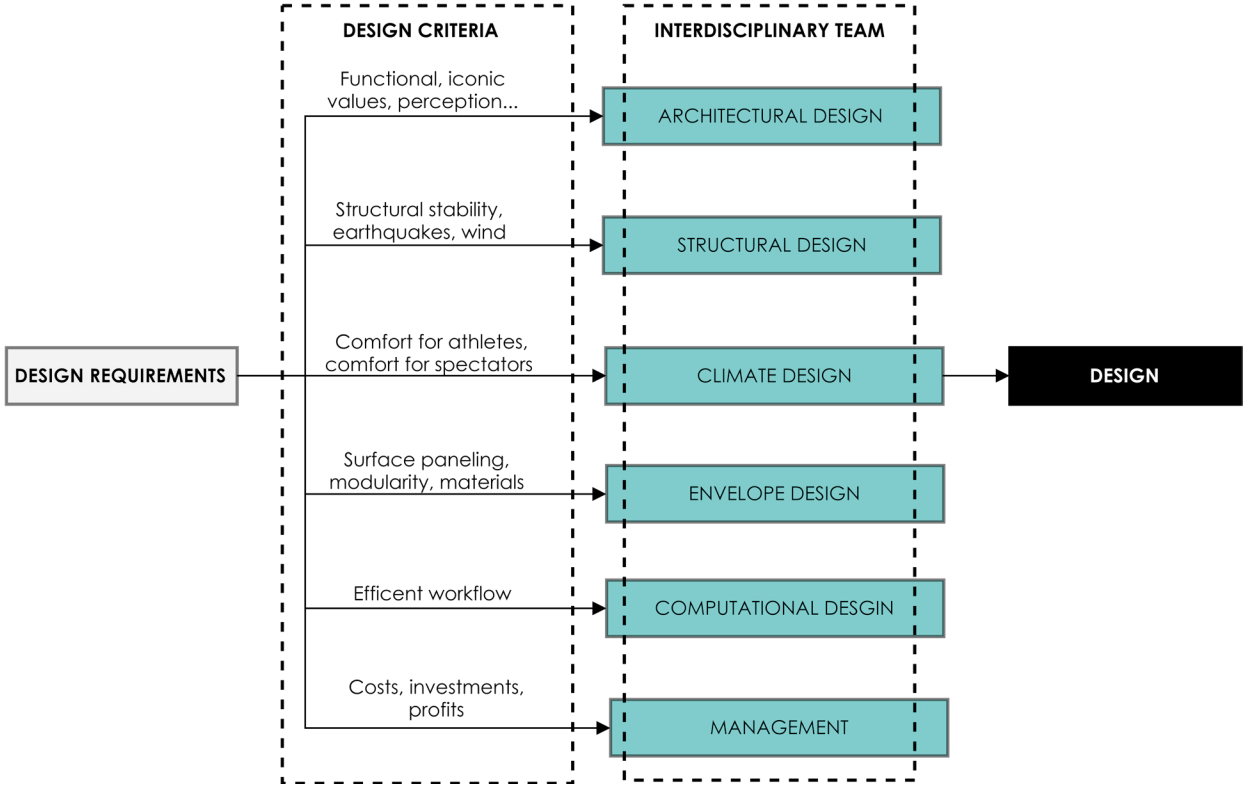


Figure 80. Interdisciplinary design criteria Turrin, et al. (2015)

and coordinating the couplings or interactions among these subsystems. These diverse objectives could furthermore include creating a combination of spaces that meet different applicable codes and standards. Moreover, as stated by (Shi, 2011), the objectives could be to produce a beautiful building while minimizing the consumption of energy, materials and simultaneously maximizing the thermal comfort, natural lighting etc... Due to the fact that most of the time the different disciplines in the AEC Industry are uncoupled unlike in the Aerospace problems, parallel computation for the different subsystems can be implemented.(Yang, et al. 2015)



In the paper “Multi-objective and multidisciplinary design optimization of large sports building envelopes: a case study”, Yang, et al.(2015) experimented a process based in MDO with a MDF (Multidisciplinary feasibility) approach into the design of a Sports hall in Guangzhou China. Where they essentially coupled daylight and energy analyses, which are intrinsically related, while the structure analyzer is independent. Then they simplified NURB surfaces and converted them into meshes. For this exercise, the used software was DSM (Design structure Matrix) to

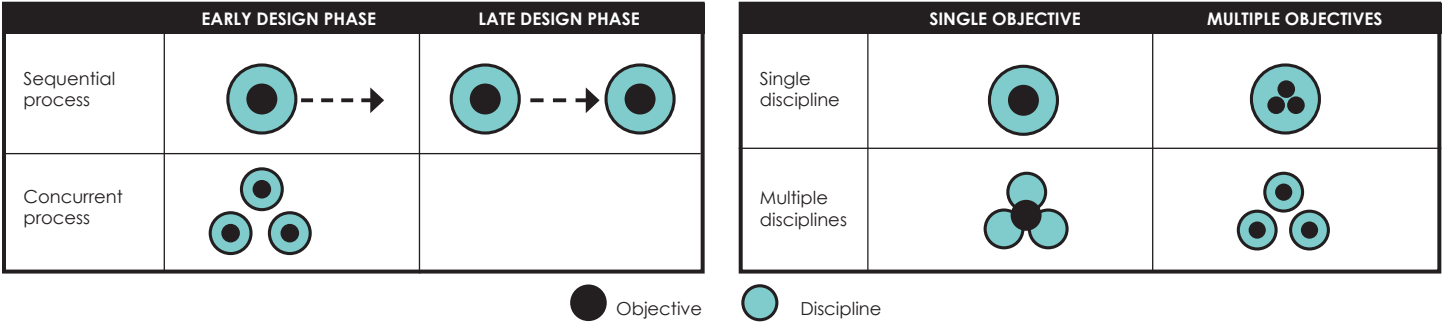


Figure 81. Different types of optimization processes. Yang, et al. (2015)

organize and illustrate the workflow, Rhino/Grasshopper as modeling tools and modeFRONTIER as a multidisciplinary optimization platform which according to Yang, et al. (2015) facilitates the automation of the design simulation process, and enhances analytic decision making. Finally, they utilized a customized interface (plug-in) to communicate software with each other and run the process automatically. The simulations were done in the Grasshopper plug-ins Ladybug and Honeybee for the daylight and energy while Karamba was applied for structural analysis. Using for daylight the energy engine Daysim and for energy Energy Plus using the NSGA-II algorithm for the optimization process. For the design variables, the total floor area of the hall was fixed while the aspect ratio of the plan and the roof height could be changeable (Maintaining an overall spherical shape).

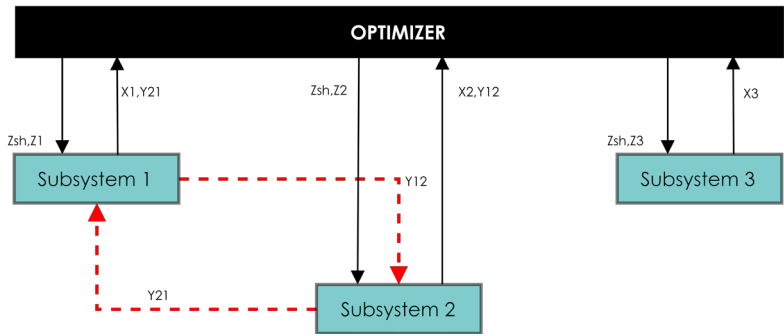


Figure 82. Multidisciplinary design optimization problems in AEC industry. Yang, et al. (2015)

For the objectives and constraints, the selection was to maximize Spatial Daylight Autonomy which is a metric that describes how much of a space receives sufficient daylight in one year, previously described. Having as a constraint 300lux for at least 50% of the operating hours (According to LEED v4)

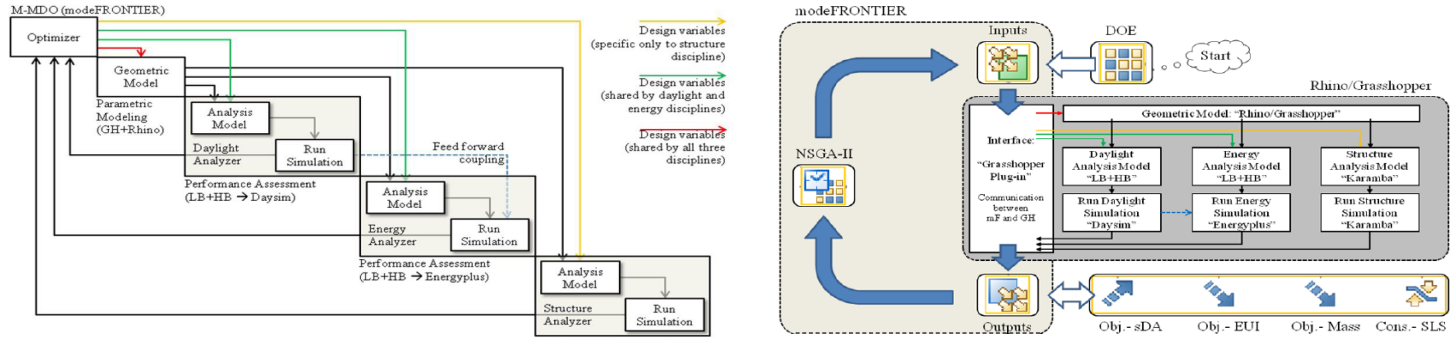


Figure 83. (Left) Methodology structure matrix. (Right) Overview of the tools integration. Yang, et al. (2015)

For the energy discipline, EUI (Energy Use Intensity ) was utilized to benchmark energy efficiency defined by Kwh/m2 of a building measured over one year. Which according to Yang, et al. (2015) it is an indicator which facilities direct comparison with other buildings.

Finally, for the structure, the objective was to minimize the total mass of the roof structure where a stiffness criterion and service limit state were also included as structural design constraints. Checking at the end the maximum displacement of the roof to decide the feasible solutions. For the final visualization and interpretation of data (Post- processing), they had employed several representation techniques provided by the mode FRONTIER platform shown in Fig.[85]

Disciplines	Variable Names	Unit	Lower Bound	Upper Bound	Step	Variable Type	Factor	sDA [%]	EUI [%]	Mass [%]
Daylight	Plan dimension in the X axis	m	40	70	-	cont.	Plan dimension in the X axis	23.0	23.5	9.0
Energy	Roof_height	m	1	9	-	cont.	Roof_height	28.5	33.7	9.5
Structure	Glazing_ratio	-	0.1	0.9	-	cont.	Glazing_ratio	30.5	22.2	6.9
	Truss_depth	m	2	5	-	cont.	Truss_depth	2.5	7.2	1.0
	Chord_diameter	mm	250	400	50	discrete	Chord_diameter	5.1	4.6	18.1
	Chord_thickness	mm	8	16	4	discrete	Chord_thickness	3.5	2.1	24.6
	Web_diameter	mm	150	300	50	discrete	Web_diameter	0.4	3.5	14.9
	Web_thickness	mm	4	12	4	discrete	Web_thickness	6.8	3.2	15.9

Figure 84. Selection of design variables and ranges. Yang, el al. (2015)

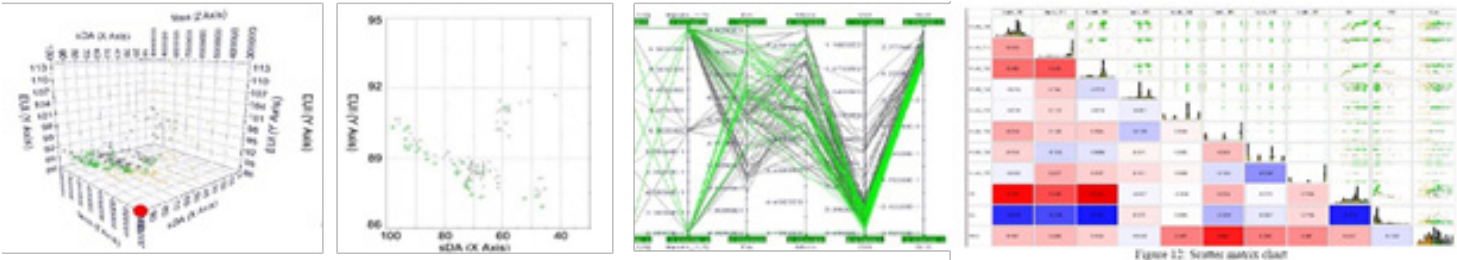


Figure 85. Data analytics and visualization strategies. Yang, et al. (2015)



3.2.3 POST-PROCESSING

3.2.3.1 Design exploration

“An optimal design does not necessarily equal a good design”  
-Scott Marble, 2012

According to Yang et al. (2017) the concept of design optimization is different from design exploration. Design exploration is the process of extracting information and applying it to propose or re-propose a design concept. On the opposite, design optimization refers to the process that is only focused on searching optimal design solutions by applying diverse optimization algorithms, once the design concept has been already defined. Hence, optimization generally occurs in a later stage, during which the definitions of objective variables, constraint objectives and design variables remain fixed.

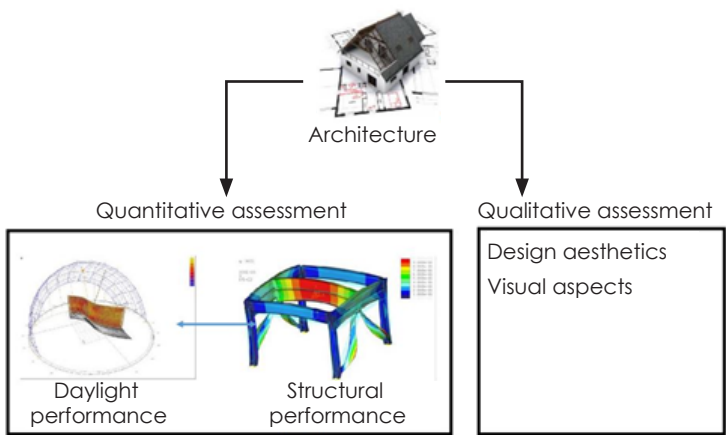


Figure 86. Types of design performance evaluation

According to Yang et al. (2017), The design exploration precedes the design optimization and it is more important. He explains that if one defines an improper or a bad design concept , he might probably get poor results no matter how advanced the optimization algorithm is. Lamentably, the majority of existing research does not consider the process of formulating a good design concept, and focuses on the late-stage optimization based on a single given design concept instead. Therefore, the research should focus more on the formulation of a good geometrical building design concept based on the information or knowledge extracted from a multi-objective design exploration. (Yang et al. ,2017) However, according to Turrin, et al.(2016), “the automated optimization procedures fail to take advantage of the designer expertise” while instead it should be incorporated providing feedback of the trade-offs between the

different disciplines and performance objectives. In this scope, as stated by Lin & Gerber (2014) MDDO as a combination of MOO algorithms and with parametric design demonstrates a great potential as an initial design exploration methodology that is capable of providing analytical feedback combined with geometry visualizations for early-stage design decision making. Nevertheless, according to Turrin et al. (2015) the majority of MMDO proposed tools and procedures are based on some techniques and platforms unfamiliar to architects, having a weak ability to deal with complex parametric geometry. Many current research tends to pay less consideration to the post-processing and interpretation of optimization results “They usually stop after obtaining the Pareto Front” (Turrin, et al. 2015). Proof of this is that for instance, statistically, more than 30 energy efficient optimization programs have been developed, unfortunately these are mainly used as research tools and cannot be readily used by designers without specialized expertise as according to Penna, et al. (2015).

CRITERIA	PARALLEL COORDINATES	PARALLEL SETS	SCATTERPLOT MATRIX	DECISION TREE	DENDROGRAM	FORCE DIRECTED
R1 Size < 100k	+	+	+	+	-	-
R3 Data Type	+	0	-	+	+	+
R4 Overview	+	+	-	-	-	-
R5 Impact	-	-	-	+	-	-
R2-6 Similarity	-	-	+	-	-	-
R7 Frequency	+	+	-	-	-	-
R8 Filtering	+	+	+	-	-	-
Score (points)	12	9	10	10	8	8

Figure 87. Visualization techniques comparison. Jusselme, et al. (2017)

In this sense, there are several data visualization techniques that are currently being applied to analyze and compare design alternatives. Among them, as defined by Jusselme, et al. (2017) and shown in Fig.[87] the decision tree and the parallel sets are the two more suitable techniques to understand the impact of the parameters in a design when not having a fully computational background.

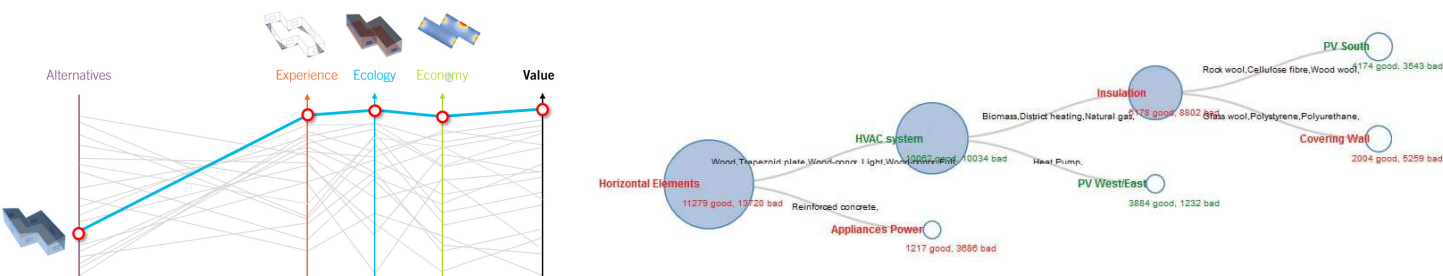


Figure 88. Comparison of data visualization techniques for Building performance simulation datasets. Jusselme, et al.(2017)

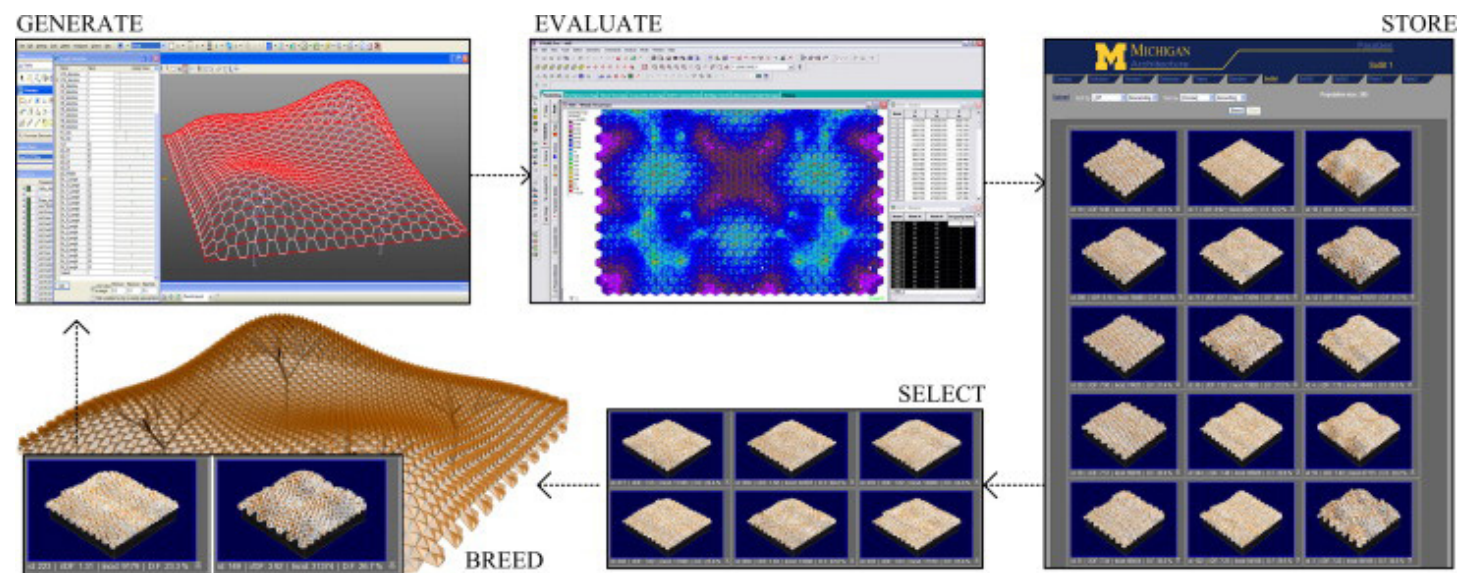


Figure 89. Para Gen visualization cycle. Turrin, et al. (2011)

### Examples:

In the paper “Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms” Turrin, et al. (2011). Developed a design tool based on parametric design and interactive design exploration called “Paragen”. The tool methodology consisted of 4 main stages:

1. The selection of variables
2. The generation of forms (Parametric modeling)
3. The evaluation of the generated forms, (Thermal and daylight)
4. Graphics of the design options (visualization)

This tool makes use of an online platform which stores the performance results in a SQL database linked to the data files so the designer can observe, compare and retrieve information through this web interface. This occurs in two levels, firstly, the designer is intended interactively generate the design solutions, and secondly, the designer is allowed to explore the results database. Therefore, the designer can observe both the numeric data from the performance evaluations and visualize the 3D geometry being able to focus the generation towards other sub-optimal solutions that better meet other criteria such as personal preferences

Another example of an interactive design visualization alternative is “Structure Fit” developed by Mueller & Ochsendorf (2016), it is an interactive web-based tool for structural 2D web trusses design. It works by using a proposed interactive evolutionary algorithm framework together with a graphical user interface to provide design feedback of diverse design alternatives to the designer in a fast and intuitive way. It consists of a CAD-like environment that works in combination with structural information stored in spreadsheets.

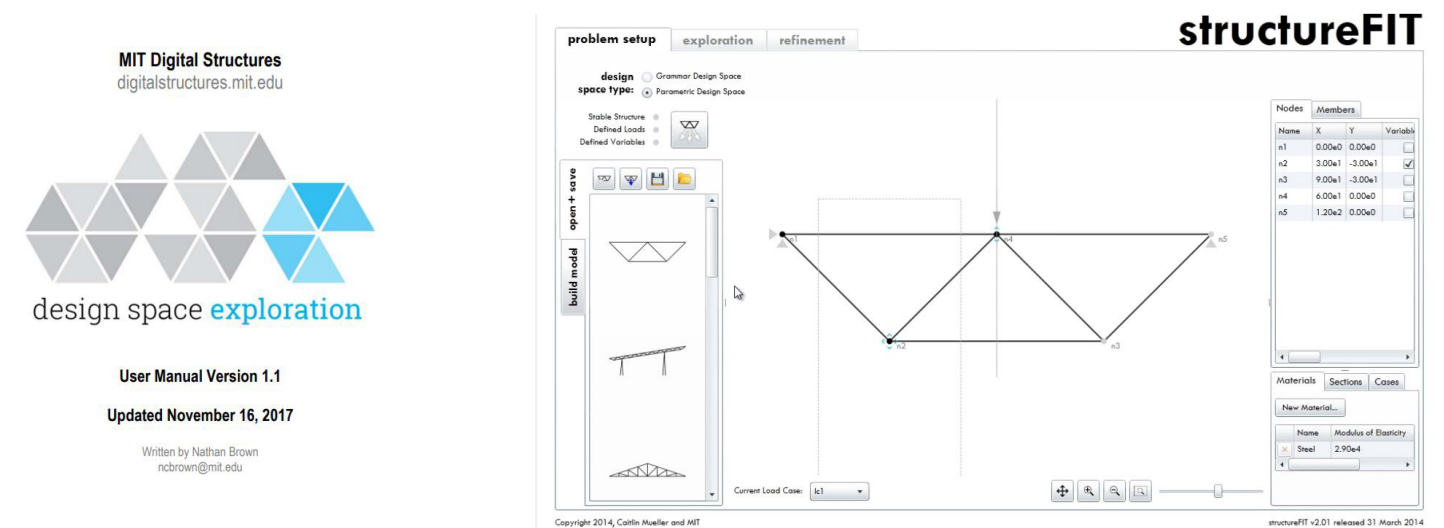


Figure 90. Design explorer web interface. Core studio (Thornton Tomasetti) (2016)

### 3.2.3.2 Data managing and visualization

Recently, with the previously mentioned growing interest towards post processing and visualization in the optimization practice and with the aid of online /cloud-based platforms several tools are now being developed. An example of this is the Design explorer tool, developed by CORE studio (2017). It consists of an open source tool for exploring design spaces allowing the designer to visualize and filter groups of iterations across a high-dimensional possibility space. The design spaces are exported by the user (using parametric applications) like csv. (data files) and a series of images are generated accordingly. Then the design space data is generated by crossing the parametric model automatically. Design Explorer reads the data.csv file and generates a 2D visualization of the design space called a parallel coordinates plot (with a grid of thumbnails and

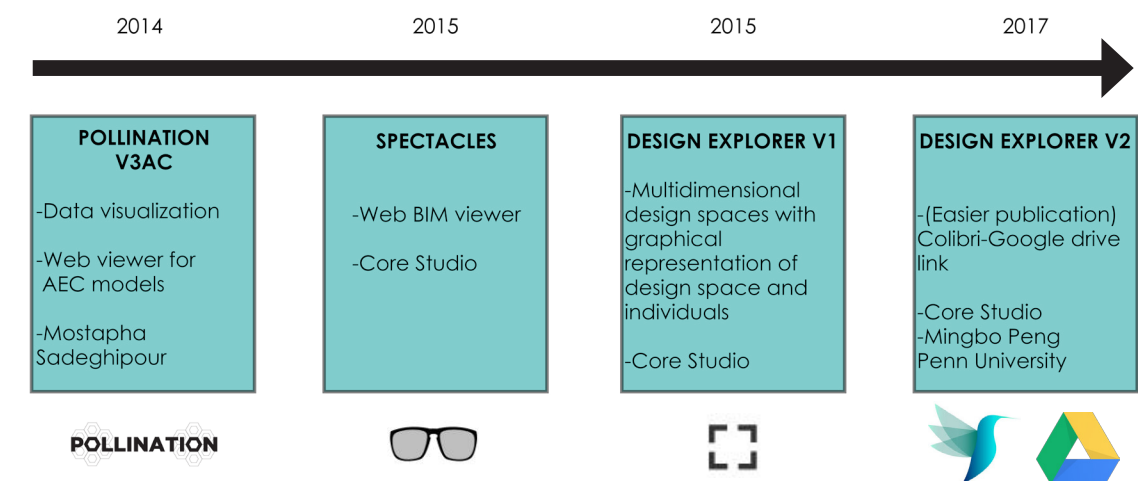


Figure 91. Design explorer web interface. Core studio (Thornton Tomasetti) (2016)



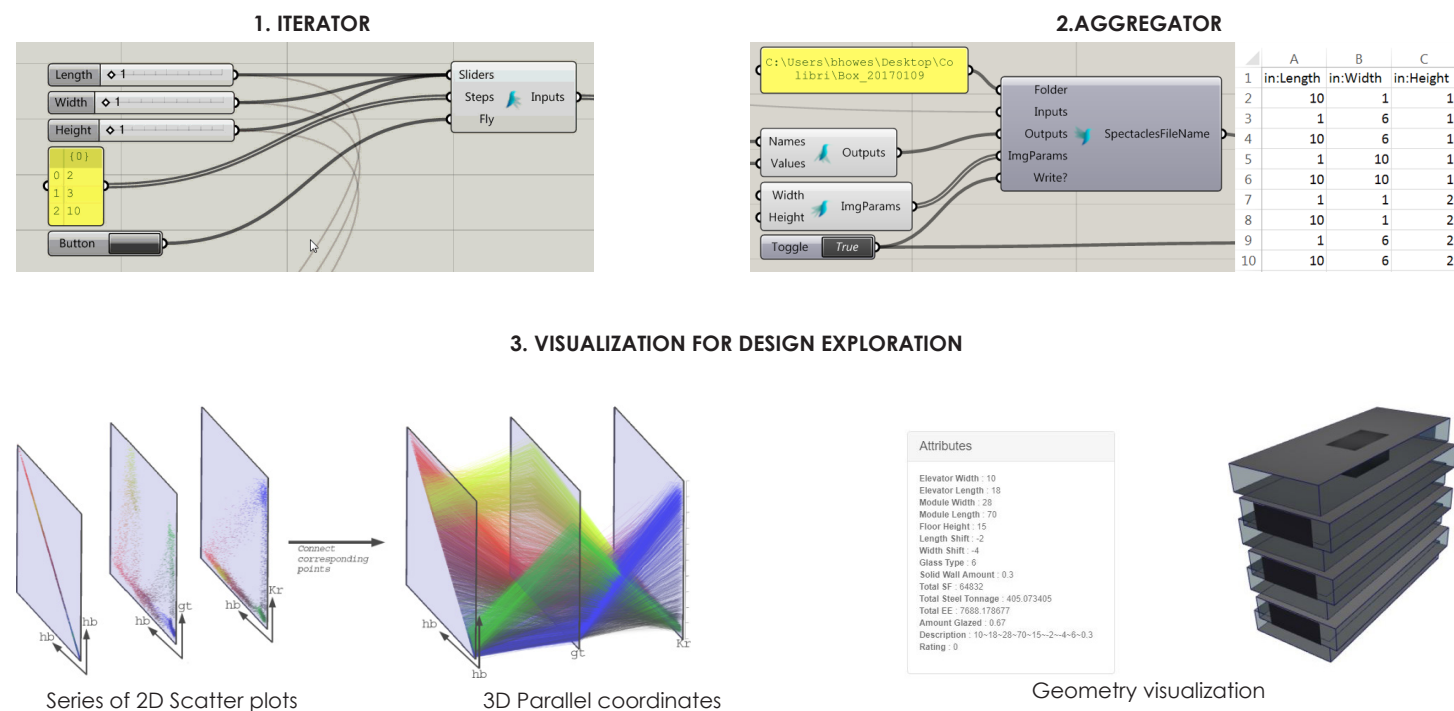


Figure 92. Design explorer workflow general overview

some other human interface). In this way, the design space can be filtered by altering the vertical filters up and down, at the same time, this specific options can be analyzed by visualizing the geometry and even the 3D ModelFig. [80] This visualization tool utilizes Grasshopper as a parametric 3D modeling software combined with a plug-in called Colibri developed by Mingbo Peng in 2016. It essentially generates the images and 3D models of the different options which are then stored in a Microsoft Excel .csv spreadsheet and uploaded to an on line platform using Google drive to finally utilize the Design explorer web server to explore and visualize the results and geometries in an intuitive way. Having the possibility to share the link with the different members of the design team or even with the clients.

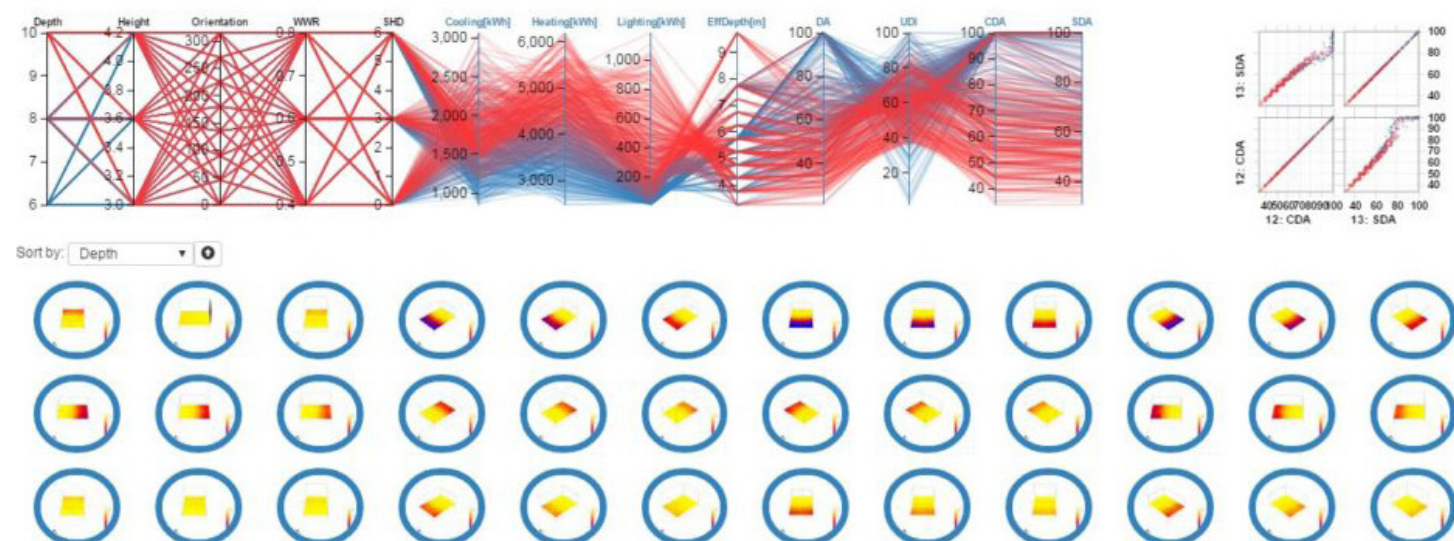


Figure 93. Design explorer web interface. Core studio (Thornton Tomasetti) (2016)

Another novel tool is Project Fractal developed by Autodesk. It is a computational tool based on a workflow that compiles, parametricism + computational design + generative design + optioneering as shown in Fig. [94]. It works by setting up the geometry in Dynamo or Form it to later on via a cloud-based web interface explore the design space while being able to generate new combination based on quantitative and qualitative preferences. Opening the possibility to explore thousand of combinations instead of only a couple of them by using the power of cloud computing.

Autodesk also developed an intuitive tool to evaluate designs according to energy efficiency while comparing the costs that these measures involve. By linking the geometry that could be generated either by Revit or by Form it with a cloud-based web interface.

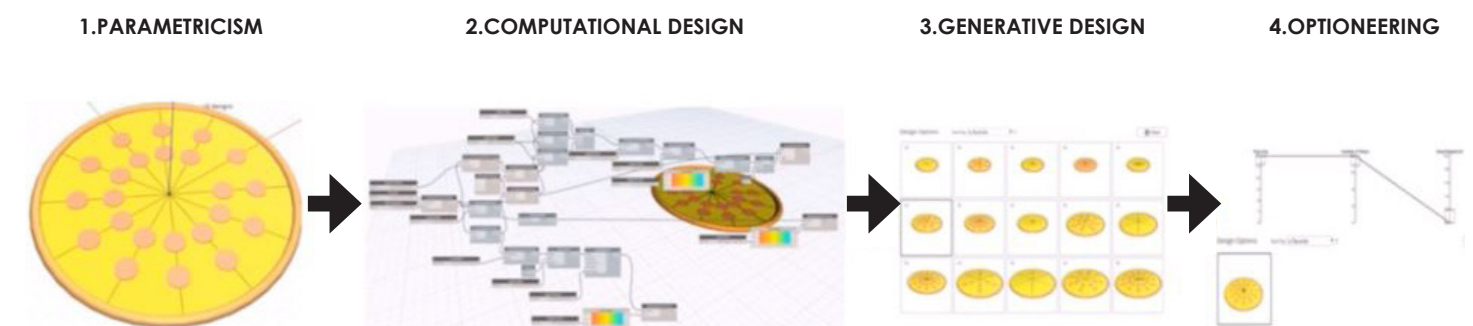


Figure 94. Autodesk Project Fractal, design interface

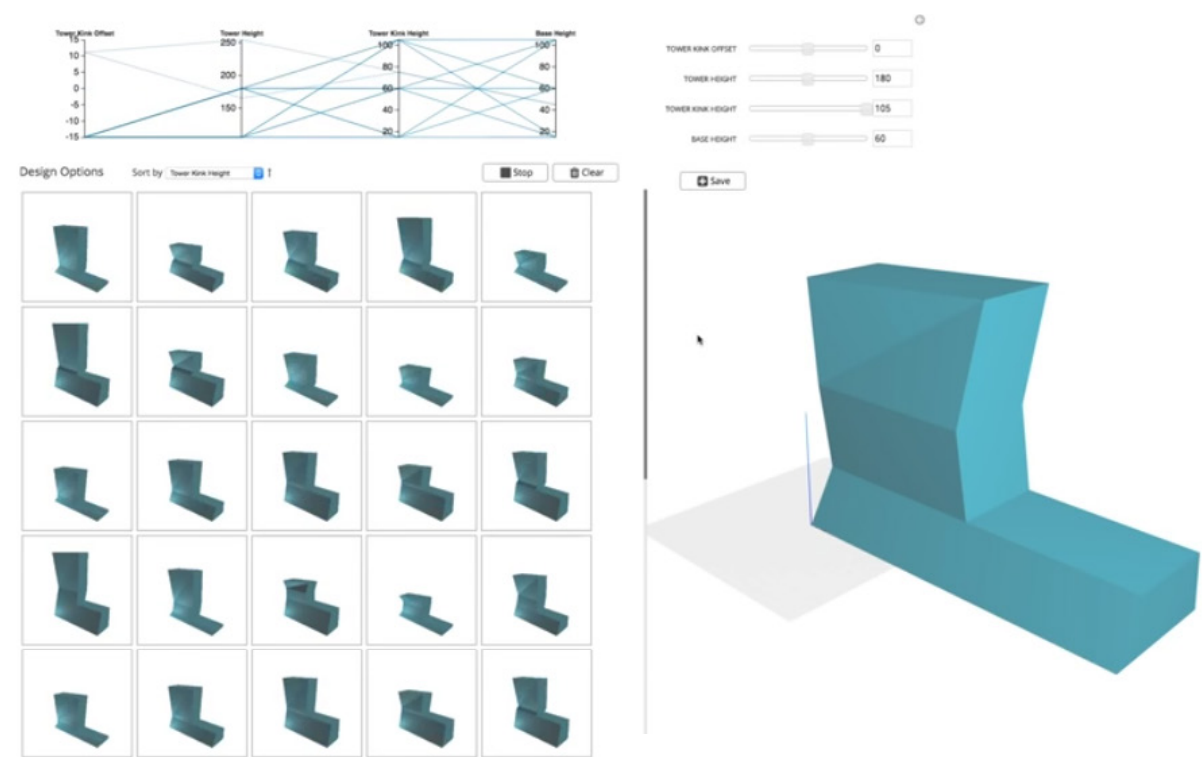


Figure 95. Autodesk Project Fractal design workflow



Different projects can be compared and analyzed in diverse stages of development. It also provides the possibility to play with some parameters such as passive measures like WWR ratio in the different orientations or to implement and modify active strategies like the efficiency of the solar panels or the HVAC and lighting systems.

The interface also rates the different options according to the Netzero 2030 challenge (Architecture2030.org, 2018), giving an idea of the implications that the changes in the design can have on the overall cost and energy aspects.

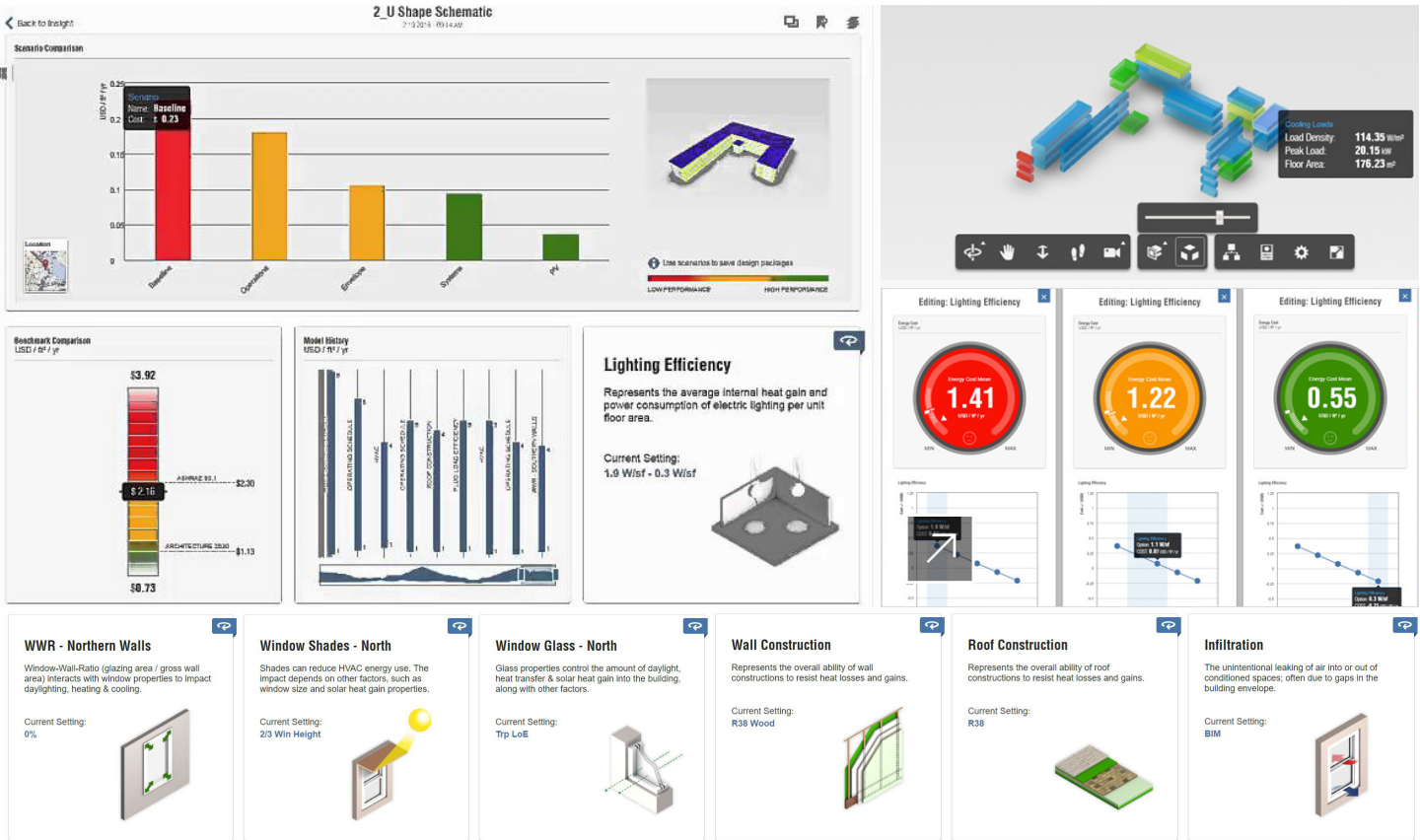



Figure 96. Autodesk Insight, web-based interface.

3.2.4 INTERVIEWS

1

QUESTIONNAIRE (TECHNOLOGY DEVELOPER)  
MINGBO PENG  
COLIBRI & DESIGN EXPLORER DEVELOPER



**1. What is your background?**

I studied Architecture in Bachelor and Master, and my second Master is environmental building design.

**2. Which kind of algorithms do you normally use for optimization problems related to Buildings design?**

I don't use any algorithm specifically in my daily work. What I do the most is parameter sensitivity test, and this is what Colibri and Design Explorer mainly do. They are designed to assist the design process, instead of providing the answer.

**3. Which are the most common aspects or disciplines that you apply performance simulations and optimization procedures?**

I use annual daylight simulation (sometime use point-in-time daylight simulation when designer is hard to understand the annual matrix), point-in-time glare study, along with cooling and heating peak load for hvac sizing.

**4. What kind of software do you use for energy and cost simulation and which one for optimization purposes?**

For the energy, I use EnergyPlus along with Honeybee and OpenStudio. I don't do any cost simulation, that is usually done by our façade team.

I wouldn't say I do any optimization work, most of my work is exploring study and sensitivity test as I mentioned above.

**5. Why do you think Performance-based generative design (Quantitative /numerical assessment of a design) and design optimization procedures are still a not that common practice in most of the architectural firms?**

Well, first I think the performance based design is not common yet, but it is moving toward it. Second, what we can say about performance-based design is mainly focusing on daylight and energy, which are two aspects currently feasible to do alone with architecture design process. Designing a building is not only about daylight and energy, there are more others consideration that cannot be easily quantified. Just as same as "AI" world, AI can do everything except the art, which is the part that still require human to be involved. Third, even though we want to generate a building only focusing on energy, there are still too many parameters to test without cloud computing ability. But this one will be generally available in next five years, I believe.

**6. What do you think about the phrase "the designer as a tool builder"**

I totally agree with it, or "the designer should be a tool builder", which I believe is similar to "everyone should learn a computer language". It is a different thinking process than "doing one thing", instead, it requires designer to abstract the common rules from "dong one thing" and make this process or "tool" reusable or adaptive.

**7. Do you think that in a near future Artificial intelligence and Machine learning will replace the designers or trigger a jobless future?**

Mentioned above in 5.

TECHNOLOGY DEVELOPER

**QUESTIONNAIRE (TECHNOLOGY DEVELOPER)**  
**JEROEN COENDERS**  
**WHITE LIONESS TECHNOLOGIES**



**1. What is your background?**

I am a trained Civil / Structural Engineer (Delft University of Technology/MSc/PhD) with programming experience since I was nine. I have worked for Arup for about 10 years where I have developed one of the first computational design departments. Since 4.5 years I have co-founded White Lioness technologies, a company that develops a next generation platform called Packhunt.io. Packhunt.io is an online platform which allows you to create Digital Twins by making use of parametric modelling. We are specialists in advanced computational methods which we apply in various industries.

**2. Which kind of algorithms do you normally use for optimization problems related to Buildings design?**

Anything we can get our hands on and what we find useful. We have probably used almost any optimization technique over the years.

We are quite practical in our approach: if a specific well-performing algorithm exists, we probably use that if it is easy enough to implement. Otherwise we might fall back on one of the general purpose algorithms.

Our aim is to offer multiple algorithms in Packhunt.io in the future.

**3. Which are the most common aspects or disciplines in which you apply performance simulations and optimization procedures?**

We do not apply these directly to building design anymore as we have switched to software development. Our clients use Packhunt.io for various situations, but at the moment I would not characterize these use cases as performance simulations or optimization procedures. Most of the ones that I am allowed to talk about are design and production configurators for advanced products.

**4. What kind of software do you use for energy and cost simulations and which ones for optimization purposes?**

We develop Packhunt.io – so that is our software of choice. Modelling we do in Grasshopper at the moment which is read by Packhunt.io. Energy, cost and optimization use cases we do not directly have (see above).

**5. Why do you think Performance-based generative design (Quantitative /numerical assessment of a design) and design optimization procedures are still a not that common practice in most of the architectural/design firms?**

This is a difficult question as it has to do with the question why do people (not) adopt software. In my view this has to do with trust. People need to trust their tools to switch. Many tools are black boxes of which the internals cannot be inspected. This does not build trust. This is why we believe in parametric design technology / visual programming: this lowers the boundary for designers to inspect the internal workings of a tool so that you can build trust in the method. (By the way: there are many other good reasons for parametric modelling).

**6. What do you think about the phrase “the designer as a tool builder”**

Designers should focus on designing and use tools or tool building platforms. Programming should be left to programmers in my opinion. The best programmers will never be good designers, and vice versa.

People very often ask me this question after lectures. I fully agree with the fact that designers should build their own tools; however, we feel that designers should do this through parametric modelling as this is the latest 'high-level language' out there with a lot of power and advantages over scripting and programming.

In our view scripting and programming creates black boxes that do not build trust (see above), but are computationally also not very performant on the latest platforms.

Using programming as a designer these days is a bit like saying to a programmer to go back to Assembler instead of using Python because it is more powerful or in theory can perform better. This is true, but it brings a lot of additional complexity that distracts you from performing well on the real problem: your design. Programmers use high-level programming languages these days, designers in our view should use high-level visual programming tools: parametric design.

**7. Do you think that in a near future Artificial intelligence and Machine learning will replace the designers or trigger a jobless future?**

The short answer is yes: current designers will be replaced, but the future will not be jobless. Designers need to reinvent themselves and take the new opportunities that are arising.

Should we worry?

My grandfather was a saddle-maker when horses still pulled carts and plowed the lands. When he saw tractors and trucks coming, he changed his company into a company that sold paper rather than making saddles – as did many of his colleagues. Was he out of a job for a while? Yes, he had to transform. Was he out of a job indefinitely? No, because humans always find something useful to do. Is the saddle making business gone? No, not completely, there are still specialist saddle makers around, but not in the quantity that they used to be.

In my view AI and other developments will mean that people and companies will need to transform to something else. Maybe 5% can remain to be a specialist. The other 95% will need to find something new to do. However, new roles are already emerging.

## 3.3 CONCLUSIONS

Multi-objective and multi-disciplinary have proved to be efficient and resourceful techniques, that are not entirely new since they have been used from a long time ago in several application fields. However, compared with other industries such as the automotive or the aerospace, the AEC industry has been slow in adopting these kind of technologies into the design processes.

In this way, as mentioned previously, the majority of the architectural offices work in a traditional and outdated way where a new technological era is already here, buildings are going to be more data driven in the future so the designers and architects should start being more involved in this kind of processes.

“Architects should play a more active role in designing the core software”

-Scott Marble (2012)

Despite the fact that current global and local conditions are pushing the profession towards a more involved practice in terms of energy performance and environmental considerations. The use of new technologies such as computer aided design, simulation and optimization tools seem to be the way to go. Nevertheless, most of the times it is necessary to have a highly technical background in order to apply them, besides the current use of these techniques fail to couple the aesthetic and non-quantifiable factor so the approach in which designers deal with these innovation techniques needs to change.

In this scope, it is important to think about integrated workflows that take into account several aspects at the same time, and it is by using the multi-objective and multi-disciplinary optimization strategies in combination with design exploration and visualization techniques that this can be successfully achieved. However, this is not an easy task, after reviewing several research projects and analyzing the interviews realized to different specialists it can be concluded that several factors need to be considered and incorporated inside this processes, listed as follows:

- Fast generation and assessment of design alternatives
- A Designer friendly user interface
- A platform that deals with the software interoperability issues.
- Trade-off analysis for competing criteria, (energy, costs, aesthetics)
- Sensitivity analysis and charts to inform the impact of decisions (Educational process)
- Easy data interpretation guidance and software availability.
- User friendly visualization performance data in combination with 3D geometries and spatial visualization in order to compare design alternatives.



## 4.PROPOSED WORKFLOW DEFINITION

# 4.1 PROPOSED WORKFLOW DEFINITION

The following workflow was established based on the review of several articles and papers regarding multi-objective optimization and design exploration. The objective was to determine a methodology which could support the early decision making during the design process. Taking into account the fact that it is during this initial stage of the process when the decisions that have the principal influence in terms of energy and costs during the entire life span of the building are taken. In this way, the proposed method is based on a simulation-based multi-objective and multi-disciplinary optimization to improve energy efficiency and costs.

At these days, as mentioned during the literature review, optimization workflows applied to design problems had been severely criticized and avoided by designers because as stated by Geyer & Beucke (2010) the one optimal solution or a numerically non-dominated set in a

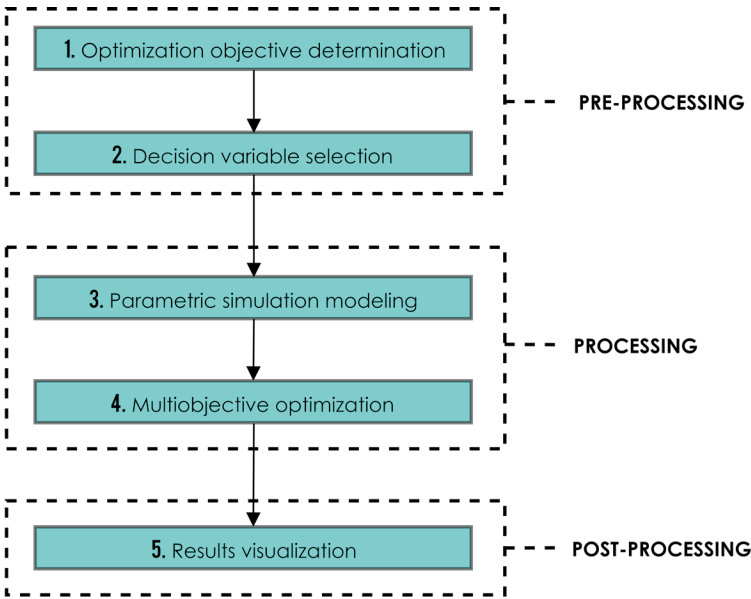


Figure 97. Typical optimization workflow

way “anticipates” the design decisions limiting the freedom of choosing based on personal preferences. For instance, sometimes a designer or a client might accept higher costs of a solution that is not considered as “optimal” or is not included inside the Pareto set of solutions if the appearance fits better his preferences or personal requirements. As defined by Negendahl & Nielsen (2015) there are several limitations when using BPS tools applied to optimization processes during the early design stages. It is highly complicated to combine quality defined objectives with a Machine automation process. Souza, et al (2007) suggests that the people that simulate needs to understand the way designers think: “exploring interactions of all parameters together and dealing with all the variables at the same time”. In this way an integrated dynamic model that considers both qualitative and performance based criteria into account should be proposed, illustrated by Fig.[98]

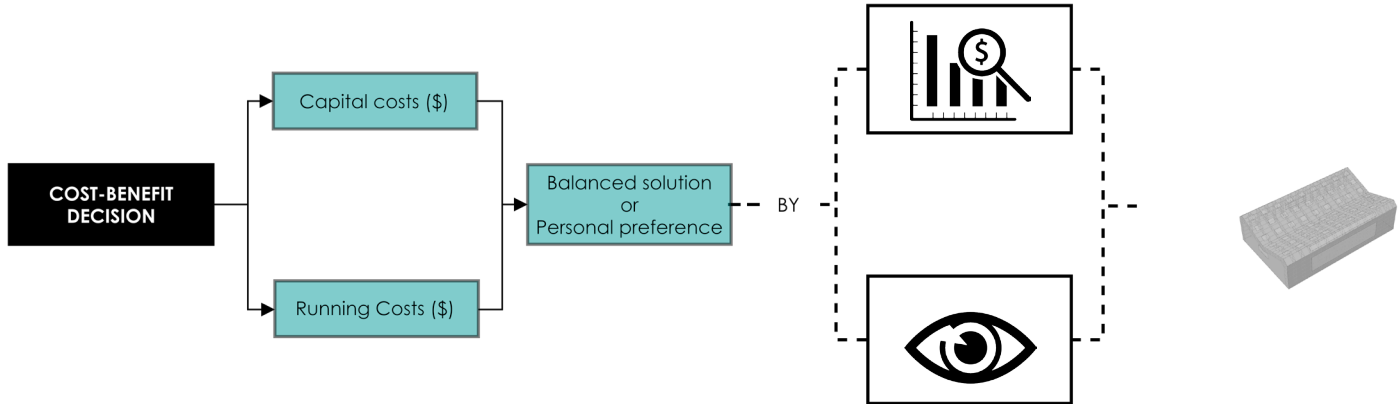


Figure 98. Balanced decision intention (combination of performance aspects with aesthetics)

As described in the first part, generally in automated workflows, aesthetic considerations are ignored in optimization models as they involve complicated ways of assessment and they are very difficult to quantify mathematically. Must of the times this kind of workflows finish with the visualization of only the results in a numeric/complicated way of understanding. Nevertheless, aesthetics have also an important and high influential role in the overall project development, specially for architects and designers.

Currently, there is a lack of real time analysis and feedback between geometry visualization and performance metrics, the existing tools and processes are not fully developed to support a rapid evaluation of alternative design solutions. Hence, designers spent a lot of time in managing and representing the design information manually, making this process an inefficient and non-productive practice. Most of the times, this kind of processes take long times and a considerable high computational power, not to mention the necessity of utilizing highly specialized software which generally results particularly expensive and difficult to deal with in terms of installation and usability.

Besides these previous conditions, the design of a building involves a large amount of design phases, parameters and aspects from different disciplines that need to be considered simultaneously and therefore large amounts of information and sometimes technical descriptions are required. This is in great manner why optimization strategies are used mainly during the latest stages of the design processes once several design factors are already defined . Representing a design limitation for the architects because it already filters out a large number of possibilities. In addition to this, there are different design processes and design intentions, and current optimization workflows most of the time are limited to one fixed procedure principally applying it when a complete amount of information is available as shown in Fig. [99]. However, when designing a building sometimes this is far away to happen, specially when talking about the conceptual design stage. Therefore it is necessary to propose a certain flexibility within the workflow that allow the designer to choose which procedure to take depending on the project condition, the available information or the design sequence that is intended.

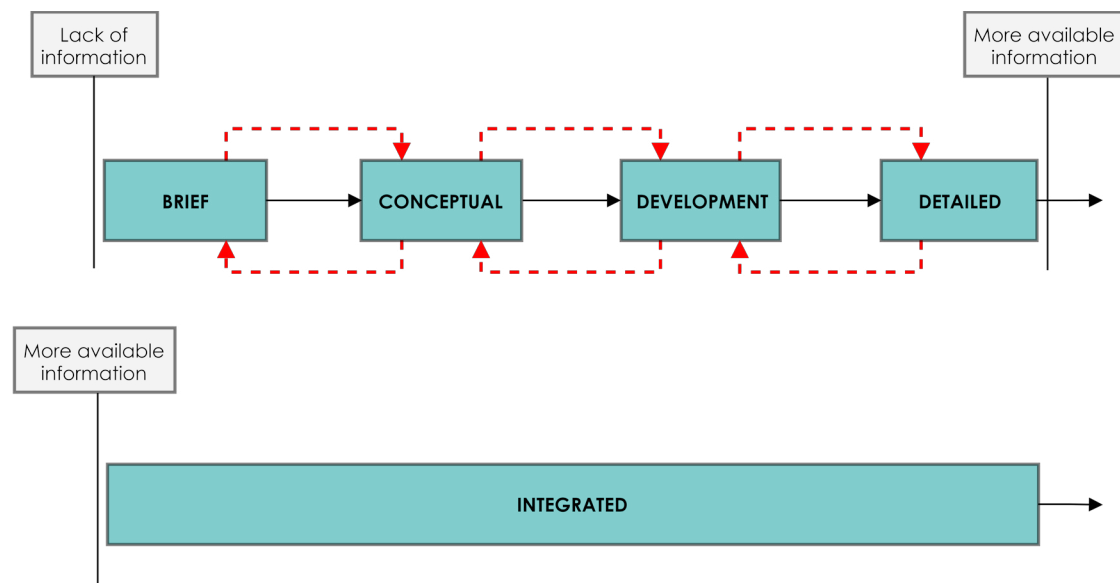


Figure 99. Different types of design processes

In this scope, the proposed workflow considers several new implementations to the current traditional optimization design procedure, enabling the designer to sort and filter designs based on performance metrics while at the same time evaluating the aesthetics of the diverse solutions. But this not only limits to the designer or namely the architects exploration but also to the possible clients, stakeholders or specialists by giving the possibility to filter the information according to the individual interests of the people involved. After several paper work and an extensive sketching process based on a “trial and error” strategy in combination with a deep and extensive exploration of the available tools (described in the following chapters) finally, a general workflow was established and later on tested on a real case study.

The overall workflow consists on a Performance Based Design Method, with the objective of linking the information generated by previously BPS (Building Performance Simulation) tools with a design exploration platform. Starting by proposing the flexibility to choose among two possible approaches, the first one is called “Sequential strategy” which consists of a linear strategy that gathers information from the different phases of the design and the diverse disciplines involved, considering them individually. This method works an educational informative process and splitting long computational times. This approach considers the design as a system composed by different “subsystems”, organized on a hierarchical order. Based on the different cost estimation methods described on the first part by Bierkfield (2013) and Gerritse (888) also known as “Top Down”. (Ashour & Kolarevic,2015). In this scope, the design is approached in different scales, from general (overall shape of the building) to a more detailed level (material and energy systems) . In this way, the workflow splits in four main stages or design phases that were selected according to the typical design process of a sports building design described previously: massing, structure, envelope and systems.

This scheme can be considered as an “information work-flow” where outputs, and evaluation of results of each stage becomes the inputs and constraints for the next one and inversely. In this way, the overall workflow consists of two main feedback levels of depth: firstly relies on taking better informed decisions by looking back and reconsidering decisions that were

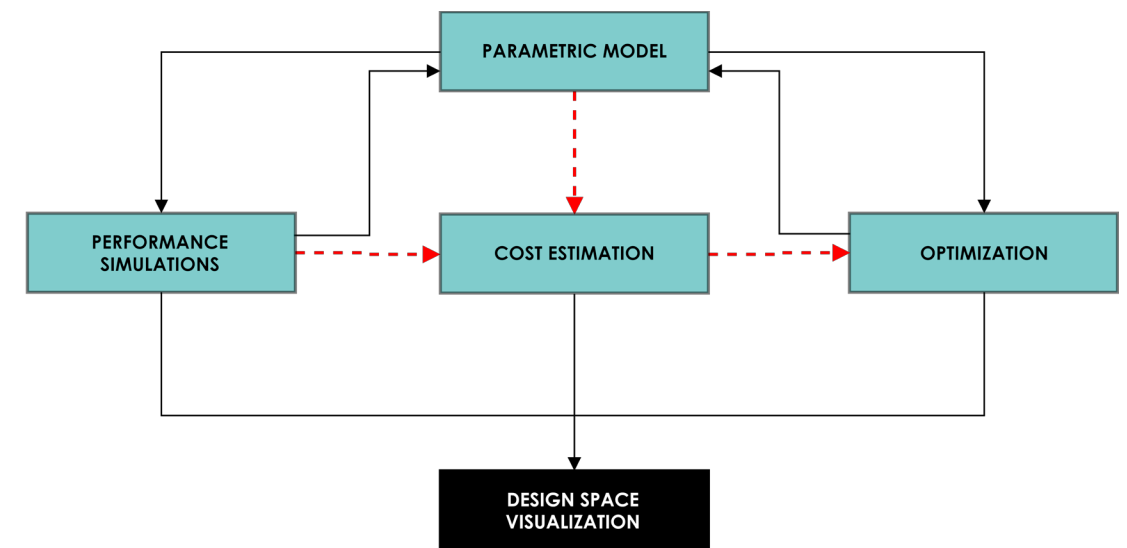


Figure 100. Overall workflow intention

anteriorly made in previous design phases. Secondly is a decision based strategy made individually at each design phase using spatial, structural, daylight and energy simulations with cost estimations accordingly.

The second design process is called “Integrated strategy”, it consists of a combined multidisciplinary design optimization technique which was previously described during the literature review. In this approach, all the stages will be merged and evaluated at the same time using a multi-objective and multi-disciplinary approach. Giving the possibility to provide the designer with the “big picture” of the entire design space and the relation among the different disciplines involved.

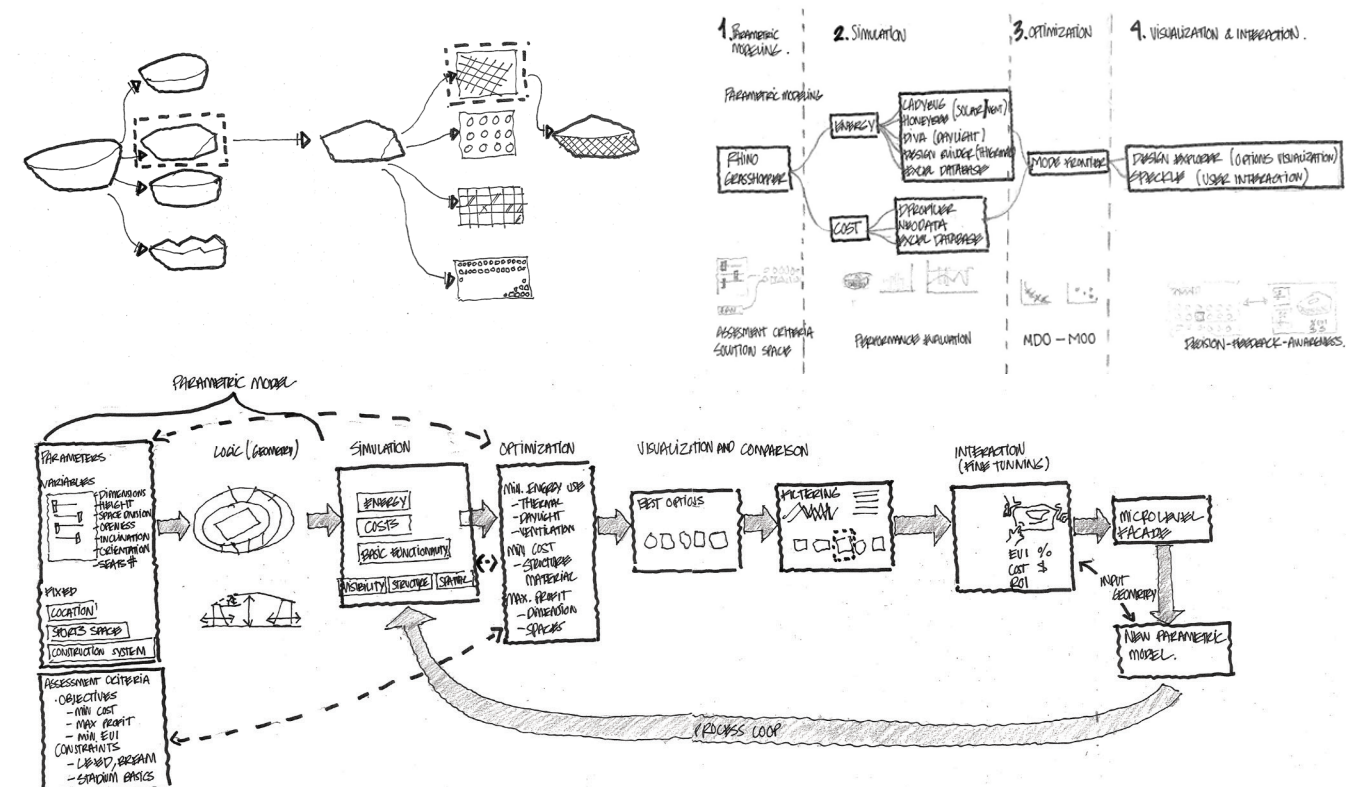


Figure 101. Sketches of the initial workflow design process



Another important features of the proposed workflow as it can be seen in Fig. [103] is from one side an optimal selection of tools based on a deep study and comparisons where the commercial availability, the possibility to get user support, the reliability, a user friendly interface and the interoperability among the diverse applications were considered in order to overcome to the current problems that come with the normal optimization procedures. From another side, the strategy to develop a database that involve costs is proposed, this consists of two main aspects, a research about local and typical materials applied to this kind of buildings with different energy and costs performances and an investigation about its costs in addition to local energy fees is also defined and described in the following chapters.

The intention of the proposed workflow is to aim at the exploration of the design and solution space rather than at finding a final solution. Allowing the designer to explore the design space while simultaneously see the impact of this changes on the geometry and performance. Synchronizing the separated simulation processes in order to reflect the consequences of the changes immediately, creating an awareness of the influence of the decisions regarding energy efficiency and costs effectiveness.

