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Department of Civil Engineering

MSc Thesis

Parametric Structural Design

Integration of structural verifications in the early design phases

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Preface

This project is the final master thesis to acquire the MSc. in Architectural Engineering (120 ECTS) part of the Civil Engineering Department at the Technical University of Denmark.

The master thesis is credited with 30 ECTS points and has been written during the Spring Semester 2016, started on the 25th of January and handed in on the 25th of June.

It is focused on the integration of structural considerations in the first phases of the designing process, developed in the frame of the parametrical modeling. This research is carried out in collaboration with Withe Architects AB as part of the STED program (Nordic Built).

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Furthermore, I would like to thank Elise Grosse from White Architects Stockholm for her Skype meetings through this process which have helped me to understand the real value of the project and the necessary demands for the architectural projects. Additionally, I would also thank to make possible the meeting with Jonas Jonas Runberger, Director of the Dsearch digital design development department of White Architects Stockholm, who provided me the necessary feedback to know the use of this work for future projects. Within the Nordic Built program, I would like to also thank to Mikkel Kirkeskov Knudsen for provided me with all the necessary information about The Eko-Canopy project.

Lastly, I would like to thank to my master colleagues for his advices regarding the technical aspects of this thesis, and finally thanks to my friends and family for their great support during this long process.

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Abstract

This thesis project is based on the study of an integrated dynamic method to be applied in the early design stages of the designing building process, which deals with the idea of introducing structural verifications in the models since the beginning. As part of the STED (Sustainable Transformation & Environmental Design) program inside of the Nordic Built, Nordic Innovation program, which principal goal is to achieve sustainable solutions in the Nordic region, the objective of the proposed method is to find reliable structures with the maximum utilization ratio of its members and using the minimal amount of material, which means less kilograms of mass and consequently less emissions of CO2, benefiting the LCA process.

This is done by means of parametrical modeling using the parametric tool for Rinho 3D, Grasshopper, which includes a Finite Element program, Karamba used to perform structural calculations of the created geometries. The combination of Grasshopper and Karamba allows to the user to couple designing tools with calculations tools, which means the mixture of creativity and technical knowledge. Optimization techniques have been integrated, which are based on form-findings methods by means of evolutionary computation. This consists in topological and sizing optimizations procedures of the structures which provide the landscape of optimal structures.

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Part I: INTRODUCTION

1.1 Scope of the project (Motivation)

Nowadays the building industry is continually changing and new technologies are being introduced every day. The working methods should be adapted to the new times to be able to deal with the challenges presented.

The roles involved in the construction process are being rethinking in the process of looking for new methods and workflows which improve the productivity of the projects and their quality (W Young Jr. et al. 2009). In this scenario appears the concept of “Building Information Modeling – BIM”, which main principle deals with the idea of establish a better collaboration and coordination between all the agents involved in the building process; based on the concept of having a central model where the data is exchange through different platforms/tools. Being in these ones include all the design tools, FEM software, Mathcad and spreadsheet data tools, etc.

Furthermore, in the last decade one of the main goals of the building processes is to establish methods for sustainable constructions, in this case in the frame of the Nordic countries.

In this context the aim of this master thesis project is to study a methodology to integrate the structural aspects within the architectural designs in the first stages of the designing process, introducing the new tools of the building industry. This concept will lead to achieve more reliable structures from the beginning, which means a reduction of cost through the entire building process, as the design and construability are the goals from the starting point.

Furthermore, this is also connected to the concept of sustainability. Taking into account structural considerations during the design phase helps to accomplish the maximum efficiency of the members of the structure, as the same time than an aesthetic design is reached. This way of working, at the end, means a reduction of the material consumption, benefiting the Life-cycle assessment (LCA) process.

Consequently this philosophy is based on the total collaboration between the architect and the engineer from the beginning, or in another way in the idea of creating a third figure in the process, called as the *hybrid practitioner, which has equal insight in technical analyses as well as architectural design* (Negendahl 2015a) and operates as connection between them.

However, this concept is difficult to introduce in the building industry, as traditionally the Architects are being the ones in charge of the design, which concerns all the aspects related to the space distribution, materials, textures and light; while the engineers are the ones which analyze the structural systems to ensure the integrity and safety of the proposal design. In other words, *architects are concerned with spaces, while engineers are concerned with forces.* (Byrne et al. 2011)

Parallel to this idea, as it has been mentioned before, new digital tools have been developed during the last decade, which makes more obvious the necessity of studying this approach. In this case, the method is based on parametrical modeling tools, as common link, between the two practitioners.

Accordingly to these two main principles, this project tries to demonstrate the importance of this third element in the building design phases through the proposal of an integrate process; which is based on parametrical modeling, combining, both design and structural calculations.

1.2 Problem Statement

Based on the premises introduced before, it is possible to define the research questions which have been formulated for the developing of this master thesis.

Firstly, in the scope of Building Information Modeling it is seen the importance of creating a good workflow between the different agents who participate in the building process, which at the same time means to set a logic data exchange through the different tools to achieve a good result.

Added to this point, it is clear the objective of seeking for building designs which are the most sustainable as possible. In this case, this is going to be based on the idea of achieve structures using the minimal amount of material, in the context of the LCA. Thanks to the parametrical modeling, as is going to be explained further on, optimization process will be carried out in this search for minimized the mass of the structures.

As last point is going to be study the scope and application of the method proposed as well as its feasibility.

These three statements lead to formulate the following questions:

1) What should be the logic workflow to integrate the different design and FEM tool in the early design stages?

2) It is possible to establish a specific method which can be applied to several projects and which decisions should be made in each step?

3) Who should be the agent in charge to lead this process: the architect, the engineer or the hybrid combination of both?

4) How feasible and beneficial is the idea of introducing structural aspects in the first stage of the designing process? And related to this, how the optimization processes can benefit to reduce the overall amount of mass based on designing parameters?

To be able to solve this questions, the processes haven been applied to a specific case study, which is going to be explained in Part II.

1.3 Structure of the report

The report is divided in seven different parts. Part I and Part II are focused on the presentation of the project, defining first its objectives and secondly introducing the specific case to study. Then in Part III is analyzed the background which has motivated to develop this work, explaining the building process and its tools.

The fourth part and the most important of this thesis, presents the integrated method proposed, as well as the procedure followed for the developing of this work. This is applied using a specific case study, the EKO-Canopy project, in Part V, where the structural analyses, as well as optimization methods are carried out.

Finally, the Part VI and Part VII discuss the findings of this master thesis and present the corresponding conclusions.

Part II: CASE STUDY

2.1 Background: Nordic Build Program & STED

This master thesis is based in a specific case study as it has been already introduced. The project is the EKO-Canopy proposal by White Architects for the Mullion Program in Upplands Väsby, Sweden. This collaboration is the result of the partnership between the Technical University of Denmark and White Arkitekter through the STED program.

STED stands for *Sustainable Transformation & Environmental Design,* which is the shorter version of *Innovation in Design Methods for Sustainable Transformation of the Existing Nordic Building Stock: Energy, Environmental Design and Life cycle Thinking*[1](http://stednetwork.org/, n.d.).

At the same time, STED is part of the Nordic Built, Nordic Innovation program, which was first initiated by Peter Andreas Sattrup in 2014.(Nordicbuilt 2012)

The Nordic Built program is a Nordic initiative to accelerate the development of sustainable building concepts. It was first initiated by the Nordic Ministers for Trade and Industry and consists of an integrated program divided in three different modules: The Charter, The Challenge and the Change.

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[11] http://stednetwork.org/index.php?p=/article/2015/what-is-sted

STED is part of the last one, as its main objective is to establish design methods and solutions for sustainable transformation in the frame of Life-cycle Assessment, which can be generics and used for projects in the Nordic region.

The project involves four universities in the Nordic Region: Chalmers University of Technology, (Sweden), Norwegian University of Science and Technology, (Norway), The Royal Danish Academy of Fine Arts Schools of Architecture, Design and Conservation (Denmark) and the Technical University of Denmark, (Denmark); as well as the five architectural studios: White Arkitekter, (Sweden), Vandkunsten Arkitekter, (Denmark), Helen & Hard, (Norway), Studio Granda, (Iceland) and OOPEAA, (Finland). (http://stednetwork.org/, n.d.)

As a result of this collaboration this master thesis work was presented and discussed during the Nordic Build Sustainable Transformation & Environmental Design Network conference at NTNU Trondheim on the 9th of June 2016. [APPENDIX B: STED PROGRAM TASKS]

In this case, as it has been said, the project is a proposal of White Arkitekter, (Sweden), and it is going be presented in the following section.

2.2 Presentation of EKO-Canopy project

The project of study consists in an EKO-Canopy construction between two exiting apartment blocks belonging to the Swedish Million Program. (Miljonprogrammet 1965) This was a housing program developed in Sweden between 1965 and 1974 with the aim of building one million new houses to provide to the population with a place to live at a reduced cost.

Over the years, the social environment of these areas has been retrogressed. Therefore, with the aim of achieve their social transformation as the same time that do a sustainable transformation of the block apartments, the White proposal was presented for the Swedish Competition "Innovative utilization of excess heat in future cities" in September 2015.

Figure 2.2-1: Location of the project Dragonvägen, municipality of Upplands Väsby in Sweden

The area to study is located in Dragonvägen in the municipality of Upplands Väsby in Sweden. This district is located at twenty-five kilometers in the north respect the center of Stockholm, as it can be seen in Figure 2.2-1. It consists in a group of eight buildings of similar characteristics, arranged four by four (Figure 2.2-2, up). They are eight stories high with a total height of 22.63m. Each apartment block is 12.10m width by 72.56m length (Figure 2.2-2, down); and they are separated a distance of 28.25m approximately.

Figure 2.2-2: Space to be studied (up) and floor plan of the one block apartment (down)

The main structure consists of prefabricated concrete elements, and the materials used for the walls and the claddings are poor quality and at the present time are in bad conditions. The area around the apartments is now a bit deserted and desolated (Figure 2.2-3). All the technical documentation, floor plan drawings, materials information and measurements are included in the APPENDIX A: THE EKO-CANOPY PROJECT of this report.

Figure 2.2-3: Area of the surroundings (left) and space between two apartment blocks to be renovated (right)

Figure 2.2-4: Front façade (left) and back façade (right)

The proposal of White Architects consists on a Canopy construction between the two apartment blocks (Figure 2.2-5, right). The main concept is to create a nice and good environment, where social activities can be done, combined with playground spaces and green areas. The main structure is made with wood elements covered by a glass surface. The construction includes a serial of sustainable measures to fulfill with the goal of the competition.

The Figure 2.2-5 on the left shows the indoor environment created between two of the apartment blocks, where it can be seen the idea of the social transformation of the area.

Figure 2.2-5: Render inside Canopy (left) and scheme of overall concept of the Canopy(right) (White 2015)

Consequently, it is seen that a serial of design considerations should be taken into account. The aesthetic aspects should be in equilibrium with the energy and structural premises. Therefore the following parameters were studied: surface area to cover, solar potential, snow handling, ventilation of the Canopy to avoid the green effect, wind considerations, cost, and LCA.

One of the questionable aspects from the jury after the competition was the *"The major construction and the dimensioning of the structure*" (Knudsen 2016) included in the (Appendix XX). Therefore this master thesis is going to focuses its investigations on the structural considerations as a particular case study for the proposed design-analytical integrated method. All the aspects related to energy and indoor comfort have been investigated by Mikkel Kirkeskov Knudsen. (Knudsen 2016)

Part III: BACKGROUND

3.1 Literature review

In the context of the proposed research, two wide areas are the main focus of study, which at the same time are correlated.

On the one hand this work is based on the idea of looking for a logic method to be applied in the early design stages of the constructions projects, integrating both architectural and structural considerations. Within this area, firstly is important to introduce the traditional building process, and its evolution until how is interpreted nowadays. Related to this, the concept of BIM plays a significant role, as it constitutes the new way of understanding the building industry, where the architecture, the engineering and the construction coexists. This is the result of the seeking of reinvention to adapt the technological advances to the new decade. (W Young Jr. et al. 2009).

Although the term BIM is not the focus of this research, it is important to define its meaning. In this way, The National Building Information Model Standard Project Committee defines BIM as *"a digital representation of physical and functional characteristics of a facility. A building information model is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition"*[2]

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[2] Building Smart. International home for Open BIM. http://buildingsmart.org/standards/technical-vision/

Moreover, The National Institute of Building Sciences defines BIM as "*a fundamentally different way of creating, using, and sharing building lifecycle data*" (NIMBS Committe 2007). It divides the idea of BIM in three different meanings, firstly it is understood as a *product*, (BIM technology – modelling) secondly as a *collaborative process* and thirdly as a *facility lifecycle management requirement (BIM Methodology – Management Model)* (NIMBS Committe 2007) (W Young Jr. et al. 2009)

Therefore, it can be concluded that BIM involves all the processes of collaboration and exchange of data between all the agents who participate in the building process, based on the use of several software, which support a common data format (IFC format) and in last instance but being the key issue, that everything is connected by a central shared model.

This concept of collaboration of the building agents and data exchange between different platforms will be the basis of the method for this master thesis work, but express from a different approach that the BIM concept. In this frame is introduced the idea of integrated dynamic models. The IEA, International Energy Agency[3], introduce this concept on its guide "*Integrated Design Process, a guideline for Sustainable and Solar-Optimised Building Design"*(G. Löhnert, A. Dalkowski, and W.Sutter 2003), where is clearly stated the necessity of re-think the structure the design process with the aim of combine "*more knowledge and creativity in the early stages of the process"*(Task 23 IEA 1997). This mentality leads to study different design options but analyzing its potential performance as the technical knowledge is included from the beginning. When the engineer point of view is introduced in the process in last stages, it is not possible that the technical knowledge has an influence on the design choice.

In this way, Integrated design process (IDP) is "*based on the idea of an optimized teamwork, a qualified design process management including application of modern tools and strategies which fit to the project goals"* (G. Löhnert, A. Dalkowski, and W.Sutter 2003).

This philosophy is further discussed by Negendahl in its article "*Building performance simulation in the early design stage: An introduction to integrated dynamic models*" (Negendahl 2015a), where is study the idea of combining analysis tools with design tools. In this way, it is possible to consider multiple alternatives while a technical feedback is provided. Therefore, in Figure 3.1-1 (Negendahl 2015a)the definition of an integrated dynamic model is illustrated.

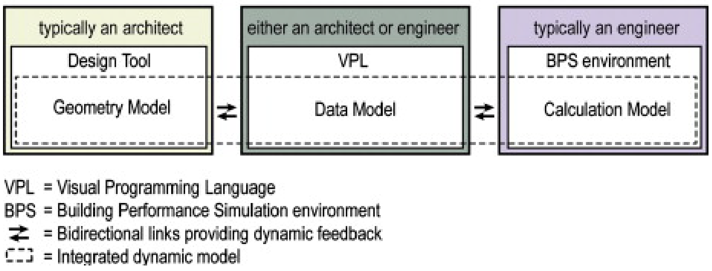

Figure 3.1-1: Definition of an integrated dynamic model (Negendahl 2015a)

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[3] http://task23.iea-shc.org/description

It consists in the interaction of the design tools, often used by architects, and the calculation tools (Building Performance Simulation Tools), which normally are run by engineers. The main issue is to integrate both in a way that the use of the computer tools is maximized. Solving this, it would possible to manage a tool which gives both, aesthetic evaluation and technical feedback, allowing to identify structural problems in the first steps of the designing process. (Klitgaard, Kirkegaard, and Mullins 2006)

Both groups design and BPS tools are interconnected by means of Visual Programming Language (VPL). The model data, both geometry definition and calculations, is transferred through the different platforms in a bidirectional way. This concept is the basis to set up the method which is further explained in Part IV: Method (24).

Moreover, as it is state by Negendahl (Negendahl 2015b) the visual programing language is often based on Parametrical tools integrated in the Design softwares. These are for example, Grasshopper, the graphical algorithm editor tightly integrated with Rhino's 3-D, Autodesk® Dynamo Studio, software integrated in Autodesk Revit, as the standalone programming environment for the design, or Bentley’s Generative Components. These platforms allow to the user to create multiple variables providing great flexibility to the designs.

In this scenario it should be contemplated that the idea of a common link, as is the VPL tools, contradicts the philosophy of BIM, as while “*VPLs facilitate data across any content- and object relationship, schemas like IFC prescribe object relationships through attribute data”* (Negendahl 2015b).

The idea of parametrical modeling leads to the second big topic of this research work. Accordingly with this, on the other hand, the second area of research is the optimization techniques to be developed with the aim of finding efficient and sustainable structures, where the minimal amount of mass for the overall construction is used.

The optimization process is a complicated practice which has been investigated for numerous researches over the years. Its complexity is mainly related that the practice of optimization is based on mathematical problems. Therefore in order to understand it numerous articles and books have been investigated, as the works from (Kirsch 1993), (Byrne et al. 2011), (Christensen and Klabring 2009), (Bendsøe 1989), (Christiansen et al. 2015), and (Sigmund 2001) etc. The aim of this thesis is incorporate the structural optimization process in early stages of the architectural designs, so it would be study from the design point of view based on the use of parametrical tools, leaving aside the mathematical formulation itself connected with programming. These aspects would be further on developed in *4.3 Optimization process description*, as this section would set the basis of the optimization processes done for this thesis.

3.2 The Building Design Process and its tools

From the previous chapter, it is clearly seen the importance of the use of the different software along the long building process. They could be divided in two main different big categories: Design Tools and Building Performance Simulations Tools.

Inside the design tools group, there are found platforms such as Autodesk Revit, Rinhoceros 3D by Robert McNeel & Associates, ArchiCAD, etc.

Additionally, within the group of Building Performance Simulation Tools, softwares as Autodesk Robot Structural Analysis, FEM-Design, Staad.Pro of Bently, ANSYS, etc are found.

The features which provide each of these tools make the basis which establishes the working flow of the building process. Depending on their performance, the data exchange direction is set. However, regarding to this, the process can be unidirectional o bidirectional, as it has been introduced before. Within this context is important to also mention the agents who participate in each of the steps of this process.

In this way, the unidirectional approach is based on the traditional understanding of the designing process, which according to numerous researchers is called *linear approach* (Klitgaard, Kirkegaard, and Mullins 2006). It consists in the basic idea that is the architect in charge of the design, including both phases, sketching and creation of the 3D model; and then the engineer analyses the model once that it has been already finished, as it shown in the scheme a) Figure 3.2-1 (Klitgaard, Kirkegaard, and Mullins 2006).

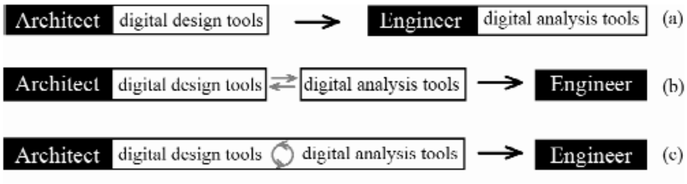

Figure 3.2-1: Three approaches for the working flow of the different agents in the building process. [Figure 2, (Klitgaard, Kirkegaard, and Mullins 2006)*, The three approaches – (a) the architects, (b) the hybrid practitioner and (c) the approach provided by the prototype, showing the initial sketching phase on the left side of the black arrow and the detailing phase on the right side.*

This way of working is, in most of the cases, really time consuming. Probably, after the post analysis of the engineer, the model decided by the architect has to suffer changes, so it is necessary to go back in the process and do the steps again, repeating this until achieve a reliable configuration. The Figure 3.2-2 proposed by *Klitgaard (Klitgaard et al. 2006*) shows this linear approach.

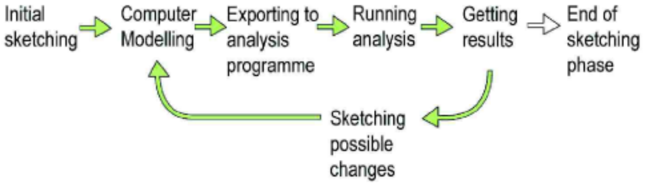

Figure 3.2-2: linear approach. Working flow scheme proposed by Klitgaard (Klitgaard et al. 2006*, figure 3)*

Otherwise, the second case, the bidirectional approach, is then based on the idea of forward-back flow, where the data is transferred dynamically back and forward by VPL, as it was illustrated in Figure 3.1-1. This also corresponds with the scheme b) of the Figure 3.2-1 (Klitgaard, Kirkegaard, and Mullins 2006).

Therefore, it should be mentioned that exists different approaches when the idea of exchange data is studied. This is clearly explained by Negendahl 2014. The three different concepts are illustrated in the Figure 3.2-3, which could be understood in the following way: the first scheme corresponds to the traditional working process, which is usually based in the use of a simulation package. Additionally, the second scheme deals with the concept of having a central model where the data is shared by different softwares, which is clearly the idea of BIM. Lastly, the third scheme represents the lately introduced method which consists in a bidirectional process where the platforms are coupled by a middleware based on VLP. The main objective of this last approach is to use a tool which provides to the practitioner both, aesthetical and technical features (Klitgaard, Kirkegaard, and Mullins 2006), leading this again to the idea of the hybrid practitioner.

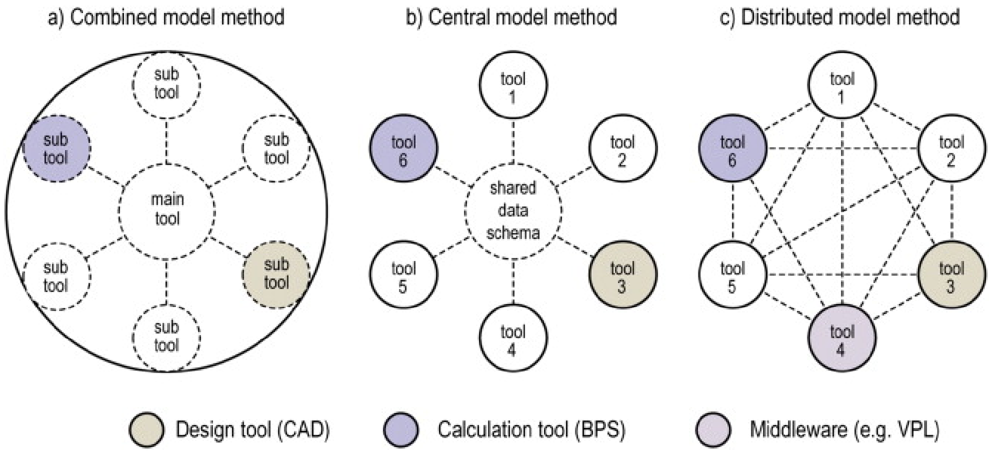

Figure 3.2-3: Differences between coupling methods [Negendahl 2014. Figure6: a) combined model method (typically operated in a simulation package), b) central model method (using a central database/file format/schema), c) distributed model method (utilizing a middleware)]

Consequently, due to the differences between the idea of Building information modeling and Parametric design is should be found a balance where both interact, as it was stated by Boeykens (Boeykens 2012), "*it is worthwhile to further elaborate the integration of these approaches in the design process, to benefit from advantages in both*". This is the main objective of the method proposed in Part IV: Method, where different softwares, including both Parametric Design and BIM tools, are integrated in a flow working process.

3.2.1 Potential of visual programming language tools in the building Industry

The importance of the VPL tools is clearly stated in the previous introduction referred to the building design process. However, before enumerate its benefits; it is important to understand what *Parametric modelling* is.

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The term parametric is originally related to mathematics. According to the science Oxford dictionary, parametric is all "*Relating to or expressed in terms of a parameter or parameter*"[4]; being defined parameter as "*a numerical or other measurable factor forming one of a set that defines a system or sets the conditions of its operation*" and within the mathematical field as "a *quantity whose value is selected for the particular circumstances and in relation to which other variable quantities may be expressed*"[5]. Later on, the term was related with design according to the work developed by Daniel Davis (Davis 2013), where it is stated that Moretty (1971) introduced the term "parametric architecture", which he defines as "*the study of architecture systems with the goal of defining the relationships between the dimensions dependent upon the various parameters."* (Davis 2013).

According to these definitions, it can be said that parametric modeling is based on the creation of several relations between certain numbers of parameters to create logic representations, which in relation with the architecture, means the definition of geometry based on links and nodes (Gallas et al., n.d.). In this way in parametric modeling the designer controls the creation of geometries from an overall logical script or scenario (Boeykens 2012).

Furthermore, it should also mention that the use of parametric modeling in the architectural field has led to a change of mentality. According to Woodbury in his book *Elements of Parametric Design* (Woodbury 2010), "*parametric modelling introduces fundamental change: 'marks', that is, parts of the design, relate and change together in a coordinated way*". In this way, while the old philosophy of the architects was "*pencil, eraser and paper*", they now have progressed to the ideal of "*add, erase, relate and repair"*.

In this scenario, in relation with the work of M. Stavric and O. Marina, *Parametric Modeling for Advanced Architecture*, the development of digital design did not end with simple parametric modeling, it has taken a step ahead by using generative algorithms (Stavric and Marina 2011). Nowadays, these are integrated in the 3D design modeling tools, which makes easier for non-programmers to use, as they are Grasshopper, Dynamo or Generative Component from Bently.

At this point, we should ask ourselves, what are the real benefits of the parametrical modeling using this kind of tools?

The first benefit is the fact that they provide great flexibility to the designs. Determining a certain number of parameters, it is possible to play with the geometry until achieve the desired configuration. The parameters will vary depending on the last goal of the designer, being these parameters such as structural considerations, daylight, sun, angles, climatic data, energy limitations, etc. These parameters are often specified as number sliders, which are modified in accordance with different premises, creating different geometric models depending on the specific value.

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[4] http://www.oxforddictionaries.com/definition/english/parametric

[5] http://www.oxforddictionaries.com/definition/english/parameter#parameter__5

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This process helps to reduce the time required during the design phase, as it is possible to evaluate several configurations for a certain domain compared to the conventional 3D modeling tools.

Thanks to the new technology advances, every day appears new platforms which are fully integrated in the parametrical tools. This fact allows to the user to evaluate his designs from different perspectives, including both energy and structural aspects. For example, the plug-in Karamba for Grasshoper, allows to the user to perform Finite Element Calculations of the designed geometry in a dynamically way. This feature is the perfect example which link the labor of the architect and the engineer, as in order to use its features, it is necessary to have good structural knowledge.

Other benefit that provides these VPL tools is the possibility of performing form-finding and topological optimization processes. This is related with the idea of optimization that was earlier introduced. For example, in the case, optimization processes are carried out in grasshopper thanks to its component “Galapagos”.

Furthermore, these parametrical modeling tools allow to the user to export the final desired model using the generic IFC format. This has a vital importance, as once that the parametric model design has been finished; it is possible to import it into a BIM software to continue with the corresponding analysis.

3.2.2 Softwares used for this master thesis

Once that it has been studied the different tools that coexist nowadays in the building industry, this section is meant to indicate the software used for the realization of this master thesis, including a brief explanation of their main features. Mainly, all the procedures have been done in the Grasshopper interface using the FEM plug-in Karamba, but other software have been also used in the process which is going to be explained in Part IV. (The descriptions have been taken from the corresponding webpages)

3.2.2.1 Grasshopper 3D. algorithmic modeling for Rinho[6]

It is developed by Scott Davidson and is a graphical algorithm editor tightly integrated with Rhino’s 3-D modeling tools. Unlike RhinoScript, Grasshopper requires no knowledge of programming or scripting, but still allows designers to build form generators from the simple to the awe-inspiring.

It allows to install several plug-ins, in this case have been mainly used:

- GeomtryGym (Export data as IFC format)
- ToolBox (Inludes Galapagos listener)
- Karamba (FEM – calculations)

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[6] http://www.grasshopper3d.com/

3.2.2.2 Karamba Parametric engineering[7]

Karamba is developed by Clemens Preisinger in cooperation with Bollinger-Grohmann-Schneider ZT GmbH Vienna and it is a parametric structural engineering tool which provides accurate analysis of spatial trusses, frames and shells.

Karamba is fully embedded in the parametric design environment of Grasshopper, a plug-in for the 3d modeling tool Rhinoceros. This makes it easy to combine parameterized geometric models, finite element calculations and optimization algorithms like Galapagos.

3.2.2.3 Autodesk Revit[8]

Revit® BIM software powered by Atodesk Comunity is specifically built for Building Information Modeling (BIM), including features for architectural design, MEP and structural engineering, and construction. Revit is a single software application that supports a BIM workflow from concept to construction.

3.2.2.4 FEM – Design - StruSoft[9]

FEM-Design is an advanced modeling software powered by StruSoft for finite element analysis and design of load-bearing concrete, steel and timber structures according to Eurocode. The quick and easy nature of FEM-Design makes it ideal for all types of construction tasks from single element design to global stability analysis of large structures and makes it the best practical tool for structural engineers.

3.2.2.5 Autodesk Robot Structural Analysis[10]

Robot™ Structural Analysis Professional software powered by Autodesk Community provides engineers with advanced BIM-integrated analysis and design tools to understand the behavior of any structure type and verify code compliance

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[7] http://www.karamba3d.com/

[8] http://www.autodesk.com/products/revit-family/overview

[9] http://www.strusoft.com/products/fem-design

[10] http://www.autodesk.com/products/robot-structural-analysis/overview

Part IV: METHOD

The objective of this part is to describe the method which has been set up and followed for this Master Thesis, with the aim of providing the necessary premises to the reader to be able to understand all the different approaches and calculations which has been done.

Accordingly, the first step has been to estipulate the main objective of the method; followed by the description of the process based on its flow illustration. This shows how the different tools which have been used form an integrated process, giving a clear understanding of how everything interacts and establishing the decisions and considerations which should be made in each step.

4.1 Objective

The main objective is to apply a highly effective workflow that integrates structural analysis in the early stages of the design process, combining design and calculation tools trying to solve the first question formulated for this master thesis work. This would allow to the designers to reduce the overall time of the design process stage, including the technical knowledge, as the structural verifications, from the beginning.

When we are talking about the method, it should be mention that two different types of methods exist. The first one is referred to the work process and how the data is transferred through the different platforms and which steps are done in each one (4.2 Applied integrated process description) the second one is more practical and is referred to the different processes which have been carried out to achieve the optimal designs, based on different optimization processes (4.3 Optimization process description)

4.2 Applied integrated process description

The idea of integrated design process (IDP) was first introduced in section *3.1 Literature review* based on the scheme of *the Figure 3.1-1: Definition of an integrated dynamic model introduced by* Negendahl (Negendahl 2015a), where the design tools, often use to create the geometries of the models, where connected to the BPS tools, which analyze the model configurations, by means of the VPL tools.

The parametrical tool Grasshopper can include certain plug-ins which allows to the practitioner to perform calculations inside the parametrical modeling frame. In this case, *Karamba* execute the FEM calculations for the structure modeled in grasshopper. This dynamic exchange of data allows to the engineer/architect to play with different designs (parametric modeling) obtaining an automatic feedback in terms of technical aspects, which speeds up the design process. In this way, the scheme of dynamic model (*Figure 3.1-1:* Definition of an integrated dynamic model has been developed to be applied to this specific method. As it can be seen the exchange of data between Rinho 3D, Grasshopper and Karamba is produce dynamically way. When the desired design is achieved, this model can be exported to another FEM software to continue with more detailed calculations.

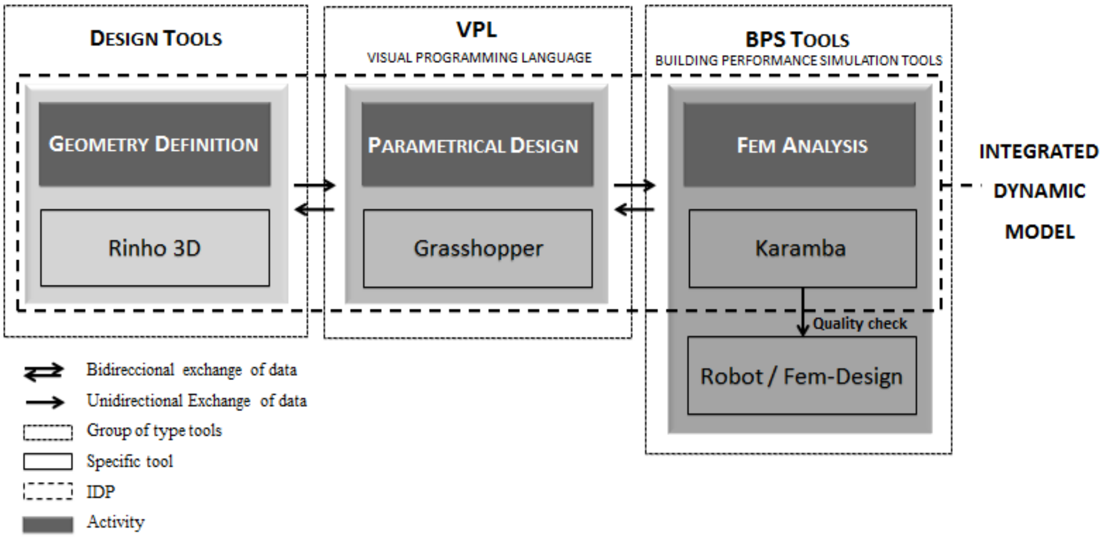

Figure 4.2-1: Developed Integrated Dynamic model

Consequently in this context, the following diagram (Figure 4.2-2) shows the working flow based on VPL (Parametrical design tools), which is Grasshopper in this case. It is divided in five different stages, which go from the definition to the geometry until reach the group of optimal configurations, going through FEM calculations and optimization processes.

In the first stage is necessary to input a series of parameters, which will vary depending on the model geometry. Furthermore, the structural definition (stage 3) will also depend on the configuration and it requires technical knowledge in order to set it correctly.

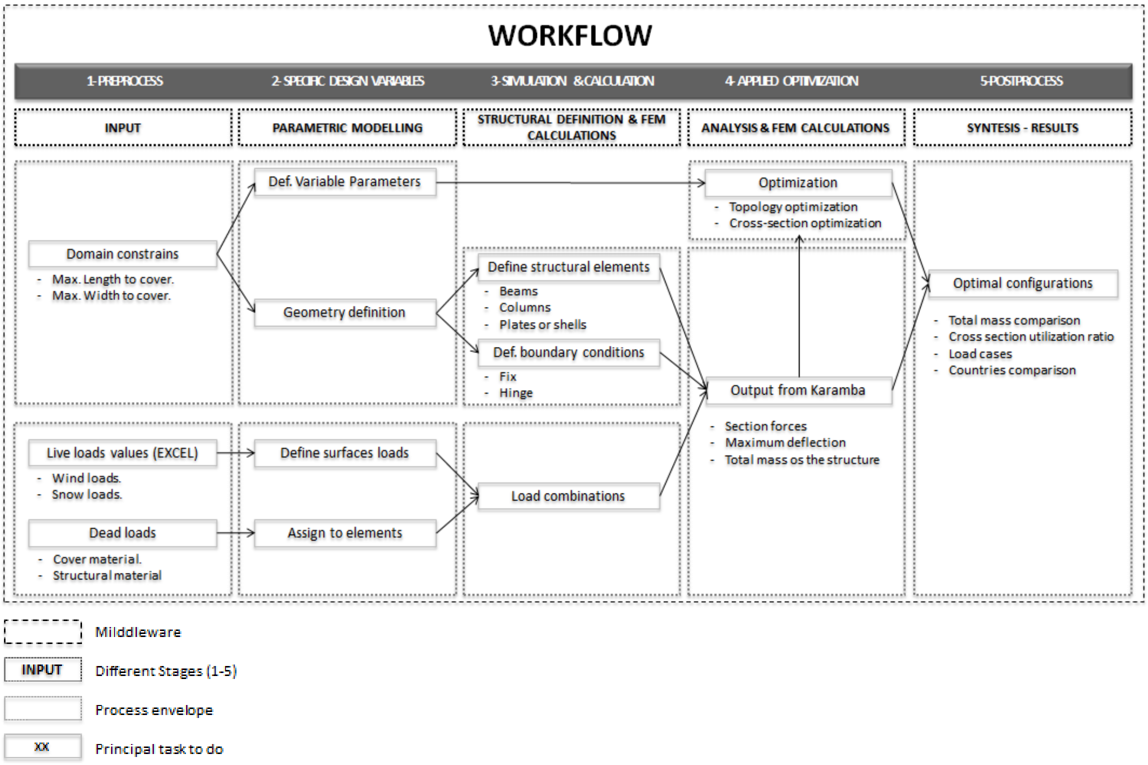

Figure 4.2-2: Workflow for the specific method. Steps carried out in each stage.

As a result, it is obtained the performance of different geometry models, knowing their maximum deflection, the total amount of mass of the structure, the utilization ratio of the cross-sections, etc. This allows to the practitioner to choose the best solution basing his decision on the parameters that he considers or the requirements that he must fulfill to accomplish the desires of the client.

In Part V: Results-Structural Analysis (5.2) different model configurations will be studied, and the workflow will be adapted to each of them, indicating the parameters considered in each case.

Furthermore based on the previous schemes (Figure 4.2-1 and Figure 4.2-2), the following diagram (Figure 4.2-3) shows the connection between the different platforms used, giving an overview of how the Design Tools, VPL tools and BPS tools are connected. Additionally, here the math and spreadsheets softwares have been also added.

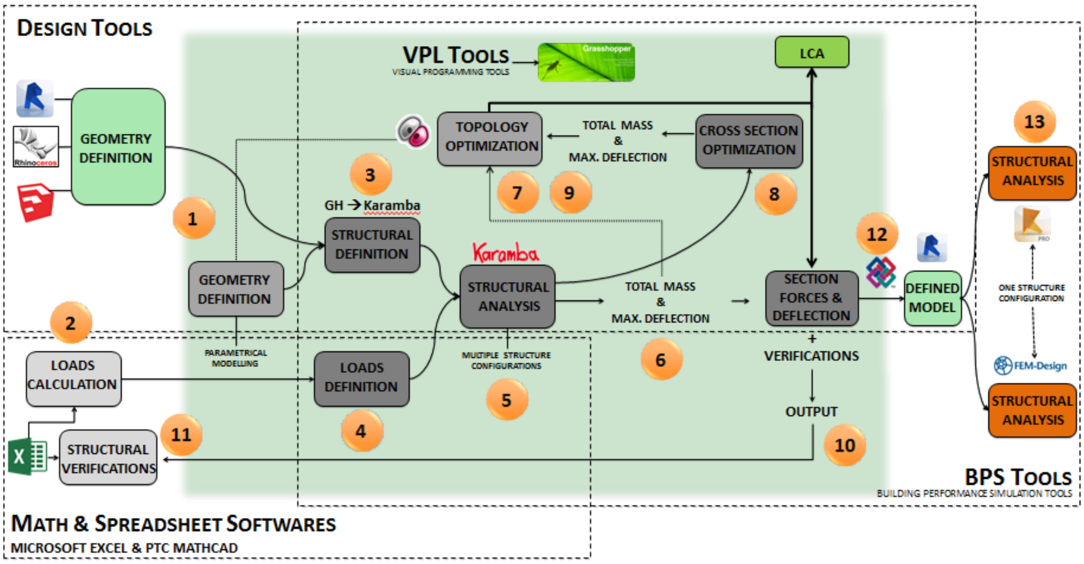

Figure 4.2-3: Applied Integrated design process

It is clearly seen that again the VPL tools serve as a common link between the other three type of tools (Design, BPS and Spreadsheets tools).

In this way the brief description of the process is as follows:

1. ***First step: Creation of the geometry*** either in the design tools (Rinho 3D, Sketch up or Revit) or in the Grasshopper interface.
2. ***Second step: Loads calculations*** in the Excel spreadsheet (Calculations for all the Nordic countries)
3. ***Third step: From GH to Karamba***. Transformation of all the geometry elements into structural elements: beams, columns or plates. Definition of the boundary conditions (supports) and dimensions of the cross-sections (approximate).
4. ***Fourth step: Definition of the loads in Karamba***. Specification of the different wind and snow load areas on the model reading the values from excel. Integration of the load combinations in Grasshopper.
5. ***Fifth step: Perform the FEM analysis using Karamba.***
6. ***Sixth step: Analysis of the results.*** Check that structure doesn't collapse with the estimated cross-sections. Find ways to improve it.
7. ***Seventh step: Topology optimization 1.*** Perform the 1st optimization process using Galapagos component for GH.
8. ***Eight step: Cross-section optimization.*** Perform the 2nd optimization process using the component for Karamba, "Cross-section optimization"
9. ***Ninth step: Topology optimization 2.*** Perform the 3rd optimization process using Galapagos based on the results from the 8th step – cross-cross section optimization.
10. ***Tenth step: Export the results to excel.*** Comparison for the total mass of the structure before and after the cross section optimization.
11. ***Eleventh step: Analysis of the configurations***. Extract the different combinations, analyse the optimal ones based on the amount of mass and the utilization ratio of the

cross sections. Check that the elements of the structure fulfil the requirements specified in the Eurocode. Repite the optimization loop from step 7 if it is necessary.