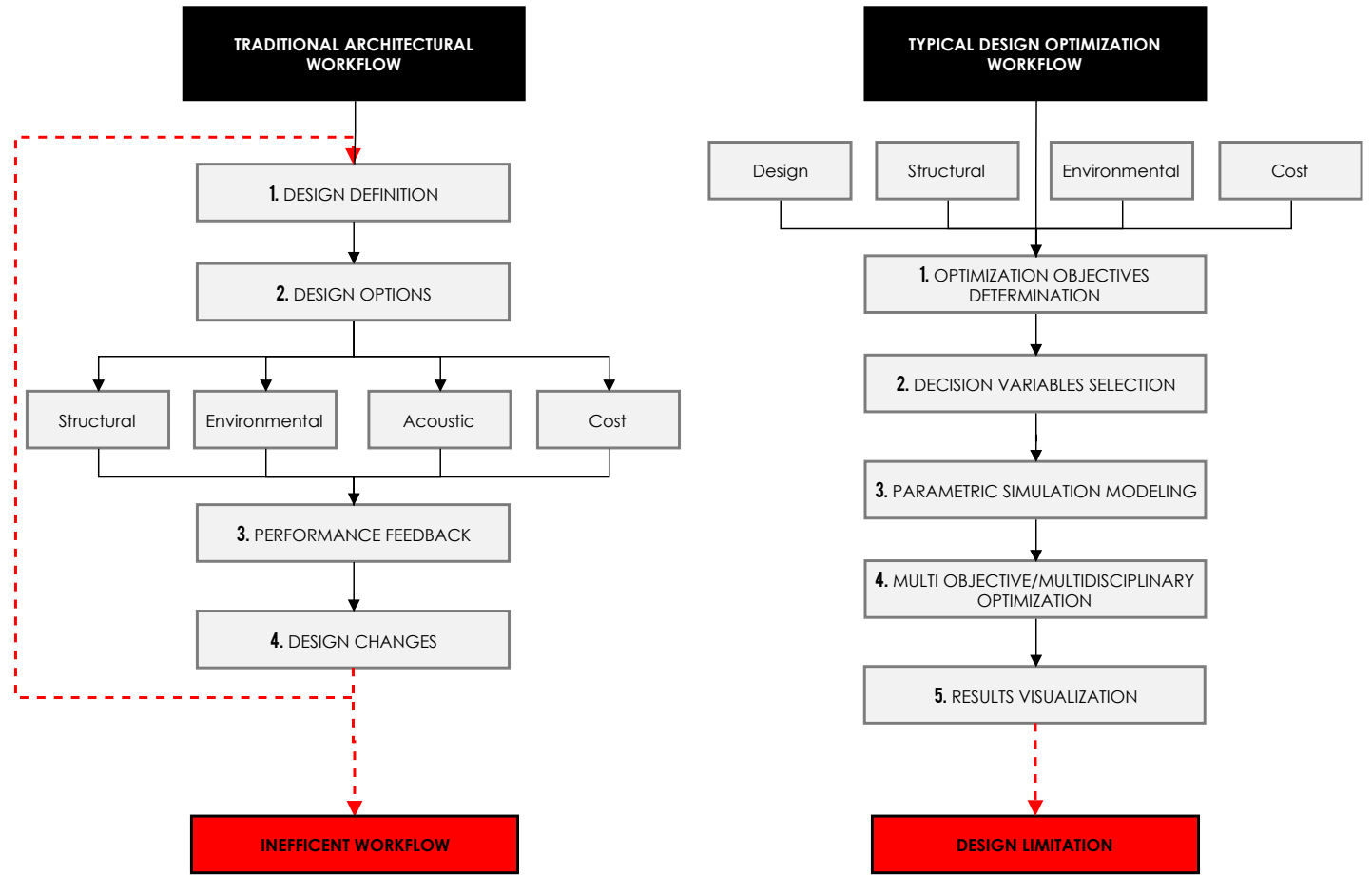


Figure 102. Comparison between a traditional architectural workflow and a typical design optimization workflow

This is achieved by combining parametric modeling tools with simulation and optimization engines with a human web interface to visualize the 3D geometries while comparing the numeric performance values. Facilitating the design rather than automating the design by instead of a customized two or three design iterations conducted in a typical design project, having the possibility to analyze over thousands of design options and choosing from a range of near-optimal solutions.

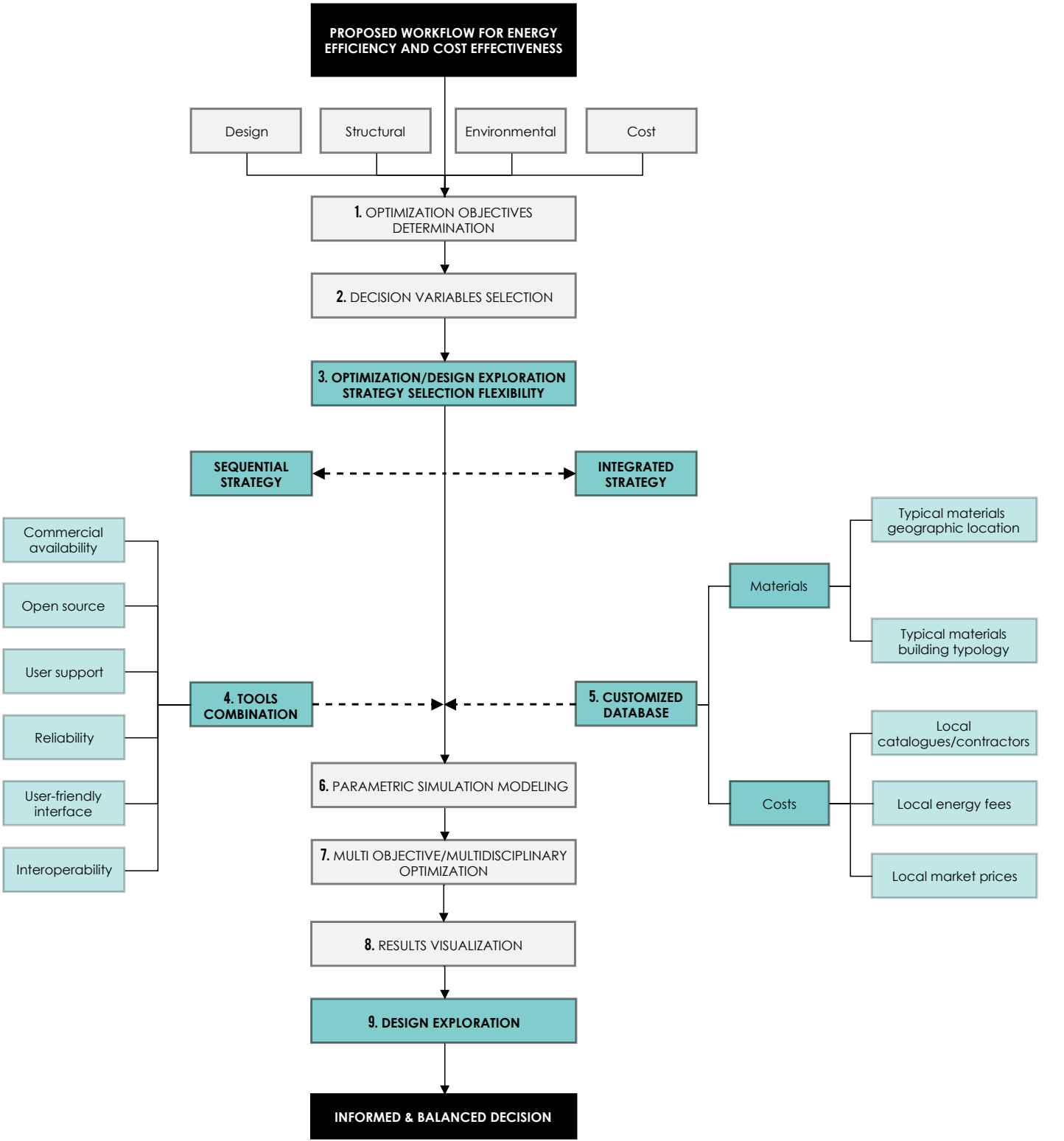


Figure 103. General overview of the proposed workflow and its implementations

### 4.1.1 OBJECTIVES DEFINITION & EVALUATION CRITERIA

As described previously, for the aim of this thesis, optimization has been set up with the purpose of improving indoor daylighting, reducing energy consumption and reducing construction and operational energy costs. Four main objectives were selected for the overall process, however, as it will be explained later on, the process is divided in design stages. Each of which has its own diverse objectives, and therefore different and specific design parameters and constraints.

The selected design objectives are explained as follows:

#### 1. Energy Use Intensity (EUI)

It is an index utilized to describe the energy consumption of a building. Defined as the energy consumed during the year per unit area and it is measured in KWh divided by the total floor area of the building. This indicator was selected because it provides the possibility to be used for the comparison between buildings performances. To calculate this, as explained in previous chapters only the heating, cooling and artificial lighting energy demand will be considered.

#### 2. Total Cost

For the aim of this thesis the total cost is defined as the sum of two main aspects, the first one is cost spent as and investment for the building. For instance, building materials and energy systems. Secondly, the annual costs for the building operation (Energy fees). For the scope of this investigation that intends to focus on the conceptual stage of the design, several types of costs were excluded such as labor costs, maintenance and demolition costs.

- Structure mass: Inside the costs objective there is a sub-objective that has to do with the structural system and its material properties, this was proposed because of the importance and the influence that this part of the building has on the total costs, specially when talking about long span buildings, like the proposed case study

#### 3. Maximize Profits (Rental space)

In order to counter balance the search for minimizing the cost, and therefore minimizing the area of the building, a financial scenario was proposed. As the value of a building generally increases according to the amount of m2 that can be sold, this objective was implemented to investigate how to find a balance between investment and return of investment.

#### 4. Useful Daylight Illuminance (UDLI<sub>100-2000lx</sub>)

UDLI is defined as a dynamic daylighting evaluation index, it describes the percentage of the occupied hours of the year across the “useful area” when all the illuminance is within a range of 100-2000 lux. The values under the lower boundary (100lux) represent places where the daylighting level is generally considered as insufficient. While the values that are higher than the upper limit (2000 lux) have the possibility to experience glare problems. This value was selected among a long list of indicators for daylight because of the possibility to have a “constraint” in a certain way for the optimization to find alternatives that are inside a predefined performance value.

### 4.1.2 DECISION VARIABLES & CONSTRAINTS

As mentioned before, each different stage of the design process will have a diverse set of objectives, parameters and constraints, with the intention to get an overall view of the diversity of values, the following list will enumerate them:

- Parameters
  - Width of the building
  - Dept of the building
  - Height of the building
  - Peak height
  - Location of the peak
  - Beam depth
  - Column depth
  - Chord diameter
  - Chord thickness
  - Web diameter
  - Web thickness
  - Lateral connection diameter
  - Lateral connection thickness
  - Divisions of the beam
  - Divisions of the column
  - Number of frames
  - Building orientation
  - Window to wall ratio (N,S,W,E)
  - Window to roof ratio (Skylights)
  - Wall materials
  - Roof materials
  - Window materials
  - Number of shading devices
  - Cooling system
  - Heating system
  - Lighting system
- Constraints
  - Minimum usable space
  - Maximum volume
  - SLS (maximum allowable deflection)
  - Maximum allowable temperatures

The next page will show an image which describes the overview of all these parameters in relation with the objectives and the entire process of the workflow. Fig. [104]

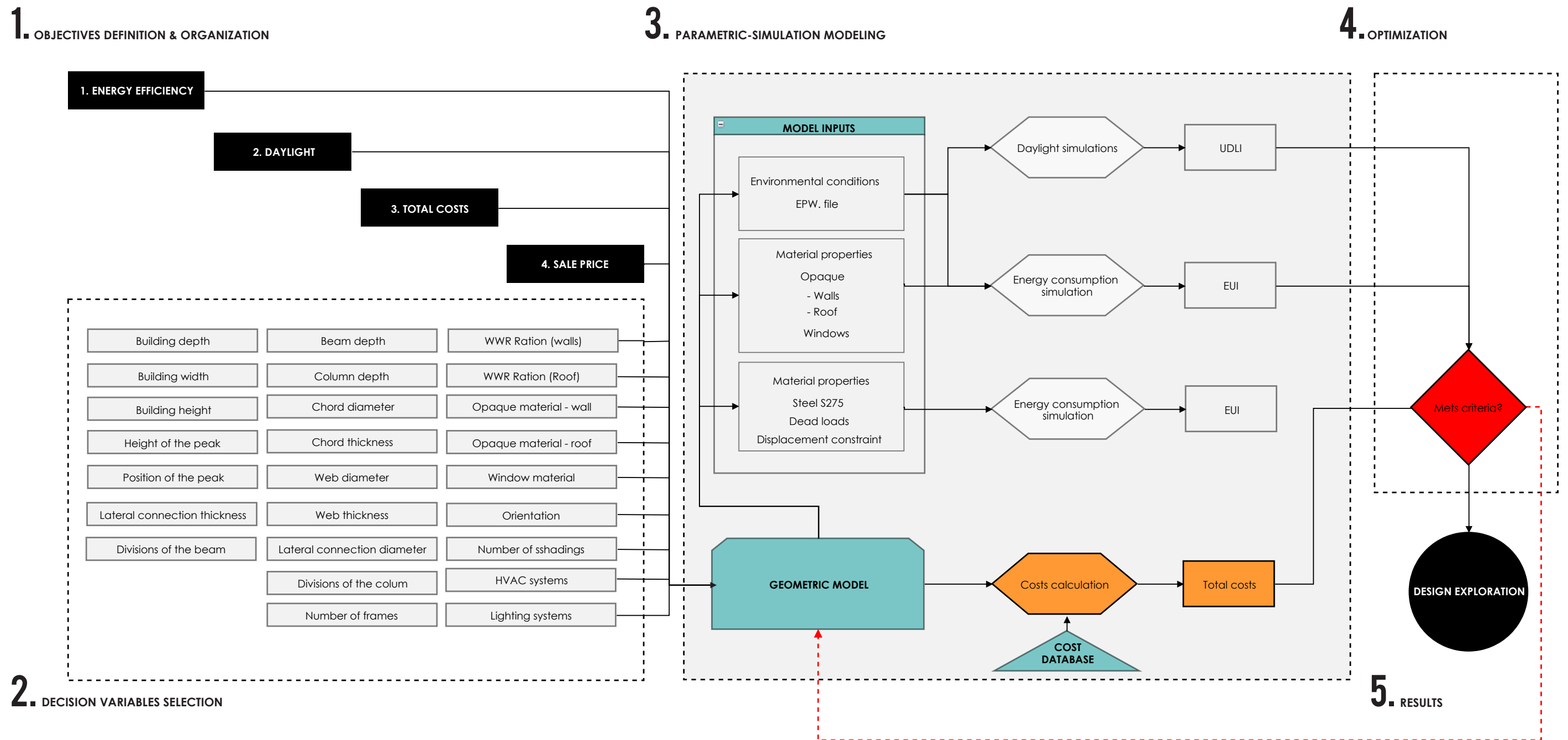


Figure 104. Workflow overall organization scheme



4.1.3 STRATEGY SELECTION

The two different design strategies proposed in the workflow were thought in an holistic way, taking into account all the objectives, parameters and constraints at the same time. However, the “Sequential strategy” (which was based on the regular workflow in which a building is normally designed ) splits the design process in four different stages.

This was in first place with the objective of focusing on each step individually to gather more precise results and conclusions to later on comparing the effect that each of them has in the overall design procedure. Another reason for this, was that normally, during the design process information is not always available and decisions still need to be made. Besides, from a practical point of view, each instance of the project has its own complexity and not always this complexity is necessarily required since each design phase is different. For instance, when making massing studies, it is not necessary to have information about technical systems such as HVAC devices or lighting controls. In this way, this methodology proposes to have a rough conceptual phase which main intention is to provide rapid feedback to the designer. Later on, as the process follows, the complexity and the information managing starts getting more and more dense.

Another important aspect that was considered when splitting this workflow was the fact that some simulations can involve large amounts of time and computational effort. Therefore, separating the work load in diverse“sub sets” allows the possibility to decide when the designer wants to do a rapid exploration or prefers to go deeper in a specific discipline. Opening the possibility to have different “possible users” with different interest or preferences as it can be seen in Fri.[105]

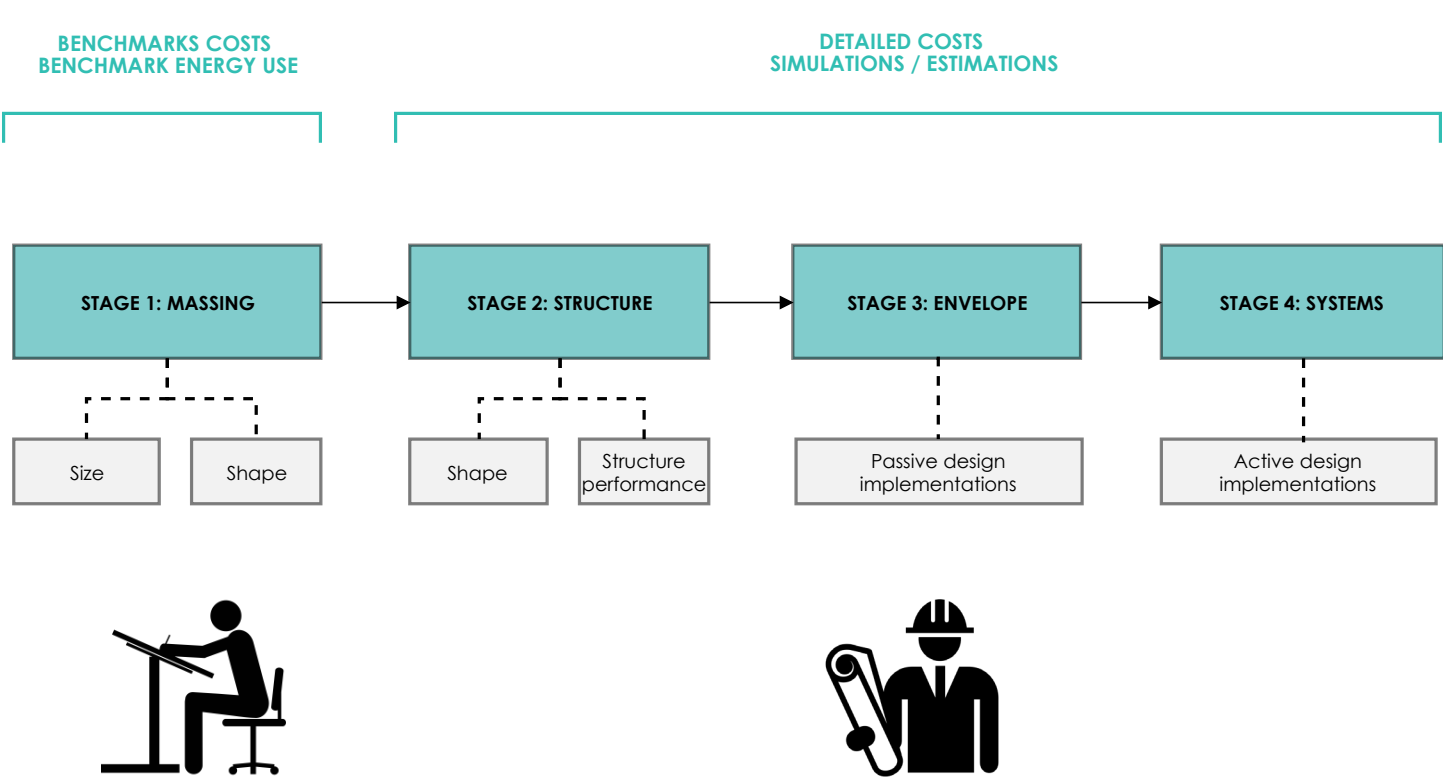


Figure 105. Sequential strategy

The “Integrated strategy” consists on having the same aspects that were considered for the sequential process but instead of considering the scheme in a linear way, this method compiles all the possible stages or disciplines at the same time as defined in Fig. [106].

It is important to mention that to work with this process it is necessary to have a considerable amount of information about the project, specially when talking about parameters and design constraints or design limitations. For instance when talking about costs in comparison with the Sequential strategy, the model is so detailed that requires also detailed costs which normally are not always available at the time of working during the conceptual stage of the process.

Therefore, it is imperative to gather together with the different specialists involved in the overall project at the beginning of the process to define an integrated strategy that can take into account every aspect of the diverse fields simultaneously. This method provides the user with an overall view of the design, giving the possibility to take decisions based on trade offs between the diverse disciplines aspects fitting to every possible user since involves all the different interests in the same model.

The main disadvantage of this scheme is that sometimes a large number of parameters are involved, resulting in the managing of a great amount of information at the same time, which consequently requires large computational times and a considerable high computational power.

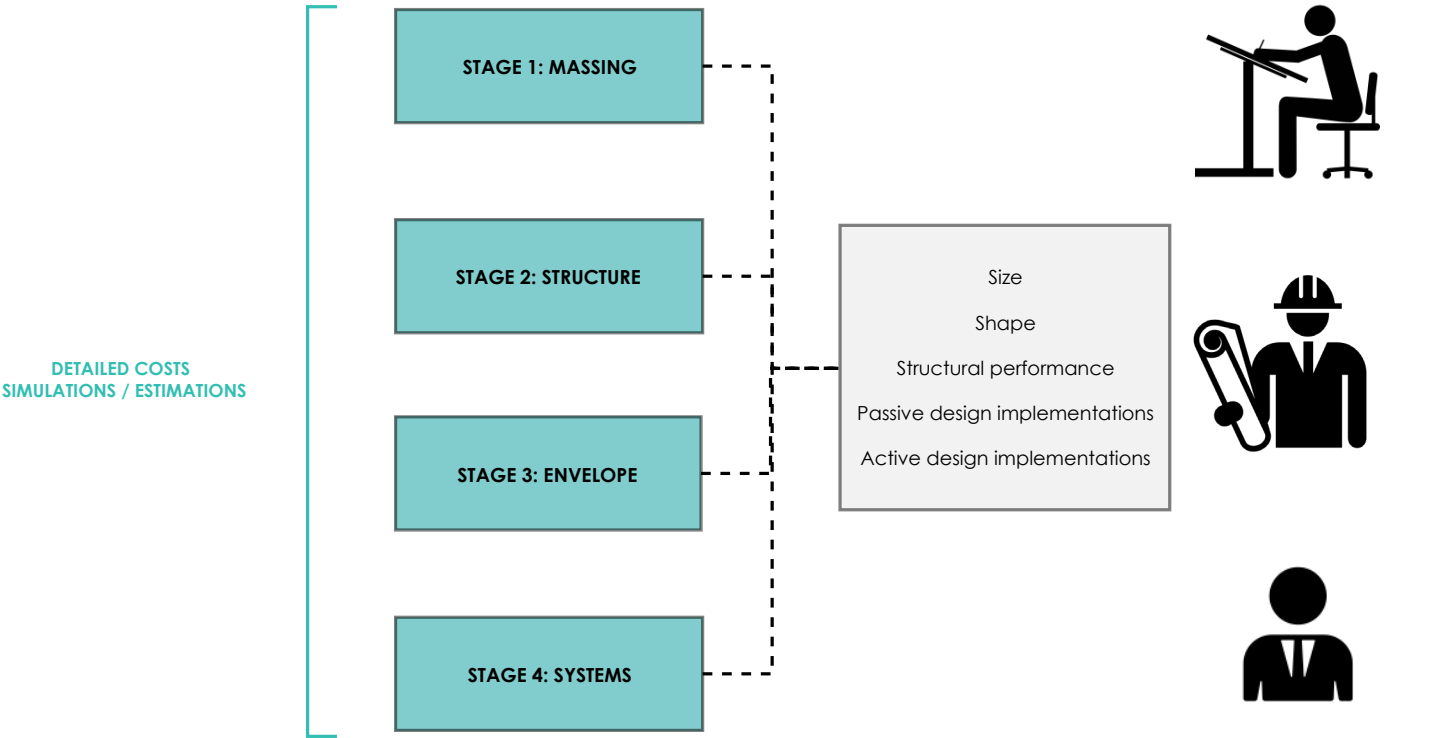


Figure 106. Integrated strategy

4.1.4 TOOLS DEFINITION

One of the most important stages of the entire workflow definition was the tools selection, to some extent, the tools determine the way the entire process will work, because of possible existing limitations for instance when talking about computational power, time availability or interoperability among the different kinds of software.

Fig. [107] shows a general overview of the large amount of existing design tools and applications, and the relation among them. Highlighting the ones that were considered for the intended workflow based on a deep analysis and an integrated comparison of them.

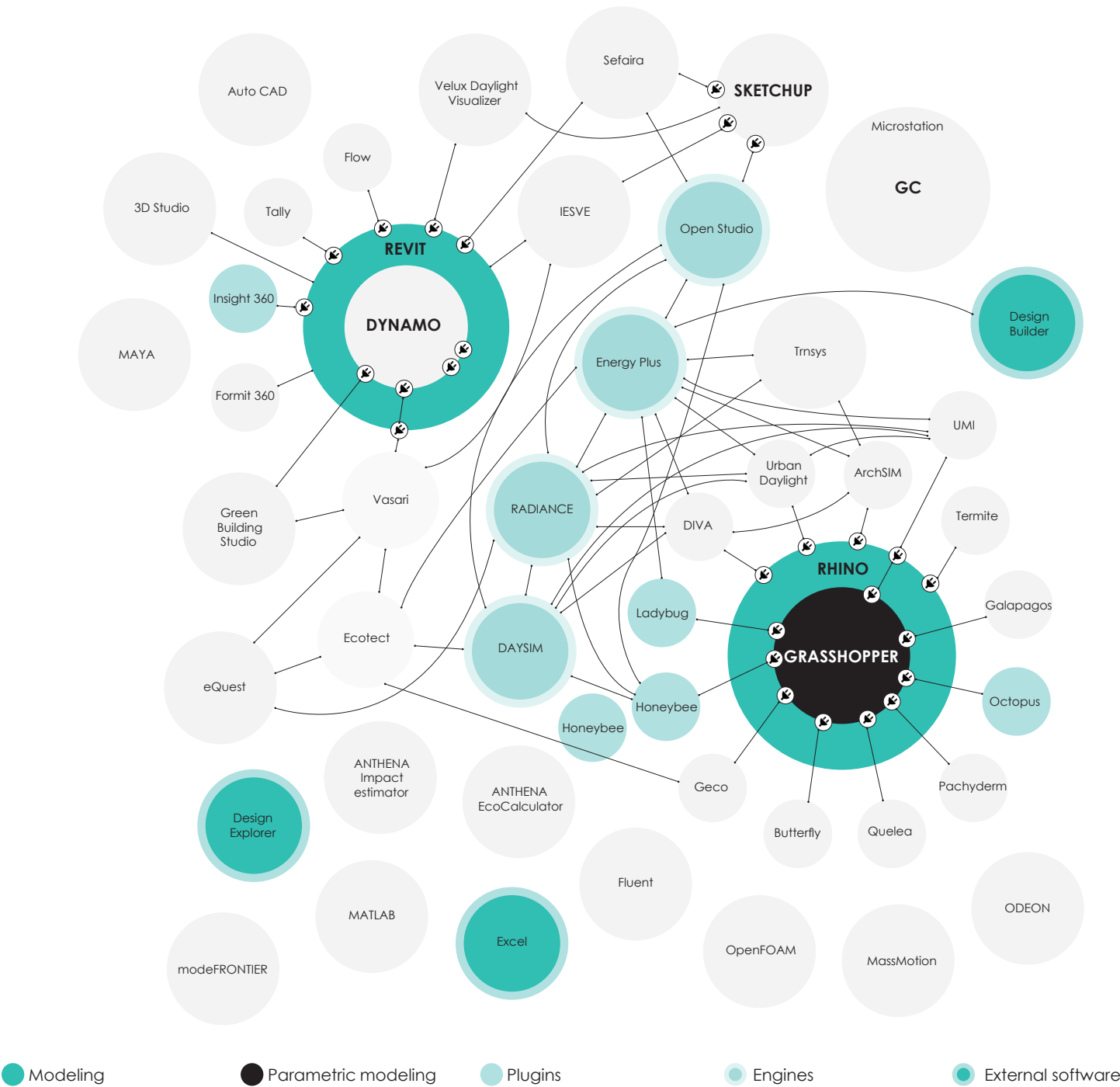


Figure 107. Diagram of the different existing tools and their application based on Peters & Peters (2018)

When deciding which tools were going to be utilized for the workflow implementation, five main aspects were considered:

- Firstly the availability (commercial existence/open source) because the application must be easily accessible for all the possible users, which must of the time are not willing to pay for getting expensive licenses or to follow complicated installation instructions and specialized computational requirements.
- Secondly, and the possibility to have user support via on-line or in this case with the TU Delft design informatics group,
- The third aspect was the reliability and robustness, when looking for a scientific approach and evaluating specific performance criteria, it is strictly necessary to use validated appliances this consideration was concluded after reviewing the experience of other users or inspecting which databases or calculation engines the tool uses.

SOFTWARE	A. USERS						B. DESIGN SPACE		C. INTEROPERABILITY		D. CORE COMPLEXITY		E. OBJECTIVES					F. PARAMETRIC SIMULATION						
	Architects	Engineers	Conceptual	Preliminary	Detailed	Management							Energy	Thermal	Daylight	Air Quality	LCA	LCC	Cloud	I/O Config.	UA	SA	OAT	Optimization
Be10 (ISO 13790 Monthly) <sup>2</sup>	(A)	E		x					Standalone		Low		x	x						x				
Bsim		E		x	x				Standalone		High		x	x	x	x							(x)	
DOE2		E			x				Standalone		Medium		x							x				
Energy Plus (E+)		E			x				Standalone		High		x	x		x				x				
EPC (ISO 13790 hourly)	(A)	E	x	x					Standalone		Medium		x							x				
ESP-r		E			x				Standalone		High		x	x		x				x				
IDA-ICE		E		x	x				File exchange		High		x	x	x	x				x			x	
Idbuild		E	x	x					Standalone		Medium		x	x	x	x						x		
IESVE	(A)	E		x	x	x			File exchange		High		x	x	x	x	x	x						
Radiance	(A)	E		x	x				Standalone		High			x						x				
VELUX Daylight Visualizer	A	E	x	x	x				File exchange		High			x										
A+E3D	A		x	x					Integrated		Be10		x	(x)	(x)									
Daysim	(A)	E	x	x	x				Run-time		Radiance				x					x				
Design Builder		E		x	x				File exchange		E+, Radiance, Je+		x	x	x	x			x	x				x
eQuest		E		x	x				Standalone		DOE2		x											
N++		E		x	x	x			Separated		E+, Je+, GenOpt		x	x		x				x			x	x
Open Studio		E		x	x				File exchange		E+, Radiance		x	x	x	x			x	x	x			
Riuska		E	x	x					File exchange		DOE2, own engine		x	x		x					x	x		
Sefaira	A		x	x	x				Run-time		E+, Radiance		x	x	x					x	(x)	(x)		x
DIVA For Rhino	A (E)		x	x					Run-time		Radiance				x									
Green Building Studio	A (E)		x	x	x				File exchange		DOE2		x							x				
HoneyBee (GH)	A	E		x	x				File exchange		OpenStudio, E+, Radiance		x	x	x					x				
JEPlus (+JESS)		E		x	x				Run-time		E+, DesignBuilder, N++		x	x	x	x			x	x	(x)	(x)	x	
Parametric Analysis Tool		E		x	x				File exchange		OpenStudio		x	x	x	x				x	x	x	x	x
Solon	(A)	E		x	x				File exchange		Green Building Studio		x							x		(x)	x	
Dynamo	A	E	x	x					-		-													
Grasshopper (GH)	A	E	x	x					-		-													

1 Glue refers to software that enables linking between BPS and geometrical modeling through graphical programming (also referred to as algorithmic modeling)  
2 Be10 is mandatory to use for code compliance in Denmark

Figure 108. Comparison of different software and plug-ins based on Ostergard, et al. (2016)

- Finally, the interoperability among other software necessary to complete the entire procedure, this is highly important because if there is non correct and steady compatibility it will result impossible to import and export the correspondent data and models.
- Finally, the user friendliness of the interface was also analyzed, mainly when talking about the post production phase of the workflow and the design exploration stage.

After analyzing and comparing all the existing tools based on the afore mentioned criteria, in first place the parametric modeling platform needed to chosen. There where two main options to consider; using Autodesk's tools Revit and Dynamo or Mcneels tools (Rhino and Grasshopper). The last ones were selected because of the current lack of exploration in the matter of costs when applying these parametric tools to conceptual stages, and for another side because of the available support and advice support within TU Delft personnel. Once selecting the modeling platform, the next stage was to choose the performance simulations software, this decision was made taken into account the demands of the objectives previously defined and the interoperability with the parametric modeling software and the correlation among some file extensions that would be used all along the entire procedure such as .csv(excel database) and .idf(energy files). In this sense, the selected appliances

were Karamba for the structural simulations, Ladybug and Honeybee for energy and climate calculations (using Energy plus). Microsoft excel to store the different data like the costs databases and the results of the simulations. For the next stage, the interoperability was crucial because it was needed to have a tool that could iterate the diverse options among the design space while recording and exporting all the produced data from the performance simulations. For this purpose Octopus was selected for the optimization procedure while Colibri was selected as a data managing tool. Finally, as explained in the first chapter the Design explorer platform was selected in order to explore the different design solutions in an easy, free and compatible way using a cloud based interface easy to share and explore by the different team members or even possible clients. The figure below, illustrates the sequential operation and the correlation among the different utilized software.

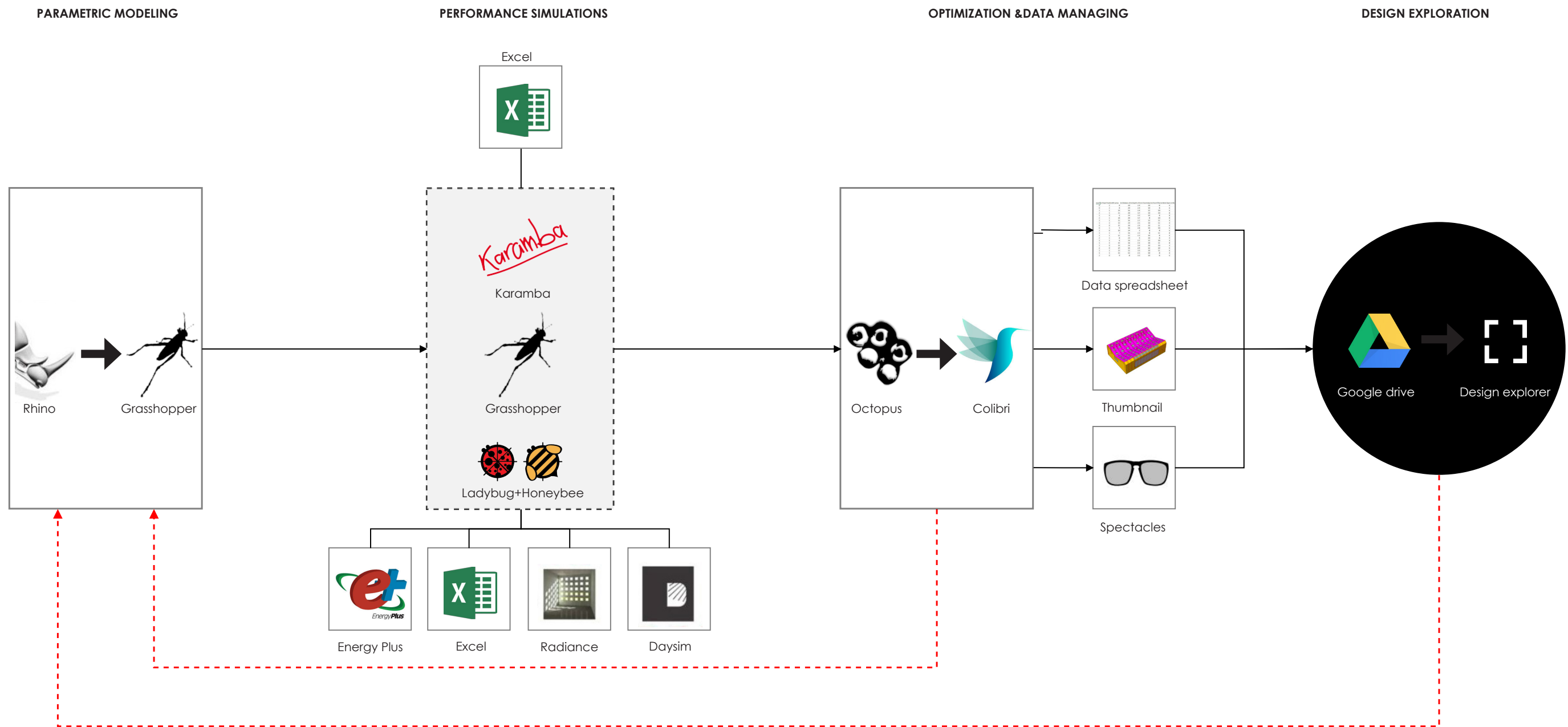


Figure 109. Software, tools and plug-ins flowchart



4.1.5 DATABASE DEFINITION (MATERIALS & COSTS)

The strategy was based on the Gerritse (2008) methodology, where based on the project definition and the design stage of the project, diverse specifications will be provided and based on them and in the quantities retrieved from the geometrical model the calculations will be elaborated.

Nowadays there is not a generic tool to use for calculating costs parametrically, and this represents a fail point because, costs have the same or even more important part in the design process.

According to the reviewed literature, a methodology is proposed based on Gerritse (2008) and Bilfields(2013) approaches in which is depending of the stage of the project and the available information that costs can be analyzed and compared. In this way following the step-by step strategy explained before the cost database will follow a sequential strategy as defined in Fig. [110]

The database will consist of two main sections: conceptual and detailed. The first one will be based on a benchmark study based on the typology of the building in this case a Dry Sports hall. Due to the lack of information about local examples, also international cases were analyzed and time and currency factors were applied accordingly.

The benchmark analysis was made considering two kind of costs:

- Construction costs = \$ / m2
- Operational costs = \$KWh / m2 / year

The second stage of the cost database will be compiled using local material prices catalogues and indicators. Across this detailed database analysis two type of costs will be considered following the next strategy:

- Total Costs = Material costs + Operational costs
- Where:
- Material costs = Structure + Glass materials + Opaque materials + Mechanical Systems

This second approach will vary according to the stage of the process, considering diverse factors as follows:

1. Stage 1 : Conceptual stage (massing): Prices by benchmark
2. Stage 2: Structure: Local prices of steel Kg
3. Stage 3: Envelope: Local prices of transparent materials and opaque materials (including insulation)
4. Stage 4: Local prices of mechanical systems (heating, cooling and lighting ) in a future, solar PV panels can be also added.

For the structure a calculator component based on the sum of the mass of each member of the structure multiplied by the local value of the price of the steel (by kg). The unit cost for electricity and gas were based in two levels, the first one is on a benchmark made by analyzing 5 similar buildings based on typology, size and use. For the second stage (more detailed) the unit costs for the energy sources was calculated based on local utility rates.

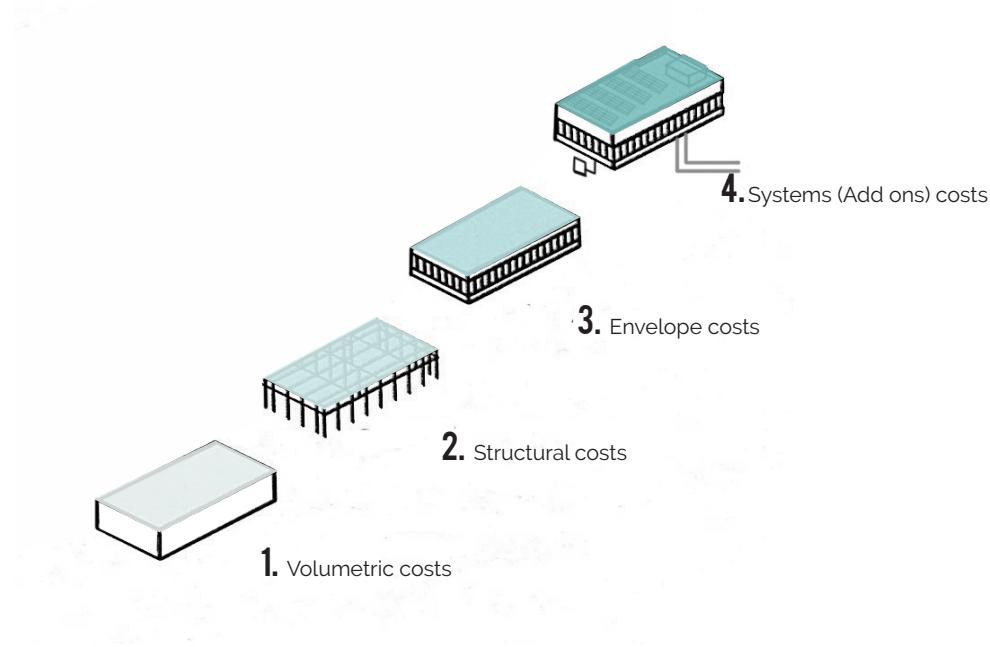


Figure 110. Parametric costs workflow steps, based on (Gerritse, 2008)

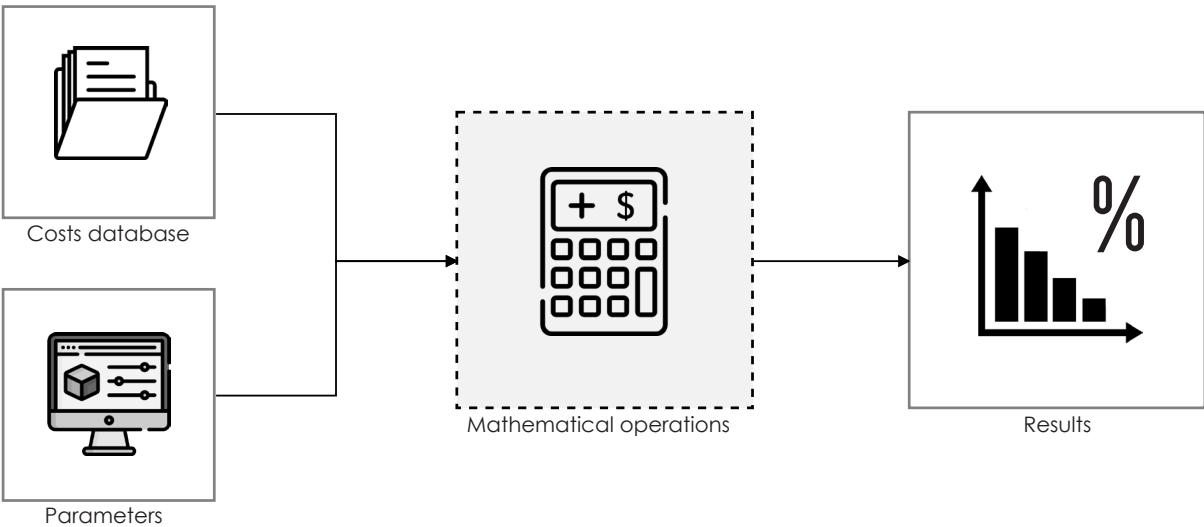


Figure 111. Diagram of the information flows among different software and data bases

4.1.5.1 Associative parametric model take-off strategy

The take-off strategy consist of having a previously defined database that considers from one side the materials that are normally used in the specific location and from another the typical materials that are used for the particular type of building which in this case will focus on the available and most commonly used materials in Mexico and the most typically used materials for the construction of Sports halls. The profits or possible incomes where defined after a benchmark study of several similar buildings and general local sale market prices.

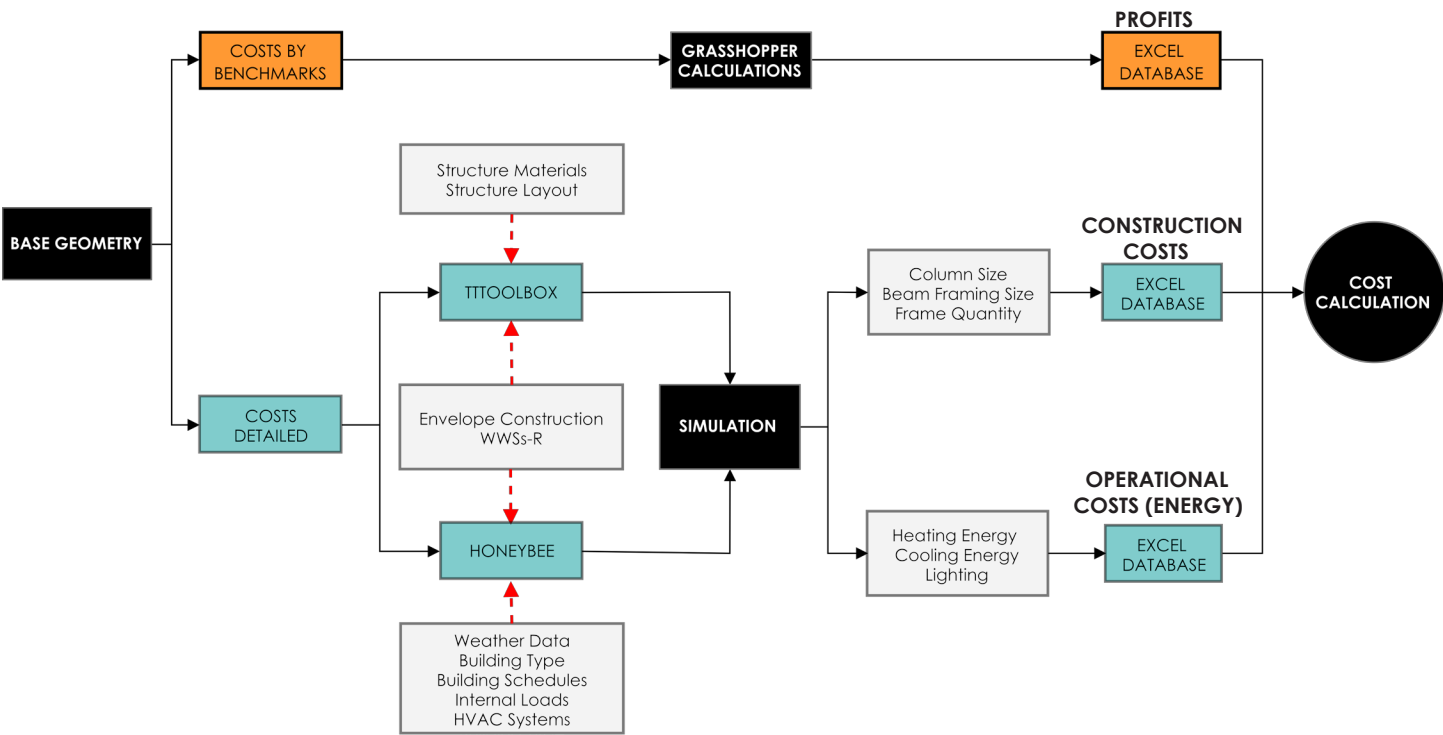


Figure 112. Associate parametric take -off strategy

As shown in Fig.[112] there are three main types of costs; profits, energy costs and construction costs. Each of them varies according to the specific stage of the project. For instance when talking about the second stage, only the structural costs will be considered, while for the third stage, only the envelope costs will be contemplated as construction costs. In the same way the energy costs will be a result of the simulation of the diverse material options and active systems energy performance multiplied by local energy fees. For the aim of this thesis, the idea was to have a trade off between energy cost / construction costs, therefore the selection of materials was also based on the diversification of prices according to energy performances. In this way the most expensive ones are the ones that perform better in terms of energy efficiency as illustrated by Figs [115-120].

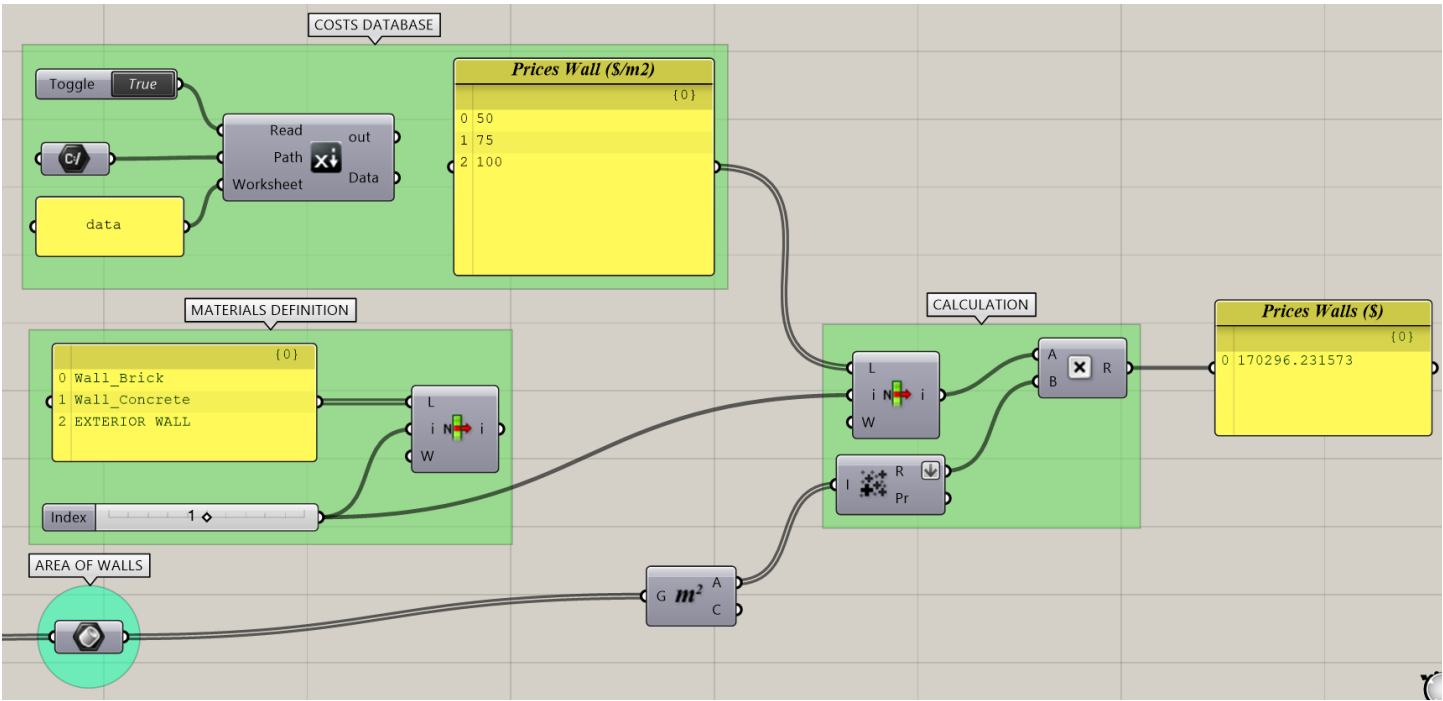


Figure 114. Grasshopper script for parametric costs calculations

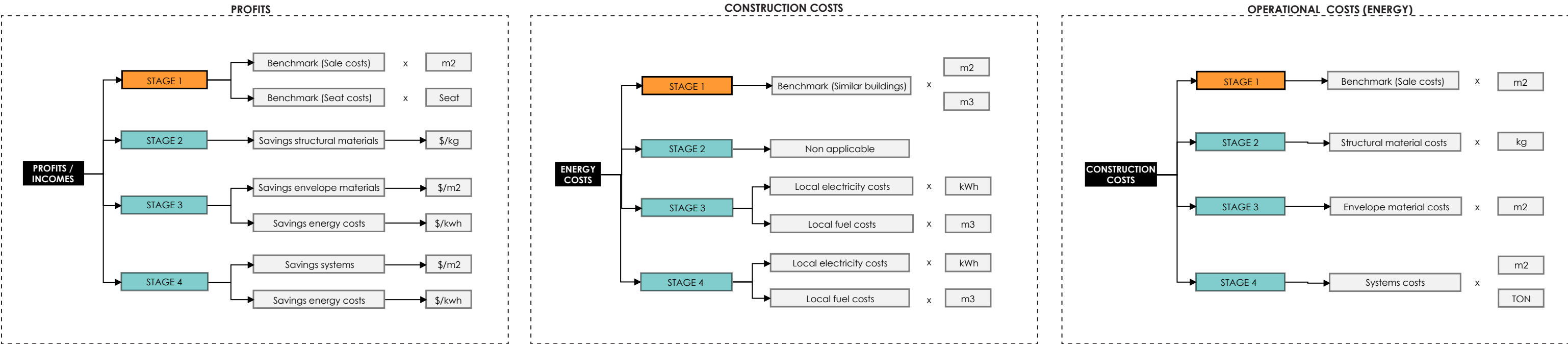


Figure 113. Different kind of costs calculation strategies

4.1.5.2 Cost database organization

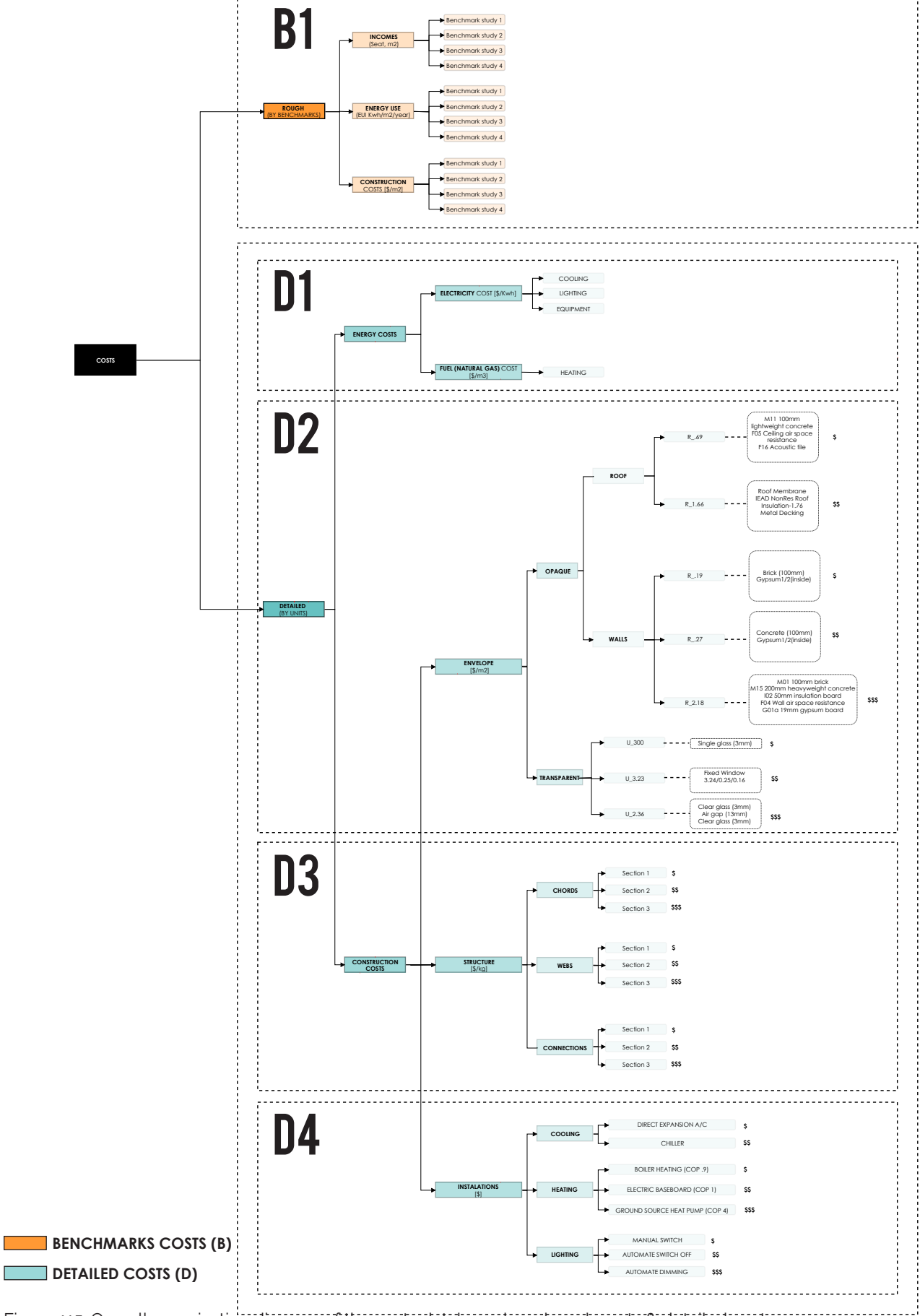


Figure 115. Overall organization diagram of the costs database: benchmark costs & detailed costs

B1

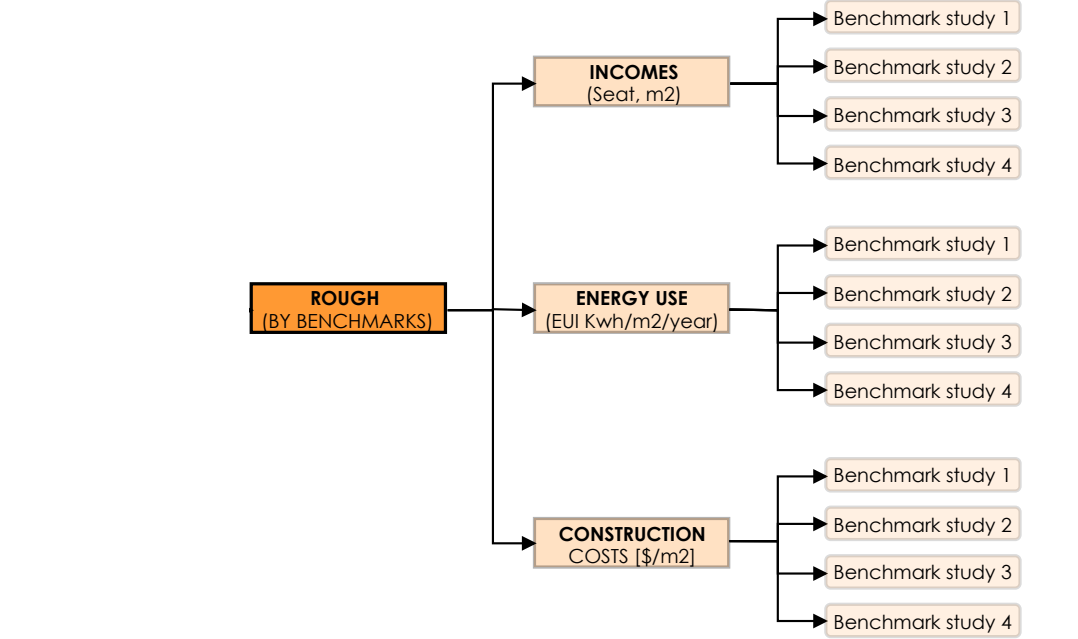


Figure 116. Benchmarks costs

D1

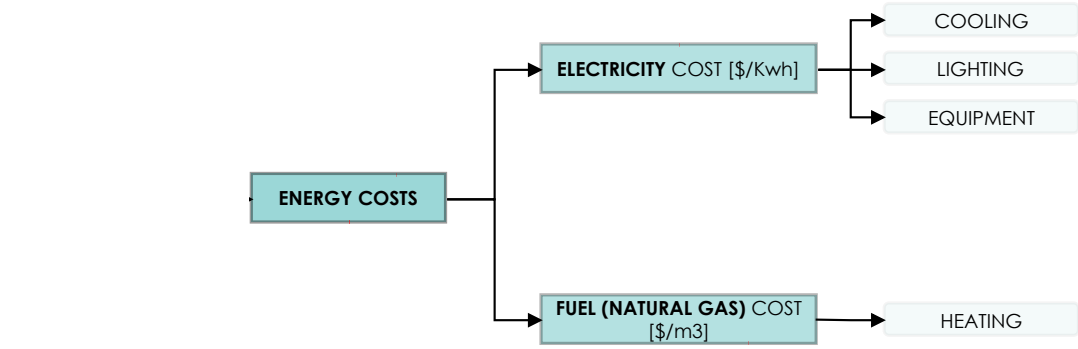


Figure 117. Energy costs organization



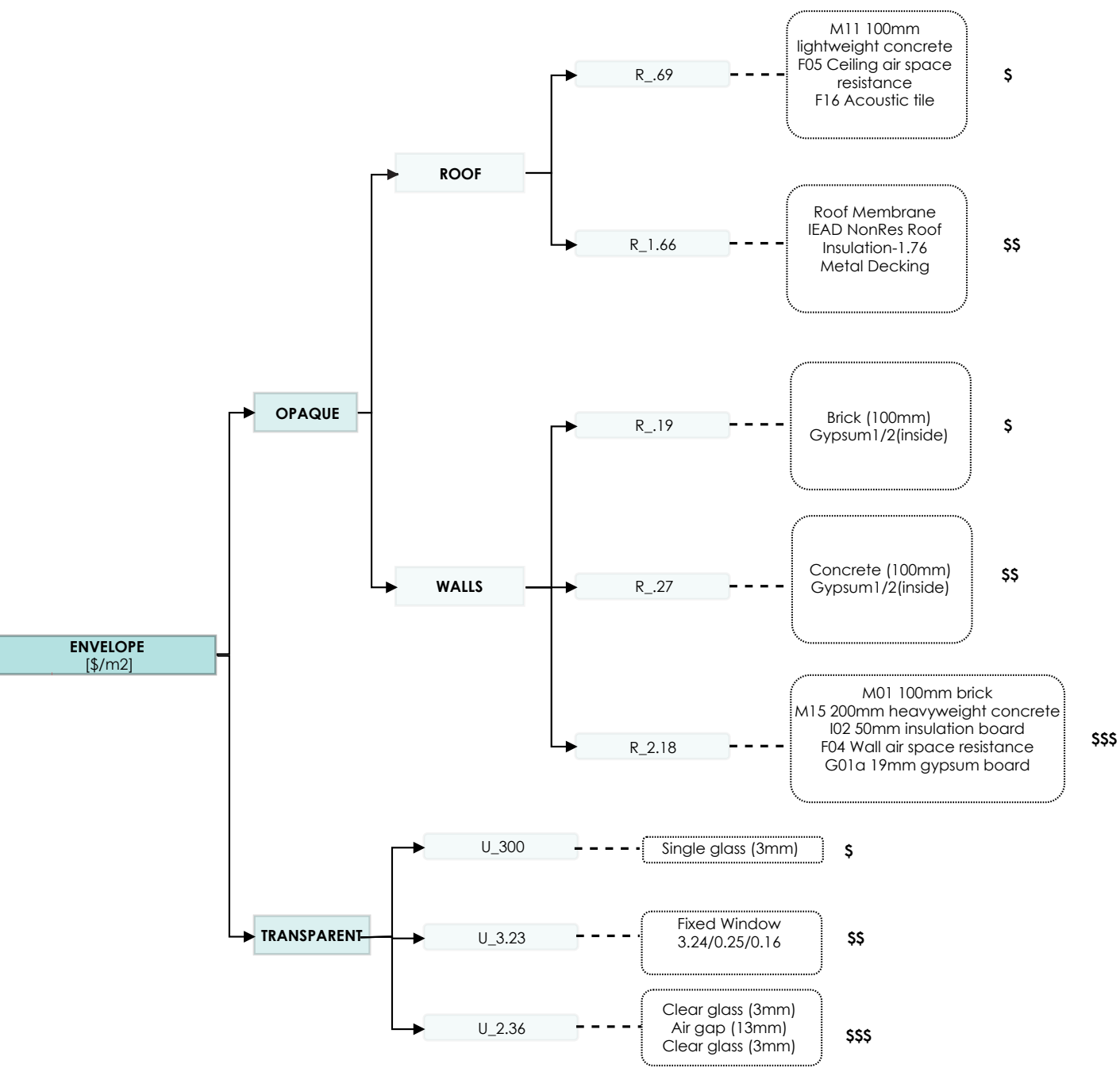


Figure 118. Construction costs (Envelope materials)

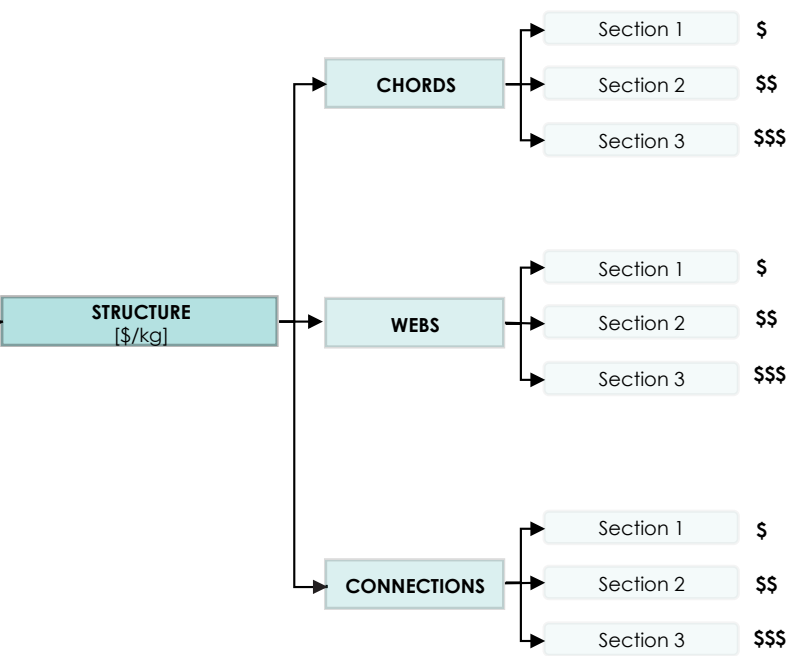


Figure 119. Construction costs (structural materials)

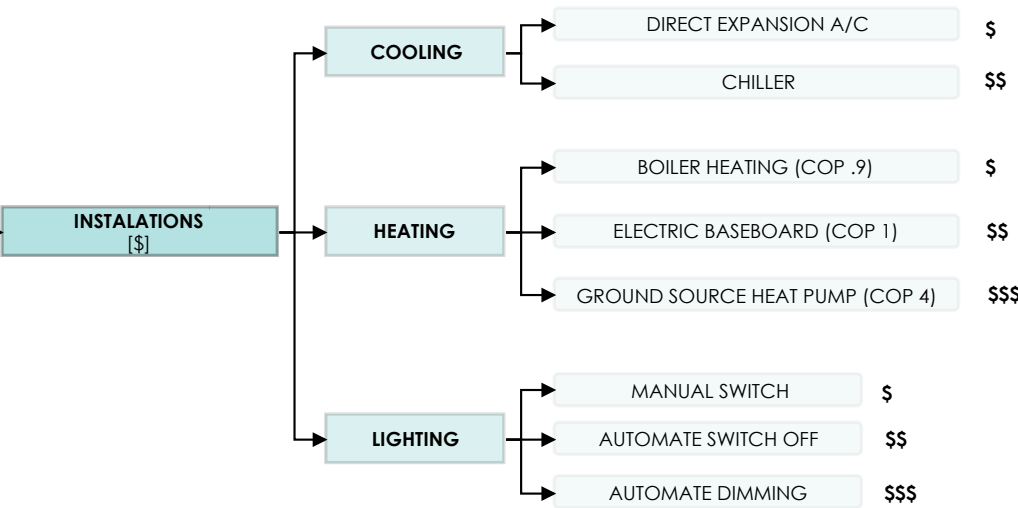


Figure 120. Construction costs (installations/systems)

4.1.6 PARAMETRIC MULTIDISCIPLINARY SIMULATION BASED MODEL SETTING

Since the workflow is based on a multi-disciplinary approach, this section consist of several sub topics or so called disciplines which will be described separately. This phase of the workflow will be defined directly by the objectives and variables definitions described at the beginning of this chapter.

It is important to mention that an extensive amount of performance aspects could be chosen to evaluate the design of a building. However, for the aim of this project, energy demand, daylight and structure will be considered due to the previously mentioned importance that this features have in the design of this kind of venues, always relating this aspects to the overall energy and costs performance described in the following pages.

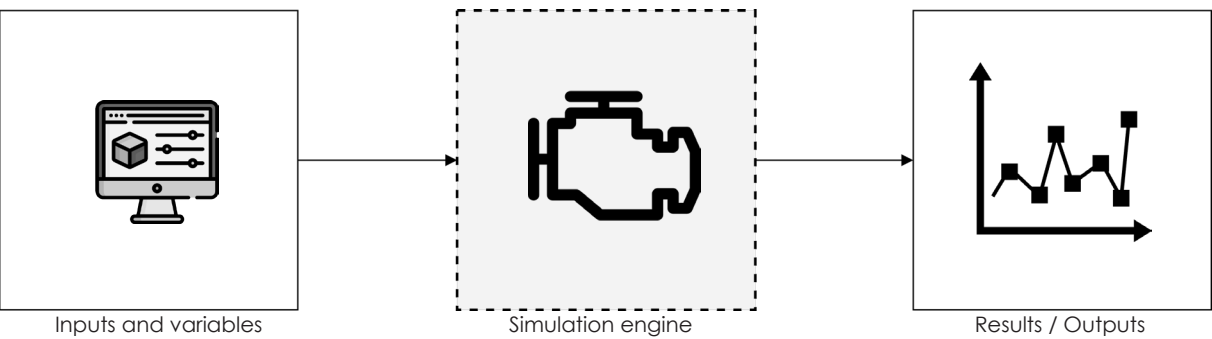


Figure 121. Parametric based simulation based process

4.1.6.1 Parametric model

As described by the figure above (Fig.[121]) this iterative process starts by defining a parametric model that relates in this case a given or specified geometry that is able to change or modify its properties such as the size or the shape or its materials and the relations within them.

When changing these parameters, the performance of the new design definition changes consequently, resulting in new outputs that are simulated and recalculated each time there is a new design option with the idea of having a continuous and automated process achieved by the optimization and exploration processes which will be explained later on.

When defining this parametric model it is necessary to think about what is going to change and what is not, it is necessary to see “the big picture” and consider all the disciplines involved in the process as well as the relation among them.

For instance for this very project, the cost factor will be present in every aspect of the design variations. From another side, the structural simulations will work independently, while for the case of daylight and energy demand simulations, both disciplines are coupled in the parametric model since the results of the first one will affect directly to the second one. This last aspect was crucial during the decision of the tools because it was necessary to find applications that could work together correctly in a straightforward manner.

4.1.6.2 Energy simulation model

In order to calculate the operational energy use of the entire building a calculation method based in ISO 13970 was considered. The standard describes two methods a monthly and an hourly calculation. The monthly calculation was chosen, since the scope of this thesis is to have a rapid feedback of the energy performance. In this way, annual building energy use is calculated for heating and cooling, and also for electricity use for lighting appliances. For the objectives of this thesis and due to the specific performance requirements of a Sports hall only mechanical ventilation will be considered and the energy for hot water and humidification will be ignored. The internal heat gains from people are calculated according to the ISO 7243. The electricity use from lighting is generated by dividing the required lux level by the luminous efficacy of the chosen devices (incandescent, halogen, fluorescent, or LED) and by multiplying this result with the distance between the working surface and the luminaire. The required lux level in this case will be considered as a minimum of 100 lux and a maximum of 2000lux. The luminous efficacy (in lm/W) is the one defined by the simulation software (Honeybee). Furthermore, the different control systems such as manual switch, automate switch and dimming sensors will be analyzed. Electricity consumption of these appliances is retrieved from the results of the simulations. All the energy used for lighting and appliances was assumed to be transferred as internal heat gains.

For the annual heating and cooling demand a building energy balance is calculated considering:

- The heat transmission between the conditioned space and the external environment (heat transmission between building envelope and outdoor air)
- The ventilation heat transfer between conditioned space and the external environment (only including mechanical ventilation)
- Internal heat gains ( including gains from users, appliances and lighting)
- Solar heat gains (including direct and diffuse solar radiation through windows)

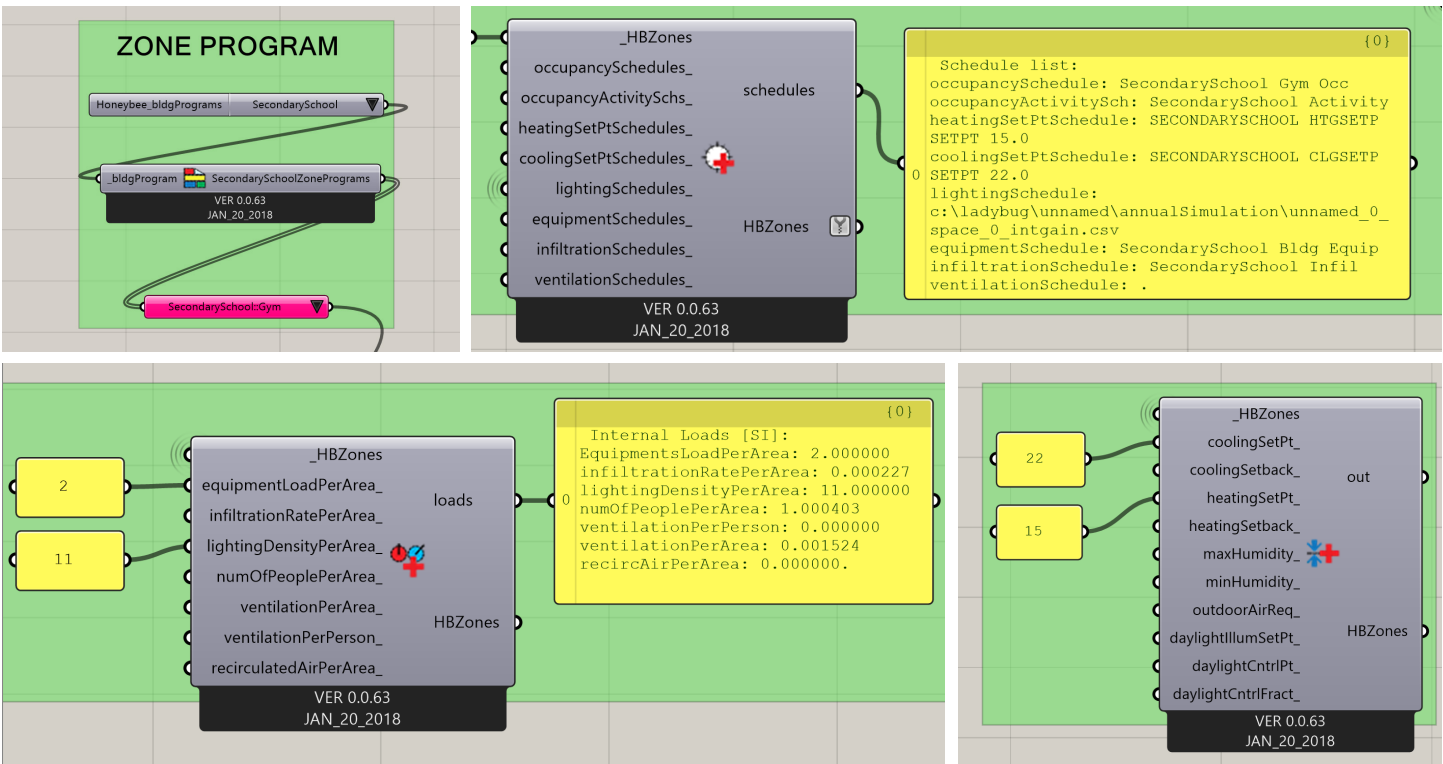


Figure 122. Energy simulation settings and weather data

For the objective of this thesis and for practicality purposes, considering that a single activity will be developed in the building the simple zone division described in the Energy plus users manual discussed in chapter 3.2.2.1.1 will be selected for this case study.

The walls, roof and floors were modeled as surfaces (without thickness) as specified by the Energy Plus user manual and the specific utilized software requirements (Honeybee).

For the thermal performance analysis Energy Plus was selected because It provides an integrated and robust prediction of energy performance and can be successfully linked to the parametric model interface by Plug ins such as Honeybee or Archsim. For the case study the building program “Secondary School Gym” will be selected as a basis as shown in Fig. [123].

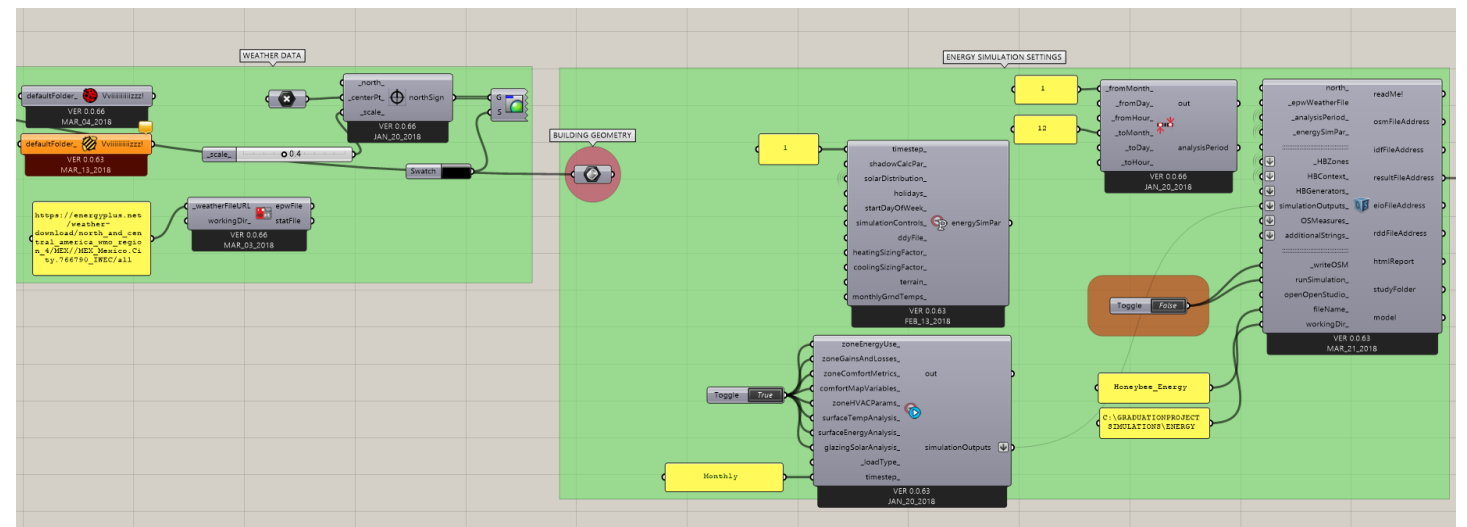


Figure 123. Energy plus settings and weather file connection

#### 4.1.6.3 Daylight simulation model

For the daylight simulation process, an annual simulation will be carried out using Radiance and Daysim to later on in combination with Open studio generate an artificial lighting schedule that will influence directly the energy demand for artificial lighting. The glazing materials will be the same that were applied for the thermal energy model and they will be modified as well as the orientation and the window to wall ratio in the different sides of the building and in the roof by introducing skylights.

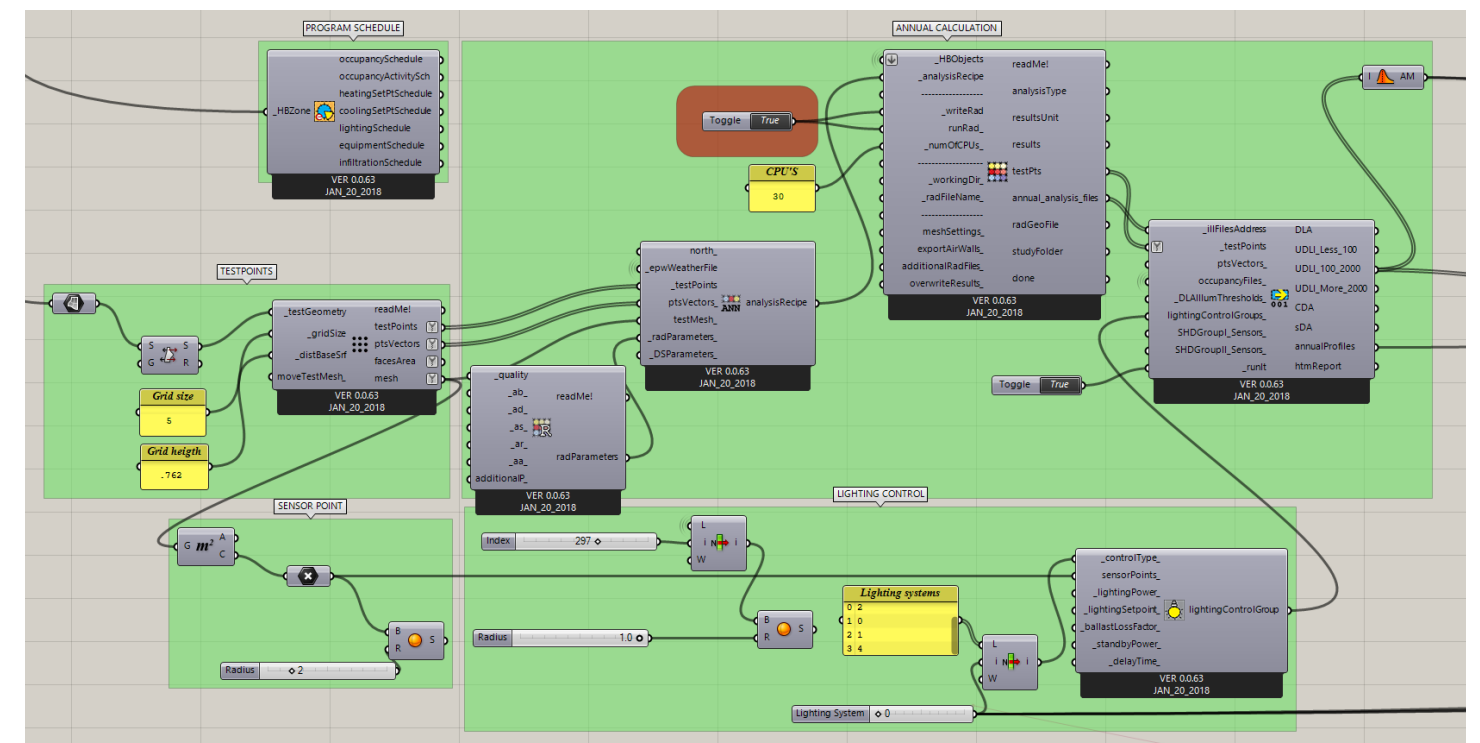


Figure 124. Daylight simulation model settings

For these simulations, a grid of testpoints needs to be defined on the buildings surface, after this a daylighting sensor location will be placed in the middle of the volume normally at 75 cm above the ground level. The size of this previously described grid will be defined considering the fact the smaller the grid the more accurate results but the more time and computational effort the simulation needs to run. Since the intention of this master thesis is to develop a large amount of design variants the grid size will be kept at 5 as shown in the figure below, Fig.[125].

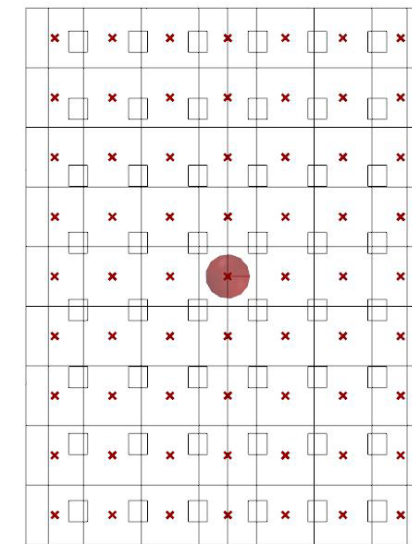


Figure 125. Daylight analysis grid and test points (Honeybee)



4.1.6.4 Structural simulation model

For the structural simulations, the finite element analysis will be chosen and will be performed using Karamba, a structural analysis Plug-in for Grasshopper. As described before, for the purpose of the rapid feedback (considering a conceptual design intention) only symmetrical dead loads will be applied (Gravity load), and several assumptions will be made such as neglecting wind/snow-loads and live-loads.

It is important to mention that Karamba needs independent lines and points to run the analysis and to recognize the different elements of the geometry to apply the correspondent properties,. To calculate the total mass of the structure, the Karamba’s sizing optimization component called (OptiCrosec) will be utilized. This feature applies a procedure for steel beams according to the Eurocode 1993-1-1 to check if a section is sufficient for the axial, bending, torsion, sheer and buckling loads imposed on each member.

For the sake of this thesis, a brief conceptual stage of a structural model will be developed, taking into account, supports, beams, gravity load and different material properties such as diameters and thicknesses. This structure will be proposed based on a typical structural system composed by column trusses and beam trusses which is normally applied for this kind of venues as described in chapter 2.3.1.4 illustrated in Fig:[126]. The material selection will be also fixed to a normally applied kind of Steel (S275) included in the default Karamba materials library. The parametric model will have three types of elements:

- Chords
- Webs
- Lateral connections

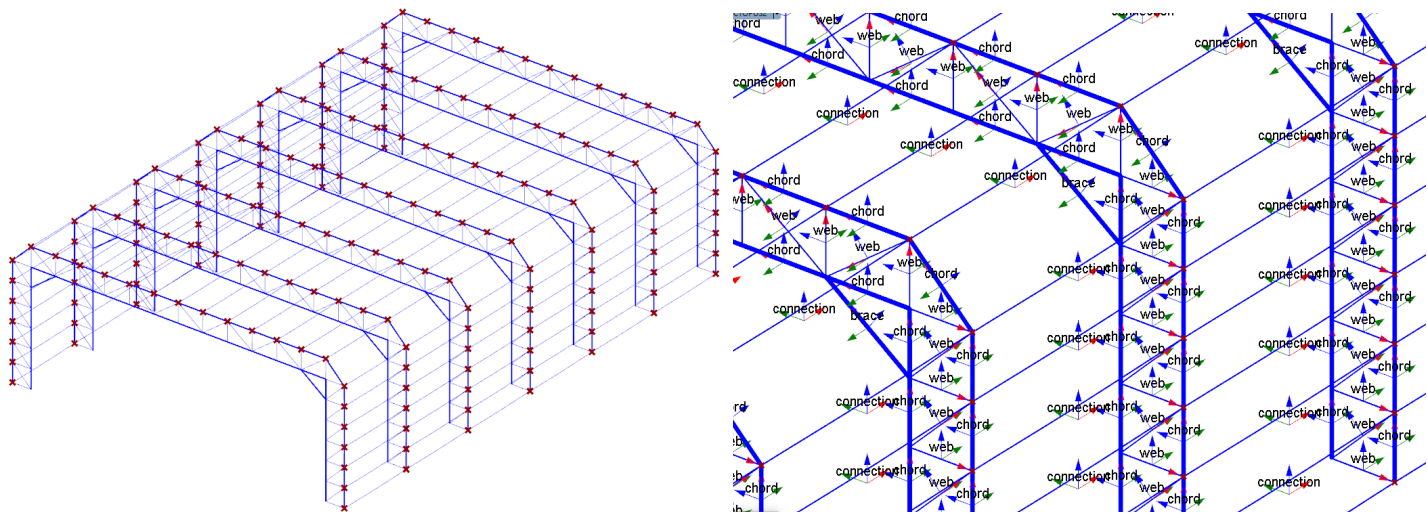


Figure 126. Karamba structural loads and materials settings

These three kind of elements will change its diameter and thickness, which will influence directly from one side to the mass which consequently will affect the overall material costs, and to the displacement which will be the two outputs of interest when analyzing this projects performance aspect.

As part of the simulation process which will be later on linked to the optimization Plug-in, a maximum allowable deflection was conceived as a safety measure for the proposed structure based on the Eurocode (Netherlands Normalisate-Institut 2011) and described as follows:

$$\text{Maximum allowable deflection} \leq \frac{\text{Span}}{250}$$

In this way, only the “feasible” solutions will be considered by the optimization model, filtering out the options that do not accomplish with this consideration while looking to minimizing the mass and therefore the cost of the overall structure.

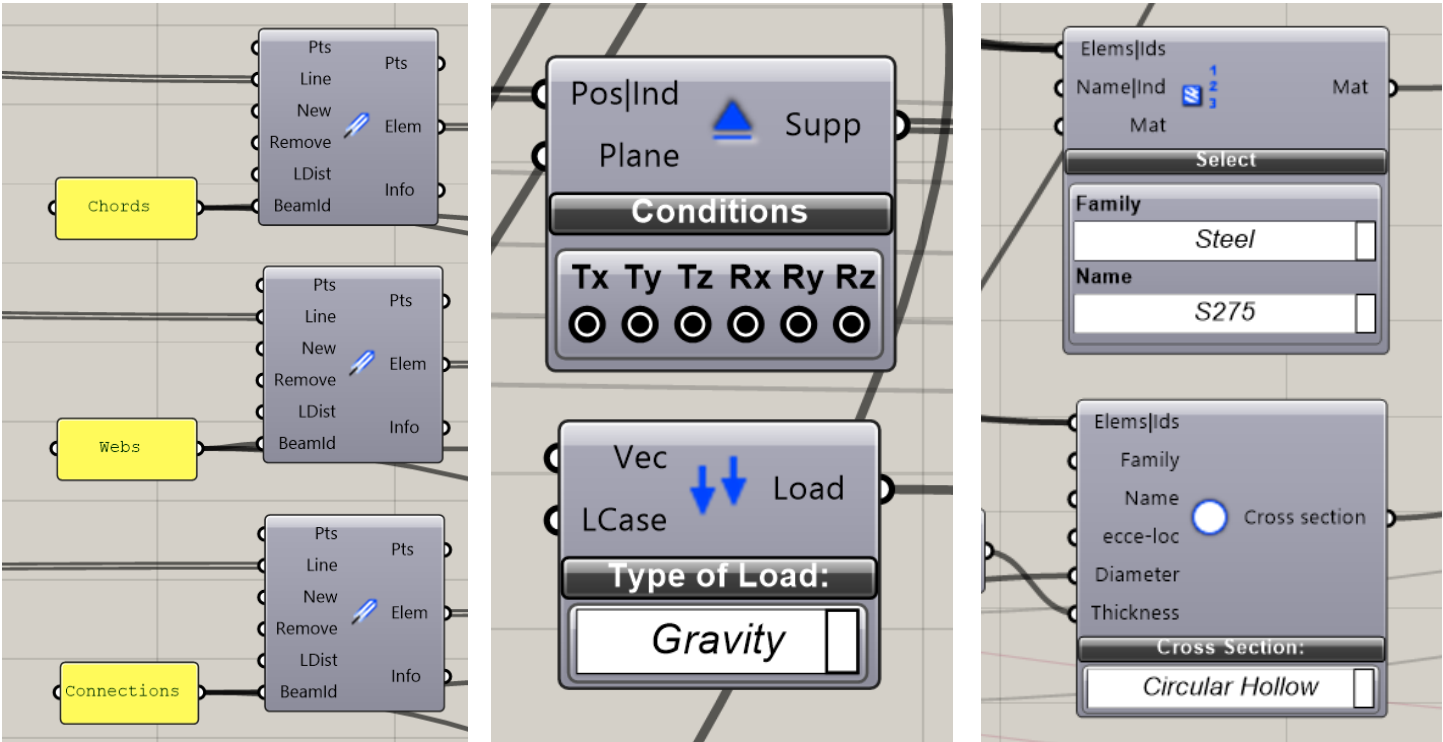


Figure 127. Karamba structural loads and materials settings

4.1.7 OPTIMIZATION PROCESS SETTING

For the optimization process Octopus, a Grasshopper plug in based on evolutionary principles applied to parametric design created by Robert Vierlinger, et al in 2012 is used. This multi-objective optimization engine uses a Pareto-Based optimization described in previous chapters of this thesis.

According to Ashour & Kolarevic (2015) Octopus utilizes two multi-objective genetic algorithms:

- SPEA-2  
As described by Zitzler et al,(2001). It is a technique for finding or approximating the Pareto-optimal set (Zitzler et al., 2001). SPEA was one of the first algorithms to apply elitism, which showed great value in multi-objective search. SPEA uses a regular population and an external archive. In the first step, all non-dominated members of the population are copied to the archive and the (now) dominated or duplicate solutions are removed from the archive. If the size of the archive exceeds a predefined limit, a clustering technique deletes certain archive members. This technique preserves the characteristics of the non-dominated front (Zitzler et al., 2001). In the next step, fitness values are assigned to both the population and archive members. This is done as follows(Zitzler et al., 2001).
  - Each individual in the archive is assigned a strength value, which represents its fitness and is dependent on the number of population members that are dominated by the individual.
  - Each individual in the population is assigned a fitness value by summing the strength values of the archive members which dominate the individual.

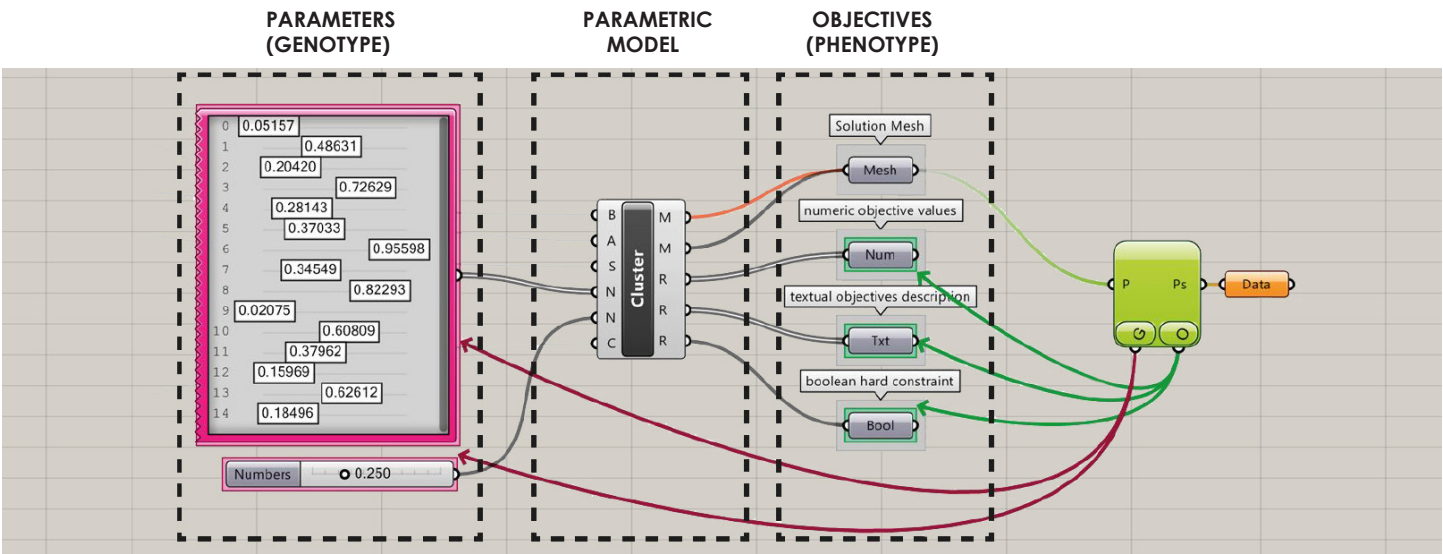


Figure 128. Diagram showing the Octopus optimization process

During the mating selection, binary tournaments are used to select members from both the archive and population. SPEA however shows several weaknesses (Zitzler et al., 2001). The fitness assignment leads to problems when the archive contains only one member; in that case the entire population is assigned the same fitness value. Density information is only known for archive members. This causes problems when many individuals do not dominate each other. On top of that, the clustering technique which is used, may lose outer solutions of the archive. SPEA-2 solves these issues, by altering some characteristics of the SPEA algorithm. First of all, the fitness assignment is based on both how many individuals a solution dominates and by how many individuals it is dominated by. Secondly, a nearest neighbour density estimation allows a more precise guidance of the search process. Finally, an improved reduction method preserves boundary solutions of the archive (Zitzler et al., 2001). Drawback of these improvements are the computationally costs that they come with them (Konak et al., 2006).

- HypE  
It is a hyper volume estimation algorithm, developed at the ETH Zurich. The hypervolume indicator is the only set measure that is known to assess the quality of a Pareto set approximation (Bader and Zitzler, 2008). This means that whenever a Pareto set approximation entirely dominates another, the hypervolume indicator will be better as well being of great relevance for problems involving a large number of objective functions (Bader and Zitzler, 2008). It however does require great computational power for the calculation. HypE is able to make a trade-off between the accuracy of the hypervolume estimation and available computing resources.

Octopus uses an interface based on David Rutten's Galapagos (Vierlinger, 2012) as shown in Fig.[122]and according to Ashour & Kolarevic (2015) it provides flexibility for the designer to choose between the above two different reduction strategies and between three different

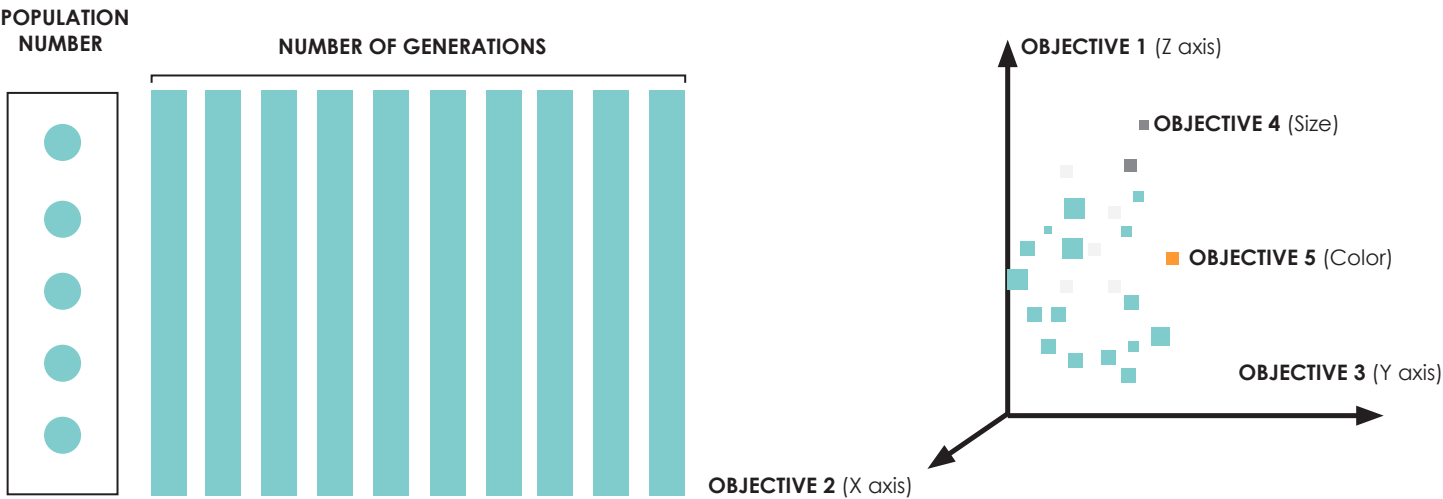


Figure 129. (Left)Octopus optimization interface. (Right) Optimization procedures

mutation strategies based on the population size and the number of objectives. Elitism, mutation probability, mutation rate, crossover rate, population size and the maximum amount of generations can be defined manually before or during the optimization adapting to the scale of the design problem

The way it works is as also defined by Ashour & Kolarevic (2015) as an iterative process where the first solution set is randomly generated and the following generations are generated by an algorithm emulating the biological reproduction by pairing solutions. After each iteration, the genes of the two of the best performing solutions are combined to create a new set of genes, these genes form the design variables of the new generations. By mimicking the natural selection process the fittest solutions survive, nevertheless, they are not automatically the fittest

solutions within the context. In this sense, the solutions with highest performing designs will be the ones that best fit with the required objectives. A possibility of mutations is defined in the algorithm to diversify the populations offspring avoiding the algorithm of getting stuck in a local optima.

Octopus plots the results of the optimization in a real time 3D graph in which every cube is a mathematical representation of the performance of a design. In this 3-dimensional graph, each axis represents an objective, and the color and size can also be used as the fourth or fifth objective respectively. In the case of this thesis, the objectives vary according to the different stage of the process and when talking about the compiled model will be. 1.Total cost (Materials + Operational) 2. Energy Use Intensity 3. Useful Daylight Illuminance.

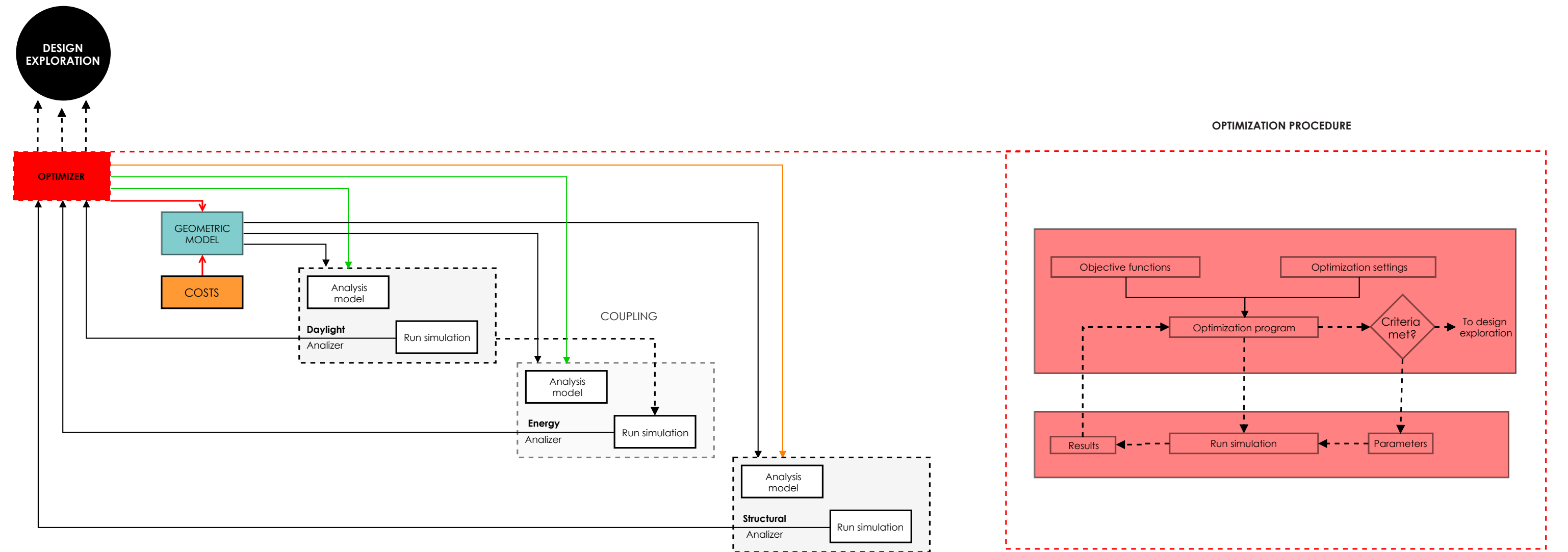


Figure 130. Overview of the multidisciplinary optimization process based on Yang, et al. (2015)



4.1.8 EXPLORATION & OPTIONEERING PROCESS SETTING

This process was designed after analyzing and combining the different plug-ins and software, in this way the parametric model is directly linked from one side with the iterator (which will run all the possible alternatives within the design space) and from another to the aggregator plug-in which will gather and organize the data for later visualization. The iterator could be a brute force solver (incorporated by default inside Colibri) or in this case an optimizer (Octopus) which will also run all the possible options but will evaluate them and will try to find the optimum solutions based on the Pareto front previously described. After the information is organized, all the information will be translated to the web-based Design explorer platform as shown in the next page.

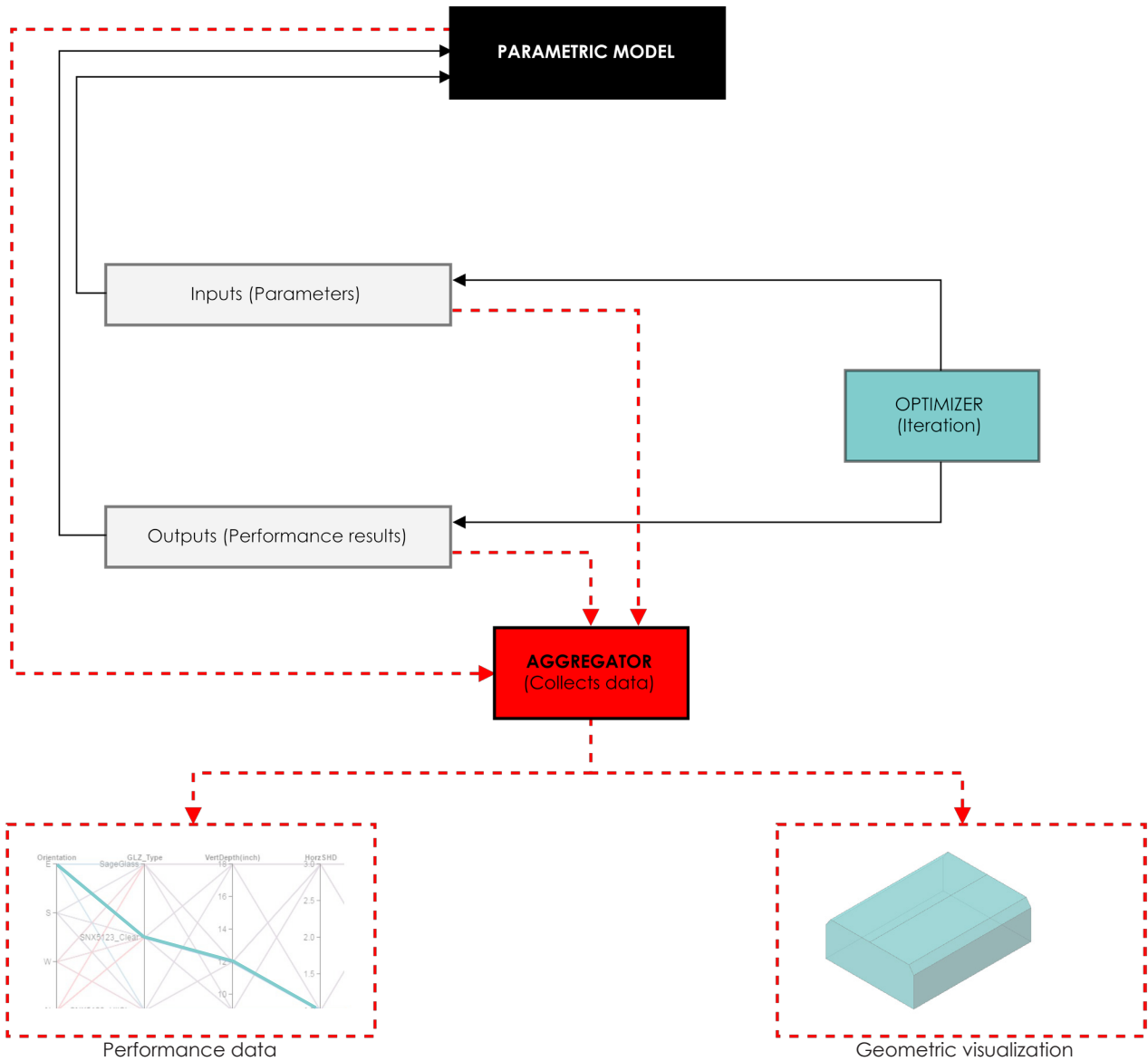
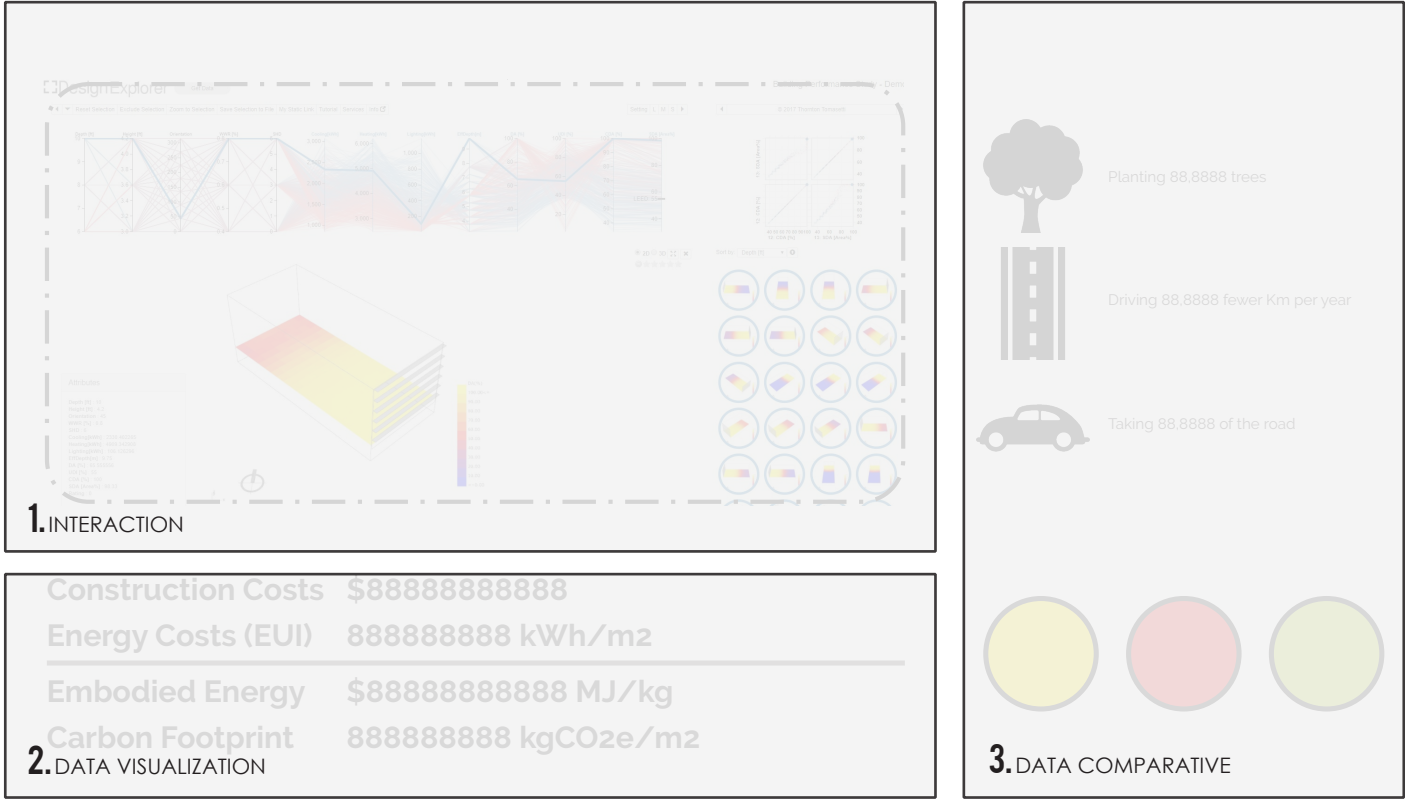


Figure 131. Workflow for design exploration and visualization



Despite that the Design interface provided by Design explorer is highly complete and successfully allows the user to explore the design space by filtering the options according to the user preferences. Possible incorporations to the platform are suggested based on the first part of the research of this thesis as shown in Fig. [132]. When comparative data and scores are also involved in order to make the design exploration even more complete and understandable.

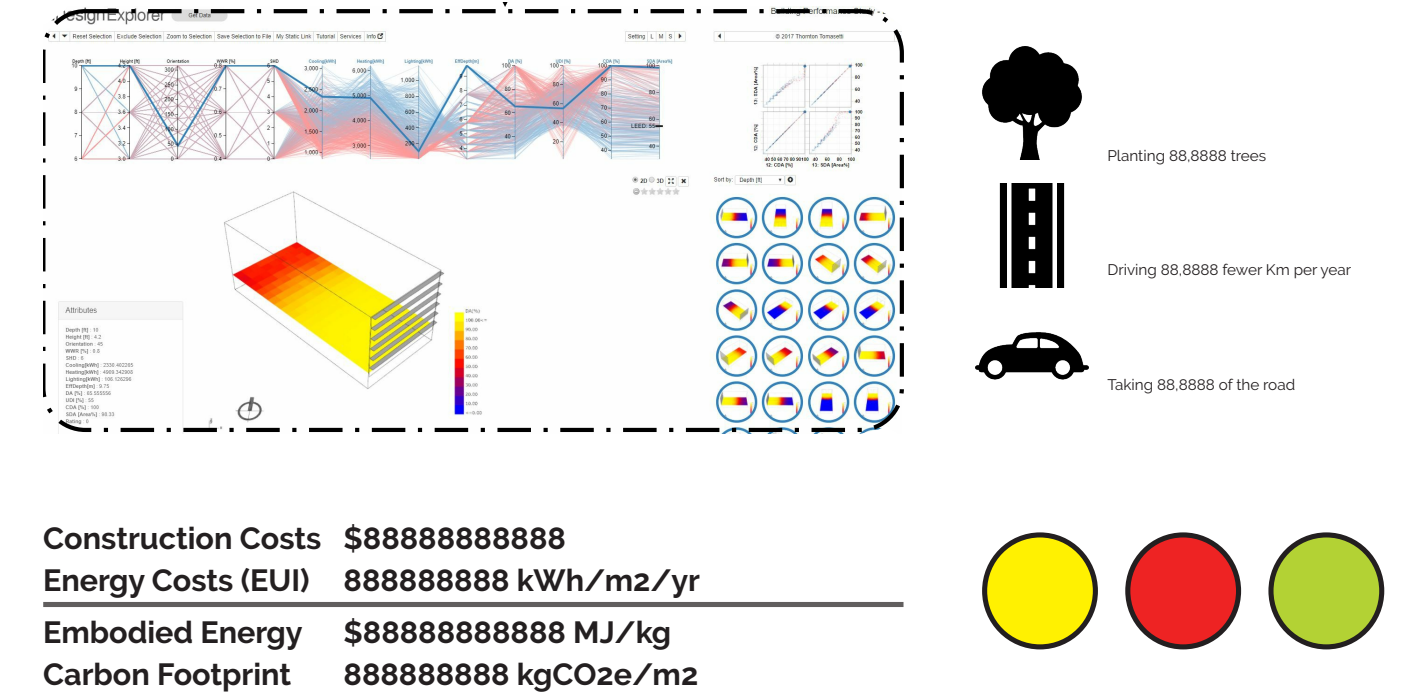


Figure 132. (Up) Design explorer interface. (Down) Proposed elements for results visualization

## 5. CASE STUDY



5.1CASE STUDY

For the application of the previously defined workflow, the case study of a dry Sports hall that hosts sports such as basketball and indoor football was considered. The size was selected according to the typical measurements of this type of buildings based on the literature review. This case study will intend to prove how with an integrated computational design workflow, can aid the designer along the design process. By developing optimization techniques and later on using design optioneering and visualization strategies a design that considers both the buildings performance and the personal intuition will be proposed.

This typology of building was selected because of the complexity that involves in terms of energy and costs, specially when talking about trading off costs with energy savings. Besides , because of the capacity of this venues to generate a positive impact in the social aspect . In this way, the requirements, models, properties and costs analysis were fitted to prove the intended design workflow.

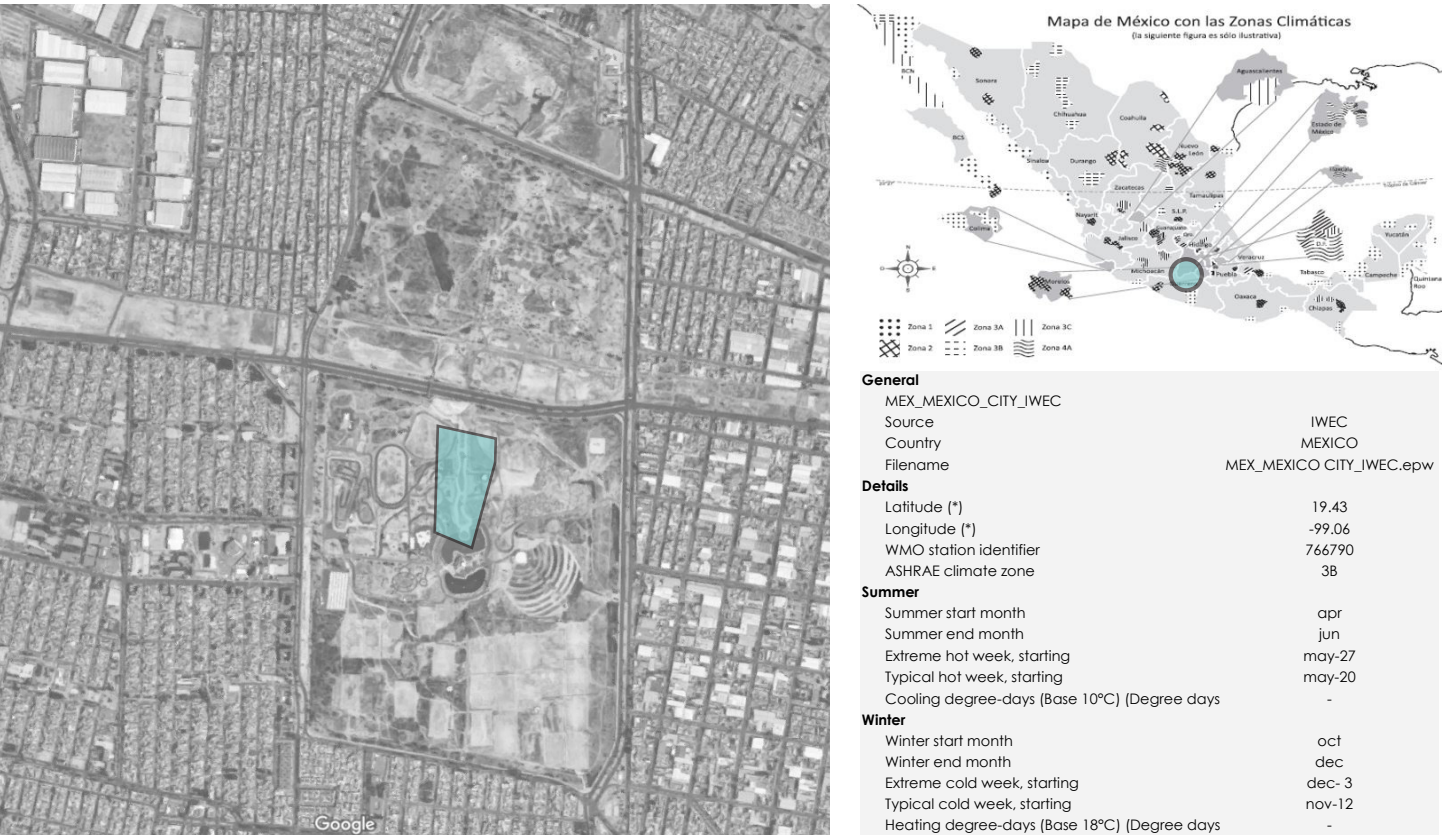


Figure 133. Image of the current location and climate classification, according to ASHRAE 90.1

5.1.1 LOCATION

The project is located in the South of Mexico City, which as shown in Fig. [127] belongs to the zone 3B as defined by ASHRAE 90.1. It is placed inside a municipality called Iztapalapa, which is a quite peculiar and interesting zone. First of all is considered to be the most populated area in the city with a population of almost 2,000,000 people having a density of 15, 635,80 , INEGI (2010). It is also considered the poorest area in the city, condition that triggers several social problems such as delinquency and bad quality of life.

Therefore, it is a place that needs all the possible amount of public policies and infrastructure that can detonate social interaction and the local economy. In this scope, the local government is showing a significant interest towards the implementation of recreative areas and sports facilities.

In this scope, a large green area called “Parque Cuitlachuac” which is a currently abandoned open area with a context conformed mainly by residential constructions with a maximum of two stores height. This location represents the ideal location for developing this new public infrastructure projects.



Figure 134. Images of the physical and social context around the proposed area



5.1.2 LAYOUT & REQUIREMENTS

5.1.2.1 Layout & spatial requirements

The initial layout of the building was based on the reviewed literature and design standards for sports venues. For the aim of this study a single zone was planted excluding the building services such as bathrooms and storage rooms. In this way, the floor plan consists of a regular rectangular shape which has the possibility to grow in its depth, width and height for the generation of diverse design options as illustrated in the images below:

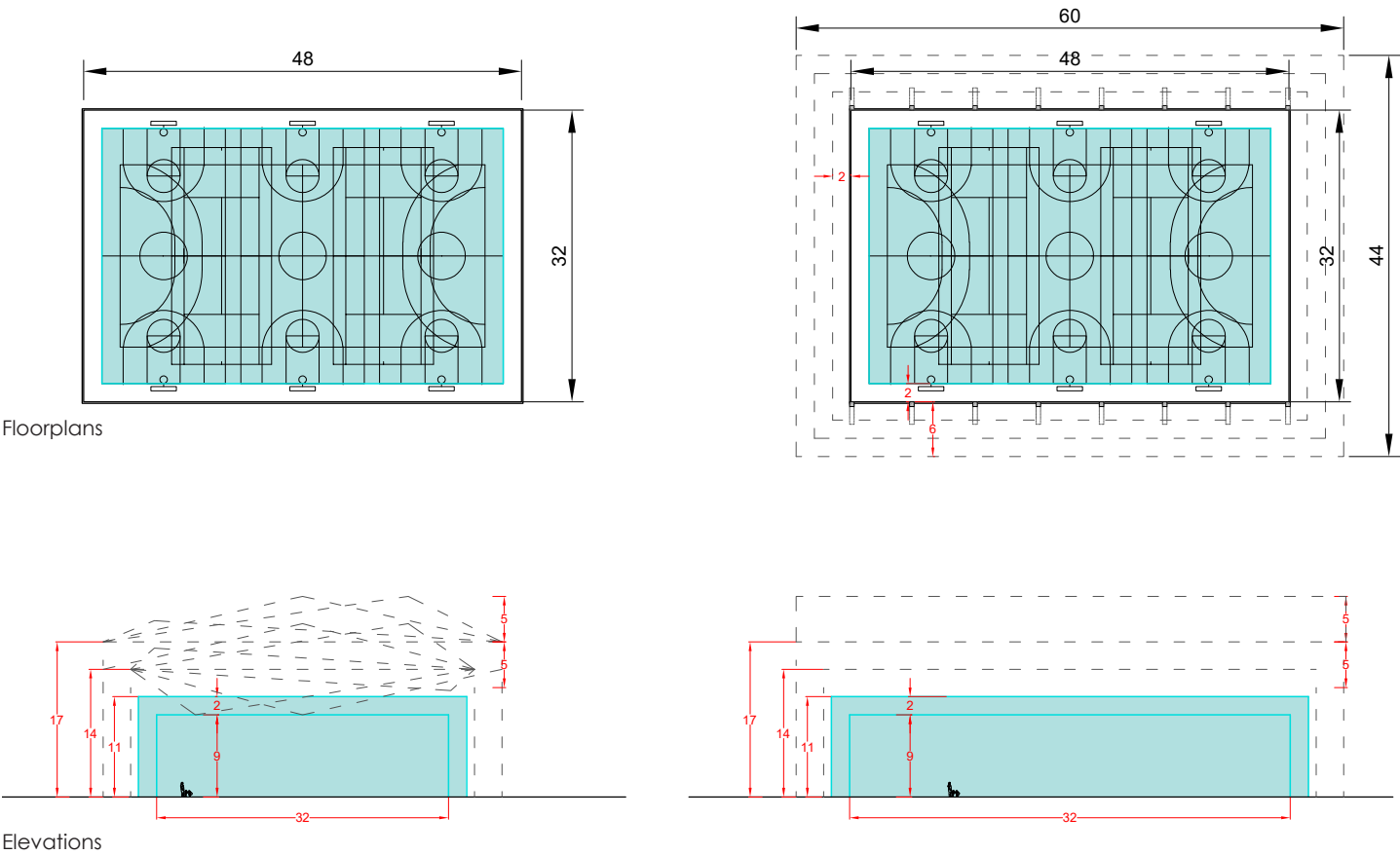


Figure 135. Blueprints of the required building

Situation 1 (Without spectators)

Area : 11536 m2

Volume : 16,896 m3

- Program:
- 3 Basketball courts
  - 2 Volleyball courts
  - 1 Soccer space
  - 1 Circulation space
  - 1 Steps space

Situation 2 (With possible spectators)

Area: 2,640 m2

Volume: 44,880 m3

Fig. [136] Shows different types of space that can change according to the internal space of the venue, giving the possibility to have more area to host spectators places or to rent or sell the building per surface of area. This consideration was thought in first place because as reviewed in the literature review, it is important to consider the design of a building from a commercial point of view, planing it as a possible business or a financial case.

Secondly, this was implemented to counter balance the fact that reducing the area and volume respectively diminishes the construction and energy costs. Hence this growing possibility was implemented in order to being able to have a trade-off evaluation between from one

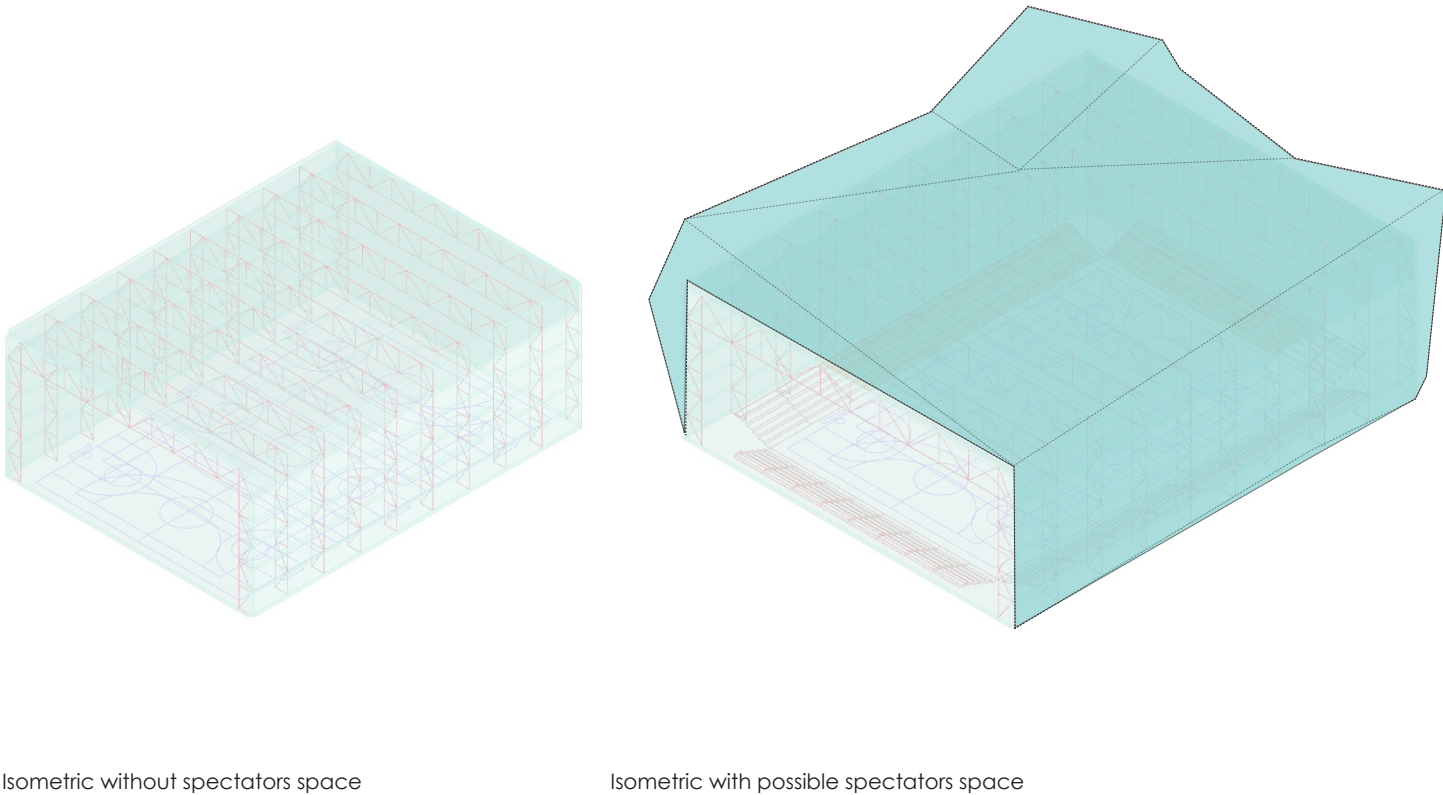


Figure 136. 3D views of the required building

side minimizing the area, and from another maximizing it to get more possible incomes. In addition to this, as defined in previous chapters, the formal /expressive aspect has a high importance in this kind of buildings which sometimes host important events an can even become city milestones. Therefore, the architects normally play with the volume and the mass of the building, increasing the size of it without being aware of the consequences of this when talking about costs and energy use.

This massing studies can result in regular or irregular building shapes as it can be observed in Fig. [136]. However, for the aim of this study, a regular shape will be intended in order to be able to run the simulations successfully an clearly explore the design parameters and design variations.

5.1.2.2 Occupancy and schedules

For the occupancy and activity schedules of the proposed venue a combination among typical time schedules gathered from a benchmarks research with the contextual situation of the buildings location, a time table was proposed as described in Fig.[137].

This occupation times were simplified for practicality reasons having a fixed schedule for the entire days of the week not considering holidays periods.  
This schedule changes along the day, starting early in the morning with a low occupation (only by the staff that starts arriving) to having an intensive occupancy until the lunch break (1 to 3 pm) to continue again with another exhaustive occupancy use to end up around 9 pm when only the staff that is in charge of cleaning or closing the doors remain inside the building.  
The heating, cooling and lighting systems were also adapted to this schedules, having set points and setbacks according to the buildings occupancy, maintaining a continuous infiltration rate always on.

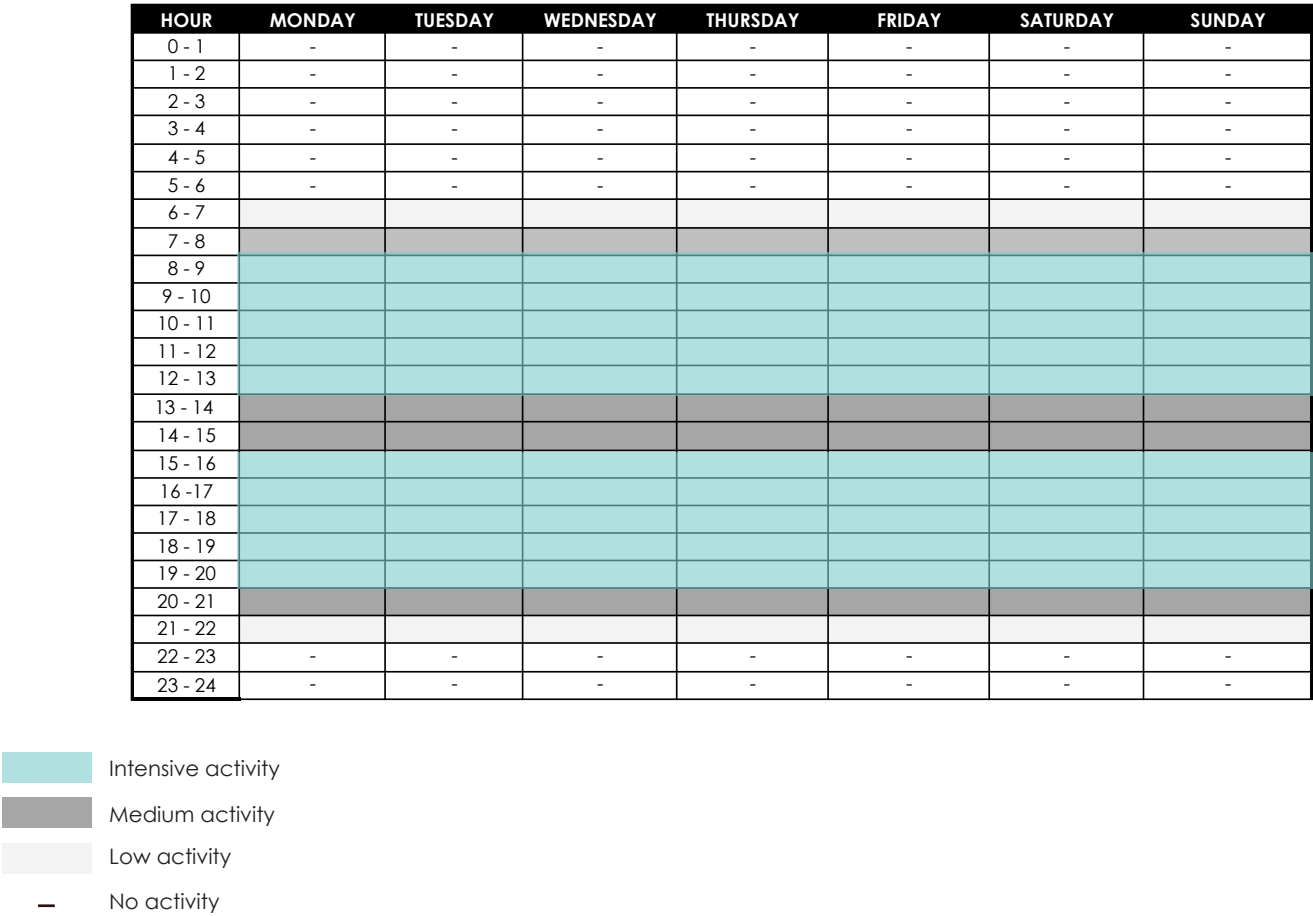


Figure 137. Occupancy schedule (Weekly)

When talking about comfort requirements, the ASRHRAE 90.1 code was considered, in combination with the available settings included in the utilized software (Honeybee).  
In this way, as described in chapter 3.1.4.2.1 Honeybee hosts a library of default building programs from which the most similar was the so called "Secondary School Gym". This building program was selected as a basis for the energy simulations and later on modified to try to accomplish with the standard requirements.

5.1.3 CLIMATE ANALYSIS

As described before, weather conditions have a fundamental impact on the building thermal behavior and its overall energy performance, therefore a preliminary analysis of the local conditions was developed using a specialized plug-in for Grasshopper called Ladybug that features several types of climate analysis by using Energy Plus (.epw )weather files as a basis. For the application of the case study, the Mexico city. Iwec file was selected.

Besides the use of Ladybug also Climate Consultant 6.0 was utilized to elaborate different information charts like temperature graphs and a Psychrometric chart to conclude about the weather situation and the possible design measures to be taken.

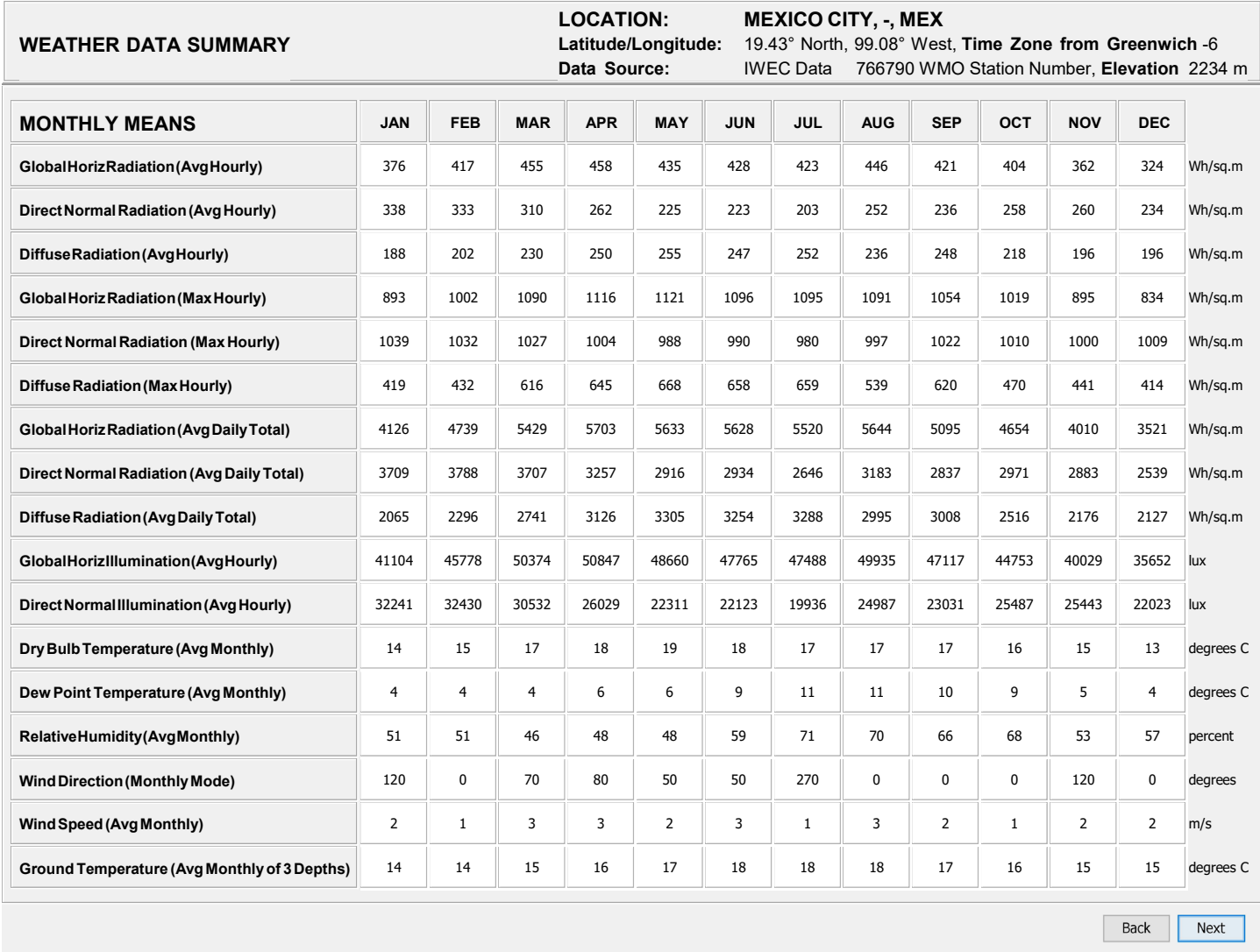


Figure 138. Weather data summary made in Climate Consultant 6.0

Fig.[138] shows an overview of all the climatic conditions in the specific location based on a monthly analysis.