12. ***Twelfth step: Export the chosen geometry (IFC format).*** Based on the analysis of the step 11th, choose one of the optimal configurations and export it to Revit using the plug-in for GH *GeometryGym*.
13. ***Thirteenth step: Analysis of the Structure in FEM software***. Analyses of the structure either in Robot or FEM-design. Compare the section forces values with the ones calculated from Karamba.

4.3 Optimization process description

The last diagram leads to introduce the method followed for the optimization process. As it was presented before, this procedure implies the use of mathematical programing techniques as it is stated in the paper of Y.M. Xie and G.P.Steven (Xie and Steven 1993). For example the work developed by O. Sigmund presents a Matlab script to carry out topology optimization for compliance minimization of statically loaded structures (Sigmund 2001).

However, the objective is to combine those practices coming from the engineer field within the architectural designs. This is study by means of the evolutionary structural design computation by Byrne (Byrne et al. 2011) . The concept is based in an evolutionary search of reducing the material usage and cost of the structure, but being this able to resist the stresses produced by the loads without collapse. This is done using Finite Element Methods.

In this way, the new architectural-engineers approaches tend to see the optimization processes as a way to generate aesthetic and efficient structural configurations. (Block et al. 2014). Numerous studies show that this combination adds great value to the projects.

In the work developed by Peter W. Christensen and Anders Klarbring, "*An Introduction to Structural Optimization*" (Christensen and Klabring 2009) it is formulated the optimization process as: "*minimize f(x,y) with respect to x and y;subject to behavioral constraints on y, and design constrains on x*" Where *"f"* is the *Objective function, "x"* is the *design variable* changed during the optimization, and *"y"* is the *state variable* which is the response of the structure.

In the case of this master thesis, the optimization procedures will be carried out thanks to the component Galapagos of Grasshopper, which is an evolutionary solver developed by David Rutten. This is a generic platform for the application of Evolutionary Algorithms to be used on a wide variety of problems by non-programmers. [11] To run Galapagos is necessary to define the goal of the optimization, called as Fitness value (objective function) and the parameters to optimize, called as genes (design variables) (Rutten 2016). In this way, the state variables would be the structural verifications (stresses, buckling and deflection) that the structure should fulfill.

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[11] http://www.grasshopper3d.com/group/galapagos

Before described the optimization method, it is important to clarify that for this particular project "optimization" is understood as the semi-automated process of finding feasible structural configurations through an integrated dynamic model (coupled to an optimization algorithm). Hence, the optimization is only applied to the design of elements that concerns structure of the selected design principle, and very important to state, do not apply to other disciples, such as energy performance, cost, functional requirements, aesthetics etc.

In this way, in order to set up the optimization process (steps 7,8 and 9), it is important to explain the types of procedures which exits. According to (Christensen and Klabring 2009) there are three types of structural optimization problems:

- Shape optimization. It is referred to the boundary of the structural domain.
- Sizing optimization. It is referred to the cross-sections of the elements of the structure.
- Topology optimization. It is the process of form-finding the optimal shape and configuration of the structure. In (Nyman and Andreas 2015) is define as the "*discipline of computing the optimal shape and topology of a structure with respect to some desired effect"* (Bendsøe and Kikuchi, 1988; Bendsøe and Sigmund, 2003)

The last two processes have been implemented in the Grasshopper script, as the first one (domain) is fix. Below the process of optimization is described in seven steps. These steps may be read as if they were included in a larger loop that continues until "optimality" has been found.

To be able to carry the topology optimization is necessary to pre-define a structure configuration, setting its boundary conditions and cross-sections. After this, it is run Galapagos, defining the genes and the fitness for each case (***Seventh step: Topology optimization 1.*** Perform the 1st optimization process using Galapagos component for GH.), followed by the second optimization step (***Eight step: Cross-section optimization.*** Perform the 2nd optimization process using the component for Karamba, "Cross-section optimization".Thanks to the component Optimized Cross Section' from *Karamba*, it is possible to run at the same time the ***Ninth step: Topology optimization 2.*** Perform the 3rd optimization process using Galapagos based on the results from the 8th step – cross-cross section optimization. and record the values of both processes (Galapagos listener). This second topology optimization considers the cross sections defined in step 8.

It should be mentioned that the 'Optimized Cross Section'-component from *Karamba* takes into account the buckling of each specific member depending on the buckling length (6.5.4 Buckling Modes, Preisinger 2015), however when the results are verified analytically, not always fulfill the requirements against buckling. This component considers the load bearing capacity of each member, checking that is sufficient for all the load cases of the structure. This is done following the requirements established in the Eurocode 1993-1-1. The values Cmy and Cmz are limited to a maximum of 0.9 (Section 6.5.9, Preisinger 2015)]. It is also taken into account the lateral torsional buckling of the elements according to the cross-section classification for class 1 to 4 (*Table 5.2* Eurocode3 2001). See also *Cross section class*.

Furthermore, as according to (Eurocode3 2001) there is a limitation of the maximum deflection of the components which form a structure; the maximum deflection allowed has been also implemented in the component in order to provide the most efficient result for the cross section.

This process is schematized in the following diagram, described in the following steps:

- Study of the space
- Optimization: from basic construction to a complex design
  1. Load analysis: wind, snow and self-weight
  2. Structural analysis single member: theory and limitations
  3. Pre-definition of the cross sections
  4. First optimization process (Step 7 - topology) → Goals: minimal deflection and minimal mass of the structure.
  5. Second optimization process (Step 8 - sizing) → optimal cross section working at 90% of their capacity
  6. Third optimization process (Step 9 - topology) Goals: minimal deflection and minimal mass of the structure.
  7. Structural verifications. If the members defined do not fulfill the requirements a/EC repeat the optimization loop until a suitable solution is achieve.

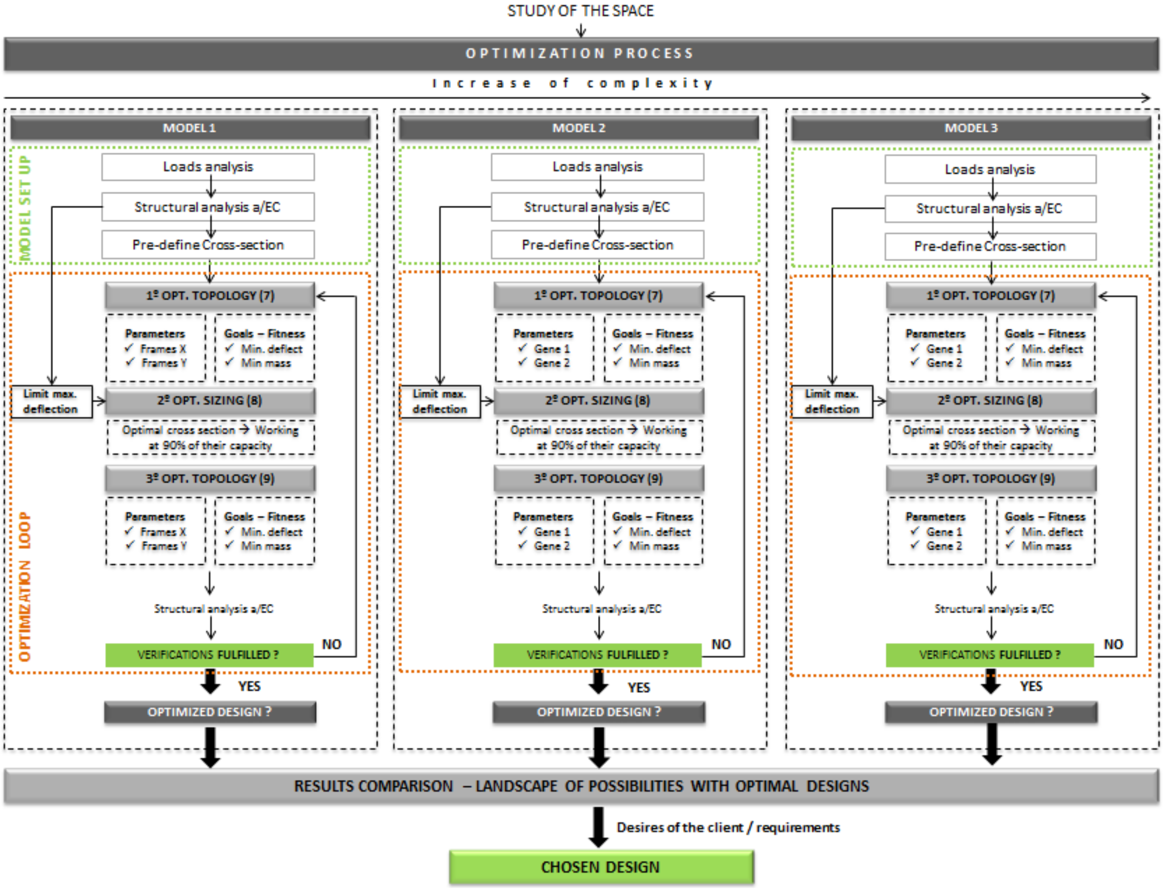

Figure 4.3-1: Optimization method scheme

4.4 Normative

The structural verifications should be implemented in the method described before; therefore this section establishes all the necessary theory regarding the structural calculations. It is based on the premises specified by the Eurocode, including all the conditions set by the corresponding National Annex.

It should be noted that this chapter formulate all the basic equation to carry out the calculations, but express in a general way. Further on, in Part V: Structural analysis, it would be mentioned the different assumptions which have been done for each specific case.

First are going to be explained the procedures to calculate the wind loads, followed by the calculation of the snow loads, and in last instance, all the necessary formulations to estimate the bearing capacities for the steel elements and their verifications.

4.4.1 Wind loads calculations

´The wind loads are calculated following the specifications in the Eurocode 1, part four (DS/EN 1991-1-4 2007) and the corresponding National Annex for each country.

As it is specified in the section 3 of DS/EN 1991-1-4 : 2007, the wind actions will depend on each design situation, which means that for each of the models they will vary, but all follow the same calculation procedure which will be described as follows:

4.4.1.1 Basic wind velocity (DS/EN 1991-1-4 2007, eq. no.4.1)

$$v_b = c_{dr}\, c_{season}\, v_{b,0} \text{ [m/s]} \tag{4.1}$$

Where:

- V_b is the basic wind velocity, defined as a function of wind direction and time of year at 10 m above ground of terrain category II
- $V_{b,0}$ is the fundamental value of the basic wind velocity
- c_{dr} is the directional factor
- c_{season} is the season factor

4.4.1.2 Mean wind velocity (DS/EN 1991-1-4 2007, eq. no.4.3)

$$v_m(z) = c_r(z)\, c_0(z)\, v_b \text{ [m/s]} \tag{4.2}$$

Where:

- $c_r(z)$ is the roughness factor calculated according *section 4.3.2 DS/EN 1991-1-4 2007*
- $c_0(z)$ is the orography factor calculated according *section 4.3.3 DS/EN 1991-1-4 2007*

4.4.1.3 Wind turbulence (DS/EN 1991-1-4 2007, eq. no.4.6)

$$\sigma_v = k_r \, v_b \, k_l \tag{4.3}$$

Where:

- k_r is the terrain factor calculated according *eq. 4.5 DS/EN 1991-1-4 2007*
- v_b is the basic wind velocity.
- k_l is the turbulence factor. This value may be given in the National Annex. The recommended value is 1.0

4.4.1.4 Turbulence intensity (DS/EN 1991-1-4 2007, eq. no.4.7)

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_l}{c_0(z)\ln(\frac{z}{z_0})} \text{ for } z_{min} \leq z \leq z_{max} \tag{4.4}$$

$$I_v(z) = I_v(z_{min}) \text{ for } z \leq z_{min} \tag{4.5}$$

Where:

- $c_0(z)$ is the orography factor calculated according *section 4.3.3 DS/EN 1991-1-4 2007*
- z_0 is the roughness length, given in *Table 4.1 DS/EN 1991-1-4 2007*.
- k_l is the turbulence factor. This value may be given in the National Annex. The recommended value is 1.0

4.4.1.5 Peak velocity presure (DS/EN 1991-1-4 2007, eq. no.4.8)

$$q_p(z) = [1 + 7I_v(z)] \, \frac{1}{2}\rho \, v_m^2 \, (z) = c_e(z)q_b \; [kN/m^2] \tag{4.6}$$

Where:

- ρ is the air density, which depends on the altitude, temperature and barometric pressure to be expected in the region during wind storms. In all the cases is taken as 1.25 kg/m^3
- $c_e(z)$ is the exposure factor given by *eq. 4.9 DS/EN 1991-1-4 2007* [$c_e(z) = \frac{q_p(z)}{q_b}$]
- q_b is the basic wind velocity pressure given by *eq. 4.10 DS/EN 1991-1-4 2007* [$q_b = \frac{1}{2} \rho \, v_0^2$]
- $I_v(z)$ is the turbulence intensity specified in eq. (4.4) or (4.5)

4.4.1.6 Wind pressures on surfaces (DS/EN 1991-1-4 2007, eq. no.4.1)

$$w_e = q_p(z_e)c_{pe} \tag{4.7}$$

Where:

- $q_p(z_e)$ is the peak velocity pressure specified in eq. (4.6)
- z_e is the reference height for the external pressure. *[Section 7 DS/EN 1991-1-4 2007]*
- c_{pe} is the pressure coefficient for the external pressure. *[Section 7 DS/EN 1991-1-4 2007]*

4.4.2 Snow loads calculations

Accordingly, the snow loads are calculated following the specifications in the Eurocode 1, part three (DS/EN 1991-1-3:2007 2007) and the corresponding National Annex for each country.

In the same way that for wind loads, the snow loads will depend on each design situation, which means that for each of the models they will vary. The characteristics causing different values are stated in *section 5.1 Nature of the load* (DS/EN 1991-1-3:2007) and are:

a) The shape of the roof.
b) Its thermal properties.
c) The roughness of its surface.
d) The amount of heat generated under the roof.
e) The proximity of nearby buildings.
f) The surrounding terrain.
g) The local meteorological climate, in particular its windiness, temperature variations, and likelihood of precipitation.

Furthermore, the load arrangement can be considered as "*undrifted snow load on roods*" or as ¨*drifted snow load on roofs*". The first one is defined by *section 1.6.5* DS/EN 1991-1-3:2007 as "*load arrangement which describes the uniformly distributed snow load on the roof, affected only by the shape of the roof, before any redistribution of snow due to other climatic actions*". Meanwhile, the second one is defined by *section 1.6.6* DS/EN 1991-1-3:2007 as "*load arrangement which describes the snow load resulting from snow having been moved from one location to another location on a roof, e.g. by the action of the wind*".

In case of the snow load calculation, there are three different situations:

4.4.2.1 *Persistent / transient design situation*

$$s = \mu_l\, C_e\, C_t\, s_k \tag{4.8}$$

4.4.2.2 *Accidental design situations where exceptional snow load is the accidental action*

$$s = \mu_l\, C_e\, C_t\, s_{Ad} \tag{4.9}$$

4.4.2.3 *Accidental design situations where exceptional snow drift is the accidental action*

$$s = \mu_l\, s_k \tag{4.10}$$

Where:

- μ_l is the snow load shape coefficient, it wil depends on the shape of the roof (two different cases will be calculated, explained in Part V: Structural Analysis)
- s_k is the characteristic value of snow load on the ground specified in the corresponding National Annex for each country.
- s_{Ad} is the pressure coefficient for the exernal pressure. *[Section 7 DS/EN 1991-1-4 2007]*
- C_e is the exposure coefficient specified in *Table 5.1 DS/EN 1991-1-4 2007.* In this case it is taken as 1,0 for Normal topography.
- C_t is the thermal coefficient. It is taken as 1, as the heat transmittance is larger than 1 W/m^{2}K

4.4.3 Steel Calculations

The necessary steel verifications, including the checks regarding the capacities of the cross section, the buckling resistance, the lateral torsional resistance and the requirements for the deflections of the elements, are calculated according to the premises in Eurocode 3: Design of steel structures (Eurocode3 2001).

It should be mention that depending on the element which is being calculated the different coefficients to adopt will vary, so all the equations are listened in their general form, and the corresponding considerations will be made for each case during the calculation process.

The verifications are divided for the two main elements which form the structure; being on the one side the verifications regarding the beams and on the other side the verifications for columns.

Beams Verifications

The following formulations show the procedure which has been followed to check the beams cross section capacities. First must be specified the steel class and the section properties.

The beam capacity control is done for Ultimate Limit States (ULS) for members subjected to bending and shears forces. The resistance of the cross section according to the *clause 6.2* (6) of the Eurocode 3: Design of Steel structures (Eurocode3 2001) shall be verified by finding a stress distribution which equilibrates the internal forces and moment without exceeding the yield strength. As a general rule the stresses are calculated following *Navier's formula*, stated in the equeqtion (3.11)

$$\sigma = \frac{N}{A} + \frac{M_y}{I_Y} z - \frac{M_z}{I_z} y \leq f_{yd} \text{ [kN/m}^2\text{]} \tag{4.11}$$

Furthermore, the individual checks for axial, shear and bending must be also fulfilled, being the design forces smaller than the capacities.

4.4.3.1 Cross section class

For the internal compression parts (web of the profile), case: Part subject to bending. *Table 5.2* (Eurocode3 2001)

Section class 1 → $\frac{c}{t} \leq 72\,\varepsilon$ (4.12)
Section class 2 → $\frac{c}{t} \leq 83\,\varepsilon$
Section class 3 → $\frac{c}{t} \leq 124\,\varepsilon$
Section class 4 → $\frac{c}{t} > 124\,\varepsilon$

Where:

- c is the efficient length of the web, calculated as: $c = h_w - 2\,t_f$, being h_w the height of the profile and t_f the thickness of the flange.
- t is the thickness of the web (t_w)
- $\varepsilon = \sqrt{235/\,f_y}$

For the outstand flanges (flange of the profile, *Table 5.2* (Eurocode3 2001)

Section class 1 → $\frac{c}{t} \leq 9\,\varepsilon$ (4.13)
Section class 2 → $\frac{c}{t} \leq 10\,\varepsilon$
Section class 3 → $\frac{c}{t} \leq 14\,\varepsilon$
Section class 4 → $\frac{c}{t} > 14\,\varepsilon$

Where:

- c is the efficient length of the web, calculated as: $c = \frac{b-t_w}{2} - r$ being b the width of the profile, t_w the thickness of the web and r the root radius.
- t is the thickness of the flange (t_f)
- $\varepsilon = \sqrt{235/\,f_y}$

4.4.3.2 Bending moment Capacity control

The cross section must fulfill:

$$\frac{M_{Ed}}{M_{c,Rd},} \leq 1 \qquad (4.14)$$

Where the Bending resistance is calculated according to the cross-section class:

Class 1 or 2 → $M_{c,Rd} = \frac{W_{pl}\,f_y}{\gamma_{M0}}$ [kNm] (4.15)
Class 3 → $M_{c,Rd} = \frac{W_{el,min}\,f_y}{\gamma_{M0}}$ [kNm]

Class 4 → $M_{c,Rd} = \frac{W_{eff,min}\ f_y}{\gamma_{M0}}$ [kNm]

Where:

- W_{pl} is the Plastic modulus of Elasticity [cm^3]
- $W_{el,min}$ is the min Elastic modulus of Elasticity [cm^3]
- W_{eff} is the Effective modulus of Elasticity [cm^3]
- f_y is characteristic yield strength [kN/cm^2]
- γ_{M0} is the partial safety factor specified in *Section 6.1* (Eurocode3 2001)

4.4.3.3 *Shear Capacity control*

The cross section must fulfill:

$$\frac{V_{Ed}}{V_{pl,Rd}} \leq 1 \tag{4.16}$$

The shear resistance is calculated as follows:

$$V_{pl,Rd} = \frac{A_v\ (f_y/\sqrt{3}\,)}{\gamma_{M0}} \text{ [kN]} \tag{4.17}$$

Where:

- A_v is the shear area [cm^3]. For rolled sections is calculated as:

$$A_v = A - 2bt_f + (t_w + 2r)t_f \text{ [kN]} \tag{4.18}$$

- f_y is characteristic yield strength [kN/cm^2]
- γ_{M0} is the partial safety factor specified in *Section 6.1* (Eurocode3 2001)

4.4.3.4 *Interaction of shear and bending moment*

According to the *clause 6.2.8 (2)* (Eurocode3 2001), the effect of the plastic shear resistance of the cross-section on the moment resistance should be taken into account when the applied shear force is larger than the half of the shear resistance.

$$\frac{V_{pl,Rd}}{2} < V_d \rightarrow M_{y,V,Rd} = \frac{(W_{pl,y} - \rho A_W^2/4t_w)\ f_y}{\gamma_{M0}}\ \leq\ M_{y,c,Rd} \tag{4.19}$$

Where:

- $V_{pl,Rd}$ is the plastic shear resistance calculated according to eq. (4.17)
- V_d is the design shear resistance
- W_{pl} is the Plastic modulus of Elasticity [cm^3]
- f_y is characteristic yield strength [kN/cm^2]
- γ_{M0} is the partial safety factor specified in *Section 6.1* (Eurocode3 2001)

4.4.3.5 Lateral torsional buckling

Non-dimensional slenderness

$$\lambda_{Lt} = \sqrt{\frac{W_y f_y}{M_{cr}}} \tag{4.20}$$

Where:

- M_{cr} is the critical bending moment of the cross-section. Its calculation is done based on the cases specified in the *Lateral-torsional buckling (LTB) loads* tables from *Teknisk Ståbi* (Jensen 2007)
- W_y is the modulus of Elasticity [cm^3], which will be equal to:
    - $W_y = W_{pl,y}$ for cross-section class 1 or 2
    - $W_y = W_{el,y}$ for cross-section class 3
    - $W_y = W_{eff,y}$ for cross-section class 4

Imperfection factor

$$\phi_{Lt} = 0.5\ [\ 1 + \alpha_{LT}(\lambda_{LT} - \lambda_{LT,0}) + \beta\lambda_{LT}^2] \tag{4.21}$$

Where:

- $\lambda_{LT,0} = 0.4\ and\ \beta = 0.75$ for rolled sections according to the National Annex.
- α_{LT} is the imperfection factor determined by the buckling curved according to the *table 6.1* (Eurocode3 2001)

Reduction factor for lateral torsional buckling eq. (6.47) (Eurocode3 2001)

$$\chi_{Lt} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \beta\lambda_{LT}^2}} \leq \begin{cases} 1 \\ 1/\lambda_{LT}^2 \end{cases} \tag{4.22}$$

Where:

- ϕ_{LT} is calculated according to the equation (3.21)
- λ_{Lt} is calculated according to the equation (3.20)

Lateral Torsional Buckling capacity check eq. (6.46) (Eurocode3 2001)

$$M_{Ed} \leq M_{b,R} = \chi_{LT} W\ f_y/\gamma_{M1} \tag{4.23}$$

Where:

- W_y is the modulus of Elasticity [cm^3], which will depend on the cross-section class as it was specified before.
- χ_{LT} is the reduction factor calculated according to eq. (4.21)

Columns Verifications

The verifications necessaries to carry out to check the cross-sections of the columns follow similar procedure than the specified for beams. First must be determined the steel class and the section properties.

In the case of the columns, the axial force will drive the final cross section, as the elements are subjected to compression forces. The capacity control is done for Ultimate Limit States (ULS).

According to the Eurocode 3: Design of Steel Structures (Eurocode3 2001), when the elements are subjected to bending and axial compression the following verifications should be carried out for cross sections such as IPE, IPN, HEB, etc.

$$\sigma = \frac{N_{Dc}}{\chi_y A} + k_{y,LT}\frac{M_{dy}}{\chi_{LT} W_{pl,y}} + k_z \frac{C_{m,z} M_{dzy}}{W_{pl,z}} \leq f_{yd} \tag{4.24}$$

Furthermore, the individual checks for axial, shear and bending must be also fulfilled, being the design forces smaller than the capacities.

4.4.3.6 Cross section class

For the internal compression parts (web of the profile), case: Part subject to compression). *Table 5.2* (Eurocode3 2001)

$$\begin{aligned} &\text{Section class 1} \rightarrow \frac{c}{t} \leq 33\,\varepsilon \\ &\text{Section class 2} \rightarrow \frac{c}{t} \leq 38\,\varepsilon \\ &\text{Section class 3} \rightarrow \frac{c}{t} \leq 42\,\varepsilon \\ &\text{Section class 4} \rightarrow \frac{c}{t} > 42\,\varepsilon \end{aligned} \tag{4.25}$$

Where:

- c is the efficient length of the web, calculated as: $c = h_w - 2\,t_f$, being h_w the height of the profile and t_f the thickness of the flange.
- t is the thickness of the web (t_w)
- $\varepsilon = \sqrt{235/f_y}$

For the outstand flanges (flange of the profile, *Table 5.2* (Eurocode3 2001)

$$\begin{aligned} &\text{Section class 1} \rightarrow \frac{c}{t} \leq 9\,\varepsilon \\ &\text{Section class 2} \rightarrow \frac{c}{t} \leq 10\,\varepsilon \\ &\text{Section class 3} \rightarrow \frac{c}{t} \leq 14\,\varepsilon \\ &\text{Section class 4} \rightarrow \frac{c}{t} > 14\,\varepsilon \end{aligned} \tag{4.26}$$

Where:

.

- c is the efficient length of the web, calculated as: $c = \frac{b-t_w}{2} - r$ being b the width of the profile, t_w the thickness of the web and r the root radius.
- t is the thickness of the flange (t_f)
- $\varepsilon = \sqrt{235/f_y}$

4.4.3.7 Buckling length

The buckling length is determined as:

- $L_{xy} = 0.7\ L_{column}$ for columns in connection with the foundation.
- $L_{xy} = L_{column}$ for intermediate columns.

4.4.3.8 Flexural buckling around the y-axis and z-axis

For both axes is done the same procedure. It should be taken the corresponding moment of inertia depending on the axis that is being calculated. It should be calculated the design buckling resistance which is:

$$N_{b.Rd} = \frac{\chi A f_y}{\gamma_{M1}} \leq N_{Ed} \text{ for Class 1,2 and 3 cross-sections} \tag{4.27}$$

$$N_{b.Rd} = \frac{\chi A_{eff} f_y}{\gamma_{M1}} \leq N_{Ed} \text{ for Class 4 cross-sections}$$

The general procedure to calculate $N_{b.Rd}$ is as follows:

Critical axial force:

$$N_{cr.y} = \frac{\pi^2 E_d I_y}{l_{xy}^2} \tag{4.28}$$

Where:

- E_d is the design modulus of elasticity.
- I_y is the moment of inertia around the y axis (or I_z for the second case).
- L_{xy} is the buckling length.

Non-dimensional slenderness

$$\lambda = \sqrt{\frac{A f_y}{N_{cr}}} \text{ for Class 1,2 and 3} \tag{4.29}$$

$$\lambda = \sqrt{\frac{A_{eff} f_y}{N_{cr}}} \text{ for Class 4}$$

Where:

- M_{cr} is the critical bending moment of the cross-section. Its calculation is done based on the cases specified in the *Lateral-torsional buckling (LTB) loads* tables from *Teknisk Ståbi* (Jensen 2007)

- W_y is the modulus of Elasticity [cm^3], which will be equal to:
  - $W_y = W_{pl,y}$ for cross-section class 1 or 2
  - $W_y = W_{el,y}$ for cross-section class 3
  - $W_y = W_{eff,y}$ for cross-section class 4

Imperfection factor

$$\phi = 0.5\ [\ 1 + \alpha(\lambda - 0.2) + \lambda^2] \tag{4.30}$$

Where:

- λ is the non-dimensional slenderness eq. (4.28)
- α is the imperfection factor determined by the buckling curved according to the *table 6.1* (Eurocode3 2001)

Reduction factor for lateral torsional buckling eq. (6.47) (Eurocode3 2001)

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \lambda^2}} \leq \begin{cases} 1 \\ 1/\lambda_{LT}^2 \end{cases} \tag{4.31}$$

Where:

- ϕ is calculated according to the equation (4.29)
- λ is calculated according to the equation (4.28)

4.4.3.9 *Lateral torsional buckling*

Non-dimensional slenderness

$$\lambda_{Lt} = \sqrt{\frac{W_y f_y}{M_{cr}}} \tag{4.32}$$

Where:

- M_{cr} is the critical bending moment of the cross-section determined by:

$$M_{cr} = \frac{C_1 \pi^2 E I_z}{L^2} \left(\frac{I_w}{I_z} + \frac{L^2 G I_T}{\pi^2 E I_z} \right)^{0.5} \tag{4.33}$$

- W_y is the modulus of Elasticity [cm^3], which will be equal to:
  - $W_y = W_{pl,y}$ for cross-section class 1 or 2
  - $W_y = W_{el,y}$ for cross-section class 3
  - $W_y = W_{eff,y}$ for cross-section class 4

Imperfection factor

$$\phi_{Lt} = 0.5\ [\ 1 + \alpha_{LT}\left(\lambda_{LT} - \lambda_{LT,0}\right) + \beta \lambda_{LT}^2] \tag{4.34}$$

Where:

- $\lambda_{LT,0} = 0.4\ and\ \beta = 0.75$ for rolled sections according to the National Annex.
- α_{LT} is the imperfection factor determined by the buckling curved according to the *table 6.1* (Eurocode3 2001)

Reduction factor for lateral torsional buckling eq. (6.47) (Eurocode3 2001)

$$\chi_{Lt} = \frac{1}{\phi_{LT} + \sqrt{\phi_{LT}^2 - \beta\lambda_{LT}^2}} \leq \begin{cases} 1 \\ 1/\lambda_{LT}^2 \end{cases} \tag{4.35}$$

Where:

- ϕ_{LT} is calculated according to the equation (3.21)
- λ_{Lt} is calculated according to the equation (3.20)

Lateral Torsional Buckling capacity check eq. (6.46) (Eurocode3 2001)

$$M_{Ed} \leq M_{b,R} = \chi_{LT} W\, f_y/\gamma_{M1} \tag{4.36}$$

Where:

- W_y is the modulus of Elasticity [cm^3], which will depend on the cross-section class as it was specified before.
- χ_{LT} is the reduction factor calculated according to eq. (3.35)

Deflection verifications

4.4.3.10 Maximum vertical deflection

According to Section 7.2.1 (B), the vertical deflection for beam in roof and plates should be:

$$u_{max,y,beams} = l_1\ /\ 200 \tag{4.37}$$

$$u_{max,y,roof} = l_2\ /\ 150 \tag{4.38}$$

Where:

- l_1 is the span of simple supported and continuous beams.
- l_2 is the span of the roof plate.

4.4.3.11 Maximum deflection columns

According to Section 7.2.1 (B), the maximum horizontal deflection for columns in frames is:

$$u_{max,x} = h\ /\ 300 \tag{4.39}$$

Where:

- h is the height of the building.

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Part V: RESULTS - Structural Analysis

The purpose of this chapter is to apply the method which has been proposed in the previous chapter (Part IV, 4.1), in order to study its feasibility, and study its advantages as well as disadvantages compare to the traditional working approaches. In this way it would be possible to discuss and solve the research questions posed for this master thesis.

As it was introduced in Part II (2.2), the project to study is the EKO-Canopy project [APPENDIX A: THE EKO-CANOPY PROJECT], a proposal of White Architects Sweden. The project was chosen for the great flexibility which provides, as the purpose is to build a Canopy between two existing apartment blocks. This means that is possible to play by means of the parametrical modeling with all the space in between to create a realistic and sustainable configuration.

First it is going to be explained the load analysis which has been done in appliance to the specific construction. Secondly, the method based on the parametrical model is developed and its results presented.

The following table shows the measurements for the buildings and the space in between which are essential in order to understand the considerations which have been made.

Parameter	Unit [m]	Apartment block	Space in between
Height	m	22.63	22.63
Length	m	72.57	72.57
Width	m	12.1	28.25

Table 4.4-1: Basic measurements of the site for the Canopy construction

5.1 Loads analysis

This section is focus on the study and analysis of the loads which act on the structure of the EKO-Canopy project. They are calculated following the specifications on (DS-EN 1990 – Basis of structural design 2007, sec. 4.1.1 Classifications of actions), where the actions are classified as *Permanent actions* (G), *Variable actions* (Q) and *Accidental actions* (A). For the purpose of this project only the first two categories are going to be considered. The *permanent actions (G)* are referred to the self-weight of the structure, while the *variable actions, Q*, are the wind loads, snow loads and imposed loads. In this specific case the last ones are neglected as the model taken as study, as it has been described before, is a Roof-Canopy which is not accessible for public.

Firstly are going to be calculated the variable actions. These are the different live loads which will influence the design, as the wind loads and the snow loads. Most areas of the Nordic countries have strong climatological conditions during the autumn-winter period every year; therefore a deep study of the wind and snow loads should be done. For this reason, as this master thesis form part of the NORDIC BUILD PROGRAMME (2.1), these are going to be estimated in different locations along the Nordic countries, following the premises specified in *Section 4.4*, both *4.4.1 Wind loads calculations* and *4.4.2 Snow loads calculations*.

Analyzing the loads for different locations will be used as a basis to evaluate how the loads could condition the design. Hence the wind pressures and snow loads are calculated for Sweden, Norway, Denmark, Finland and Iceland. However it should be noted that the main calculations are performed for the loads considering the climatological data from *Upplands Väsby*, Sweden, the original location of the project which is being studied.

Secondly, the permanent actions will be estimated. They consist mainly in the self-weight of the different elements of the structure. This is being automatically assumed for the calculations by the structural plug-in *Karamba* in *Grasshopper*, so its implementation on the script would be explained. The parametrical modeling using Karamba allows to easily change the material for the structure, however in order to verify the capacities of the structural elements are necessary a serial of checks, which requires a more deeply post processing analysis. Consequently, for the main models only steel has been considered as structural material. It has been considered primordial evaluate how considering a specific structural material it can be set a method which seeks for one of the optimal configurations based on form-finding and optimization processes.

5.1.1 Live loads analysis in the Nordic countries: Wind and Snow

5.1.1.1 *Wind calculations*

The wind actions will depend on each design situation, as it is specified in the section 3 of DS/EN 1991-1-4 : 2007, which means that for each of the models they will vary. They act as pressures on the different surfaces of the EKO-Canopy, (roof and facades), as normal forces to the structural components or the cladding. The load component for *Karamba* allows to distribute the surface load on the area and project it according to the global coordinate planes (Preisinger 2015, bk. Karamba User Manual), so it will change as the parametrical model changes.

In order to determine the basic wind velocity, [eq. (4.4.1.1)], it is necessary to know the fundamental value of the basic wind speed, $v_{b,0}$, which procedure calculation is given for the corresponding National Annex. This value will then change with the different locations to be studied. In this way, the following table 5.1-1 shows the data considered for each case:

Country	Chosen location	$v_{b,0}$ [m/s]	Reference
Denmark	Copenhagen	24	DS/EN 1991-1-4 DK NA:2015
Sweden	Upplands-Väsby	24	(BFS 2013:10 EKS 9 2011)
Finland	South part	21	(NF EN 1991-1-4 1991)
Norway	Trondheim	26	(NS-EN 1991-1-4:2005/NA:2009)
Iceland	Reykjavik	24	(IST EN 1991-1-1:2002/NA:2010 2010)

Table 5.1-1: Values for the basic wind velocity for each Country

The second parameter that should be calculated is the mean wind velocity, $v_{,m}$ [eq. (4.4.1.2)] which depends on the terrain roughness, orography and the basic wind velocity.

The terrain category for all the cases has been considered as category IV (DS/EN 1991-1-4 2007, Table no. 4.3), as the given location is an area in which at least 15% of the surface is covered with buildings. However, this implementation can be easily changed for each location as the calculations have been also performed for category III.

Furthermore, the orography has been taken as 1 as the area where the project is located is considered as valley.

Lastly, the wind pressures are calculated according to [eq. (4.4.1.6)] which is determine by the peak velocity pressure, the reference height for the external pressure and the pressure coefficient for the external pressure. As the last two parameters are related to the shape and height of the element which is being analyzed, their values will change depending on the model. To be able to carry out the calculations the wind rose of the area has been analyzed, in order to determine which wind direction is the most unfavorable. Based on the report (Söderberg and Bergström 2008) about the climatological condition in Sweden and climate data from *Meteoblue*[12] in Upplands Vasby, it has been estimated that the most unfavorable wind direction is from Southwest (Figure 5.1-1 left). As a simplification of how the buildings are oriented with respect to the North, it has been assumed that the most unfavorable wind direction is west direction (Wind 90º for considerations in the Eurocode) as shows the Figure 5.1-1 on the right.

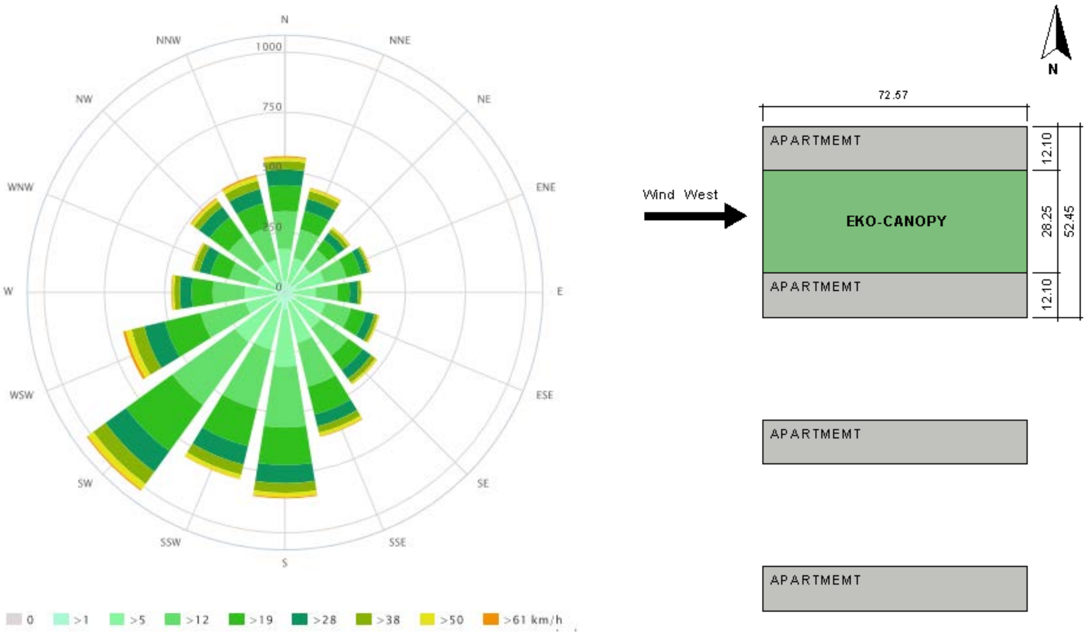

Figure 5.1-1: Wind rose for the area[13] (left] and scheme of the are (right)

To calculate the coefficient pressures for the roof, two different assumptions have been made. For the first model (Case A), the roof is considered as a flat roof (Figure 5.1-2 left); while for the second model (Case B) the pressures on the roof are calculated for a monopitch roof (Figure 5.1-2 right).