Analyzing the climate data, it can be observed that the location has a highly regular climate, by having small temperature variations among the 17°C and the 25°C. However, from a personal point of view as an inhabitant of Mexico City I can say that sometimes specially

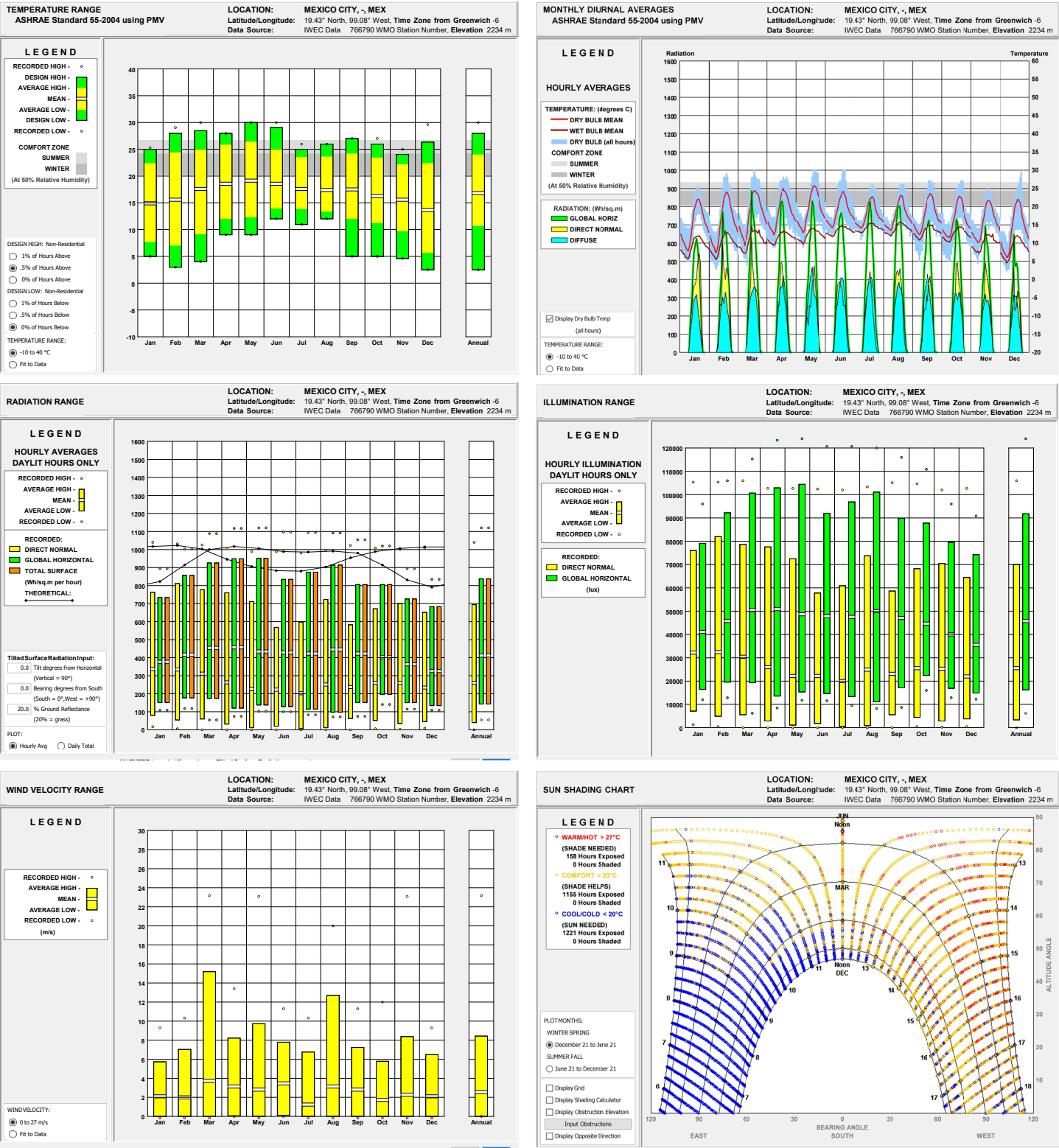


Figure 139. Climate charts made in Climate consultant 6.0

during the summer, the temperatures rise even to 35 °C and during some winters to -5°C. This is in great manner because of the pollution problems that are an important and urgent problem issue in this urban area and of course the global climate change. Unfortunately, the climate data provided by the available software does not update regularly enough to describe this irregular variations.



The following set of charts and graphs describe the behavior of the climatic conditions specifically about the temperature variations, relative humidity and wind speed in an hourly scale. It can clearly be noted that the main high temperatures are around 8 am until 6pm extending until 10pm during the spring an the summer period. The relative humidity rises principally during the mornings been more intense in the fall season. The wind velocity has its peaks during may and august respectively, however it remains regular during the major part of the year.

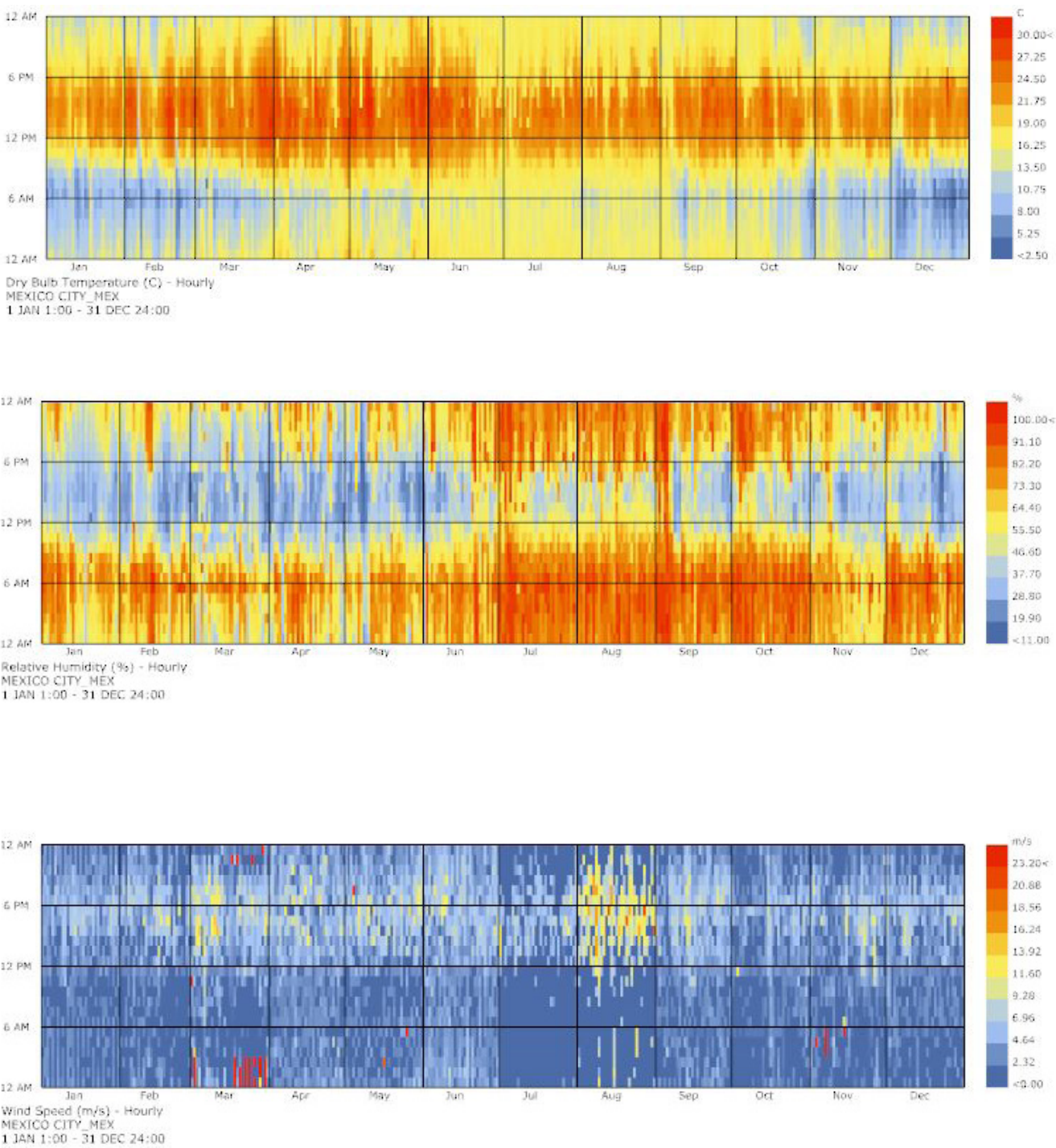


Figure 140. 2D Climate charts made in Ladybug

From the Psychrometric chart presented below in Fig. [141] it can be deduced that around 16% of the time the temperature is comfortable. In the graph that describe the comfortable hours along the entire year in an hourly basis it is clear that the main comfort hours are during the evenings from 12 pm to 6pm, which represents that special attention should be paid for the morning hours and the afternoon hours during the summer period.

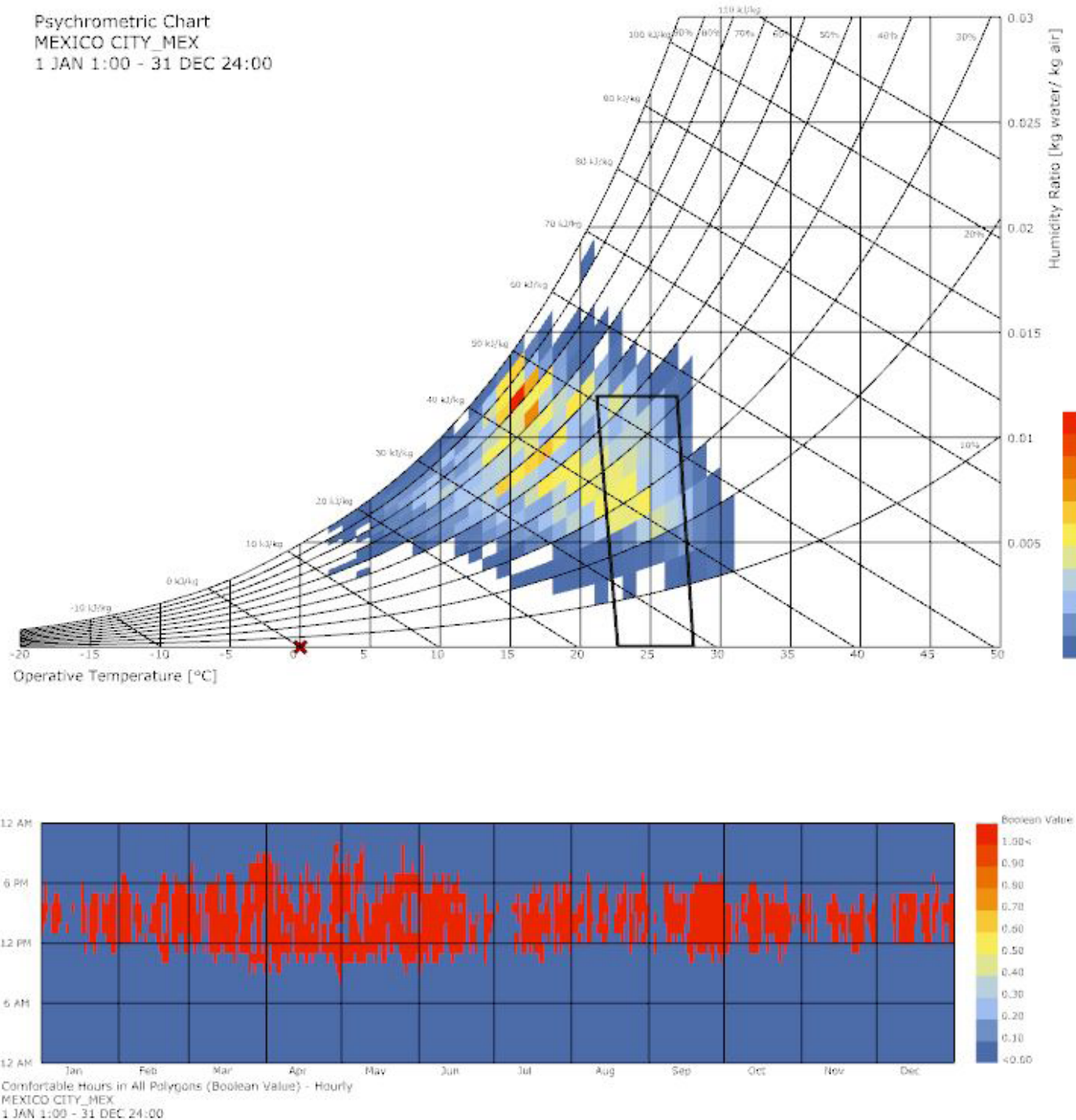


Figure 141. Comfort hours and Psychrometric chart made in Ladybug



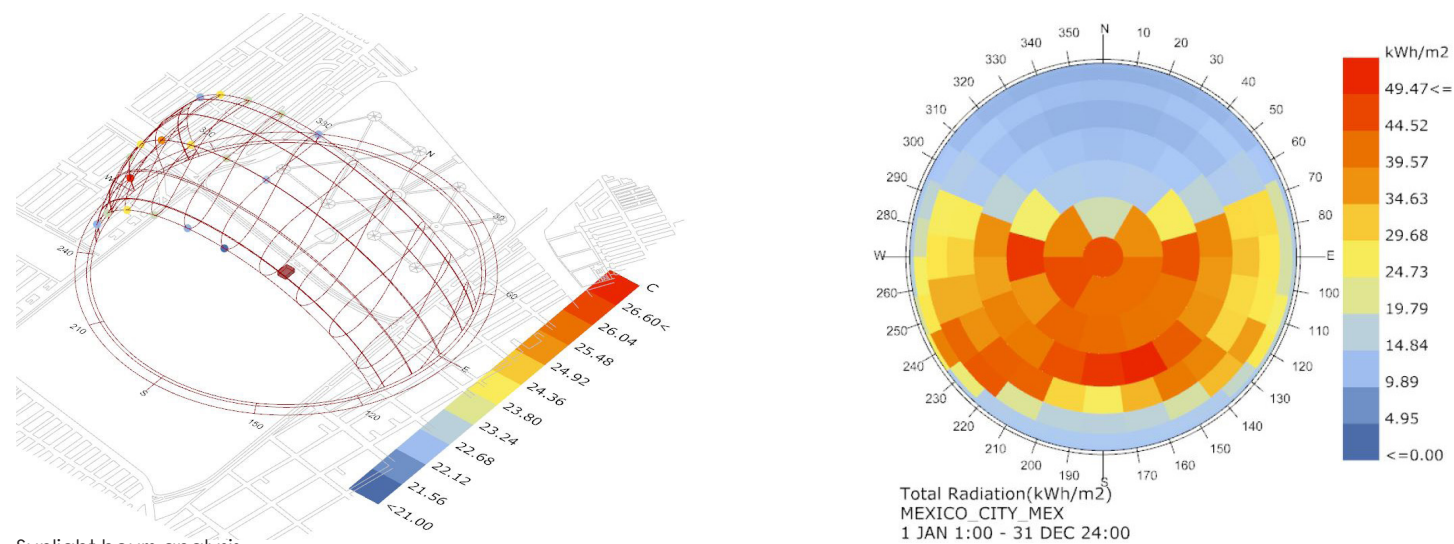


Figure 142. Climate analysis made in Ladybug

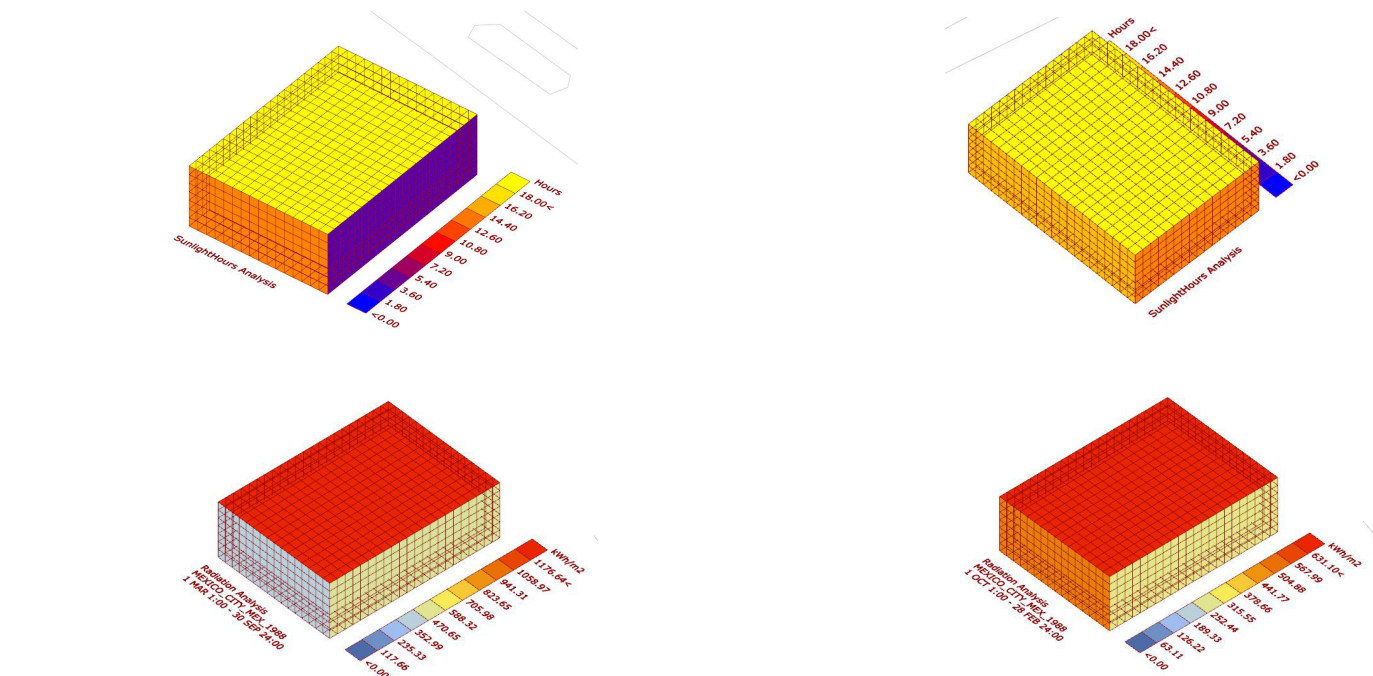


Figure 142. Climate analysis made in Ladybug

After reviewing the illumination and solar analysis it can be defined that there is a high radiation during the summer period (around 1200 kwh/m²) specially on the south and east orientations condition that should be consider for the design of the building. Talking about the available illumination there is a mean of 5000 lux with sun light hours that vary from the summer period having natural daylight from 6 am to 7pm to the winter season having natural illumination from 8am to 5pm.

The wind analysis presented in Fig. [138] show that the average wind speed is 2 m/s having the main wind flows coming from the north orientation, specially during August and September.

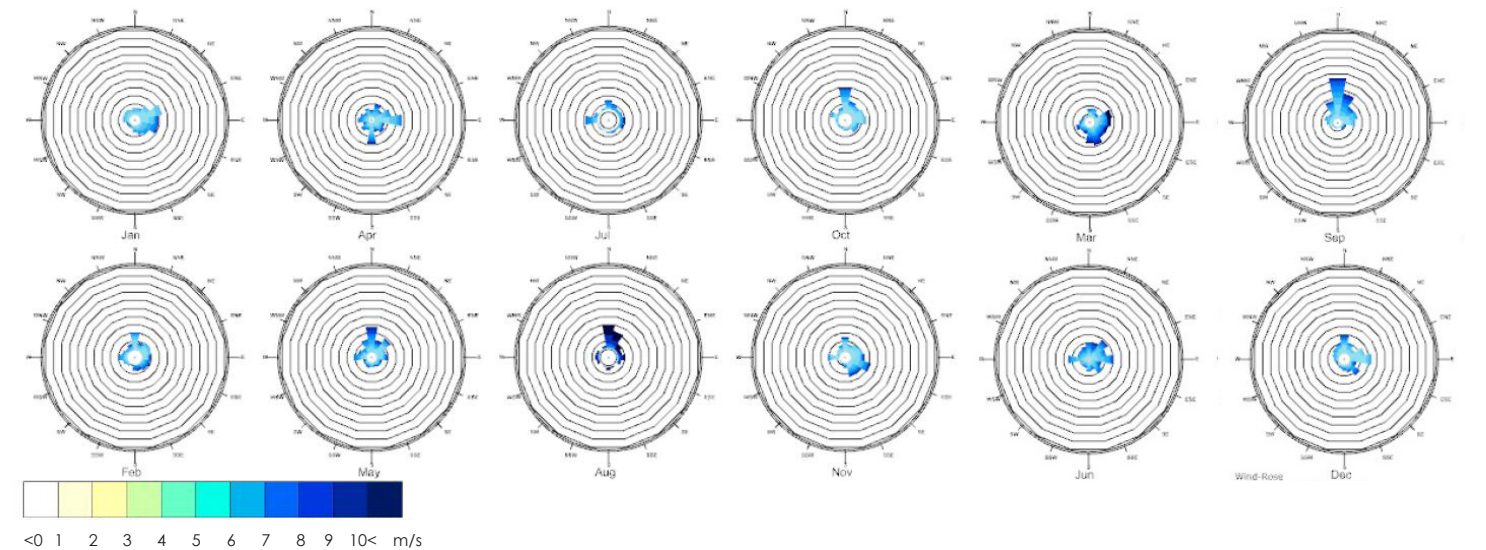
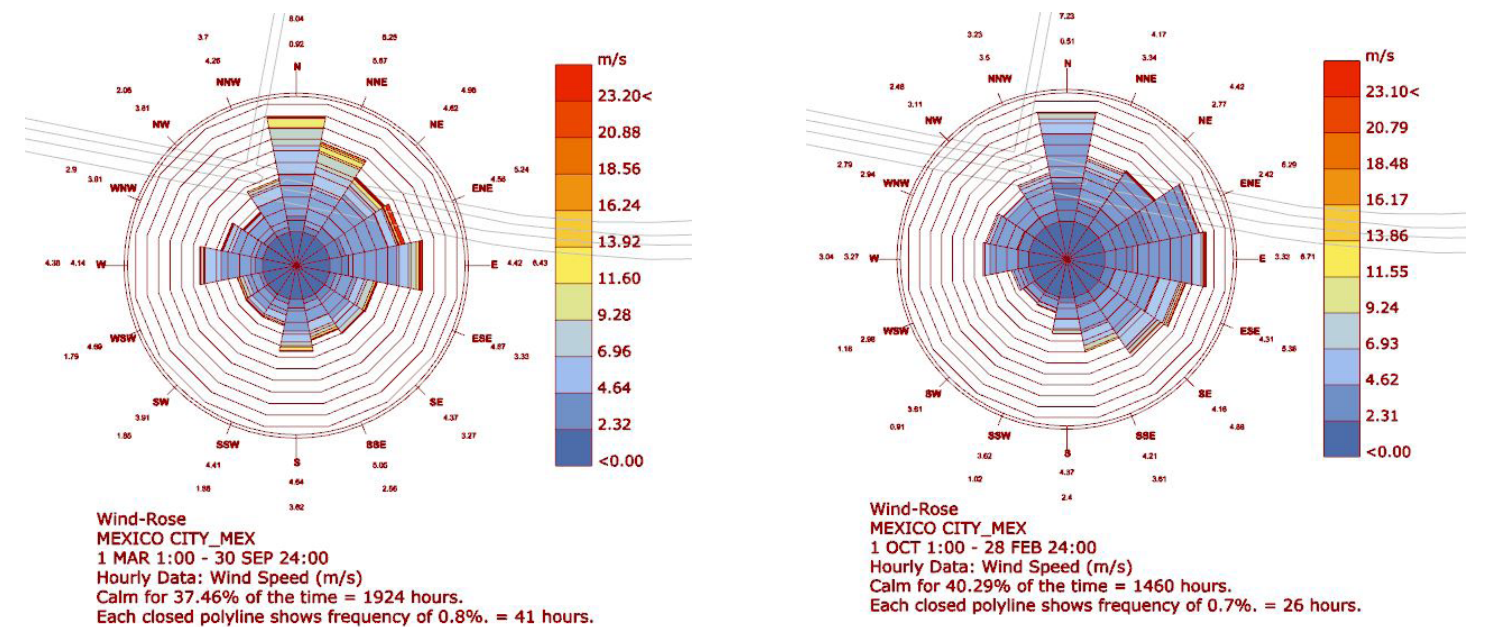


Figure 143. Climate analysis made in Ladybug

As it could be seen in the diverse climate analysis and as defined by the Psychrometric chart, this location can be well suited to incorporate several passive measures such as, evaporative cooling, windows towards the north orientation, natural crossed ventilation procuring the north-south orientation. From another side, the south and east orientation should be protected probably with the use of shading devices or shaping strategies. Nonetheless, the design needs to respond to the climatic and environmental conditions, as a re creative building the relation with the context should be also considered. In this way, the implementation of windows to provide views from the interior to the exterior and vice-versa could be proposed considering of course, the consequences that this might have regarding thermal/visual comfort and the energy performance of the building.

# 5.2 WORKFLOW IMPLEMENTATION

The organization of the general workflow application consisted of three main parts as shown in Fig. [144]. In the first place, a parametric model was elaborated based on the previously mentioned objectives and design variables, in the same way a costs database was created by taking into account from one side the benchmarks studies and from another the local prices of the construction materials, and energy fees.

Later on, once this two previous aspects were defined, the computational workflow itself was implemented by testing the two different design strategies. The first one (Sequential strategy) consisted on splitting the design process into four different stages that were held independently and fed back the subsequent design stages and disciplines in a linear fashion. The second strategy (Integrated strategy) combined all the different disciplines simultaneously having an holistic approach when optimizing and exploring the design space.

At the end of both strategies, the design results together with the comparison among the processes will be analyzed and compared.

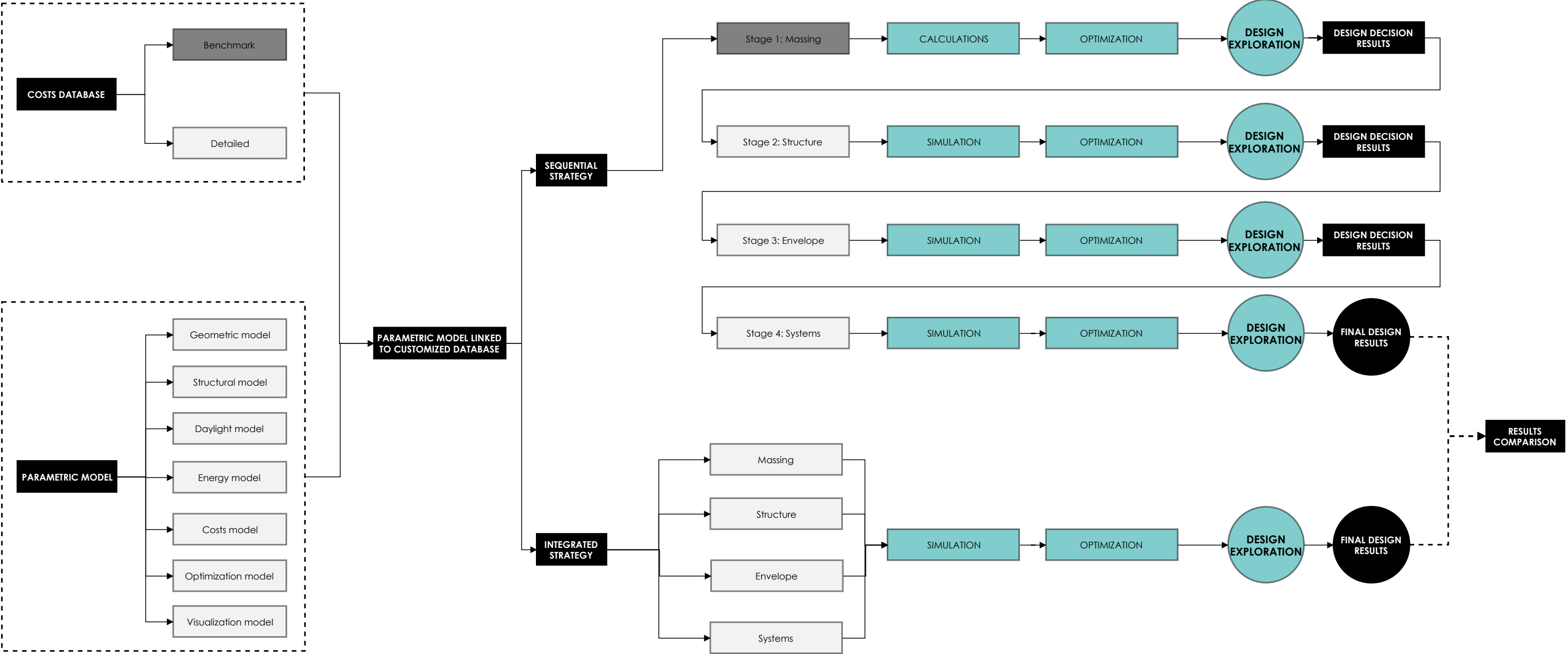


Figure 144. Diagram showing the general design workflow applied to the case study



5.2.1 DATABASE COST DEFINITION

5.2.1.1 Costs database (Benchmarks)

The costs database consisted of two principal sections, the first one considered the costs based on the study of several similar buildings shown in Fig. [145] analyzing from one side its construction costs per square meter and from another the typical energy consumption of them. For the second part of the database a detailed study that was built by reviewing the local prices inside the supplier catalogues and also by speaking with some local contractors specially for the active systems such as Chillers and Gas boilers. It is important to mention that conversion factors were applied due to the fact that the applied currency was the Mexican peso and sometimes the available information was from another location, in addition to this, a time conversion factor was also considered. The following figures will show the diverse types of costs applied to the different phases of the workflow.

FIRST STAGE (AVERAGES)	Construction costs (Material costs)					
	Type	Description	Finishes	Size (m2)	Price per Surface (\$/m2)	Price per Volume (\$/m3)
	Sportshall	Gimnasium /Sportshall Indoors	Medium	2955	\$ 8,707.03	\$ 926.09
	Operational costs (Energy)					
	Type	Description	Heating (KWh/m2/year)	Cooling (kWh/m2/year)	Lighting(kWh/m2/year)	Total (kWh/m2/year)
	Sportshall	Gimnasium /Sportshall Indoors	105	150	42.9	297.9
	Profits (Return of investment)					
	Type	Description	Membership (\$/person)	Rent per hour (\$/m2)	Seat ticket (\$/seat)	Rent price (\$/m2)
	Sportshall	Gimnasium /Sportshall Indoors	100	1000	50	\$ 800.00
	Sell price Total (\$/m2)					
	Sportshall	Gimnasium /Sportshall Indoors				\$ 11,319.14

Figure 145. Tables benchmarks averages costs



Figure 147. Reviewed buildings for benchmarks



Figure 148. Materials considered for the database

FIRST STAGE (BENCHMARKS)	Construction costs Benchmark (Capital costs)												
	N°	Name	Location	Year	Surface (m2)	Heigth (m)	Volume (m3)	TOTAL COST (\$)	Cost per m2	Conversion currency factor	Conversion time factor	TOTAL COST PER M2	TOTAL COST PER M3
	1	Redbridge Sports Trust	London England	1972	648	9	5832	\$ 111,000.00	\$ 171.30	\$ 27.00	-	\$ 4,625.00	
	2	Derby Arena	Derby England	2014	8600	-	-	\$ 2,891,300.00	\$ 336.20	\$ 27.00	-	\$ 9,077.34	
	3	Gimnasium Varela	Mexico	2013	1796	-	-	\$ 17,998,845.14	\$ 10,021.63	\$ 27.00	-	\$ 10,021.63	
	4	Gimnasium Neodata	Mexico	2017	1100	9	9900	\$ 9,913,076.00	\$ 9,011.89	-	-	\$ 9,011.89	\$ 1,001.32
	5	Sports Club	Mexico	2017	4800	8	38400	\$ 50,783,240.20	\$ 10,579.84	-	-	\$ 10,579.84	\$ 1,322.48
	6	Storage	Mexico	2017	1536	8	12288	\$ 5,584,414.90	\$ 3,635.69	-	-	\$ 3,635.69	\$ 454.46
	7	Polideportivo Conca	Cataluña	2002	2205	-	-	\$ 1,402,962.75	\$ 636.26	\$ 22.00	\$ 621.40	\$ 13,997.81	
	Operational energy Benchmark (Capital costs)												
	N°	Name	Location	Year	Surface (m2)	Heigth (m)	Volume (m3)	Fossil fuels	Electricity	TOTAL ENERGY (KWH/M3/YEAR)			
	2	Channel view Leisure Centre	Cardiff	1976	2887	13	37531	216901	66023	7.538408249			
	3	Gimnasium Ceforma	Tlalpan Mexico	2012	2500	13	32500	80000	450000	16.30769231			
	4	Eastern leisure Centre	Cardiff	1980	3854	12	46248	857787	0	18.547548			
	5	Western Leisure centre	Cardiff	1976	4392	15	65880	791070	260553	15.96270492			
	Profits (Return of investment)												
	N°	Name	Location	Year	Surface (m2)	Schedule	Membership	Ticket price	Rental	TOTAL INCOME (\$/m2)			
	1	Fut 7	Mexico City	1980	1500	12 to 23	-	-	10000	0.15			
	2	Delta fut	Mexico City	2015	700	10 to 21	-	-	15000	0.046666667			
	3	Deportivo Vivanco	Mexico City	2005	1000	9 to 23	-	-	800	1.25			
4	Villa Olímpica	Mexico City	2008	1503	17 to 23	-	-	800	1.87875				
5	Fut del Valle	Mexico City	2015	800	17 to 23	-	-	1200	0.666666667				

Figure 146. Table of benchmarks costs

Figure 149. Tables of the detailed construction costs and energy fees

Operational costs (Energy)								
Code	Type	Name	Description	Unit	Amount	Cost (\$)		TOTAL (\$)
EN_01	Energy	Electrical Energy Low Demand	Energy from the electrical grid	kwh	1	0.793	-	0.793
EN_02	Energy	Electical Energy Medium Demand	Energy from the electrical grid	kwh	1	0.956	-	0.956
EN_02	Energy	Electical Energy High Demand	Energy from the electrical grid	kwh	1	2.8	-	2.8
EN_02	Energy	Fuel Energy	Energy using specifically Natural Gas	m33	1	8	-	8

166

5.2.2 OVERALL PARAMETRIC MODEL

After defining all the design objectives and having clear what was going to change during the entire process, the initial parametric model was defined. This process is also called “the definition of the problem” or the “design of the problem” . It was necessary to organize in a systematic way all the different parts of the building at the same time. Thinking about how the parametric model was going to serve to the following stage. The figure above shows an exploded view of the main components of the geometric model, this elements will be modified during the diverse stages of the process but nevertheless, the general typology will be always kept.

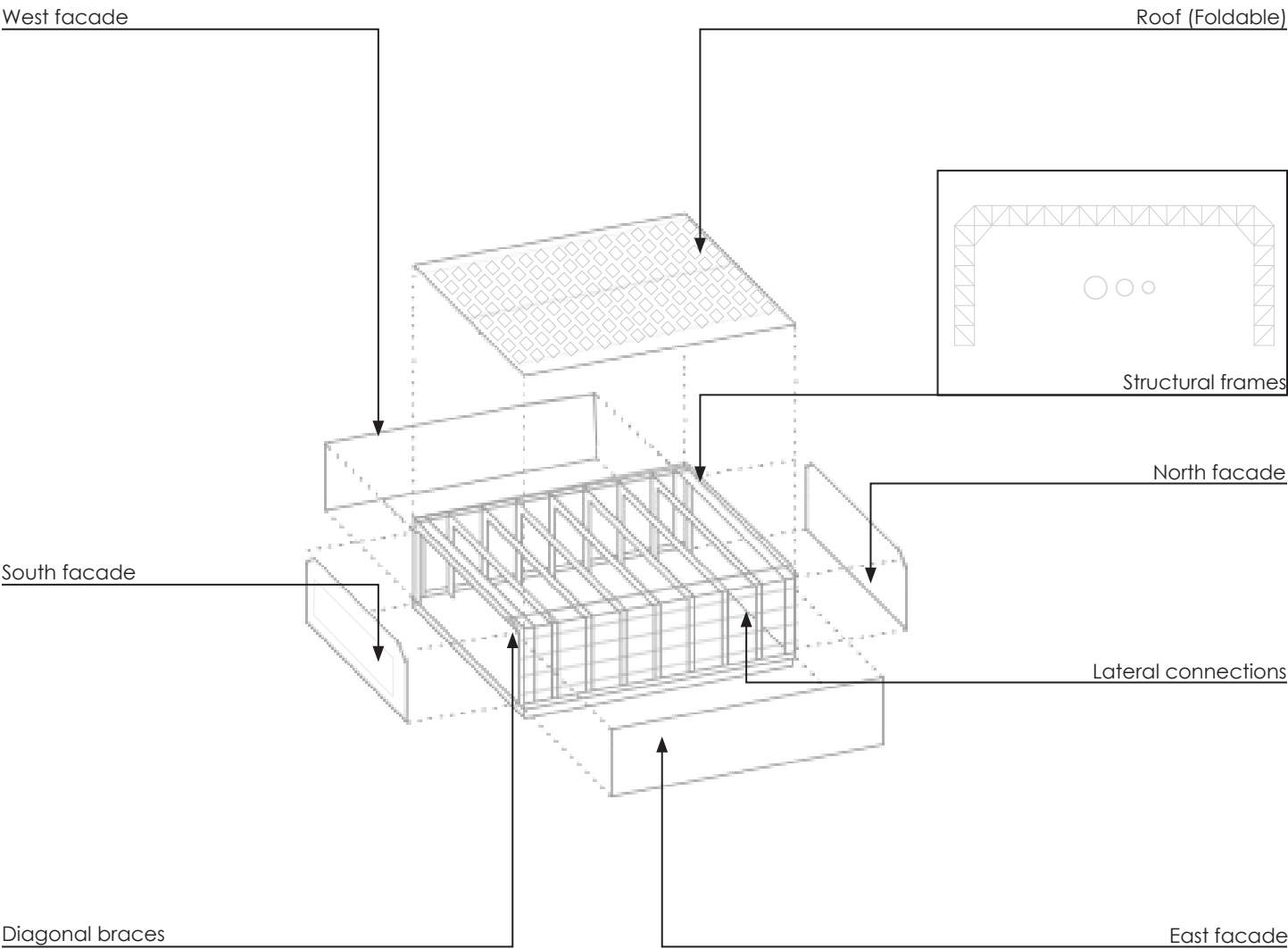


Figure 150. Exploded view of parametric model

This model was elaborated by taking into account all the specific requirements from the different simulation and optimization Plug-ins. For instance for Karamba, it was necessary to have individual lines, meaning that each component of the structure should be considered as a unique element. For Honeybee, the order of the surfaces and the correct elaboration and joining among them was crucial to make the simulations work properly. In this way, creating the parametric model was thinking about specific procedures while at the same time considering “the whole picture”. It could be said that the final parametric model is the sum of several smaller parametric models that work in combination as shown in Fig. [151].

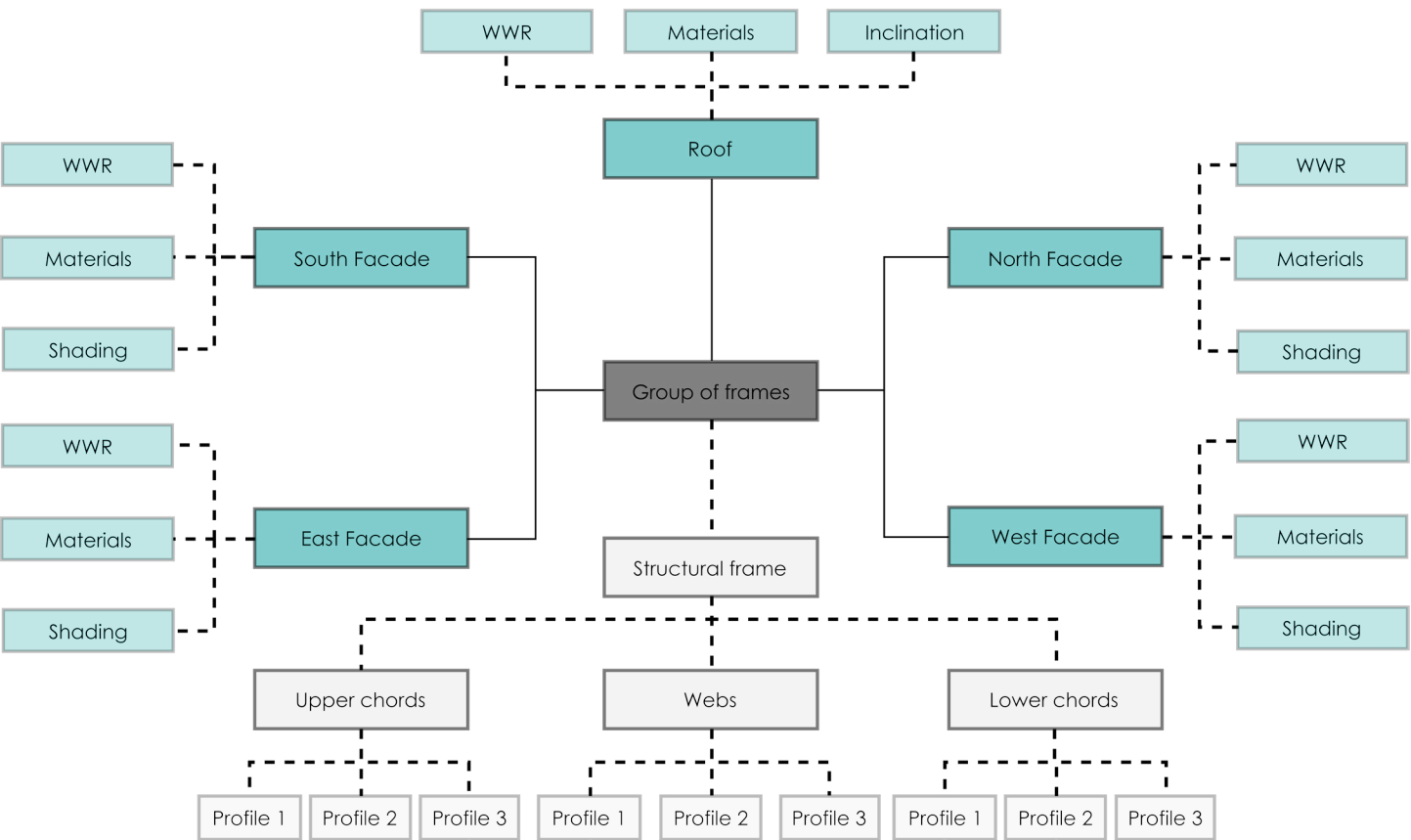


Figure 151. Diagram of the parametric model organization



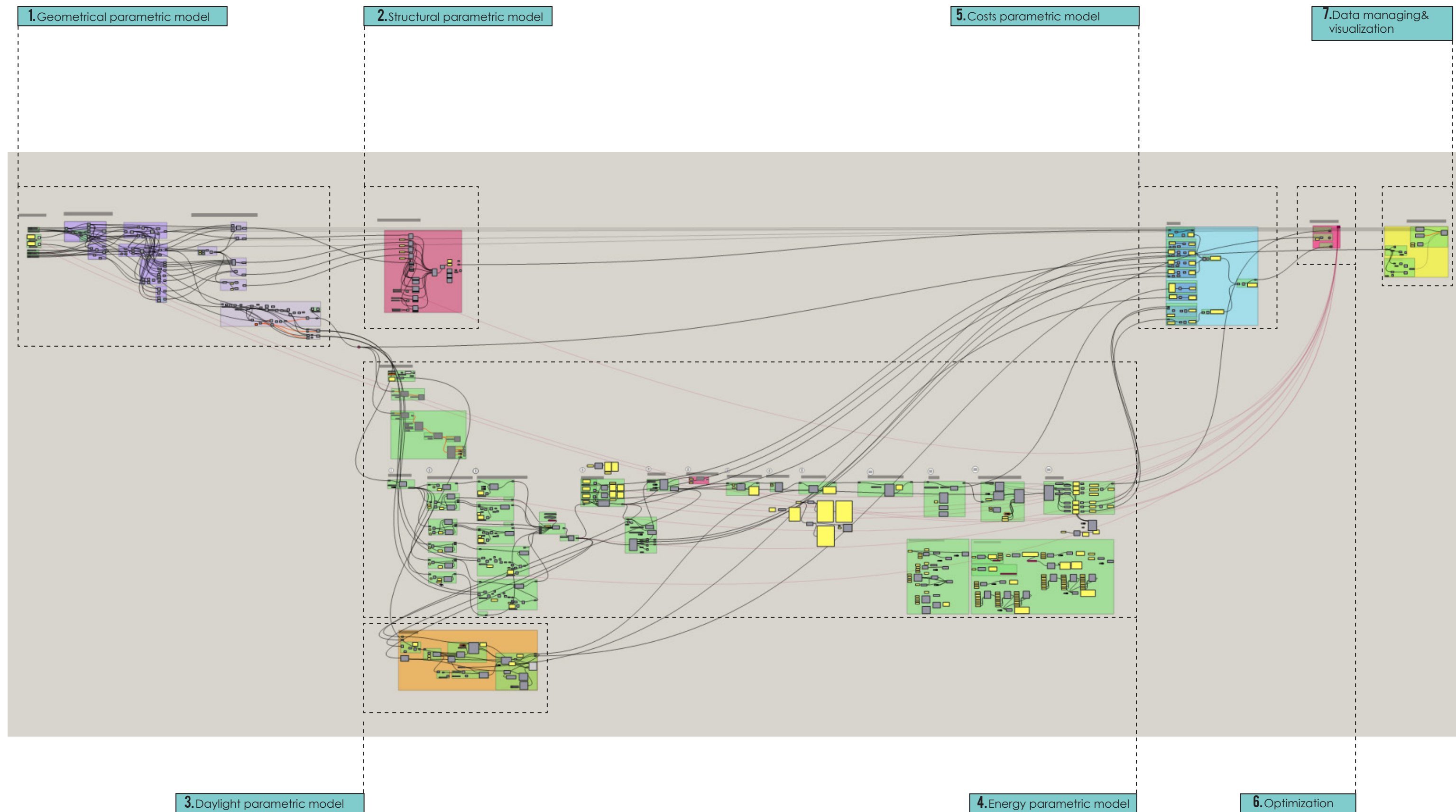


Figure 152. Overview of the Grasshopper definition for the workflow

5.2.3 MODEL CALIBRATION (INTER-COMPARISON)

In order to validate the results from the parametric energy model built in Honeybee (V. 0.0.63), a similar model was build in a specialized energy simulation software called Design Builder (V. 5.4)which is well known as a reliable software based on Energy plus. The settings and data from the models were similar (among the different software limitations); having the same occupancy schedules, WWR ratios, hvac values , the location of the windows, orientation of the building and the applied materials shown in the graph below, Fig.[153]:

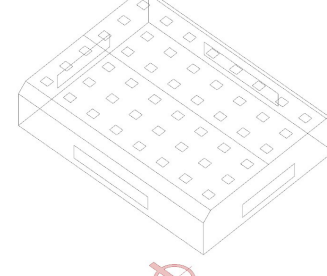
	HONEYBEE MODEL	DESIGN BUILDER MODEL
		
<b>General</b>		
Location (weather file)	Mexico City.iwec	Mexico City.iwec
Orientation	N-S	N-S
<b>Geometry</b>		
Height	11m	11m
Widht	36m	36m
Depth	48m	48m
WWR Skylight	10%	10%
WWR (All walls)	40%	40%
<b>Materials</b>		
Floor	500mm Ins. 200mm Heavy weight concrete	500mm Ins. 200mm Heavy weight concrete
Roof	100MM lightweight concrete, f05 ceiling air space resistance , f16 acoustic tile	100MM lightweight concrete, f05 ceiling air space resistance , f16 acoustic tile
Walls	100mm concrete 1/2" Gypsum	100mm concrete 1/2" Gypsum
Windows	3mm clear glas-13mm ai gap r-3mm clear glass	3mm clear glas-13mm ai gap r-3mm clear glass
<b>Activity</b>		
Occupancy schedule	6am-9pm (Monday-Sunday)	6am-9pm (Monday-Sunday)
Occupancy density	50m2/person	.02ppl/m2
Heating setpoint	28°C	28°C
Heating setback	8°C	8°C
Cooling setpoint	22°C	22°C
Cooling setback	28°C	28°C
Metabolic rate	120W	120W
Equipment	2W/m2	2W/m2
Lighting density	11W/m2	11W/m2
<b>HVAC</b>		
Infiltration rate	.000257 m3/s/m2	.085 Ach
Infiltration schedule	Always on	Always on
Mech vent. Per person	.001524m3/s	15.24 ls/person
HVAC System	Ideal Loads-fuel natural gas/electricity from grid	Ideal Loads-fuel natural gas/electricity from grid
Supply temperatures	Heating 35°C / Cooling 12°C	Heating 35°C / Cooling 12°C
Heat recovery	Yes (.7)	Yes (.7)
Economizer	None	None
<b>Results</b>		
Area	1728m2	1728m2
Volume	18816m3	19008
Wall area	3060m2	3573m2
Window area	395.52m2	450m2
Annual Cooling demand	42.70 kWh/year	45.09 kWh/year
Annual Heating demand	0.011 kWh/year	0.015 kWh/year
Annual Lighting demand	64.24 kWh/year	60.22 kWh/year
Total Annual energy demand	102.935 kWh/m2/year	106.395 kWh/m2/year

Figure 153. Simulation settings and simulation results of the comparative energy models

It is also important to mention that the model shape was simplified in order to run the simulations without further complications. After analyzing and comparing the results from the Honeybee model and the Design Builder model, it can be concluded that both were almost the same. Nevertheless, there is slight variation due to possible differences in the geometry (limitation of the software) and some minor differences among platforms and components. Several assumptions were also taken into account for both models such as, the exclusion of humidity controls, ventilation aspects and lighting controls.

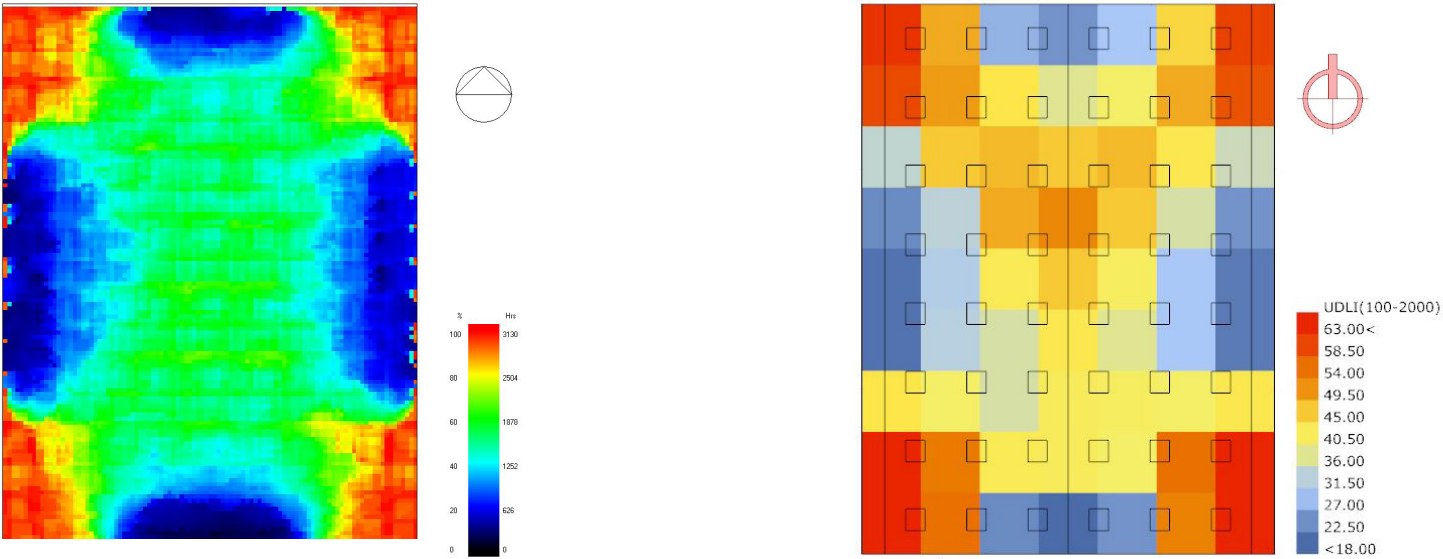


Figure 154. (Left) Design Builder UDI analysis results. (Right) Honeybee UDLI analysis results

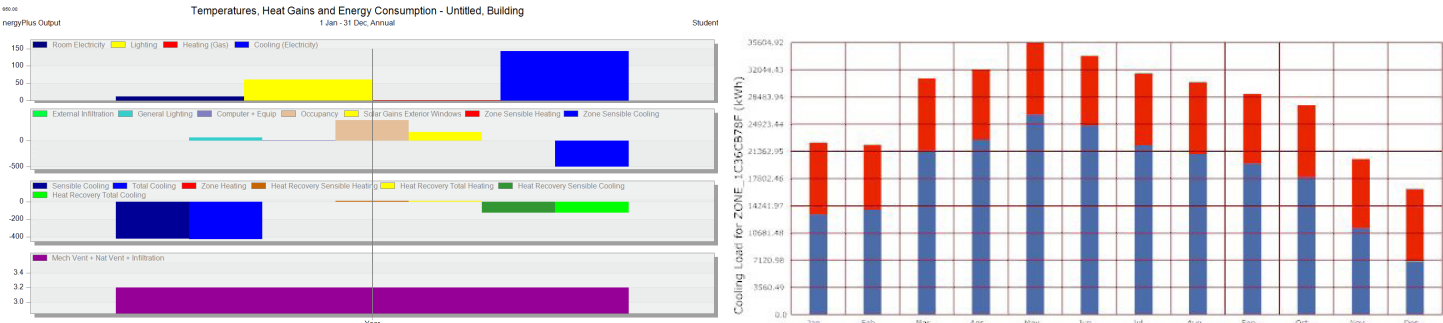


Figure 155. (Left) Design Builder energy demand results. (Right) Honeybee energy demand results

As it can be seen in Fig.[155] in both simulations, cooling and lighting are predominant with a small tendency towards the electricity needed for lighting. Which reiterates the importance of the inclusion of natural daylight in the design of this kind of buildings. From the graphs and tables from both platforms it can also be concluded that the energy demand for heating is very small since the outside temperature hardly declines to low temperatures throughout the year. When talking about the simulation times and computational effort of the compared software, both took approximately the same amount of time. This is certainly true since the parameters of the simulation processes are both based on Energy plus, taking approximately 1 minute for the energy simulations and around 2.5 minutes for the daylight analysis.

5.2.4 COMPUTATIONAL WORKFLOW - SEQUENTIAL STRATEGY

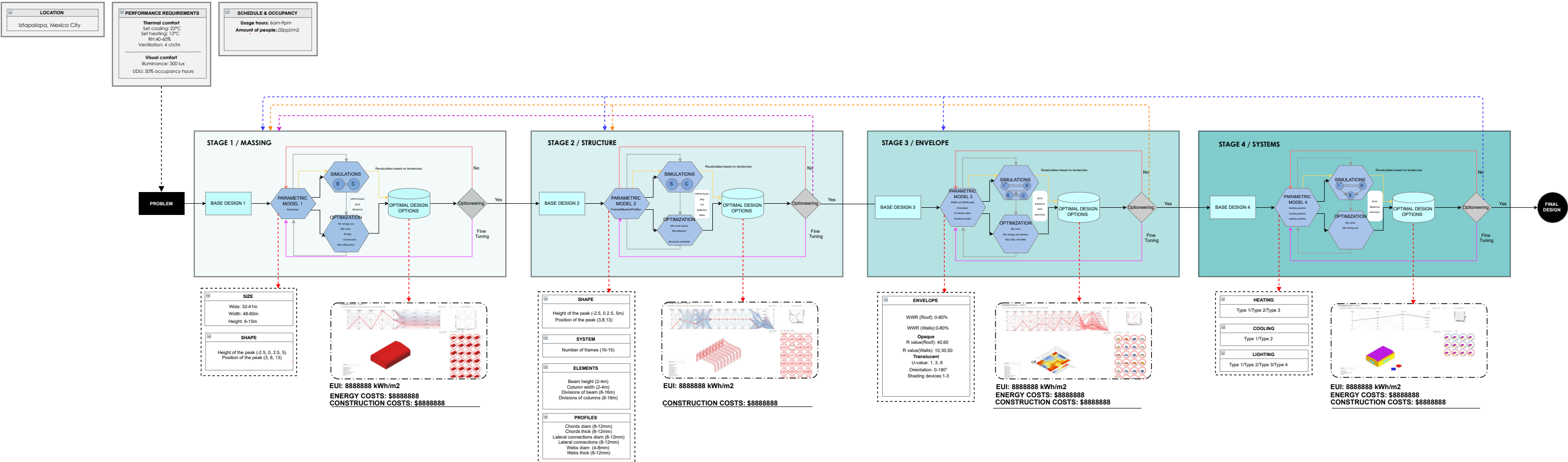


Figure 156. Sequential strategy detailed workflow



5.2.4.1 Stage 1: Massing

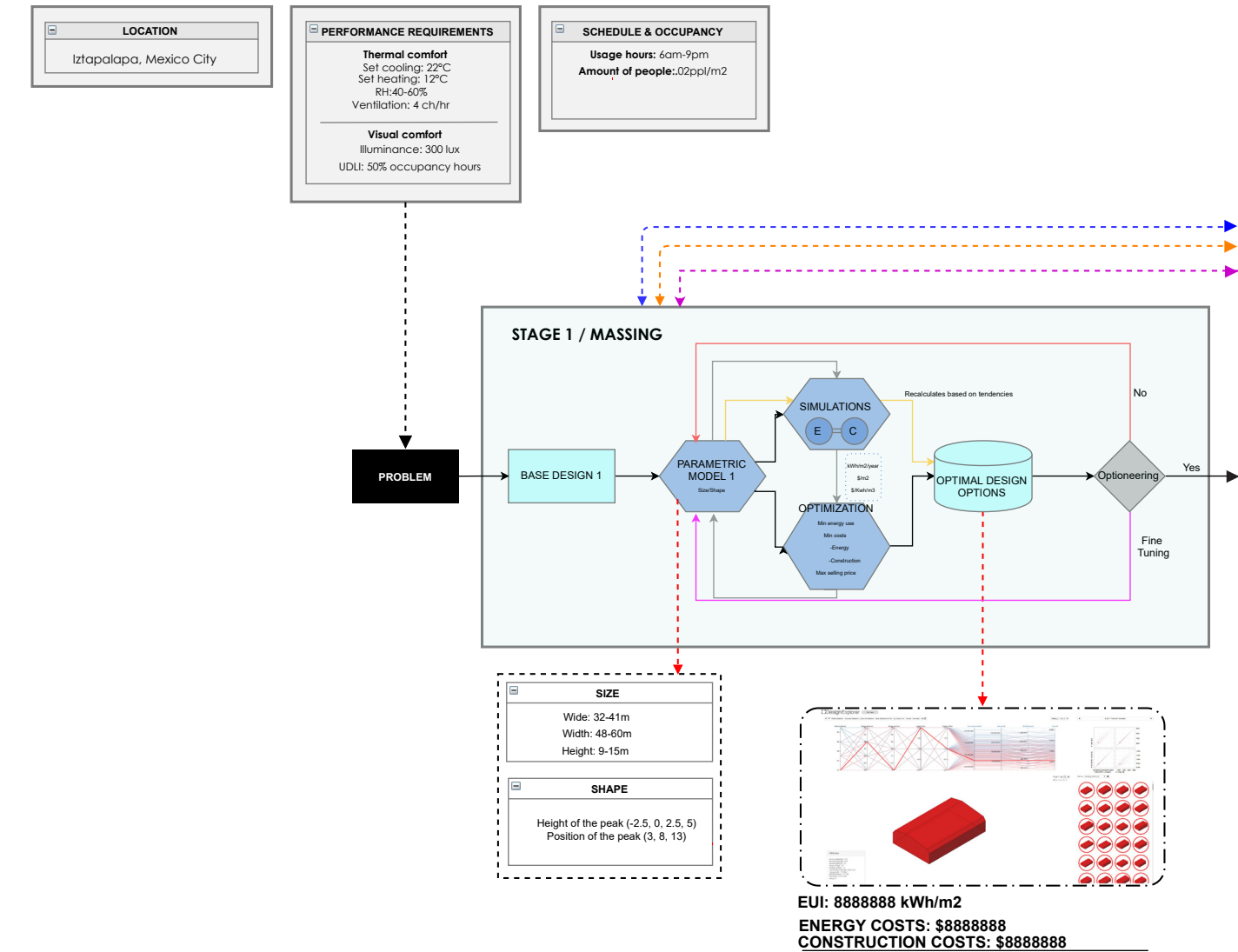
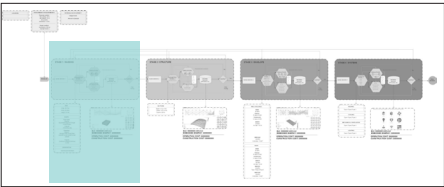


Figure 157. Diagram of the massing stage (Sequential workflow)

The first stage of the workflow consists of the massing and shaping exploration process, where playing with the form, volume and area are the principal intentions. In the first place, the minimum spatial boundaries were set, according to the specific requirements of the case study. Three main things are to consider, in the first place the Energy Use Intensity (kwh/m2/year), Construction costs, and the sale price of the building. For this phase, the information about this values was calculated based on a benchmark study as described in the previous chapter. This is with the aim of having a fast and rough idea of how the building compares with similar buildings and typological masses.

5.2.4.1.1 General description & parametric model

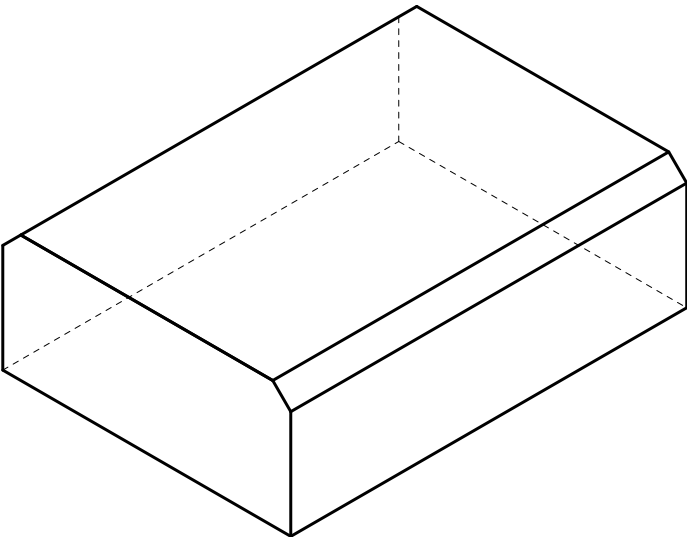


Figure 158. Base model for massing stage

STAGE 1 / MASSING

OBJECTIVES					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	HOW TO OBTAIN
1	Economic	Minimize cost	\$/m2	N/A	GH + Excel database (Benchmark construction costs)
2	Economic	Maximize profits	\$/m2	N/A	GH + Excel database (Benchmark energy costs)
3	Climate (Energy)	Minimize energy use	Kwh/m3	N/A	GH + Excel database (Benchmark energy costs)
4	Aesthetical	Increase aesthetics	N/A	N/A	Design explorer

CONSTRAINTS					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	WHERE TO FIND
1	Geometry	Min Layout (Interior)	m	32*48	Sports England.org
2	Geometry	Max Layout (Interior)	m	41*60	Sports England.org
3	Geometry	Min Height (Interior)	m	9	Sports England.org
4	Geometry	Max Height (Interior)	m	15	Sports England.org

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
v1	Geometry	Width	m	Continuous	32 to 41	3	4
v2	Geometry	Depth	m	Continuous	48 to 60	3	4
v3	Geometry	Height	m	Continuous	9 to 15	3	3
v4	Geometry	Peak height	m	Continuous	-2.5 to 5	2.5	4
v5	Geometry	Location of the peak	-	Discrete	3, 8, 13	1	3
FIXED							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
f1	Location	Location in Plot	N/A	N/A	N/A	N/A	N/A

Figure 159. Objectives, constraints and parameters for the massing stage

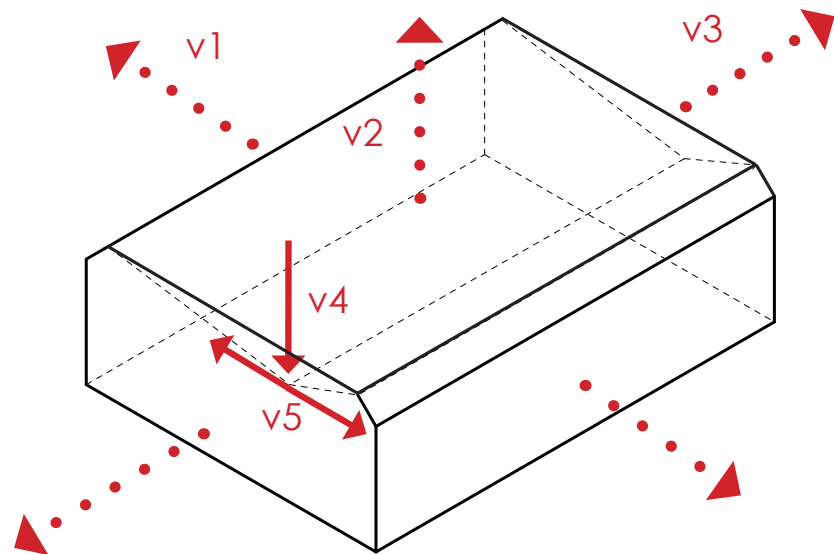


Figure 160. Variable parameters diagram for the first stage

The parametric model for this stage, was elaborated based in the list of objectives, variables and constraints shown by Fig. [160]. It is important to highlight that among all the phases of the parametric process this one is the most important. It was necessary to understand and to clarify which values of the entire process were going to change, therefore this phase of “designing the problem” is a highly difficult stage. It is needed to think in advance considering the future stages of the procedure because the overall shape of the building will rule the following stages. For instance when talking about the peak location and the additional height of it, the structural aspect needed to be also considered, and when developing the surfaces of the envelope, the climate part was also taken into account.

In this scope, the first part was to develop a geometric model in Grasshopper composed of several sections as shown in Fig.[161]. Firstly, a set of points distributed along X axis representing the width of the building were drawn, after this, the possible divisions of the structure were also set as points along the same axis (this was done in order to modify the peak of the building in height and position). After this, the Z Axis was defined by moving this points towards “the height” of the building. The second part of this process was making the profile of the structural trusses, so they could be arrayed later on towards the depth of the building. After defining this lines that represent the frames of the structure, all this frames were arrayed on the Y axis defining the width of the mass.

Once having defined the overall boundaries of the shape (with parameters that could vary accordingly). The last step was to make the envelope surfaces, this was a great challenge because again foreseeing a future stage, (in this case climate) Honeybee identifies the surfaces assigning an specific order, and when this changes, for instance when the peak goes higher or lower “breaking” the roof surface into two sub-surfaces this order changes so it was necessary to develop a special algorithm to have the two possible scenarios keeping the same order of this faces.

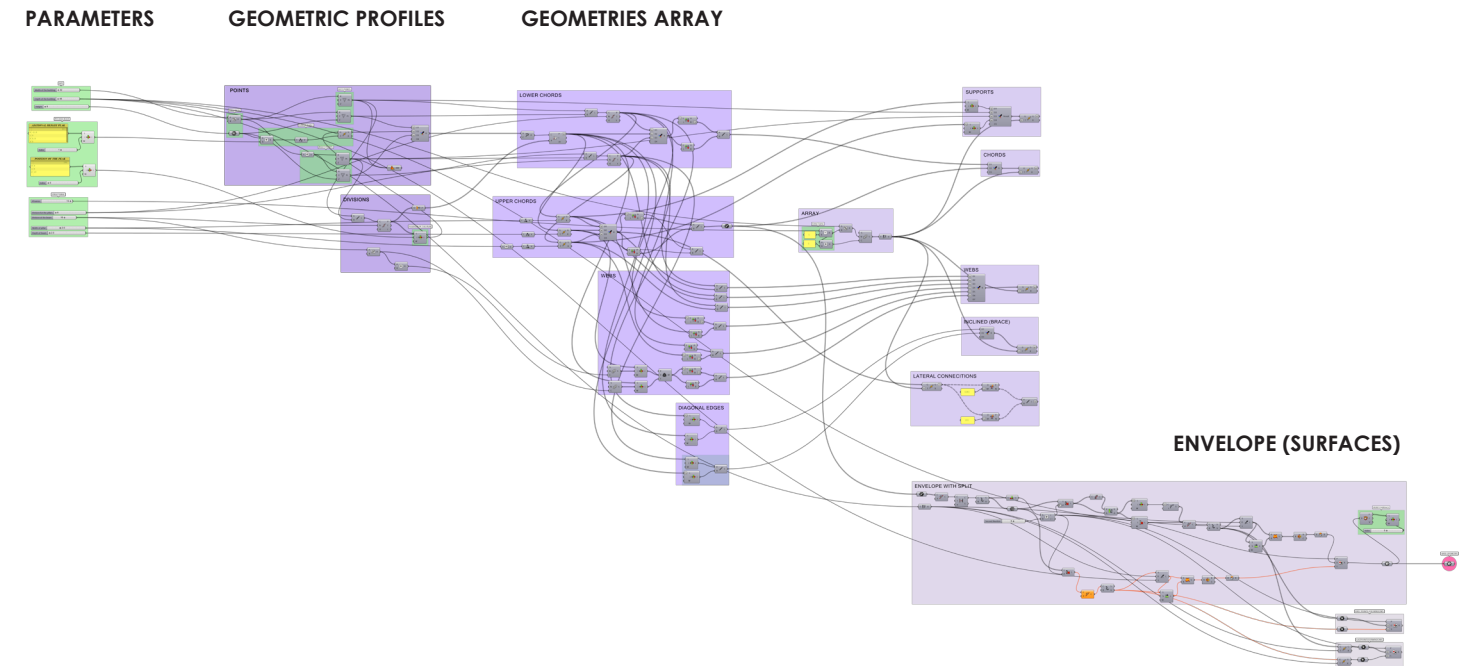


Figure 161. Grasshopper script for the geometric parametric model

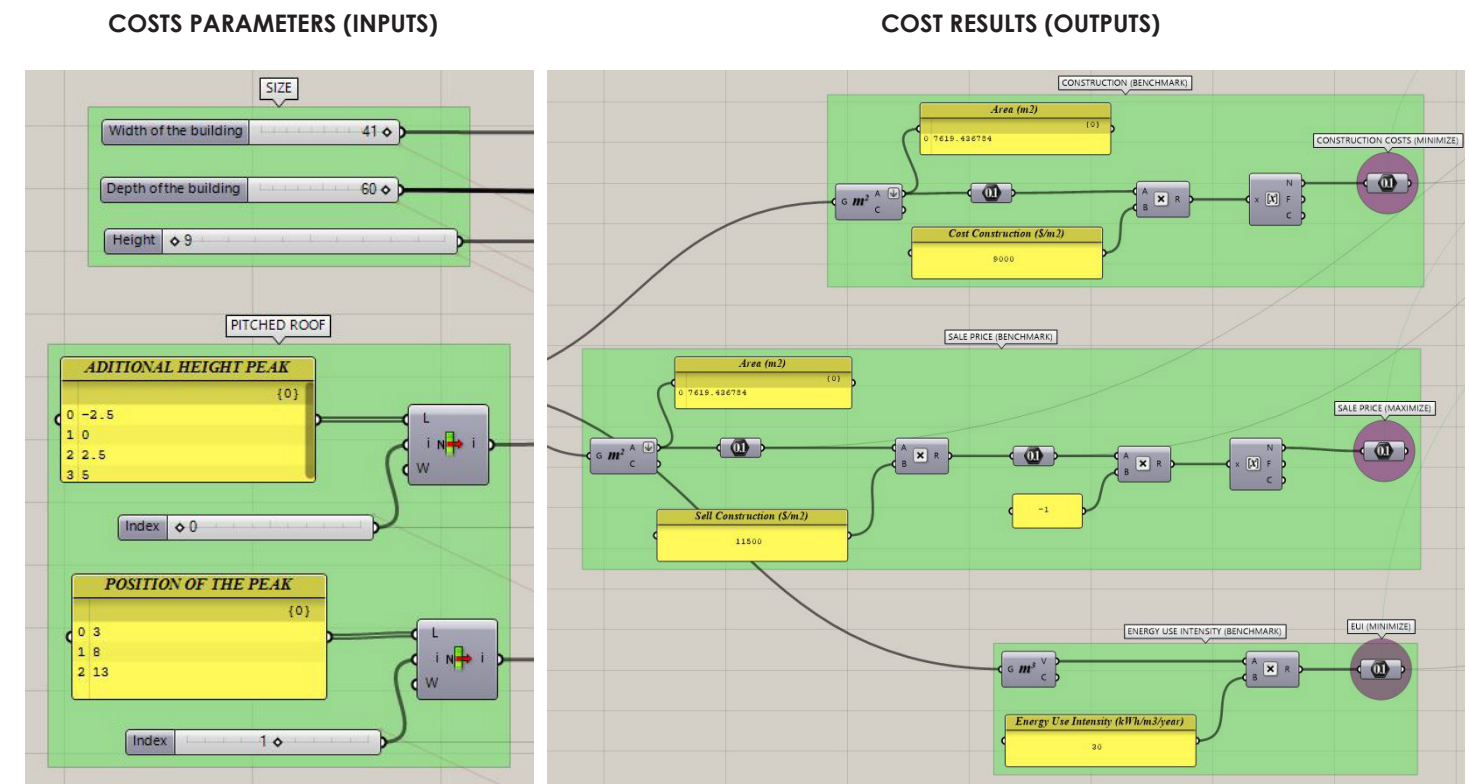


Figure 162. Inputs and results for the costs calculations for the massing stage



5.2.4.1.2 Optimization results

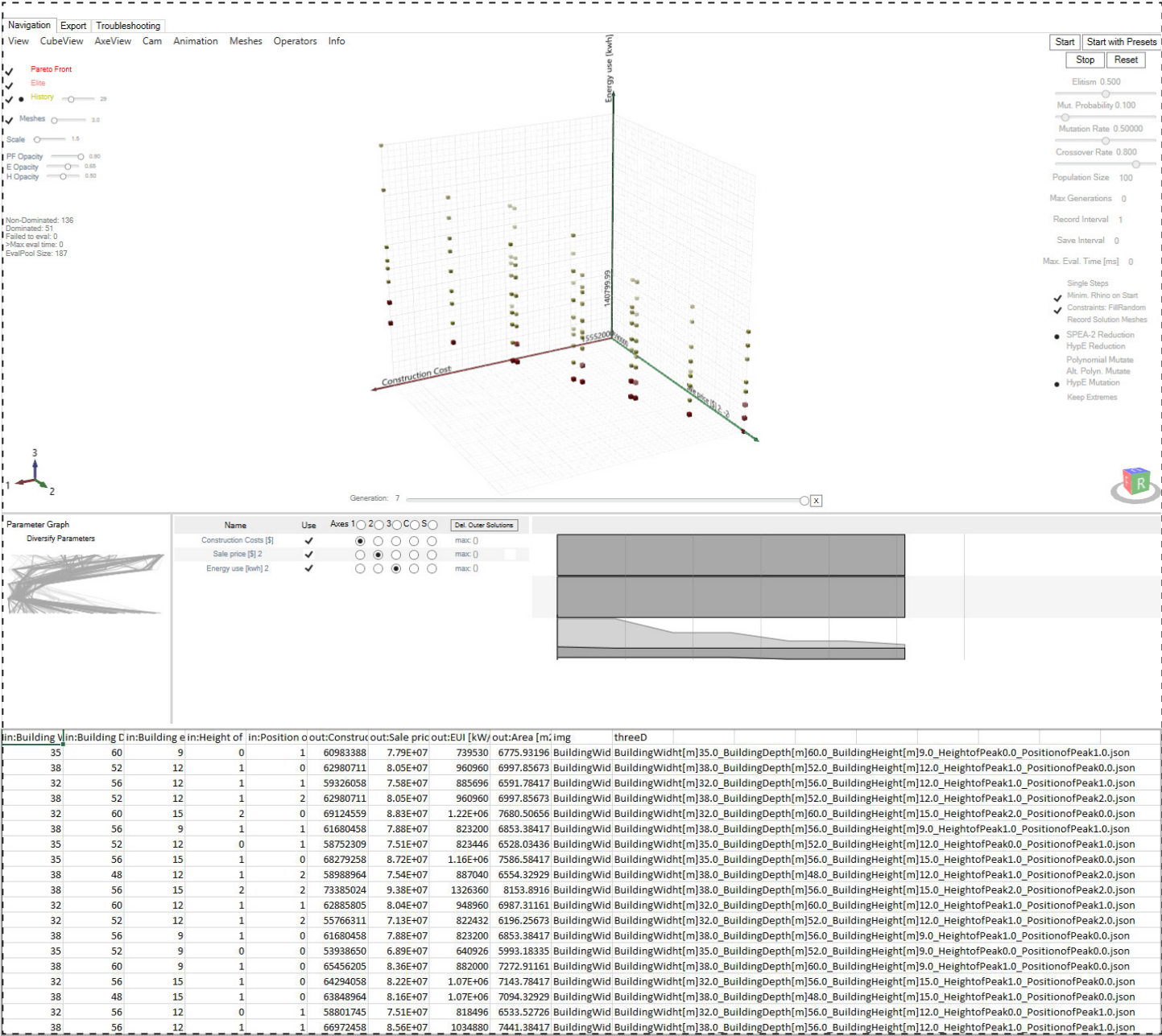


Figure 163. (Up) 3D chart of Octopus optimization results. (Down) Data organization in a csv. file

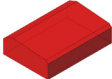
STAGE	NUMBER OF PARAMETERS	NUMBER OF GENERATIONS	DESIGN SPACE	DOMINATED / NON DOMINATED	COMPUTATIONAL TIME
	5 Parameters	6 Generations 100 Population	313-576	115 Non-dominated 73 Dominated	15 Minutes

Figure 164. 2D charts of the Octopus optimization results

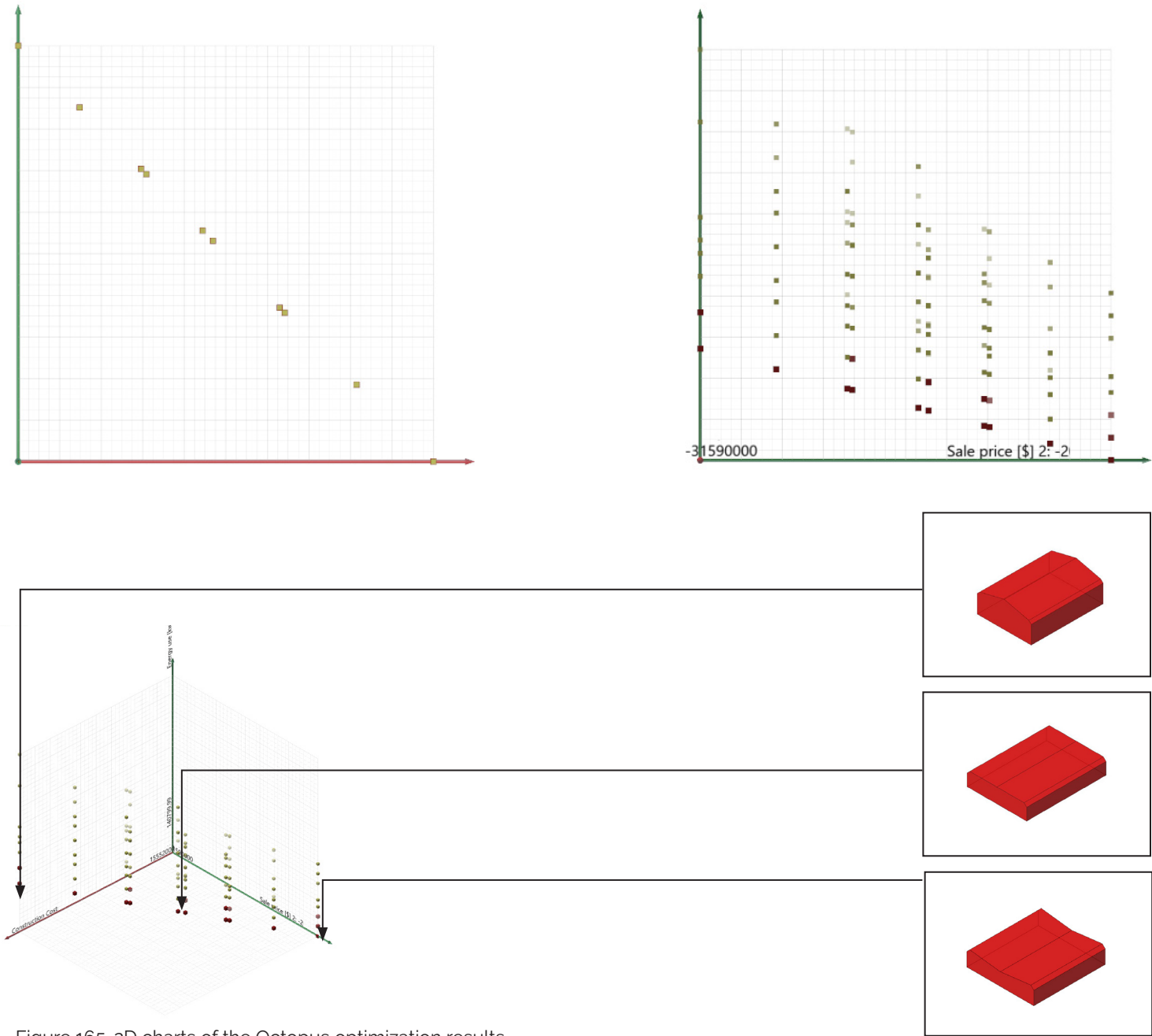


Figure 165. 2D charts of the Octopus optimization results

The first stage analyzed essentially building volumes and shapes, showing results that were quite straightforward, which in a way proved the correct functioning of the optimization process an visualization tools. When looking at the charts resulted from the Octopus optimization -(Fig. [165]), there is a direct correlation between the increase of construction costs, (due to the increase of the building's volume) and the increment in the selling price. Therefore, the majority of the solutions have the parameters that were located in the middle of their correspondent ranges.

Thus, based on a previous study about the average costs of this typology as well as their typical energy consumption it was possible to have a rapid set of diverse options. This stage was quite fast, handling the total of five parameters and resuming to only 15 minutes of computational time which resulted in 7 generations and retrieving a set of around 300 options to explore. since there was no need to do simulations of any kind, instead, only simple mathematical operations



5.2.4.1.3 Design optioneering results

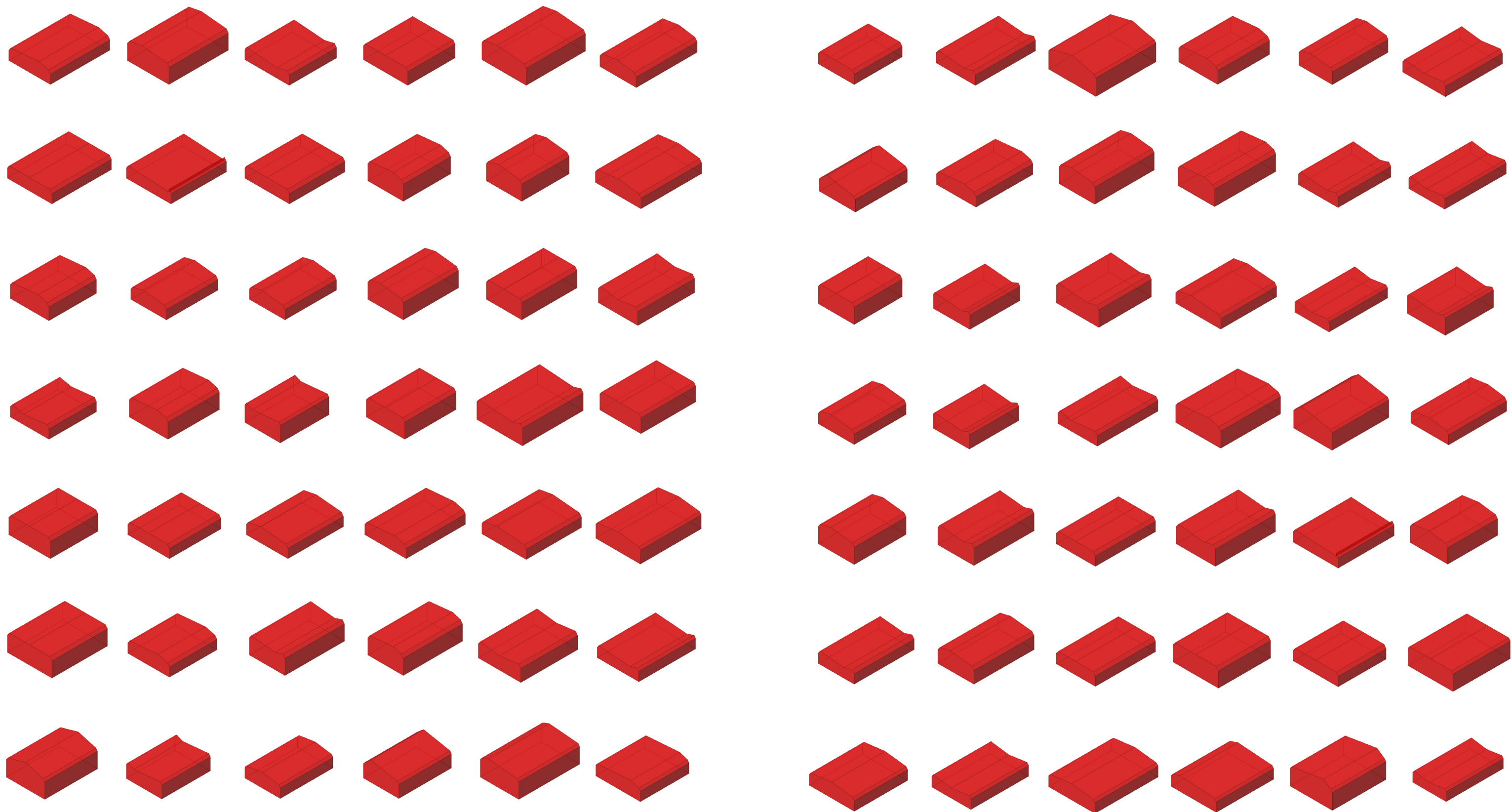


Figure 166. Images of the design alternatives iterated by the optimizer

5.2.4.1.4 Results & observations

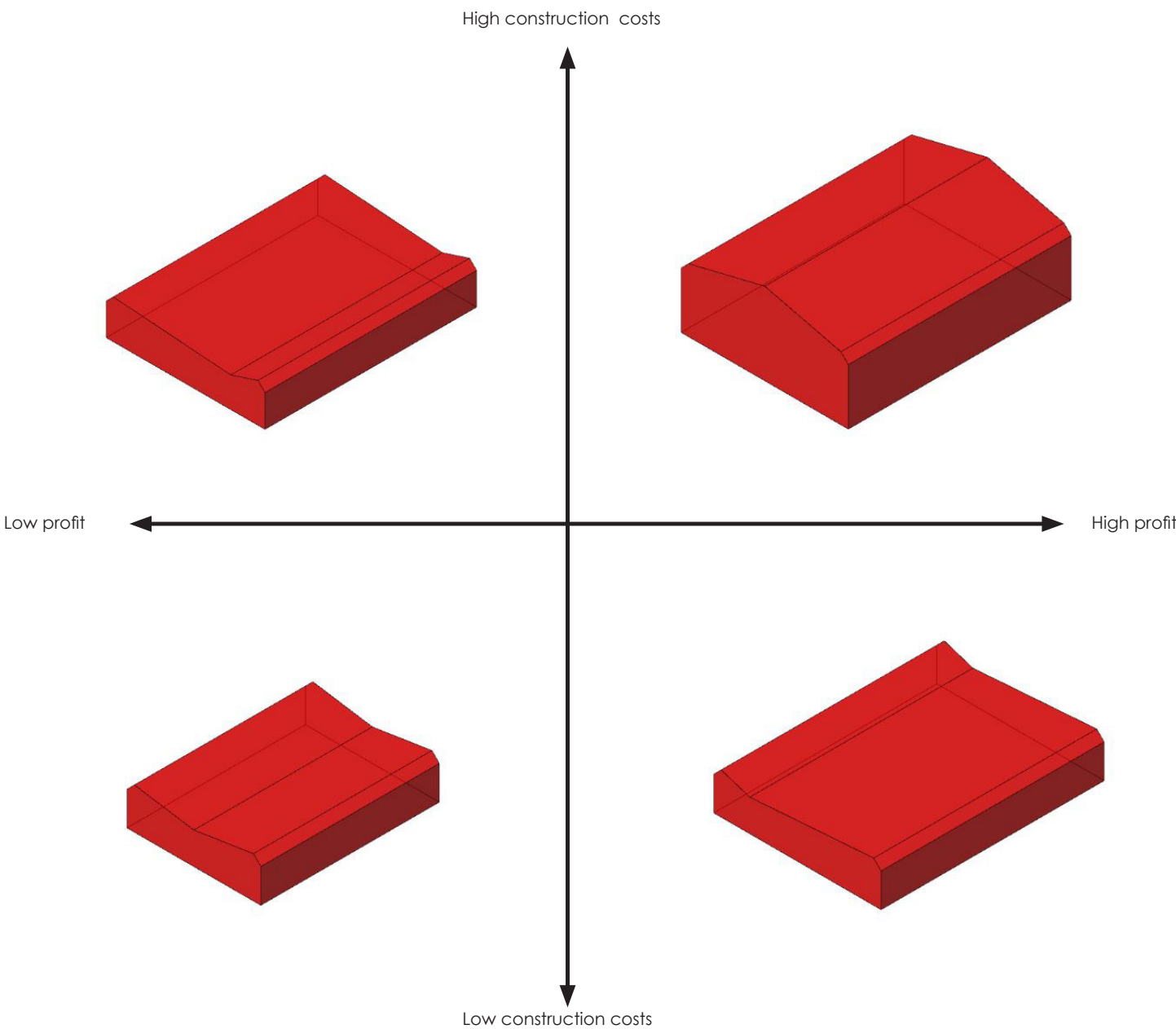


Figure 167. Sensitivity analysis and comparative of the designs general performance tendencies

were held by Grasshopper. It can also be observed that the options with the extreme values such as the highest value for the peak height were filtered out, and some of the parameters such as the position of the peak seemed to have a very low impact on the output results. During the optimization process as it can be observed in the graphs, (Fig.[167]) as the generations went further they became much more intensive towards the axis. Another direct correlation among results was that the size of the area and volume affects the energy consumption, in this way the options with the peak located inwards seemed to be more energy efficient (because of a reduction in the volume).

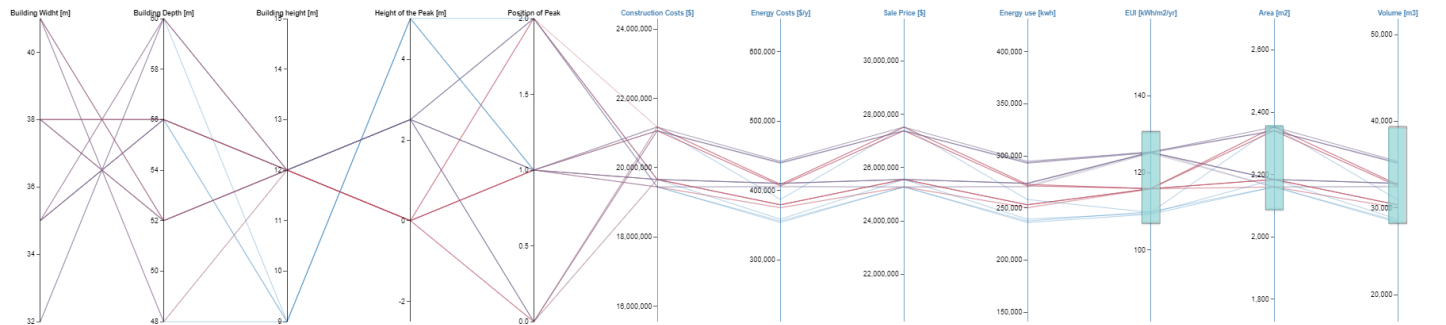
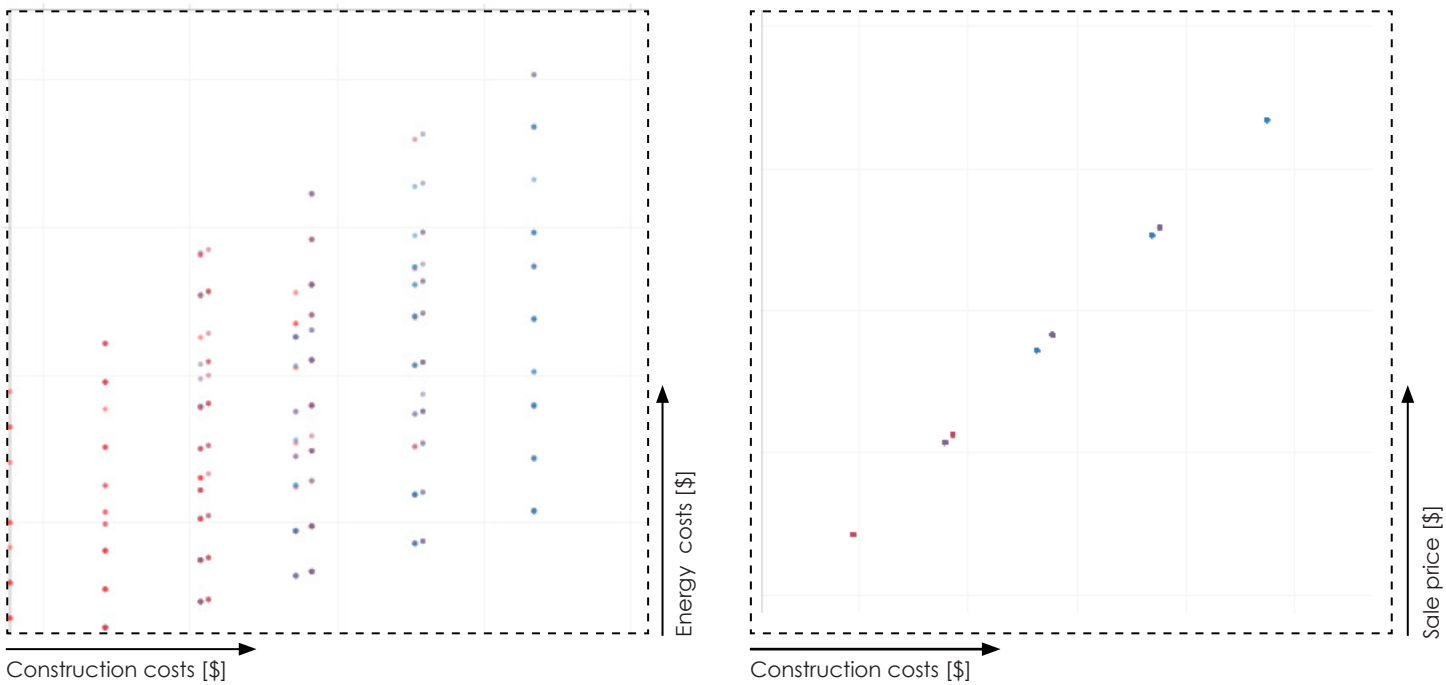


Figure 168. Sensitivity analysis charts and parallel coordinated chart of the selected design

playing around with the different parameter sliders on the Design explorer platform. The selected option has been defined through a set of intervals, indicating the mean values for optimization. Thus, the more suitable an option is as it's construction cost, energy cost, sale price, energy use, EUI, area and volume are approaching a mean, common value, resulting in more compact value intervals. However, design decisions have to be made based on ethical hierarchy and situational conditions. Consequently, the selected option was one of the choices that traded the construction costs and the energy use for an aesthetical factor, focusing on an asymmetrical alternative with the roof tilted towards the east orientation.



5.2.4..5 Design decision

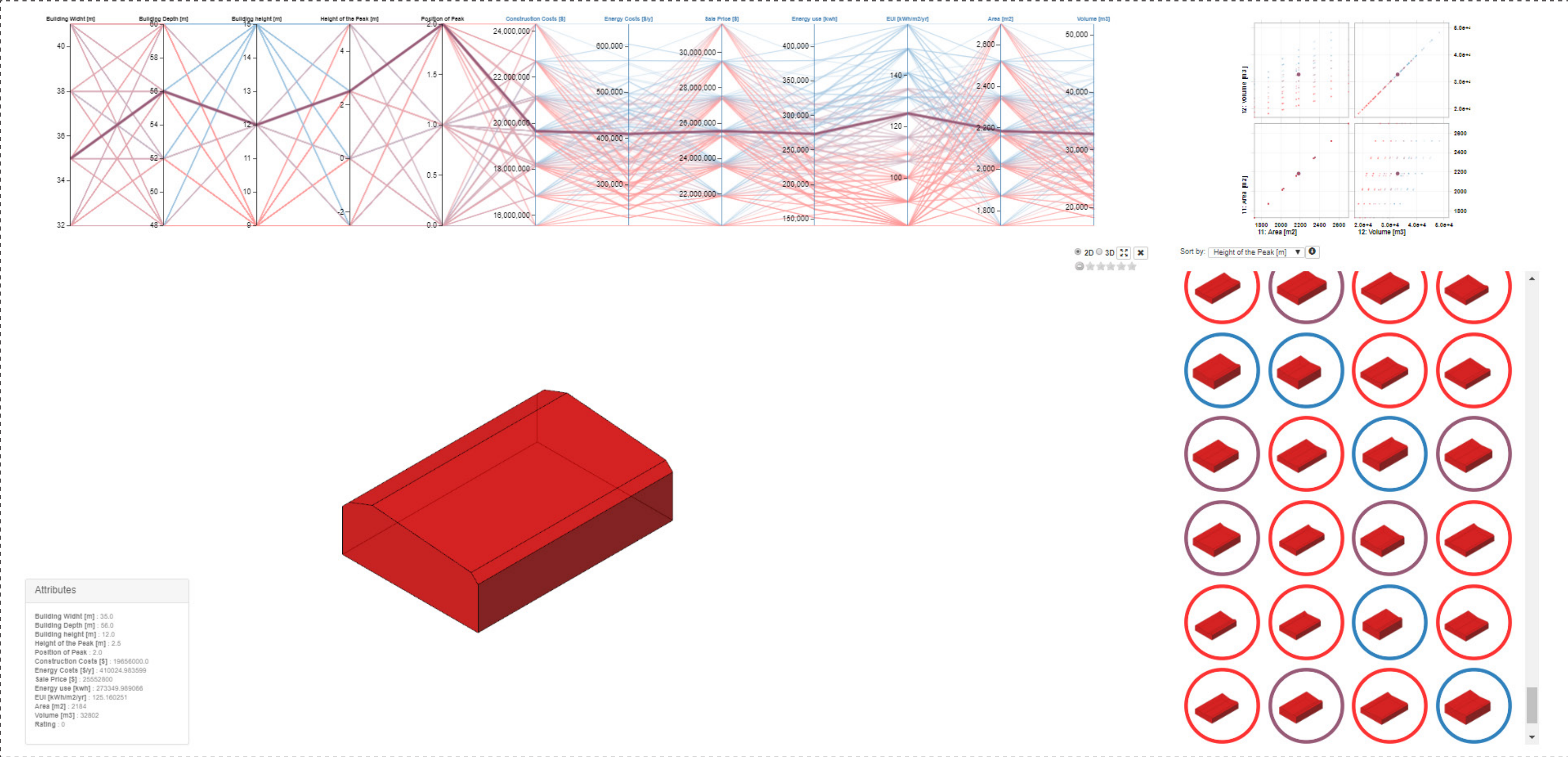


Figure 169. Design exploration, filtering and selection interface

Once the option typology has been identified, based on construction costs, energy and return revenue, the graph in Fig. [169] focuses on specific design characteristics that further shape the building, taking into consideration as main criteria the environmental conditions. To ensure a dynamic flow, dictated by the solar movement in order to maximize the daylight exposure, for this step the key factors that have been considered are the height and position of the peak, as they would result in a roof slope, directly interlinked with the construction costs. Distinct from the choice of option typology, the value intervals of interface selection vary in an inverted

correlation. For instance, for the chosen design option, the filtering and selection interface started from a 35.0m building width, resulting in a 56.0m building depth and 12 m building height. As the chosen building height value was close to the mean value, the height (2.5m) and position of the peak (2.0) are independent of building costs, being a direct result of the designer's decision and climate factors. The option results in an estimated construction cost of 19mil, a more feasible solution from a wide range that varies from 16mil to 24mil. As the proportional relation between building size (sqm) and costs is unmistakable, it is important to have in mind that for this incipient stage, the most important factor is the range of options - the wider the better, giving more freedom of choice to the designer.



5.2.4.2 Stage 2: Structure

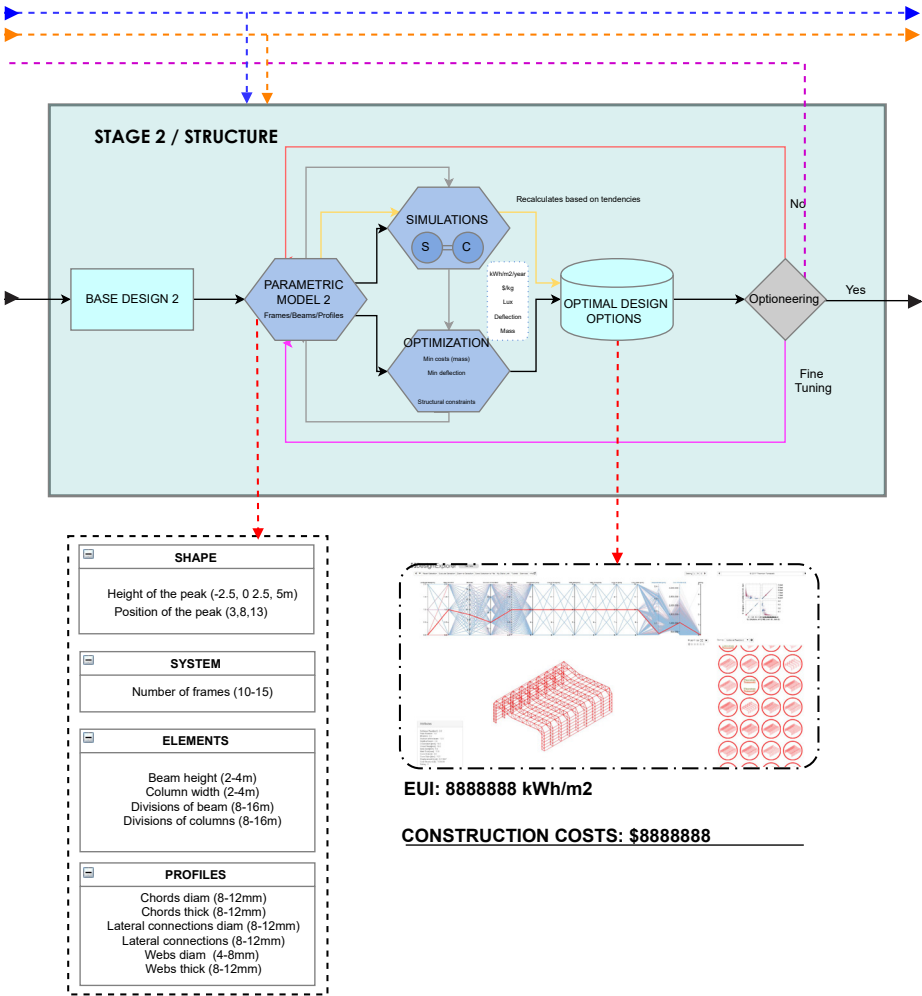
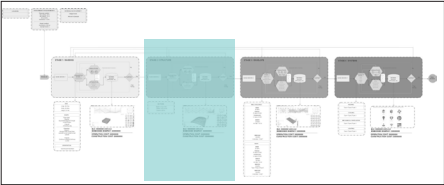


Figure 170. Diagram of the structure stage (Sequential workflow)

The structural phase, focuses specifically in the constructive system of the building by linking the previous massing study with a set of feasible structural options. For this study a truss based framed structure was proposed. This was based on the conclusion that the majority of this kind of buildings use this system because of functional aspects (long spanning) and economic factors as described in chapter 2.3.4. The model in this case was elaborated according to the particular requirements of the simulation software (Karamba). Therefore, it was necessary to have every single line defined individually together with the corresponding points that will be taken as the supports. In this way, all the lines were clearly organized in three main types: Upper chords, lower chords, webs, lateral connections, diagonal braces and supports points.

5.2.4.2.1 General description & parametric model

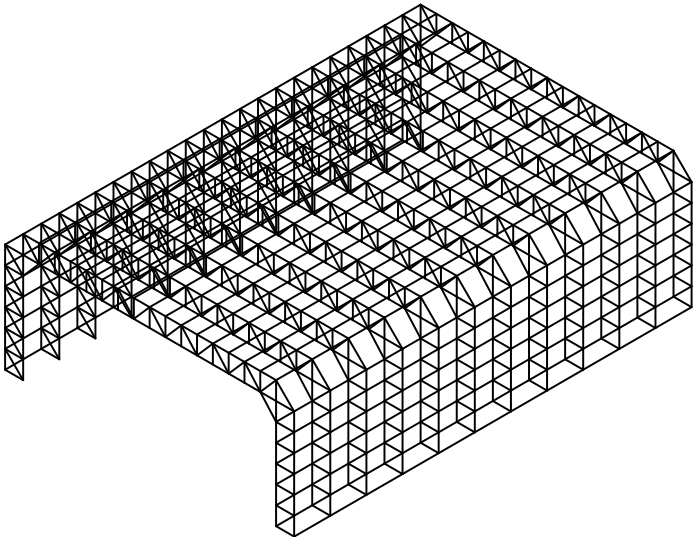


Figure 171. Objectives, constraints and parameters for the structure stage

STAGE 2 / STRUCTURE

OBJECTIVES					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	HOW TO OBTAIN
1	Structural/Economic	Minimize mass/Cost	kg	N/A	Karamba
2	Structural	Minimize max deflection	mm	N/A	Karamba
3	Aesthetical	Increase aesthetics	N/A	N/A	Design explorer

CONSTRAINTS					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	WHERE TO FIND
1	Structural	Max deflection	m	1/300 span	Eurocode
2	Structural	Max stress	Mpa	100	Eurocode

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vs1	Structural	Beam depth	m	Continuous	2 to 4	2	2
vs2	Structural	Column depth	m	Continuous	2 to 4	2	2
vs3	Structural	Chord diameter	mm	Continuous	250 to 400	10	15
vs4	Structural	Chord thickness	mm	Continuous	8 to 16	1	15
vs5	Structural	Web diameter	mm	Continuous	150 to 300	10	15
vs6	Structural	Web thickness	mm	Continuous	4 to 12	1	4
vs7	Structural	Purlins diameter	mm	Continuous	200 to 400	10	20
vs8	Structural	Purlins thickness	mm	Continuous	8 to 16	1	8
vs9	Structural	Divisions beam	#	Continuous	8 to 16	1	8
vs10	Structural	Divisions column	#	Continuous	8 to 16	1	8
vs11	Structural	# Frames	#	Continuous	10 to 15	1	5
FIXED							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
fs1	Structural	Material	N/A	Discrete	Steel*	N/A	1
fs2	Structural	Circular section	N/A	Discrete	Hollowed circular	N/A	1

ASSUMPTIONS					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	WHERE TO FIND
as1	Structural	Dead Load	Kn/m2	3	Eurocode
as2	Structural	Live Load	Kn/m2	2	Eurocode
as3	Structural	Wind Load	Kn/m2	1.5	Eurocode

Figure 172. Base model for the structure stage

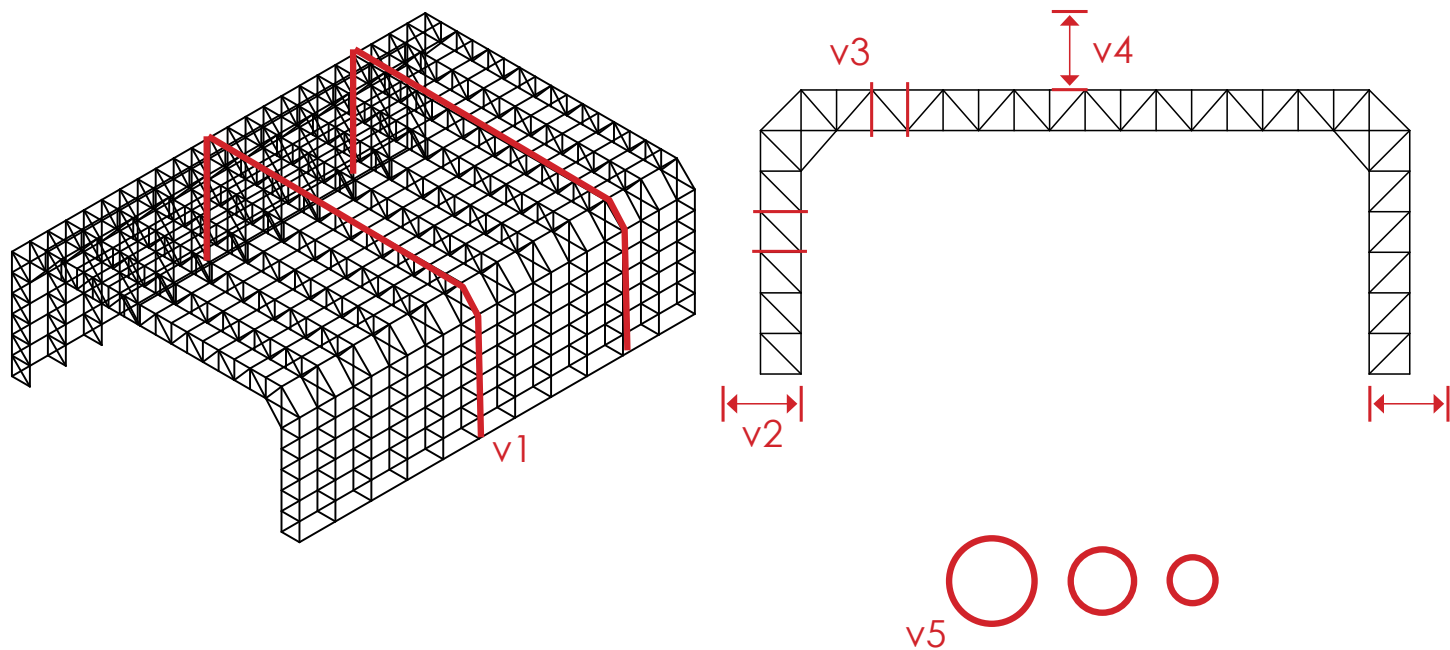


Figure 173. Variable parameters diagram for the second stage

Taking into account this previous “types” of elements, the variables were incorporated, they can be divided in three sub-sections:

- General scale (number of frames)
- Medium scale (definition of frame)
- Detailed scale (definition of profiles)

For this stage in order to have a sequential process and with the idea of narrowing down the options in a logical manner, several considerations were fixed, namely the size of the building. Nevertheless, with the aim of having the possibility to “fine tune” the shape some variables remained enabled for this stage, which his the case of the height and the position of the peak. This was specially interesting because during the simulations this variable showed how the structural system can behave differently according to different definitions of this parameters. In this way, by having the results of the simulations it is also possible to make a design decision based on the structural performance of it together with the aesthetical and economic factor. For this phase, the economic factor was the main driver, with the aim of calculating the general mass of the structure to later on by setting up the price of the material (in this case steel (\$275) based on local market prices. For the scope of this thesis only a hollowed steel profile was consider, however this could be extended to analyze and compare a wide selection of possible structural materials and profiles.

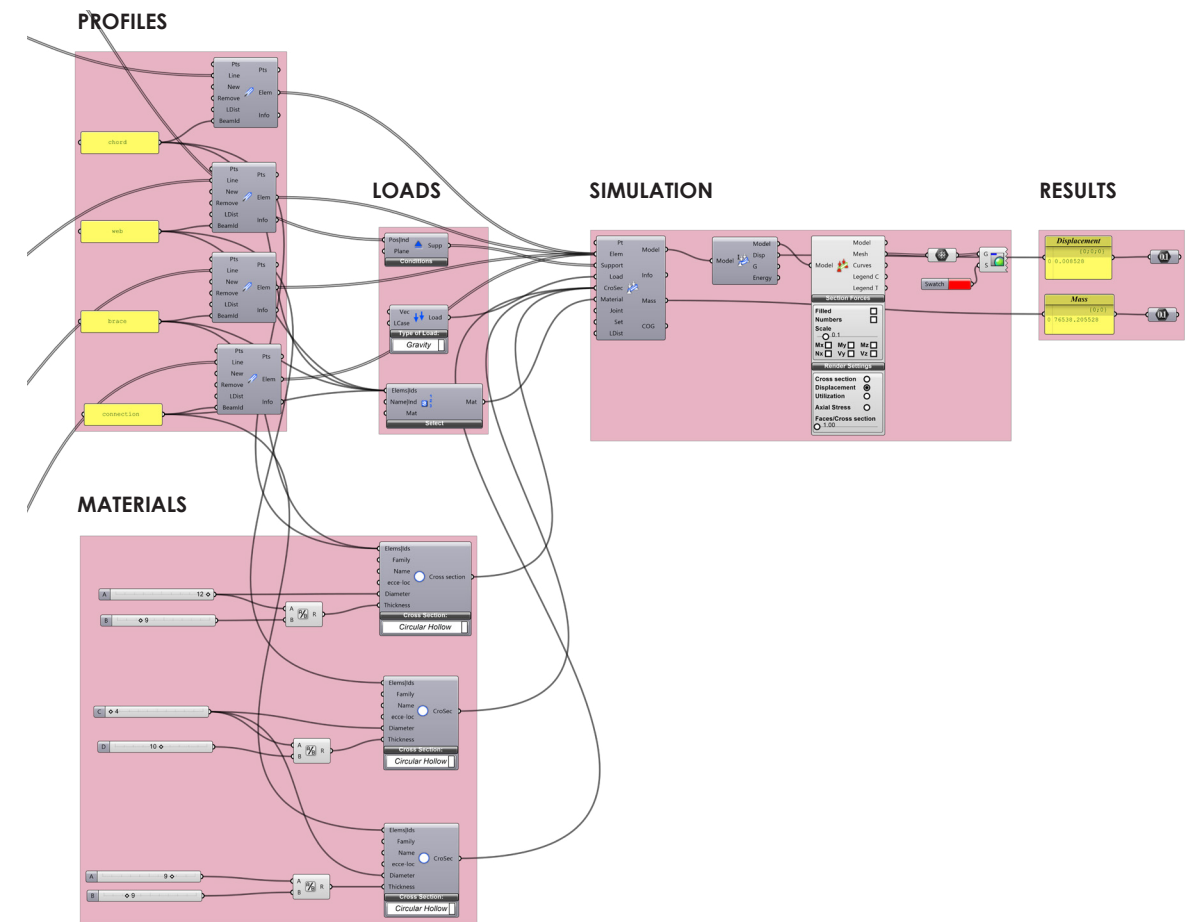


Figure 174. Grasshopper script for the structural simulation

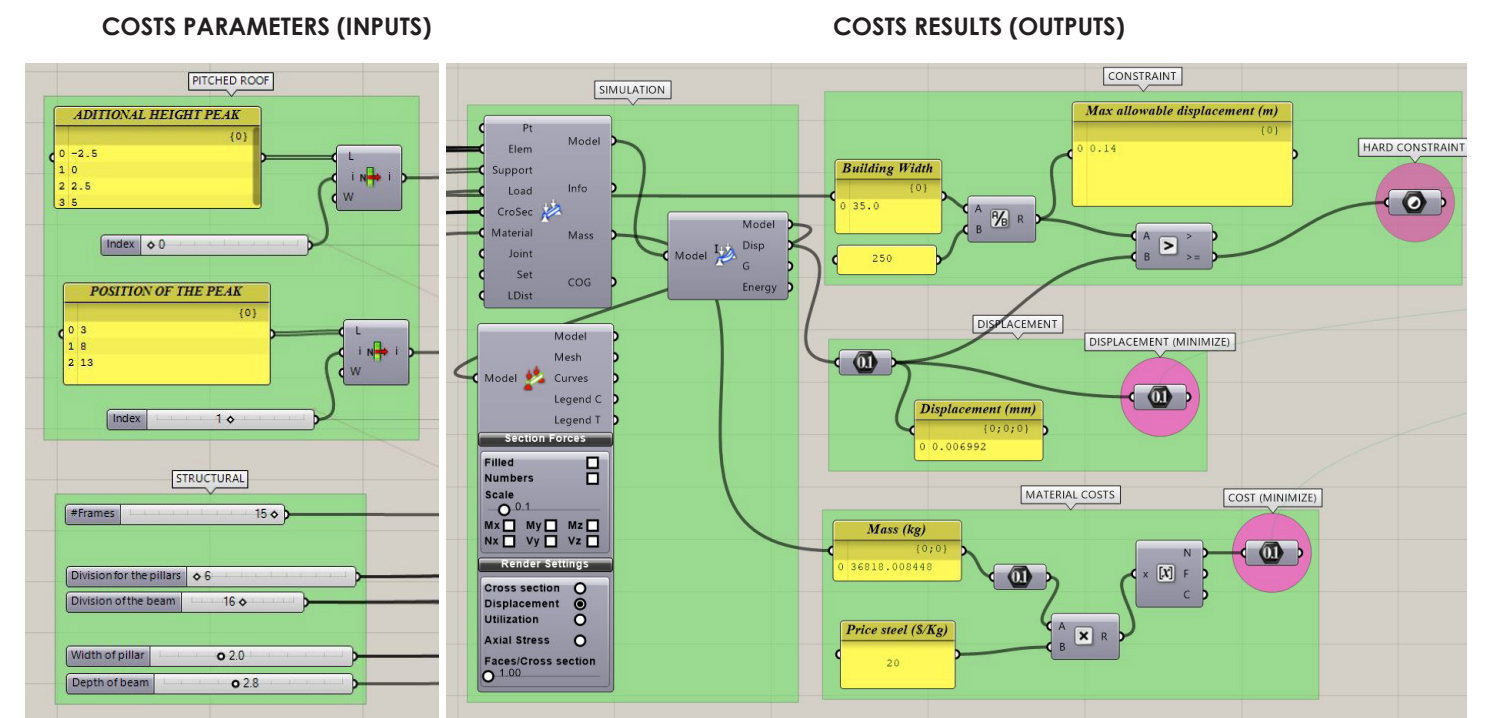
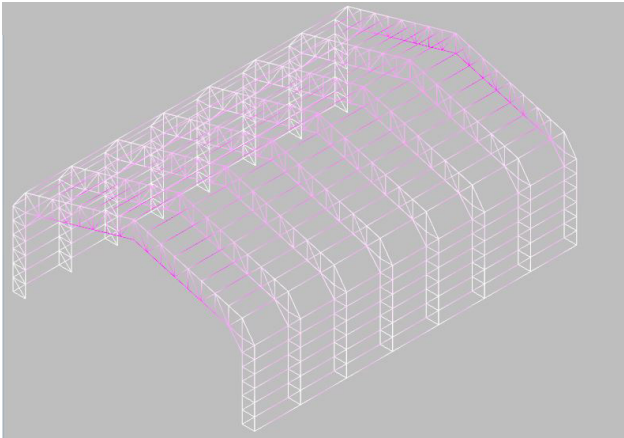


Figure 175. Inputs and results of the costs calculations for the structure



5.2.4.2.2 Simulation results

**Inputs:**  
-#Frames: 8  
-Peak height: 5m  
-Chord diam: 10  
-Chord thickness:10  
-Web diam:6  
-Web thickness:10

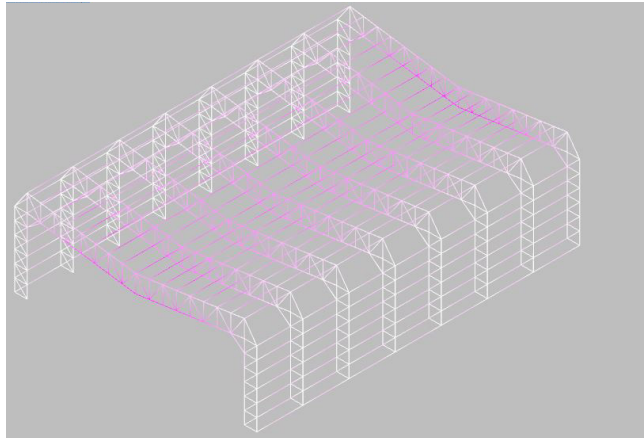


**Outputs:**  
-Max deflection: .020m  
-Mass: 51080 kg

For the simulation process, it was needed to set the geometries, materials, cross sections, materials and loads. By using the previously described Karamba plug-in, it was possible to assign correctly the real structural properties to the different geometries, taking each line as a structural beam and the bottom points of each frame as supports. For this stage, the structural simulations were carried out smoothly, having the feedback in real time, therefore it was possible to play and see how the structure behaved according to the different shapes and variables.

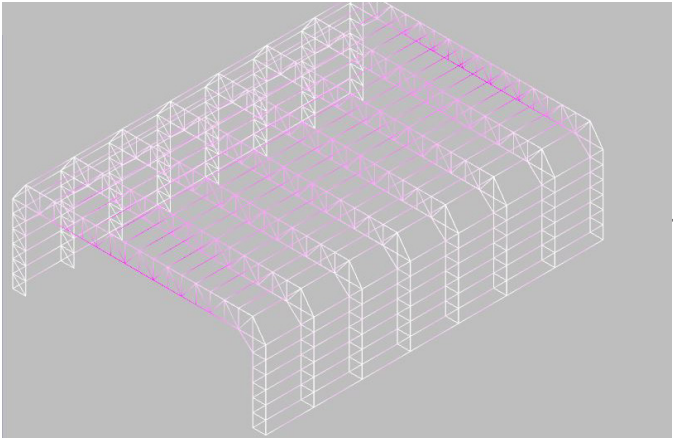
Inside this model, a maximum allowable deflection was set as defined in chapter 3.1.4.2.3 in order to be able of exploring only feasible solutions inside the design space. Among several results provided by Karamba, the ones that were mainly considered for the aims of this research were maximum deflection (mm), and mass (kg), in this way, this two aspects were evaluated in a later stage by the optimization engine and the visualization platform.

**Inputs:**  
-#Frames: 8  
-Peak height: -2.5m  
-Chord diam: 10  
-Chord thickness:10  
-Web diam:6  
-Web thickness:10



**Outputs:**  
-Max deflection: .024m  
-Mass: 50461kg

**Inputs:**  
-#Frames: 8  
-Peak height: 0 m  
-Chord diam: 10  
-Chord thickness:10  
-Web diam:6  
-Web thickness:10



**Outputs:**  
-Max deflection: .024m  
-Mass: 50400 kg

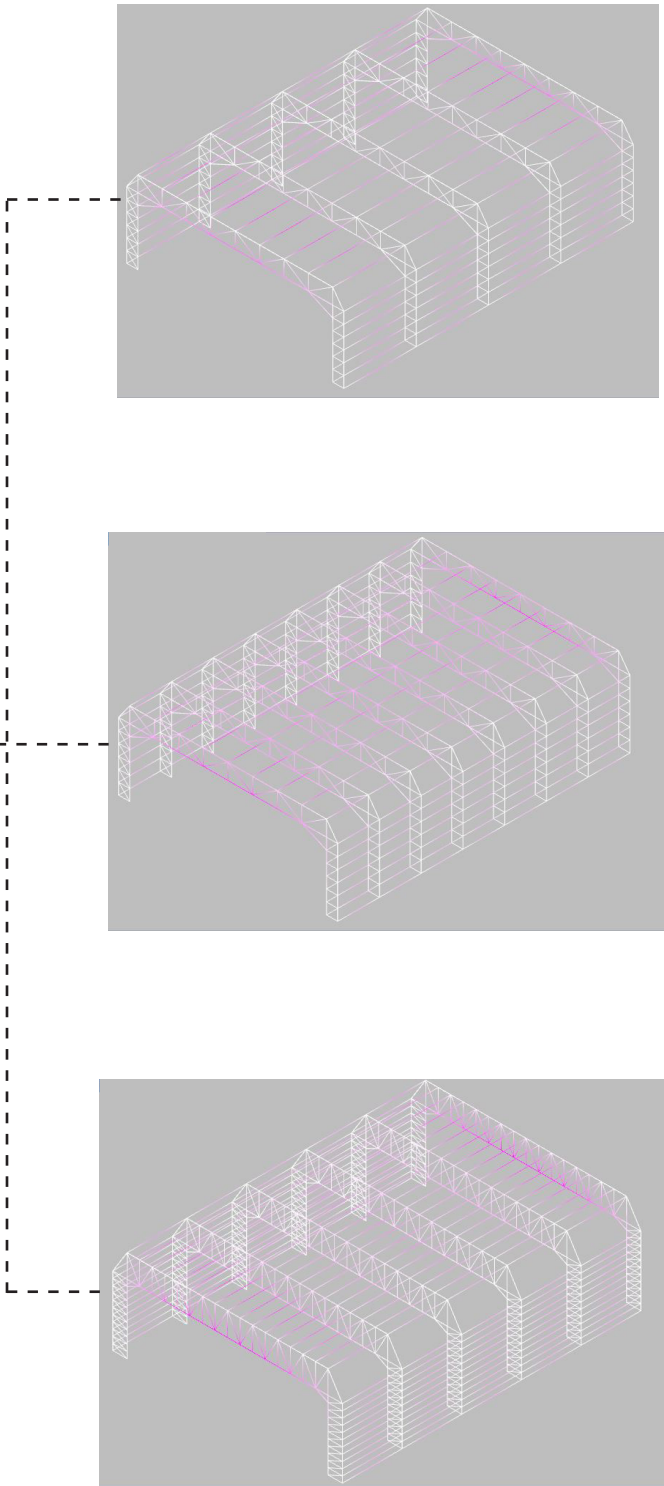


Figure 176. Images showing the deflection analysis and the influence of the parameters in the results



5.2.4.2.3 Optimization results

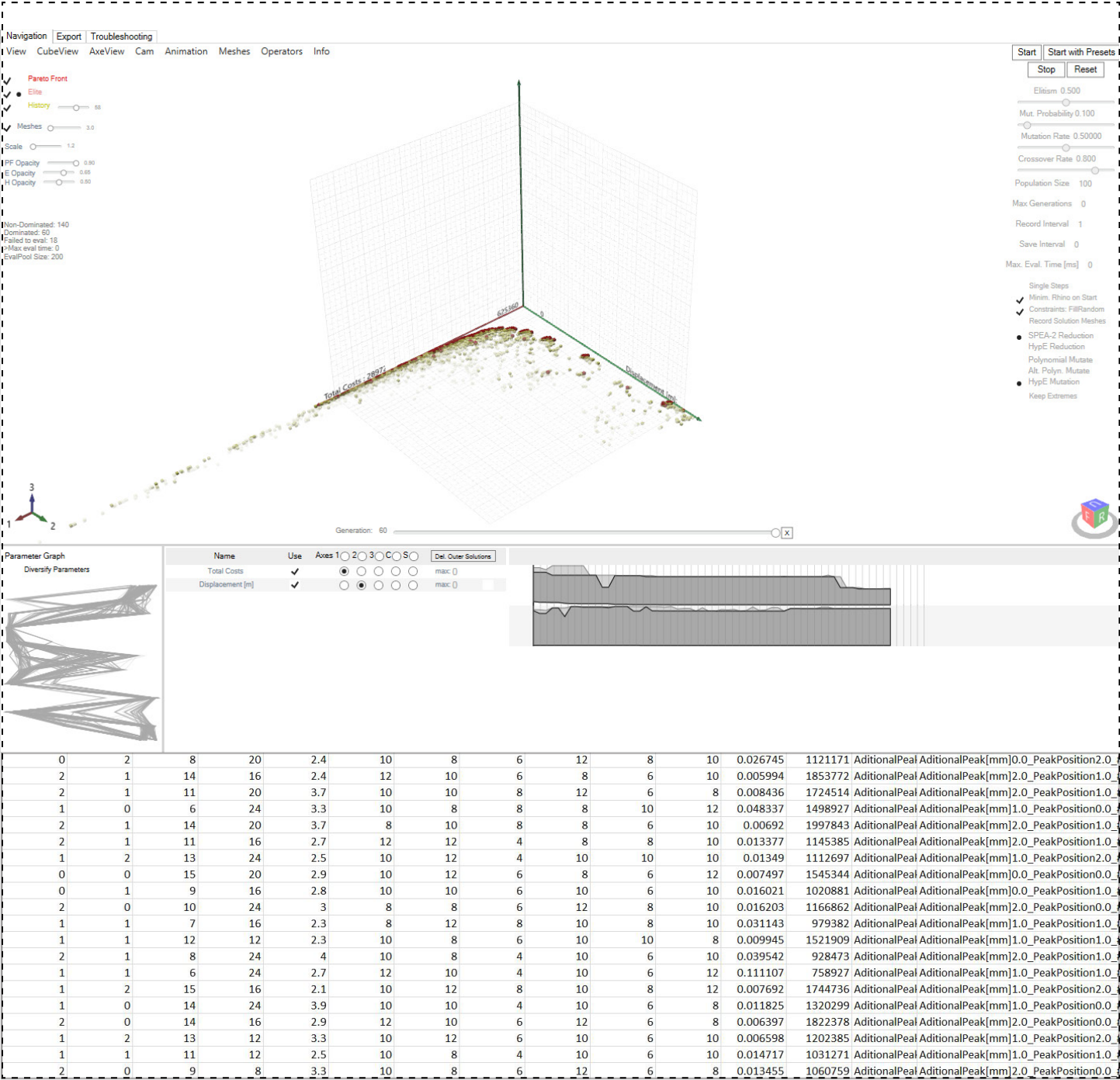


Figure 177. (Up) 3D chart of Octopus optimization results. (Down) Data organization in a csv. file

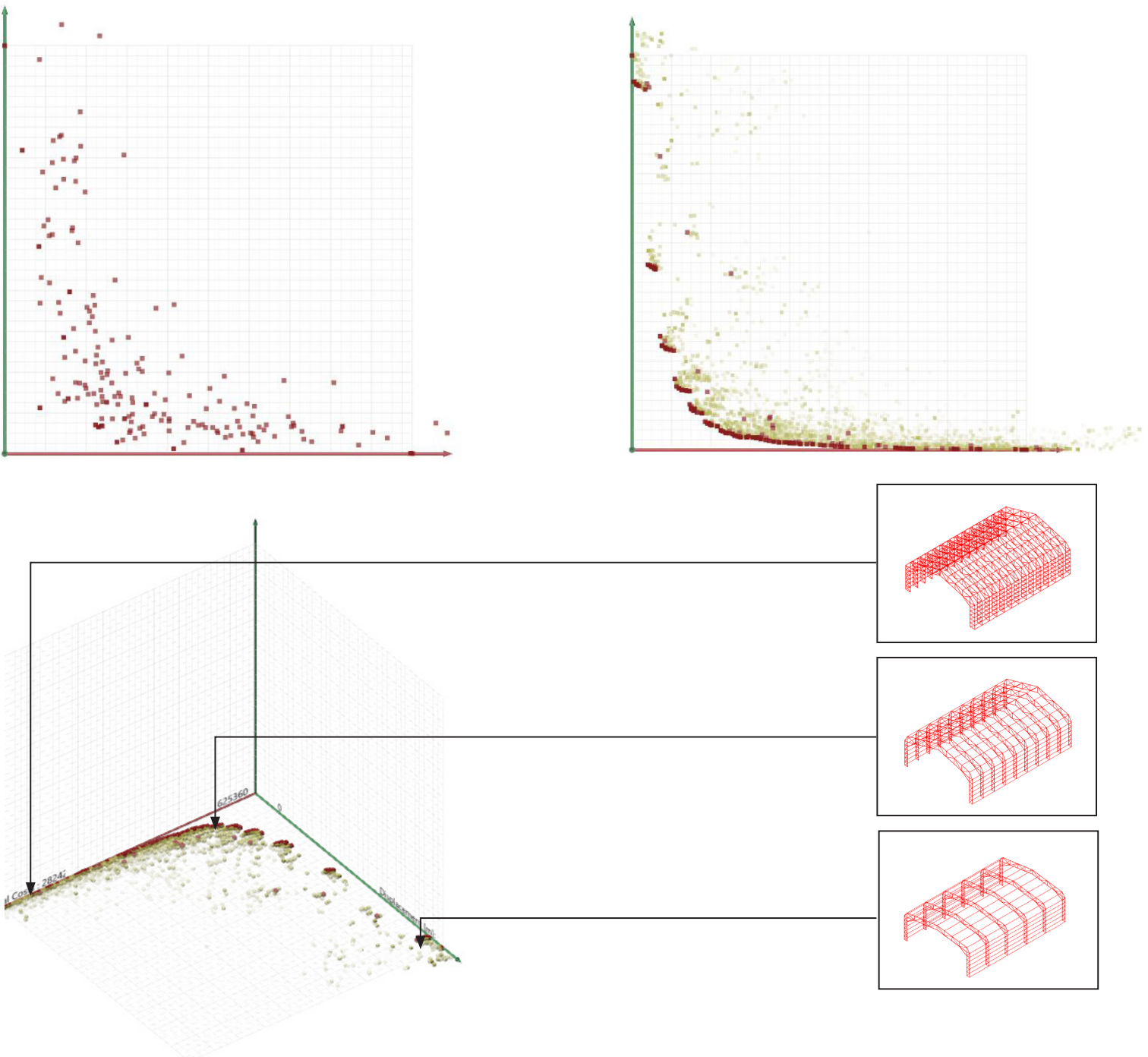


Figure 178. 2D charts of the Octopus optimization results

During the optimization phase, the process ran smoothly in a simple laptop in a time lapse of about 2.5 hours dedicated to the computational process, handling a total of 13 parameters, which resulted in 50 generations and retrieved a set of 3558 general options, out of which 140 were optimal options for further exploration. From the beginning of the process, it could be observed that a clear Pareto front was formed. By trying to minimize the material costs and therefore reducing the mass from one side and minimizing the displacement from another, the optimization algorithm searched for design options that successfully balanced this two contrary objectives.