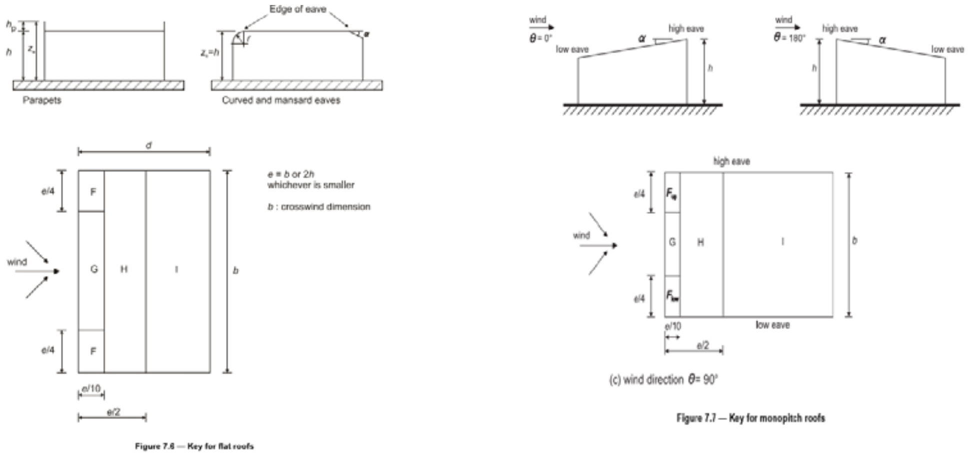

*Figure 5.1-2 Flat roof wind areas (left) and monpith roof wind areas (right) a/EC1-4 (*DS/EN 1991-1-4 2007)

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[12] https://www.meteoblue.com/en/weather/forecast/modelclimate

[13] https://www.meteoblue.com/en/weather/forecast/modelclimate/upplands-vasby_sweden_2666238

While in the case for the pressures on the walls of the Canopy, the premises specified in the *figure 7.5 – Key for vertical walls* (DS/EN 1991-1-4 2007) have been followed. The heigth is lower than the width so the following assumptions have been followed to estimate the wind profile acting on the facades.

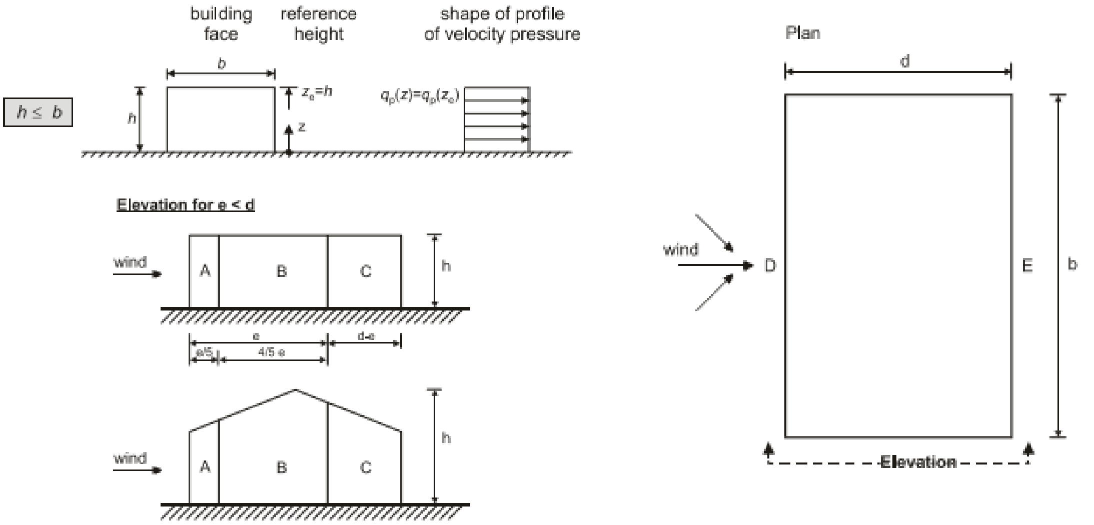
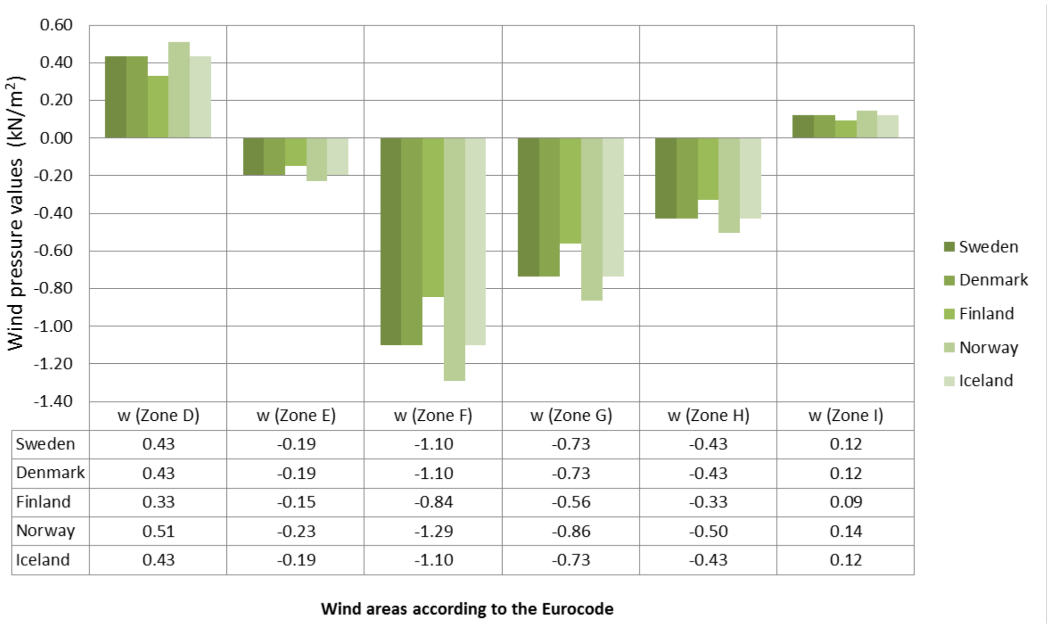


*Figure 5.1-3: Diagrams from EC1-4 (*DS/EN 1991-1-4 2007) *to calculate pressure coefficient on the facades.*

The following charter shows in a graphical way how the wind loads differs for the different countries for the flat roof case. It is seen, that according to the values from the Table 5.1-1, Norway has the most unfavorable values and Finland the most favorable. However there are not notable differences between the values.



	w (Zone D)	w (Zone E)	w (Zone F)	w (Zone G)	w (Zone H)	w (Zone I)
Sweden	0.43	-0.19	-1.10	-0.73	-0.43	0.12
Denmark	0.43	-0.19	-1.10	-0.73	-0.43	0.12
Finland	0.33	-0.15	-0.84	-0.56	-0.33	0.09
Norway	0.51	-0.23	-1.29	-0.86	-0.50	0.14
Iceland	0.43	-0.19	-1.10	-0.73	-0.43	0.12

Graph 5.1-1: Wind loads pressure values depending on the country. Flat roof case.

5.1.1.2 Snow Considerations

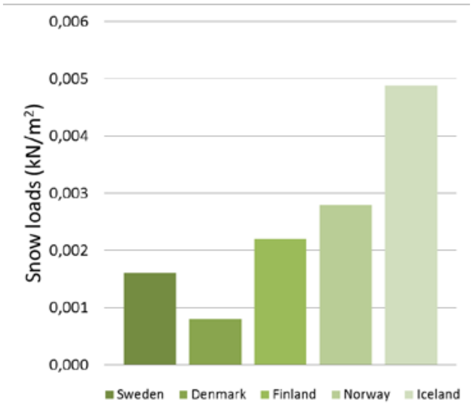
Regarding the calculation of the snow loads, the same factors specified for the wind loads will influence in its determination. The aspects that should be considered are already enumerated in 4.4.2 Snow loads calculations, and all of them, except the first one, the shape of the roof, depend on the climatological data and the area where the construction is located and its surrounding, therefore will be the same for all the models. The only factor that will change with the design is the shape coefficient, as depending on the slope of the roof (angle) the value of the load distribution will vary.

The design situation which will be adopted for the calculations is the persistent or transient situation [eq. (4.4.2.1)] and in order to calculate the snow load it is necessary to know the characteristic value of the snow load on the ground. In the same way that for the wind loads, this characteristic value depends on the location which is being taken as reference to perform the calculations. The following table listen the characteristic values for the five different countries which are being investigated.

Country	Chosen location	s_k [kN/m^2]	Reference
Denmark	Copenhagen	1	(DS/EN 1991-1-3 DK NA:2015 2011)
Sweden	Upplands-Väsby	2	(BFS 2013:10 EKS 9 2011)
Finland	South part	2.75	(SFS-EN 1991-1-3 NA 2003)
Norway	Trondheim	3.5	(NS-EN 1991-1-3:2005/NA:2009, n.d.)
Iceland	Reykjavik	6.5	(IST EN 1991-1-1:2002/NA:2010 2010)

Table 5.1-2: Characteristics values for the snow load on the ground for the different locations

In contrast to the wind loads, the snow loads have really extreme values for the regions of Iceland, Norway and Finland compare to Denmark o Sweden (Graph 5.1-2). This fact will have a huge influence in the design, as it is going to add a big amount of weight to consider for the calculation of the structure.



Graph 5.1-2: Snow loads for the different countries

Consequently, the snow in the Nordic regions should be deal with special attention, and the constructions should be built according to this. In the case of the EKO-Canopy project this issue was investigated by Mikkel Knudsen in his investigation about the Canopy construction (Knudsen 2016), where he proposed to use EFTE instead of glass for the roof covering, as it has numerous advantages in comparison to glass regarding the management of snow. His proposal for the EKO-Canopy project includes the installation of diffusers on the roof, which will be used to melt the snow on the roof in the winter time. Therefore, this material as covering for the Canopy construction will be also investigated.

5.1.2 Load combinations

In order to perform the calculations it is necessary to carry out the corresponding load combinations, where the live loads and the permanent loads are considered. Its implementation in *Karamba* is a bit tricky, as the platform allows to the user to specify different load cases to later choose one to perform the calculations, but it does not consider the combinations according to the Eurocode, hence this should be implemented manually.

The capacities of the elements which form the structure should be checked for the Ultimate Limit States (ULS) based the premises of the *Eurocode 0* (DS-EN 1990 – Basis of structural design 2007) is specified in equation (5.1.2) and in the same way the deflection of the members should be check for the Serviceability Limit States (SLS) according to the equation (5.1.2).

$$q_d = \gamma_{Gj,sup} G_{Kj,sup} + \gamma_{Q,1} Q_{k,1} + \sum \psi_{Q,i}\, \gamma_{Q,i} Q_{k,i} \tag{5.1}$$

$$q_k = G_{Kj,sup} + Q_{k,1} + \sum \psi_{Q,i} Q_{k,i} \tag{5.2}$$

Where:

- $\gamma_{Gj,sup}$ is design coefficient for unfavorable permanent actions taken as 1.15.
- $\gamma_{Q,1}$ is design coefficient for lead variable action taken as 1.5.
- $\gamma_{Q,i}$ is design coefficient for accompanying variable actions taken as 1.5.
- $\psi_{Q,i}$ is the simultaneity factor taken from table A.1.1 (DS-EN 1990).
- $G_{Kj,sup}$ are the permanent actions.
- $Q_{k,1}$ is the lead variable action.
- $Q_{k,i}$ are the sum up of the accompanying variable actions.

To obtain the most unfavorable situation, five different load combinations have been implemented in Grasshopper using the VB programming component as follows:

- Load case 0 : Self-weight
- Load case 1: Self-weight + Live loads. This LC is subdivided in:
    - Load case 1: Only wind
    - Load case 2: Only Snow
    - Load case 3: Wind Dominant + Snow accompanying.
    - Load case 4: Wind accompanying + Snow Dominant
    - Load case 5: Wind + Snow (Characteristics values – ULS)

This loads combinations correspond with the following table with values listened as a generic way (Not specific values considered). The code implementation could be seen in APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION.

Nº Load case		Dead loads - Permanent actions				Imposed loads - Accompanying variable actions						Result. design value
		Selfweigth - structure		Selfweigth - others		Wind load - WL			Snow load - SL			
		Gk,str (kn/m2)	γ_{Gj}	Gk,oth (kn/m2)	γ_{Gj}	Qk (kN/m2)	ψ_{Qi}	γ_{Qi}	Qk (kN/m2)	ψ_{Qi}	γ_{Qi}	q_d [kN/m2]
	Ultimate limit states (ULS)											
0	DL (Self weight)	1.00	1.15	0	1.15	1.00	1	0	1.00	0	0	1.15
1	DL + WL	1.00	1.15	0	1.15	1.00	1	1.5	1.00	0	0	2.65
2	DL + SL	1.00	1.15	0	1.15	1.00	0	0	1.00	1	1.5	2.65
3	DL + WL (Dominant) + SL (acomp)	1.00	1.15	0	1.15	1.00	1	1.5	1.00	0	1.5	2.65
4	DL + SL (Dominant) + WL (acomp)	1.00	1.15	0	1.15	1.00	0	1.5	1.00	1	1.5	2.65
	Service limit states (SLS)											
5	DL + WL + SL	1.00		0		1	1	1	1	1	1	2.00

Table 5.1-3: Load combinations

5.2 Structural analysis of the different shape configurations

The main objective is to reach a point where the practitioner can take the decision of the optimal solution based on several factors. Normally when we are dealing with design there is not a unique best option, there are different better options depending on the aspect which is considered primordial.

Nevertheless, in all design process one of the main goals is always to achieve a sustainable construction. In relation with the structure, this objective is associated to the type of material and the total amount of mass (kg) necessaries for its construction, as these two parameters will determine the LCA calculations.

For instance, when we are talking about optimal solutions we are talking about efficiency; and the efficiency of the structure will be achieved when an equilibrium between the total amount of mass and the utilization ratio of the members which form it coexists.

As it was explained in *Section 4.3* the optimization process in done using the component Galapagos of Grasshopper in which the genes represent the different parameters to study. These have to reach a target optimization value, called fitness, which depending on the optimization process which is being carried out will vary: mass of the structure, minimal deflection, etc.

In the same way, the parameters for the optimizations processes will vary depending on the model which is being studied. Each of them should be delimited into a domain of different possibilities which represent the landscape of variations. These aspects are developed further on for the specific cases.

Therefore, in order to perform the optimization process it is necessary to previously define:

1) The characteristics of the different geometries, which set the landscape of possibilities.

2) The loads which are going to be applied to each specific model.
3) Set up the support conditions for the structures.
4) Describe the input to carry out the optimization process.

This is going to be explained in the following section for each of the different models. The reason of repeating the same procedure several times is that the optimization process is a complex practice which requires a deep analysis. In order to establish a simple method which can be used as the basis to create and analyze complex structures, the first approach has been to model a basic geometry between the two existing buildings based on a simple structure form by beams and columns.

Consequently, once that the optimization process has been settled down, a more complex structure has been analyzed. This second model is based on the design proposal that white architects presented, going again from a basic configuration until reach the complexity.

5.2.1 Case A: Basic Frame Configuration

5.2.1.1 *Design properties (geometry):*

Before analyzing complex geometries for the ECO-Canopy construction is important to study how the single elements of the structure will work against the loads acting on it. Therefore the first approach which has been considered is a simple construction, modeled as a box form by different frames in X and Y direction (Figure 5.2-1). Depending on the case, the elements will be included in the global structure or not, taking special attention to the column buckling and lateral torsional buckling of the elements as the span in some of the iterations could be considerable big.

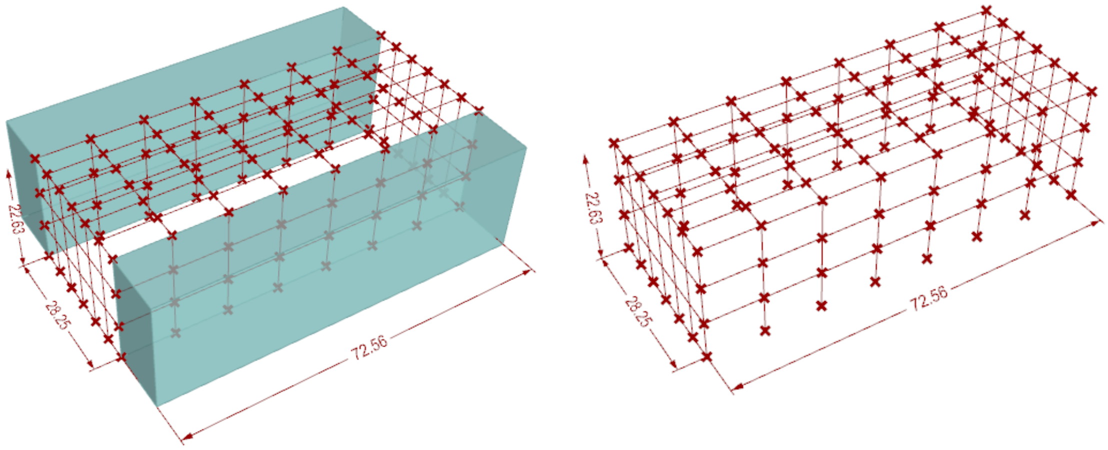


Figure 5.2-1: Case A – Parametric geometry

As it seen, the structure is placed in the space in between (measurements Table 4.4-1) so the frame will be placed in a box of maximum measurements of 28.25x72.56x22.63 m.

Thanks to the parametrical modeling is really easy to change this box domain. So, the first input of the modeler should be set these maximum measurements. Regarding the type of elements, as the loads are transferred to the ground through beams and columns, no plate elements or shells are included in the design, which simplifies the calculations.

5.2.1.2 *Loads and materials:*

The script developed with grasshopper allows to the user to choose between different structural materials, load cases and locations. The first study is focused on the implementation of the optimization process (form-finding) and its results. Hence a specific case has been chosen, being the parameters for the first optimization process as follows:

- Location: Sweden
- Structural material: Steel 275s
- Cover material : Glass (Including self-weight of the auxiliary profiles)
- Load case: 4 (ULS) 5 (SLS)

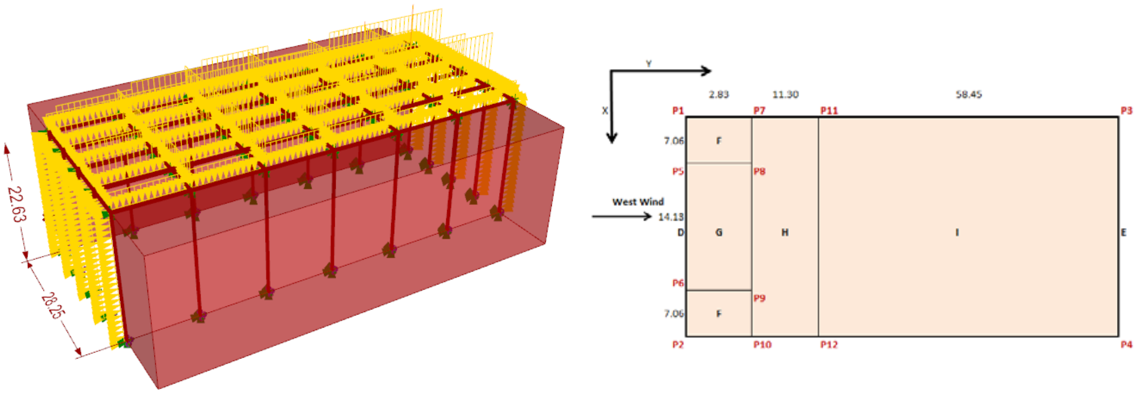


Table 5.2-1: Loads applied to the geometry (left) and roof load areas (right) case A

5.2.1.3 *Support conditions*

To perform the calculations it is necessary set the support conditions for the model. The connection of the columns to the foundation has been set as a totally fix supports. This means that the three translations, on the X axis, the Y axis and the Z axis, have been restrained; as well as the three rotations around the these axes, which leads to a cero DOF for all the supports at the base. This input can be seen on the APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION, where the support-component from Karamba is used.

On the other hand, the support conditions for the joints between the different elements of the structures have been set as hinge connections (as a general simplification) where the DOF for the translations in the X axis, Y axis and Z axis have been set to cero, allowing the rotations around the three axis. This input can be seen in the APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION.

5.2.1.4 Results: Structural optimization

There are three different considerations that should be taken into account when the optimization process is carried out, which are firstly the parameters to optimized (genes); secondly, the goals to achieve (fitness); and thirdly the verifications that should be fulfilled when the process is being developed (maximum stress, resistances of the elements, deflection and buckling).

Hence, for this specific model case the parameters to optimize would be:

- Number of frames in X direction.
- Number of frames in Y direction.
- Cross sections of the different elements which form the structure:
  - Cross sections beams on top surface X direction
  - Cross sections beams on top surface Y direction
  - Cross sections beams on both lateral sides, left and right, Y direction
  - Cross sections beams on front and back surfaces, X direction
  - Cross sections columns front and back
  - Cross sections columns both lateral sides, left and right.

Following the process specified in *4.3* first all the cross sections for the frames have been chosen following the structural verifications (4.4.3) and checking the maximum deflection using the utilization model to avoid the failure of the structure during the first optimization process.

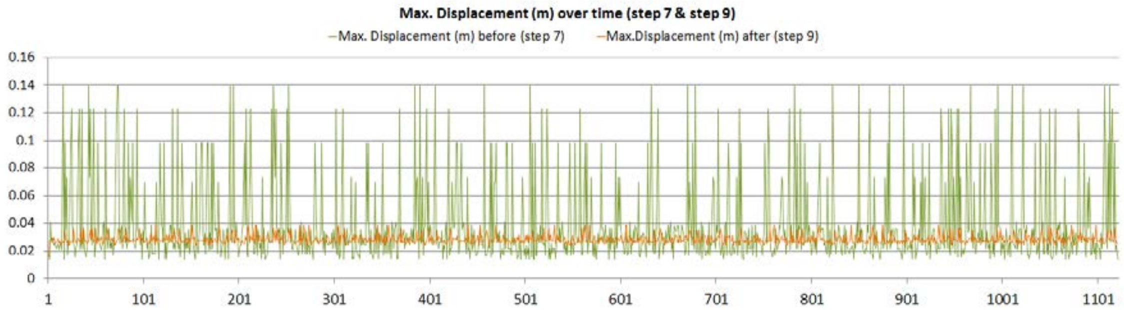
After this, the first loop of the optimization process (***Seventh step: Topology optimization 1.*** Perform the 1st optimization process using Galapagos component for GH., ***Eight step: Cross-section optimization.*** Perform the 2nd optimization process using the component for Karamba, “Cross-section optimization”, and ***Ninth step: Topology optimization 2.*** Perform the 3rd optimization process using Galapagos based on the results from the 8th step – cross-cross section optimization.) is carried out, where the first goal is to achieve the minimal maximum deflection of the model and the second goals is to minimize the total amount of mass (Fitness values). Meanwhile, the genes of the optimization are the number of frames in X direction and in Y direction (APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION)

In order to achieve a feasible solution it has been limited the possible total number of frames for each direction, being the domains:

- Frames in X direction [3,8]
- Frames in Y direction [3,8]

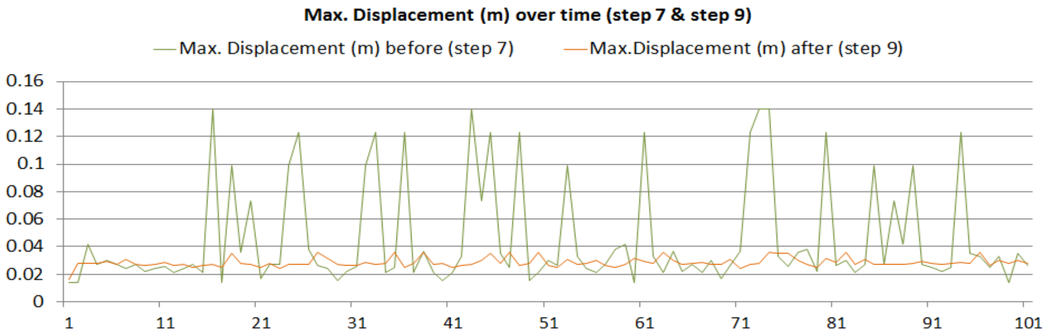
This domain reduces the variables to 36, which means that the combination of 4 frames in both directions (x=3, y=3) will have 64 elements, and the combination 9 frames in both directions (x=8, y=8) will have a total number of 244 elements.

The maximum deflection over time (number of iterations) for the steps 7 and 9 for the first optimization loop is shown in the Graph 5.2-1, where the process should try to reach a converge solution.



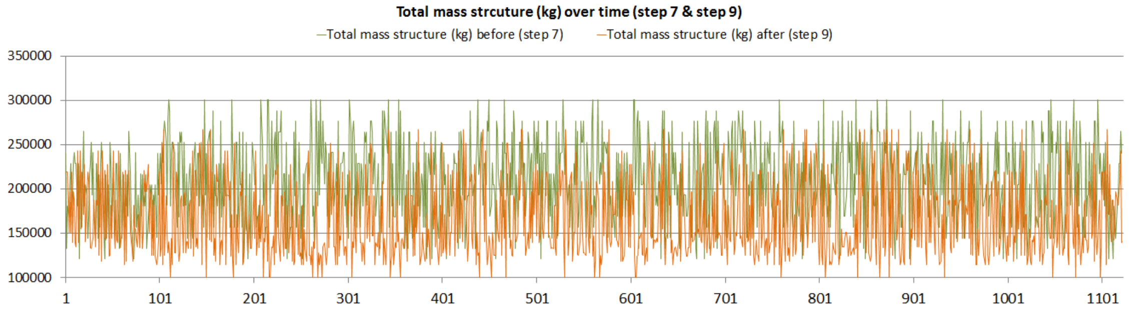
Graph 5.2-1: Maximum displacement [m] over time for the steps 7 (green) and step 9 (orange)

However it is observed that the values oscillate around the same values, between [0.01; 0.14] for the step 7 and between [0.02; 0.04] for the step 9, which means there is not an optimal minimum value, if not that there might be multiple optimum values. The repetition of the pattern is a sign of this, where several minimum values are reached. The Graph 5.2-2 shows a zoom in Graph 5.2-1 for the first 100 iterations. The reason of the short domain for the second topology optimization is than the deflection was limited to 0.03 m to perform step 8, Cross-section optimization. This process has been repeated several times (10) in order to verify that the results were correct.

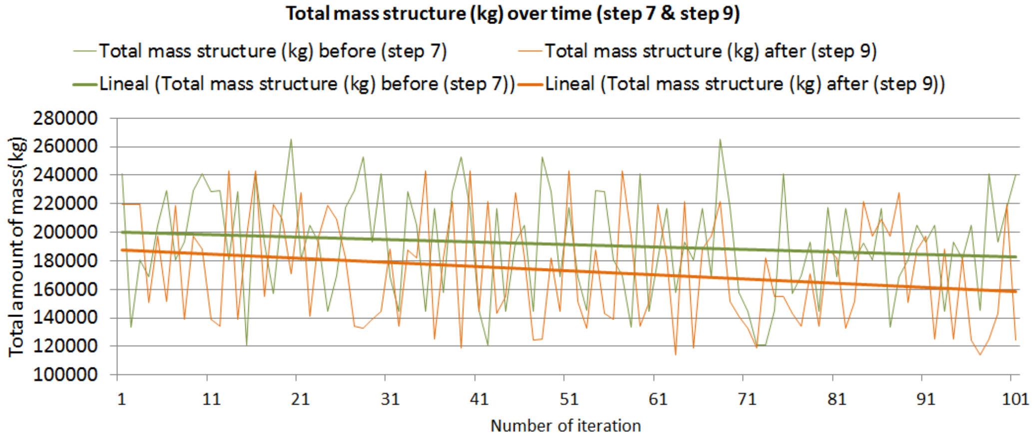


Graph 5.2-2 Zoom in first 100 iterations of maximum displacement [m] for the steps 7 (green) and step 9 (orange)

Additionally, on the Graph 5.2-3 has been plotted the total mas of the structure for the steps 7 (green) and 9 (orange). It is verified that the values of the second topology optimization where the cross-section of the elements have been already optimized, tends to have less amount of mass in comparison with the first topology optimization. This is clearly seen on the Graph 5.2-4 for the 100 first iteration, where it is plotted the tendency line for each case.



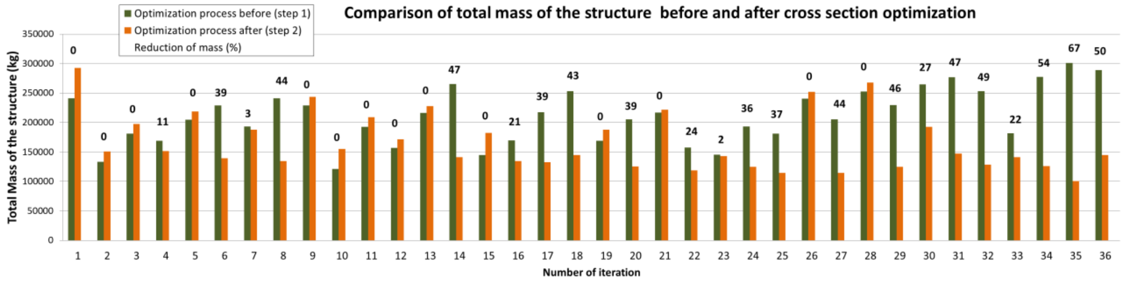
Graph 5.2-3: Total amount of mass [kg] over time for the steps 7 (green) and step 9 (orange)



Graph 5.2-4: Zoom in first 100 iterations of total amount of mass [kg] for the steps 7 (green) and step 9 (orange)

5.2.1.5 Post-process – Quality check

Finished the first loop of the optimization process, the results are analyzed in *Karamba* and exported to excel (***Eleventh step: Analysis of the configurations***. Extract the different combinations, analyse the optimal ones based on the amount of mass and the utilization ratio of the cross sections. Check that the elements of the structure fulfil the requirements specified in the Eurocode.) in order to verify that the elements accomplish the requirements of the Eurocode. The Graph 5.2-5 shows the comparison of mass for the 36 different structure variables (Table 5.2-2) of the model, where is indicated the percentage of saved material in each combination, being the maximum reduction of mass 67% respecting the first model, which is produced in the case number 35. (APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION)



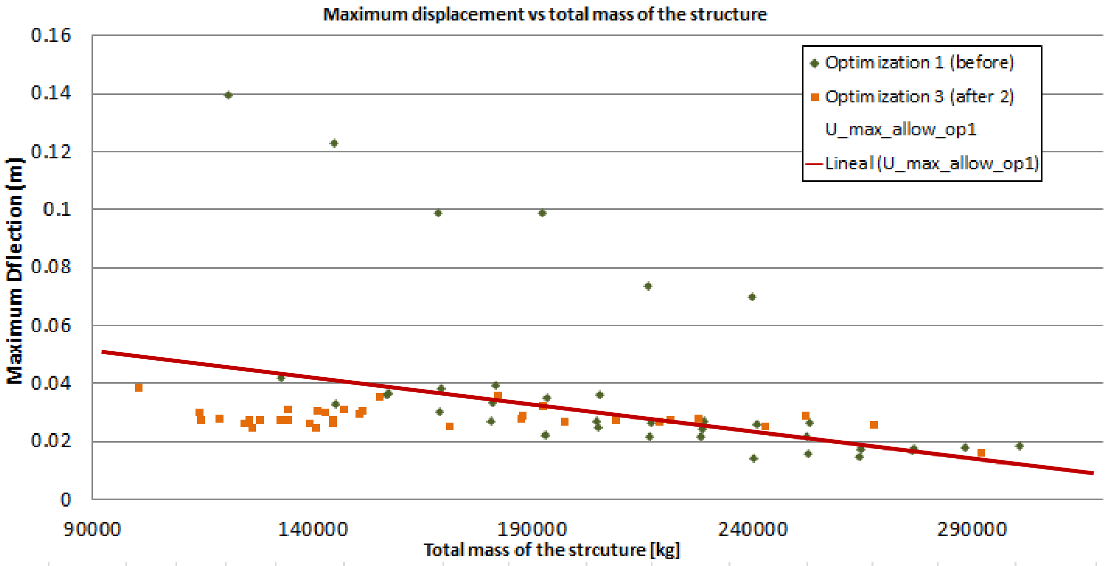
Graph 5.2-5: Comparison of total mass for the 36 different iterations

Nº it	X	Y
1	7	5
2	3	4
3	5	4
4	4	5
5	6	4
6	6	6
7	5	5
8	6	7
9	7	4
10	3	3
11	6	3
12	4	4
13	7	3
14	7	7
15	4	3
16	3	7
17	5	7
18	7	6
19	5	3
20	5	6
21	6	5
22	3	6
23	3	5
24	4	7
25	**4**	**6**
26	8	3
27	4	8
28	8	4
29	5	8
30	8	5
31	8	6
32	6	8
33	3	8
34	7	8
35	**8**	**8**
36	8	7

Table 5.2-2: Combination of frames X and Y direction for the 36 variables

However, it is seen that in some of the combinations the amount of material is bigger in the second optimization than in the first one, so these arrangements have been neglected.

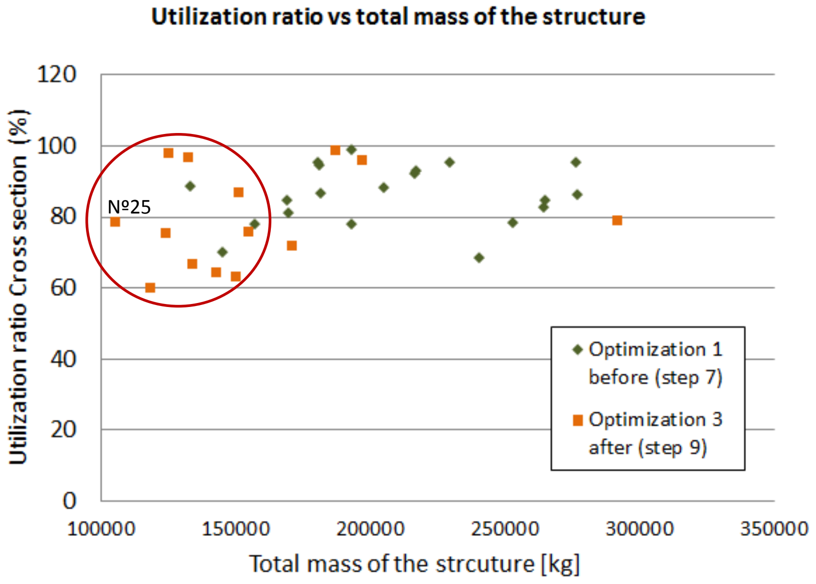
The Graph 5.2-6 shows the results for the 36 variables (step 7 – green and step 9 –orange), plotting the total amount of mass of the structure and the maximum deflection. As the second topology optimization (step 9) is done after the cross section optimization where it is limited the maximum deflection, it is seen that most of the values are under the red line (allowed deflection). However, when the bearing capacity of the biggest cross section of the set of HEB profiles is smaller than the minimum load bearing capacity needed, this limit is overpassed as the configuration necessary is not accepted.



Graph 5.2-6: Maximum deflection and total mass for the 36 variables

Lastly, in order to analyze which configurations are the most optimal, it has been plotted the utilization ratio of the cross sections over the total amount of mass used. The utilization ratio of the cross section indicates the percentage of the cross section which is fully working, in this way a percentage of 100% means that the bearing capacity of the element is totally reached, while a percentage of less than 50% indicates that the element is oversized, as half of the cross section is not being utilized. Being conservatives the percentage should in between 60 % and 90% to avoid the failure of the structure.

Consequently the optimal solutions would be the ones which have a balance between the total amount of mass and the utilization ratio. The Graph 5.2-7 shows this relation for the iterations with utilization ratio less than 100%. The iterations inside the red circle are the configurations of the structure which have better performance.



Graph 5.2-7: Utilization ratio versus total mass of the structure.

The iteration number 25 could be considered the optimal one, which has 5 frames in X direction and (x=4) and 7 frames in Y direction (y=6). This leads to a total of 106 elements out of 244 possible elements for the whole structure. The cross sections for each of the elements are:

- Beams on top surface X direction: HEB 180, HEB 220 and HEB 160
- Beams on top surface Y direction middle: HEB 300, HEB 550, HEB 450, HEB 400
- Beams on top surface Y direction sides – left and right: HEB 300
- Columns front and back: HEB 700, HEB 340, HEB 300, HEB 280, H6EB 280, HEB 240
- Columns both lateral sides, left and right: HEB 140, 160

This configuration reduces in 42 % the amount of mass respect the first one. The main reason is that the initial cross sections were estimated to fulfill the requirements when the model had the minimal amount of elements (64 elem.), so when this number is potentially increased the cross sections of the models result oversized.

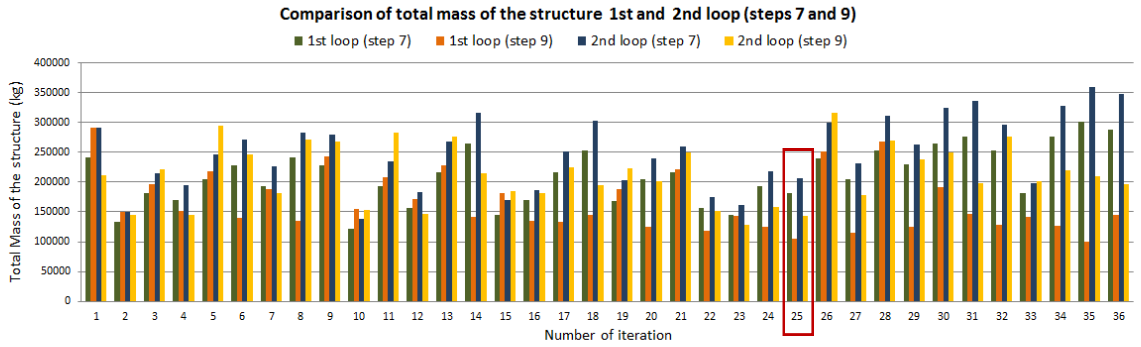
It should be taken into account that *Karamba* does not understand about construability, it might happen that a lower column has a smaller cross section than the one above or the same type of element has five different cross section; therefore all the connections between the elements which form the structure, as well as their orientation should be cautiously check after the first process of optimization.

The values for each of the process are listened in the the Appendix F. After the first optimization loop, it is carried out the ***Eleventh step*** where it could be checked that the cross sections suggested by *Karamba* didn't fulfill the requirements of the Eurocode for lateral buckling resistance (HEB 140), so a new iteration process was done were the cross section for the columns were set to remain the same for all the elements, (Step 11-7). Also, the orientation of the columns in the front and back façade are being rotated, as the main frames are in Y direction with this combination, so they should be placed with the strong axis perpendicular to this direction (web of the profile in Y direction).

Based on this a new optimization process incorporating the new changes has been done. The results are compared in Table 5.2-3, where it is seen that this modified configuration has decreased in a 21% the amount of material used respect the initial structure. As it was expected the reduction of mass is now less than in the previous case, as it has been included construability considerations which make to increase the size of some of the cross sections. The results for the two loops of optimization process (step 7 and 9 for each) are plotted in Graph 5.2-8.

1st optimization loop			2nd optimization loop		
Step 7	Step 9	*Reduction*	*Step 11-7*	*Step 11-9*	**Final reduction**
Total mass [kg]	Total mass [kg]	S7 / S9 [%]	Total mass [kg]	Total mass [kg]	S7 / S11-9 [%]
181326.04	105619.93	42	206757.76	**142844.88**	**21%**

Table 5.2-3: Characteristics values for the snow load on the ground for the different locations



Graph 5.2-8: Comparison of total mass of the structure 1st and 2nd loop

Consequently the final configuration has the following characteristics:

- Beams on top surface X direction: HEB 180, HEB 160, HEB 140
- Beams on top surface Y direction middle: HEB 360, HEB 320, HEB 300
- Beams on top surface Y direction sides – left and right: HEB 240, HEB 260
- Columns front and back: HEB 340 (set as uniform cross section)
- Columns both lateral sides, left and right: HEB 450 (set as uniform cross section)

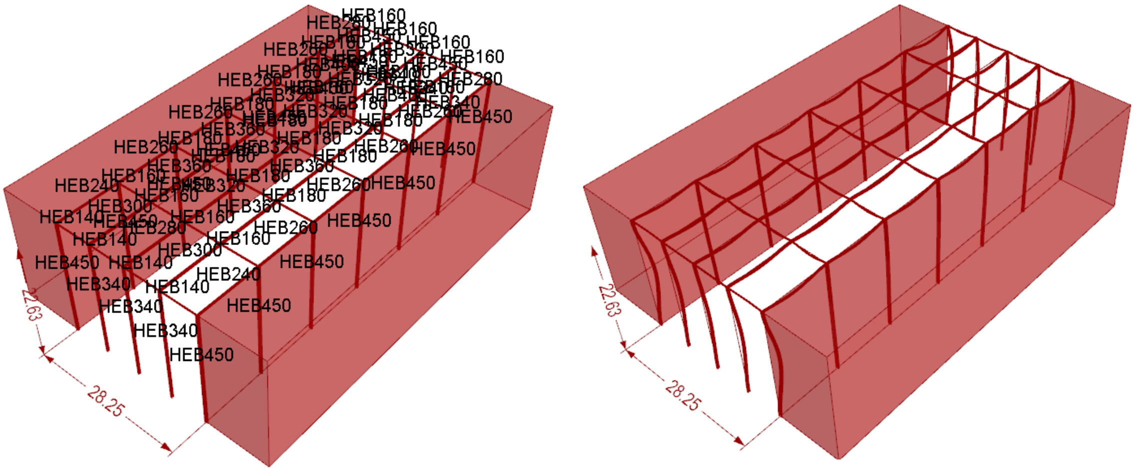


Figure 5.2-2 Final configuration.Cross section values (left) deformation of the structure (right)

The stresses and the bearing capacities for the elements, as well as the maximum deflection are checked to verify that fulfill with requirements of the Eurocode. (APPENDIX E: OUTPUT FROM GRASSHOPPER. SECTION FORCES AND VERIFICATIONS)

The parametrical modeling allows to test different materials, different class of Steel, different cover materials (EFTE) and different cross section profiles. The results for the different cases have been investigated but they are not relevant for the explanation of the method.

Lastly, it has been studied what would happen if the same construction would be located in a different country, to see the influence of the wind and snow loads on the structure.

5.2.2 Case B: White Architects configuration – From Basic to Complex Structure

The proposal of White Architects is shown in (Figure 2.2-5: Render inside Canopy (left) and scheme of overall concept of the Canopy(right) *(White 2015)*, consisting in a combination of plate – shell surfaces and boundary frames. In order to be able to carry the loads from the top surface to the ground and reduce the loads transferred by the boundary frame, two internal columns, shaped as a 'tree', have been designed. This model would be the last approach, as it requires more complex calculations.

Accordingly, three different configurations for the same box domain (Figure 5.2-3) have been done in order to evaluate at the end the aesthetics values and efficiency, as en equilibrium should exists. The starting point consists in a simple frame construction (frames in X and Y direction) based on the Case A. The second case consists in a more complex configuration where plate surfaces have been modeled in between the boundary frames. Lastly, the third model tries to reproduce the initial proposal, having the two tree columns in the middle.

Therefore, based on the same process applied in case A, it is going to be study the EKO-canopy going from simple to complex structures following the scheme in Figure 4.3-1. In this way, this part only shows the results relevant for the investigation and they are not going to be explained with the same degree of detail than from the previous case. It is assumed that the process is already verified and settled down.

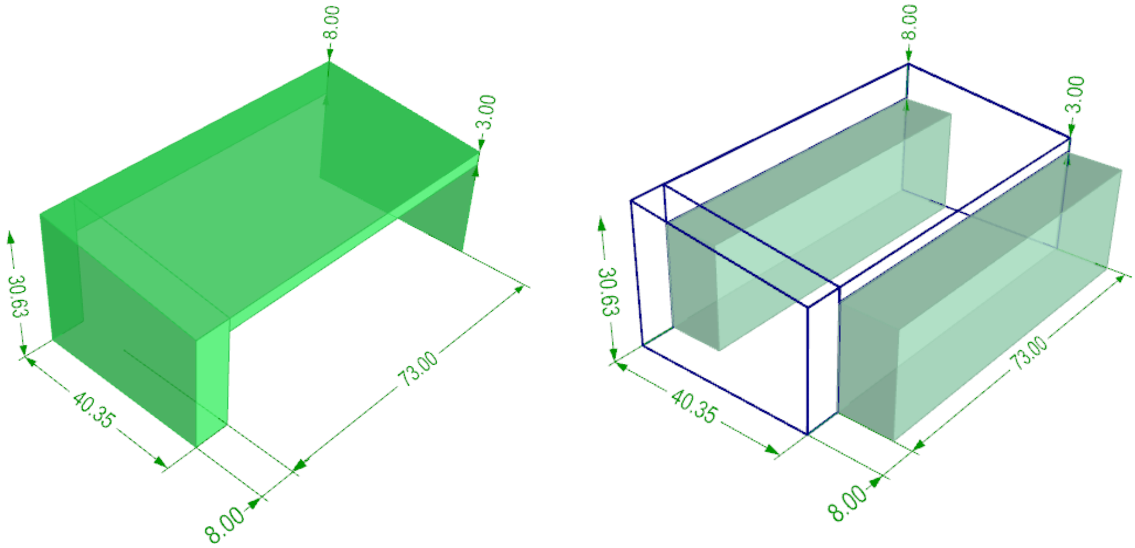


Figure 5.2-3: Box domain for case B

The geometry properties for the box domain of the three cases are based on the Table 4.4-1, to which should be added:

Parameter	Unit [m]	Measurement
Extension length front	m	8
Extension roof (high eave)	m	8
Extension roof (low eave)	m	3
Slope of the roof	[º]	7.06

Table 5.2-4: Basic measurements of the site for the Canopy construction

As all the process have been detailed described for case A, for this second case only the differences regarding the input or the definition of the script would me mentioned.

Case B – 1: Basic frame construction

5.2.2.1 *Design properties:*

Regarding the geometry properties, this configuration is really similar to previous one (Case A). It consists in a frame-type construction form by Beams and columns. After a first analysis, it was necessary to include transversal beams in the front and back facade to reduce the buckling length of the columns to the half.

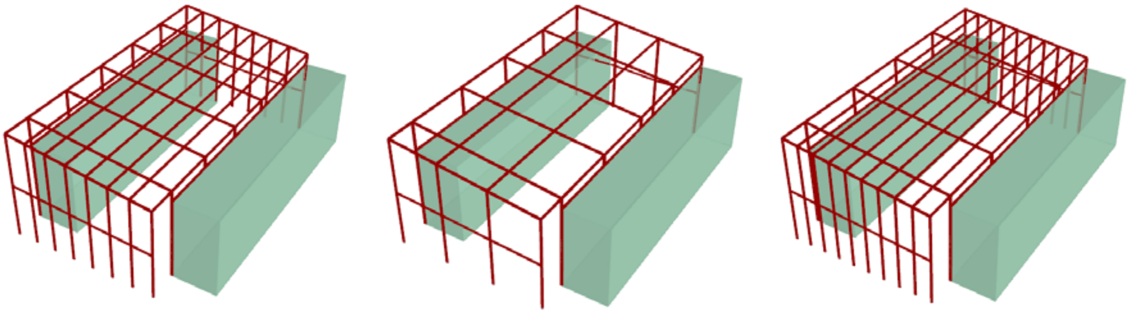


Figure 5.2-4: Possible geometries case B-1(only shown the main load bearing structure, not the covering)

5.2.2.2 Loads:

The loads for this second case are calculated for a monotpitch roof (See Appendix XX) and are applied in the different load areas as it is shown below. Karamba project the surface load in the corresponding line load in each of the elements.

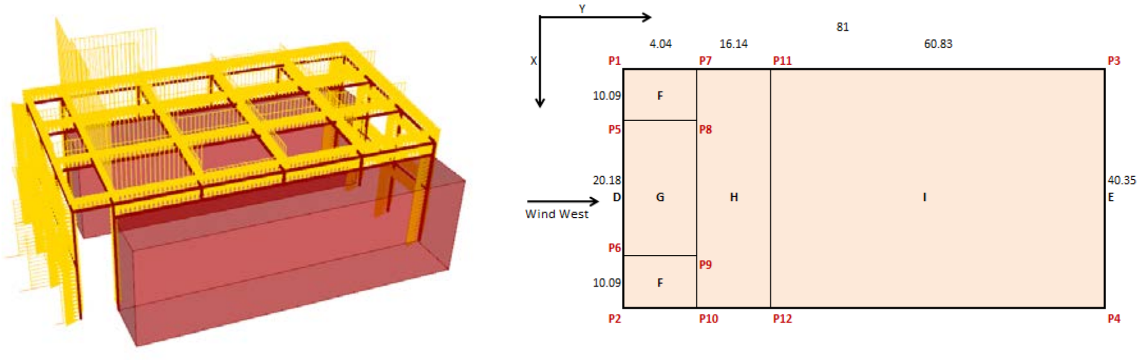


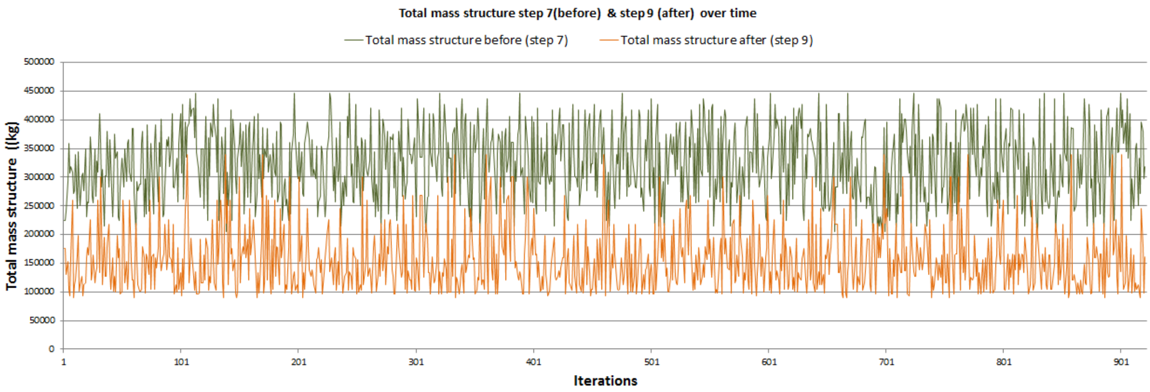
Figure 5.2-5: Loads applied to the geometry (left) and roof load areas (right) case B - 1

5.2.2.3 Support conditions

The connection of the columns to the foundation is defined as fully fix support, while the connections between the different elements are defined as hinge connections.

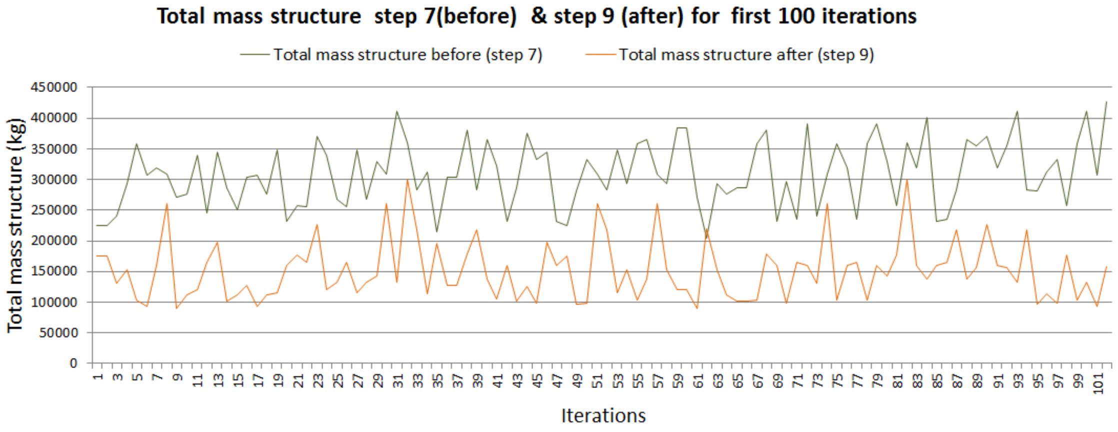
5.2.2.4 Results: Structural optimization

Regarding the optimization process, the main difference is that directly in this second model the limitation of the deflection has been input in a dynamic way. This means that for each combination of frames that Galapagos takes, the maximum allowed deflection is calculated based on the span of the elements, providing more feasible results. In this way, according to the Graph 5.2-3, the difference between the total mass of the structure before and after the cross section optimization is bigger than for the case A.



Graph 5.2-9: Total amount of mass [kg] over time for the steps 7 (green) and step 9 (orange)case B - 1

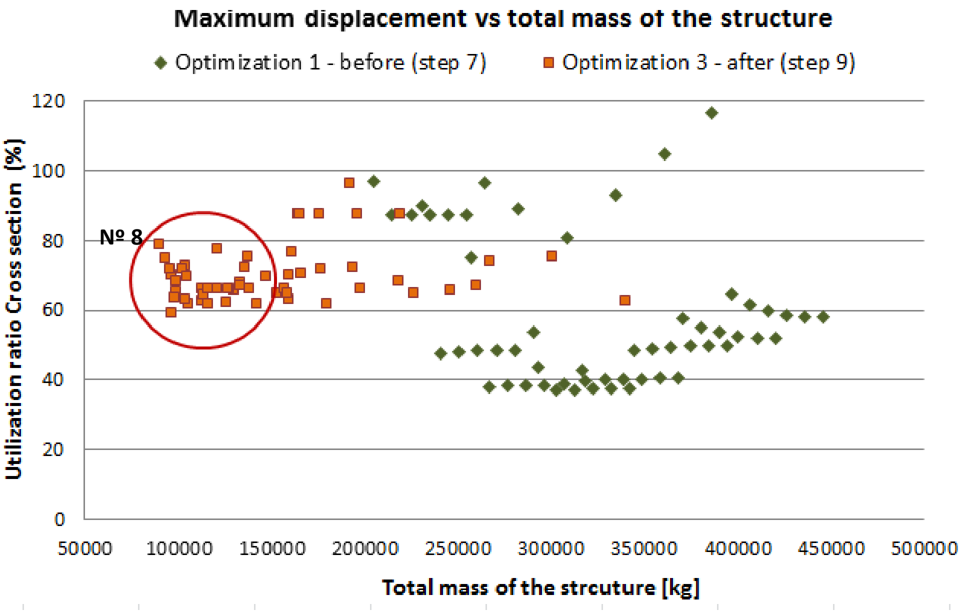
Furthermore, it can be seen that both iterations follow the same pattern (Graph 5.2-4), which indicates a better implementation of the method. Lastly, it is confirmed again that there is not an optimal solution if not several minimums, as there is not convergence in the results.



Graph 5.2-10: Zoom in first 100 iterations of total amount of mass [kg] for the steps 7 (green) and step 9 (orange)

5.2.2.5 Post-process – Quality check

This structure shows a bigger difference between the first optimization process (step 7) and the second optimization (step 9). In this way, according to the Graph 5.2-11, it is clearly seen than the optimal designs (inside the red circle) correspond to the iteration Nº8 (step 9).



Graph 5.2-11: Utilization ratio vs total mass of the structure.

In this case, this combination corresponds with the structure which has less amount of mass (89979.64 kg) having X equal to 4 and Y equal to 8. Furthermore the structure is working at 79% of its capacity in terms of maximum deflection. It saves 67% of total amount of mass respect the first model.

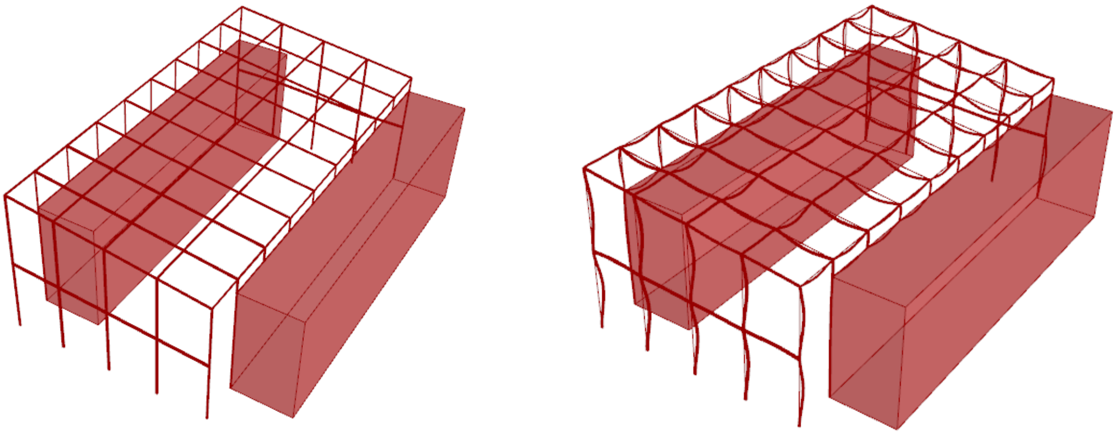


Figure 5.2-6: Configuration iteration Nº 8 (X=4, Y=8)

Case B – 2: Plate & Frame structure

5.2.2.6 Design properties:

The idea of this third model, second option for model B, is to move a bit further in terms of design and originality. Based on the same configuration presented before, this includes a grid between the main frames which form the structure creating a mesh geometry.

5.2.2.7 Loads:

The loads are applied in the same way than from the previous case, as the roof and the façade have the same geometry, so the load surfaces are calculated in the same way. Thanks to the mesh load plug-in of Karamba then these surface load are changing parametrically, and they pressures are distributing on the elements depending on the iteration which is being calculated.

5.2.2.8 Support conditions

The support conditions are defined in the same way than in the previous case, as this is a transformation of the previous one. However a new implementation has been necessary. As now there are created plate grid surfaces between the elements, it has been set all the points on the boundaries which connect the plate surfaces to the main frames as simple supports. These points would be different depending on the size of the mesh (grid) and depending also on the number of principal frames which has the structure, so to make it work it has been necessary a more complex definition. Below is shown the structure with the support definition, in the first one only the supports between the different elements which form the main frames and the connection to the foundation are shown. The picture on the right shows also the supports on the boundaries of the plates.

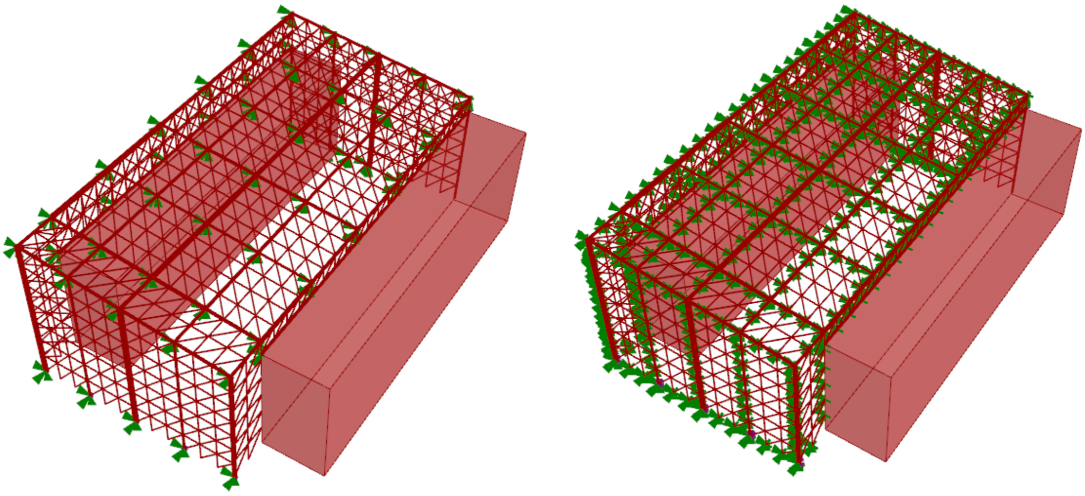
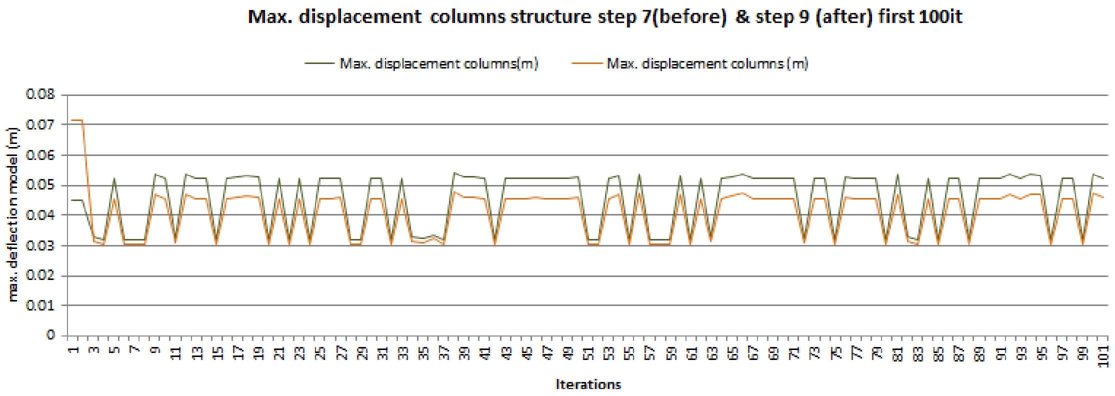


Figure 5.2-7: Support definition - beams and columns (left) and support definition beams, columns and plates (right)

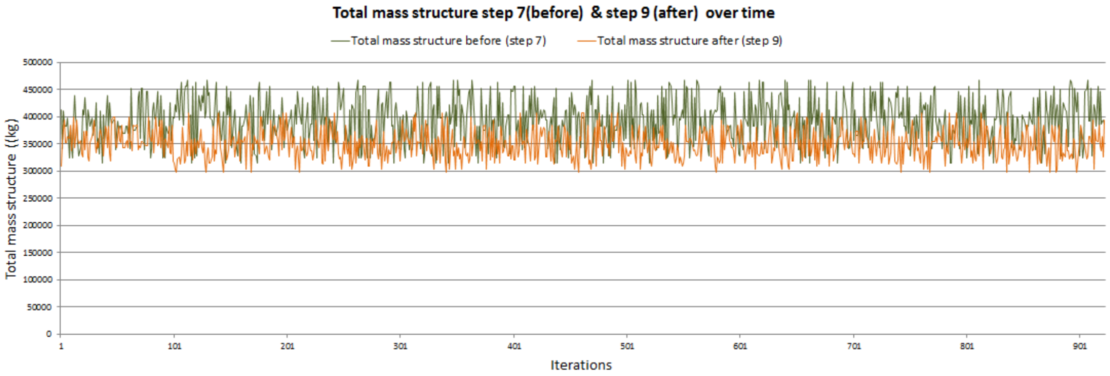
5.2.2.9 Results: Structural optimization

This model has three different types of elements: beams, columns and plates. As the maximum allowed deflection is different depending on the element, it has been divided the cross section optimization in the script in this three categories, which mean more accurate results. This is verified in the Graph 5.2-12 where the maximum deflection before and after the cross-section optimization follows exactly the same pattern.



Graph 5.2-12: Maximum displacement columns case B-2

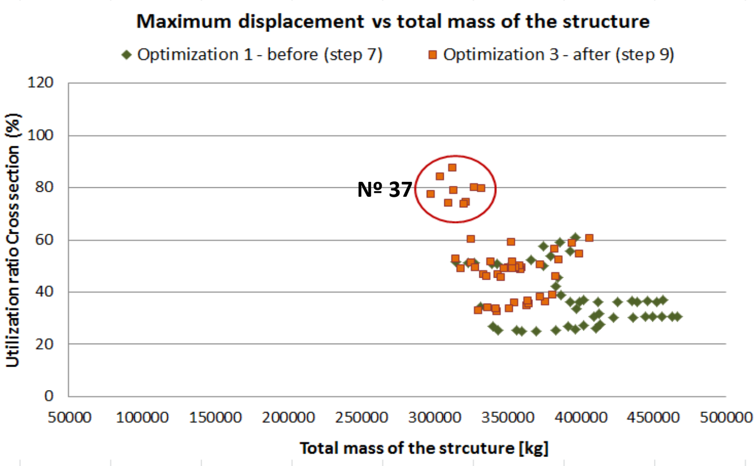
Furthermore, it is seen that this configuration tends to use much more amount of material than the previous one (Graph 5.2-13)



Graph 5.2-13: Total mass structure case 2-B

5.2.2.10 Post-process – Quality check

The results after the optimization process are analyzed, and according to the Graph 5.2-14, it is clear which options would be the optimal ones (inside the red circle).



Graph 5.2-14: Utilization of Cross-section vs Mass of the Total Structure

The combination which has less amount of mass is the number 37, having 6 frames in Y direction (X = 5) and 10 frames, taking into account the extension, in Y direction (Y =8).

The deflections and the stresses for the elements are checked automatically in Karamba as a first overview simplification to have an indication if the members which form the structure will resist. To carry out a deep post - analysis the results are exported to excel (Step 11) (APPENDIX D: RESULTS OPTIMIZATION PROCESSES). The final configuration for the iteration number 37 is shown below.

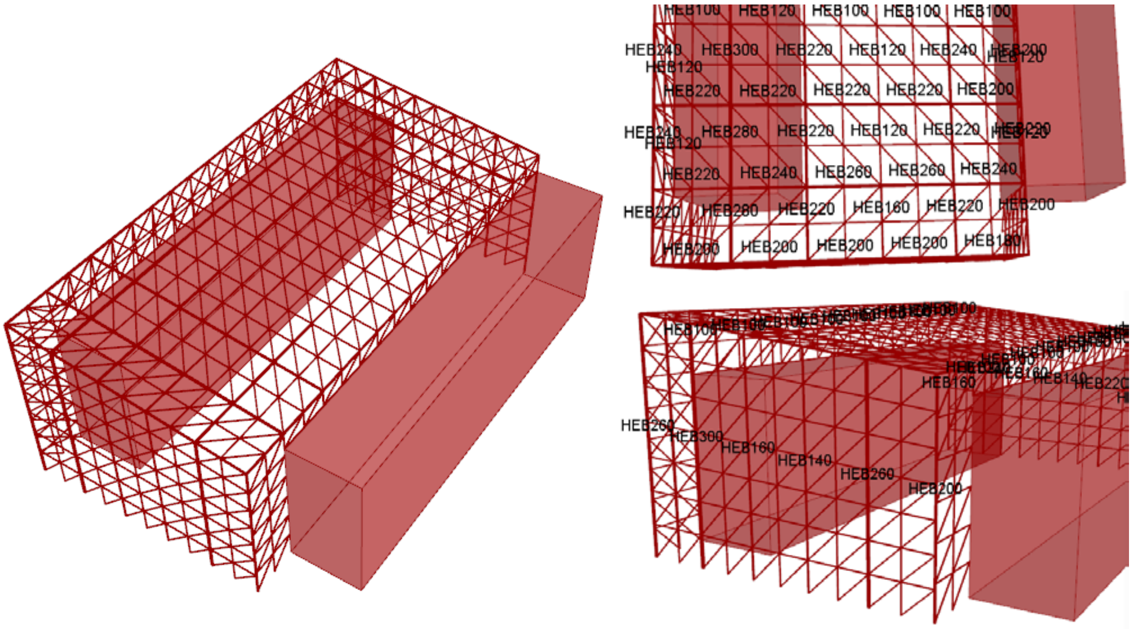
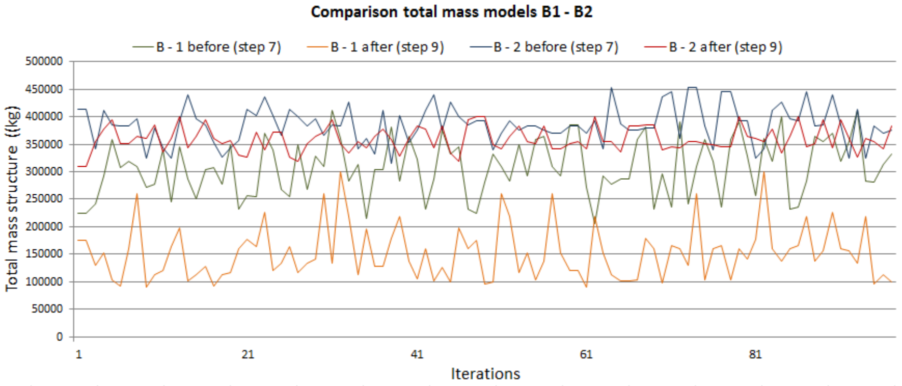


Figure 5.2-8: Final Geometry for case B - 2

The results for the optimizations processes (step 7 and step 9) for the model the model B – 2 are analysed and compare with the case B – 1 (Graph 5.2-15). This shows that the second model, which has incorporated the mesh grid, needs to use more amount of material. It is also observed that the difference between the first and the second topology optimization is not as big as before.



Graph 5.2-15: Comparison Total mass of structure for case B- 1 and B - 2

In this way, the Table 5.2-5 indicates that the second structure, B -2 would need to used 70% of steel more than the previous case, which means more impact on the environment regarding the LCA process.

Case B - 1			**Case B - 2**			**B1 / B2**
Step 7	Step 9	*Reduction*	*Step 11-7*	*Step 11-9*	**Reduction**	**Increase of mass**
Total mass [kg]	Total mass [kg]	S7 / S9 [%]	Total mass [kg]	Total mass [kg]	S7 / S11-9 [%]	S9 (B2)/S9 (B1) [%]
270,940.49	89,979.64	**67**	409,466.37	298,337.56	**27**	**70**

Table 5.2-5: Comparison structures B -1 and B - 2

Case B - 3: White Architects proposal

5.2.2.11 Design properties:

Finally the third model for case 3, reproduces a similar configuration of the proposal of White Architects (Figure 2.2-5). It is a combination of beams, columns and shell surfaces. The main loads of the structure would be carried by the boundary frames and by the two columns placed in the middle of the space.

This model represents the one which has more aesthetical value, as it plays with geometry and forms reproducing an original configuration.

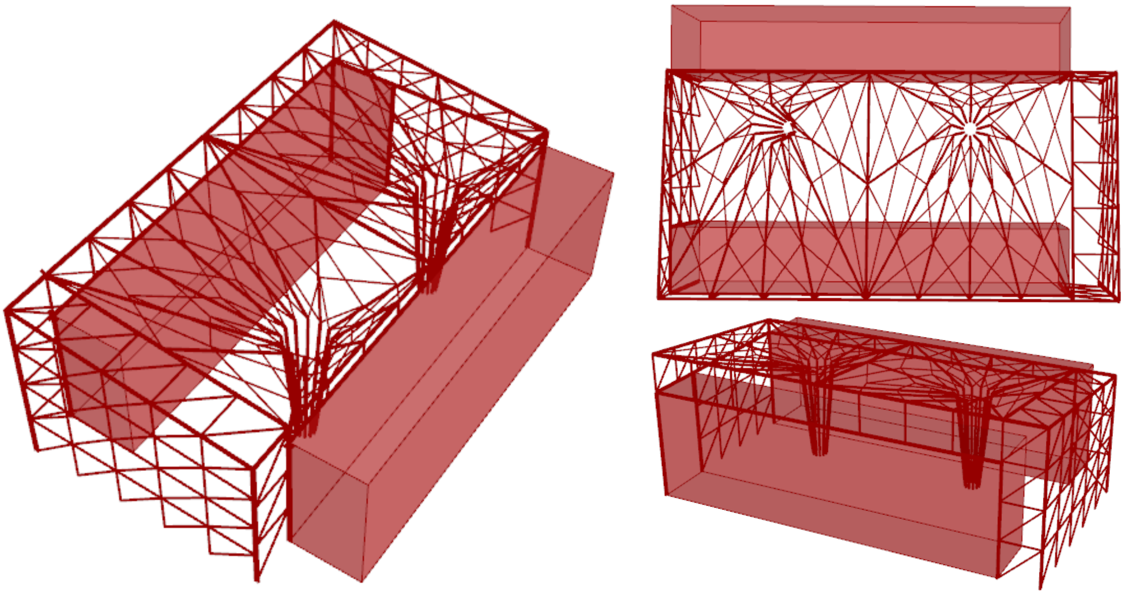


Figure 5.2-9 Geometry for case B - 3

5.2.2.12 Loads

The loads for this model are applied in the same surfaces areas described for the previous models, as the external geometry has the same measurements.

5.2.2.13 Support conditions

Regarding the support conditions, this configuration follows in general terms the same principle than the previous case. In this case the main frames are the boundary frames on the sides and the radial beams which go from the sides to the middle tree columns. In between this radial beams is created a mesh grid.

The connections of the columns, both the ones in the middles and the columns which form the boundary frames, are fully fix supported at the base. While the connections between the elements which form the main load-bearing structure are defined as hinge supports, allowing the rotation around the three axis.

5.2.2.14 Structural optimization

This model has required a deep analysis to create the geometry. As it is form by shell surfaces which are not the focus of this report and required deep analysis and new incorporations to the script, this model has been only calculated in general terms to be able to compare the total amount of mass that would require with the other two options. However, it has not investigated in deep every element which forms the structure. Therefore not topological optimization processes have been carried out for this third model. However, the geometry has been created in a way that this implementation is possible. For example, the parameters which could be investigated are the number of divisions on the sides which are connected to the number of divisions of the central columns. Additionally, the diameter of the columns is also variable.

For the main load bearing elements, beams and columns it has been implemented the cross-section optimization component, giving a save of material of 17% respecting the preliminary specified geometry.

5.2.2.15 Post-process – Quality check

The following table shows the total mass necessary for the construction of the three different models, B - 1, B – 2 and B – 3.

Model B - 1		Model B - 2		Model B - 3	
Step 7	Step 9	*Step 11-7*	*Step 11-9*	*Step 11-7*	*Step 11-9*
T. mass [kg]	T. mass [kg]	T. mass [kg]	T. mass [kg]	T. mass [kg]	T. mass [kg]
270,940.49	89,979.64	409,466.37	298,337.56	312943.98	260569.96

Table 5.2-6 : Comparison of the total amount of mass for the three models.

Part VI: DISCUSSION

Through the developing of this master thesis project it has been studied the idea of integrating structural verifications in the early design phases of the building practices, including a method of form-finding geometries based on optimization processes. This has been done by means of parametrical modeling with the definition of a script in Grasshopper which can be interpreted as designing tool. Consequently, the purpose of this sixth part is to analyze the findings to discuss the advantages, as well as disadvantages or limitations of the applied method and the created script.

6.1 Integrated method proposal: advantages and disadvantages

Since the beginning it has been discussed the idea of replace the traditional working flow of the building process for a dynamic workflow approach. As it has been stated in Part III, this has been already happening since the last decade with the idea of Building information modeling based on the concept of the total collaboration between the building agents and the model data exchange through the different software. However, the integrated dynamic model moves a step forward, not only considering the idea of transfer the model information if not that it proposes a combination of aesthetical and technical aspects using the same tool, or a system where the data is transferred dynamically between design and calculation tools.

This has been deeply studied using the parametrical tool Grasshopper as a design platform which thanks to the incorporation of the FEM plug-in *Karamba* has allowed to perform structural calculations using the same middleware.

As it has been seen, this has provided great flexibility in terms of design, at the same time than a technical feedback is automatically provided. In this way, several structural configurations have been modeled and analyzed for the same construction, which with the traditional working approach would have been really time consuming. Within this context it should be distinguished two different things about the geometry definition. For the developing of this thesis it has been created three different models (case A, case B – 1 /B – 2 and case B – 3), and inside each of them it has been generated different structural configurations. Normally, in the building design process only one model would be created and all the alternatives would be generated based on that one. The reason of creating different models is to study the possibility of developing a script in grasshopper which can be used for several projects, in which the most of the features are already pre-defined. In this way, this tried to answer to the second research question of this thesis.

Accordingly based on the followed process, it can be concluded that it is possible to pre-define a script, which is divided in different sections; some of them can be made in a generic way and be used in several models, while others must be specific for the single projects. The different sections are:

- Calculation and definition of loads.
- Geometry definition
- Structural definition (elements, supports and cross-sections) (from GH to Karamba).
- Analysis of the structure.
- Optimization process input.
- Verifications (stresses and deflection).
- Output: Section forces and deflection.

All of them, except the geometry, could be interpreted as generic using the defined script and making the necessaries adaptations in each case. The creation of the geometry is of course specific for each case. It should be noted that special considerations should be made during its creation, taking special attention to small details. In this way to later transform the model to Karamba all the elements and connections should be modeled cautiously. This means that each line should be modeled as a single element, and all the points which connect those lines should be perfectly identified to be able to later define them as moveable, hinge or fix connections (support definition). This fact adds complexity to the designs, and it requires for its development a practitioner who has both creativity and technical skills. Therefore, it appears in this scenario the figure of the hybrid practitioner, who would be a key piece in this integrated dynamic model proposal.

Regarding the flow process between the different platforms where the data is transferred, it has been seen that it is working correctly. Once that the different ways of transferring the data have been already specified and settled down it would be really easy for an external person follow the same procedure, as all the connections have been already tested.

6.2 Results and optimization process: benefits, limitations and its future improvements

Regarding the optimization techniques applied, it has been seen that they represent a feasible method which can be easily implemented in the design process at the beginning to help to the practitioner to choose the best option for his design based on a certain number of parameters.

In this context it is clear the idea that not an unique optimal option exits. The results from the topological optimization processes carried out for the EKO-Canopy project are a sign of this, where several minimums were found for the same construction. However based on these results it is possible to do an evaluation of several variations for the same structure. Comparing the total amount of mass used for the construction and the utilization ratio of the elements which form it, it is possible to know the performance of the structure. This allows to the designer to make the corresponding decisions since the beginning to create a model which at the end, it would be possible to build without the necessity of doing several changes.

Furthermore, it has been also checked through the creation of the different models that is really important an accurate definition, as based on this, the optimization process would provide more or less worthily and trustily results. When we are dealing with the idea of calculating the structure at the same time that it is being modeled, every element which forms it should be perfectly defined. Not only with the action of generate the model is enough, if not that the modeler should move a step forward and think if that specific line which is drawing would be a beam, a column, a tension cable, etc.

Regarding the optimization process carried out for the specific model, the EKO-Canopy, it has been possible to estimate which structures would be optimal based on their efficiency after carried out several iterations, as it was summarized through the chapter. In this way it is possible to reach until 70% of savings in material respect the first configurations. However there are several factors which affect to the results of the optimization, as they are the level of definition of the joints (eccentricities), the orientation of the elements to use the maximum of its capacity, etc. Thus the process can be done one or two times, or based on the results it can be repeated multiple times until reach "the perfect solution". This also proves that increasing the level of accuracy, decreases the amount of saved material, as was demonstrated for the model A. In that process after the first loop of optimization the percentage of saved material was almost to the half, 42%, while after the new changes, the amount of saved material was 21% respect the initial configuration.

Part VII: CONCLUSION

This seventh and last part of this thesis work concludes and summarizes the main points deals during this project.

The first thing studied was the idea of substitute the linear working approach for an integrated dynamic model. Within this aspect this thesis has showed the potential benefits that this method could provide to the construction industry. However, there are still so many features for discover and study, as one of the main things that can be learned through this work, is that doing this in the frame of parametrical modeling provides endless possibilities. Grasshopper, which is the main tool used, is based on Visual Programing Language which allows to the user to incorporate under the same software several features including of codes by means of programming. Every day there are developed new plug-ins or components that allows to the user from performing energy analysis to carry out FEM calculations, as it was this specific case. Additionally, as all is based in basic geometry (lines, points, surfaces, etc) leads to the designer to create from the most simple configuration, as it was Case A, to more complex designs, as it was case B-3. Sometimes these designs could be really complicated as one of the goals of the architect is to look for original concepts. In this way the incorporation of structural aspects since the beginning would help to achieve the most original and creative geometries but being at the same time reliable.

The integration of the structural verifications in grasshopper allows to the architect to play with geometries, and to the engineering to calculate them, incorporating in this way its knowledge and suggestions from the beginning. This makes gain time during the construction process and makes a more detailed and well-defined conceptual designs. This also demonstrates the necessity of incorporate to the building process the hybrid practitioner.

Furthermore, regarding the optimization techniques integrated in Grasshopper, it has been seen that on the one side they are easy tool to use for non-programmers as they are not based in difficult mathematical problems; and on the other side, the optimization process itself based on form-finding and sizing methods provides important savings of materials for the overall structure if it is implemented in a successful way.

This objective deals with one of the main goals of this master thesis, which was to establish a method to look for sustainable constructions in the Nordic Region. This could be used in a generic way for several projects as the script created is a kind of receipt which is modified depending on the desires of the architect. For example thanks to the loads definition on the script, it is possible to take the climatological data for several regions, calculating the same construction in different locations along the Nordic Region.

In relation with the EKO-Canopy project, the thesis provides some indications which establish the basis to let the client or the designer to choose. It has been seen that the most effective and sustainable solution is the most basic one, as it used less amount of material, which at the end benefits to the LCA process. However, in all design process, the creativity and originality are key issues, so at the end should be a balance between aesthetics and efficiency.