5.2.4.2.4 Design optioneering results

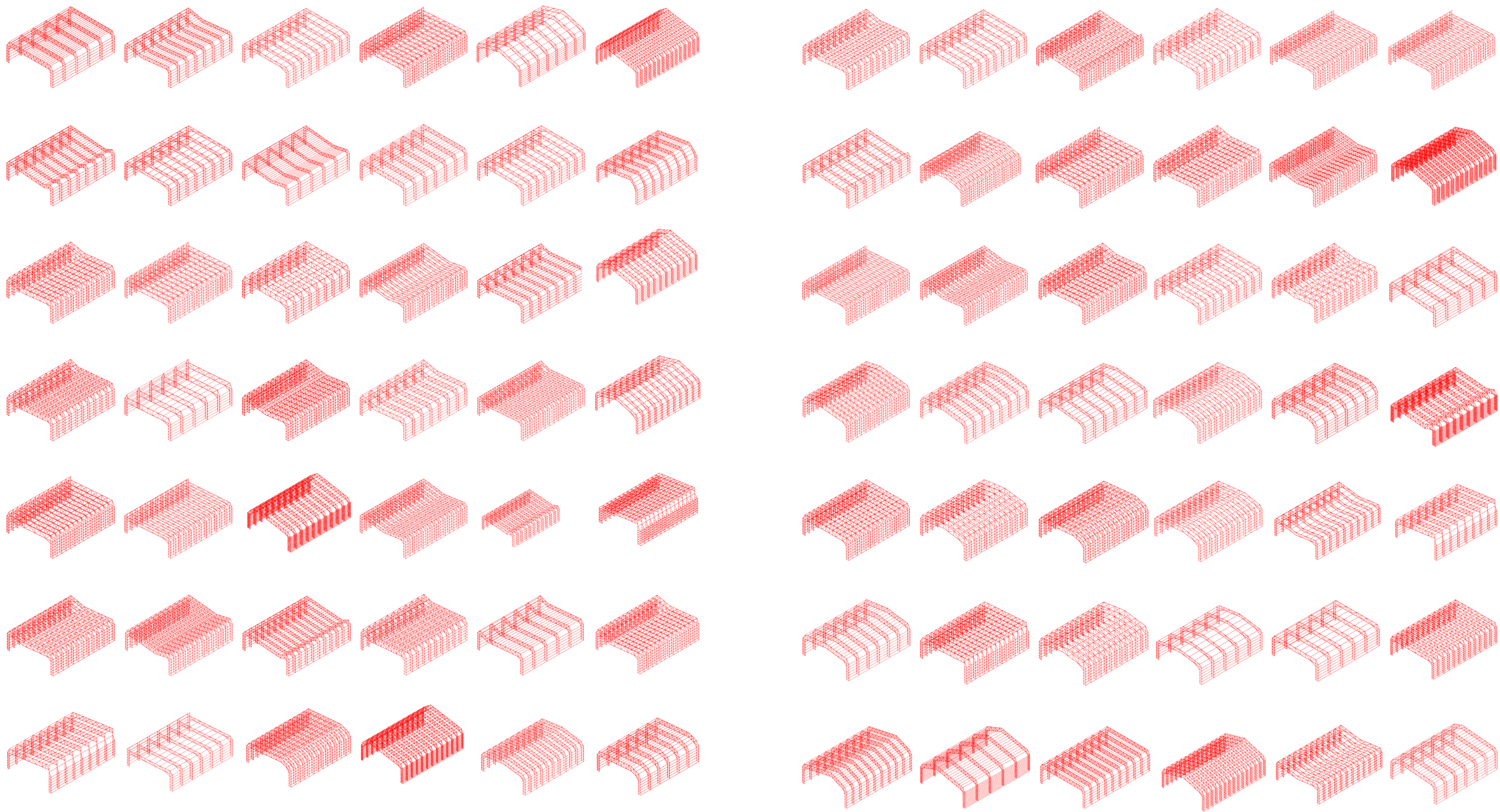


Figure 179. Images of the design alternatives iterated by the optimizer



5.2.4.2.5 Results & observations

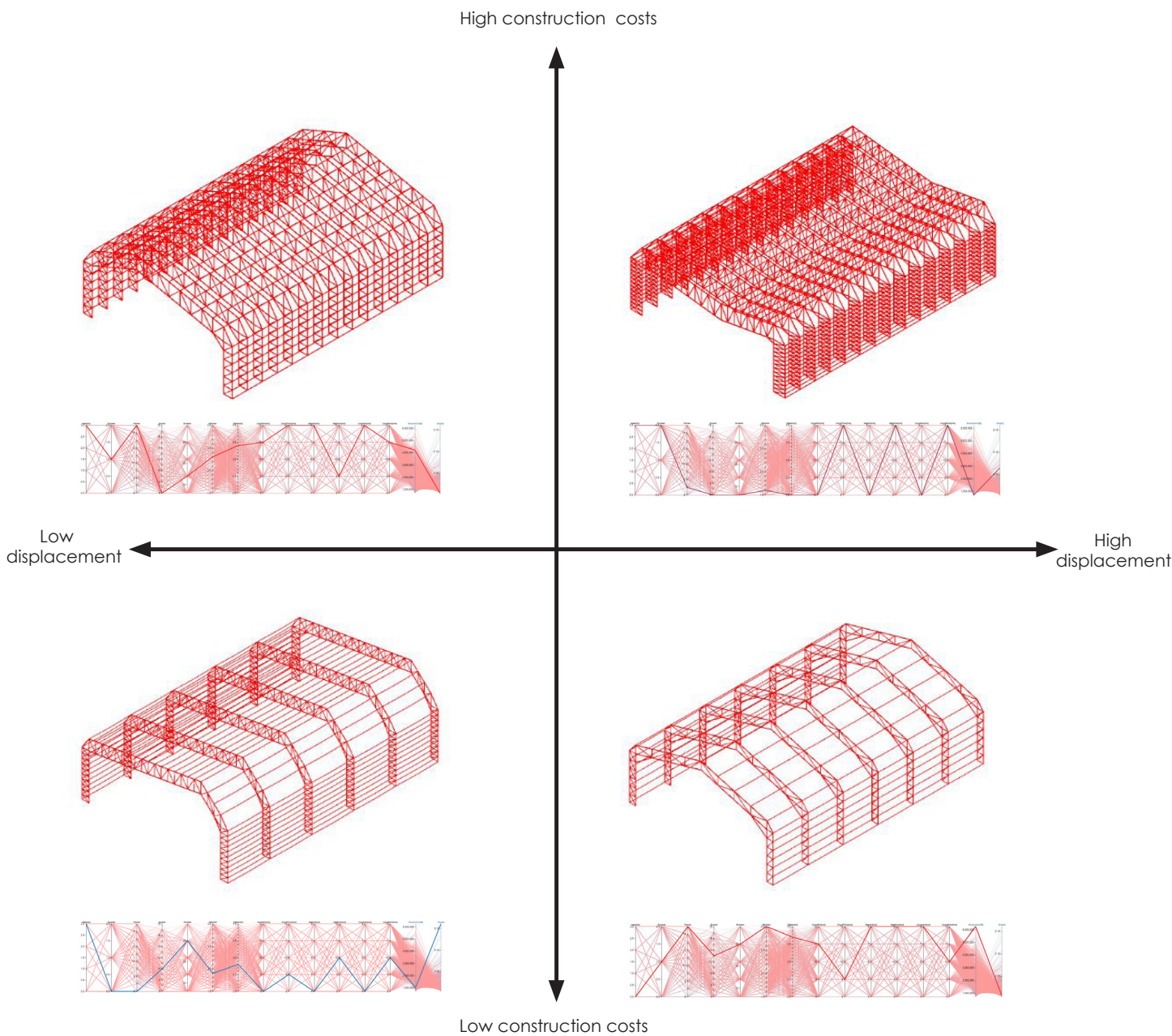


Figure 180. Sensitivity analysis and comparative of the designs general performance tendencies

The structural design phase showed interesting results from the beginning of the simulation settings. Even though the selected Plug-in realizes a simulation, this one is capable to show the results almost immediately so it is even possible to realize the changes manually and observe the modifications in performance. However, for this stage a large number of parameters were considered, moreover a specific requirement regarding safety issues was also implemented. During the 2.5 hours optimization process, the software reduced a significant large number of options by filtering them using the previously defined constraint. In this way, from 118,125,000 possibilities the optimizer reduced the design space to an amount of 3200 options within 50

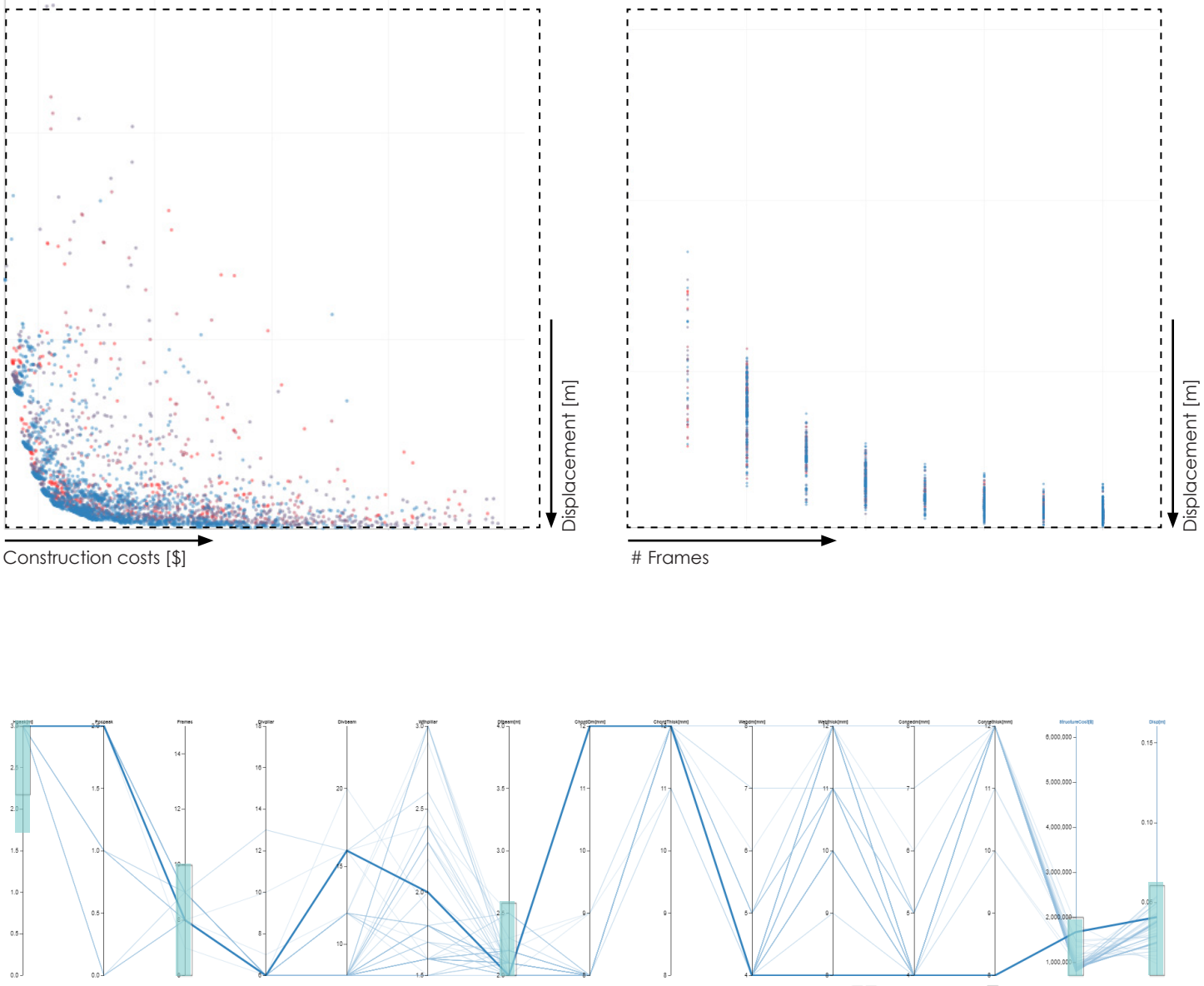


Figure 181. Sensitivity analysis charts and parallel coordinated chart of the selected design

generations and a population of 100. The final result was a set of 140 non-dominated options. From the 3D charts of the optimization results, it can be observed that a wide set of non-dominated solutions was found successful. Also, the results have presented a wide range of options for beam thickness, however not visible on the scale of the drawing due to the level of detail it entails.

The selected option has been defined mainly by the height and position of the peak as well as the number of frames and the displacement. . Thus, the 3D charts of the optimization results, reveal that a wide set of non-dominated solutions was found successful. With a clear tendency of narrowing down towards the origin of the neutral axis as the generations continued. From the sensitivity graphs it can be concluded that the factor that affects the displacement the most is the amount of frames. However this, logically increases considerably the building costs



5.2.4.2.6 Design decision

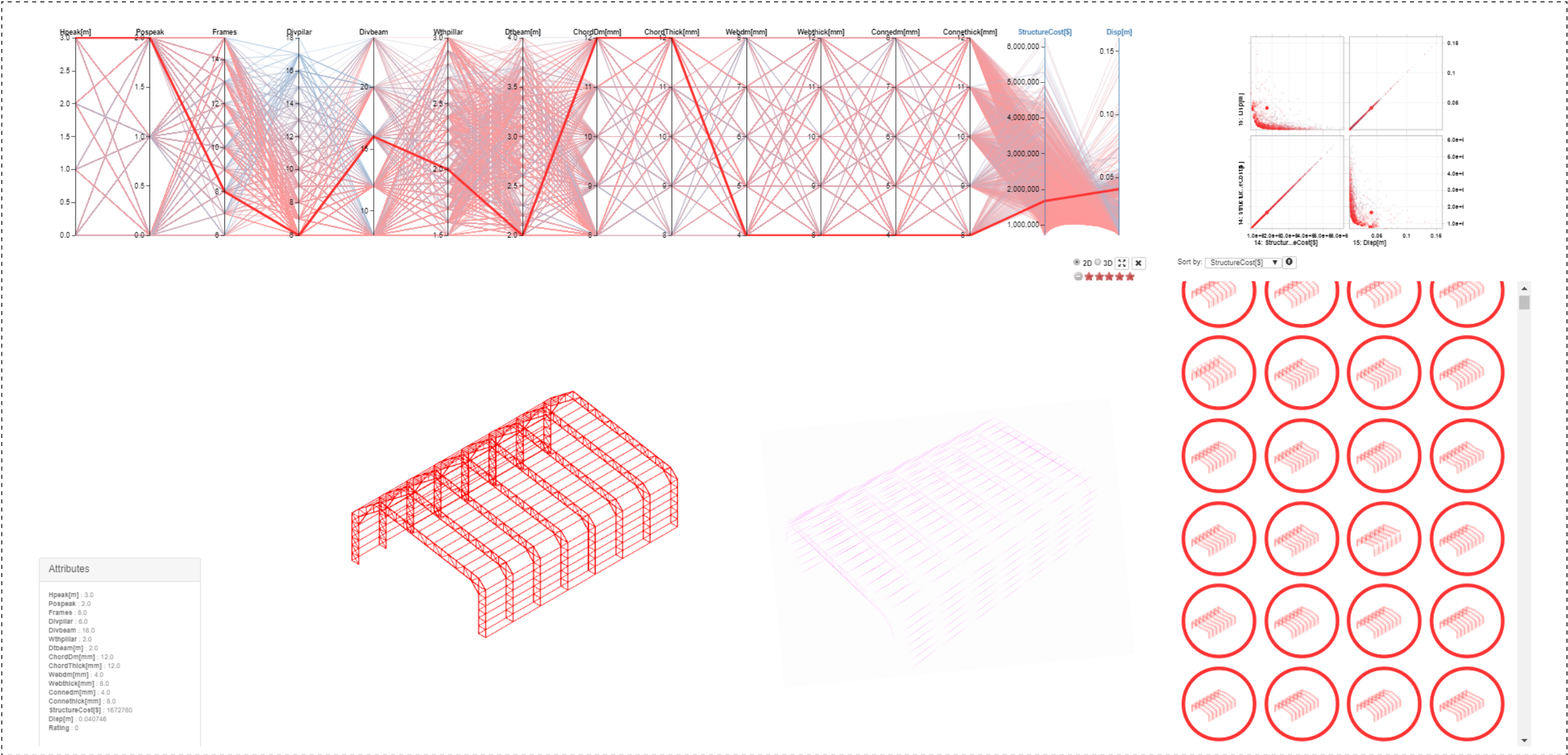


Figure 182. Design exploration, filtering and selection interface

and specially the look of the building itself (from an aesthetical point of view). Regarding the shape parameters, it was interesting to find that while the values of the peak's height are higher the displacement is reduced in the majority of the cases. In fact this is specially true if we consider the principle of an arch structure where compression efforts are distributed in a more uniform and optimal manner. Considering this, a "fine tuning" modification was held rising even more the height of the peak, in comparison to the base model (massing stage).

Fig. [182] shows a clear tendency of the incremental of costs while reducing the displacement, this is because the mass is also increased probably when increasing some diameters or adding more divisions inside the same trussed structure. In this case, the selected option followed the initial shape selected during the stage 1, after having this values as a driver, the next decision was to avoid having a large number of frames so to avoid that, increasing the diameters and thicknesses of the individual elements was considered. An additional decision making factor of this stage, besides the structural performance, considered achieving a certain rhythm for the structure.

5.2.4.3 Stage 3: Envelope

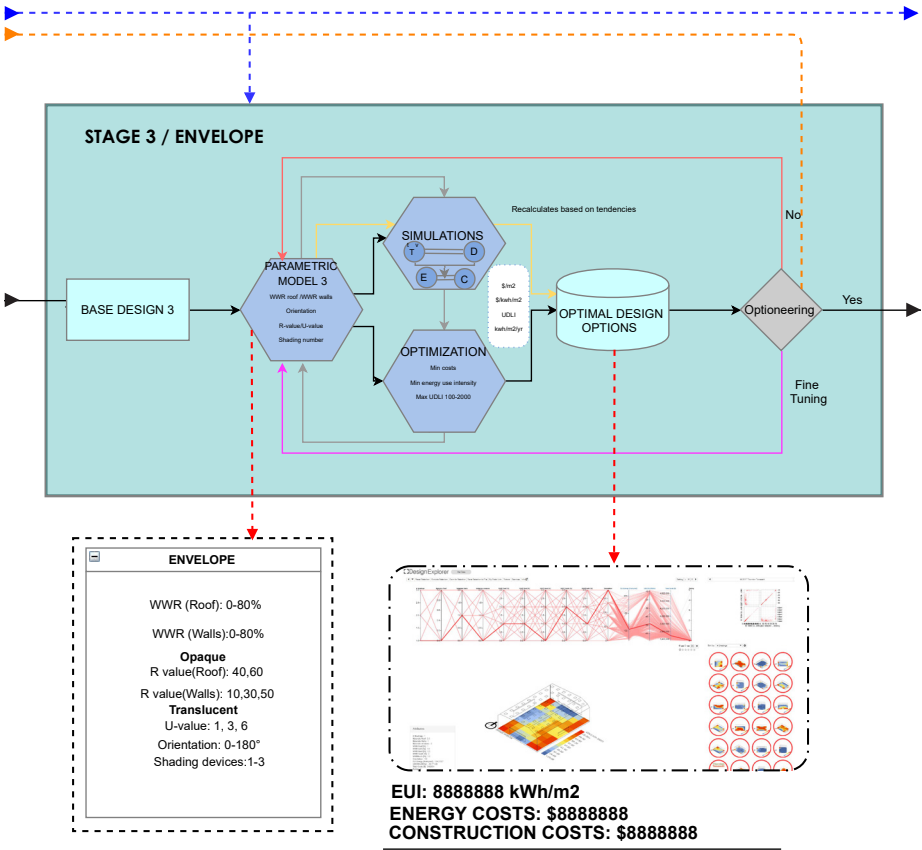
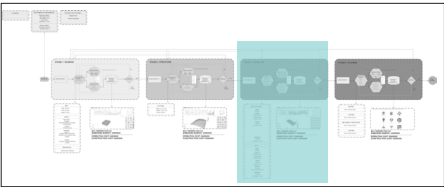


Figure 183. Diagram of the envelope stage (Sequential workflow)

The base model for this stage of the design process has an already fixed surface and overall shape, selected during the previous two phases. This section was developed in deep correlation with the first stage of the design, together with the initial geometry, the subdivision of surfaces into what later on Honeybee will understand as walls, roofs, ground floor and windows was carried out. Once having the “selected” option from the previous strategies, this new several values were assigned to the model envelope as shown in Fig. [186]. The first part of this stage was placing windows and skylights with a changeable WWR ratio. In addition to the already mentioned types of surfaces, after this, two more considerations were also involved as stated by the variable parameters. From one side the orientation, rotating the geometry within its own central axis, and from the other side, adding shading geometries, varying its number and its depth.

5.2.4.3.1 General description & parametric model

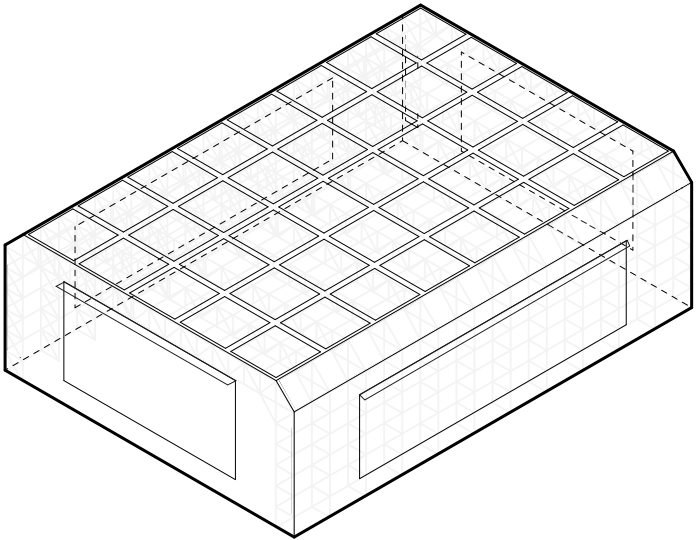


Figure 184. Base model for the envelope stage

STAGE 3 / ENVELOPE

OBJECTIVES					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	HOW TO OBTAIN
1	Economic	Minimize cost	\$	N/A	GH + Exel database
2	Climate (Energy)	Minimize energy use (Heating, cooling lighting)	kwh	N/A	Honeybee
3	Climate (Daylight)	Maximize UDI 100-2000	%	N/A	Diva
4	Aesthetical	Increase aesthetics	N/A	N/A	Design explorer

CONSTRAINTS					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	WHERE TO FIND
1	Climate (Daylight)	Min SDA	%hr	50	LEED V4
2	Climate (Daylight)	Max ASE	% hr	250	LEED V4
3	Climate (Thermal)	Max Indoor Temp	°	25	LEED V4

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vc1	Geometry	Orientation	°	Discrete	0 to 180	45	4
vc2	Climate	Walls (N,S,E,W)					
vc3	Climate	WWR	%	Continuous	0 to 80	20	4
vc4	Climate	WWPVR	%	Continuous	0 to 80	20	4
vc5	Climate	Opaque	R-Value	Discrete	R1, R2, R3	1	3
vc6	Climate	Transparent	U-Value	Discrete	U1,U2,U3	1	3
vc7	Climate	# Shadings	#	Continuous	1 to 3	1	3
vc8	Climate	Roof					
vc9	Climate	WWR	%	Discrete	10,30,50,80	1	4
vc10	Climate	Opaque	R-Value	Discrete	R1, R2	1	2
vc11	Climate	Transparent	U-Value	Discrete	U1,U2,U3	1	3
FIXED							
fc1	Climate	Ideal Airloads	Type	Boolean	1	1	1
fc2	Climate	Manual switch on off	W/m2	Discrete	1	1	1

Figure 185. Objectives, constraints and parameters for the envelope stage



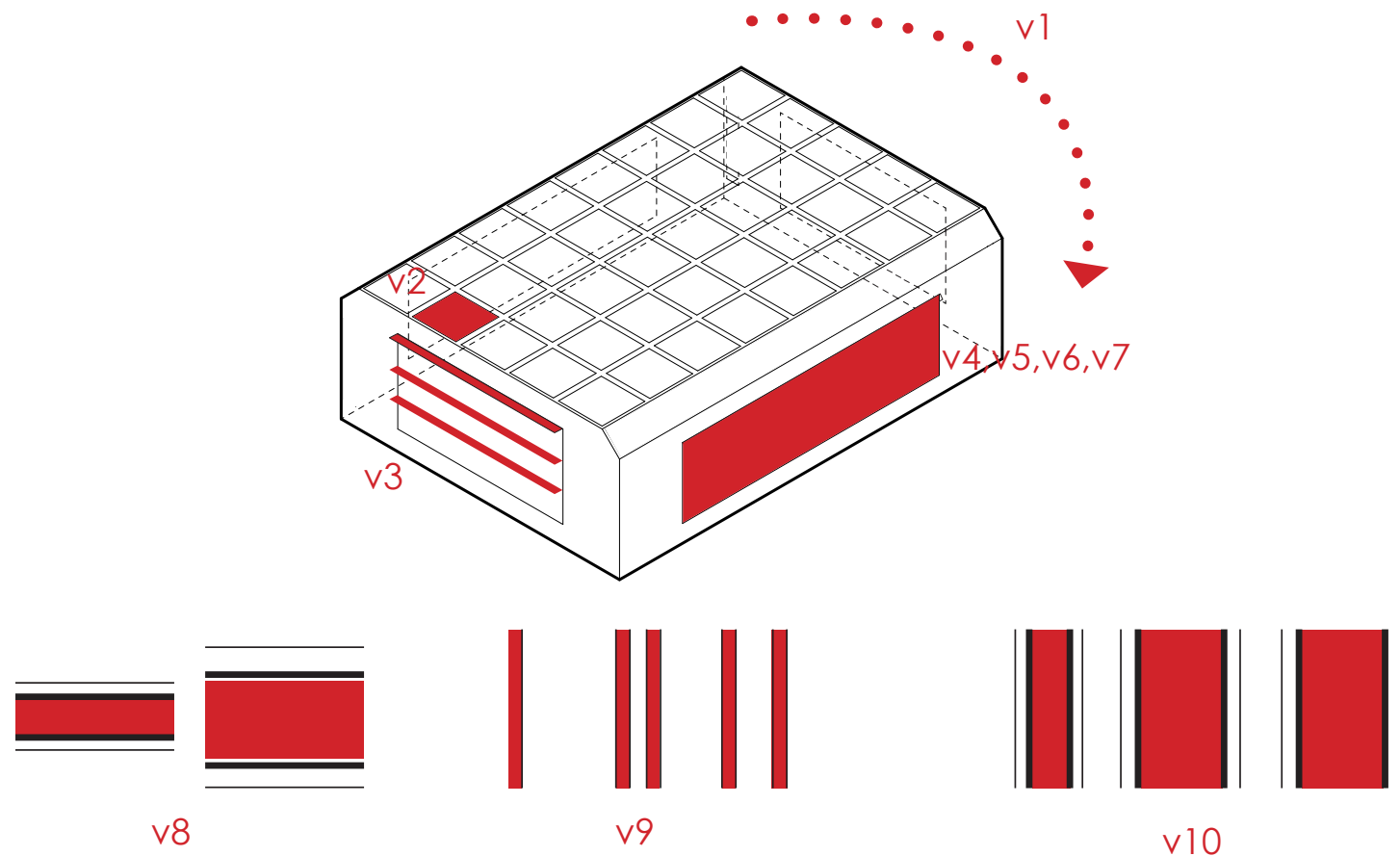


Figure 186. Variable parameters diagram for the third stage

The second part of this process was to assign the right properties for the daylight and energy simulations, in this way firstly, the materials were added, this was based on a market study about the more common local materials used for this kind of buildings in combination with the availability of these ones inside the simulation software. This selection was divided in three main parts; walls materials, roof materials and window materials having all of them different alternatives regarding thermal and optical performance in combination with a variation on the material costs.

After defining the material properties, the next part was to assign the occupancy schedules and thermal loads both for the daylight calculation and later on the energy simulation. For this, the option of a Secondary school GYM was selected as a template and only some specific aspects such as heating and cooling set points were adjusted manually. As mentioned in previous chapter for the aim of this research and the technical specifications of the specific case study, natural ventilation was not considered.

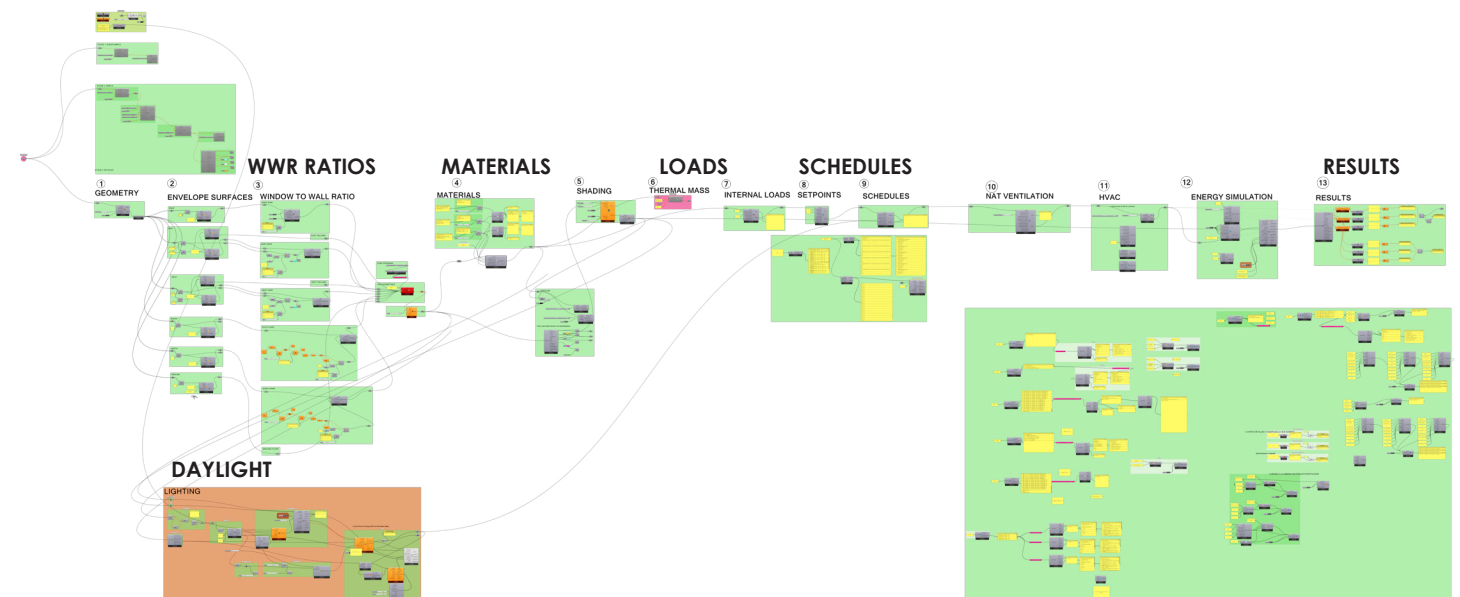


Figure 187. Grasshopper script for the energy and daylight simulations

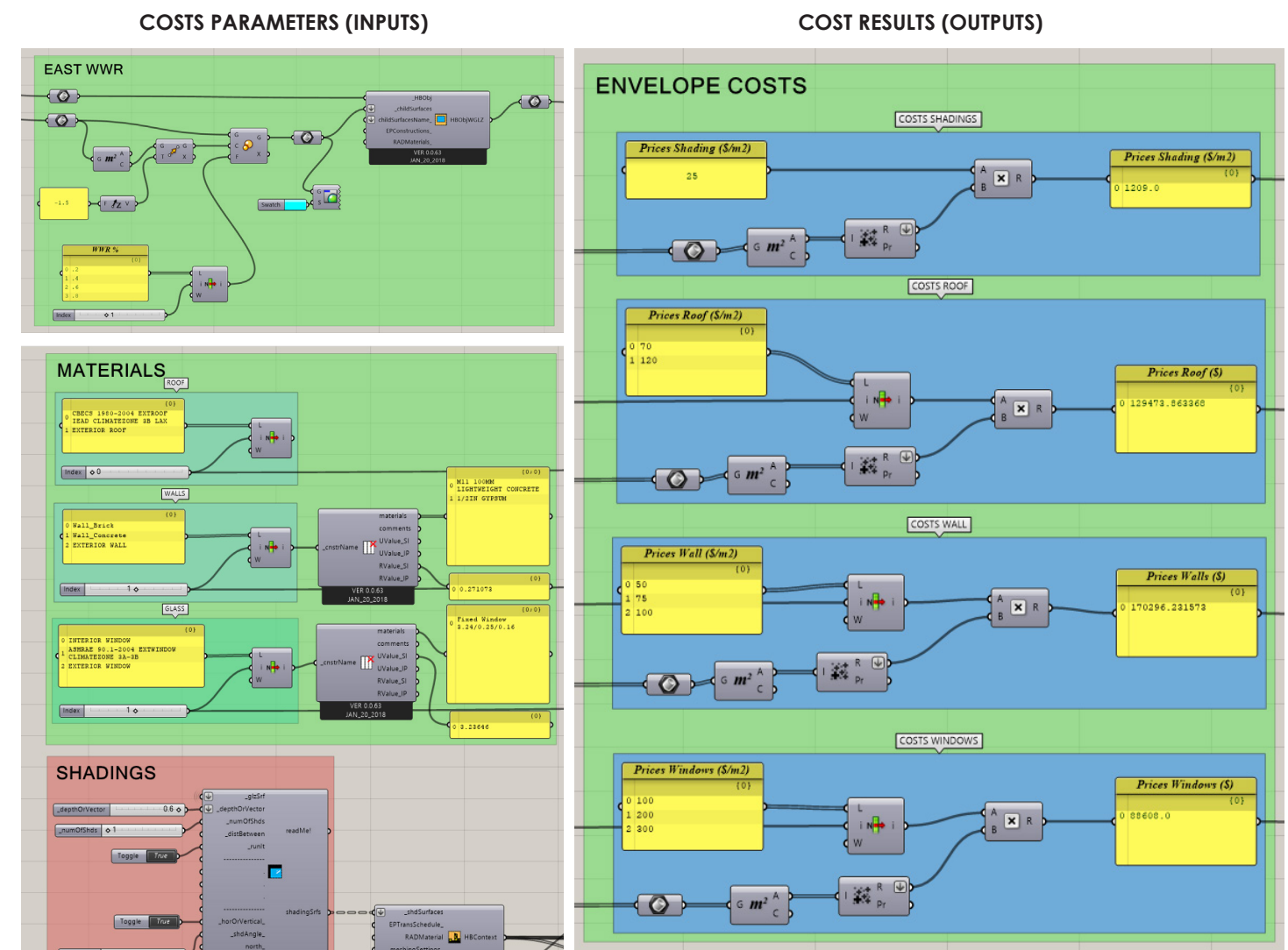


Figure 188. Inputs and results of the costs calculations for the envelope



5.2.4.3.2 Optimization results

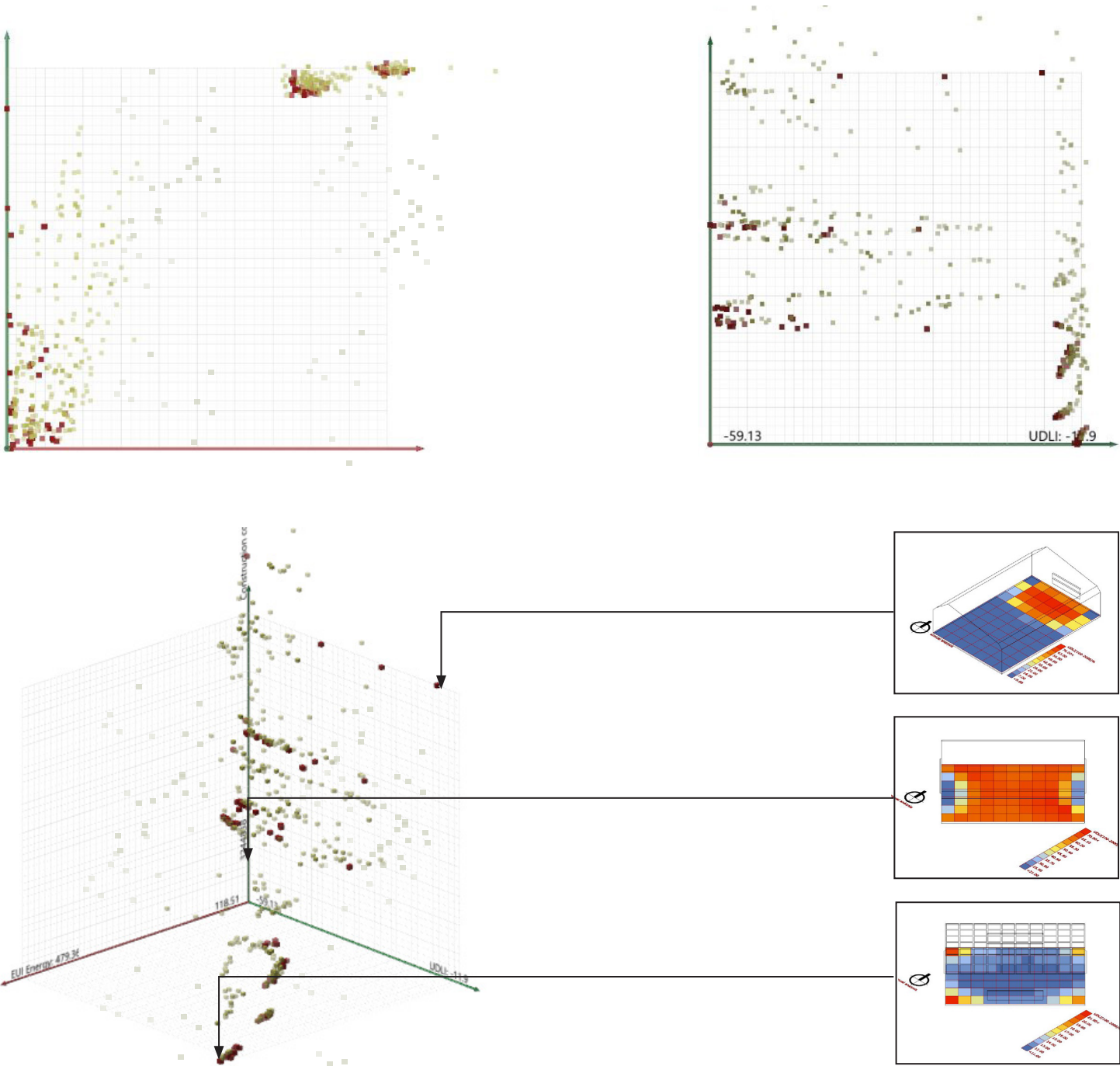
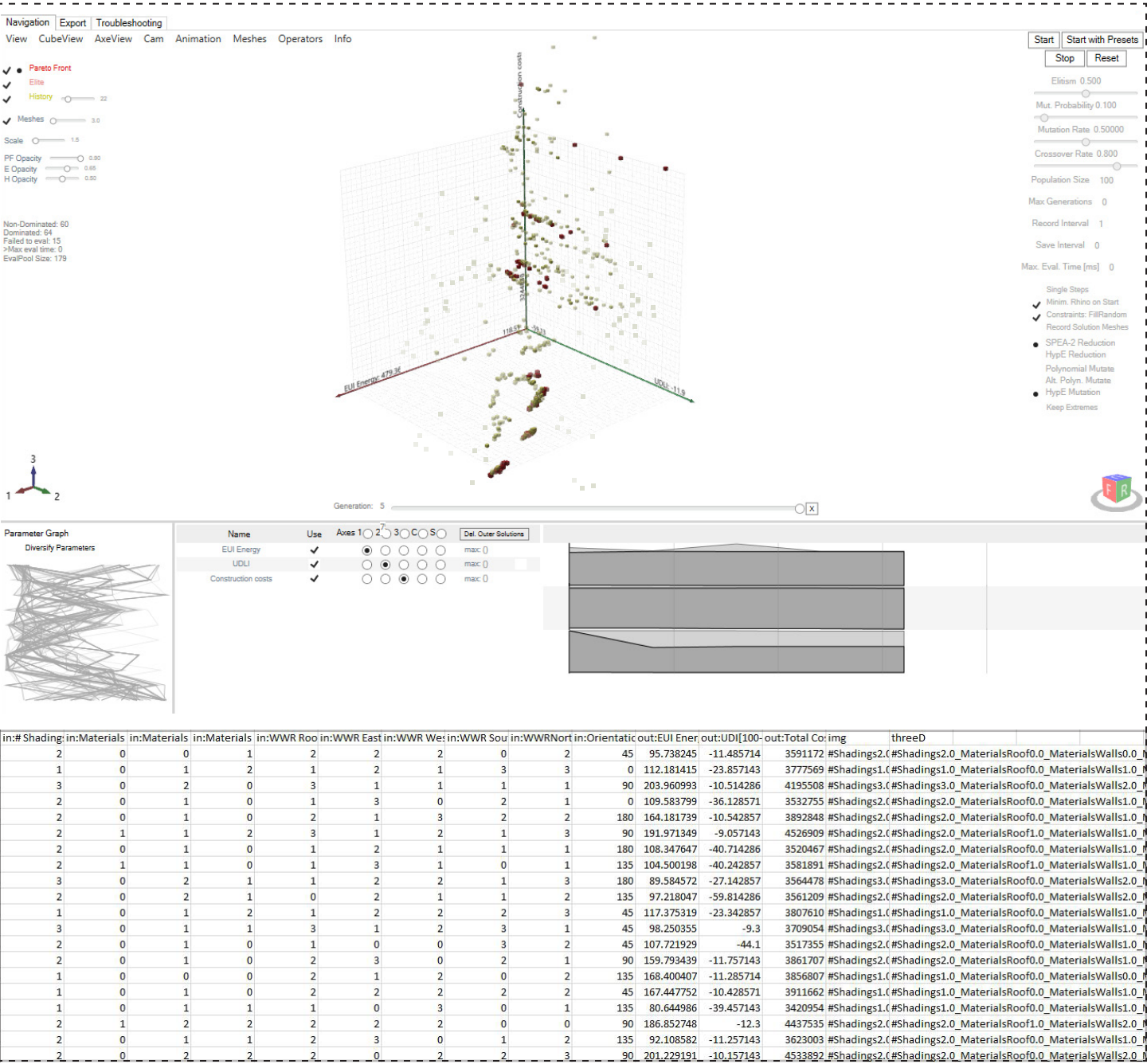


Figure 190. 2D charts of the Octopus optimization results -Pareto Front (non-dominated solutions)

STAGE	NUMBER OF PARAMETERS	NUMBER OF GENERATIONS	DESIGN SPACE	DOMINATED / NON DOMINATED	COMPUTATIONAL TIME
	10 Parameters	7 Generations 100 Population	980 from 2774800	60 Non-dominated 64 Dominated	1.5 Days

Figure 189. (Up) 3D chart of Octopus optimization results. (Down) Data organization in a csv. file

The multi-objective optimization was performed over a period of almost 1.5 days, due to the fact that both daylight simulations and energy simulations were performed for each one of the diverse design alternatives. By taking approximately 3.5 minutes per iteration, it was necessary to utilize a bigger computer (Desktop Dell, 16 GB). So this process was conducted remotely by utilizing the Team viewer application linked to one of the computers inside the VR lab at the TU Delft Faculty of Architecture. A total of 980 options were filtered and after a long process only 7 generations of 100 individuals each were achieved, finishing with the finding of 60 non-dominated solutions which formed a clear Pareto-optimal set in a curved shape as shown in Fig. [190].

5.2.4.3.3 Design optioneering results

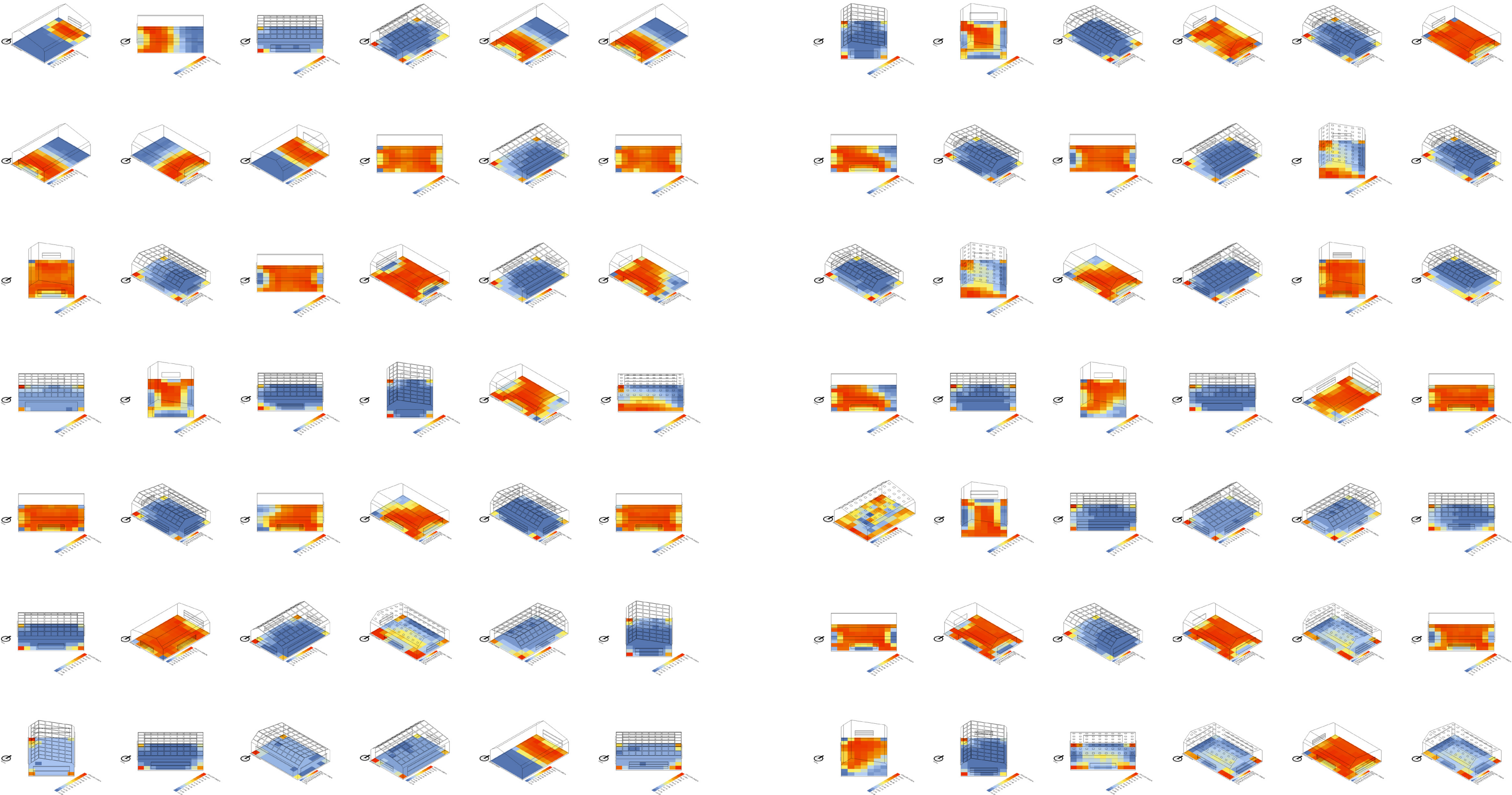


Figure 191. Images of the design alternatives iterated by the optimizer



5.2.4.3.4 Results & observations

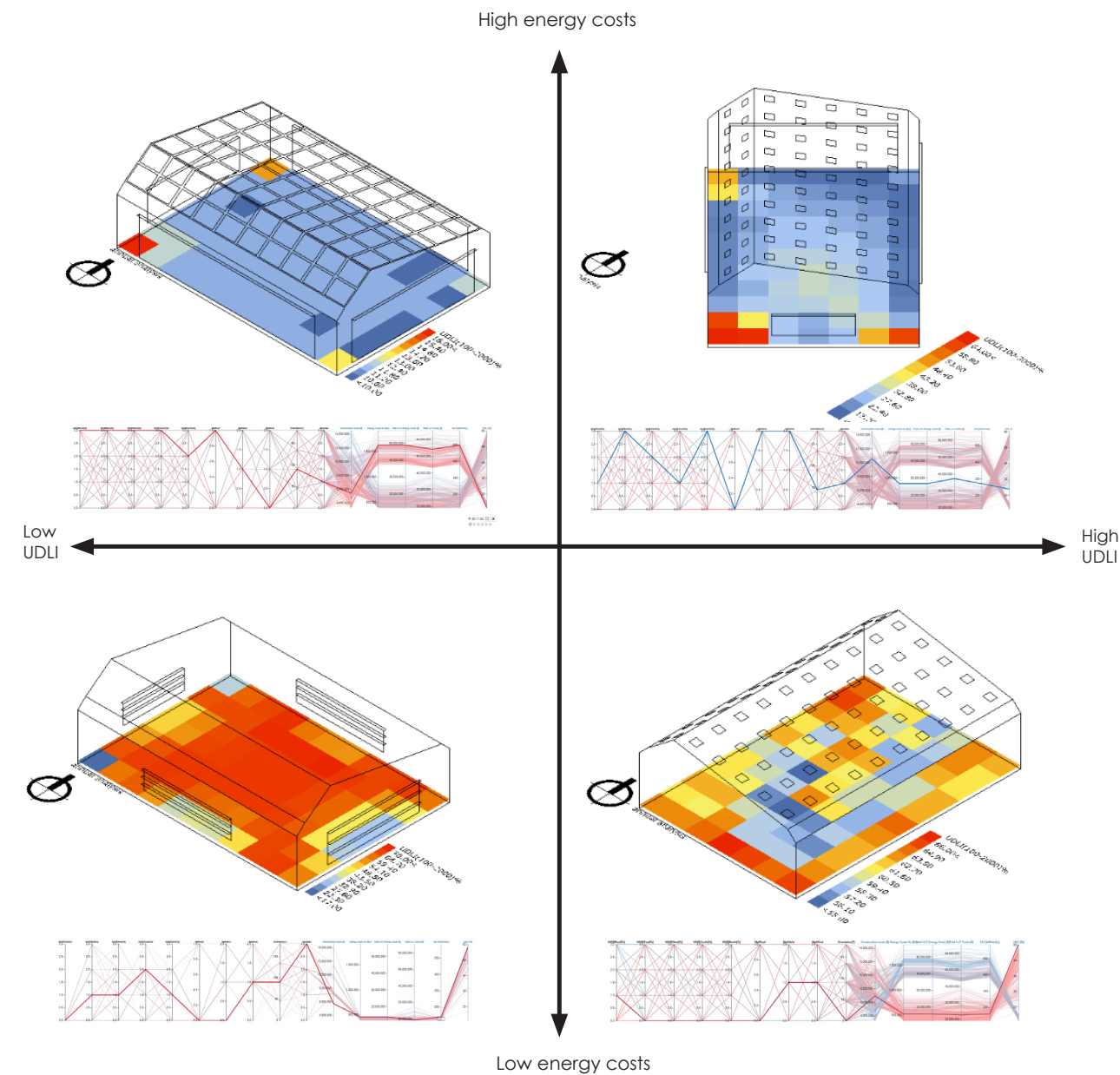


Figure 192. Sensitivity analysis and comparative of the designs general performance tendencies

It can be observed that an increase in the WWR ratio leads to an increase in the Energy Use Intensity specially for cooling, but at the same time reduces the demand for artificial lighting. For the shading devices, the influence over the energy performance was quite low in comparison with the other parameters, the orientation affected considerably the EUI and UDLI values, the best orientations being the ones from 0 to 60° and the worst ones the ones from 90° to 180°. Because of the selected indicator for Daylight performance, contrarily from what it would be logical to think, “the more light the better” the results showed that the options with the highest UDLI values were the ones with a controlled amount of windows. In this scope, lateral windows most of the time generated unequal light qualities having dramatic changes of illumination conditions in the areas around the windows because of the different orientations. The previous,

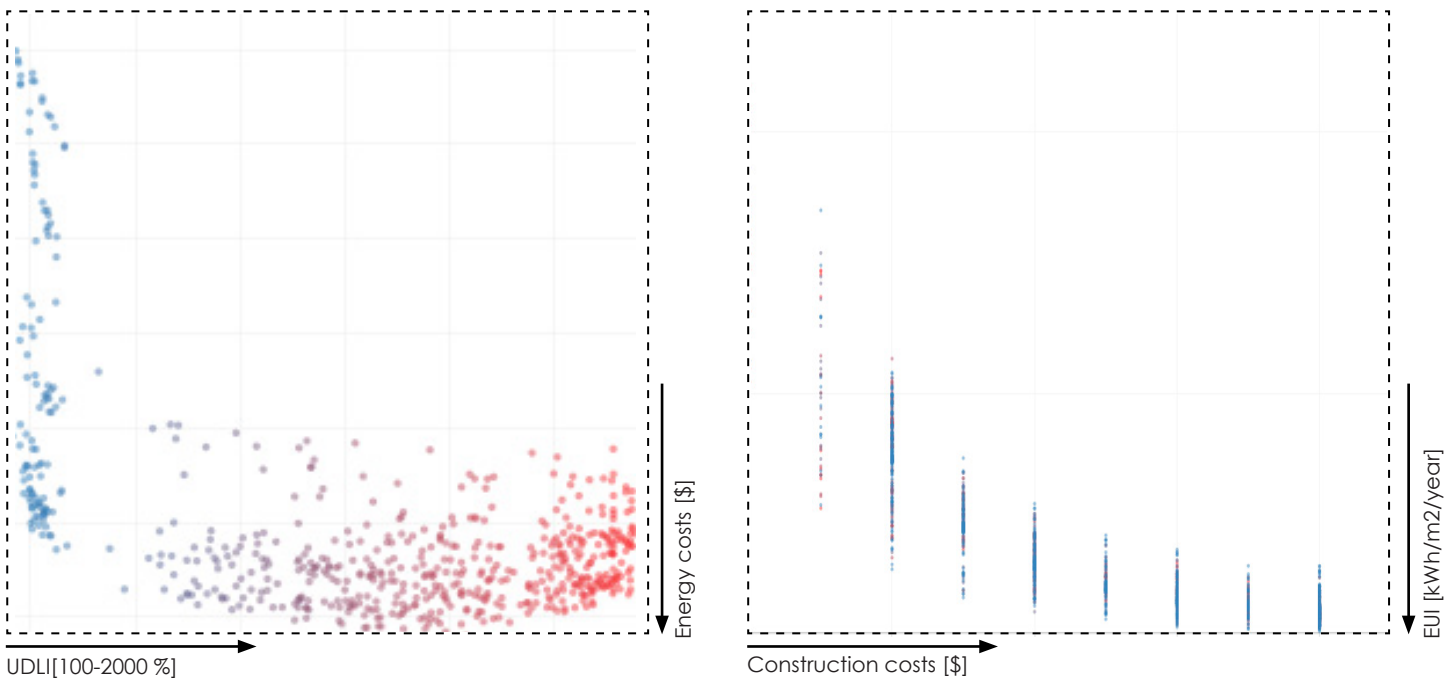


Figure 193. Sensitivity analysis charts and parallel coordinated chart of the selected design

also increased the solar gain raising the cooling demand. This is an interesting turning point of the project, since a first parametric model was proposed with the lowest possible bound set up to 20% due to software limitations. After discussing the possibility of exploring design alternatives with only skylights, a new parametric model was elaborated and all the simulations and optimization were done again. The result was that effectively the highest UDLI average value was achieved by an option with only a 10% of skylights in the roof which later on was selected as a design choice. As deductible from the 3d charts, the aim of the daylight distribution is to be as balanced as possible throughout the whole spatial print, in order to avoid contrasting perceptions between light intensity, ensuring the optimal conditions for the sheltered activity. From the sensitivity analysis chart it can be also observed that there is a direct relation between



5.2.4.3.5 Design decision

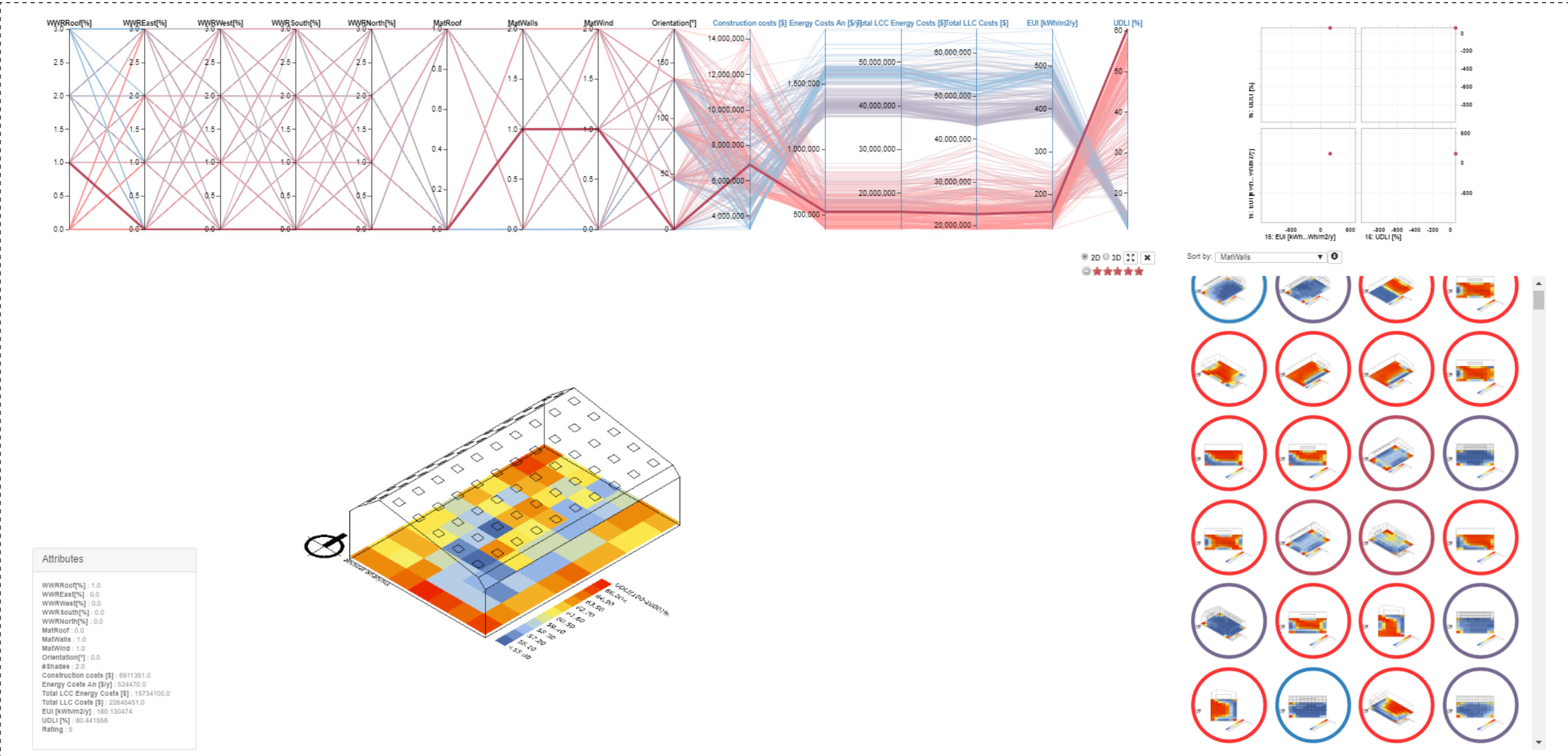


Figure 194. Design exploration, filtering and selection interface

UDLI value and construction costs. Thus, higher UDLI value causes the costs to decrease and From another side, Fig. [194] shows that (as expected) when having less Energy Use Intensity values the costs increase exponentially. This situation is, to a larger degree, caused by the materials that have better thermal properties than others. For the reference option, the material costs are within the mean range, however European practices regard the most expensive material as most feasible. Taking into consideration that the case study is located in Mexico City, one of the most important conditions to be considered is the high temperature. Thus, the energetic criteria is crucial and as a result the mean value materials are the ones that have

been chosen as optimal due to their best behavior for climate control. Higher R-values in the case of the opaque materials and U-values when talking about windows, such materials are normally more expensive and therefore the overall costs increases notably, that is why it can be seen a relation among the cheapest (lightest) materials with a better energy performance. It is also shown that at the same time with the reduction of the EUI the costs tend to decrease because of the possible energy savings. When exploring this options on the on-line platform, the changes made by altering the parameters did not work properly, this could be because of the complexity of the model in comparison with the one of the first stage.

5.2.4.4 Stage 4: Systems

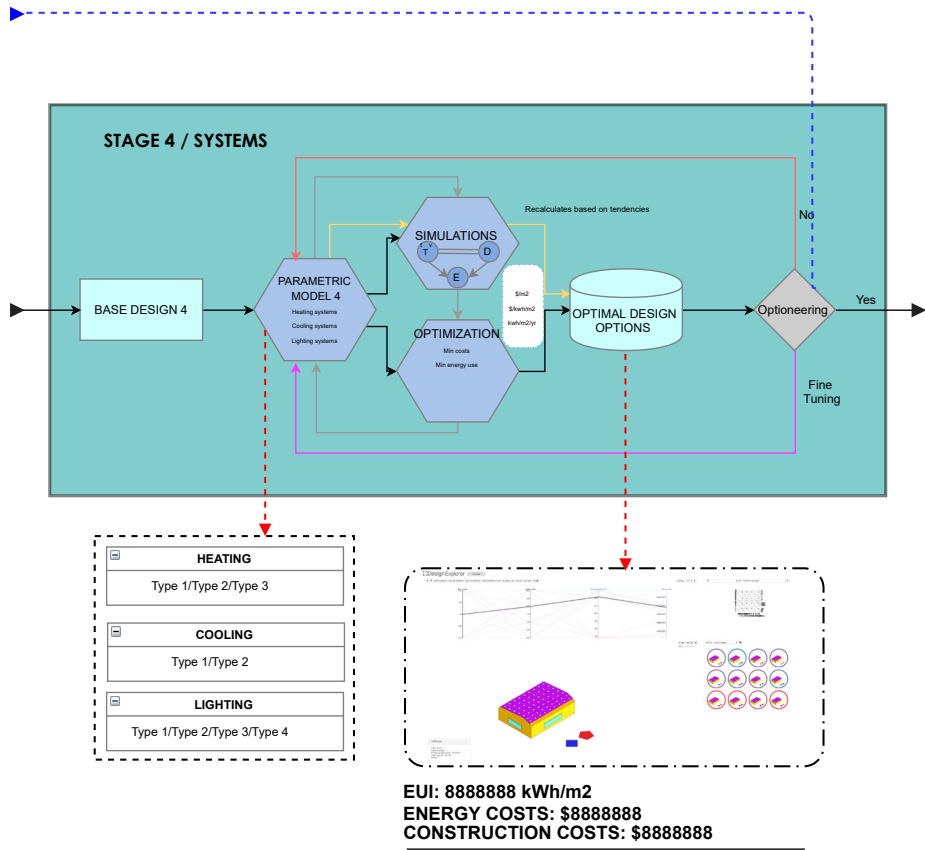
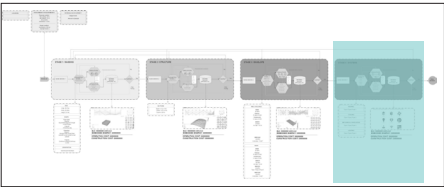


Figure 195. Diagram of the systems stage (Sequential workflow)

The last stage of the process, is a stage in which generally there is more information available, in this way several specific and technical aspects can be analyzed. For the elaboration of the model, the one with the previous characteristics (Stage 3\_Envelope) was kept. Taking this model as a basis, only a set of particular parameters where changed. It is important to mention that sometimes this parameters can be already included in the simulation software such as Honeybee or Archsim, however for instance in this case, a set of customized and general values of HVAC systems were taken into account. Namely a Gas boiler heating system, an Electric baseboard and lastly a Ground heat pump system.

5.2.4.4.1 General description & parametric model

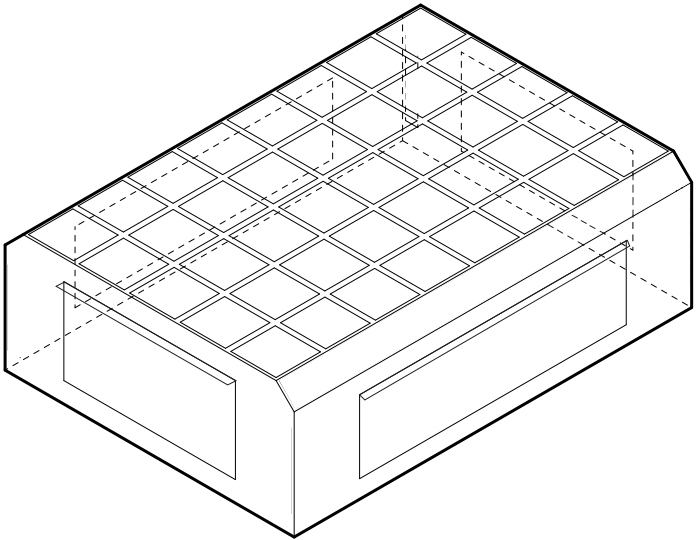


Figure 196. Base model for the systems stage

STAGE 4 / SYSTEMS

OBJECTIVES					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	HOW TO OBTAIN
1	Economic	Minimize cost	\$	N/A	GH + Exel database
2	Climate (Energy)	Minimize energy use (Heating, cooling lighting)	kwh	N/A	Honeybee
3	Aesthetical	Increase aesthetics	N/A	N/A	Design explorer

CONSTRAINTS					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	WHERE TO FIND
1	Climate (Thermal)	Max Indoor Temp	°	25	LEED V4

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vc1	Climate	Cooling systems	Type	Discrete	Direct expansion A/C, Ground Source Heat Pump	1	2
vc2	Climate	Heating systems	Type	Discrete	Boiler Heating, Electric Baseboard, , Ground Source Heat Pump	1	3
vc3	Climate	Lighting systems	Type	Discrete	Always on, Manual switch, Automate switch, Automate dimming	1	4
FIXED							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
fc1	Climate	Mecanichal ventilation	Type	Boolean	1	1	1
fc2	Climate	Heat Recovery	Type	Boolean	1	1	1
fc3	Climate	Infiltration Rate	m3/m2	Boolean	1	1	1
fc4	Climate	No natural ventilation	Type	Boolean	1	1	1

Figure 197. Objectives, constraints and parameters for the systems stage

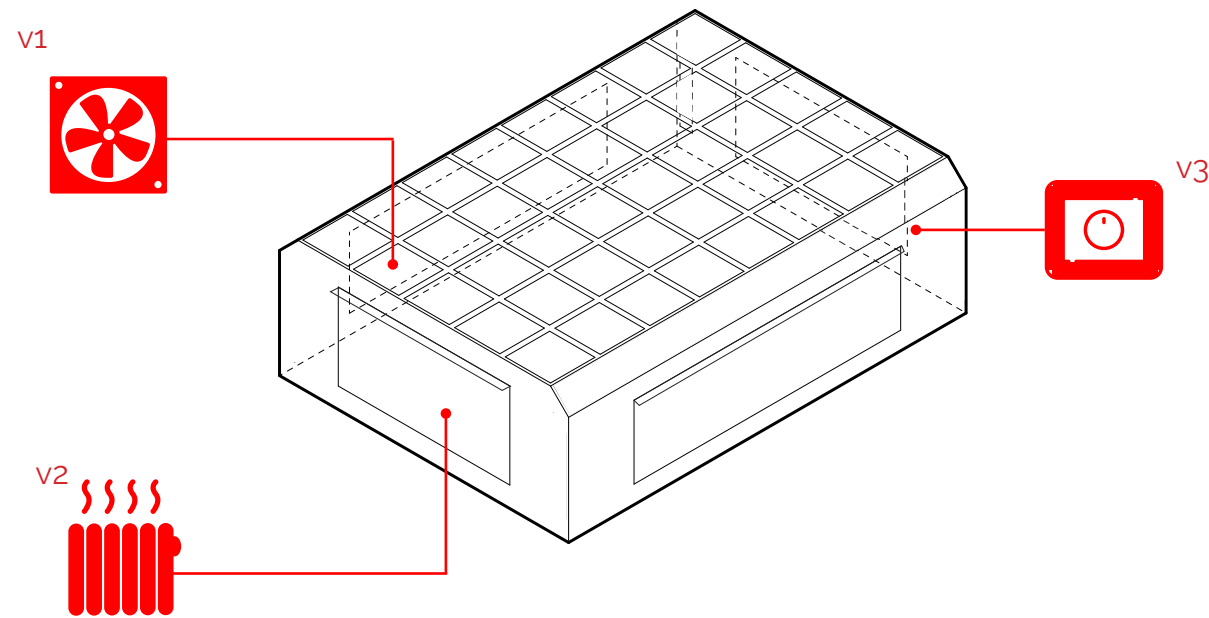


Figure 198. Variable parameters diagram for the fourth stage

The selection of these was based on the notable difference in performance (considering COP as a measure) and their costs.

From the other side, the lighting systems were already incorporated inside the Honeybee Daylight platform, however only some of them were considered based on the basis of having a significant difference in terms of energy performance and costs. For this last stage, the majority of the design options are already fixed, however, the designer can always go back and change the design in any of the previous stages. This stage is specially complex because in order to produce a parametric model it is necessary to have a deep knowledge about the settings and requirements of these systems, besides it is also important to note that not all the systems included in the software default database are applicable to certain locations which is the case of the case study in Mexico City.