Lastly it can be concluded that the script presented provides some small tools which can be applied to several projects. It establishes the basis relations of components of how to define the loads, how to calculate the deflection for single elements and based on that carry out optimization processes, how to know the section forces for the different elements, etc. Therefore, when a new project is started this small parts which form the big script can be joined together to be able to develop the whole process. However, as the parametrical modeling including *Karamba* is a world itself, it should be specified which level of detail for the calculations is needed or wanted to achieve.

6.3 Further studies

As further studies for this work, it could be interesting the possibility of incorporate other optimization process including other type of structural material, as for example wood. This implies that other verifications should be added to the script. If this point is achieved, it would be really beneficial for the designs to connect in last instance the method to the already created scripts for the calculation of LCA, as it was stated in Part IV.

Additionally, it would be really interesting to continue the works in more complicated geometries, because at the end the new architecture consists in fancy and magnificent designs.

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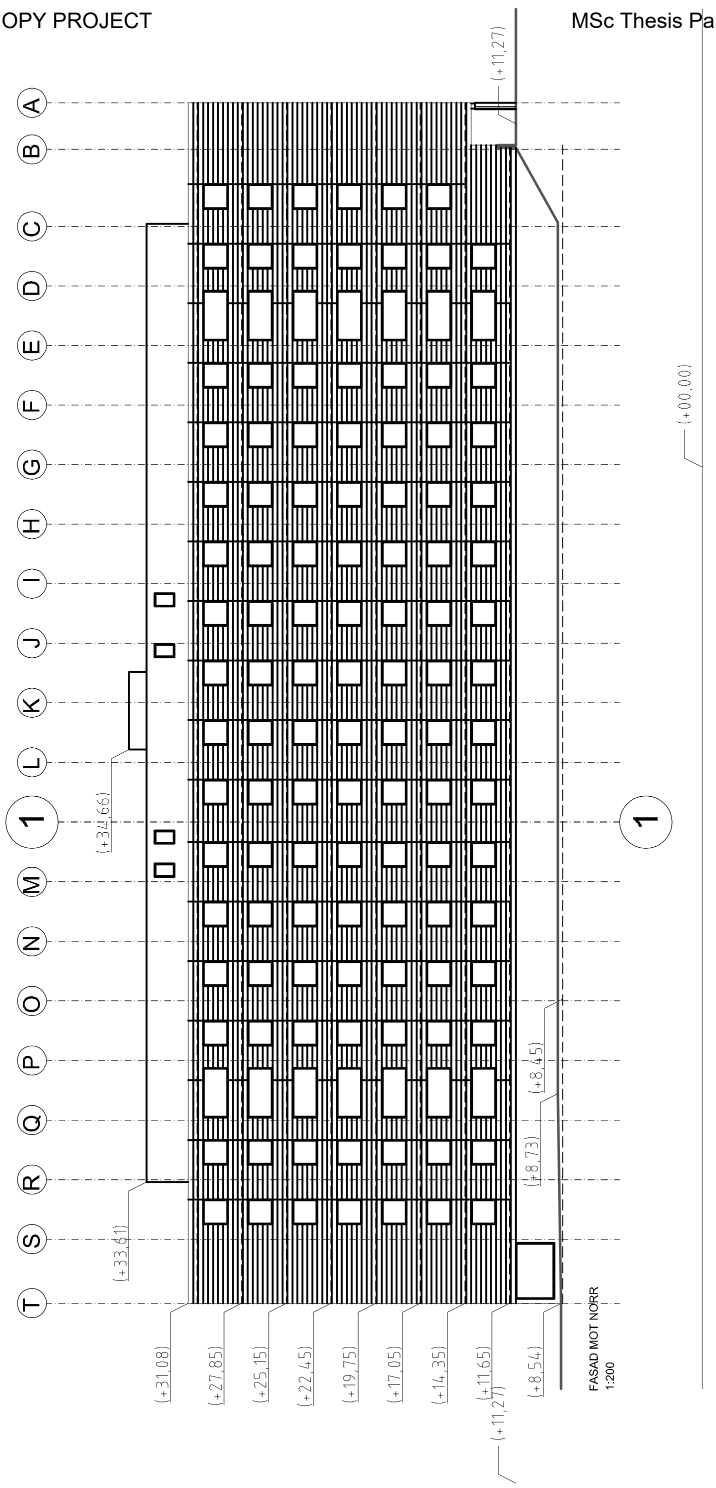
APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION

APPENDIX A: THE EKO-CANOPY PROJECT



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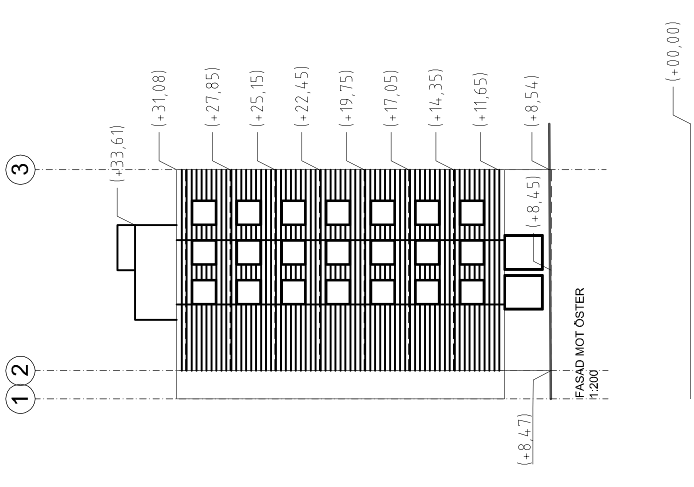

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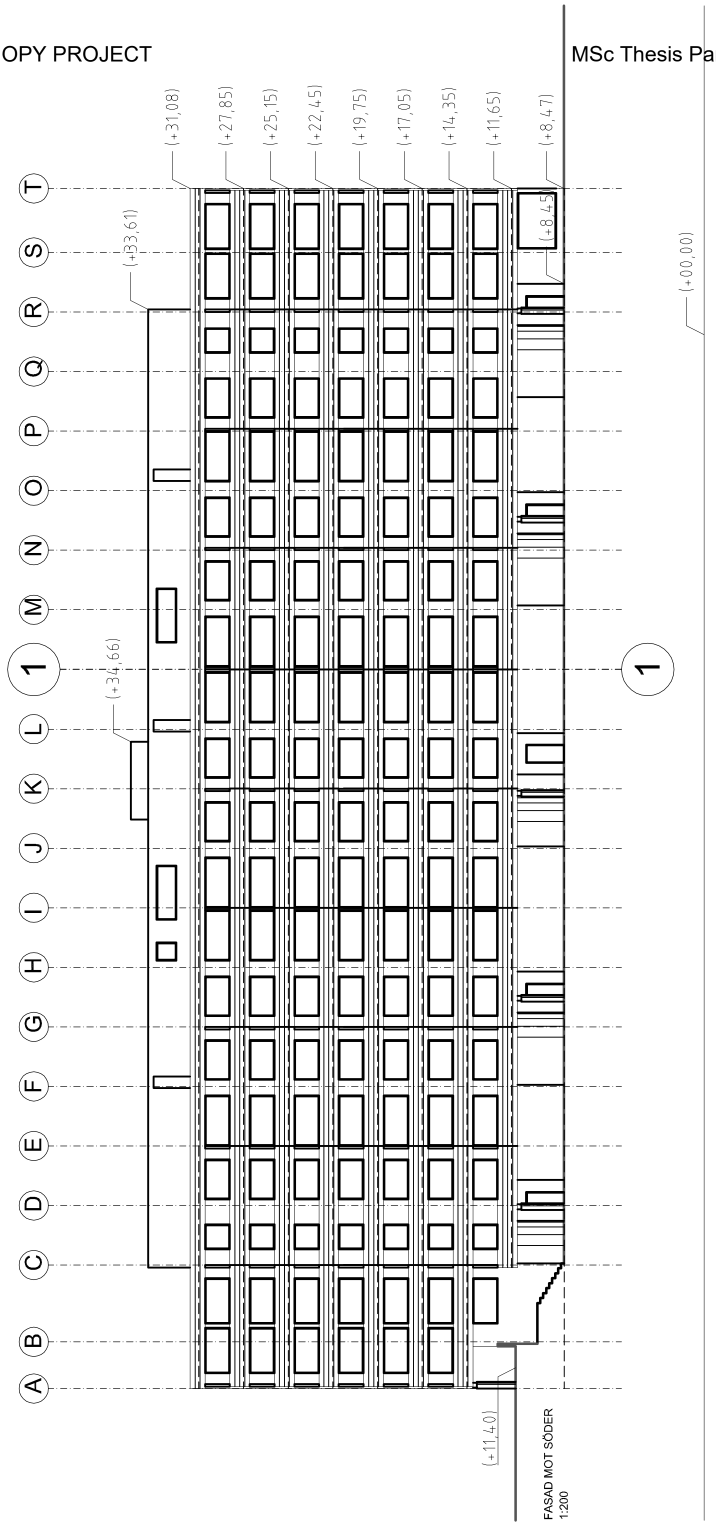

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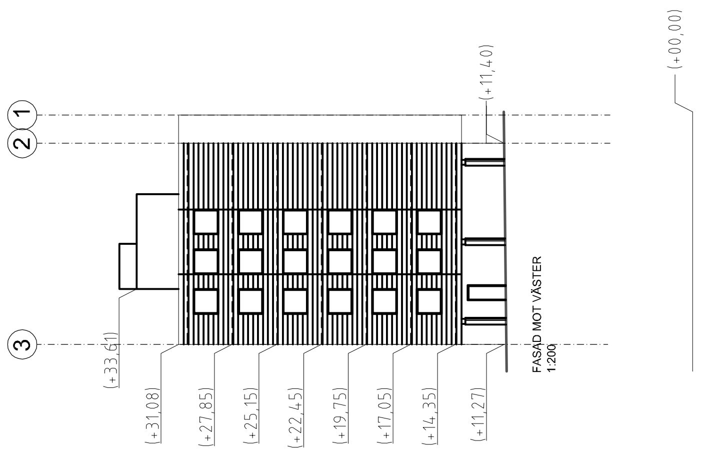

FASAD MOT VÄSTER

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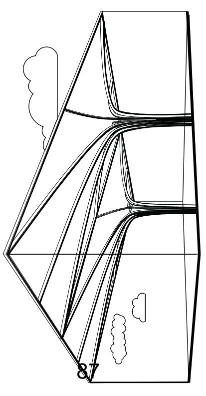
PLAN 15

EKO-CANOPY

HUS I HUS-ARKITEKTUR MED INNOVATIV ANVÄNDNING AV RESTVÄRME



GEMENSKAPSBYGGANDE FÖR GRANNSKAPET

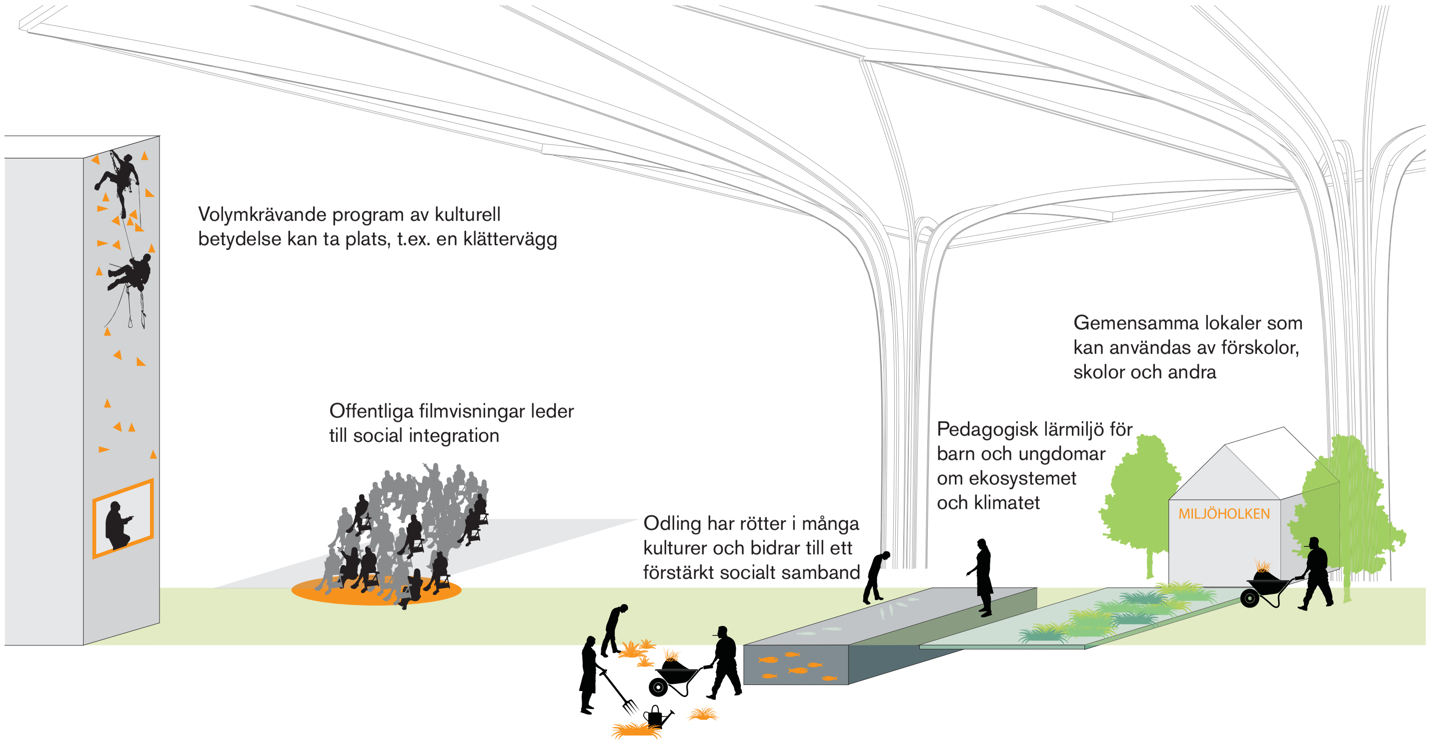
Målbilden är att skapa ett gemensamt rum för alla grannar. En mötesplats för socialt utbyte och en högre integration av människor från olika kulturer i miljonprogrammet.

Många av dagens miljonprogramsområden saknar en gemensam plats att mötas i. De flesta bor mycket tätt i sina lägenheter och de saknas pengar till att använda kostnadspliktiga kulturella mötesplatser i staden.

Eko-Canopy skapar en lokal mötesplats där grannarna kan mötas och umgås. Många i miljonprogramsområdena har tidigare invandrat från sydliga länder, där det av tradition finns en större användning av utomhusmiljön som vardagsrum. En ytterligare fördel med glasstrukturen är att befintliga hus inte behöver en strukturell helhetsrenovering, bara ett tillägg som minskar husens energianvändning delvis på passivhusstandard. Dock fungerar strukturen och konceptet även i andra miljöer, eftersom det inte direkt påverkar eller gör något ingrepp i bebyggelsestrukturen. Även i nya bebyggelseområde kan konceptet användas, t. ex. i offentliga byggnader.

ETT AKVAPONISKT SYSTEM

Akvaponik är ett hållbart matproduktionssystem som kombinerar konventionellt vattenbruk (odling av akvatiska djur såsom fisk, skaldjur eller alger i bassänger) med hydroponik (odling av växter i vatten) i en symbiotisk miljö. Vattnet leds till ett hydroponiskt system där avföringen bryts ner av kvävefixerande bakterier och sedan filtreras av växterna som tar upp näringsämnena. Det renade vattnet återförs sedan till fiskarna. Restvärmen kan användas att hålla rätt temperatur i bassängerna och i växthuset och sparar mycket energi i jämförelse med konventionella akvaponiska system. Anläggningen som ska finnas i projektet tar en yta av totalt 120 kvm och producerar 150 kg fisk och 600 kg grönsaker per år.



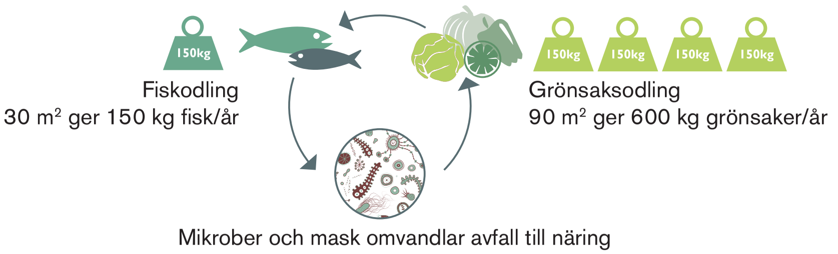
Volymkrävande program av kulturell betydelse kan ta plats, t.ex. en klättervägg

Offentliga filmvisningar leder till social integration

Odling har rötter i många kulturer och bidrar till ett förstärkt socialt samband

Pedagogisk lärmiljö för barn och ungdomar om ekosystemet och klimatet

Gemensamma lokaler som kan användas av förskolor, skolor och andra

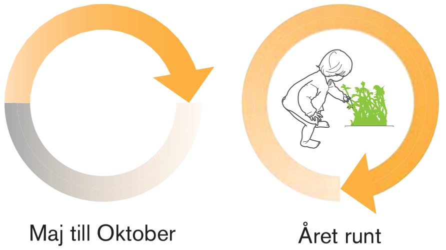


Växterna renar vattnet till fiskodlingen

Fiskodling
30 m^2 ger 150 kg fisk/år

Grönsaksodling
90 m^2 ger 600 kg grönsaker/år

Mikrober och mask omvandlar avfall till näring



Odling året runt

Med den förlängda odlingssäsongen och med hjälp av uppsamlandet av regnvatten kan man upprätthålla ett samutnyttjande ekosystem.

Den vertikala trädgården

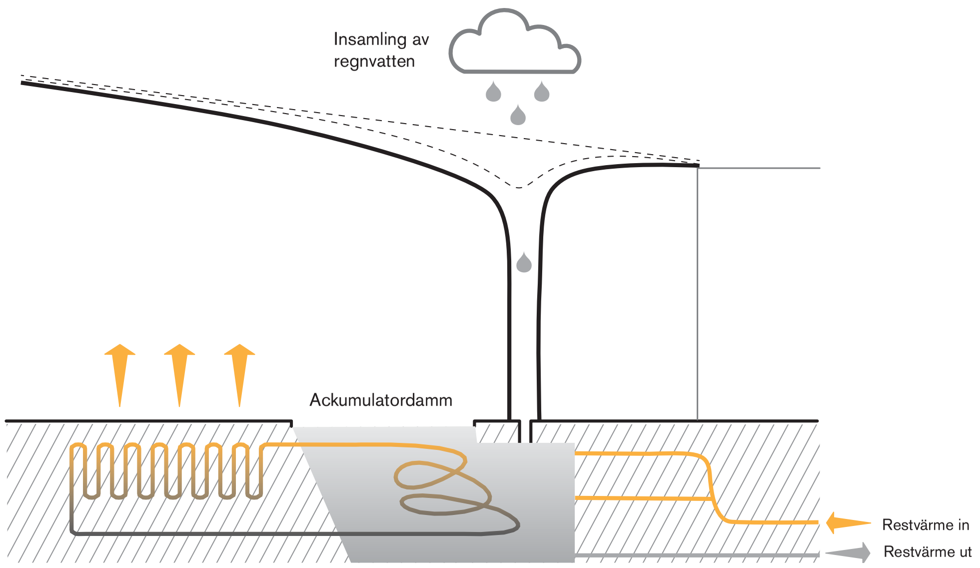
MFO Park Zürich, Schweiz. Terrasserna och strukturen möjliggör planteringsytor och växter i den vertikala dimensionen. Det bidrar till flera platsbildningar och en högre grönytefaktor. Terrasserna kan även sammanläggas med balkongerna och de kan bli uppdelade i offentliga, semi-offentliga och privata delar.

Foto: Roland Fischer

Sociala mötesplatser med gemensam aktivitet och odling

Tropenhaus Frutingen, Schweiz, är ett exempel på användning av restvärme för ett akvaponiskt system. Turister och den lokala befolkningen besöker verksamheten. Här finns även ett integrerat museum som berättar om de hållbara tankarna kring projektet.

Foto: Beate Makowsky



SÅ FUNGERAR SYSTEMET

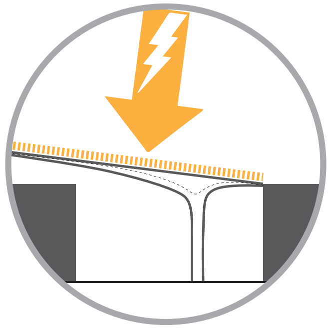
Restvärmen (som har en temperatur av 30-50°C) går förbi området i ett rör. Via en värmeväxlare växlas värmen över till det lokala nätet. Här löper ett rör i marken som går in under glasbyggnaden till en ackumulatordamm. Ju högre temperatur restvärmen har desto högre upp i dammen tas den in för att få en bra temperaturskiktning i dammen. Trattkantarellstrukturen i glastaket samlar regnvatten som leds ner i dammen.

I dammen i sin tur finns ett slingsystem som hämtar värme och sedan transporterar runt den i marken för att avge värmen till "uterummet". Dammen fungerar som en ackumulatortank och regnvattenuppsamlare samt jämnar ut temperaturfluktuationer över dygn och årstider.

Slingsystemet fungerar likt ett golvärmesystem för att skapa en stor värmeöverförande yta. Detta gör att värmeeffekten blir tillräckligt stor för att hålla klimatet i glasstrukturen på en behaglig temperatur året om.

Den återstående restvärmen som går ut från ackumulatordammen leds vidare för att värma upp busskurer, lekplatser mm via dels samma princip med slingor men även lufthängda rörstrukturer som kan bilda komfortabelt lagom uppvärmda bänkar och sittplatser.

Det inglasade området förvärmer ventilationsluften som sen går in i byggnaderna och sparar på så sätt på värmeenergi. Frisk luft tas in långt ner i glasfasaden och stiger sedan uppåt genom att den blir varmare. För ventileringen av själva glashuset sker detta på helt naturlig väg. För att undvika övertemperaturer finns luckor i taket som öppnas via styrning på temperatur. Luckorna öppnas så inte temperaturen når över 25°C så länge det inte är varmare utomhus.

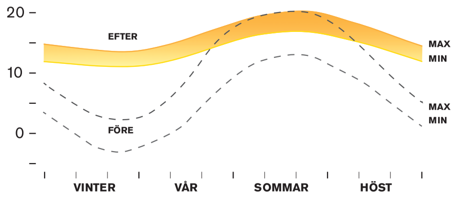


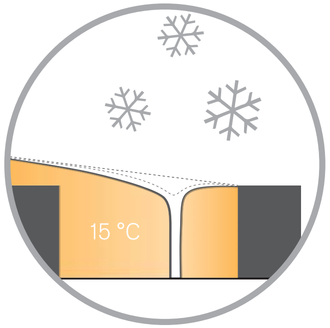
SOLCELLER

Transparenta solceller är integrerade i glasstrukturens tak. Eftersom största delen av taket är riktat mot söder i bra vinkel mot solen (ca 10-15 grader) kan mycket el produceras. I glastaket mellan byggnaderna är täckningagraden 50 % för att skapa en bra balans mellan energiproducering och inflöde av dagsljus. Fönstrena är ljusa för att skapa en illusion av att brukaren befinner sig utomhus även om det egentligen är tillstängt. Högre upp i glasstrukturen, ovanför ena byggnadens tak, kan solcellsandelen öka ända till 100 %.

EXTRA KLIMAT- OCH VINDSKYDD

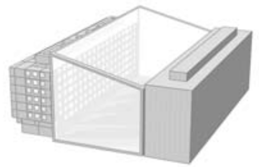
Genom det extra skalet fås ett naturligt skydd mot yttre påverkan. Vind, regn och blåst hålls ute vilket ger ett bra "utomhusklimat inomhus".





ENERGIANVÄNDNING

Genom att addera ett extra klimatskal skapas en buffert till befintlig eller nybyggnation. Eftersom området är inglasat skapas en växthuseffekt där solens strålar värmer upp luften innanför. Då solen inte räcker som värmekälla kommer restvärmen in. Restvärmen bidrar med en värmeeffekt som räcker för att hålla temperaturen vintertid på cirka 15 °C. Glasen ska väljas med omsorg, lågt U-värde (<0,7 W/m^2,K) för att restvärmen ska räcka långt. Samtidigt måste glaset släppa in mycket dagsljus via hög ljustransmittans. Istället för lågt g-värde på glasen (solfaktor) balanseras solen med transparenta solceller.



En energiberäkning har utförts i IES Virtual Environment där varje rum byggts upp med en zon vardera. Programmet tar hänsyn till solinstrålning, byggnadens tröghet och skuggningar från omkringliggande byggnader. Det inglasade området uppvärms med restvärme vilket är modellerat i modellen som ett golvvärmesystem där inkommande vatten är 40°C. Resultatet visar på en 50% sänkning av energianvändningen.

EKO-CANOPY

- 20 kWh/m^2

Genom att förvärma ventilationsluften i det inglasade uterummet sparas 20 kWh/m^2 i värmeenergi. Dessutom erhålls bättre inomhusklimat. Detta gör att en installation av ett FTX-system, där plats för kanaler i byggnaden är ett problem, inte behöver göras.

+15 kWh/m^2

Med transparenta solceller integrerade i glastaket kan fastighetsel motsvarande för två bostadshus produceras. Mitt över gården finns det en täckningsgrad av solceller på 50 % medan uppe på bostadstaket kan täckningen sakta övergå till 100 %.

2 000 000 liter/år

Samlad regnvatten kan användas för t ex toaspolning i 100 lägenheter och bevattningssystemet ute. Vatten är också tillför akkumulatortanken kopplas till spillvärmen och bassängarna att odla fisk och växter.

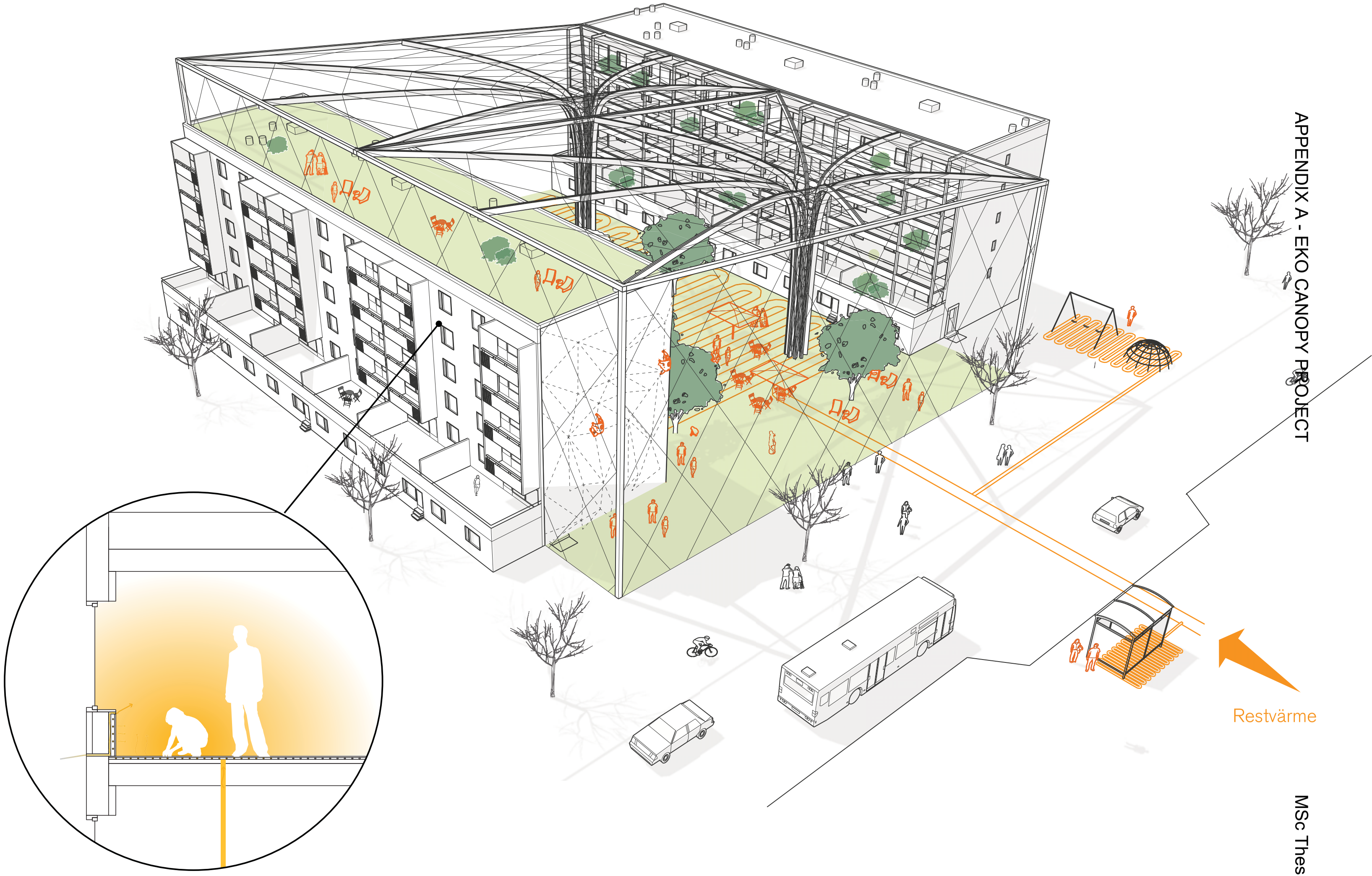
EKONOMI

Grundtanken i detta förslag är att trattkantarellstrukturen ska vara genomförbar, såväl byggnadstekniskt som ekonomiskt. Den uppbyggda strukturen är i trä och materialsnål. Istället för att byta ut alla fönster och tilläggsisolera fasaderna mot uterummet byggs detta skyddande skal upp av glas. Pengarna läggs på att få denna struktur tät och energisnål samt energiproducerande. Det extra skalet tar också om hand energiläckaget från de köldbryggor som ofta finns vid balkongerna på miljonprogramshus. Eftersom uterummet minskar behovet av prima värme i byggnaderna kan dessa energikostnader skjutas till i projektet.

INNOVATION

Genom ett till synes enkelt glasöverdrag skapas helt nya unika miljöer. Vi tillåts att byta klimatzon genom att stiga utanför vår dörr. Att skapa växthus i det nordiska klimatet uppvärmt från restvärme är ingen nyhet. Att däremot sätta det i ett socialt sammanhang där människor kan mötas, odla, se på fiskar, ha picknick eller bara hänga på en filt och läsa en god bok. Genom att skapa effektiv uppvärmning med stora värmeöverförande ytor i väggar och golv i nya byggnader (se figur till höger) eller vid renovering kan restvärmen även räcka för att värma våra bostäder. Addera solceller som integreras i glasfasaden för att täcka byggnadernas elbehov för fastighetsel. Utanför glastäcket värms busshållplatser och lekplatser upp.

En hel rad av befintlig teknik som samlas under ett täcke och sätts i en social kontext. Denna innovation är enkel, genomförbar och duplicerbar samtidigt som den strävar mot ett modernt samhälle där resurseffektivitet och gemenskap är ledord.



Restvärmen kan användas i en kombinerad lösning av vattenburen golv- och väggvärme.

-50% Energianvändning

Energianvändningen i de befintliga eller nya byggnaderna kan halveras eller mer tack vare den smarta glasstrukturen. Strukturen skapar en buffertzon som värms upp av sol och restvärme vilket gör klimatskalet bättre samtidigt som det är en elproducent. Förvärmning av ventilationsluft samtidigt som nya byggnader kan värmas upp av vägg- och golvvärme bidrar till den höga energiprestandan.

Bovieran
Ett seniorboende som finns på ett antal platser i Sverige där man kopplar samman bostadshus med en fjärrvärmeuppvärmd gemensam gård att vistas i.

Foto: Benno Nilsson

Gardens by the bay
Gardens by the bay är en integrerad del i strategin av regeringen i Singapore att förvandla en "trädgårdsstad" till en "stad i trädgården". Parken har blivit väldigt populär, bland annat för olika evenemang.

Foto: Allie Caulfield

EKO-CANOPY

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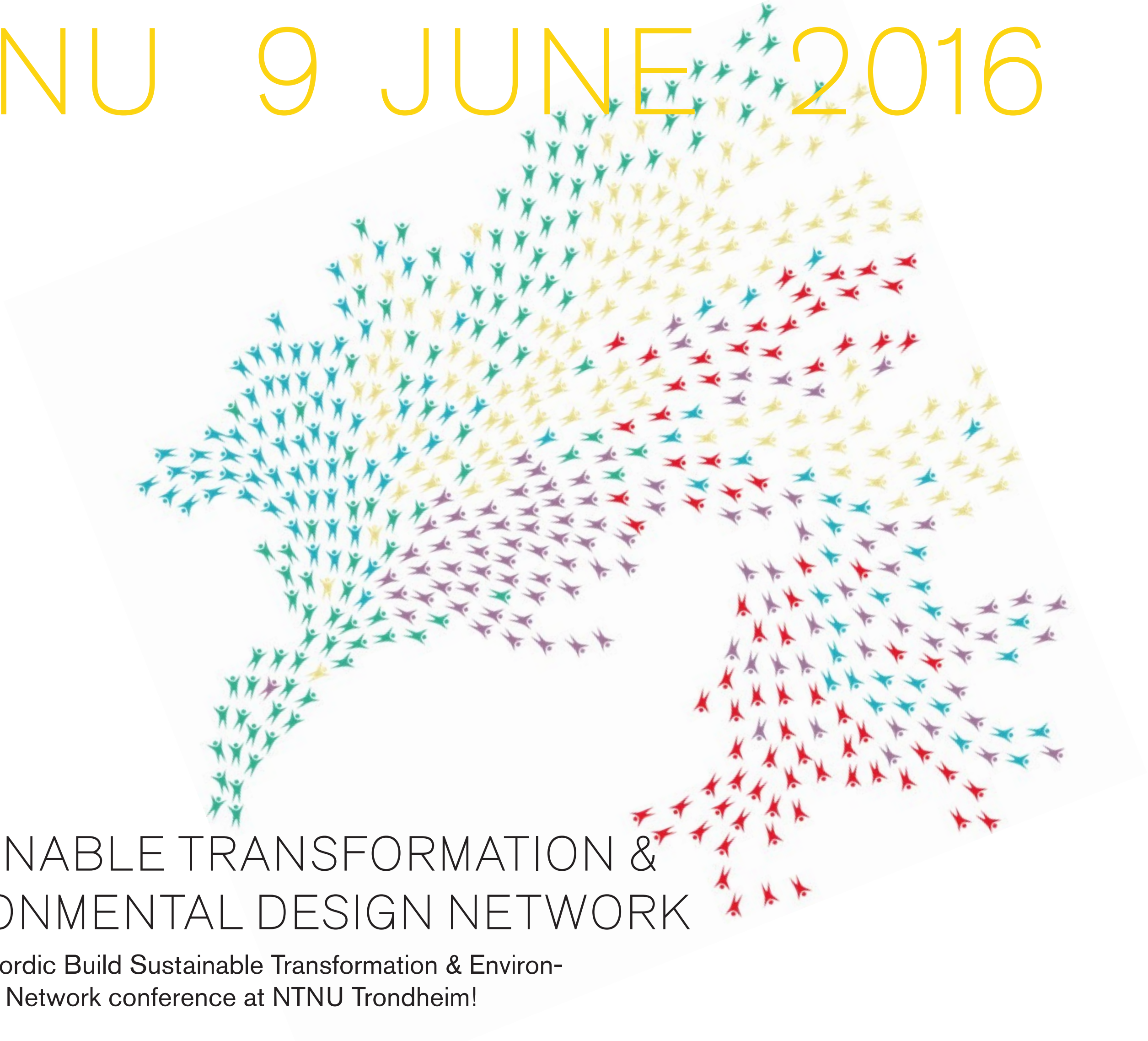
APPENDIX B: STED PROGRAM TASKS

THE STED NETWORK
NTNU 9 JUNE 2016



SUSTAINABLE TRANSFORMATION & ENVIRONMENTAL DESIGN NETWORK

Welcome to Nordic Build Sustainable Transformation & Environmental Design Network conference at NTNU Trondheim!

With the aim of coming together and share the knowledge we hope to have a day full of interesting reviews and transformational discussions on how we can create more quality and fast-forward the track to a sustainable world.
Dialogue and exchange between academy and practitioners is key in this program, so we hope this day together will instigate new encounters for new perspectives and great ideas.
We start with an introduction exercise in order to set an open communication between every-one. After that we go through a series of fast elevator-pitches on the work that has been done. In short repetitive interval, we discuss the findings for a broad overview and so get the oppor-tunity to meet. For the afternoon we divide into 2 groups for more in depth discussions on your chosen theme.
Please note:
Practitioners please bring your research questions. What should be studied next? Are you ready to implement results?
For the ones that presents with posters, please note that it has to be hung and ready for 9.00 am.
A reminder to send all posters as pdf to Kristoffer Negendahl krnj@byg.dtu.dk

Program 8.30 - 16.30
8.30 Arrival NTNU, placing posters
9.00 Welcome by Aoife Houlihan Wiberg
9.10 The STED project, Lotte Bjerregaard Jensen
9.25 Circle event by Elise Grosse, White Arkitekter
10.00 3 minutes pitches of each poster combined with short pier-discussions.
12-13.30 tour NTNU and lunch
13.30 Choose your sessions
14.30 coffee brake
15.00 Choose your sessions
16.00 Check-out…Elise Grosse, White
16.30 End
18.30 Dinner

CONTACT

Lotte Bjerregaard Jensen lbj@byg.dtu.dk

Building Design
Department of Civil Engineering

Technical University
of Denmark

PARAMETRIC STRUCTURAL DESIGN

OPTIMIZATION OF STRUCTURES BASED ON PARAMETRIC MODELLING & LCA

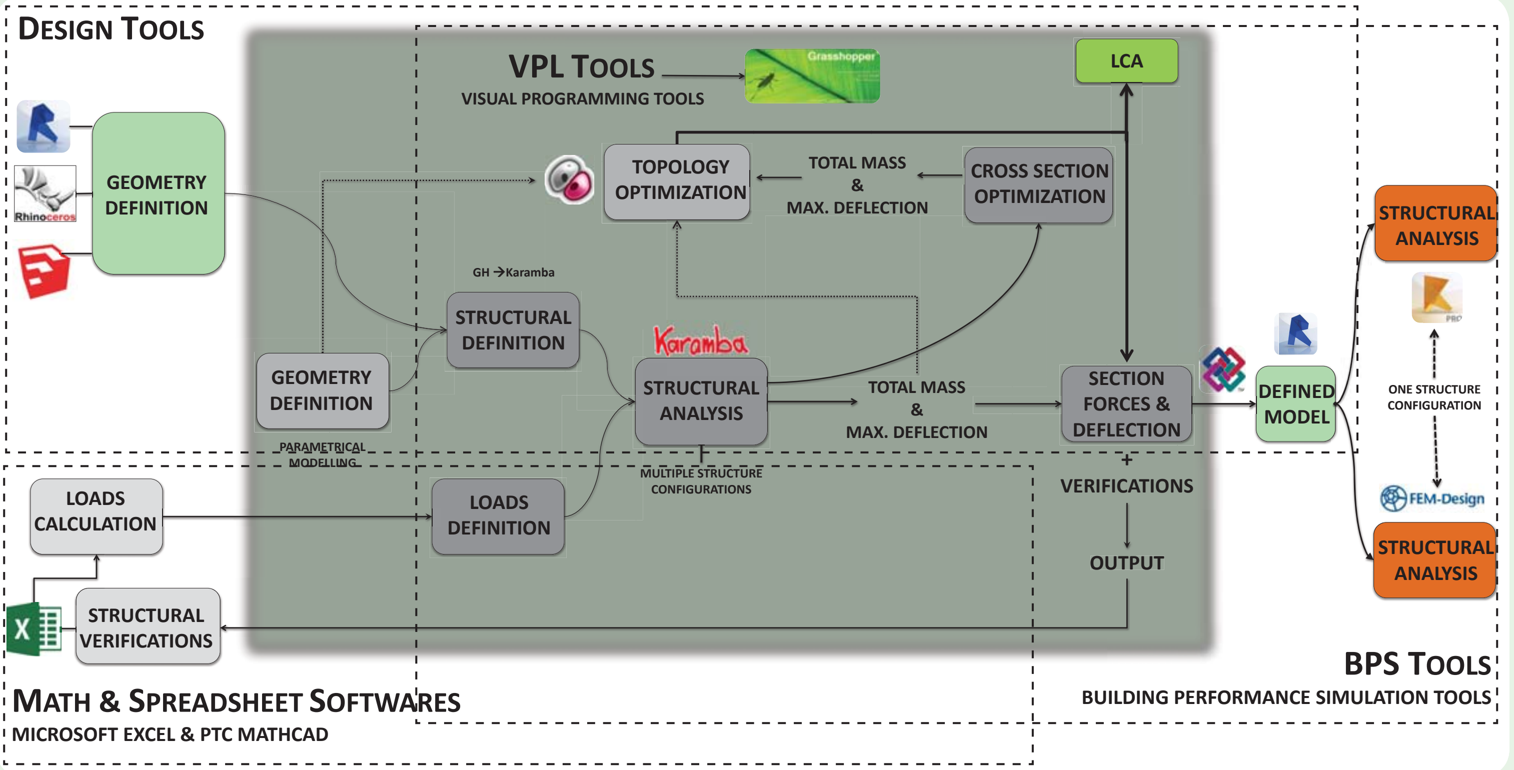
Laura Fernandez Vila
Master Thesis - Msc Architectural Engineering - Structural Design
Department of Civil Engineering - Technical University of Denmark
Advisors: Kristoffer Negendahl & Lotte Bjerregaard Jensen

Abstract - Integrated design process

The purpose of this project is to look for a method to integrate the structural aspects within the architectural designs in the first stages of designing process. As part of the STED (Sustainable Transformation & Environmental Design) programme inside of the Nordic Built, Nordic Innovation program, the principal goal is to achieve sustainable solutions in the Nordic region, the objective of the proposed method is to find reliable structures using the minimal amount of material, which means less kilograms of mass and consequently less emissions of CO2, benefiting the LCA process.