In order to be able to identify the changes (because they are not evident in this stage) placing geometric shapes with colors and a text describing the specific systems was proposed. In this way, blue was assigned to the HVAC systems and Red to the Lighting systems. The polygons increase their sides according to the sophistication of the selected option.

Finally, complexity could be added in this stage, by adding more active systems such as solar panels, special shading systems and of course natural ventilation strategies which for the sake of this investigation and the time being were excluded from the analysis.

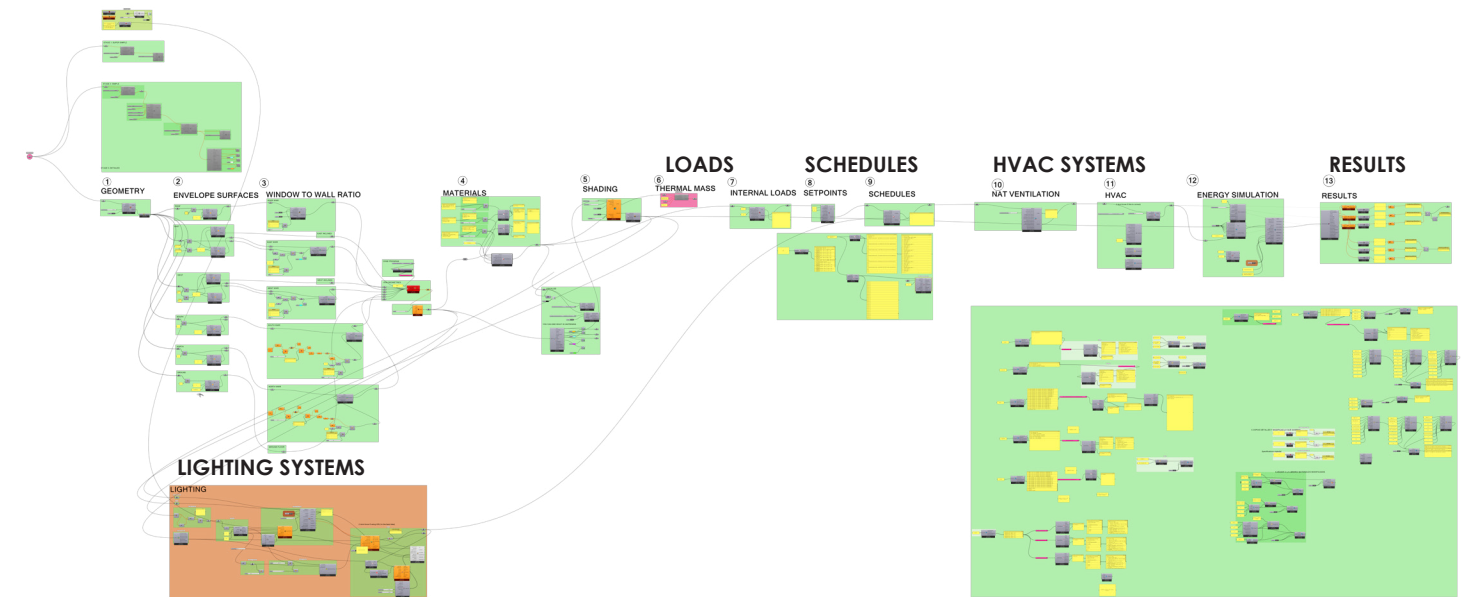


Figure 199. Grasshopper script for the energy simulations

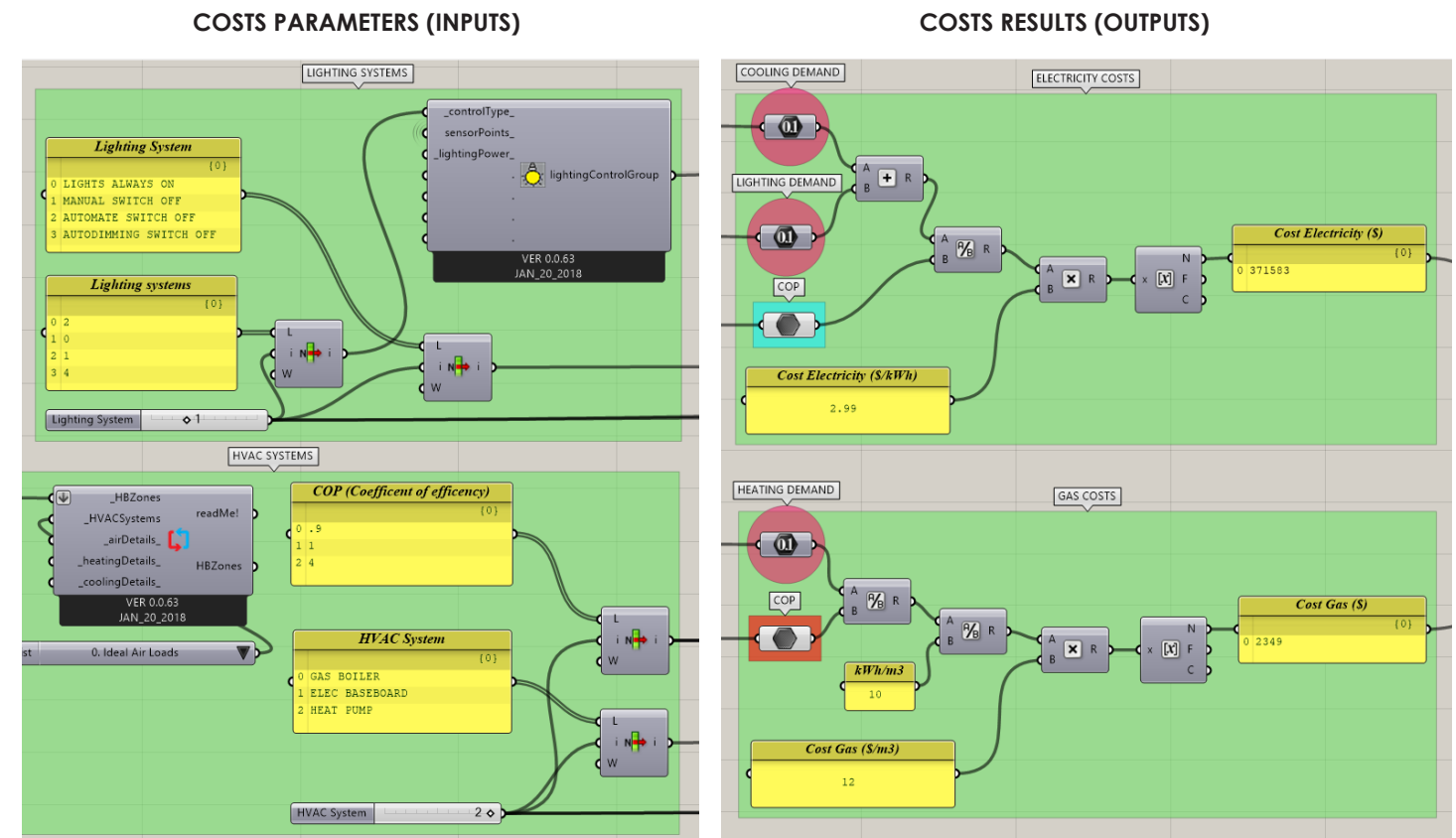


Figure 200. Inputs and results of the costs calculations for the active systems



5.2.4.4.2 Optimization results

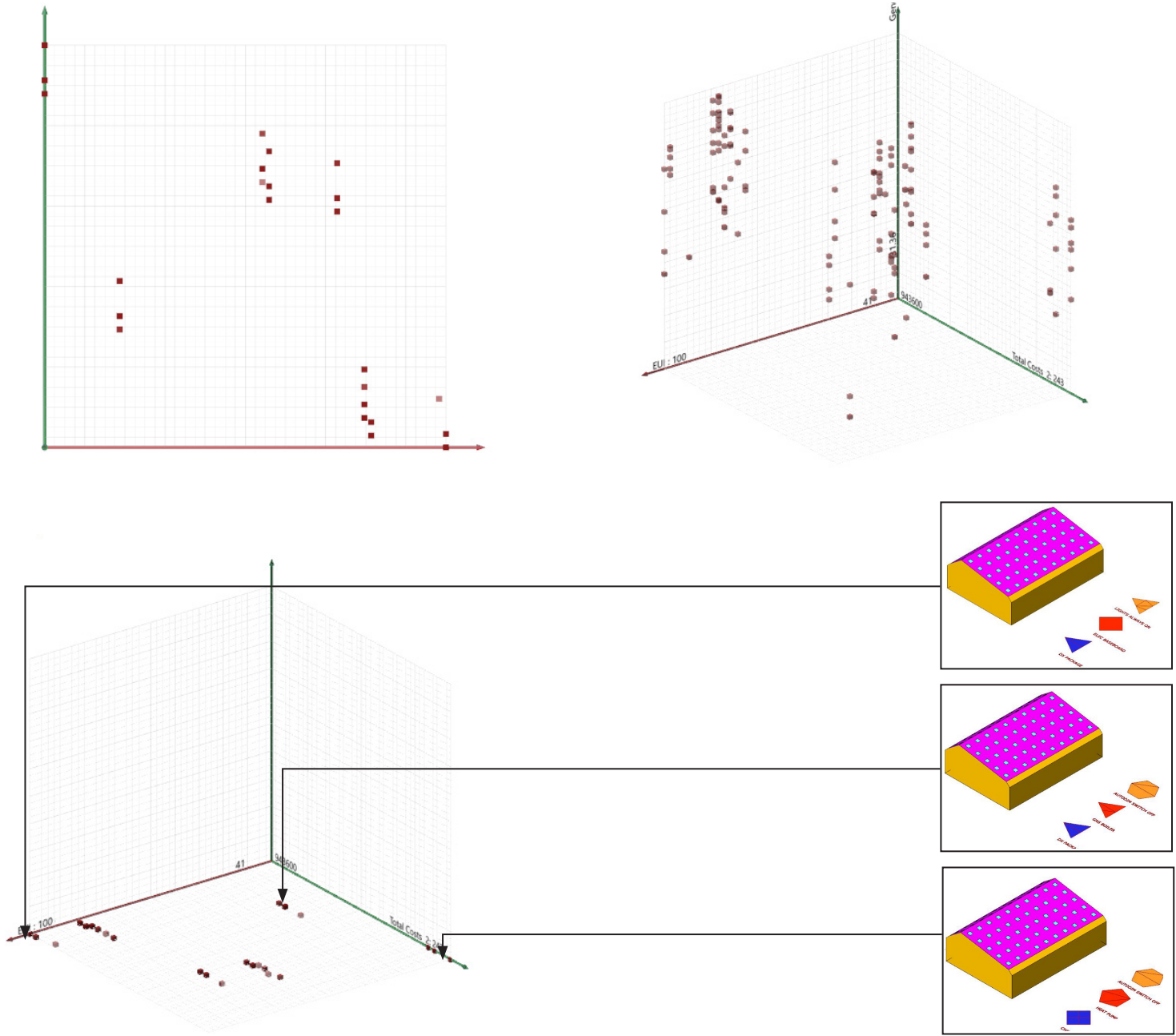
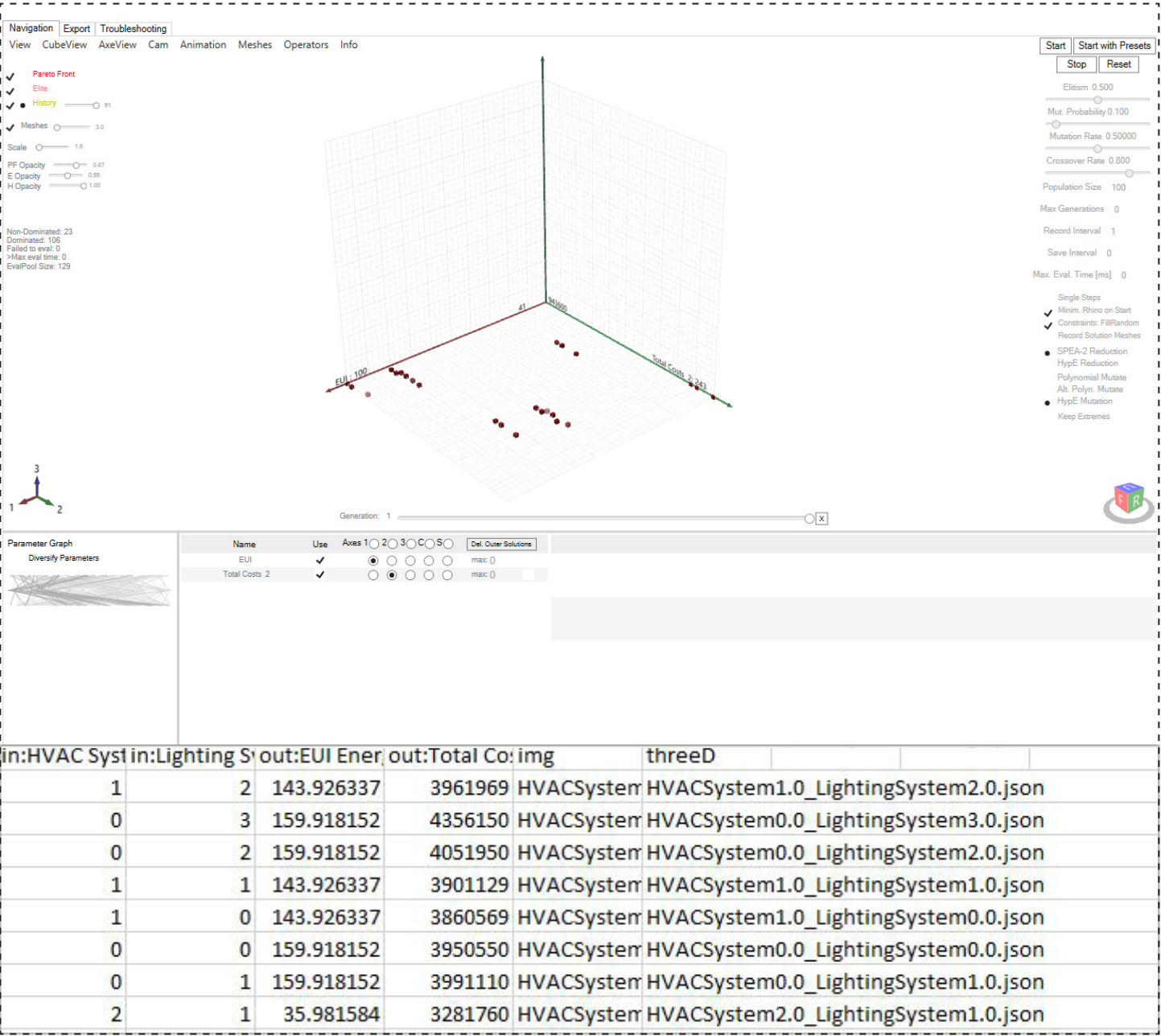


Figure 202. 2D charts of the Octopus optimization results

STAGE	NUMBER OF PARAMETERS	NUMBER OF GENERATIONS	REDUCTION	DOMINATED / NON DOMINATED	COMPUTATIONAL TIME
	3 Parameters	1 Generations 100 Population	24-24	23 Non-dominated 106 Dominated	5 Hours

Figure 201. (Up) 3D chart of Octopus optimization results. (Down) Data organization in a csv. file

Due to the fact that for this specific case, only a few alternatives were considered, the simulation and the optimization processes were completed in a relative short time. However, this stage was particularly difficult, since in order to propose the systems that were going to be evaluated, it was necessary to have a highly technical background about the performances, requirements and the costs that they could involve. This stage required a total computational time of about 5 hours, handling a total of three parameters, achieving only one generation until the optimizer stopped automatically because the amount of parameters and design options was relatively small . The considered optimization, aims for revealing the interdependency between the costs of the systems and

5.2.4.4.3 Design optioneering results

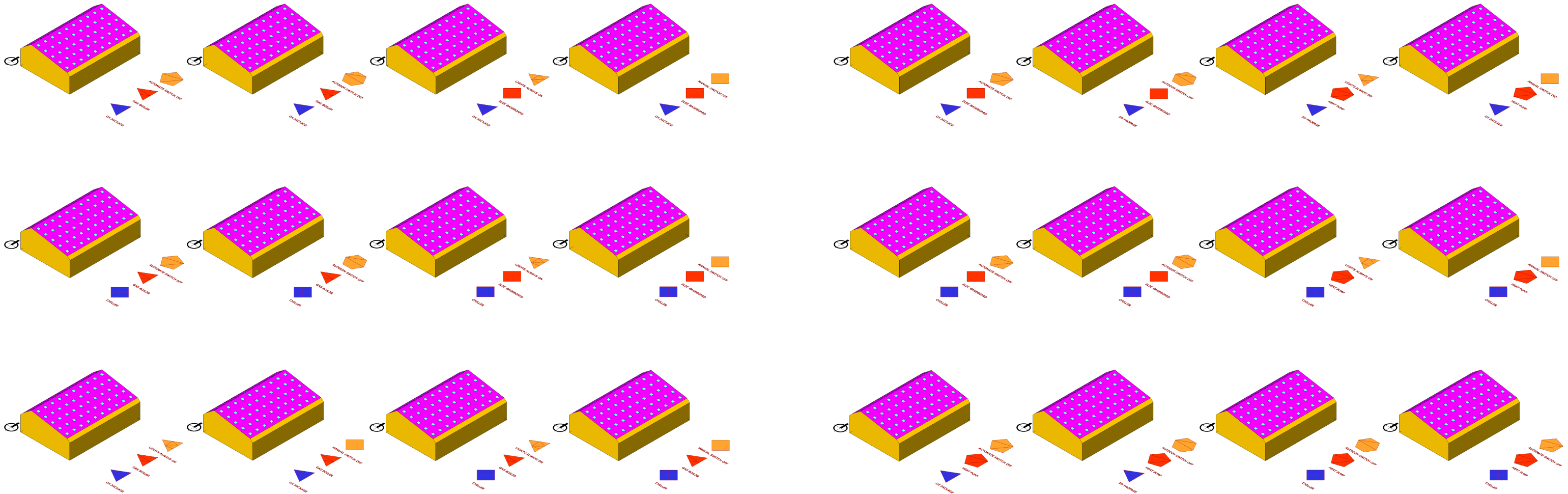


Figure 203. Images of the design alternatives iterated by the optimizer

5.2.4.4 Results & observations

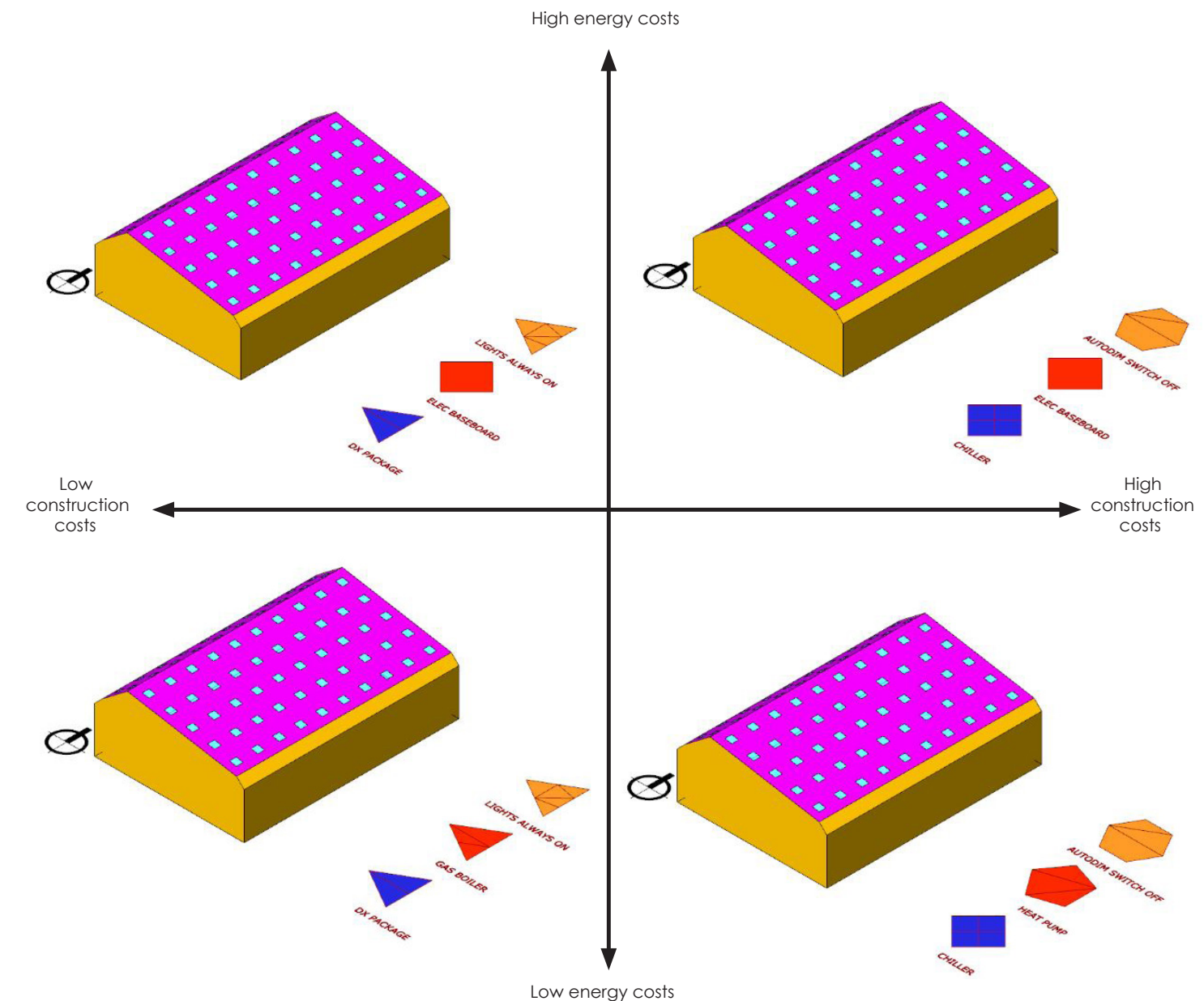


Figure 204. Sensitivity analysis and comparative of the designs general performance tendencies

the Energy Use Intensity, implementing the previously defined active systems and combining them. After reviewing the results from the optimization it can be said that for this particular stage since the short amount of possibilities, the design selection process will be more based on a design exploitative approach instead on an optimized one. This of course with the addition of more technical aspects ( which for these kind of systems could be considerably high) can required a more sophisticated oncoming. However for the aim of this thesis the specific interest was in finding a balanced combination among the more common options applied to this kind of building in this very specific location.

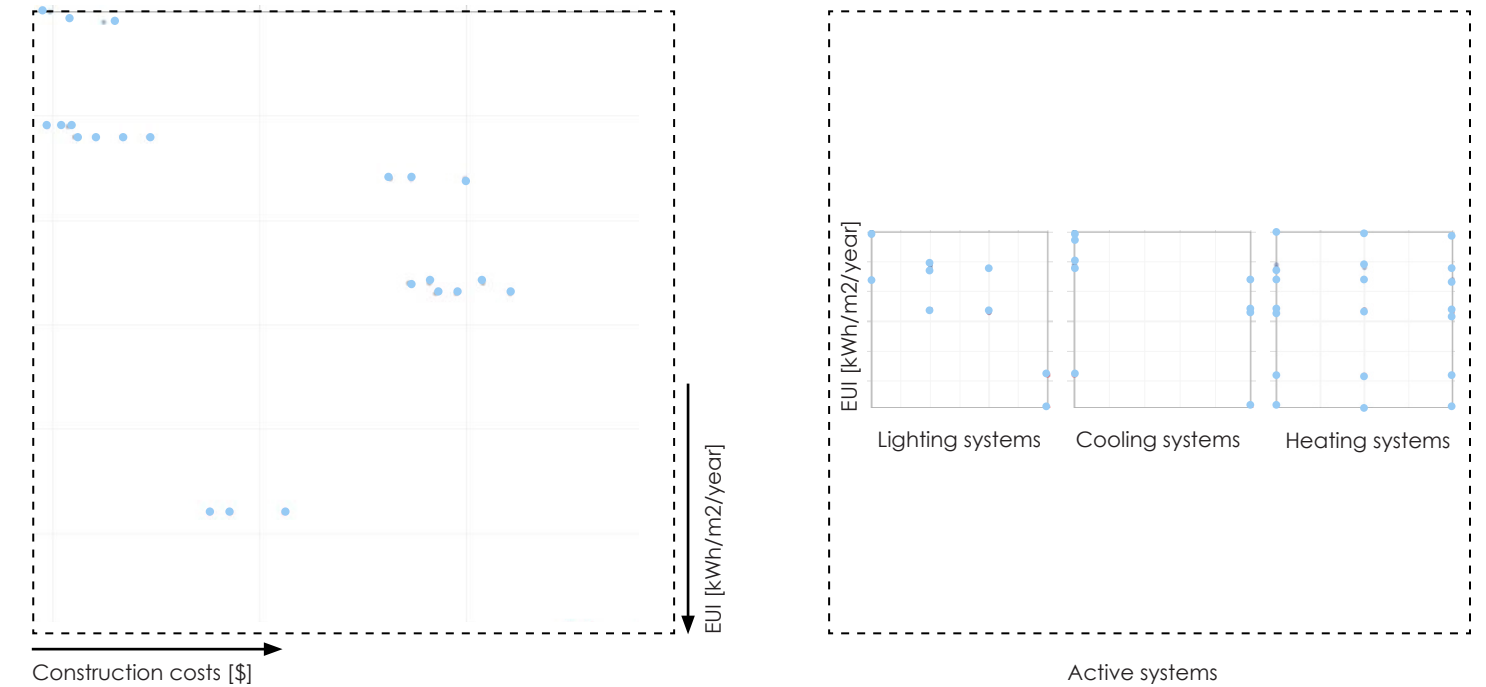


Figure 205. Sensitivity analysis charts and parallel coordinated chart of the selected design

To be able to communicate the changes of this different systems inside the design exploration platform it was necessary to develop a visual code based on geometrical shapes and colors, in this way the more sides the figure has the more sophisticated is the system applying to the three of them. Once again, as shown by the graphs above, there is a direct relation among the costs of the systems and the Energy Use Intensity, when the firsts ones go higher, the second one decreases and vice-versa. From the results it can also be concluded that the cooling system has considerably more



5.2.4.4.5 Design decision

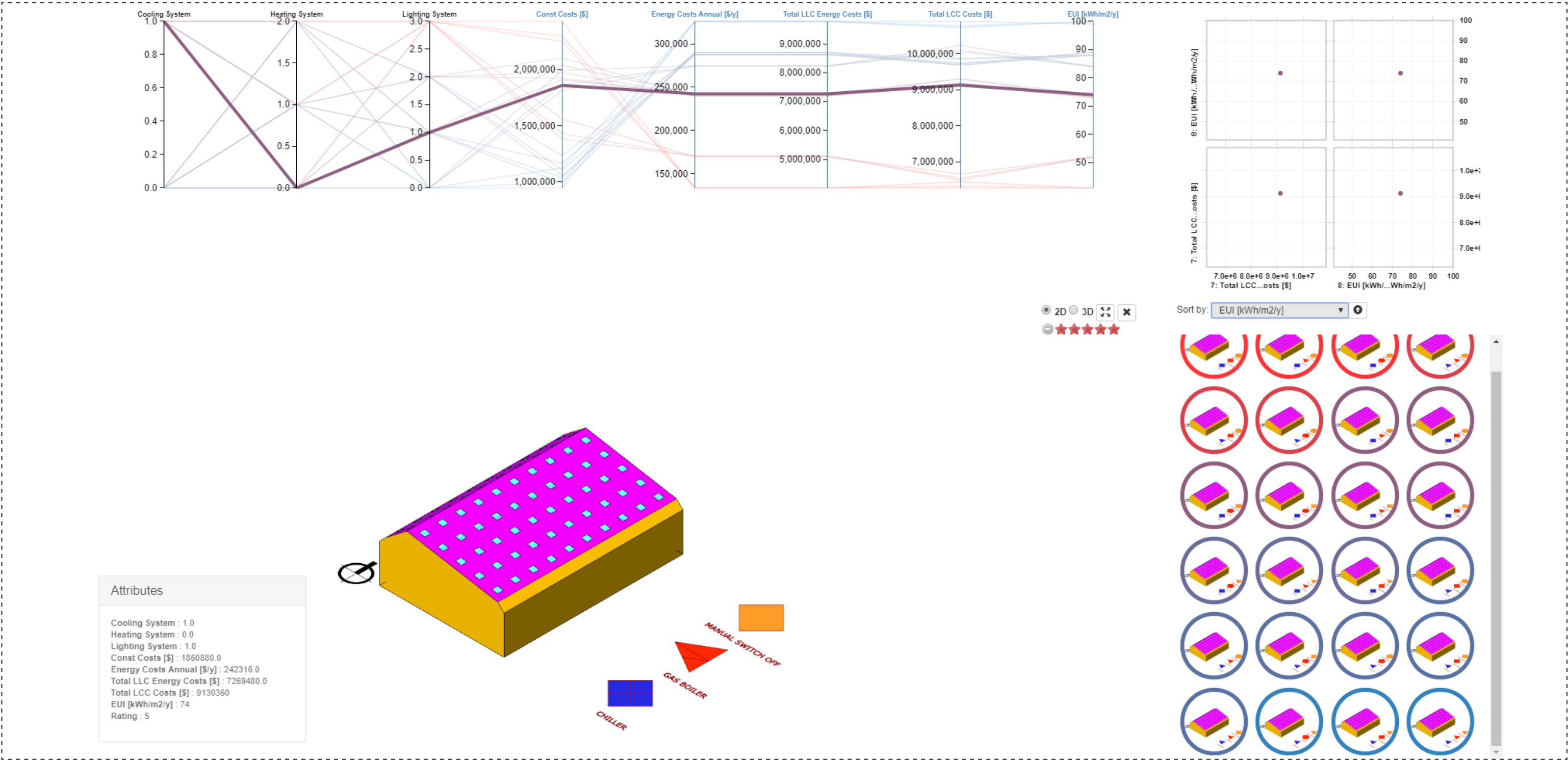


Figure 206. Design exploration, filtering and selection interface

achieve savings around the 50% of the EUI and therefore the energy costs. For the selection of the active systems for the design, a balanced intention between costs and energy performance was considered. As seen in Fig:[206] all the filters of the design space were set first of all to the simplest heating system because as described before due to the climate conditions is almost not required. Then the filters were applied to the middle of the performance indicators to be able to choose a cost-effective balanced design alternative.

5.2.4.4 Final design Sequential strategy results

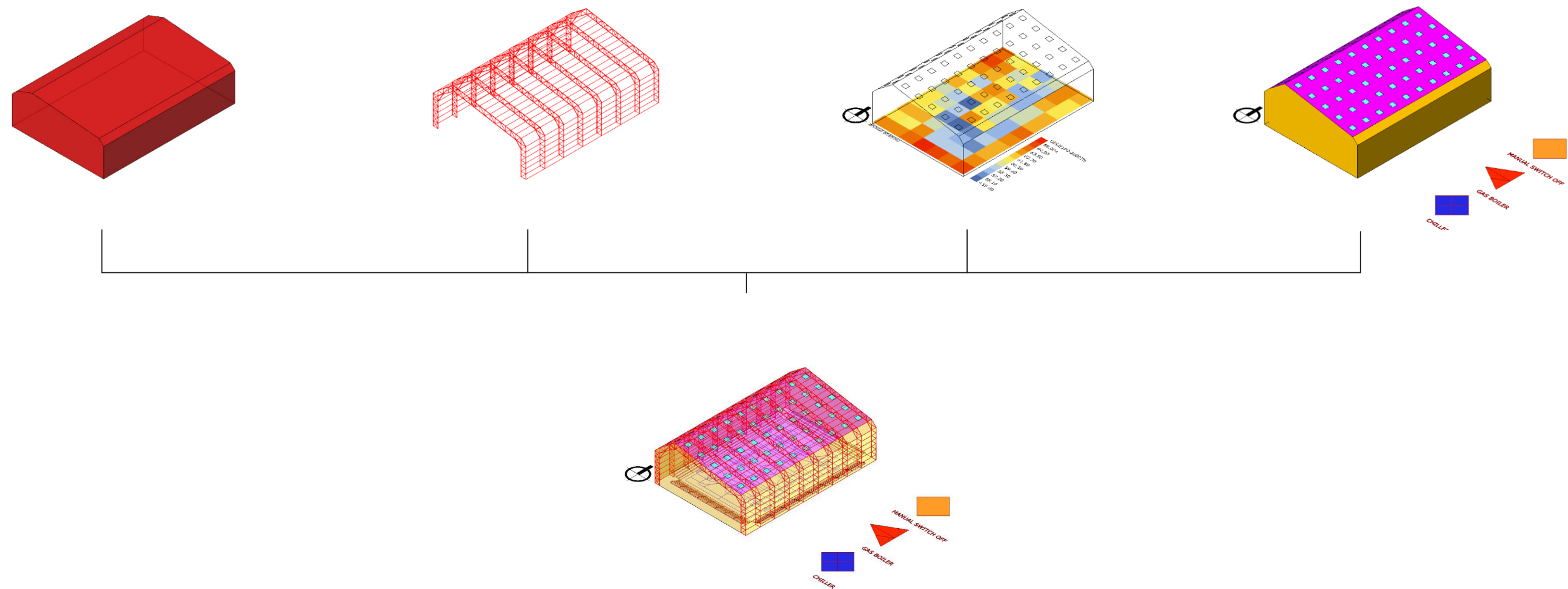


Figure 207. Final overview of the design choices results

At the end of this strategy once all the stages were held a final integrated design was achieved by looking for optimal - well balanced decisions in terms of energy performance in combination with costs effectiveness coupling personal and design choices along the selection of the different design alternatives.

It was interesting to realize how the different stages can shape or define the outcome of a building, it is important to mention that design space should be more open on each of the stages to have the possibility of exploring more design options instead of strictly narrow it down the options to a limited number.

It is important to mention that for this strategy, a basic knowledge about how to use Grasshopper is needed when modifying and re-instating the parameters to get the base model of the next subsequent stage or to make fine-tuning changes on the model. Therefore this process has to be more a collaboration among the designer of the parametric model and the person involved in the design decisions all along the Strategy development.

5.2.5 COMPUTATIONAL WORKFLOW - INTEGRATED STRATEGY

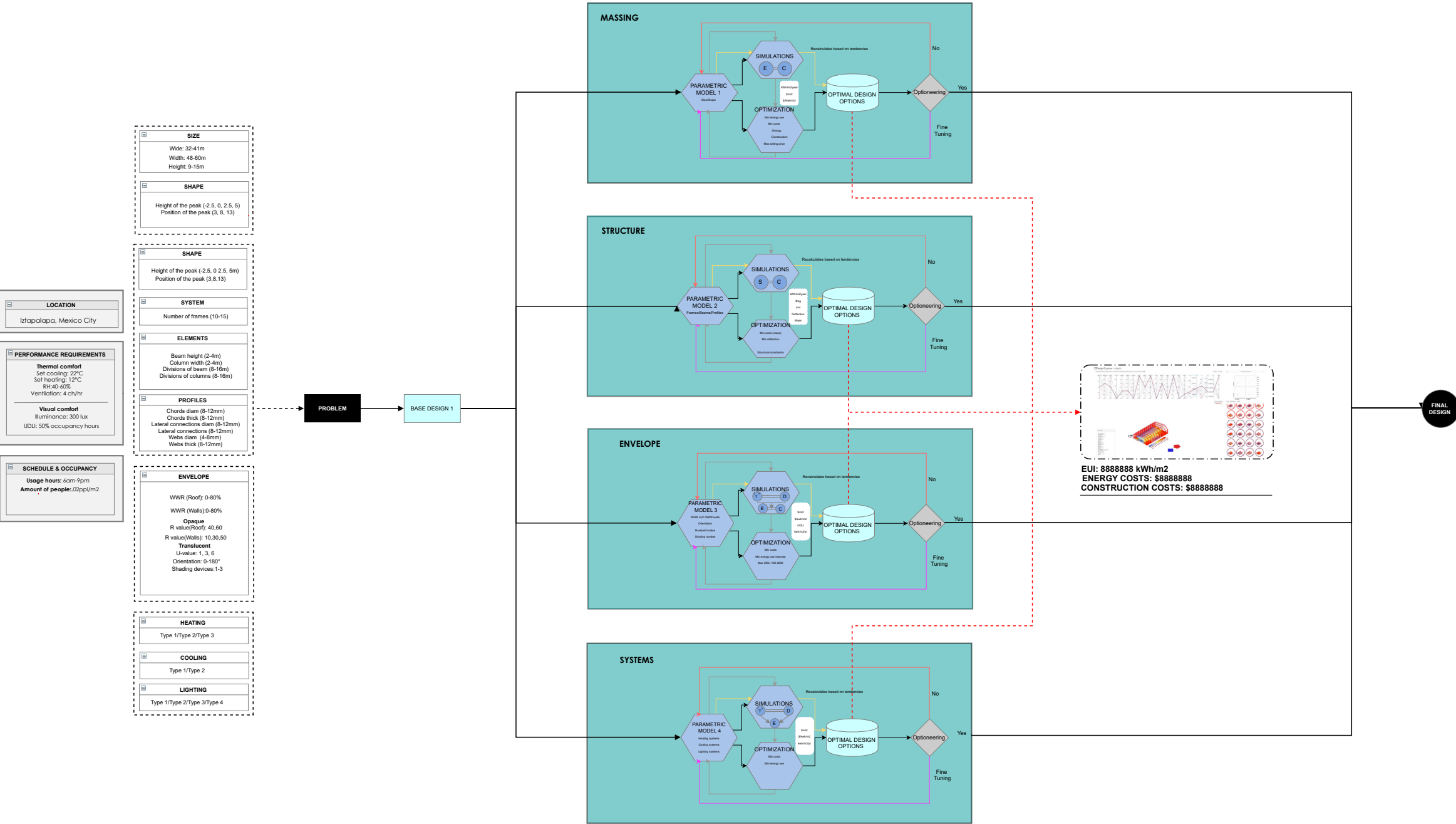


Figure 208. Integrated strategy detailed workflow



5.2.5.1 INTEGRATED STAGE

5.2.5.1.1 General description & parametric model

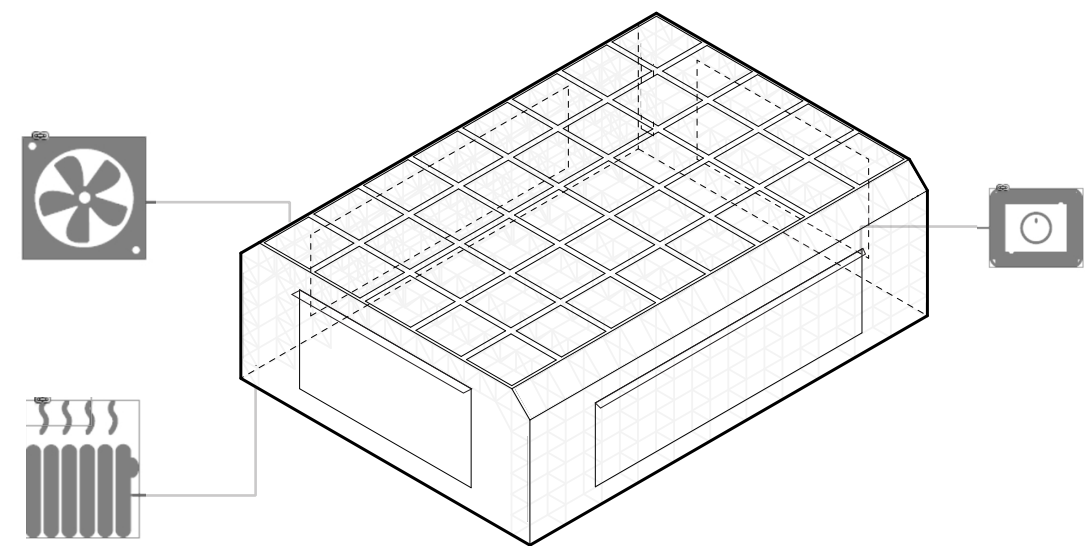


Figure 209. Base model for the Integrated strategy

This second workflow strategy consist of realizing the same procedure as the previously revised method, however for this “unique stage” all the information is integrated as once, as it can be seen in the base model shown by Fig. [209]

When organizing the parametric model for this strategy, there was an important limitation when defining the overall procedure because of the large amount of parameters and the maximum allowed number of variables permitted by Colibri and the Design explorer interface.

It is also important to mention that the due to the large names of the produced files (due to the amount of parameters) there might be computational complications when talking about compatibility so shorts names and abbreviations should be considered when naming the performance indicators and the diverse variables. In this way and with the aim of exploring the overall relation among the diverse disciplines described during the previous chapters and explored in the Sequential strategy, a minimum of two variables was considered inside the

INTEGRATED STAGE

OBJECTIVES					
Nº	DISCIPLINE	NAME	UNIT	RANGE/VALUES	HOW TO OBTAIN
1	Economic	Minimize cost	\$	N/A	GH + Exel database
2	Climate (Energy)	Minimize energy use (Heating, cooling lighting)	kwh	N/A	Honeybee
3	Climate (Daylight)	Maximize UDI 100-2000	%	N/A	Diva
4	Aesthetical	Increase aesthetics	N/A	N/A	Design explorer

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
v1	Geometry	Width	m	Continuous	32 to 41	3	4
v2	Geometry	Depth	m	Continuous	48 to 60	3	4
v3	Geometry	Height	m	Continuous	9 to 15	3	3
v4	Geometry	Peak height	m	Continuous	-2.5 to 5	2.5	4
v5	Geometry	Location of the peak	-	Discrete	3, 8, 13	1	3
FIXED							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
f1	Location	Location in Plot	N/A	N/A	N/A	N/A	N/A

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vs1	Structural	Beam depth	m	Continuous	2 to 4	2	2
vs2	Structural	Column depth	m	Continuous	2 to 4	2	2
vs3	Structural	Chord diameter	mm	Continuous	250 to 400	10	15
vs4	Structural	Chord thickness	mm	Continuous	8 to 16	1	15
vs5	Structural	Web diameter	mm	Continuous	150 to 300	10	15
vs6	Structural	Web thickness	mm	Continuous	4 to 12	1	4
vs7	Structural	Purlins diameter	mm	Continuous	200 to 400	10	20
vs8	Structural	Purlins thickness	mm	Continuous	8 to 16	1	8
vs9	Structural	Divisions beam	#	Continuous	8 to 16	1	8
vs10	Structural	Divisions column	#	Continuous	8 to 16	1	8
vs11	Structural	# Frames	#	Continuous	10 to 15	1	5
FIXED							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
fs1	Structural	Material	N/A	Discrete	Steel*	N/A	1
fs2	Structural	Circular section	N/A	Discrete	Hollowed circular	N/A	1

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vc1	Geometry	Orientation	°	Discrete	0 to 180	45	4
vc2	Climate	Walls (N,S,E,W)					
vc3	Climate	WWR	%	Continuous	0 to 80	20	4
vc4	Climate	WWPVR	%	Continuous	0 to 80	20	4
vc5	Climate	Opaque	R-Value	Discrete	R1, R2, R3	1	3
vc6	Climate	Transparent	U-Value	Discrete	U1,U2,U3	1	3
vc7	Climate	# Shadings	#	Continuous	1 to 3	1	3
vc8	Climate	Roof					
vc9	Climate	WWR	%	Discrete	10,30,50,80	1	4
vc10	Climate	Opaque	R-Value	Discrete	R1, R2	1	2
vc11	Climate	Transparent	U-Value	Discrete	U1,U2,U3	1	3

PARAMETERS							
VARIABLES							
Nº	DISCIPLINE	NAME	UNIT	TYPE	RANGE/VALUES	STEP SIZE	# OF CHOICES
vc1	Climate	Cooling systems	Type	Discrete	Direct expansion A/C, Ground Source Heat Pump	1	2
vc2	Climate	Heating systems	Type	Discrete	Boiler Heating, Electric Baseboard, , Ground Source Heat Pump	1	3
vc3	Climate	Lighting systems	Type	Discrete	Always on, Manual switch, Automate switch, Automate dimming	1	4

Figure 210. Objectives, constraints and parameters for the integrated strategy

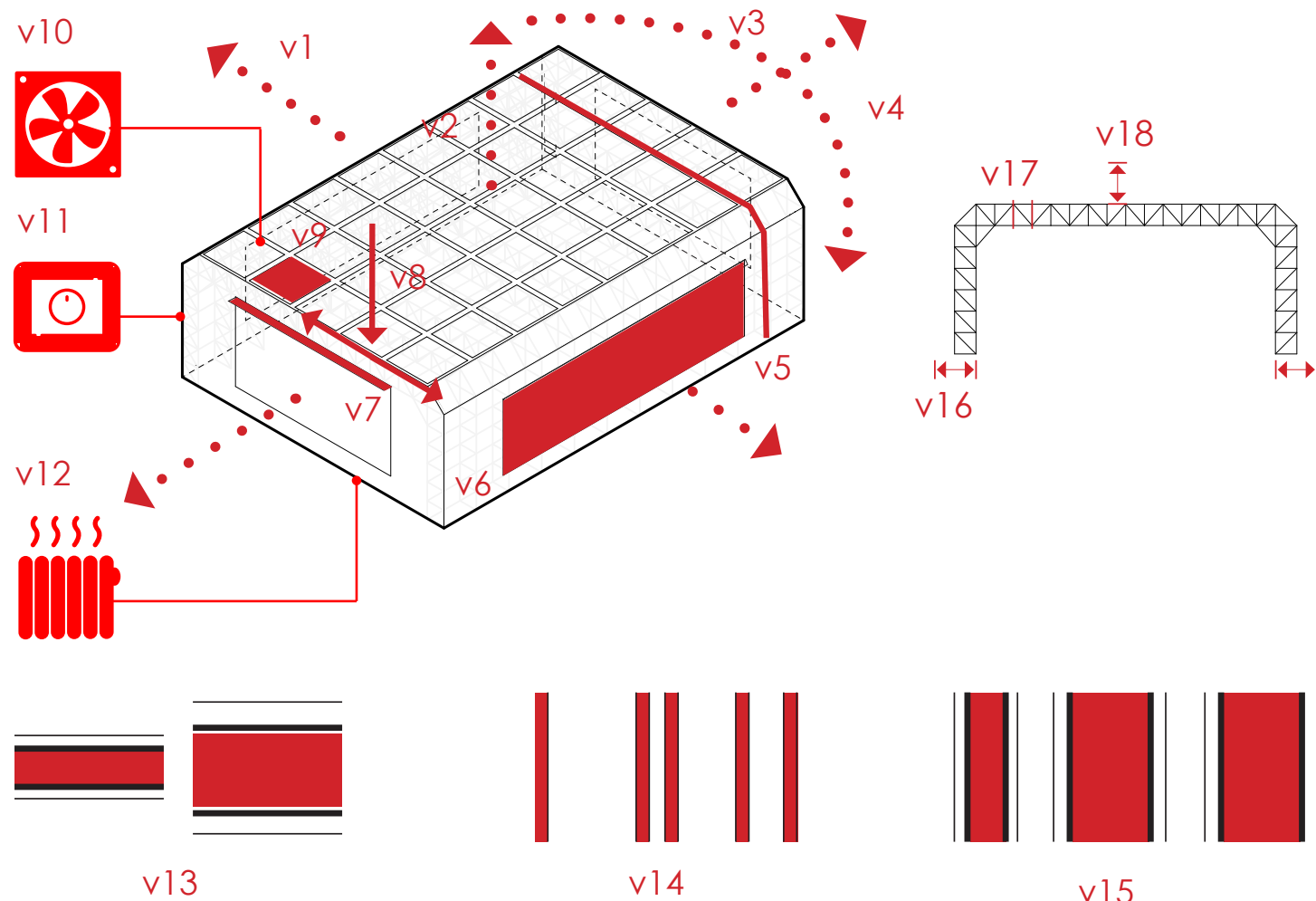


Figure 211. Base model for the integrated strategy

parametric model. Due to the large amount of values regarding the envelope, the window to wall ratio of all the walls (north, east, west and south) was combined in a single parameter, having the same possibility to have variations without any window to wall ration on its walls. Besides, the heating system was removed, leaving only the option of having a Gas boiler and only being able to change the cooling system.

The same geometric parametric from the previous strategy was utilized, however, for this method all the different “sub-sections” of it where linked and coupled to later on realize the optimization and the design exploration of design alternatives. Nonetheless all the “sub-models” where linked, the simulation and optimization procedures ran in parallel.

Four objectives were considered for the optimization namely, minimize construction costs, maximize UDLI and maximize profit in order to have a balanced decision as a final output. The displacement for the structure model was consider only as a constraint.

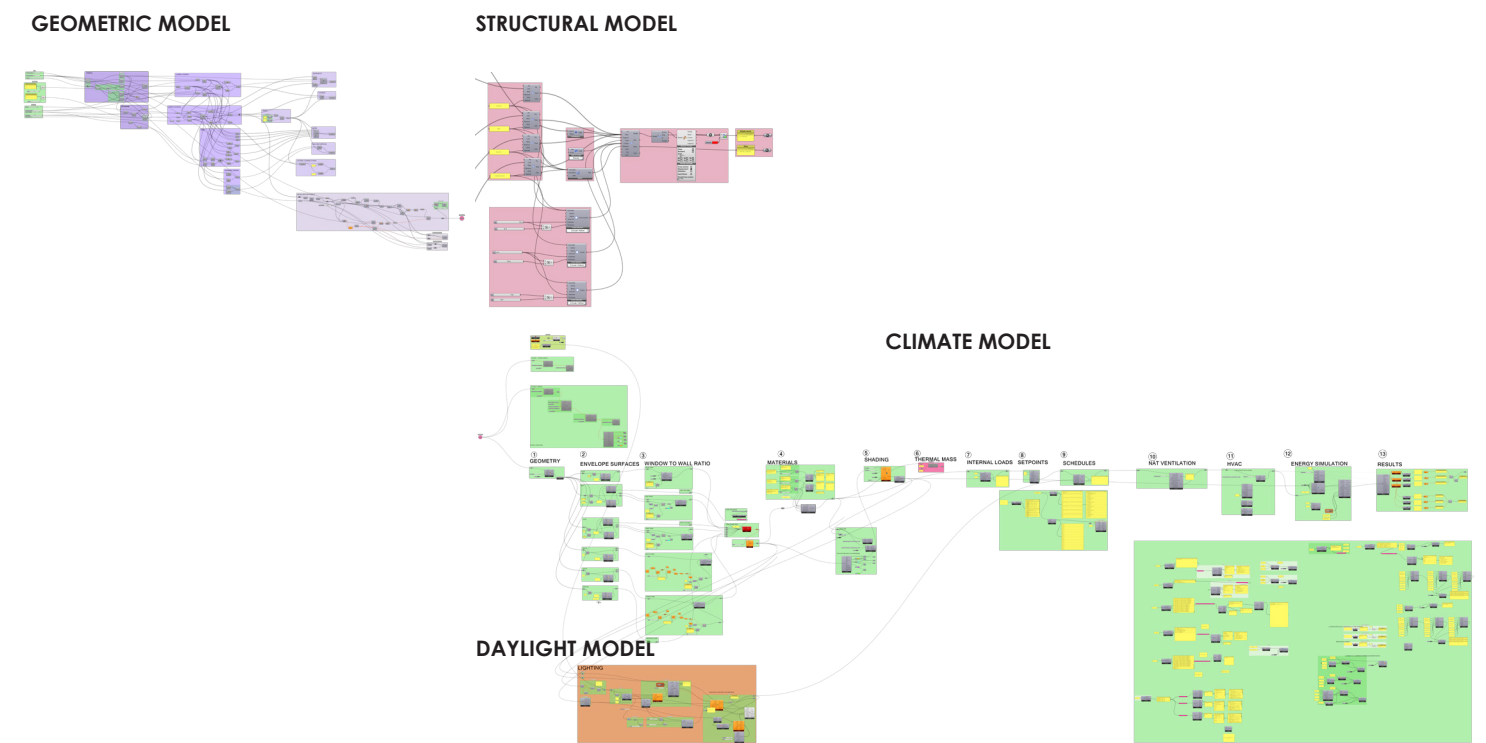


Figure 212. Base model for the integrated strategy

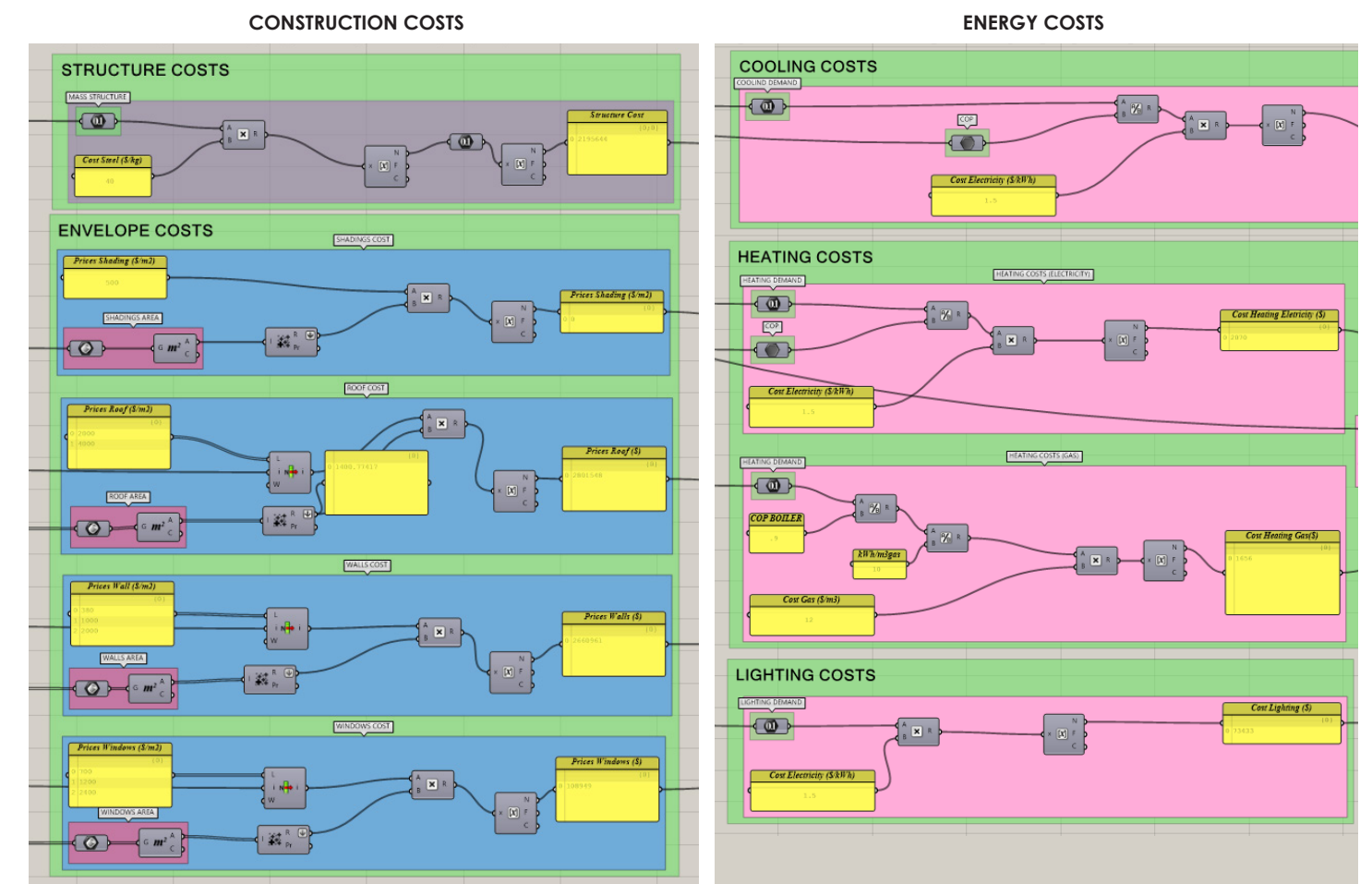


Figure 213. Cost parameters Integrated strategy



5.2.5.1.2 Optimization results

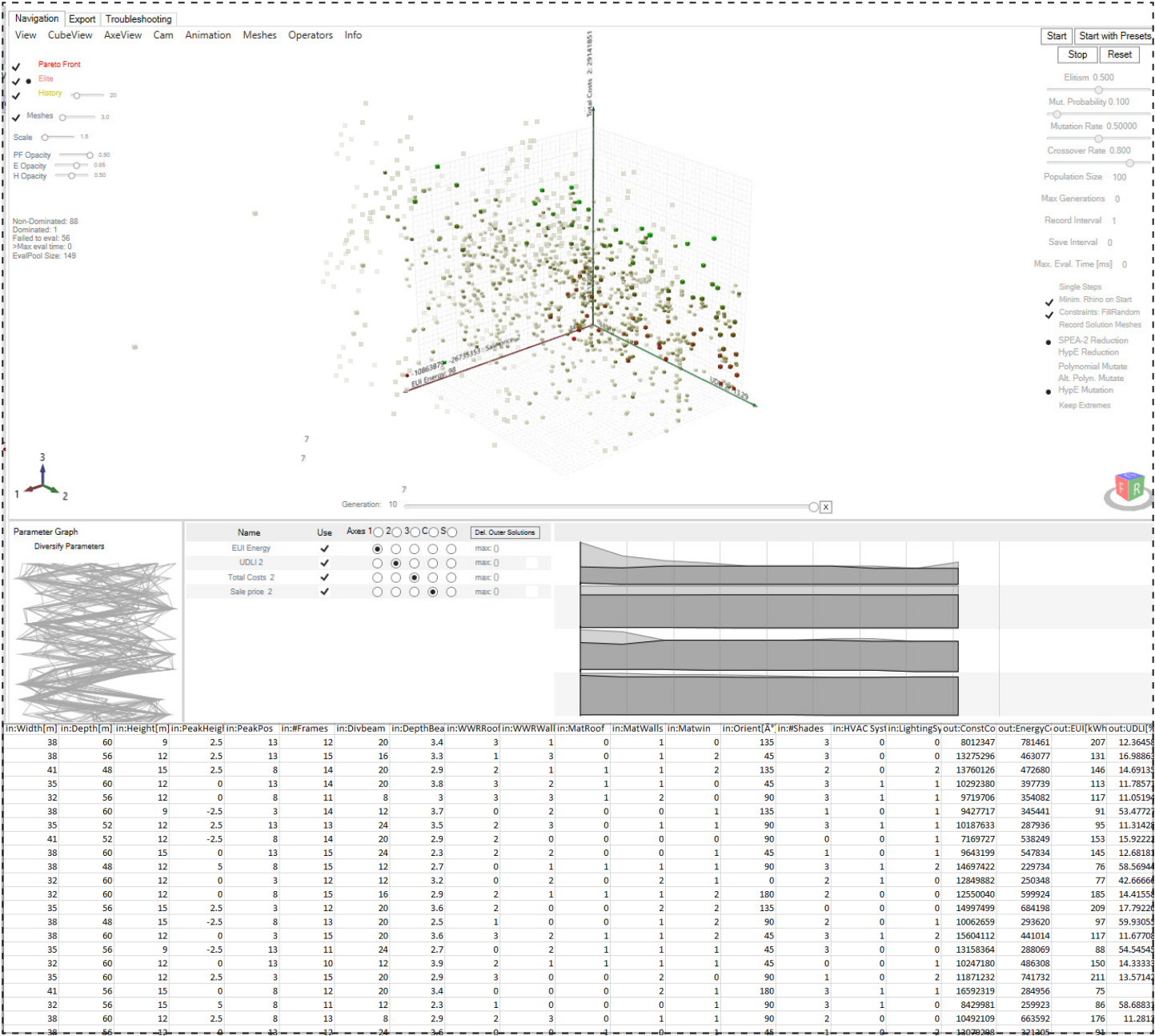


Figure 214. 2D charts of the Octopus optimization results

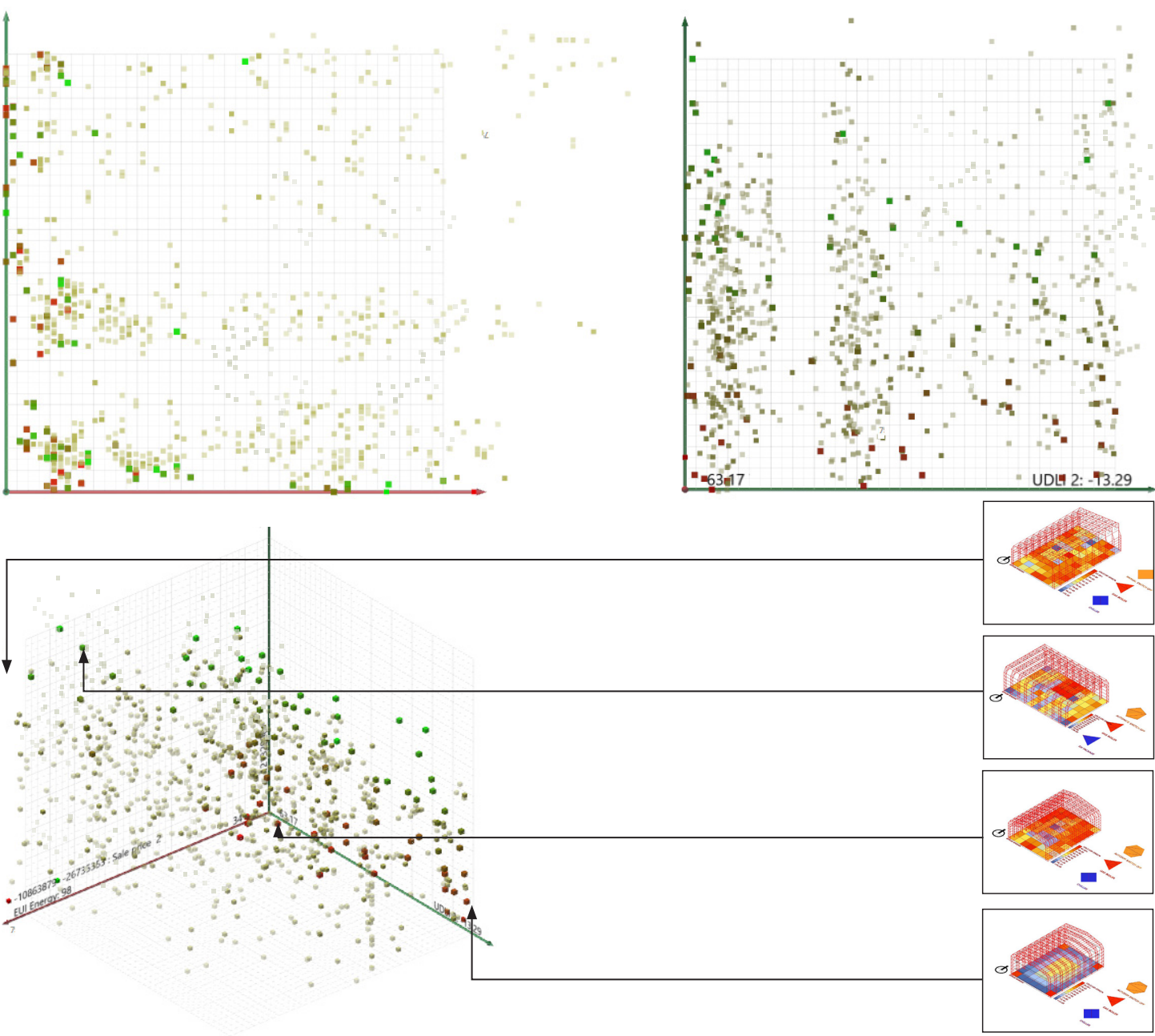


Figure 215. 2D charts of the Octopus optimization results

For this multi-objective and multi-disciplinary optimization process, a high amount of parameters were involved. Including, structural calculations in combination with daylight and energy demand simulations. Therefore, this process demanded for one side a considerable high computational power and from another a large amount of time to produce enough design alternatives. For this purpose, a robust hardware was utilized (Desktop Dell, 16 GB). Conducting the entire process remotely by utilizing the Team viewer application linked to one of the computers inside the VR lab at the TU Delft Faculty of Architecture.



5.2.5.1.3 Design optioneering results

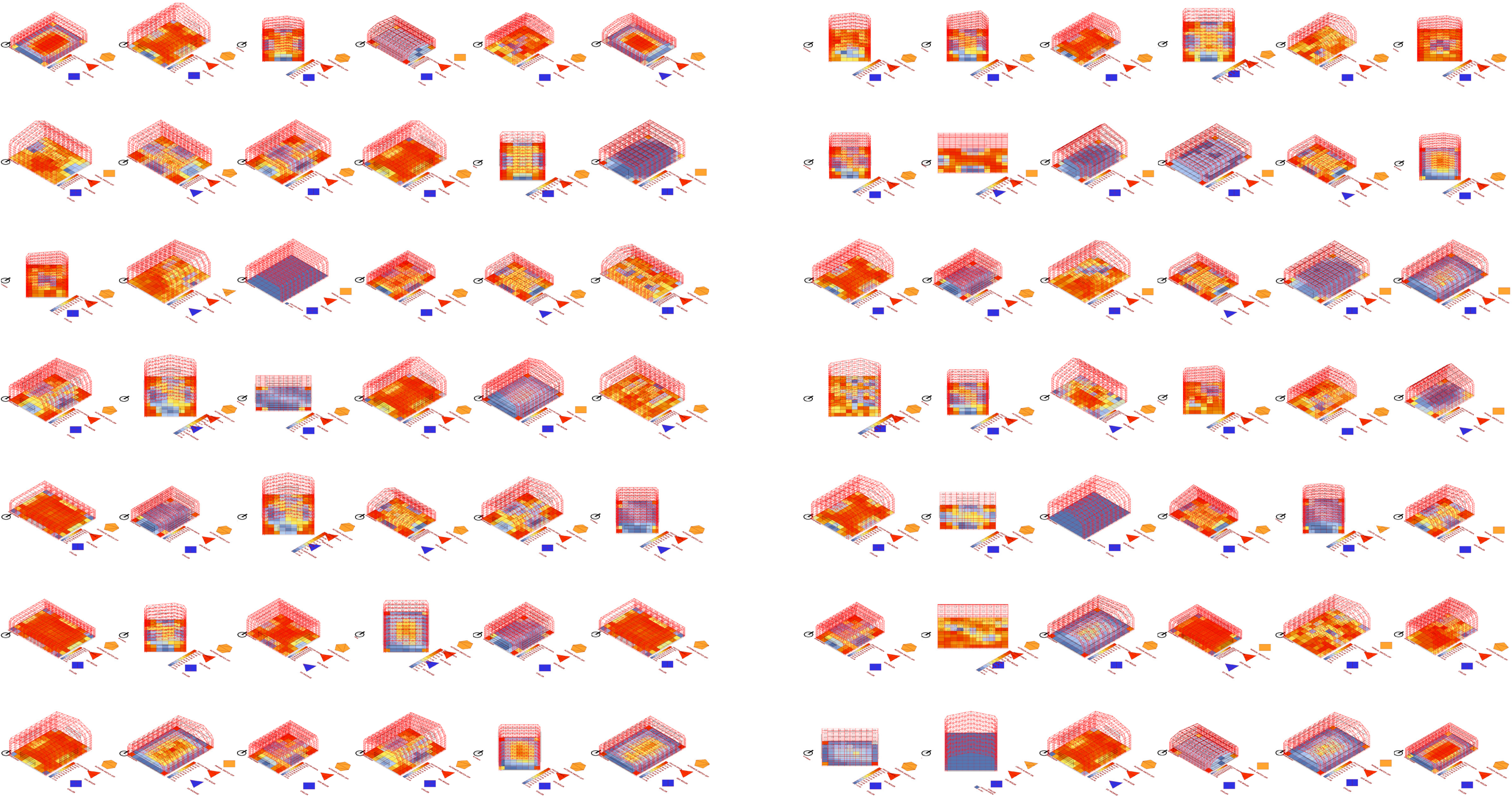


Figure 216. Images of the design alternatives iterated by the optimizer



5.2.5.1.4 Results & observations

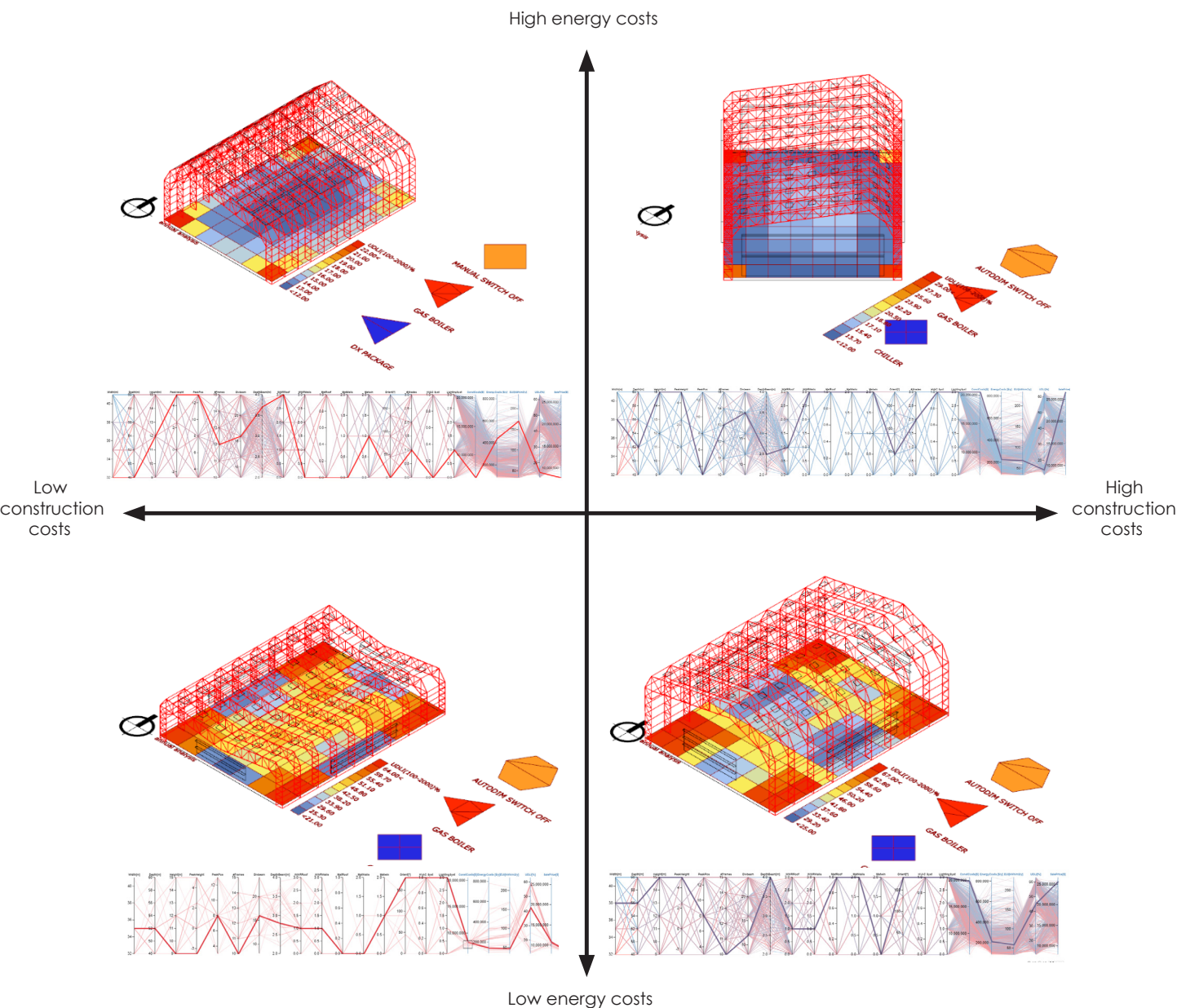


Figure 217. Sensitivity analysis 2D charts

Four objectives were held, using the 3 axis and a color scale for the “maximize profit” objective as it can be observed, logically the options that represent the worst profit are the ones closer to the origin point (utopia point) of the other objectives because the profit calculates the surface and obviously when having less area meaning less construction costs and less energy use the possible incomes decrease as well. There is also a large range of UDLI varying from 10.74 t% to the highest option with 63 %, even more than the one that was choosen during the climate stage of the Sequential strategy. Another large range of values is the EUI, fluctuating from 34 KWh/m2 /year to 234 kWh/m2/year.

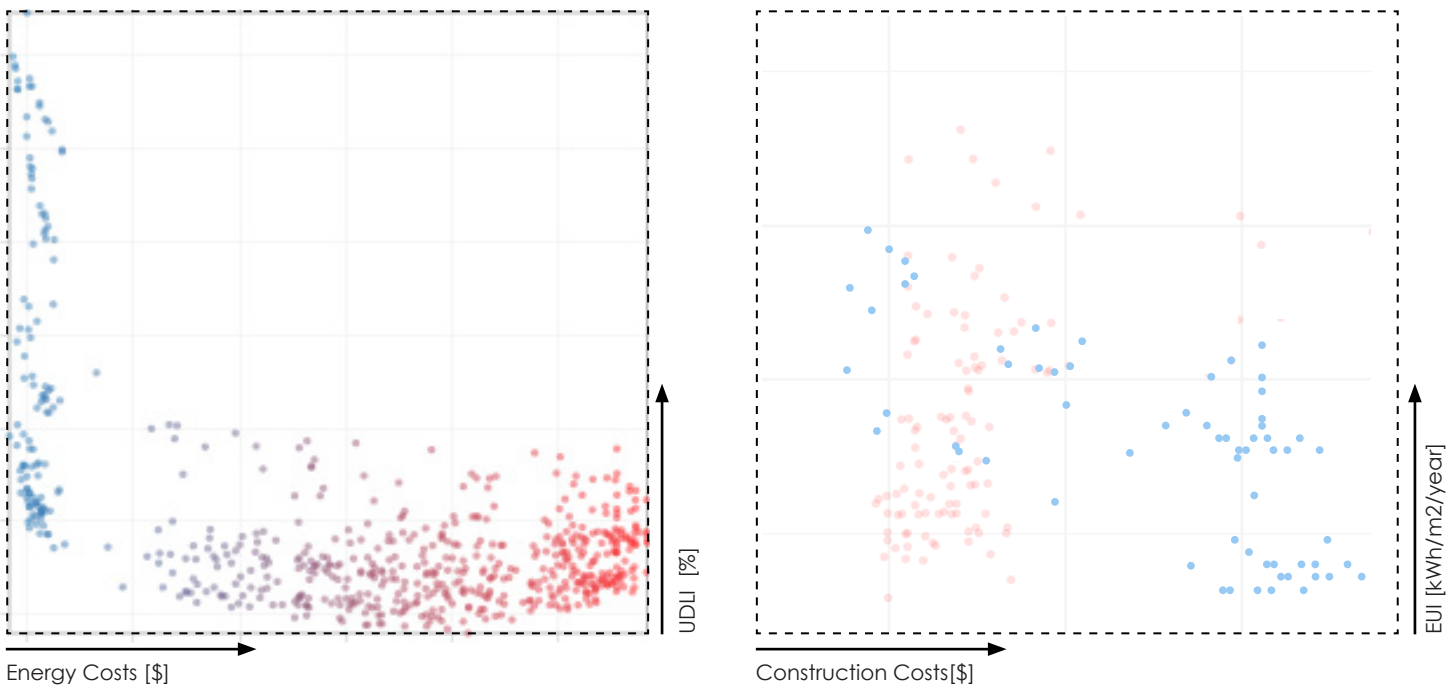


Figure 218. Parallel chart filtering

After reviewing the several design options, it could also be observed that by having more height in the peak the UDLI increases. Besides, it could also be concluded ,by playing with the vertical filters of the parallel charts, that the Roof material plays an important role on the EUI performance. Another consideration that could be seen in the results was that the best orientation for the UDLI is the north-south while the worst one is 135°.

5.2.5.1.1.5 Design decision

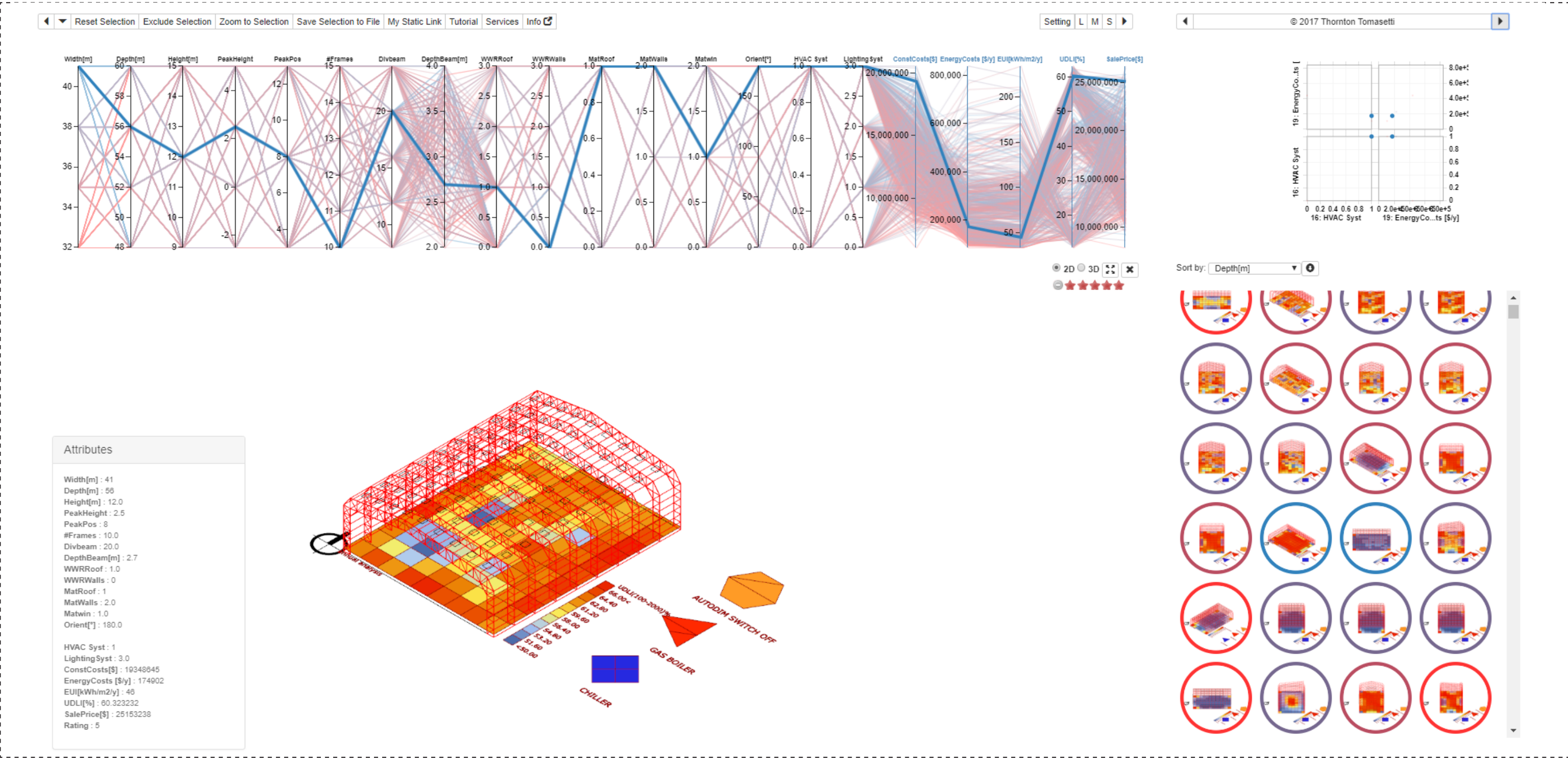


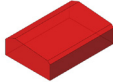
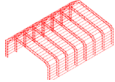
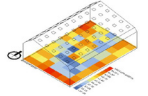
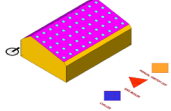
Figure 219. Design exploration, filtering and selection interface

For the design selection the filters were set with the intention of looking for a balanced option which could be energy efficient by having a good UDLI average value, in combination with a low energy use to get low energy cost as a final output. In that way, the same WWR ratio in the walls and the skylights from the option selected for the envelope stage of the Sequential strategy was kept and the north-south orientation was also maintained as shown in Fig.[219].

The Chiller based cooling system was also considered as a primary value since this parameter showed an important reduction for the energy costs. Another important consideration was to search for an option which represented a good alternative as a financial case. Therefore a high sale price was also attempted.



# 5.3OPTIMIZATIONSTRATEGIESCOMPARISON

STAGE	NUMBER OF PARAMETERS	NUMBER OF GENERATIONS	DESIGN SPACE	DOMINATED / NON DOMINATED	COMPUTATIONAL TIME
	10 Parameters	7 Generations 100 Population	313-576	72 Non-dominated 245 Dominated	1.5 Hours
	13 Parameters	50 Generations 100 Population	3200 from 118125000	140 Non-dominated 60 Dominated	2.5 Hours
	10 Parameters	7 Generations 100 Population	980 from 277544800	60 Non-dominated 64 Dominated	1.5 Days
	3 Parameters	1 Generations 100 Population	24-24	23 Non-dominated 106 Dominated	5 Hours

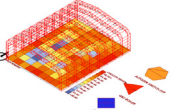
STAGE	NUMBER OF PARAMETERS	NUMBER OF GENERATIONS	DESIGN SPACE	DOMINATED / NON DOMINATED	COMPUTATIONAL TIME
	18 Parameters	10 Generations 100 Population	1200 from 97820835840000	88 Non-dominated 1 Dominated	3 Days

Figure 220. Graph showing the comparison among the Sequential strategy and the Integrated strategy

Both strategies have their own features and disadvantages, the first one guides the designer in a more educational way narrowing the design space narrowed space as the process goes further which gives the possibility to think in a more detailed/focused way. Besides, splitting the process into phases gives the possibility to choose among the diverse time lapses of the simulation / optimization processes, avoiding unnecessary waiting times. Another benefit from applying this strategy is that more parameters regarding a specific discipline can be added, since as mentioned before, when applying this methodology and using the proposed tools, the user needs to be aware of their limitations. The main disadvantage is that without having a larger vision about what happens with the

other building aspects when modifying or altering a parameter sometimes decisions are taken unconsciously. So it is important to consider in each of the different stages an design space big enough to explore all the different possibilities . When talking about the second stage, it is considerably more difficult to set it up at the beginning because everything should be included and connected , however from a designer point of view it is more useful to see “the big picture” when taking design decisions. With this approach, it is more feasible to make conclusions and evaluate the overall performance of the building in an holistic manner.

## 6.RESULTS&DISCUSSION

# 6.1.RESULTS&DISCUSSION

After applying the workflow to solve a real design problem, it can be said that the results were satisfactory in terms of proving how a sensible combination of computational tools with optimization and design exploration techniques can help and support the designer when taking important decisions specially during the conceptual design phase.

By trying the different design strategies, it can be said that generally speaking both options could be applied depending to the user necessities or the specific situation of the project in terms of development and the availability of information. From one side, splitting the process into several stages was a suitable idea. In the first place because each stage of the project has its own necessities and level of depth. For instance, complex daylight and energy simulations are not really needed at the very beginning of a project, besides, this kind of simulations take a lot of time and effort. Therefore, for instance, when exploring the mass, a brief calculation can be done based on benchmarks averages of costs and energy gathered after analyzing buildings from the same typology and with similar conditions as proposed by the workflow. In this way, it was possible to involve a considerable amount of variables for each stage, being able to explore a large amount of alternatives individually among the different design phases.

Secondly, as it could be seen during the design exploration phase, specifically with the use of the sensitivity analysis tools, it was possible to determine which aspects affected the most at every different stage of the workflow. Like for instance when talking about the mass, modifying the area of the plot was the value that affected more the outputs. Or when analyzing the structure, it was with the increasing of the number of frames together with the height of the peak that improved the overall structural performance.

The stage regarding the envelope showed that for the specific case study heating energy was almost not required while cooling took the majority of the energy demand instead.

Lastly, when varying the systems, the HVAC systems were the ones that affected the most the Energy Use Intensity of the building, therefore, special attention should be paid when analyzing this aspect.

As it could be seen during all the different stages of the design , the costs and the energy use are most of the times opposite objectives. As in real the real life, design decisions are intrinsically related to costs, hence, it is important to always try to find the right balance among this considerations in combination with the design and environmental factors.

For future research, it would be interesting to add more complexity to the volume (considering the fact that this will involve more simulation times and computational effort). Furthermore, also including natural ventilation strategies and operable windows could be an interesting aspect to analyze in a future workflow. When talking about active systems, adding PV panels on the roof of the building could be also a proper consideration to take into account. Besides, the embodied energy and the CO2 Footprint emissions could be also incorporated inside this process.



# 6.2 WORKFLOW COMPARISON

## 6.2.1 AUDODESK INSIGHT

With the aim of evaluating how good the proposed method was in comparison with other similar design workflows, the geometry selected during the Sequential strategy was modeled in a BIM platform to later on test another online platform that intents similarly to explore several design combinations and optimize buildings specially for energy performance. At the end the conclusions were that this interface allows the user to compare better having energy benchmarks and standards as comparison, so one can modify the building until achieve a desired energy label.

This tool also allows the user to see how much money is being saved by the new implemented energy measures and additions to the building. The main disadvantage is that this platform does not allow to see the changes in geometry nor to compare different alternatives at once.

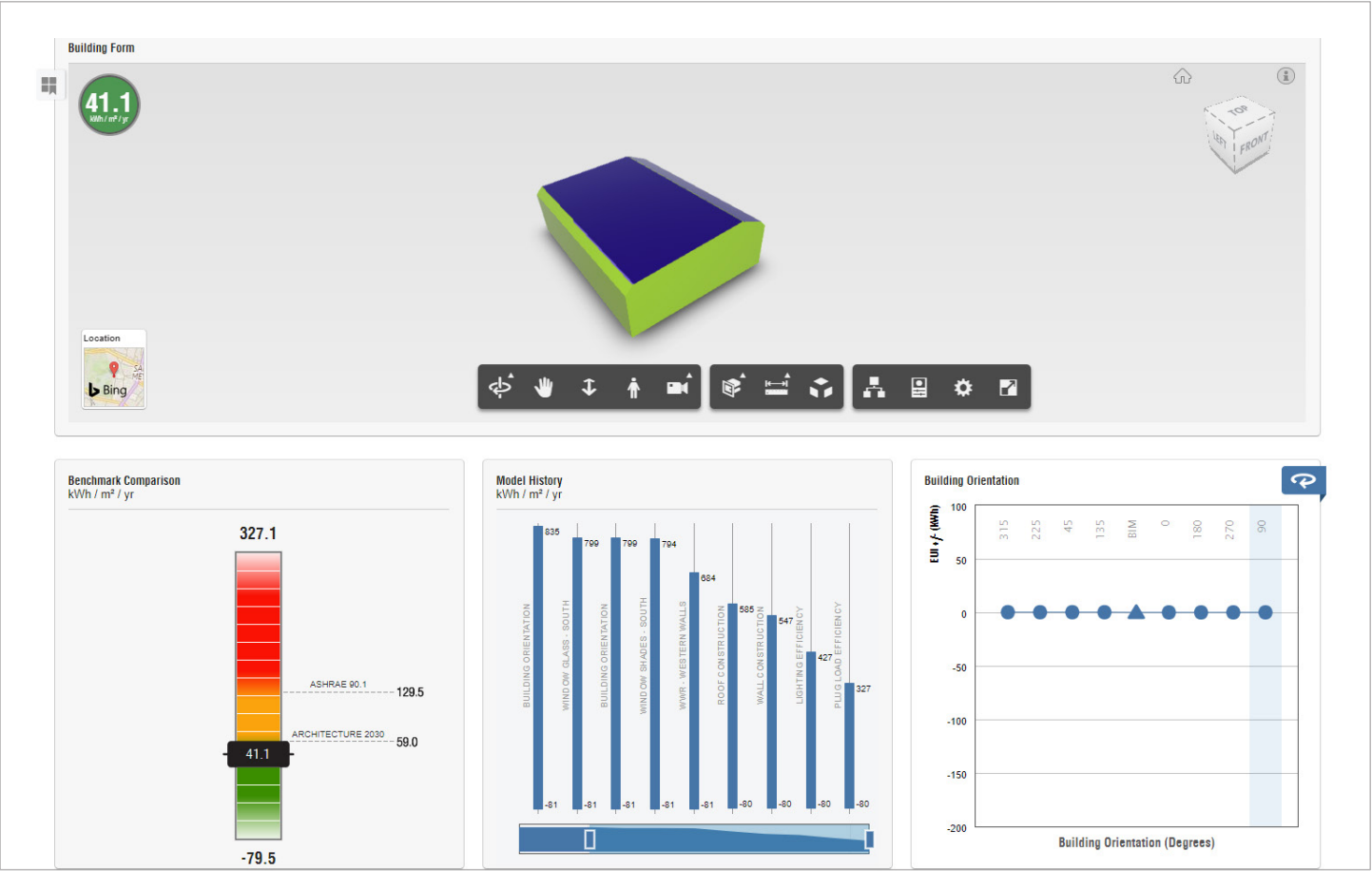


Figure 221. Comparison with Insight Autodesk.

The energy results were almost the same as the initial model simulated in Design builder, having a Energy Use Intensity of 139kwh /m2/year which after the implementation of active systems and the change of construction materials could reduce this demand to 41.1kWh/m2/yr as shown in Fig. [221]

The general conclusion of the comparison, was that this interface deals better with the energy

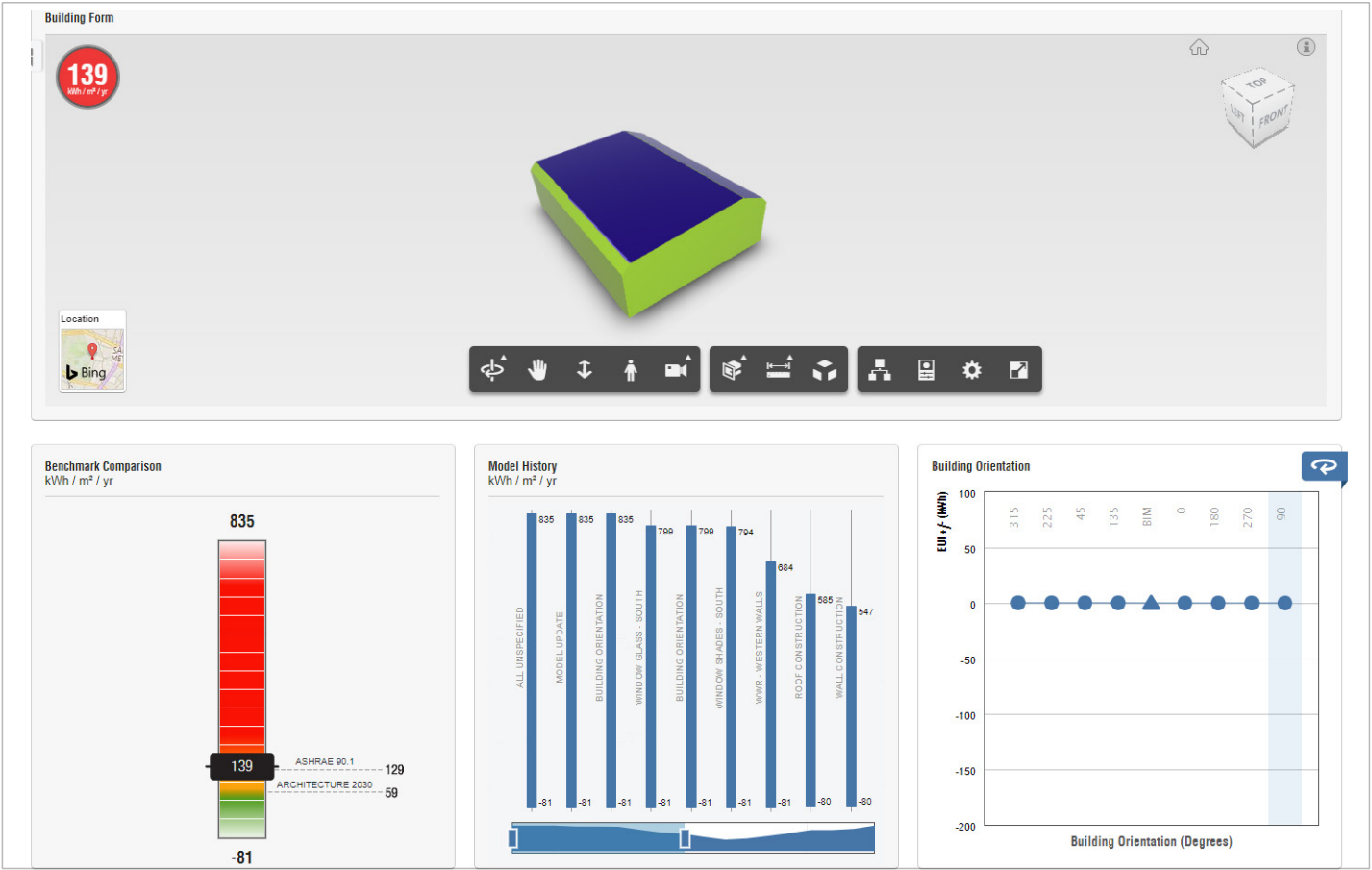


Figure 222. Comparison with Insight Autodesk.

optimization and the exploration of energy saving techniques. Besides, it gathers information about diverse energy standards which can be always compared. However, with this tool it still not possible to parametrize a geometry and to get the results in an automated fashion. Being this tool not meant to focus on a BIM methodology instead. So this platform could better applied for later stages of the design process.

6.3 VALIDATION BY USERS

To test the proposed workflow, a collaboration with a local based architectural office in Mexico city called Pabellón de arquitectura (which also participated during the interviews of the research part of this thesis) was carried out. In first place the overall workflow was explained via Skype to one of the main partners who later on explained it to several colleagues and to a group of young architects that collaborate within the studio.

The user group was composed by seven architects with diverse roles in the office and with different educational backgrounds, however all of them with the same intention of learning more about computational design strategies and sustainability practices. In this way, after explaining the Design explorer platform and how to filter and look over the diverse design options, each user utilized the model to come out with a selected design as shown by Fig. [224] at the end of this practice, a simple questionnaire composed by 7 short questions was conducted to get feedback about the usability of the proposed strategies.

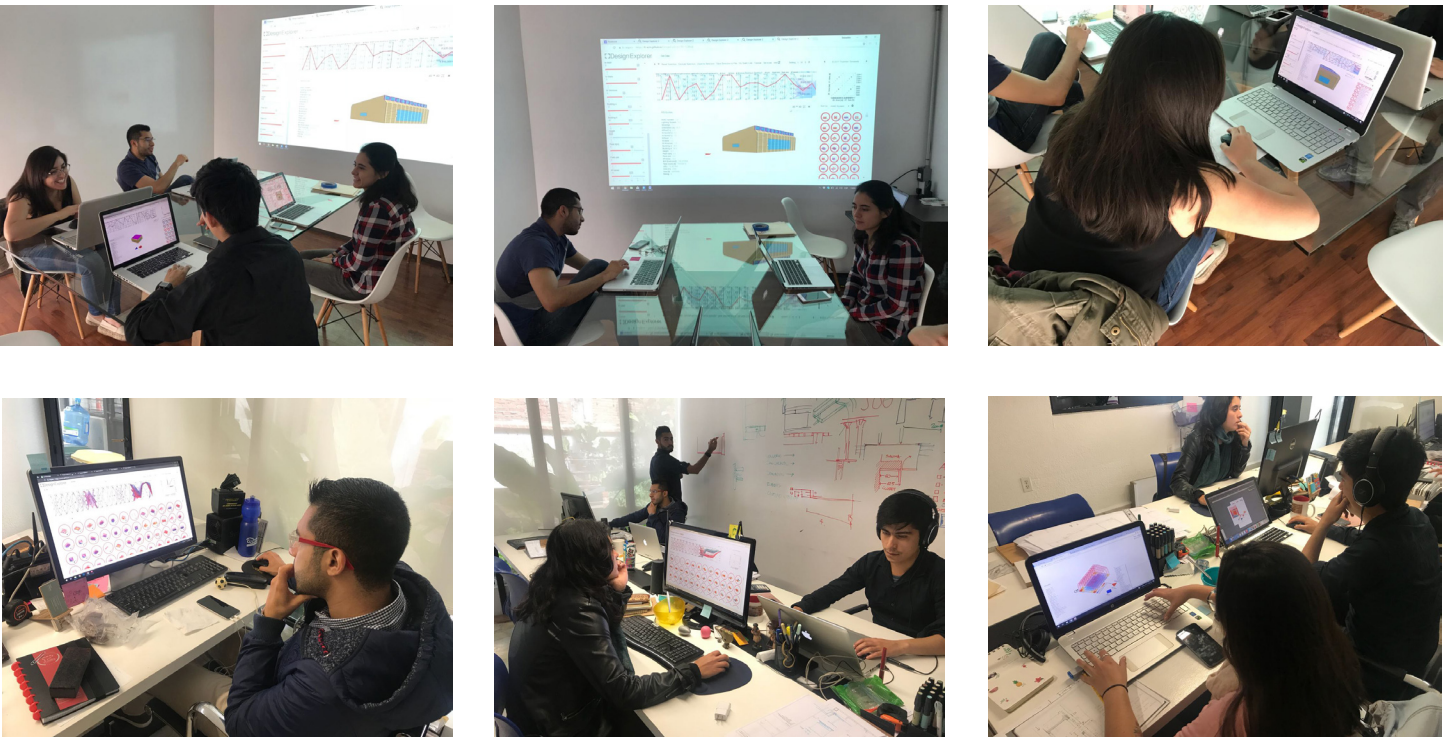


Figure 223. Images of the participants applying the workflow

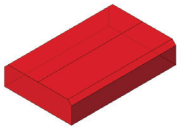
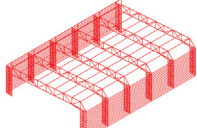
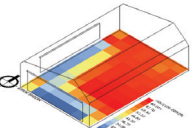
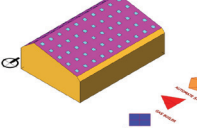
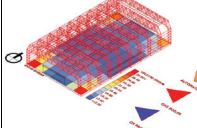
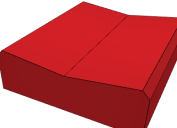
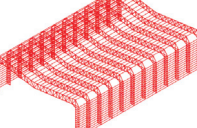
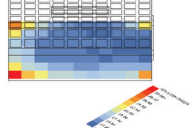
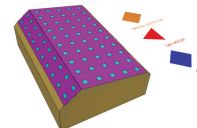
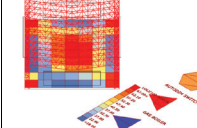
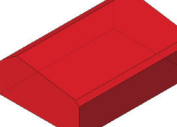
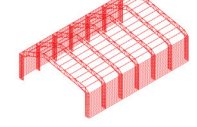

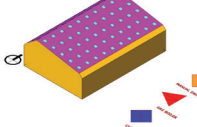
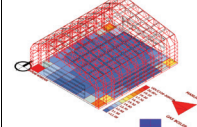
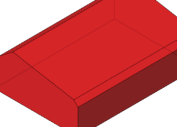
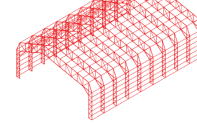
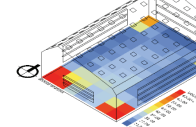
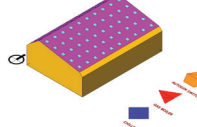
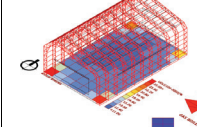
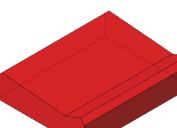
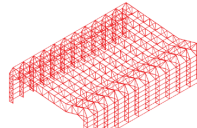
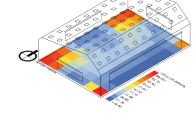
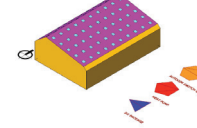
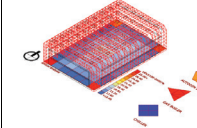
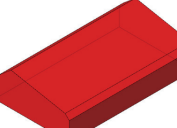
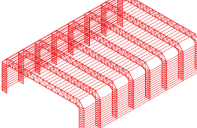
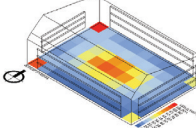
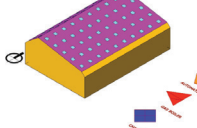
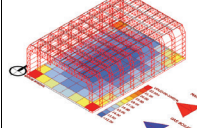
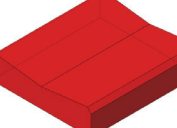
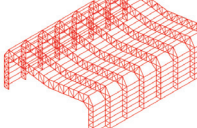
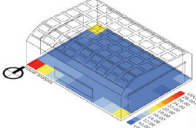
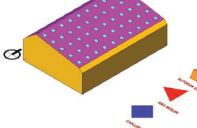
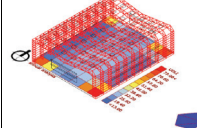
DANIEL LAREDO ARCHITECT	 THIS SHAPE FITS THE STRUCTURE I CHOSE.	 I WAS LOOKING FOR A STRUCTURE WITH THE LOWEST AMOUNT POSSIBLE OF SUPPORTS.	 THE BUILDING WILL BE MOSTLY USED ON DAY TIME, SO IT TAKE ADVANTAGE OF SOLAR ENERGY AND SUN LIGHT.	 LOW COST .	 THIS SYSTEM COMBINES FUNCTION, ENERGY EFFICIENCY AND THE LOCATION OF THE BUILDING.
ISRAEL HERNÁNDEZ ARCHITECT	 SHAPE WITH AVERAGE VOLUME	 AVERAGE COST OF STRUCTURE WITH THE FIRST SHAPE.	 LOWER COST OF ENERGY FOR ORIENTATION	 ONLY NEED LIGHTING SYSTEM, AND COOLLING SYSTEM.	 THE MOST SIMILAR BETWEEN SHAPE AND STRUCTURE WITH A AVERAGE ENERGY COST.
JAYANTI JUÁREZ ARCHITECT	 I WAS LOOKING A TALL PEAK	 I WAS LOOKING FOR FEW FRAMES AND DIVISION OF THE BEAMS	 I PREFER AN OPTION WITH LITTLE USE OF ENERGY	 I DON'T UNDERSTAND IF THE SYSTEMS ARE NATURAL, IF THEY'RE NOT I PREFER USE COOLING SYSTEM THAN HEATING AND LIGHTING SYSTEM	 TRIED TO COMBINE ALL THE ASPECTS BEFORE WRITTEN
MONSERRAT MARTÍNEZ ARCHITECT	 BY FORM H	 EIGHT AND NUMBER OF FRAMES	 ORIENTATION AND LOWER USE OF ENERGY	 LOW USE OF COOLING AND LIGHTING	 COMBINES ALL THE ASPECTS
SELENE GUERRA ARCHITECTURE STUDENT	 IRREGULAR FORM	 LOW COST	 LOW ENERGY CONSUMPTION	 LOW ENERGY COST	 LOW ENERGY CONSUMPTION
SEBASTIÁN NAVARRO ARCHITECT	 BY FORM	 LOW COST	 ORIENTATION AND LOW COST	 ONLY USE OF COOLING AND LIGHTING	 I CHOSE FOR THE LIGHTING, STRUCTURE, SHAPE AND HEIGHT.
HÉCTOR FUENTES ARCHITECT	 BY FORM	 STRUCTURE ACCORDING TO FORM	 LOWER ENERGY USE	 LOW COST	 LOW COST

Figure 224. Images of the design options selected by the participants



USERSQUESTIONNAIRE

Name: Israel Hernández Pérez

Background: Architect

1. How complex do you consider the interface?

☐Easy

☒Medium

☐High

2. Which stage was more helpful when talking about decision support?

☐Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☒Stage 3\_Envelope

☐Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☐☒

Stage 3\_Envelope: 

☐☐☐☒☐

Stage 4\_Systems: 

☐☐☐☒☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☐

Complete ☒

6. For which phase of the project would you think this strategy would be more helpful

☒Conceptual

☐Development

☐Documentation

7. What else would you also include inside the interface?

-It would be nice to have the possibility to see the volume (m3)

USERSQUESTIONNAIRE

Name: Monserrat Martínez

Background: Architect

1. How complex do you consider the interface?

☐Easy

☒Medium

☐High

2. Which stage was more helpful when talking about decision support?

☒Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☐Stage 3\_Envelope

☒Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☐☒

Stage 3\_Envelope: 

☐☐☐☒☐

Stage 4\_Systems: 

☐☐☐☒☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☒

Complete ☐

6. For which phase of the project would you think this strategy would be more helpful

☒Conceptual

☒Development

☐Documentation

7. What else would you also include inside the interface?

Add the possibility having more spaces

USERSQUESTIONNAIRE

Name: Jayantí Juárez Barragán

Background: Architect

1. How complex do you consider the interface?

☐Easy

☒Medium

☐High

2. Which stage was more helpful when talking about decision support?

☐Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☒Stage 3\_Envelope

☐Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☐☒

Stage 3\_Envelope: 

☐☐☐☒☐

Stage 4\_Systems: 

☐☐☒☐☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☐

Complete ☒

6. For which phase of the project would you think this strategy would be more helpful

☐Conceptual

☒Development

☐Documentation

7. What else would you also include inside the interface?

More specifications in the parameters table

USERSQUESTIONNAIRE

Name: Selene Guerra

Background: Architect

1. How complex do you consider the interface?

☐Easy

☐Medium

☒High

2. Which stage was more helpful when talking about decision support?

☐Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☐Stage 3\_Envelope

☒Stage 4\_System

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☒☐

Stage 3\_Envelope: 

☐☒☐☐☐

Stage 4\_Systems: 

☐☐☒☐☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☒

Complete ☐

6. For which phase of the project would you think this strategy would be more helpful

☐Conceptual

☒Development

☐Documentation

7. What else would you also include inside the interface?

Information about the geographic location and season of the year

USERSQUESTIONNAIRE

Name: Sebastian Navarro Mora

Background: Architect

1. How complex do you consider the interface?

☐Easy

☒Medium

☐High

2. Which stage was more helpful when talking about decision support?

☐Stage 1\_Massing

☒Stage 2\_Structure

☒Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☐Stage 3\_Envelope

☒Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☐☒

Stage 3\_Envelope: 

☐☐☐☐☒

Stage 4\_Systems: 

☐☐☒☐☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☒

Complete ☐

6. For which phase of the project would you think this strategy would be more helpful

☒Conceptual

☐Development

☐Documentation

7. What else would you also include inside the interface?

More specifications to understand the values and more options to modify the form

USERSQUESTIONNAIRE

Name: Daniel Laredo

Background: Architect

1. How complex do you consider the interface?

☐Easy

☐Medium

☒High

2. Which stage was more helpful when talking about decision support?

☐Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☒Stage 3\_Envelope

☐Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☐☒☐

Stage 2\_Structure: 

☐☐☐☐☒

Stage 3\_Envelope: 

☐☒☐☐☐

Stage 4\_Systems: 

☐☐☐☒☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☐

Complete ☒

6. For which phase of the project would you think this strategy would be more helpful

☒Conceptual

☒Development

☐Documentation

7. What else would you also include inside the interface?

-The possibility to change everything at once on each stage

USERSQUESTIONNAIRE

Name: Hector Rene Fuentes Veyna

Background: Architect

1. How complex do you consider the interface?

☐Easy

☒Medium

☐High

2. Which stage was more helpful when talking about decision support?

☒Stage 1\_Massing

☒Stage 2\_Structure

☐Stage 3\_Envelope

☐Stage 4\_Systems

3. Which stage was more complicated to understand or to deal with it?

☐Stage 1\_Massing

☐Stage 2\_Structure

☐Stage 3\_Envelope

☒Stage 4\_Systems

4. In a scale of 1 to 5 how did each section helped you to take a design decision?

Stage 1\_Massing: 

☐☐☒☐☐

Stage 2\_Structure: 

☐☐☐☒☐

Stage 3\_Envelope: 

☐☐☐☐☒

Stage 4\_Systems: 

☐☐☒☐☐

5. When comparing the two different approaches (Stages / Complete) which one do you prefer?

Stage division ☐

Complete ☒

6. For which phase of the project would you think this strategy would be more helpful

☒Conceptual

☒Development

☐Documentation

7. What else would you also include inside the interface?

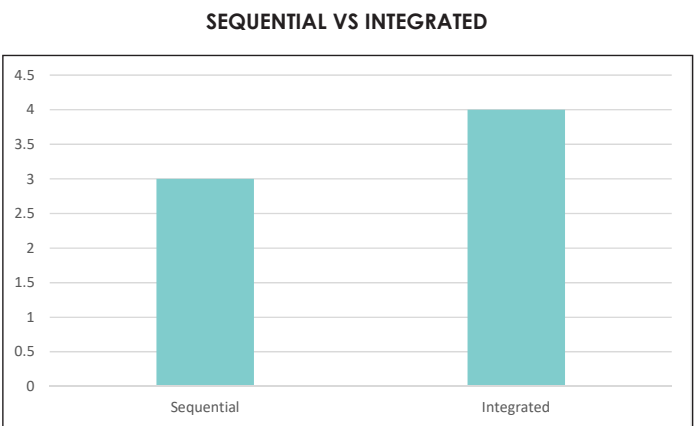
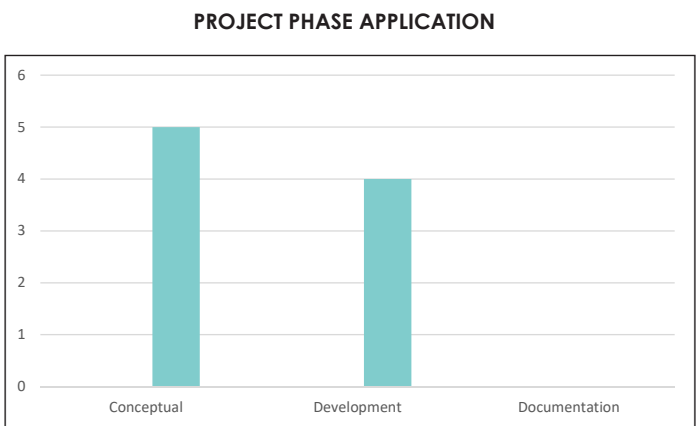
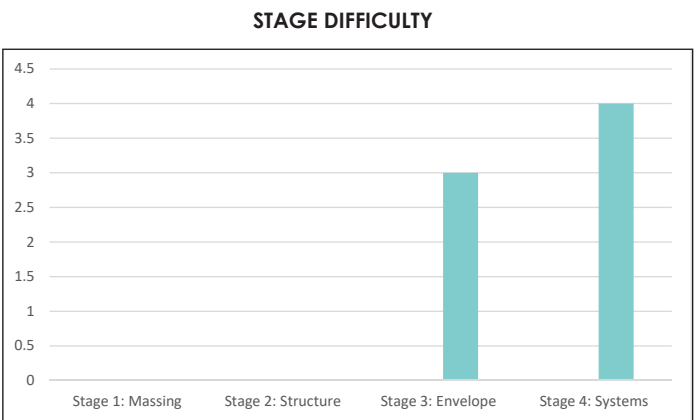
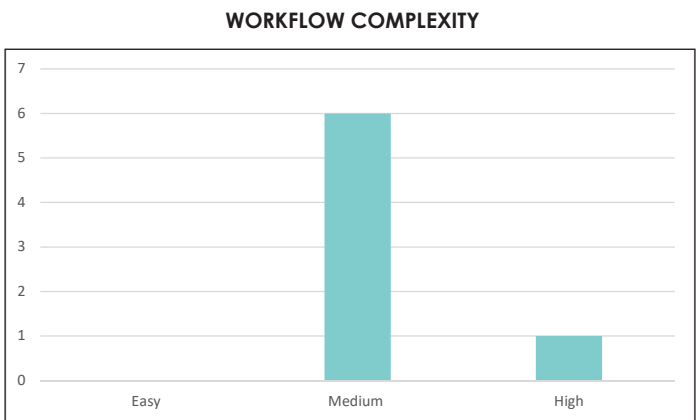
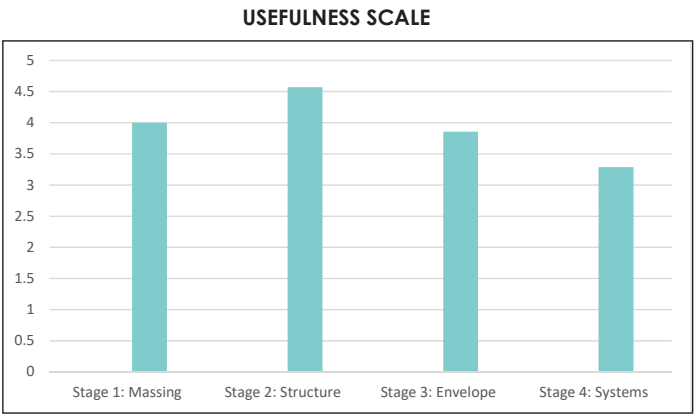
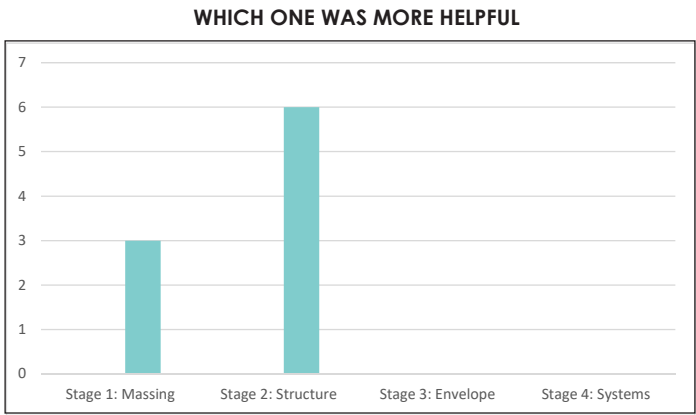
I don't know if you have the possibility in the massing option to have more options of volume. No only a square one, if you want a circle o a sphere.

Figure 225. Users application questionnaires

252

253





As it could be seen in the table showing the selected designs by the different users a set of conclusions can be made,

Regarding the shape, in the first aspect the majority of the participants choose the shape of the building according to a personal choice, where six of the participants selected a pitched roof while only one choose a flat roofed one.

When talking about the structure, two participants choose the frame to match exactly with the choose shape from the massing stage . Two participants had choose the structure based on the lowest cost and three selected it according to the number of frames the shape of it and the amount of divisions of the beam.

For the envelope section, the totality of the participants mentioned that their choice was based on the lowest energy use, the orientation in addition to the lowest costs. Searching for natural daylight and the optimal orientation.

During the systems stage, three of the participants based their choice in the lowest cost and four of them choose the design options neglecting the heating system due to the fact that in this specific location this is rarely utilized.

Finally for the Integrated strategy, five participants took into account for their choice the combination of all the previously mentioned aspects. Having diverse tendencies between choosing among the lowest construction costs and options with the minimum energy use.

The graphs of the previous page, show the information gathered by the user questionnaires that were answered after developing the workflow. A couple of interesting results can be observed, first of all as it can be seen, most of the participants consider to be more useful for design purposes the structural stage, considering the overall workflow to have a medium complexity. This complexity gets apparently higher towards the further detailed development of the project. And this is probably because of the technical aspects that this involves.

At the end of the survey, successfully the majority of the users think that this workflow is quite useful principally for the conceptual phase of a project preferring to use the Integrated strategy over the Sequential one.

Figure 226. User questionnaires results

## 7.CONCLUSIONS

# 7.CONCLUSIONS

Designing buildings at these days is a very complicated task, as Architects, we have the great responsibility to design constructions that are capable of dealing with the environment issues that nowadays aggrieve society's quality of life, and it is by saving energy and reducing the CO2 emissions that this can be accomplished. For this, passive measures such as modifications in the building shape, saving materials, defining the right building orientation and fenestration strategies together with efficient active systems for indoor comfort are combined holistically. However, applying these strategies to the project results in an even more complicated assignment when talking about economic trade-off decisions. Unfortunately for this, the majority of designers and clients do not have a technical background to know about energy and environmental aspects, and most of the times they are unaware of the impact that a particular design could have.

In the first part of this thesis, the current issues of the common architectural practice were outlined, stressing out the lack of design exploration techniques and optimization strategies. By reviewing a large amount of literature and conducting interviews to knowing not only about the scientific approach but also about the actual practice and the current overall educational approach in architecture schools. It can be said that there is a general absence of the appliance of computational technologies inside the design practice in comparison with other industries such as the automotive or the aerospace. This is especially true when talking about the first phases of the design which, as discussed previously, has the most important influence on the total overall cost and energy use of the building.

Several novel techniques such as parametric design, computational design, generative design and design optioneering together with optimization strategies represent a good solution. However, these strategies are commonly implemented in the last stages of the designs and normally not by architects leading to the exploration of several design options without knowing the effect of specific design decisions.

During the second part of this document, with all the previous knowledge and intentions gathered from the first chapters, a computational design workflow based on a combination of optimization with design exploration / optioneering techniques was developed.

In this scope the workflow outlined the importance of the following points:

- The filtering and exploration of the design space based on optimization objectives.
  - Energy efficiency.
  - Cost-effectiveness.
- Involving the designer inside an educational design approach by creating awareness of the design decisions from an economic and environmental point of view.
- Flexibility in the design strategies or the design approaches.
- The easy availability of the involved software and Plug-ins (Opensource and interoperability).
- User friendliness and easy interactivity.
- Inclusion of the visual / non-quantitative assessment and the designers expertise.

During the process of the design of this workflow, it can be concluded that architectural design is a process of searching for the best solutions based on a long list of several factors at the same time. Architects need to consider diverse optimization objectives to get a balance between them. For this, multi-objective and multidisciplinary optimization together with design exploration techniques represent a good solution as it had been described in this document. However, these processes have several difficulties such as the complexity regarding certain computational knowledge mainly during two parts of the process:

- The definition of the problem (Setting up the parametric model and the possible design variables)
- The complexity and long times for the simulation and optimization procedures

In this thesis, it was analyzed the fact of using the computer not only as a tool but as a design supporter when taking decisions by having the possibility of getting real time feedback about the performance of several design alternatives. During this process, it could be clearly observed that it is also fundamental to involve the aesthetical factor (non-quantitative) inside an optimization-performance based workflow since an "optimal" solution is not necessarily the one that performs better in terms of non-numerical assessment. As it could be seen during the case study application, from one side the performance aspects such as UDLI, WWR ratio and the application of active systems play a determinative factor on the design of this kind of venues. Nevertheless, personal design intentions should also be involved in the design process and for this last aspect, there is a still need to be done from a technological and educational point of view. However, with the further development of the Artificial Intelligence and Machine-learning techniques certainly, those barriers will be surely tackled in the near future.

As a general conclusion, Architects and designers should be more involved in the use of new technologies; the technology already exists, we only need to improve the way we use it and apply it. It is by mixing intuition and logic in combination with having the right information at the right time that the best decisions can be made.

At the end of the day, Architects need to keep the right balance among several factors regarding from one side the artistic and aesthetical values and from another the technical and functional aspect of the building. And this is not new. It has been already clearly defined since Vitruvius thousands of years ago:

"An architect should focus on three central themes when preparing a design for a building: firmitas (strength), utilitas (functionality), and venustas (beauty)..."

Nevertheless, in addition to Vitruvius words, at these days, it is urgently to also involve the economic factors together with a sustainable approach especially at the beginning of the design process. The previous, to be able of proposing buildings that help to reduce the environmental damage and the shortage of natural resources while at the same time representing a viable project from a financial point of view. And it is by using the available technology in combination with the specialized knowledge and expertise that this can be successfully achieved.



## 8. REFERENCES

# 8. REFERENCES

## BOOKS:

- Agkathidis, A. (2016). *Generative Design*. London: Laurence King Publishing.
- Andia, A. and Spiegelhalter, T. (n.d.). *Post-parametric automation in design and construction*
- Bielefeld B. (2016) *Planning architecture*, Bierkhauser.
- Bielefeld B. (2013) *Basics Project Management Architecture*, Palgrave Macmillan, Basel
- Culley, P. (2015). *Stadium and arena design*. London: ICE Publ.
- Culley, P. and Pascoe, J. (2015). *Sports facilities and technologies*. New York: Routledge.
- Crane, R. and Dixon, M. (1991). *Indoor sports spaces*. New York: Van Nostrand Reinhold.
- Domingos Pedro (2013). *The master Algorithm*, Newyork, Penguin
- Felkner, J, ChatziE&Kotnik, T (2013) *Architectural feedback in the structural optimization process*. Structure and architecture
- Gerritse Kees. (2008) *Controlling Costs and Quality*. VSSD, Delft Netherlands.
- Hensel, M., Menges, A. and Weinstock, M. (2010). *Emergent technologies and design*. Oxon: Routledge.
- Hensel, M.A, Menges and Weinstock, M. (2006) *Techniques and Technologies in Morphogenetic Design*, Wiley & Sons
- Hudson R. (2010) *Strategies for Parametric Design in Architecture*. An application of practice (Doctor al dissertation, University of Bath)
- Jabi, W. (n.d.). *Parametric design for architecture*. Taylor & Francis.
- John Wiley and Sons, 2015. *Multidisciplinary design optimization supported by knowledge based engineering* Chichester, UK
- Linden A.C, Gaalen, Zeegers.(2018), *Building Physics*, 2nd edition, ThiemeMeulenhoff, Amersfoort, Netherlands.
- Marble Scott, (2012) *Digital Work flows in architecture, Design-Assembly-Industry*, Birkhauser.
- Marks W. *Multi-criteria Optimization of Shape of Energy-Saving Buildings*. Build Environment 1997
- Perrin, G. (1971). *Community sports halls*. London: National Playing Fields Association.
- Peters, B. and Peters, T. (2018). *Computing the environment*. Wiley
- Peters, T. (2013). *Inside smart geometry*. [United Kingdom]: John Wiley & Sons Inc.
- Radford Anthony, Gero John, *Design Optimization in Architecture, Building and Construction*.
- Sheard John, Vickery Ben, (2010) *Stadia – The Populous Design and Development Guide*, Routledge
- Tedeschi, A., Andreani, S. and Wirz, F. (2016). *AAD\_Algorithms-Aided Design*. Brienza: Le Penseur Publisher.
- Terzidis, K. (20067) *Algorithmic Architecture*, Oxford Architectural Press.
- Wimmer, M., Humann, I. and Martovitskaya, A. (2016). *Stadium buildings*. Berlin: DOM Publishers.
- Riccobono Alessia (2013) *Architectural design in the digital era, identifying computer influences and new expressive trends in current architecture*. Dottorato di Ricerca in "Recupero dei Contesti Antichi e PROCESSI Innovativi nell Architettura XXIV Ciclo Univesita degli studi di Palermo

## STANDARDS:

- ASHRAE (2009). *ASHRAE Handbook of fundamentals*. Atlanta, Georgia, American Society of Refrigerating and Air Conditioning Engineers
- Código de Conservación de Energía para las Edificaciones de México (IECC-México) (2016)

- NEN-EN-ISO13790 (2008) *Energy performance of buildings-Calculation of energy use for space heating and cooling*
- NEN-EN-ISO 52000-1 (2017) *Energy performance of buildings-Overarching EPB assessment-Part 1: General framework and procedures*
- NEN 2699 (2017) *Investing and operating costs of property- Terminology and classification*
- NEN-EN 15459-1 (2017). *Energy performance of buildings- Economic evaluation procedure for energy systems in buildings- Part 1: Calculation procedures, Module M-14*
- NEN-ISO 15686-5 (2017) *Buildings and constructed assets- Service life planning-Part 5: Life-cycle costing ( ISO 15686-5:2017, IDT)*

## VIDEOS/TUTORIALS:

- [www.au.autodesk.com](http://www.au.autodesk.com)
- [www.esteco.com](http://www.esteco.com)
- [www.hydrashare.github.io](http://www.hydrashare.github.io)
- [www.lynda.com](http://www.lynda.com)
- [www.worldstadiums.com](http://www.worldstadiums.com)
- [www.thinkparametric.com](http://www.thinkparametric.com)

## DOCUMENTARIES:

- Building the Emirates Stadium
- Megastructures (National geographic) Beijing National Stadium
- Megastructures Build up to the Cup: Stadiums
- Mercedes-Benz Stadium Design & Engineering
- Singapore Sports Hub- A Unique Design and Architecture
- The History of Dome Stadium- Docs Channel

## WEBSITES:

- <http://designadvisor.mit.edu/design/>. Reviewed in December 2017
- <https://covetool.com/>. Reviewed in December 2017
- [www.sportengland.org](http://www.sportengland.org). Reviewed in January 2018
- <http://calculeren.bouwkosten.nl/Home.aspx>. Reviewed in January 2018
- <http://nl-sfb.bk.tudelft.nl/>. Reviewed in January 2018
- <https://neodata.mx/construbase/presupuestos/>. Reviewed in February 2018
- [www.tudelft.nl/sports-engineering-institute/](http://www.tudelft.nl/sports-engineering-institute/). Reviewed in February 2018
- <http://www.sportsengineering.org/>. Reviewed in February 2018
- <https://www.ashrae.org/>. Reviewed in February 2018
- <https://energyplus.net/>. Reviewed in March 2018
- <http://step2sport.eu/>. Reviewed in March 2018
- <https://www.cfe.mx/Pages/Index.aspx>. Reviewed in March 2018
- <https://platform.carbonculture.net/communities/leisure-and-sports/23/>. Reviewed in March 2018
- [www.carbontrust.com](http://www.carbontrust.com). Reviewed in March 2018
- <http://core.thorntontomasetti.com>. Reviewed in April 2018
- [www.ladybug.tools](http://www.ladybug.tools). Reviewed in April 2018
- <https://insight.autodesk.com> . Reviewed in May 2018

## ARTICLES:

- Ascione F., Bianco N., De Stasio C. (2015) *A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance*, Energy and Buildings 88, pp. 78-90.
- Attia Shady, Hamdy Mohamed, Calucci Salvatore (2013) *Computational optimization for Zero Energy Buildings Design: Interview results with twenty-eight International experts*, BS2013, pp. 26-28.
- Caldas, L. (2008). *Generation of energy-efficient architecture solutions applying GENE\_ARCH: An evolution-based generative design system*. Advanced Engineering Informatics, 22(1), pp.59-70.
- Chi Doris, Moreno David, Navarro Jaime(2017) *Design optimisation of perforated solar facades in order to balance daylighting with thermal performance*, Building and Environment 125, pp. 383-400.
- D'Aquilio A., Sileryte R., Yang D.,Turin M. *Simulating natural ventilation in large sports buildings. Prediction of temperature and airflow patterns in the early design stages*, SIMAUD 2016,pp. 43-50.
- David J, Kim Alan, Butler A. Haeusler (2015).*Optimisation for sport stadium designs*, CAADRIA, Hong Kong ,573-582
- De Luca Francesco, Voll Hendrik (2017)*Computational method for variable objectives and context aware solar envelopes generation*, SIMAUD 2017,pp. 335-342.
- Díaz Héctor, Alarcón Luis, Mourgues Claudio, García Salvador,(2015). *Multidisciplinary design Optimization through process integration in the AEC industry: Strategies and challenges*, Automation in construction 73, pp. 102-119.
- Elbeltagi E., Werki H., Abdrabou S., Dawood M., Ramzy A.(2017) *Visualized strategy for predicting buildings energy consumption during early design stage using parametric analysis*, Journal of Building Engineering 13, pp. 127-136
- Eltaweel Ahmad, SU Yuehong (2017) *Parametric design and daylighting: A literature review*. Renewable and Sustainable Energy Reviews 73, pp. 1086-1103.
- Evins, R. (2013). *A review of computational optimisation methods applied to sustainable building design*. Renewable and Sustainable Energy Reviews, 22, pp. 230-245.
- Ferrara M, Fabrizio E, Virgone J, Filippi M, (2016) *Energy systems in cost-optimized design of nearly zero-energy buildings*, Automation in Construction 70, pp. 109-127.
- Gerber, D. and Lin, S. (2013). *Designing in complexity: Simulation, integration, and multidisciplinary design optimization for architecture*. SIMULATION, 90(8), pp.936-959.
- Gerber D., Hsing-Shih, Pan Bei, Senel Ashlihan (2012). *Design Optioneering Multi-disciplinary Design Optimization through Parametrization, Domain Integration and Automation of a Genetic Algorithm*. SimAUD 2012.
- Gerber D., Elsheikh Mohamed, Solmaz A. (2012)*Associative Parametric Design and Financial Optimization-"Cash back 1.0"*, Parametric Design for Visualizing And Optimizing Return On Investment For Early Stage Design Decision Making, CAADRIA Hong Kong, pp. 47-56.
- Geyer, P. (2009). *Component-oriented decomposition for multidisciplinary design optimization in building design*. Advanced Engineering Informatics, 23(1), pp.12-31.
- Geyer P., Beucke (2010) *An integrative approach for using multidisciplinary design optimization in AEC*, ICCCB
- H. van Dijk. Spiekman and P. de Wilde. *A monthly method for calculating energy performance in the context of european building regulations*.(2005) IBPSA Conference, Montréal 2005
- Han, Hon and Sun, (2017)*Simulation-based multi-objective optimization of timber-glass residential buildings in severe cold regions*. Sustainability 2017,9,2353
- Hamdy, M., Nguyen, A. and Hensen, J. (2016). *A performance comparison of multi-objective*

- optimization algorithms for solving nearly-zero-energy-building design problems*. Energy and Buildings, 121, pp.57-71.
- Haymaker John (2008) *Multidisciplinary process integration and design optimization of a classroom building*, ITcon Vol. 0(2018), pp1-19.
- Holzer, D. (2010). *Optioneering in Collaborative Design Practice*. International Journal of Architectural Computing, 8(2), pp.165-182.
- Ianni Manuela, Sánchez de León M.(2013) *Applying Energy Performance-Based Design in Early Design Stages*, Delft eCAADe 31, pp.11-40
- Jusselme T., Tuor R., Lalanne D., Rey E., Andersen M. (2017) *Visualization techniques for heterogeneous and multidimensional simulated building performance data sets*, International Conference for Sustainable Design of the Built Environment- SDBE London 2017
- Kolarevic B., Ashour Y. (2015)*Optimizing Creatively in Multi-Objective Optimization*, SIMAUD 2015, pp.59-66.
- Konis Kyles, Gamas Alejandro, Kensek Karen(2016).*Passive performance and building form: An optimization framework for early-stage design support*. Solar energy 125, pp. 161-179
- Lin, S. and Gerber, D. (2014). *Designing-in performance: A framework for evolutionary energy performance feedback in early stage design*. Automation in Construction, 38, pp.59-73.
- Laiserin J. *Digital (2008) Environments for Early Design*, Proceedings of the first International Conference on Critical Digital: What matters, Cambridge: Harvard University Graduate School of Design, 2008, pp. 235-241
- Lin, S. and Gerber, D. (2014). *Evolutionary energy performance feedback for design: Multidisciplinary design optimization and performance boundaries for design decision support*. Energy and Buildings, 84, pp.426-441.
- Machairas, V., Tsangrassoulis, A. and Axarli, K. (2014). *Algorithms for optimization of building design: A review*. Renewable and Sustainable Energy Reviews, 31, pp.101-112.
- Marin P., Blanchi Y., Janda M. (2015) *Cost Analysis and Data Based Design for Supporting Programmatic Phase*, Cost Analysis and Data Based Design for Supporting Programmatic Phase. CAAD Futures 2011.
- Nathan C., Mueller Caitlin. (2016) *Design for structural and energy performance of long span buildings using geometric multi-objective optimization*, Energy and buildings 127 (2016), pp.748-761
- Negendahl K., Rammer T.,(2015) *Building energy optimization in the early design stages: A simplified method*, Energy and Buildings 105, pp.88-99
- Orme, M. (2011). *Estimates of the energy impact of ventilation and associated financial expenditures*. Energy and Buildings 33(2001), pp.199-205.
- Oxman R. *Performance-based design: current practices and research issues*. International Journal of Architectural Computing(IJAC) 2008;6:1-17.In:Performance-based parametric design explorations: Erkan B, Elias-Ozkan ST. A methodology for generating appropriate building component. Design Studies 2015. Design Studies 2015; 38 (c), pp. 33-35
- Ostegard T, Jensen RL, Maagaard SE. *Building simulations supporting decision making in early design – A review*. Renew Sustain Energy Rev 2016, pp. 61,187-201
- Penna, et al., *Multi-objectives optimization of Energy Efficient Measures in existing buildings*, Energy and Buildings. 95 (2015), pp. 57–69.
- Ren, Z., Yang, F., Bouchlaghem, N. and Anumba, C. (2011). *Multi-disciplinary collaborative building design—A comparative study between multi-agent systems and multi-disciplinary optimisation approaches*. Automation in Construction, 20(5), pp.537-549.
- Shi Xing, Tian Zhichao, Chen Wenqiang, Si Binghui Si, Jin Xing, (2016) *A review on building energy efficient design optimization from the perspective of architects*, Renewable and Sustainable Energy reviews 65, pp. 872-884.



-Sileryte R., D'Aquilio A., Di Stefano D., Yang D., Turrin M.(2016) *Supporting Exploration of Design Alternatives using Multivariate Analysis Algorithms*,SIMAUG 2016, pp. 215-222.

-Tiaan Zhichao, Zhang Xinkai, Jin Xing, Si Bingui Si, Shi Xing (2018) *Towards adoption of building energy simulation and optimization for passive building design: A survey and a review*, Energy and Buildings 158 (2018) pp. 1306-1316.

-Toth, B., Janssen, P., Stouffs, R., Chaszar, A. and Boeykens, S. (2012). *Custom Digital Workflows: A New Framework for Design Analysis Integration*. International Journal of Architectural Computing, 10(4), pp.481-499.

-Turrin, M., von Buelow, P. and (2011). *Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms*. Advanced Engineering Informatics, 25(4), pp.656-675

-Turrin M., Yang D., Aquilio D' A. Sileryte R., Sun Y. (2016)*Computational Design for Sport Buildings*, Procedia Engineering 147, pp. 878-883.

-Tzannetakis, N. and Van de Peer, J. (2002). *Design optimization through parallel-generated surrogate models, optimization methodologies and the utility of legacy simulation software*. Structural and Multidisciplinary Optimization, 23(2), pp.170-186.

-Terzidis K. (2006)*Algorithmic architecture*. Burlington USA\_ Elsevier and Architectural press

-Yang D, Sun Y., Sileryte R.,DAquilio A., Turrin M. (2016)*Application of Surrogate Models for Building envelope Design Exploration and Optimization*, SIMAUD 2016, pp. 11-14

-Yang D., Sun Y., Turrin M., Buelow P. Paul Joop, (2015) *Multi-objective and multidisciplinary design optimization of large sports building envelopes: a case study*. IASS 2015

-Yang D., Sun Y, di Stefano D., Turrin M., Sariyildiz S. (2016) *Impacts of Problem Scale and Sampling Strategy on Surrogate Model Accuracy*, IEEE 2016

-Yang D., Sun Y, di Stefano D., Turrin M. (2017) *A computational design exploration platform supporting the formulation of design concepts*, SIMAUD 2017, pp. 35-42

# DESIGNEXPLORATIONLINKS

## SEQUENTIAL STRATEGY:

- Stage 1: Mass
   
<https://tt-acm.github.io/DesignExplorer/?ID=5JEefR>
  
<https://tt-acm.github.io/DesignExplorer/?ID=wQJ7Ay>
- Stage 2: Structure
   
<https://tt-acm.github.io/DesignExplorer/?ID=dHnQ5S>
  
<https://tt-acm.github.io/DesignExplorer/?ID=nx4Q4v>
- Stage 3: Envelope
   
<https://tt-acm.github.io/DesignExplorer/?ID=b5zKee>
  
<https://tt-acm.github.io/DesignExplorer/?ID=Aest9J>
- Stage 4: Systems
   
<https://tt-acm.github.io/DesignExplorer/?ID=7pifHA>
  
<https://tt-acm.github.io/DesignExplorer/?ID=ySq4Gv>

## INTEGRATED STRATEGY:

- <https://tt-acm.github.io/DesignExplorer/?ID=Zryhps>
  
<https://tt-acm.github.io/DesignExplorer/?ID=GSBeqC>





ALVARO RODRIGUEZ GARCIA

4928098

11/July/2018