The methodology followed for this master thesis consists in an integrated process, in which the data is exchanged between several softwares (Grasshopper, Karamba, Excel, Revit and FEM-Design/Robot) in order to establish a logic flow where the information is updated automatically. Thanks to the parametrical modeling using the plug-in for Rinho 3D, Grasshopper is possible to establish a form-finding method based on optimization processes, which allows to study different possibilities for the same project in order to achieve the landscape of optimal structures.

SCHEME OF INTEGRATED DESIGN PROCESS


DESIGN TOOLS

GEOMETRY DEFINITION

VPL TOOLS
VISUAL PROGRAMMING TOOLS

LCA

TOPOLOGY OPTIMIZATION

TOTAL MASS & MAX. DEFLECTION

CROSS SECTION OPTIMIZATION

GH → Karamba

STRUCTURAL DEFINITION

GEOMETRY DEFINITION

STRUCTURAL ANALYSIS

TOTAL MASS & MAX. DEFLECTION

SECTION FORCES & DEFLECTION

DEFINED MODEL

PARAMETRICAL MODELLING

MULTIPLE STRUCTURE CONFIGURATIONS

+ VERIFICATIONS

OUTPUT

LOADS CALCULATION

LOADS DEFINITION

STRUCTURAL VERIFICATIONS

STRUCTURAL ANALYSIS

ONE STRUCTURE CONFIGURATION

STRUCTURAL ANALYSIS

BPS TOOLS
BUILDING PERFORMANCE SIMULATION TOOLS

MATH & SPREADSHEET SOFTWARES
MICROSOFT EXCEL & PTC MATHCAD

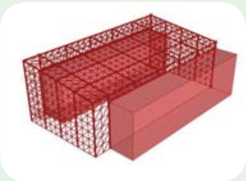
APPLICATION OF THE METHOD - BASED ON THE EKO-CANOPY PROJECT (PROPOSAL BY WHITE ARKITEKTER)

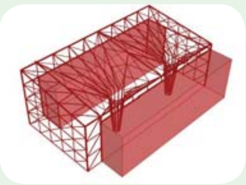
PARAMETRICAL MODELING - GEOMETRY DEFINITION -

COMPLEXITY

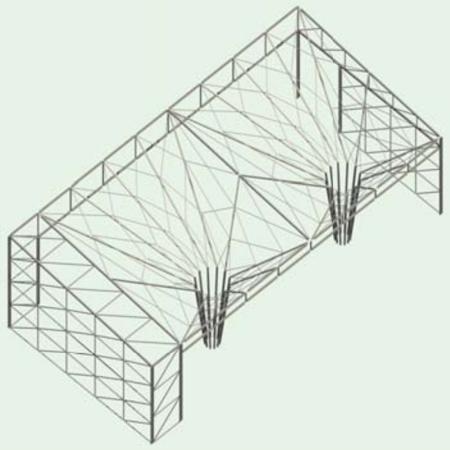
BASIC FRAME STRUCTURE

FRAME STRUCTURE & PLATES SURFACES

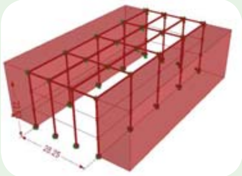




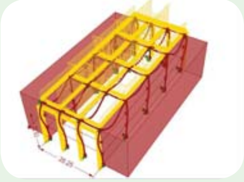
ARCHITECTURAL DESIGN - MOST AESTHETIC DESIGN



STUDY OF THE MODEL - APPLICATION OF THE DESCRIBED PROCESS



GEOMETRY DEFINITION - GH

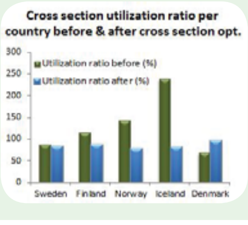


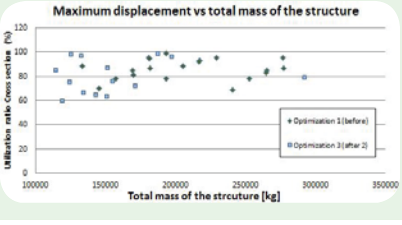
ANALYSIS - KARAMBA

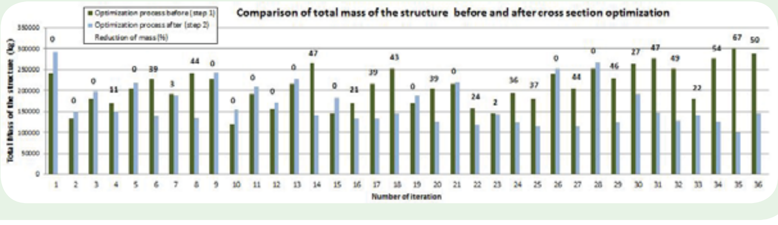
REVIT MODEL - ONE OPTIMAL DESIGN

FEM ANALYSIS

ANALYSIS - POST PROCESSING







APPENDIX C: LOAD CALCULATIONS

APPENDIX C - 1 : WIND LOAD CALCULATIONS

Wind Calculations depending on the Country

					DENMARK	SWEDEN	FINLAND	NORWAY	ICELAND
REF.		Reference		Units	**DK**	**SWE**	**FIN**	**NOR**	**ICE**
EC-1-4 wind 4.2	**Basic wind velocity**	**eq. 4.1**	v_b	**m/s**	**24**	**24**	**21**	**26**	**24**
NA - 4.2 (1)	Fundamental basic wind velocity		$v_{b,0}$	m/s	24	24	21.0	26.0	24
	Directional factor		c_{dir}	-	1	1	1	1	1
	Season factor		c_{season}	-	1	1	1	1	1
EC-1-4 wind 4.3	**Mean wind velocity (cat IV)**	**eq. 4.3**	$v_{m,IV}$	**m/s**	**17.54247273**	**17.54247273**	**15.34966364**	**19.00434546**	**17.54247273**
	Heigth above the terrain		z	m	22.63	22.63	22.63	22.63	22.63
	Roughness factor		c_r (z)	-	0.731	0.731	0.731	0.731	0.731
	zmin < z < zmax								
	Terrain category IV	Table 4.1	z_0	m	1	1	1	1	1
			z_{min}	m	10	10	10	10	10
			z_{max}	m	200	200	200	200	200
	Reference value category II		$z_{0,II}$	m	0.05	0.05	0.05	0.05	0.05
	Terrain factor	eq.4.5	k_r	-	0.234	0.234	0.234	0.234	0.234
	Mean wind velocity (cat III)	**eq. 4.3**	$v_{m,III}$	**m/s**	**22.34836246**	**22.34836246**	**19.55481715**	**24.210726**	**22.34836246**
	Roughness factor		c_r (z)	-	0.931	0.931	0.931	0.931	0.931
	zmin < z < zmax								
	Terrain category III	Table 4.1	z_0	m	0.3	0.3	0.3	0.3	0.3
			z_{min}	m	5	5	5	5	5
			z_{max}	m	200	200	200	200	200
	Reference value category II		$z_{0,II}$	m	0.05	0.05	0.05	0.05	0.05
	Terrain factor	eq.4.5	k_r	-	0.215	0.215	0.215	0.215	0.215
	Ortography factor	A.3 Note (4)	c_o (z)	-	1	1	1	1	1
EC-1-4 wind 4.5	**Peak velocity pressure**	**eq 4.8**	$q_{p\ (IV)}$	**kN/m^2**	**0.61**	**0.61**	**0.47**	**0.72**	0.61
			$q_{p\ (III)}$	**kN/m^2**	**0.79**	**0.79**	**0.61**	**0.93**	0.792
	Basic velocity pressure	eq 4.10	q_b	N/m^2	360.00	360.00	275.63	422.50	360.00
	Air density		ρ	kg/m^3	1.25	1.25	1.25	1.25	1.25
	Exposure factor	Figure 4.2	c_e (z) - IV	-	1.7	1.7	1.7	1.7	1.7
		Figure 4.2	c_e (z) - III	-	2.2	2.2	2.2	2.2	2.2
EC-1-4 wind 5.2	**Wind pressure on surfaces**								
	Pressure coefficient	Section 7							
	Wall (for $q_{p,IV}$)	figure 7.4, h<b	w (Zone D)	kN/m^2	0.43	0.43	0.33	0.51	0.43
					0.61	0.61	0.47	0.72	0.61
			w (Zone E)	kN/m^2	-0.19	-0.19	-0.15	-0.23	-0.19
					-0.19	-0.19	-0.15	-0.23	-0.19
	Flat roof (for $q_{p,IV}$)		w (Zone F)	kN/m^2	-1.10	-1.10	-0.84	-1.29	-1.10
	(case 1)				-1.53	-1.53	-1.17	-1.80	-1.53
			w (Zone G)	kN/m^2	-0.73	-0.73	-0.56	-0.86	-0.73
					-1.22	-1.22	-0.94	-1.44	-1.22
			w (Zone H)	kN/m^2	-0.43	-0.43	-0.33	-0.50	-0.43
					-0.73	-0.73	-0.56	-0.86	-0.73
			w (Zone I)	kN/m^2	0.12	0.12	0.09	0.14	0.12
					0.12	0.12	0.09	0.14	0.12
	Monotpitch roof (for $q_{p,IV}$)		w (Zone F_up)	kN/m^2	-1.45	-1.45	-1.11	-1.71	-1.45
					-1.76	-1.76	-1.35	-2.07	-1.76
			w (Zone F_low)	kN/m^2	-1.00	-1.00	-0.77	-1.18	-1.00
	(case 2)				-1.47	-1.47	-1.12	-1.72	-1.47
			w (Zone G)	kN/m^2	-1.16	-1.16	-0.89	-1.36	-1.16
					-1.50	-1.50	-1.15	-1.77	-1.50
			w (Zone H)	kN/m^2	-0.48	-0.48	-0.37	-0.56	-0.48
					-0.73	-0.73	-0.56	-0.86	-0.73
			w (Zone I)	kN/m^2	-0.42	-0.42	-0.32	-0.49	-0.42
					-0.70	-0.70	-0.54	-0.82	-0.70

APPENDIX C - 1 : WIND LOAD CALCULATIONS

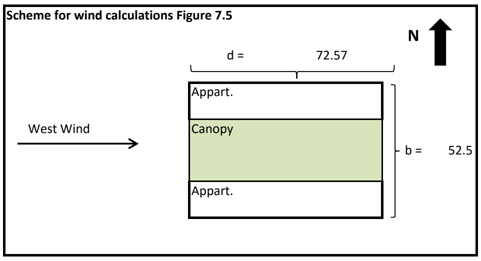
Parameters Wind Calculations

EC-1-4 wind 5.2 **Wind pressure on surfaces**

Pressure coefficient	Section 7			
Wall				
Case 1 figure 7.4, h<b				
e=min(b,2h)	Figure 7.5	e	m	28.25
		b	m	28.25
		2h	m	45.26
		d	m	72.57
Case 1 , e<d				
Zone A		e/5	m	5.65
Zone B		e (e/5+4/5e)	m	22.60
Zone C		d-e	m	44.32
Reference heigth	Figure 7.4	ze = h	m	22.63
Flat roof, case 1	Figure 7.6			
Zone F	length	e/4	m	7.06
	width	e/10	m	2.83
Zone G	length	b-2*e/4	m	14.13
	width	e/10	m	2.83
Zone H	length	b	m	52.45
	width	e/2-e/10	m	11.30
Zone I	length	b	m	52.45
	width	d - e/2	m	58.445
Pitch roof, case 1	Figure 7.6			
Cross wind direction	fig 7.7 c)	b	m	40.35
		h.1	m	30.63
		h.2	m	25.63
		2h	m	61.26
		d	m	80.57
		e		40.35
Zone F	length	e/4	m	10.09
	width	e/10	m	4.04
Zone G	length	b-2*e/4	m	20.18
	width	e/10	m	4.04
Zone H	length	b	m	40.35
	width	e/2-e/10	m	16.14
Zone I	length	b	m	40.35
	width	d - e/2	m	60.40

Canopy measurements - 1st model		
Height	m	22.63
Lenght	m	72.57
Width	m	28.25
Appartment measurements		
Height	m	22.63
Lenght	m	72.57
Width	m	12.1
Unit: Appartment - Canopy - Appartment		
Height	m	22.63
Lenght	m	72.57
Width	m	52.45
extension (length) m		8
extension (roof) - high eave m		8
extension (roof) - low eave m		3
Desnivel		5
angle		7.06

Scheme for wind calculations Figure 7.5



Pressure coefficients tables according to Eurocode

Pressure coefficient, wall — **Table 7.1 EC-1-4**

zone	**A**		**B**		**C**		**D**		**E**	
h/d	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
1	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	0.8	1	-0.5	-0.5
#¡DIV/0!	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	0.708	1.000	-0.316	-0.32
0.25	-1.2	-1.4	-0.8	-1.1	-0.5	-0.5	0.7	1	-0.3	-0.3

Pressure coefficient, flat roof — **Table 7.1 EC-1-4**

zone	**F**		**G**		**H**		**I**	
h.p/h	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
Sharp eaves	-1.8	-2.5	-1.2	-2.0	-0.7	-1.2	0.2	0.2

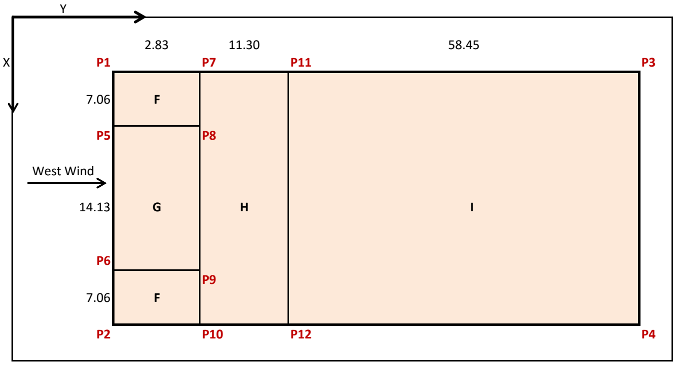
Pressure coefficient, monopitch roof — **Table 7.3b EC-1-4**

zone	**F_up**		**F_low**		**G**		**H**		**I**	
angle	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$	$C_{pe,10}$	$C_{pe,1}$
5	-2.1	-2.6	-2.1	-2.4	-1.8	-2	-0.6	-1.2	-0.5	-0.5
7.06	-2.38	-2.88	-1.64	-2.40	-1.89	-2.46	-0.78	-1.20	-0.68	-1.14
15	-2.4	-2.9	-1.6	-2.4	-1.9	-2.5	-0.8	-1.2	-0.7	-1.2

APPENDIX C - 1 : WIND LOAD CALCULATIONS

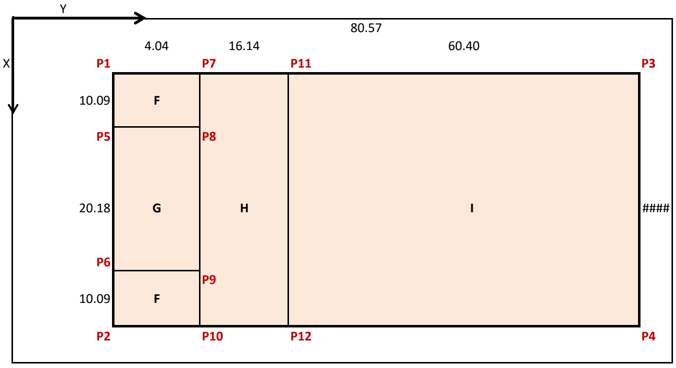
CASE A -COORDINATES WIND ZONES FLAT ROOF

Coordinates				
	Relative	Absolute		
Point	x	x	y	z
P1	0	12.1	0	22.63
P2	28.25	40.35	0	22.63
P3	0	12.1	72.57	22.63
P4	28.25	40.35	72.57	22.63
P5	7.06	19.16	0	22.63
P6	21.19	33.29	0	22.63
P7	0	12.1	2.83	22.63
P8	7.06	19.16	2.83	22.63
P9	21.19	33.29	2.83	22.63
P10	28.25	40.35	2.83	22.63
P11	0	12.1	14.13	22.63
P12	28.25	40.35	14.13	22.63



CASE B - COORDINATES WIND ZONES MONOPITCH ROOF

Coordinates				
	Relative	Absolute		
Point		x	y	z
P1		0.00	-8.00	30.63
P2		40.35	-8.00	30.63
P3		0.00	72.57	30.63
P4		40.35	72.57	30.63
P5		10.09	-8.00	30.63
P6		30.26	-8.00	30.63
P7		0.00	-3.97	30.63
P8		10.09	-3.97	30.63
P9		30.26	-3.97	30.63
P10		40.35	-3.97	30.63
P11		0.00	12.18	30.63
P12		40.35	12.18	30.63



APPENDIX C - 2 : SNOW LOAD CALCULATIONS

Snow Calculations depending on the Country

									DENMARK	SWEDEN	FINLAND	NORWAY	ICELAND
REF.			Reference					Units	**DK**	**SWE**	**FIN**	**NOR**	**ICE**
EC-1-3	**Snow load**		**5.1**										
Section 5	**Persistent/transient design situation**		**5.1**	**$s = \mu_i C_e C_t s_k$**			**s**	**kN/m^2**	**0.80**	**1.60**	**2.20**	**2.80**	**4.88**
	Accidental design situation (snow load)		**5.2**	**$s = \mu_i C_e C_t s_{Ad}$**			**s**	**kN/m^2**					
	Accidental design situation (snow drift)		**5.3**	**$s = \mu_i S_k$**			**s**	**kN/m^2**	**0.67**	**1.33**	**1.83**	**2.33**	**4.07**
	Carachteristic value	(location)	4.3 (1)				s_k	kN/m^2	1.00	2.00	2.75	3.50	6.10
	Exposure coefficient		5.1 (7)				c_e	-	1	1	1	1	1
	Thermal coefficient		5.1 (8)				c_t	-	1	1	1	1	1
	Shape coefficient		5.3										
		Monopitch	Fig. 5.1	0º < α < 30º	α_1 = (º)	7.064	μ_1	-	0.8	0.8	0.8	0.8	0.8
				30º < α < 60º	α_1 = (º)	35	μ_1	-	0.67	0.67	0.67	0.67	0.67
		Pitched roof	Fig 5.3										
		Undrifted load	**Case (i)**	0º < α < 30º	α_1 = (º)	5	μ_1	-	0.80	0.80	0.80	0.80	0.80
				30º < α < 60º	α_1 = (º)	35	μ_1	-	0.67	0.67	0.67	0.67	0.67
				0º < α < 30º	α_2 = (º)	5	μ_1	-	0.80	0.80	0.80	0.80	0.80
				30º < α < 60º	α_2 = (º)	35	μ_1	-	0.67	0.67	0.67	0.67	0.67
		Drifted load	**Case (ii)**	0º < α < 30º	α_1 = (º)	5	μ_1	-	0.40	0.40	0.40	0.40	0.40
				30º < α < 60º	α_1 = (º)	35	μ_1	-	0.33	0.33	0.33	0.33	0.33
				0º < α < 30º	α_2 = (º)	5	μ_1	-	0.80	1.80	2.80	3.80	4.80
				30º < α < 60º	α_2 = (º)	35	μ_1	-	0.67	0.67	0.67	0.67	0.67
		Drifted load	**Case (iii)**	0º < α < 30º	α_1 = (º)	5	μ_1	-	0.80	1.80	2.80	3.80	4.80
				30º < α < 60º	α_1 = (º)	35	μ_1	-	0.67	0.67	0.67	0.67	0.67
				0º < α < 30º	α_2 = (º)	5	μ_1	-	0.40	0.40	0.40	0.40	0.40
				30º < α < 60º	α_2 = (º)	35	μ_1	-	0.33	0.33	0.33	0.33	0.33
		Cylindrical roof	fig. 5.6										
				β > 60º , μ3=0	β = (º)	70	μ_1	-	0	0	0	0	0
		Case (i)	eq. 5.4	β < 60º, μ3=0,2+10*h/b	β = (º)	35	μ_1	-	0.80	0.80	0.80	0.80	0.80
							μ_3	-	1.97	1.97	1.97	1.97	1.97
					h =	5		m					
					b =	28.25		m					
					h/b =	0.177		-					
							0,5 * μ_3	-					

Note Shape coefficient:

1. Choose the case (i, ii or iii) : Undrifted or drifted load
2. Input the angle for both sides of the roof left and rigth
3. Depending on the angle should be taken the value from the row:

0º < α < 30º
30º < α < 60º

4. Then is taken the value for each side of the Pithched roof

α_1 = (º)	Angle on the left
α_1 = (º)	Angle on the rigth

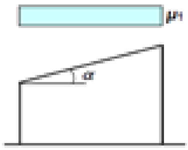


Figure 5.2: Snow load shape coefficient - monopitch roof

APPENDIX C - 3 : LOADS INPUT GRASSHOPPER

Input Grasshoper

Modelo A - Basic Frame configuration

1 . Wind

Case: Flat roof (for qp,IV)

COUNTRY

		Reference		Units	SWE	FIN	NOR	ICE	DK
Pressure coefficient		Section 7							
	Wall (for qp,IV)	figure 7.4, h<b	w (Zone D)	kN/m^2	0.43	0.33	0.51	0.43	0.43
			w (Zone E)	kN/m^2	-0.19	-0.15	-0.23	-0.19	-0.19
	Flat roof (for qp,IV)		w (Zone F)	kN/m^2	-1.10	-0.84	-1.29	-1.10	-1.10
			w (Zone G)	kN/m^2	-0.73	-0.56	-0.86	-0.73	-0.73
			w (Zone H)	kN/m^2	-0.43	-0.33	-0.50	-0.43	-0.43
			w (Zone I)	kN/m^2	0.12	0.09	0.14	0.12	0.12

2 . Snow

Case: Monopitch

	Reference		Units	SWE	FIN	NOR	ICE	DK
Persistent/transient design situation	5.1	**s = μi Ce Ct sk**	kN/m^2	1.600	2.200	2.800	4.880	0.800
Accidental design situation (snow load)	5.2	**s = μi Ce Ct sAd**	kN/m^2	0.000	0.000	0.000	0.000	0.000
Accidental design situation (snow drift)	5.3	**s = μi Sk**	kN/m^2	1.333	1.833	2.333	4.067	0.667

Modelo B - White Proposal

1 . Wind

Case: Monopitch roof (for qp,IV)

COUNTRY

		Reference		Units	SWE	SWE	SWE	SWE	SWE
Pressure coefficient		Section 7							
	Wall (for qp,IV)	figure 7.4, h<b	w (Zone A)	kN/m^2	0.43	0.33	0.51	0.43	0.43
			w (Zone B)	kN/m^2	-0.19	-0.15	-0.23	-0.19	-0.19
			w (Zone C)	kN/m^2	0.00	0.00	0.00	0.00	0.00
	Monotpitch roof (for qp,IV)		w (Zone F_up)	kN/m^2	-1.45	-1.11	-1.71	-1.45	-1.45
			w (Zone F_low)	kN/m^2	-1.00	-0.77	-1.18	-1.00	-1.00
			w (Zone G)	kN/m^2	-1.16	-0.89	-1.36	-1.16	-1.16
			w (Zone H)	kN/m^2	-0.48	-0.37	-0.56	-0.48	-0.48
			w (Zone I)	kN/m^2	-0.42	-0.32	-0.49	-0.42	-0.42

2 . Snow

Case: Monopitch roof (for qp,IV)

	Reference		Units	SWE	FIN	NOR	ICE	DK
Persistent/transient design situation	5.1	**s = μi Ce Ct sk**	kN/m^2	1.600	2.200	2.800	4.880	0.800
Accidental design situation (snow load)	5.2	**s = μi Ce Ct sAd**	kN/m^2	0.000	0.000	0.000	0.000	0.000
Accidental design situation (snow drift)	5.3	**s = μi Sk**	kN/m^2	1.333	1.833	2.333	4.067	0.667

Note:

1. Chose the country 🟩
2. Choose the case **case**
   a) For wind: Zone: III or IV and type of roof
   b) For snow: type of roof, and case (load distribution)

APPENDIX D: RESULTS OPTIMIZATION PROCESSES

APPENDIX D - 1 : MODEL A

MODEL A Optimization process (Results 36 variables)

Parameters considered:		
	Structural material	**Steel s275**
	Cladding material	**Glass**
	Load case	**4 & 5**

	Step 7 - Before cross section opt.								**Id. Family**	Middle			Rigth/left side		
Nº of it	**Steel class**	**Max. displacement (m) (Structure)**	**X - Number of Frames**	**Y - Number of Frames**	**Beams Top - X direction**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	**Beams Top - Y Direction**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)
1	**s275**	0.013791	7	5	42	HEB 400	4.036	0.02018	40	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
2		0.041698	3	4	15	HEB 400	9.417	0.04708	16	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
3		0.026916	5	4	25	HEB 400	5.650	0.02825	24	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
4		0.029933	4	5	24	HEB 400	7.063	0.03531	25	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
5		0.026862	6	4	30	HEB 400	4.708	0.02354	28	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
6		0.023915	6	6	42	HEB 400	4.708	0.02354	42	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
7		0.022023	5	5	30	HEB 400	5.650	0.02825	30	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
8		0.025726	6	7	48	HEB 400	4.708	0.02354	49	HEB 600	10.367	0.0518	HEB 450	10.367	0.05184
9	º	0.021414	7	4	35	HEB 400	4.036	0.02018	32	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
10		0.139556	3	3	12	HEB 400	9.417	0.04708	12	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
11		0.098624	6	3	24	HEB 400	4.708	0.02354	21	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
12		0.036137	4	4	20	HEB 400	7.063	0.03531	20	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
13		0.073279	7	3	28	HEB 400	4.036	0.02018	24	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
14		0.017082	7	7	56	HEB 400	4.036	0.02018	56	HEB 600	10.367	0.0518	HEB 450	10.367	0.05184
15		0.122798	4	3	16	HEB 400	7.063	0.03531	15	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
16		0.038189	3	7	24	HEB 400	9.417	0.04708	28	HEB 600	10.367	0.0518	HEB 450	10.367	0.05184
17		0.026218	5	7	40	HEB 400	5.650	0.02825	42	HEB 600	10.367	0.0518	HEB 450	10.367	0.05184
18		0.015771	7	6	49	HEB 400	4.036	0.02018	48	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
19		0.098679	5	3	20	HEB 400	5.650	0.02825	18	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
20		0.024895	5	6	35	HEB 400	5.650	0.02825	36	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
21		0.021635	6	5	36	HEB 400	4.708	0.02354	35	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
22		0.036603	3	6	21	HEB 400	9.417	0.04708	24	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
23		0.032865	3	5	18	HEB 400	9.417	0.04708	20	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
24		0.034876	4	7	32	HEB 400	7.063	0.03531	35	HEB 600	10.367	0.0518	HEB 450	10.367	0.05184
25		0.03332	4	6	28	HEB 400	7.063	0.03531	30	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
26		0.069668	8	3	32	HEB 400	3.531	0.01766	27	HEB 600	24.190	0.1210	HEB 450	24.190	0.12095
27		0.035951	4	8	36	HEB 400	7.063	0.03531	40	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
28		0.021562	8	4	40	HEB 400	3.531	0.01766	36	HEB 600	18.143	0.0907	HEB 450	18.143	0.09071
29		0.026946	5	8	45	HEB 400	5.650	0.02825	48	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
30		0.014579	8	5	48	HEB 400	3.531	0.01766	45	HEB 600	14.514	0.0726	HEB 450	14.514	0.07257
31		0.016809	8	6	56	HEB 400	3.531	0.01766	54	HEB 600	12.095	0.0605	HEB 450	12.095	0.06048
32		0.026083	6	8	54	HEB 400	4.708	0.02354	56	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
33		0.039199	3	8	27	HEB 400	9.417	0.04708	32	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
34		0.017412	7	8	63	HEB 400	4.036	0.02018	64	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
35		0.018243	8	8	72	HEB 400	3.531	0.01766	72	HEB 600	9.071	0.0454	HEB 450	9.071	0.04536
36		0.017759	8	7	64	HEB 400	3.53125	0.01765625	63	HEB 600	10.36714286	0.0518	HEB 450	10.367	0.05184

APPENDIX D - 1 : MODEL A

MODEL A Optimization process (Results 36 variables)

Step 7 - Before cross section opt.

Id. Family

Nº of it	**Columns Laterals**	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	**Columns front/back**	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	max. Allow displacement	U_max < U_max_allow ?	**Total number of elements**	**Total mass (kg)**	**Utilization ratio cross section (%)**
1	12	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	OK	106	240763.2335	68
2	10	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04708	OK	45	133206.0864	89
3	10	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	OK	67	180918.7569	95
4	12	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	OK	67	169194.2277	85
5	10	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	NOT	78	204775.0922	114
6	14	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	NOT	108	229038.7043	102
7	12	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	OK	80	193050.5629	78
8	16	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	NOT	123	241170.5103	109
9	10	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	NOT	89	228631.4274	106
10	8	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04708	NOT	36	121074.2803	296
11	8	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	NOT	63	192643.2861	419
12	10	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	NOT	56	157062.4216	102
13	8	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	NOT	72	216499.6214	363
14	16	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	OK	140	265026.8456	85
15	8	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	NOT	45	144930.6156	348
16	16	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04708	OK	72	169601.5045	81
17	16	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	OK	106	217314.175	93
18	14	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	OK	123	252895.0395	78
19	8	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	NOT	54	168786.9508	349
20	14	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	OK	93	205182.369	88
21	12	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	OK	93	216906.8982	92
22	14	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04708	OK	63	157469.6985	78
23	12	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04708	OK	54	145337.8924	70
24	16	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	OK	89	193457.8398	99
25	14	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	OK	78	181326.0337	94
26	8	HEB 450	22.630	0.0754	14	HEB 500	22.630	0.07543	0.01766	NOT	81	240355.9566	395
27	18	HEB 450	22.630	0.0754	6	HEB 500	22.630	0.07543	0.03531	NOT	100	205589.6458	102
28	10	HEB 450	22.630	0.0754	14	HEB 500	22.630	0.07543	0.01766	NOT	100	252487.7627	122
29	18	HEB 450	22.630	0.0754	8	HEB 500	22.630	0.07543	0.02825	OK	119	229445.9811	95
30	12	HEB 450	22.630	0.0754	14	HEB 500	22.630	0.07543	0.01766	OK	119	264619.5687	83
31	14	HEB 450	22.630	0.0754	14	HEB 500	22.630	0.07543	0.01766	OK	138	276751.3748	95
32	18	HEB 450	22.630	0.0754	10	HEB 500	22.630	0.07543	0.02354	NOT	138	253302.3164	111
33	18	HEB 450	22.630	0.0754	4	HEB 500	22.630	0.07543	0.04536	OK	81	181733.3106	86
34	18	HEB 450	22.630	0.0754	12	HEB 500	22.630	0.07543	0.02018	OK	157	277158.6516	86
35	18	HEB 450	22.630	0.0754	14	HEB 500	22.630	0.07543	0.01766	NOT	176	301014.9869	103
36	16	HEB 450	22.63	0.0754	14	HEB 500	22.630	0.07543	0.01766	NOT	157	288883.1808	101

APPENDIX D - 1 : MODEL A

MODEL A Optimization process (Results 36 variables)

Step 9 - After cross section opt. With max. Displacement limitation										Middle			Rigth/left side		
Nº of it	Steel class	Max. displacement (m) (Structure)	X - Number of Frames	Y - Number of Frames	Beams Top - X direction	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)
1	s275	0.01587	7	5	42	HEB 280, HEB 30	4.036	0.02018	40	HEB 550, HEB 40(	14.514	0.0726	HEB 360, HEB 300	14.514	0.07257
2		0.029555	3	4	15	HEB 500, HEB 45	9.417	0.04708	16	HEB 1000	18.143	0.0907	HEB 1000	18.143	0.09071
3		0.026989	5	4	25	variable	5.650	0.02825	24	variable	18.143	0.0907	variable	18.143	0.09071
4		0.030515	4	5	24	variable	7.063	0.03531	25	variable	14.514	0.0726	variable	14.514	0.07257
5		0.026896	6	4	30	variable	4.708	0.02354	28	variable	18.143	0.0907	variable	18.143	0.09071
6		0.026199	6	6	42	variable	4.708	0.02354	42	variable	12.095	0.0605	variable	12.095	0.06048
7		0.028964	5	5	30	variable	5.650	0.02825	30	variable	14.514	0.0726	variable	14.514	0.07257
8		0.027199	6	7	48	variable	4.708	0.02354	49	variable	10.367	0.0518	variable	10.367	0.05184
9		0.025257	7	4	35	variable	4.036	0.02018	32	variable	18.143	0.0907	variable	18.143	0.09071
10		0.035501	3	3	12	variable	9.417	0.04708	12	variable	24.190	0.1210	variable	24.190	0.12095
11		0.027246	6	3	24	variable	4.708	0.02354	21	variable	24.190	0.1210	variable	24.190	0.12095
12		0.025224	4	4	20	variable	7.063	0.03531	20	variable	18.143	0.0907	variable	18.143	0.09071
13		0.02814	7	3	28	variable	4.036	0.02018	24	variable	24.190	0.1210	variable	24.190	0.12095
14		0.024473	7	7	56	variable	4.036	0.02018	56	variable	10.367	0.0518	variable	10.367	0.05184
15		0.036191	4	3	16	variable	7.063	0.03531	15	variable	24.190	0.1210	variable	24.190	0.12095
16		0.031259	3	7	24	variable	9.417	0.04708	28	variable	10.367	0.0518	variable	10.367	0.05184
17		0.027195	5	7	40	variable	5.650	0.02825	42	variable	10.367	0.0518	variable	10.367	0.05184
18		0.026105	7	6	49	variable	4.036	0.02018	48	variable	12.095	0.0605	variable	12.095	0.06048
19		0.027773	5	3	20	variable	5.650	0.02825	18	variable	24.190	0.1210	variable	24.190	0.12095
20		0.027607	5	6	35	variable	5.650	0.02825	36	variable	12.095	0.0605	variable	12.095	0.06048
21		0.027491	6	5	36	variable	4.708	0.02354	35	variable	14.514	0.0726	variable	14.514	0.07257
22		0.028087	3	6	21	variable	9.417	0.04708	24	variable	12.095	0.0605	variable	12.095	0.06048
23		0.030144	3	5	18	variable	9.417	0.04708	20	variable	14.514	0.0726	variable	14.514	0.07257
24		0.026454	4	7	32	variable	7.063	0.03531	35	variable	10.367	0.0518	variable	10.367	0.05184
25		0.027604	4	6	28	variable	7.063	0.03531	30	variable	12.095	0.0605	variable	12.095	0.06048
26		0.028977	8	3	32	variable	3.531	0.01766	27	variable	24.190	0.1210	variable	24.190	0.12095
27		0.027226	4	8	36	variable	7.063	0.03531	40	variable	9.071	0.0454	variable	9.071	0.04536
28		0.025641	8	4	40	variable	3.531	0.01766	36	variable	18.143	0.0907	variable	18.143	0.09071
29		0.026176	5	8	45	variable	5.650	0.02825	48	variable	9.071	0.0454	variable	9.071	0.04536
30		0.032354	8	5	48	variable	3.531	0.01766	45	variable	14.514	0.0726	variable	14.514	0.07257
31		0.031274	8	6	56	variable	3.531	0.01766	54	variable	12.095	0.0605	variable	12.095	0.06048
32		0.027399	6	8	54	variable	4.708	0.02354	56	variable	9.071	0.0454	variable	9.071	0.04536
33		0.030796	3	8	27	variable	9.417	0.04708	32	variable	9.071	0.0454	variable	9.071	0.04536
34		0.024822	7	8	63	variable	4.036	0.02018	64	variable	9.071	0.0454	variable	9.071	0.04536
35		0.038684	8	8	72	variable	3.531	0.01766	72	variable	9.071	0.0454	variable	9.071	0.04536
36		0.027174	8	7	64	variable	3.531	0.01766	63	variable	10.367	0.0518	variable	10.367	0.05184

APPENDIX D - 1 : MODEL A

MODEL A Optimization process (Results 36 variables)

Step 9 - After cross section opt. With max. Displacement limitation

Nº of it	Columns Laterals	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	Columns front/back	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	max. Allow displacement	U_max < U_max_allow ?	Total number of elements	Total mass (kg)	Utilization ratio cross section (%)
1	36	HEB 450	22.630	0.0754	12	HEB 140	22.630	0.07543	0.02018	VERDADERO	130	292264.1999	79
2	30	HEB 220,HEB2	22.630	0.0754	4	HEB220, HEB	22.630	0.07543	0.04708	VERDADERO	65	150815.165	63
3	30	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	VERDADERO	87	197407.2028	96
4	36	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	VERDADERO	91	151349.4117	86
5	30	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	98	218906.1107	114
6	42	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	136	139382.0882	111
7	36	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	FALSO	104	188061.4174	103
8	48	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	155	134519.1627	116
9	30	variable	22.630	0.0754	12	variable	22.630	0.07543	0.02018	FALSO	109	243248.9379	125
10	24	variable	22.630	0.0754	4	variable	22.630	0.07543	0.04708	VERDADERO	52	155231.2059	75
11	24	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	79	209011.1311	116
12	30	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	VERDADERO	76	171122.5809	71
13	24	variable	22.630	0.0754	12	variable	22.630	0.07543	0.02018	FALSO	88	228003.4945	139
14	48	variable	22.630	0.0754	12	variable	22.630	0.07543	0.02018	FALSO	172	140902.7456	121
15	24	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	FALSO	61	182082.579	102
16	48	variable	22.630	0.0754	4	variable	22.630	0.07543	0.04708	VERDADERO	104	134401.0309	66
17	48	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	VERDADERO	138	132736.0331	96
18	42	variable	22.630	0.0754	12	variable	22.630	0.07543	0.02018	FALSO	151	144768.465	129
19	24	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	VERDADERO	70	187616.3391	98
20	42	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	VERDADERO	121	125469.1604	98
21	36	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	117	221430.7919	117
22	42	variable	22.630	0.0754	4	variable	22.630	0.07543	0.04708	VERDADERO	91	118954.0111	60
23	36	variable	22.630	0.0754	4	variable	22.630	0.07543	0.04708	VERDADERO	78	143012.0607	64
24	48	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	VERDADERO	121	124680.5959	75
25	42	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	VERDADERO	106	105619.9322	78
26	24	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	97	252232.0768	164
27	54	variable	22.630	0.0754	6	variable	22.630	0.07543	0.03531	VERDADERO	136	114680.7465	77
28	30	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	120	267762.6405	145
29	54	variable	22.630	0.0754	8	variable	22.630	0.07543	0.02825	VERDADERO	155	124971.0919	93
30	36	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	143	192348.5354	183
31	42	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	166	147153.763	177
32	54	variable	22.630	0.0754	10	variable	22.630	0.07543	0.02354	FALSO	174	128198.752	116
33	54	variable	22.630	0.0754	4	variable	22.630	0.07543	0.04536	VERDADERO	117	141013.5563	68
34	54	variable	22.630	0.0754	12	variable	22.630	0.07543	0.02018	FALSO	193	126144.5894	123
35	54	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	212	100381.5571	219
36	48	variable	22.630	0.0754	14	variable	22.630	0.07543	0.01766	FALSO	189	144637.7197	154

APPENDIX D - 1 : MODEL A

MODEL A Optimization process (Results 36 variables)

COMPARISON			
Reducction of mass (kg)	Reducction of mass (%) respect the initial value	Reducction of mass (%) respect the initial value	Nº of iteration
-51500.96649	-21	0	1
-17609.07866	-13	0	2
-16488.44586	-9	0	3
17844.81595	11	11	4
-14131.01859	-7	0	5
89656.61603	39	39	6
4989.145529	3	3	7
106651.3476	44	44	8
-14617.51054	-6	0	9
-34156.92555	-28	0	10
-16367.84495	-8	0	11
-14060.15926	-9	0	12
-11503.87316	-5	0	13
124124.0999	47	47	14
-37151.96342	-26	0	15
35200.47364	21	21	16
84578.14199	39	39	17
108126.5745	43	43	18
-18829.38821	-11	0	19
79713.20863	39	39	20
-4523.893718	-2	0	21
38515.68735	24	24	22
2325.831755	2	2	23
68777.24387	36	36	24
75706.10153	42	42	25
-11876.12021	-5	0	26
90908.89938	44	44	27
-15274.87786	-6	0	28
104474.8892	46	46	29
72271.03333	27	27	30
129597.6117	47	47	31
125103.5643	49	49	32
40719.75424	22	22	33
151014.0622	54	54	34
200633.4298	67	67	35
144245.4611	50	50	36

1 st optimization loop - Model A						
	Before cross section optimization			After cross section optimization		
Nº of iteration	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)
1	240763.2335	68	68	292264.1999	79	79
2	133206.0864	89	89	150815.165	63	63
3	180918.7569	95	95	197407.2028	96	96
4	169194.2277	85	85	151349.4117	86	86
5	204775	114	0	218906	114	0
6	229039	102	0	139382	111	0
7	193050.5629	78	78	188061	103	0
8	241171	109	0	134519	116	0
9	228631	106	0	243249	125	0
10	121074	296	0	155231.2059	75	75
11	192643	419	0	209011	116	0
12	157062	102	0	171122.5809	71	71
13	216500	363	0	228003	139	0
14	265026.8456	85	85	140903	121	0
15	144931	348	0	182083	102	0
16	169601.5045	81	81	134401.0309	66	66
17	217314.175	93	93	132736.0331	96	96
18	252895.0395	78	78	144768	129	0
19	168787	349	0	187616.3391	98	98
20	205182.369	88	88	125469.1604	98	98
21	216906.8982	92	92	221431	117	0
22	157469.6985	78	78	118954.0111	60	60
23	145337.8924	70	70	143012.0607	64	64
24	193457.8398	99	99	124680.5959	75	75
25	181326.0337	94	94	105619.9322	78	78
26	240356	395	0	252232	164	0
27	205590	102	0	114680.7465	77	77
28	252488	122	0	267763	145	0
29	229445.9811	95	95	124971.0919	93	93
30	264619.5687	83	83	192349	183	0
31	276751.3748	95	95	147154	177	0
32	253302	111	0	128199	116	0
33	181733.3106	86	86	141013.5563	68	68
34	277158.6516	86	86	126145	123	0
35	301015	103	0	100382	219	0
36	288883	101	0	144638	154	0

APPENDIX D - 1 : MODEL A

MODEL A - Comparison Loop 1 & Loop 2 (36 variables)

MODEL A - BASIC FRAME

			1 st optimization loop - Model A							2nd optimization loop - Model A						
	Genes opt.		Before cross section optimization			After cross section optimization				Before cross section optimization			After cross section optimization			
Nº of iteration	X	Y	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Reduction mass (%)	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Reduction mass (%)
1	7	5	240763.2335	68.34477876	68.34477876	292264.1999	78.64778761	78.64778761	-21	291626.693	79.89168142	79.89168142	211214.2109	96.64707965	96.64707965	28
2	3	4	133206.0864	88.56212389	88.56212389	150815.165	62.77168142	62.77168142	-13	150160.5729	96.81769912	96.81769912	145250.9902	98.79716814	98.79716814	3
3	5	4	180918.7569	95.27787611	95.27787611	197407.2028	95.53628319	95.53628319	-9	214827.7299	99.83362832	99.83362832	221259.2628	96.30088496	96.30088496	-3
4	4	5	169194.2277	84.7660177	84.7660177	151349.4117	86.41415929	86.41415929	11	194625.9575	87.26088496	87.26088496	145814.0412	93.51646018	93.51646018	25
5	6	4	204775.0922	114.1040708	0	218906.1107	114.2484956	0	-7	247161.3085	119.7833628	0	295579.3666	92.64	92.64	-20
6	6	6	229038.7043	101.5858407	0	139382.0882	111.2877876	0	39	271424.9206	136.0056637	0	246361.9074	103.0088496	0	9
7	5	5	193050.5629	77.95752212	77.95752212	188061.4174	102.5274336	0	3	226959.536	109.0477876	0	180917.1655	95.66017699	95.66017699	20
8	6	7	241170.5103	109.2785841	0	134519.1627	115.5355752	0	44	283556.7266	139.9773451	0	272039.0849	112.6300885	0	4
9	7	4	228631.4274	106.1224779	0	243248.9379	125.1674336	0	-6	279494.887	93.96106195	93.96106195	267834.1788	106.499115	0	4
10	3	3	121074.2803	296.4021239	0	155231.2059	75.40035398	75.40035398	-28	138028.7668	231.9334513	0	152588.2407	98.21946903	98.21946903	-11
11	6	3	192643.2861	418.9338053	0	209011.1311	115.7352212	0	-8	235029.5024	335.0952212	0	283563.6966	93.32389381	93.32389381	-21
12	4	4	157062.4216	102.3348673	0	171122.5809	71.43079646	71.43079646	-9	182494.1514	79.90088496	79.90088496	146805.2857	97.87752212	97.87752212	20
13	7	3	216499.6214	363.1525664	0	228003.4945	139.4548673	0	-5	267363.0809	297.8307965	0	276627.5889	95.79469027	95.79469027	-3
14	7	7	265026.8456	84.65415929	84.65415929	140902.7456	121.2821239	0	47	315890.3051	90.2739823	90.2739823	214822.6275	92.5040708	92.5040708	32
15	4	3	144930.6156	347.7465487	0	182082.579	102.4877876	0	-26	170362.3454	223.5440708	0	185422.5825	98.32778761	98.32778761	-9
16	3	7	169601.5045	81.10938053	81.10938053	134401.0309	66.39079646	66.39079646	21	186555.991	112.8042478	0	182253.2463	98.70159292	98.70159292	2
17	5	7	217314.175	92.80707965	92.80707965	132736.0331	96.26548673	96.26548673	39	251223.1481	116.640708	0	224356.2317	99.50442478	99.50442478	11
18	7	6	252895.0395	78.15716814	78.15716814	144768.465	129.3699115	0	43	303758.4991	86.30442478	86.30442478	195704.8123	94.02548673	94.02548673	36
19	5	3	168786.9508	349.3061947	0	187616.3391	98.31150442	98.31150442	-11	202695.9239	279.3451327	0	222679.3553	99.10088496	99.10088496	-10
20	5	6	205182.369	88.12389381	88.12389381	125469.1604	97.72389381	97.72389381	39	239091.342	113.5575221	0	201933.1763	92.38230088	92.38230088	16
21	6	5	216906.8982	91.90088496	91.90088496	221430.7919	116.7759292	0	-2	259293.1145	130.8955752	0	249076.7814	91.48884956	91.48884956	4
22	3	6	157469.6985	77.74088496	77.74088496	118954.0111	59.65380531	59.65380531	24	174424.185	111.1454867	0	151646.9018	97.88814159	97.88814159	13
23	3	5	145337.8924	69.80176991	69.80176991	143012.0607	64.02265487	64.02265487	2	162292.3789	107.2672566	0	127783.7653	100.6343363	0	21
24	4	7	193457.8398	98.76389381	98.76389381	124680.5959	74.9139823	74.9139823	36	218889.5696	93.31823009	93.31823009	158924.7663	100.9755752	0	27
25	4	6	181326.0337	94.35752212	94.35752212	105619.9322	78.17061947	78.17061947	42	206757.7635	90.66477876	90.66477876	142844.8782	97.77274336	97.77274336	31
26	8	3	240355.9566	394.579823	0	252232.0768	164.1175221	0	-5	299696.6594	236.9982301	0	315958.682	94.81061947	94.81061947	-5
27	4	8	205589.6458	101.8081416	0	114680.7465	77.10017699	77.10017699	44	231021.3756	93.53628319	93.53628319	178271.6092	95.95752212	95.95752212	23
28	8	4	252487.7627	122.1210619	0	267762.6405	145.2233628	0	-6	311828.4655	81.76707965	81.76707965	269214.6779	110.2782301	0	14
29	5	8	229445.9811	95.3840708	95.3840708	124971.0919	92.65840708	92.65840708	46	263354.9541	116.9061947	0	238017.8861	100.3504425	0	10
30	8	5	264619.5687	82.57132743	82.57132743	192348.5354	183.2438938	0	27	323960.2715	53.37486726	53.37486726	249326.1138	85.04637168	85.04637168	23
31	8	6	276751.3748	95.20141593	95.20141593	147153.763	177.1270796	0	47	336092.0776	58.56283186	58.56283186	198259.6977	109.8477876	0	41
32	6	8	253302.3164	110.7950442	0	128198.752	116.3851327	0	49	295688.5327	140.2916814	0	277085.1594	116.4276106	0	6
33	3	8	181733.3106	86.4246934	86.4246934	141013.5563	67.89802949	67.89802949	22	198687.7971	117.4744385	0	202327.2142	100.3478021	0	-2
34	7	8	277158.6516	86.28955752	86.28955752	126144.5894	123.0116814	0	54	328022.1112	91.15610619	91.15610619	219403.073	92.14230088	92.14230088	33
35	8	8	301014.9869	103.3231858	0	100381.5571	219.0952212	0	67	360355.6897	63.19575221	63.19575221	209625.5505	96.67964602	96.67964602	42
36	8	7	288883.1808	100.5819469	0	144637.7197	153.9058407	0	50	348223.8836	61.90442478	61.90442478	196916.2513	99.23964602	99.23964602	43

before	after	before 1st loop
1st/2nd loop	1st/2nd loop	after 2nd loop
Increment mass (%)	Increment mass (%)	Reduction mass
17	-38	**12**
11	-4	**-9**
16	11	**-22**
13	-4	**14**
17	26	**-44**
16	43	**-8**
15	-4	**6**
15	51	**-13**
18	9	**-17**
12	-2	**-26**
18	26	**-47**
14	-17	**7**
19	18	**-28**
16	34	**19**
15	2	**-28**
9	26	**-7**
13	41	**-3**
17	26	**23**
17	16	**-32**
14	38	**2**
16	11	**-15**
10	22	**4**
10	-12	**12**
12	22	**18**
12	26	**21**
20	20	**-31**
11	36	**13**
19	1	**-7**
13	47	**-4**
18	23	**6**
18	26	**28**
14	54	**-9**
9	30	**-11**
16	43	**21**
16	52	**30**
17	27	**32**

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:	Structural material	**Steel s275**
	Cladding material	**Glass**
	Load case	**4 & 5**

Canopy measurements - 1st model			extension (length) m	8	Appartment measurements				Unit: Appartment - Canopy - Appartment					
Height	m	22.63 Z direct	extension (roof) - high eave m	8	Height	m	22.63 Z direct		Height	m	22.63 Z direct			
Lenght	m	72.57 Y dirct	extension (roof) - low eave m	3	Lenght	m	72.57 Y dirct		Lenght	m	72.57 Y dirct			
Width	m	28.25 X direct	Desnivel	5	Width	m	12.1 X direct		Width	m	52.45 X direct			
			angle	7.06										

B - 1 : Step 7 - Before cross section opt.

					Id. Family				Id. Family				Id. Family							
Nº it	**Steel class**	**Max. displacement (m) (Structure)**	**X - Number of Frames**	**Y - Number of Frames**	**Beams Top - X direction**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	**Beams Top - Y Direction Extension**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	**Beams Top - Y Direction central part top**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	**Beams Top - Y Direction central sides**	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)
1	**s275**	0.034992	3	6	24	HEB 400	13.450	0.06725	4	HEB 600	8.000	0.0400	24	HEB	12.095	0.060475	12	HEB	12.095	0.060475
2		0.019008	4	5	28		10.088	0.05044	5		8.000	0.0400	25		14.514	0.07257	10		14.514	0.07257
3		0.01469	6	5	42		6.725	0.03363	7		8.000	0.0400	35		14.514	0.07257	10		14.514	0.07257
4		0.011653	7	9	77		5.764	0.02882	8		8.000	0.0400	72		8.063333333	0.040316667	18		8.063333333	0.040316667
5		0.015462	5	9	55		8.070	0.04035	6		8.000	0.0400	54		8.063333333	0.040316667	18		8.063333333	0.040316667
6		0.011406	7	5	49		5.764	0.02882	8		8.000	0.0400	40		14.514	0.07257	10		14.514	0.07257
7		0.023315	7	4	42		5.764	0.02882	8		8.000	0.0400	32		18.1425	0.0907125	8		18.1425	0.0907125
8		0.019382	4	8	40		10.088	0.05044	5		8.000	0.0400	40		9.07125	0.04535625	16		9.07125	0.04535625
9	º	0.015282	5	6	40		8.070	0.04035	6		8.000	0.0400	36		12.095	0.060475	12		12.095	0.060475
10		0.011579	7	7	63		5.764	0.02882	8		8.000	0.0400	56		10.36714286	0.051835714	14		10.36714286	0.051835714
11		0.034992	3	8	30		13.450	0.06725	4		8.000	0.0400	32		9.07125	0.04535625	16		9.07125	0.04535625
12		0.012273	8	5	56		5.044	0.02522	9		8.000	0.0400	45		14.514	0.07257	10		14.514	0.07257
13		0.01537	5	7	45		8.070	0.04035	6		8.000	0.0400	42		10.36714286	0.051835714	14		10.36714286	0.051835714
14		0.019207	4	6	32		10.088	0.05044	5		8.000	0.0400	30		12.095	0.060475	12		12.095	0.060475
15		0.012458	6	6	48		6.725	0.03363	7		8.000	0.0400	42		12.095	0.060475	12		12.095	0.060475
16		0.011639	7	8	70		5.764	0.02882	8		8.000	0.0400	64		9.07125	0.04535625	16		9.07125	0.04535625
17		0.035985	4	4	24		10.088	0.05044	5		8.000	0.0400	20		18.1425	0.0907125	8		18.1425	0.0907125
18		0.030009	5	4	30		8.070	0.04035	6		8.000	0.0400	24		18.1425	0.0907125	8		18.1425	0.0907125
19		0.034992	3	9	33		13.450	0.06725	4		8.000	0.0400	36		8.063333333	0.040316667	18		8.063333333	0.040316667
20		0.01294	9	5	63		4.483	0.02242	10		8.000	0.0400	50		14.514	0.07257	10		14.514	0.07257
21		0.015116	5	5	35		8.070	0.04035	6		8.000	0.0400	30		14.514	0.07257	10		14.514	0.07257
22		0.011515	7	6	56		5.764	0.02882	8		8.000	0.0400	48		12.095	0.060475	12		12.095	0.060475
23		0.011672	9	9	99		4.483	0.02242	10		8.000	0.0400	90		8.063333333	0.040316667	18		8.063333333	0.040316667
24		0.023481	9	4	54		4.483	0.02242	10		8.000	0.0400	40		18.1425	0.0907125	8		18.1425	0.0907125
25		0.030003	6	4	36		6.725	0.03363	7		8.000	0.0400	28		18.1425	0.0907125	8		18.1425	0.0907125
26		0.012541	6	7	54		6.725	0.03363	7		8.000	0.0400	49		10.36714286	0.051835714	14		10.36714286	0.051835714
27		0.034992	3	5	21		13.450	0.06725	4		8.000	0.0400	20		14.514	0.07257	10		14.514	0.07257
28		0.012358	9	6	72		4.483	0.02242	10		8.000	0.0400	60		12.095	0.060475	12		12.095	0.060475
29		0.012459	8	7	72		5.044	0.02522	9		8.000	0.0400	63		10.36714286	0.051835714	14		10.36714286	0.051835714
30		0.012596	6	8	60		6.725	0.03363	7		8.000	0.0400	56		9.07125	0.04535625	16		9.07125	0.04535625
31		0.012505	8	8	80		5.044	0.02522	9		8.000	0.0400	72		9.07125	0.04535625	16		9.07125	0.04535625
32		0.012628	6	9	66		6.725	0.03363	7		8.000	0.0400	63		8.063333333	0.040316667	18		8.063333333	0.040316667
33		0.019399	4	9	44		10.088	0.05044	5		8.000	0.0400	45		8.063333333	0.040316667	18		8.063333333	0.040316667
34		0.012526	8	9	88		5.044	0.02522	9		8.000	0.0400	81		8.063333333	0.040316667	18		8.063333333	0.040316667
35		0.0388	3	4	18		13.450	0.06725	4		8.000	0.0400	16		18.1425	0.0907125	8		18.1425	0.0907125
36		0.015432	5	8	50		8.070	0.04035	6		8.000	0.0400	48		9.07125	0.04535625	16		9.07125	0.04535625
37		0.034992	3	7	27		13.450	0.06725	4		8.000	0.0400	28		10.36714286	0.051835714	14		10.36714286	0.051835714
38		0.012004	9	7	81		4.483	0.02242	10		8.000	0.0400	70		10.36714286	0.051835714	14		10.36714286	0.051835714
39		0.011762	9	8	90		4.483	0.02242	10		8.000	0.0400	80		9.07125	0.04535625	16		9.07125	0.04535625
40		0.012379	8	6	64		5.044	0.02522	9		8.000	0.0400	54		12.095	0.060475	12		12.095	0.060475
41		0.011828	10	8	100		4.035	0.02018	11		8.000	0.0400	88		9.07125	0.04535625	16		9.07125	0.04535625
42		0.019323	4	7	36		10.088	0.05044	5		8.000	0.0400	35		10.36714286	0.051835714	14		10.36714286	0.051835714
43		0.013008	10	5	70		4.035	0.02018	11		8.000	0.0400	55		14.514	0.07257	10		14.514	0.07257
44		0.023421	8	4	48		5.044	0.02522	9		8.000	0.0400	36		18.1425	0.0907125	8		18.1425	0.0907125
45		0.02348	10	4	60		4.035	0.02018	11		8.000	0.0400	44		18.1425	0.0907125	8		18.1425	0.0907125
46		0.01254	8	10	96		5.044	0.02522	9		8.000	0.0400	90		7.257	0.036285	20		7.257	0.036285
47		0.011744	10	9	110		4.035	0.02018	11		8.000	0.0400	99		8.063333333	0.040316667	18		8.063333333	0.040316667
48		0.012425	10	6	80		4.035	0.02018	11		8.000	0.0400	66		12.095	0.060475	12		12.095	0.060475
49		0.012071	10	7	90		4.035	0.02018	11		8.000	0.0400	77		10.36714286	0.051835714	14		10.36714286	0.051835714
50		0.011656	9	10	108		4.483	0.02242	10		8.000	0.0400	100		7.257	0.036285	20		7.257	0.036285
51		0.011669	7	10	84		5.764	0.02882	8		8.000	0.0400	80		7.257	0.036285	20		7.257	0.036285
52		0.01172	10	10	120		4.035	0.02018	11		8.000	0.0400	110		7.257	0.036285	20		7.257	0.036285
53		0.012645	6	10	72		6.725	0.03363	7		8.000	0.0400	70		7.257	0.036285	20		7.257	0.036285
54		0.015487	5	10	60		8.070	0.04035	6		8.000	0.0400	60		7.257	0.036285	20		7.257	0.036285
55		0.01942	4	10	48		10.088	0.05044	5		8.000	0.0400	50		7.257	0.036285	20		7.257	0.036285
56		0.034992	3	10	36		13.450	0.06725	4		8.000	0.0400	40		7.257	0.036285	20		7.257	0.036285

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:		
	Structural mate	**Steel s275**
	Cladding materi	**Glass**
	Load case	**4 & 5**

B - 1 : Step 7 - Before cross section opt.

Id. Family

Nº it	Beams back facade	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams front facade	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals left short	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals rigth short	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)
1	3	HEB	13.45	0.06725	3	HEB	13.45	0.06725	6	HEB	8	0.026666667	6	HEB 450	3.000	0.0100
2	4		10.0875	0.0504375	4		10.0875	0.0504375	5		8	0.026666667	5		3.000	0.0100
3	6		6.725	0.033625	6		6.725	0.033625	5		8	0.026666667	5		3.000	0.0100
4	7		5.764285714	0.028821429	7		5.764285714	0.028821429	9		8	0.026666667	9		3.000	0.0100
5	5		8.07	0.04035	5		8.07	0.04035	9		8	0.026666667	9		3.000	0.0100
6	7		5.764285714	0.028821429	7		5.764285714	0.028821429	5		8	0.026666667	5		3.000	0.0100
7	7		5.764285714	0.028821429	7		5.764285714	0.028821429	4		8	0.026666667	4		3.000	0.0100
8	4		10.0875	0.0504375	4		10.0875	0.0504375	8		8	0.026666667	8		3.000	0.0100
9	5		8.07	0.04035	5		8.07	0.04035	6		8	0.026666667	6		3.000	0.0100
10	7		5.764285714	0.028821429	7		5.764285714	0.028821429	7		8	0.026666667	7		3.000	0.0100
11	3		13.45	0.06725	3		13.45	0.06725	8		8	0.026666667	8		3.000	0.0100
12	8		5.04375	0.02521875	8		5.04375	0.02521875	5		8	0.026666667	5		3.000	0.0100
13	5		8.07	0.04035	5		8.07	0.04035	7		8	0.026666667	7		3.000	0.0100
14	4		10.0875	0.0504375	4		10.0875	0.0504375	6		8	0.026666667	6		3.000	0.0100
15	6		6.725	0.033625	6		6.725	0.033625	6		8	0.026666667	6		3.000	0.0100
16	7		5.764285714	0.028821429	7		5.764285714	0.028821429	8		8	0.026666667	8		3.000	0.0100
17	4		10.0875	0.0504375	4		10.0875	0.0504375	4		8	0.026666667	4		3.000	0.0100
18	5		8.07	0.04035	5		8.07	0.04035	4		8	0.026666667	4		3.000	0.0100
19	3		13.45	0.06725	3		13.45	0.06725	9		8	0.026666667	9		3.000	0.0100
20	9		4.483333333	0.022416667	9		4.483333333	0.022416667	5		8	0.026666667	5		3.000	0.0100
21	5		8.07	0.04035	5		8.07	0.04035	5		8	0.026666667	5		3.000	0.0100
22	7		5.764285714	0.028821429	7		5.764285714	0.028821429	6		8	0.026666667	6		3.000	0.0100
23	9		4.483333333	0.022416667	9		4.483333333	0.022416667	9		8	0.026666667	9		3.000	0.0100
24	9		4.483333333	0.022416667	9		4.483333333	0.022416667	4		8	0.026666667	4		3.000	0.0100
25	6		6.725	0.033625	6		6.725	0.033625	4		8	0.026666667	4		3.000	0.0100
26	6		6.725	0.033625	6		6.725	0.033625	7		8	0.026666667	7		3.000	0.0100
27	3		13.45	0.06725	3		13.45	0.06725	5		8	0.026666667	5		3.000	0.0100
28	9		4.483333333	0.022416667	9		4.483333333	0.022416667	6		8	0.026666667	6		3.000	0.0100
29	8		5.04375	0.02521875	8		5.04375	0.02521875	7		8	0.026666667	7		3.000	0.0100
30	6		6.725	0.033625	6		6.725	0.033625	8		8	0.026666667	8		3.000	0.0100
31	8		5.04375	0.02521875	8		5.04375	0.02521875	8		8	0.026666667	8		3.000	0.0100
32	6		6.725	0.033625	6		6.725	0.033625	9		8	0.026666667	9		3.000	0.0100
33	4		10.0875	0.0504375	4		10.0875	0.0504375	9		8	0.026666667	9		3.000	0.0100
34	8		5.04375	0.02521875	8		5.04375	0.02521875	9		8	0.026666667	9		3.000	0.0100
35	3		13.45	0.06725	3		13.45	0.06725	4		8	0.026666667	4		3.000	0.0100
36	5		8.07	0.04035	5		8.07	0.04035	8		8	0.026666667	8		3.000	0.0100
37	3		13.45	0.06725	3		13.45	0.06725	7		8	0.026666667	7		3.000	0.0100
38	9		4.483333333	0.022416667	9		4.483333333	0.022416667	7		8	0.026666667	7		3.000	0.0100
39	9		4.483333333	0.022416667	9		4.483333333	0.022416667	8		8	0.026666667	8		3.000	0.0100
40	8		5.04375	0.02521875	8		5.04375	0.02521875	6		8	0.026666667	6		3.000	0.0100
41	10		4.035	0.020175	10		4.035	0.020175	8		8	0.026666667	8		3.000	0.0100
42	4		10.0875	0.0504375	4		10.0875	0.0504375	7		8	0.026666667	7		3.000	0.0100
43	10		4.035	0.020175	10		4.035	0.020175	5		8	0.026666667	5		3.000	0.0100
44	8		5.04375	0.02521875	8		5.04375	0.02521875	4		8	0.026666667	4		3.000	0.0100
45	10		4.035	0.020175	10		4.035	0.020175	4		8	0.026666667	4		3.000	0.0100
46	8		5.04375	0.02521875	8		5.04375	0.02521875	10		8	0.026666667	10		3.000	0.0100
47	10		4.035	0.020175	10		4.035	0.020175	9		8	0.026666667	9		3.000	0.0100
48	10		4.035	0.020175	10		4.035	0.020175	6		8	0.026666667	6		3.000	0.0100
49	10		4.035	0.020175	10		4.035	0.020175	7		8	0.026666667	7		3.000	0.0100
50	9		4.483333333	0.022416667	9		4.483333333	0.022416667	10		8	0.026666667	10		3.000	0.0100
51	7		5.764285714	0.028821429	7		5.764285714	0.028821429	10		8	0.026666667	10		3.000	0.0100
52	10		4.035	0.020175	10		4.035	0.020175	10		8	0.026666667	10		3.000	0.0100
53	6		6.725	0.033625	6		6.725	0.033625	10		8	0.026666667	10		3.000	0.0100
54	5		8.07	0.04035	5		8.07	0.04035	10		8	0.026666667	10		3.000	0.0100
55	4		10.0875	0.0504375	4		10.0875	0.0504375	10		8	0.026666667	10		3.000	0.0100
56	3		13.45	0.06725	3		13.45	0.06725	10		8	0.026666667	10		3.000	0.0100

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:		
	Structural	Steel s275
	Cladding r	Glass
	Load case	4 & 5

Minimal Mass [kg] = 205204.1627

B - 1 : Step 7 - Before cross section opt.

Nº it	Columns front	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	Columns back	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	Columns Front Ablock	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	max. Allow displacement	U_max < U_max_allow ?	Total number of elements	Total mass (kg)	Utilization ratio cross section (%)
1	8		15.3150	0.0511	8	HEB 500	15.315	0.05105	2		22.63	0.075433333	0.04000	OK	100	225097.859	87
2	10		15.3150	0.0511	10		15.315	0.05105	3		22.63	0.075433333	0.04000	OK	109	241099.9416	48
3	14		15.3150	0.0511	14		15.315	0.05105	4		22.63	0.075433333	0.03363	OK	148	292996.2937	44
4	16		15.3150	0.0511	16		15.315	0.05105	5		22.63	0.075433333	0.02882	OK	244	358731.539	40
5	12		15.3150	0.0511	12		15.315	0.05105	6		22.63	0.075433333	0.04000	OK	191	306835.6612	39
6	16		15.3150	0.0511	16		15.315	0.05105	7		22.63	0.075433333	0.02882	OK	170	318944.1464	40
7	16		15.3150	0.0511	16		15.315	0.05105	8		22.63	0.075433333	0.02882	OK	152	308997.2982	81
8	10		15.3150	0.0511	10		15.315	0.05105	9		22.63	0.075433333	0.04000	OK	154	270940.4861	48
9	12		15.3150	0.0511	12		15.315	0.05105	10		22.63	0.075433333	0.04000	OK	150	276995.1167	38
10	16		15.3150	0.0511	16		15.315	0.05105	11		22.63	0.075433333	0.02882	OK	212	338837.8427	40
11	8		15.3150	0.0511	8		15.315	0.05105	12		22.63	0.075433333	0.04000	OK	132	244991.5553	87
12	18		15.3150	0.0511	18		15.315	0.05105	13		22.63	0.075433333	0.02522	OK	195	344891.8912	49
13	12		15.3150	0.0511	12		15.315	0.05105	14		22.63	0.075433333	0.04000	OK	169	286941.9649	38
14	10		15.3150	0.0511	10		15.315	0.05105	15		22.63	0.075433333	0.04000	OK	134	251046.7897	48
15	14		15.3150	0.0511	14		15.315	0.05105	16		22.63	0.075433333	0.03363	OK	177	302943.1419	37
16	16		15.3150	0.0511	16		15.315	0.05105	17		22.63	0.075433333	0.02882	OK	237	348784.6908	40
17	10		15.3150	0.0511	10		15.315	0.05105	18		22.63	0.075433333	0.04000	OK	111	231153.0934	90
18	12		15.3150	0.0511	12		15.315	0.05105	19		22.63	0.075433333	0.04000	OK	129	257101.4204	75
19	8		15.3150	0.0511	8		15.315	0.05105	20		22.63	0.075433333	0.04000	OK	151	254938.4035	87
20	20		15.3150	0.0511	20		15.315	0.05105	21		22.63	0.075433333	0.02242	OK	222	370839.5641	58
21	12		15.3150	0.0511	12		15.315	0.05105	22		22.63	0.075433333	0.04000	OK	147	267048.2686	38
22	16		15.3150	0.0511	16		15.315	0.05105	23		22.63	0.075433333	0.02882	OK	205	328890.9945	40
23	20		15.3150	0.0511	20		15.315	0.05105	24		22.63	0.075433333	0.02242	OK	317	410626.9568	52
24	20		15.3150	0.0511	20		15.315	0.05105	25		22.63	0.075433333	0.02242	FALSO	203	360892.716	105
25	14		15.3150	0.0511	14		15.315	0.05105	26		22.63	0.075433333	0.03363	OK	153	283049.4456	89
26	14		15.3150	0.0511	14		15.315	0.05105	27		22.63	0.075433333	0.03363	OK	205	312889.99	37
27	8		15.3150	0.0511	8		15.315	0.05105	28		22.63	0.075433333	0.04000	OK	115	215151.0108	87
28	20		15.3150	0.0511	20		15.315	0.05105	29		22.63	0.075433333	0.02242	OK	253	380786.4123	55
29	18		15.3150	0.0511	18		15.315	0.05105	30		22.63	0.075433333	0.02522	OK	254	364785.5875	49
30	14		15.3150	0.0511	14		15.315	0.05105	31		22.63	0.075433333	0.03363	OK	226	322836.8382	37
31	18		15.3150	0.0511	18		15.315	0.05105	32		22.63	0.075433333	0.02522	OK	277	374732.4357	50
32	14		15.3150	0.0511	14		15.315	0.05105	33		22.63	0.075433333	0.03363	OK	245	332783.6864	38
33	10		15.3150	0.0511	10		15.315	0.05105	34		22.63	0.075433333	0.04000	OK	192	280887.3342	48
34	18		15.3150	0.0511	18		15.315	0.05105	35		22.63	0.075433333	0.02522	OK	301	384679.2838	50
35	8		15.3150	0.0511	8		15.315	0.05105	36		22.63	0.075433333	0.04000	OK	112	205204.1627	97
36	12		15.3150	0.0511	12		15.315	0.05105	37		22.63	0.075433333	0.04000	OK	207	296888.8131	39
37	8		15.3150	0.0511	8		15.315	0.05105	38		22.63	0.075433333	0.04000	OK	147	235044.7072	87
38	20		15.3150	0.0511	20		15.315	0.05105	39		22.63	0.075433333	0.02242	OK	286	390733.2605	54
39	20		15.3150	0.0511	20		15.315	0.05105	40		22.63	0.075433333	0.02242	OK	310	400680.1086	52
40	18		15.3150	0.0511	18		15.315	0.05105	41		22.63	0.075433333	0.02522	OK	244	354838.7393	49
41	22		15.3150	0.0511	22		15.315	0.05105	42		22.63	0.075433333	0.02018	OK	337	426627.7313	59
42	10		15.3150	0.0511	10		15.315	0.05105	43		22.63	0.075433333	0.04000	OK	175	260993.6379	48
43	22		15.3150	0.0511	22		15.315	0.05105	44		22.63	0.075433333	0.02018	OK	264	396787.1868	64
44	18		15.3150	0.0511	18		15.315	0.05105	45		22.63	0.075433333	0.02522	OK	206	334945.043	93
45	22		15.3150	0.0511	22		15.315	0.05105	46		22.63	0.075433333	0.02018	FALSO	241	386840.3386	116
46	18		15.3150	0.0511	18		15.315	0.05105	47		22.63	0.075433333	0.02522	OK	334	394626.132	50
47	22		15.3150	0.0511	22		15.315	0.05105	48		22.63	0.075433333	0.02018	OK	368	436574.5794	58
48	22		15.3150	0.0511	22		15.315	0.05105	49		22.63	0.075433333	0.02018	OK	294	406734.035	62
49	22		15.3150	0.0511	22		15.315	0.05105	50		22.63	0.075433333	0.02018	OK	320	416680.8831	60
50	20		15.3150	0.0511	20		15.315	0.05105	51		22.63	0.075433333	0.02242	OK	367	420573.8049	52
51	16		15.3150	0.0511	16		15.315	0.05105	52		22.63	0.075433333	0.02882	OK	310	368678.3871	40
52	22		15.3150	0.0511	22		15.315	0.05105	53		22.63	0.075433333	0.02018	OK	398	446521.4276	58
53	14		15.3150	0.0511	14		15.315	0.05105	54		22.63	0.075433333	0.03363	OK	283	342730.5345	38
54	12		15.3150	0.0511	12		15.315	0.05105	55		22.63	0.075433333	0.03629	OK	255	316782.5094	43
55	10		15.3150	0.0511	10		15.315	0.05105	56		22.63	0.075433333	0.03629	OK	227	290834.1824	54
56	8		15.3150	0.0511	8		15.315	0.05105	57		22.63	0.075433333	0.03629	OK	199	264885.2516	96

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered	Structural ma	Steel s275
	Cladding mate	Glass
	Load case	4 & 5

	B - 1 : Step 9 - After cross section opt.				Id. Family				Id. Family				Id. Family							
Nº it	Steel class	Max. displacement (m) (Structure)	X - Nº of Frames	Y - Nº of Frames	Beams Top - X direction	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction Extension	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central part top	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central sides	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)
1	**s275**	0.035095	3	6	24	HEB 400	13.450	0.06725	4	HEB 600	8.000	0.0400	24	HEB	12.095	0.060	12	HEB	12.095	0.060475
2		0.026401	4	5	28		10.088	0.05044	5		8.000	0.0400	25		14.514	0.073	10		14.514	0.07257
3		0.021933	6	5	42		6.725	0.03363	7		8.000	0.0400	35		14.514	0.073	10		14.514	0.07257
4		0.021001	7	9	77		5.764	0.02882	8		8.000	0.0400	72		8.063	0.040	18		8.06333333	0.040316667
5		0.029947	5	9	55		8.070	0.04035	6		8.000	0.0400	54		8.063	0.040	18		8.06333333	0.040316667
6		0.022155	7	5	49		5.764	0.02882	8		8.000	0.0400	40		14.514	0.073	10		14.514	0.07257
7		0.019352	7	4	42		5.764	0.02882	8		8.000	0.0400	32		18.143	0.091	8		18.1425	0.0907125
8		0.031528	4	8	40		10.088	0.05044	5		8.000	0.0400	40		9.071	0.045	16		9.07125	0.04535625
9	º	0.026487	5	6	40		8.070	0.04035	6		8.000	0.0400	36		12.095	0.060	12		12.095	0.060475
10		0.022442	7	7	63		5.764	0.02882	8		8.000	0.0400	56		10.367	0.052	14		10.3671429	0.051835714
11		0.035157	3	8	30		13.450	0.06725	4		8.000	0.0400	32		9.071	0.045	16		9.07125	0.04535625
12		0.016785	8	5	56		5.044	0.02522	9		8.000	0.0400	45		14.514	0.073	10		14.514	0.07257
13		0.028869	5	7	45		8.070	0.04035	6		8.000	0.0400	42		10.367	0.052	14		10.3671429	0.051835714
14		0.025142	4	6	32		10.088	0.05044	5		8.000	0.0400	30		12.095	0.060	12		12.095	0.060475
15		0.02224	6	6	48		6.725	0.03363	7		8.000	0.0400	42		12.095	0.060	12		12.095	0.060475
16		0.017811	7	8	70		5.764	0.02882	8		8.000	0.0400	64		9.071	0.045	16		9.07125	0.04535625
17		0.028193	4	4	24		10.088	0.05044	5		8.000	0.0400	20		18.143	0.091	8		18.1425	0.0907125
18		0.028869	5	4	30		8.070	0.04035	6		8.000	0.0400	24		18.143	0.091	8		18.1425	0.0907125
19		0.035159	3	9	33		13.450	0.06725	4		8.000	0.0400	36		8.063	0.040	18		8.06333333	0.040316667
20		0.014595	9	5	63		4.483	0.02242	10		8.000	0.0400	50		14.514	0.073	10		14.514	0.07257
21		0.027163	5	5	35		8.070	0.04035	6		8.000	0.0400	30		14.514	0.073	10		14.514	0.07257
22		0.017893	7	6	56		5.764	0.02882	8		8.000	0.0400	48		12.095	0.060	12		12.095	0.060475
23		0.01509	9	9	99		4.483	0.02242	10		8.000	0.0400	90		8.063	0.040	18		8.06333333	0.040316667
24		0.016884	9	4	54		4.483	0.02242	10		8.000	0.0400	40		18.143	0.091	8		18.1425	0.0907125
25		0.023045	6	4	36		6.725	0.03363	7		8.000	0.0400	28		18.143	0.091	8		18.1425	0.0907125
26		0.021741	6	7	54		6.725	0.03363	7		8.000	0.0400	49		10.367	0.052	14		10.3671429	0.051835714
27		0.035095	3	5	21		13.450	0.06725	4		8.000	0.0400	20		14.514	0.073	10		14.514	0.07257
28		0.013912	9	6	72		4.483	0.02242	10		8.000	0.0400	60		12.095	0.060	12		12.095	0.060475
29		0.016785	8	7	72		5.044	0.02522	9		8.000	0.0400	63		10.367	0.052	14		10.3671429	0.051835714
30		0.023458	6	8	60		6.725	0.03363	7		8.000	0.0400	56		9.071	0.045	16		9.07125	0.04535625
31		0.016785	8	8	80		5.044	0.02522	9		8.000	0.0400	72		9.071	0.045	16		9.07125	0.04535625
32		0.022087	6	9	66		6.725	0.03363	7		8.000	0.0400	63		8.063	0.040	18		8.06333333	0.040316667
33		0.028193	4	9	44		10.088	0.05044	5		8.000	0.0400	45		8.063	0.040	18		8.06333333	0.040316667
34		0.016785	8	9	88		5.044	0.02522	9		8.000	0.0400	81		8.063	0.040	18		8.06333333	0.040316667
35		0.035099	3	4	18		13.450	0.06725	4		8.000	0.0400	16		18.143	0.091	8		18.1425	0.0907125
36		0.025575	5	8	50		8.070	0.04035	6		8.000	0.0400	48		9.071	0.045	16		9.07125	0.04535625
37		0.035154	3	7	27		13.450	0.06725	4		8.000	0.0400	28		10.367	0.052	14		10.3671429	0.051835714
38		0.01417	9	7	81		4.483	0.02242	10		8.000	0.0400	70		10.367	0.052	14		10.3671429	0.051835714
39		0.016884	9	8	90		4.483	0.02242	10		8.000	0.0400	80		9.071	0.045	16		9.07125	0.04535625
40		0.016785	8	6	64		5.044	0.02522	9		8.000	0.0400	54		12.095	0.060	12		12.095	0.060475
41		0.013133	10	8	100		4.035	0.02018	11		8.000	0.0400	88		9.071	0.045	16		9.07125	0.04535625
42		0.024819	4	7	36		10.088	0.05044	5		8.000	0.0400	35		10.367	0.052	14		10.3671429	0.051835714
43		0.013327	10	5	70		4.035	0.02018	11		8.000	0.0400	55		14.514	0.073	10		14.514	0.07257
44		0.018702	8	4	48		5.044	0.02522	9		8.000	0.0400	36		18.143	0.091	8		18.1425	0.0907125
45		0.0127	10	4	60		4.035	0.02018	11		8.000	0.0400	44		18.143	0.091	8		18.1425	0.0907125
46		0.016785	8	10	96		5.044	0.02522	9		8.000	0.0400	90		7.257	0.036	20		7.257	0.036285
47		0.014047	10	9	110		4.035	0.02018	11		8.000	0.0400	99		8.063	0.040	18		8.06333333	0.040316667
48		0.014599	10	6	80		4.035	0.02018	11		8.000	0.0400	66		12.095	0.060	12		12.095	0.060475
49		0.014296	10	7	90		4.035	0.02018	11		8.000	0.0400	77		10.367	0.052	14		10.3671429	0.051835714
50		0.014004	9	10	108		4.483	0.02242	10		8.000	0.0400	100		7.257	0.036	20		7.257	0.036285
51		0.018212	7	10	84		5.764	0.02882	8		8.000	0.0400	80		7.257	0.036	20		7.257	0.036285
52		0.014593	10	10	120		4.035	0.02018	11		8.000	0.0400	110		7.257	0.036	20		7.257	0.036285
53		0.024263	6	10	72		6.725	0.03363	7		8.000	0.0400	70		7.257	0.036	20		7.257	0.036285
54		0.021579	5	10	60		8.070	0.04035	6		8.000	0.0400	60		7.257	0.036	20		7.257	0.036285
55		0.024855	4	10	48		10.088	0.05044	5		8.000	0.0400	50		7.257	0.036	20		7.257	0.036285
56		0.034932	3	10	36		13.450	0.06725	4		8.000	0.0400	40		7.257	0.036	20		7.257	0.036285

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:		
	Structural	Steel s275
	Cladding r	Glass
	Load case	4 & 5

B - 1 : Step 9 - After cross section opt.

Nº it	Beams back facade	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Beams front facade	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals left short	Tipe of profile	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals rigth short	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	Columns front	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)
1	3	HEB	13.450	0.06725	3	HEB	13.45	0.06725	6	HEB	8	0.0267	6	HEB 450	3.000	0.0100	8	HEB	15.3150	0.0511
2	4		10.088	0.0504375	4		10.0875	0.0504375	5		8	0.0267	5		3.000	0.0100	10		15.3150	0.0511
3	6		6.725	0.033625	6		6.725	0.033625	5		8	0.0267	5		3.000	0.0100	14		15.3150	0.0511
4	7		5.764	0.02882143	7		5.764285714	0.028821429	9		8	0.0267	9		3.000	0.0100	16		15.3150	0.0511
5	5		8.070	0.04035	5		8.07	0.04035	9		8	0.0267	9		3.000	0.0100	12		15.3150	0.0511
6	7		5.764	0.02882143	7		5.764285714	0.028821429	5		8	0.0267	5		3.000	0.0100	16		15.3150	0.0511
7	7		5.764	0.02882143	7		5.764285714	0.028821429	4		8	0.0267	4		3.000	0.0100	16		15.3150	0.0511
8	4		10.088	0.0504375	4		10.0875	0.0504375	8		8	0.0267	8		3.000	0.0100	10		15.3150	0.0511
9	5		8.070	0.04035	5		8.07	0.04035	6		8	0.0267	6		3.000	0.0100	12		15.3150	0.0511
10	7		5.764	0.02882143	7		5.764285714	0.028821429	7		8	0.0267	7		3.000	0.0100	16		15.3150	0.0511
11	3		13.450	0.06725	3		13.45	0.06725	8		8	0.0267	8		3.000	0.0100	8		15.3150	0.0511
12	8		5.044	0.02521875	8		5.04375	0.02521875	5		8	0.0267	5		3.000	0.0100	18		15.3150	0.0511
13	5		8.070	0.04035	5		8.07	0.04035	7		8	0.0267	7		3.000	0.0100	12		15.3150	0.0511
14	4		10.088	0.0504375	4		10.0875	0.0504375	6		8	0.0267	6		3.000	0.0100	10		15.3150	0.0511
15	6		6.725	0.033625	6		6.725	0.033625	6		8	0.0267	6		3.000	0.0100	14		15.3150	0.0511
16	7		5.764	0.02882143	7		5.764285714	0.028821429	8		8	0.0267	8		3.000	0.0100	16		15.3150	0.0511
17	4		10.088	0.0504375	4		10.0875	0.0504375	4		8	0.0267	4		3.000	0.0100	10		15.3150	0.0511
18	5		8.070	0.04035	5		8.07	0.04035	4		8	0.0267	4		3.000	0.0100	12		15.3150	0.0511
19	3		13.450	0.06725	3		13.45	0.06725	9		8	0.0267	9		3.000	0.0100	8		15.3150	0.0511
20	9		4.483	0.02241667	9		4.483333333	0.022416667	5		8	0.0267	5		3.000	0.0100	20		15.3150	0.0511
21	5		8.070	0.04035	5		8.07	0.04035	5		8	0.0267	5		3.000	0.0100	12		15.3150	0.0511
22	7		5.764	0.02882143	7		5.764285714	0.028821429	6		8	0.0267	6		3.000	0.0100	16		15.3150	0.0511
23	9		4.483	0.02241667	9		4.483333333	0.022416667	9		8	0.0267	9		3.000	0.0100	20		15.3150	0.0511
24	9		4.483	0.02241667	9		4.483333333	0.022416667	4		8	0.0267	4		3.000	0.0100	20		15.3150	0.0511
25	6		6.725	0.033625	6		6.725	0.033625	4		8	0.0267	4		3.000	0.0100	14		15.3150	0.0511
26	6		6.725	0.033625	6		6.725	0.033625	7		8	0.0267	7		3.000	0.0100	14		15.3150	0.0511
27	3		13.450	0.06725	3		13.45	0.06725	5		8	0.0267	5		3.000	0.0100	8		15.3150	0.0511
28	9		4.483	0.02241667	9		4.483333333	0.022416667	6		8	0.0267	6		3.000	0.0100	20		15.3150	0.0511
29	8		5.044	0.02521875	8		5.04375	0.02521875	7		8	0.0267	7		3.000	0.0100	18		15.3150	0.0511
30	6		6.725	0.033625	6		6.725	0.033625	8		8	0.0267	8		3.000	0.0100	14		15.3150	0.0511
31	8		5.044	0.02521875	8		5.04375	0.02521875	8		8	0.0267	8		3.000	0.0100	18		15.3150	0.0511
32	6		6.725	0.033625	6		6.725	0.033625	9		8	0.0267	9		3.000	0.0100	14		15.3150	0.0511
33	4		10.088	0.0504375	4		10.0875	0.0504375	9		8	0.0267	9		3.000	0.0100	10		15.3150	0.0511
34	8		5.044	0.02521875	8		5.04375	0.02521875	9		8	0.0267	9		3.000	0.0100	18		15.3150	0.0511
35	3		13.450	0.06725	3		13.45	0.06725	4		8	0.0267	4		3.000	0.0100	8		15.3150	0.0511
36	5		8.070	0.04035	5		8.07	0.04035	8		8	0.0267	8		3.000	0.0100	12		15.3150	0.0511
37	3		13.450	0.06725	3		13.45	0.06725	7		8	0.0267	7		3.000	0.0100	8		15.3150	0.0511
38	9		4.483	0.02241667	9		4.483333333	0.022416667	7		8	0.0267	7		3.000	0.0100	20		15.3150	0.0511
39	9		4.483	0.02241667	9		4.483333333	0.022416667	8		8	0.0267	8		3.000	0.0100	20		15.3150	0.0511
40	8		5.044	0.02521875	8		5.04375	0.02521875	6		8	0.0267	6		3.000	0.0100	18		15.3150	0.0511
41	10		4.035	0.020175	10		4.035	0.020175	8		8	0.0267	8		3.000	0.0100	22		15.3150	0.0511
42	4		10.088	0.0504375	4		10.0875	0.0504375	7		8	0.0267	7		3.000	0.0100	10		15.3150	0.0511
43	10		4.035	0.020175	10		4.035	0.020175	5		8	0.0267	5		3.000	0.0100	22		15.3150	0.0511
44	8		5.044	0.02521875	8		5.04375	0.02521875	4		8	0.0267	4		3.000	0.0100	18		15.3150	0.0511
45	10		4.035	0.020175	10		4.035	0.020175	4		8	0.0267	4		3.000	0.0100	22		15.3150	0.0511
46	8		5.044	0.02521875	8		5.04375	0.02521875	10		8	0.0267	10		3.000	0.0100	18		15.3150	0.0511
47	10		4.035	0.020175	10		4.035	0.020175	9		8	0.0267	9		3.000	0.0100	22		15.3150	0.0511
48	10		4.035	0.020175	10		4.035	0.020175	6		8	0.0267	6		3.000	0.0100	22		15.3150	0.0511
49	10		4.035	0.020175	10		4.035	0.020175	7		8	0.0267	7		3.000	0.0100	22		15.3150	0.0511
50	9		4.483	0.02241667	9		4.483333333	0.022416667	10		8	0.0267	10		3.000	0.0100	20		15.3150	0.0511
51	7		5.764	0.02882143	7		5.764285714	0.028821429	10		8	0.0267	10		3.000	0.0100	16		15.3150	0.0511
52	10		4.035	0.020175	10		4.035	0.020175	10		8	0.0267	10		3.000	0.0100	22		15.3150	0.0511
53	6		6.725	0.033625	6		6.725	0.033625	10		8	0.0267	10		3.000	0.0100	14		15.3150	0.0511
54	5		8.070	0.04035	5		8.07	0.04035	10		8	0.0267	10		3.000	0.0100	12		15.3150	0.0511
55	4		10.088	0.0504375	4		10.0875	0.0504375	10		8	0.0267	10		3.000	0.0100	10		15.3150	0.0511
56	3		13.450	0.06725	3		13.45	0.06725	10		8	0.0267	10		3.000	0.0100	8		15.3150	0.0511

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:	Structural m:	**Steel s275**
	Cladding mat	**Glass**
	Load case	**4 & 5**

Min mass **89979.64269**

B - 1 : Step 9 - After cross section opt.

Nº it	Columns back	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	Columns Front Ablock	Tipe of profile	Length element (m)	Allowed max. Displacement columns (m)	max. Allow displacement	U_max < U_max_allow ?	Total number of elements	Total mass (kg)	Utilization ratio cross section (%)
1	8	HEB 500	15.315	0.05105	2	HEB	22.63	0.07543	0.04000	OK	100	175567.8109	88
2	10		15.315	0.05105	3		22.63	0.07543	0.04000	OK	109	129959.8037	66
3	14		15.315	0.05105	4		22.63	0.07543	0.03363	OK	148	152998.3162	65
4	16		15.315	0.05105	5		22.63	0.07543	0.02882	OK	244	103647.6514	73
5	12		15.315	0.05105	6		22.63	0.07543	0.04000	OK	191	92746.76253	75
6	16		15.315	0.05105	7		22.63	0.07543	0.02882	OK	170	160654.6896	77
7	16		15.315	0.05105	8		22.63	0.07543	0.02882	OK	152	260093.0246	67
8	10		15.315	0.05105	9		22.63	0.07543	0.04000	OK	154	89979.64269	79
9	12		15.315	0.05105	10		22.63	0.07543	0.04000	OK	150	112724.6648	66
10	16		15.315	0.05105	11		22.63	0.07543	0.02882	OK	212	120965.2629	78
11	8		15.315	0.05105	12		22.63	0.07543	0.04000	OK	132	164572.2303	88
12	18		15.315	0.05105	13		22.63	0.07543	0.02522	OK	195	197916.1096	67
13	12		15.315	0.05105	14		22.63	0.07543	0.04000	OK	169	101909.9169	72
14	10		15.315	0.05105	15		22.63	0.07543	0.04000	OK	134	112292.4592	63
15	14		15.315	0.05105	16		22.63	0.07543	0.03363	OK	177	127268.9785	66
16	16		15.315	0.05105	17		22.63	0.07543	0.02882	OK	237	115794.8587	62
17	10		15.315	0.05105	18		22.63	0.07543	0.04000	OK	111	159475.3364	70
18	12		15.315	0.05105	19		22.63	0.07543	0.04000	OK	129	176763.3887	72
19	8		15.315	0.05105	20		22.63	0.07543	0.04000	OK	151	164398.5864	88
20	20		15.315	0.05105	21		22.63	0.07543	0.02242	OK	222	226203.7475	65
21	12		15.315	0.05105	22		22.63	0.07543	0.04000	OK	147	132814.7193	68
22	16		15.315	0.05105	23		22.63	0.07543	0.02882	OK	205	142114.8203	62
23	20		15.315	0.05105	24		22.63	0.07543	0.02242	OK	317	133022.1894	67
24	20		15.315	0.05105	25		22.63	0.07543	0.02242	OK	203	300785.837	75
25	14		15.315	0.05105	26		22.63	0.07543	0.03363	OK	153	218181.2698	69
26	14		15.315	0.05105	27		22.63	0.07543	0.03363	OK	205	113238.8942	65
27	8		15.315	0.05105	28		22.63	0.07543	0.04000	OK	115	195753.238	88
28	20		15.315	0.05105	29		22.63	0.07543	0.02242	OK	253	179296.3725	62
29	18		15.315	0.05105	30		22.63	0.07543	0.02522	OK	254	138107.2742	67
30	14		15.315	0.05105	31		22.63	0.07543	0.03363	OK	226	104704.7335	70
31	18		15.315	0.05105	32		22.63	0.07543	0.02522	OK	277	126359.7154	67
32	14		15.315	0.05105	33		22.63	0.07543	0.03363	OK	245	98836.51048	66
33	10		15.315	0.05105	34		22.63	0.07543	0.04000	OK	192	96493.65643	70
34	18		15.315	0.05105	35		22.63	0.07543	0.02522	OK	301	121231.1673	67
35	8		15.315	0.05105	36		22.63	0.07543	0.04000	OK	112	219055.397	88
36	12		15.315	0.05105	37		22.63	0.07543	0.04000	OK	207	97956.34104	64
37	8		15.315	0.05105	38		22.63	0.07543	0.04000	OK	147	165254.9456	88
38	20		15.315	0.05105	39		22.63	0.07543	0.02242	OK	286	159279.8195	63
39	20		15.315	0.05105	40		22.63	0.07543	0.02242	OK	310	137349.805	75
40	18		15.315	0.05105	41		22.63	0.07543	0.02522	OK	244	156982.3197	67
41	22		15.315	0.05105	42		22.63	0.07543	0.02018	OK	337	158208.4506	65
42	10		15.315	0.05105	43		22.63	0.07543	0.04000	OK	175	104997.4742	62
43	22		15.315	0.05105	44		22.63	0.07543	0.02018	OK	264	245558.4923	66
44	18		15.315	0.05105	45		22.63	0.07543	0.02522	OK	206	267333.6231	74
45	22		15.315	0.05105	46		22.63	0.07543	0.02018	OK	241	339611.2444	63
46	18		15.315	0.05105	47		22.63	0.07543	0.02522	OK	334	115606.7108	67
47	22		15.315	0.05105	48		22.63	0.07543	0.02018	OK	368	147401.3716	70
48	22		15.315	0.05105	49		22.63	0.07543	0.02018	OK	294	193858.1983	72
49	22		15.315	0.05105	50		22.63	0.07543	0.02018	OK	320	165629.8893	71
50	20		15.315	0.05105	51		22.63	0.07543	0.02242	OK	367	126093.7827	62
51	16		15.315	0.05105	52		22.63	0.07543	0.02882	OK	310	103393.6785	63
52	22		15.315	0.05105	53		22.63	0.07543	0.02018	OK	398	135554.434	72
53	14		15.315	0.05105	54		22.63	0.07543	0.03363	OK	283	95787.65432	72
54	12		15.315	0.05105	55		22.63	0.07543	0.03629	OK	255	95944.79825	59
55	10		15.315	0.05105	56		22.63	0.07543	0.03629	OK	227	98633.26296	68
56	8		15.315	0.05105	57		22.63	0.07543	0.03629	OK	199	191961.801	96

APPENDIX D - 2 : MODEL B - 1

MODEL B - 1 Optimization process (Results 56 variables)

Parameters considered:		
	Structural materi	**s275**
	Cladding materia	**Glass**
	Load case	**4 & 5**

COMPARISON			
Reducction of mass (kg)	**Reducction of mass (%) respect the initial value**	**Reducction of mass (%) respect the initial value**	**Nº of itera tion**
49530.04807	22	22	1
111140.1379	46	46	2
139997.9775	48	48	3
255083.8876	71	71	4
214088.8987	70	70	5
158289.4568	50	50	6
48904.2736	16	16	7
180960.8434	67	67	8
164270.452	59	59	9
217872.5798	64	64	10
80419.325	33	33	11
146975.7816	43	43	12
185032.048	64	64	13
138754.3306	55	55	14
175674.1634	58	58	15
232989.8321	67	67	16
71677.757	31	31	17
80338.0317	31	31	18
90539.81705	36	36	19
144635.8166	39	39	20
134233.5493	50	50	21
186776.1742	57	57	22
277604.7673	68	68	23
60106.87903	17	17	24
64868.17582	23	23	25
199651.0958	64	64	26
19397.77288	9	9	27
201490.0398	53	53	28
226678.3133	62	62	29
218132.1047	68	68	30
248372.7202	66	66	31
233947.1759	70	70	32
184393.6778	66	66	33
263448.1165	68	68	34
-13851.23428	-7	0	35
198932.472	67	67	36
69789.76156	30	30	37
231453.441	59	59	38
263330.3036	66	66	39
197856.4196	56	56	40
268419.2807	63	63	41
155996.1637	60	60	42
151228.6945	38	38	43
67611.41991	20	20	44
47229.0942	12	12	45
279019.4211	71	71	46
289173.2078	66	66	47
212875.8366	52	52	48
251050.9938	60	60	49
294480.0223	70	70	50
265284.7087	72	72	51
310966.9936	70	70	52
246942.8802	72	72	53
220837.7111	70	70	54
192200.9194	66	66	55
72923.45065	28	72	56

	Before cross section optimization			After cross section optimization		
Nº of iteration	**Total mass (kg)**	**Utilization ratio cross section (%)**	**Utilization ratio cross section (%)**	**Total mass (kg)**	**Utilization ratio cross section (%)**	**Utilization ratio cross section (%)**
1	225097.859	87	87	175567.8109	88	88
2	241099.9416	48	48	129959.8037	66	66
3	292996.2937	44	44	152998.3162	65	65
4	358731.539	40	40	103647.6514	73	73
5	306835.6612	39	39	92746.76253	75	75
6	318944.1464	40	40	160654.6896	77	77
7	308997.2982	81	81	260093.0246	67	67
8	270940.4861	48	48	89979.64269	79	79
9	276995.1167	38	38	112724.6648	66	66
10	338837.8427	40	40	120965.2629	78	78
11	244991.5553	87	87	164572.2303	88	88
12	344891.8912	49	49	197916.1096	67	67
13	286941.9649	38	38	101909.9169	72	72
14	251046.7897	48	48	112292.4592	63	63
15	302943.1419	37	37	127268.9785	66	66
16	348784.6908	40	40	115794.8587	62	62
17	231153.0934	90	90	159475.3364	70	70
18	257101.4204	75	75	176763.3887	72	72
19	254938.4035	87	87	164398.5864	88	88
20	370839.5641	58	58	226203.7475	65	65
21	267048.2686	38	38	132814.7193	68	68
22	328890.9945	40	40	142114.8203	62	62
23	410626.9568	52	52	133022.1894	67	67
24	360892.716	105	0	300785.837	75	75
25	283049.4456	89	89	218181.2698	69	69
26	312889.99	37	37	113238.8942	65	65
27	215151.0108	87	87	195753.238	88	88
28	380786.4123	55	55	179296.3725	62	62
29	364785.5875	49	49	138107.2742	67	67
30	322836.8382	37	37	104704.7335	70	70
31	374732.4357	50	50	126359.7154	67	67
32	332783.6864	38	38	98836.51048	66	66
33	280887.3342	48	48	96493.65643	70	70
34	384679.2838	50	50	121231.1673	67	67
35	205204.1627	97	97	219055.397	88	88
36	296888.8131	39	39	97956.34104	64	64
37	235044.7072	87	87	165254.9456	88	88
38	390733.2605	54	54	159279.8195	63	63
39	400680.1086	52	52	137349.805	75	75
40	354838.7393	49	49	156982.3197	67	67
41	426627.7313	59	59	158208.4506	65	65
42	260993.6379	48	48	104997.4742	62	62
43	396787.1868	64	64	245558.4923	66	66
44	334945.043	93	93	267333.6231	74	74
45	386840.3386	116	0	339611.2444	63	63
46	394626.132	50	50	115606.7108	67	67
47	436574.5794	58	58	147401.3716	70	70
48	406734.035	62	62	193858.1983	72	72
49	416680.8831	60	60	165629.8893	71	71
50	420573.8049	52	52	126093.7827	62	62
51	368678.3871	40	40	103393.6785	63	63
52	446521.4276	58	58	135554.434	72	72
53	342730.5345	38	38	95787.65432	72	72
54	316782.5094	43	43	95944.79825	59	59
55	290834.1824	54	54	98633.26296	68	68
56	264885.2516	96	96	191961.801	96	96

APPENDIX D - 3 : MODEL B - 2

MODEL B - 2 Optimization process (Results 48 variables)

Parameters considered:	Structural material	**Steel s275**
	Cladding material	**Glass**
	Load case	**4 & 5**

Height	m	22.63	Z direct
Lenght	m	72.57	Y dirct
Width	m	28.25	X direct
Appartment measurements			
Height	m	22.63	Z direct
Lenght	m	72.57	Y dirct
Width	m	12.1	X direct

Unit: Appartment - Canopy - Appartment			
Height	m	22.63	Z direct
Lenght	m	72.57	Y dirct
Width	m	52.45	X direct
Roof - high eave	m	8	
Desnivel	m	5	
Roof - Low eave	m	3	

B - 2 : Step 7 - Before cross section opt.

Id. Family

Number of iteration	Steel class	Max. displacement (m) (Structure)	X - Number of Frames	Y - Number of Frames	Max displacement beams	Beams Top - X direction	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction Extension	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central part top	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central sides	Length element (m)	Allowed max. Displacement beams (m)	Allow Max displacement beams	U_max < U_max_allow ?
1	**s275**	0.064856	5	7	0.001547	45	8.070	0.04035	6	8.000	0.0400	42	10.36714286	0.051835714	14	10.3671429	0.051835714	0.04000	OK
2		0.329934	3	5	0.00405	21	13.450	0.06725	4	8.000	0.0400	20	14.514	0.07257	10	14.514	0.07257	0.04000	OK
3		0.294949	3	12	0.003042	42	13.450	0.06725	4	8.000	0.0400	48	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
4		1.107277	2	14	0.012734	32	20.175	0.10088	3	8.000	0.0400	42	5.183571429	0.025917857	28	5.18357143	0.025917857		
					8	39	13.450	0.06725	4	8.000	0.0400	44	6.597272727	0.032986364	22	6.59727273	0.032986364	0.03299	OK
7		1.116553	2	5	0.012579	14	20.175	0.10088	3	8.000	0.0400	15	14.514	0.07257	10	14.514	0.07257	0.04000	OK
8		1.10779	2	11	0.012709	26	20.175	0.10088	3	8.000	0.0400	33	6.597272727	0.032986364	22	6.59727273	0.032986364	0.03299	OK
9	º	0.29517	3	6	0.00304	24	13.450	0.06725	4	8.000	0.0400	24	12.095	0.060475	12	12.095	0.060475	0.04000	OK
10		1.1081	2	12	0.012718	28	20.175	0.10088	3	8.000	0.0400	36	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
11		0.108249	4	11	0.001108	52	10.088	0.05044	5	8.000	0.0400	55	6.597272727	0.032986364	22	6.59727273	0.032986364	0.03299	OK
12		1.1089	2	9	0.012703	22	20.175	0.10088	3	8.000	0.0400	27	8.063333333	0.040316667	18	8.06333333	0.040316667	0.04000	OK
13		1.113359	2	6	0.012614	16	20.175	0.10088	3	8.000	0.0400	18	12.095	0.060475	12	12.095	0.060475	0.04000	OK
14		1.111067	2	7	0.012652	18	20.175	0.10088	3	8.000	0.0400	21	10.36714286	0.051835714	14	10.3671429	0.051835714	0.04000	OK
15		0.295068	3	8	0.003363	30	13.450	0.06725	4	8.000	0.0400	32	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
16		0.108188	4	9	0.001104	44	10.088	0.05044	5	8.000	0.0400	45	8.063333333	0.040316667	18	8.06333333	0.040316667	0.04000	OK
17		0.294908	3	14	0.003287	48	13.450	0.06725	4	8.000	0.0400	56	5.183571429	0.025917857	28	5.18357143	0.025917857	0.02592	OK
18		0.108232	4	13	0.001115	60	10.088	0.05044	5	8.000	0.0400	65	5.582307692	0.027911538	26	5.58230769	0.027911538	0.02791	OK
19		1.108728	2	10	0.012714	24	20.175	0.10088	3	8.000	0.0400	30	7.257	0.036285	20	7.257	0.036285	0.03629	OK
20		0.10818	4	8	0.001103	40	10.088	0.05044	5	8.000	0.0400	40	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
21		0.108229	4	10	0.001106	48	10.088	0.05044	5	8.000	0.0400	50	7.257	0.036285	20	7.257	0.036285	0.03629	OK
22		0.295249	3	7	0.003015	27	13.450	0.06725	4	8.000	0.0400	28	10.36714286	0.051835714	14	10.3671429	0.051835714	0.04000	OK
23		0.388885	3	4	0.009894	18	13.450	0.06725	4	8.000	0.0400	16	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
24		1.119293	2	4	0.012555	12	20.175	0.10088	3	8.000	0.0400	12	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
25		0.108162	4	7	0.00175	36	10.088	0.05044	5	8.000	0.0400	35	10.36714286	0.051835714	14	10.3671429	0.051835714	0.04000	OK
26		1.107412	2	13	0.01273	30	20.175	0.10088	3	8.000	0.0400	39	5.582307692	0.027911538	26	5.58230769	0.027911538	0.02791	OK
27		1.109989	2	8	0.01269	20	20.175	0.10088	3	8.000	0.0400	24	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
28		0.29502	3	9	0.003034	33	13.450	0.06725	4	8.000	0.0400	36	8.063333333	0.040316667	18	8.06333333	0.040316667	0.04000	OK
29		0.2949	3	13	0.003274	45	13.450	0.06725	4	8.000	0.0400	52	5.582307692	0.027911538	26	5.58230769	0.027911538	0.02791	OK
30		0.157972	4	5	0.005525	28	10.088	0.05044	5	8.000	0.0400	25	14.514	0.07257	10	14.514	0.07257	0.04000	OK
31		0.170862	4	4	0.011632	24	10.088	0.05044	5	8.000	0.0400	20	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
32		0.10824	4	12	0.001108	56	10.088	0.05044	5	8.000	0.0400	60	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
33		0.137617	4	6	0.003075	32	10.088	0.05044	5	8.000	0.0400	30	12.095	0.060475	12	12.095	0.060475	0.04000	OK
34		0.108242	4	14	0.001114	64	10.088	0.05044	5	8.000	0.0400	70	5.183571429	0.025917857	28	5.18357143	0.025917857	0.02592	OK
35		0.082663	5	6	0.00286	40	8.070	0.04035	6	8.000	0.0400	36	12.095	0.060475	12	12.095	0.060475	0.04000	OK
36		0.050644	5	9	0.000678	55	8.070	0.04035	6	8.000	0.0400	54	8.063333333	0.040316667	18	8.06333333	0.040316667	0.04000	OK
37		0.058982	5	8	0.000893	50	8.070	0.04035	6	8.000	0.0400	48	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
38		0.044529	5	11	0.000661	65	8.070	0.04035	6	8.000	0.0400	66	6.597272727	0.032986364	22	6.59727273	0.032986364	0.03299	OK
39		0.083341	5	5	0.004863	35	8.070	0.04035	6	8.000	0.0400	30	14.514	0.07257	10	14.514	0.07257	0.04000	OK
40		0.044599	5	10	0.000617	60	8.070	0.04035	6	8.000	0.0400	60	7.257	0.036285	20	7.257	0.036285	0.03629	OK
41		0.044486	5	12	0.000602	70	8.070	0.04035	6	8.000	0.0400	72	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
42		0.294976	3	15	0.003237	51	13.450	0.06725	4	8.000	0.0400	60	4.838	0.02419	30	4.838	0.02419	0.02419	OK
43		0.08209	5	4	0.012072	30	8.070	0.04035	6	8.000	0.0400	24	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
44		0.04454	5	13	0.000597	75	8.070	0.04035	6	8.000	0.0400	78	5.582307692	0.027911538	26	5.58230769	0.027911538	0.02791	OK
45		0.044505	5	14	0.000599	80	8.070	0.04035	6	8.000	0.0400	84	5.183571429	0.025917857	28	5.18357143	0.025917857	0.02592	OK
46		0.108229	4	15	0.001114	68	10.088	0.05044	5	8.000	0.0400	75	4.838	0.02419	30	4.838	0.02419	0.02419	OK
47		0.044479	5	15	0.00062	85	8.070	0.04035	6	8.000	0.0400	90	4.838	0.02419	30	4.838	0.02419	0.02419	OK
48		1.107224	2	15	0.012725	34	20.175	0.10088	3	8.000	0.0400	45	4.838	0.02419	30	4.838	0.02419	0.02419	OK

APPENDIX D - 3 : MODEL B - 2

MODEL B - 2 Optimization process (Results 48 variables)

Parameters considered:	Structural mate	Steel s275
	Cladding materi	Glass
	Load case	4 & 5

Height	m	22.63 Z direct	Unit: Appartment - Canopy - Appartment		
Lenght	m	72.57 Y direct	Height	m	22.63 Z direct
Width	m	28.25 X direct	Lenght	m	72.57 Y dirct
Appartment measurements			Width	m	52.45 X direct
Height	m	22.63 Z direct	(roof) - low eave	m	8
Lenght	m	72.57 Y dirct	Desnivel	m	5
Width	m	12.1 X direct	angle	m	3

Minimal Mass [kg] = 315252.5683

B - 2 : Step 7 - Before cross section opt.

Nº it	Max displacement columns	Columns Laterals left short	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals rigth short	Length element (m)	Allowed max. Displacement columns (m)	Columns front	Length element (m)	Allowed max. Displacement columns (m)	Columns back	Length element (m)	Allowed max. Displacement columns (m)	Columns Front Ablock	Length element (m)	Allowed max. Displacement columns (m)	Allow Max displacement columns	U_max < U_max_allow ?	max. Allow displacement	U_max < U_max_allow ?	Total number of elements	Total mass (kg)	Utilization ratio cross section (%)
1	0.044936	7	8.00	0.026666667	7	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	2	27.63	0.0921	0.0921	OK	0.12252	OK	135	413176.5714	53
2	0.032771	5	8.00	0.026666667	5	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	3	27.63	0.0921	0.0921	OK	0.12252	Not	76	340763.8279	269
3	0.031842	12	8.00	0.026666667	12	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210										
				7	14	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	5	27.63	0.0921	0.0921	OK	0.12252	Not	144	386007.0921	904
5	0.03192	10	8.00	0.026666667	10	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	6	27.63	0.0921	0.0921	OK	0.12252	Not	134	383342.4683	241
6	0.031864	11	8.00	0.026666667	11	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	7	27.63	0.0921	0.0921	OK	0.12252	Not	146	396948.3939	241
7	0.053659	5	8.00	0.026666667	5	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	8	27.63	0.0921	0.0921	OK	0.12252	Not	66	323768.2964	911
8	0.052369	11	8.00	0.026666667	11	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	9	27.63	0.0921	0.0921	OK	0.12252	Not	121	379879.7387	904
9	0.032512	6	8.00	0.026666667	6	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	10	27.63	0.0921	0.0921	OK	0.12252	Not	94	344279.9961	241
10	0.052324	12	8.00	0.026666667	12	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	11	27.63	0.0921	0.0921	OK	0.12252	Not	132	393494.3832	904
11	0.052181	11	8.00	0.026666667	11	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	12	27.63	0.0921	0.0921	OK	0.12252	OK	178	439332.7801	88
12	0.052572	9	8.00	0.026666667	9	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	13	27.63	0.0921	0.0921	OK	0.12252	Not	107	352910.3442	905
13	0.05329	6	8.00	0.026666667	6	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	14	27.63	0.0921	0.0921	OK	0.12252	Not	81	327363.1599	909
14	0.052882	7	8.00	0.026666667	7	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	15	27.63	0.0921	0.0921	OK	0.12252	Not	91	343297.2202	907
15	0.032133	8	8.00	0.026666667	8	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	16	27.63	0.0921	0.0921	OK	0.12252	Not	122	356419.9396	241
16	0.052413	9	8.00	0.026666667	9	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	17	27.63	0.0921	0.0921	OK	0.12252	OK	157	412650.5099	88
17	0.031855	14	8.00	0.026666667	14	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	18	27.63	0.0921	0.0921	OK	0.12252	Not	190	402751.7929	241
18	0.052148	13	8.00	0.026666667	13	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	19	27.63	0.0921	0.0921	OK	0.12252	OK	211	435340.6953	88
19	0.052469	10	8.00	0.026666667	10	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	20	27.63	0.0921	0.0921	OK	0.12252	Not	123	366346.9367	905
20	0.052523	8	8.00	0.026666667	8	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	21	27.63	0.0921	0.0921	OK	0.12252	OK	148	399480.5229	88
21	0.052278	10	8.00	0.026666667	10	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	22	27.63	0.0921	0.0921	OK	0.12252	OK	175	425939.8118	88
22	0.032252	7	8.00	0.026666667	7	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	23	27.63	0.0921	0.0921	OK	0.12252	Not	118	360330.0163	241
23	0.033346	4	8.00	0.026666667	4	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	24	27.63	0.0921	0.0921	OK	0.12252	Not	86	332248.0998	317
24	0.054376	4	8.00	0.026666667	4	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	25	27.63	0.0921	0.0921	OK	0.12252	Not	74	315252.5683	914
25	0.052647	7	8.00	0.026666667	7	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	26	27.63	0.0921	0.0921	OK	0.12252	OK	140	402819.1885	88
26	0.052322	13	8.00	0.026666667	13	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	27	27.63	0.0921	0.0921	OK	0.12252	Not	157	375211.3285	904
27	0.05272	8	8.00	0.026666667	8	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	28	27.63	0.0921	0.0921	OK	0.12252	Not	113	339587.0162	906
28	0.03205	9	8.00	0.026666667	9	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	29	27.63	0.0921	0.0921	OK	0.12252	Not	146	369827.1803	241
29	0.031865	13	8.00	0.026666667	13	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	30	27.63	0.0921	0.0921	OK	0.12252	Not	191	391910.797	241
30	0.053234	5	8.00	0.026666667	5	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	31	27.63	0.0921	0.0921	OK	0.12252	Not	119	383361.1714	129
31	0.053856	4	8.00	0.026666667	4	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	32	27.63	0.0921	0.0921	OK	0.12252	Not	107	374845.4433	139
32	0.052179	12	8.00	0.026666667	12	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	33	27.63	0.0921	0.0921	OK	0.12252	OK	212	452815.7517	88
33	0.052969	6	8.00	0.026666667	6	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	34	27.63	0.0921	0.0921	OK	0.12252	Not	135	387103.3257	112
34	0.052127	14	8.00	0.026666667	14	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	35	27.63	0.0921	0.0921	OK	0.12252	OK	240	446057.6271	88
35	0.045259	6	8.00	0.026666667	6	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	36	27.63	0.0921	0.0921	OK	0.12252	OK	154	397242.5112	67
36	0.04467	9	8.00	0.026666667	9	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	37	27.63	0.0921	0.0921	OK	0.12252	OK	200	422789.6954	41
37	0.044835	8	8.00	0.026666667	8	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	38	27.63	0.0921	0.0921	OK	0.12252	OK	186	409466.3674	48
38	0.044529	11	8.00	0.026666667	11	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	39	27.63	0.0921	0.0921	OK	0.12252	OK	232	449759.09	36
39	0.045422	5	8.00	0.026666667	5	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	40	27.63	0.0921	0.0921	OK	0.12252	OK	143	393647.6476	68
40	0.044599	10	8.00	0.026666667	10	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	41	27.63	0.0921	0.0921	OK	0.12252	OK	219	436226.2879	36
41	0.044486	12	8.00	0.026666667	12	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	42	27.63	0.0921	0.0921	OK	0.12252	OK	250	463373.7345	36
42	0.031819	15	8.00	0.026666667	15	3.000	0.0100	4	27.6300	0.0921	4	27.630	0.09210	43	27.63	0.0921	0.0921	OK	0.12252	Not	226	413631.1941	241
43	0.045998	4	8.00	0.026666667	4	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	44	27.63	0.0921	0.0921	OK	0.12252	OK	132	385131.9195	67
44	0.04454	13	8.00	0.026666667	13	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	45	27.63	0.0921	0.0921	OK	0.12252	OK	268	445090.6797	36
45	0.044505	14	8.00	0.026666667	14	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	46	27.63	0.0921	0.0921	OK	0.12252	OK	284	455886.4433	36
46	0.052131	15	8.00	0.026666667	15	3.000	0.0100	5	27.6300	0.0921	5	27.630	0.09210	47	27.63	0.0921	0.0921	OK	0.12252	OK	265	456813.6804	88
47	0.044479	15	8.00	0.026666667	15	3.000	0.0100	6	27.6300	0.0921	6	27.630	0.09210	48	27.63	0.0921	0.0921	OK	0.12252	OK	301	466721.2793	36
48	0.052283	15	8.00	0.026666667	15	3.000	0.0100	3	27.6300	0.0921	3	27.630	0.09210	49	27.63	0.0921	0.0921	OK	0.12252	Not	197	396841.9281	904

APPENDIX D - 3 : MODEL B - 2

MODEL B - 2 Optimization process (Results 48 variables)

Parameters considered:	Structural materi	**Steel s275**
	Cladding material	**Glass**
	Load case	**4 & 5**

Height	m	22.63	Z direct	Unit: Appartment - Canopy - Appartment			
Lenght	m	72.57	Y dirct	Height	m	22.63	Z direct
Width	m	28.25	X direct	Lenght	m	72.57	Y dirct
Appartment measurements				Width	m	52.45	X direct
Height	m	22.63	Z direct	(roof) - low ea	m	8	
Lenght	m	72.57	Y dirct	Desnivel	m	5	
Width	m	12.1	X direct	angle	m	3	

B - 2 : Step 9 - After cross section opt.

Id. Family

Number of iteration	Steel class	Max. displacement (m) (Structure)	X - Number of Frames	Y - Number of Frames	Max displacement beams	Beams Top - X direction	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction Extension	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central part top	Length element (m)	Allowed max. Displacement beams (m)	Beams Top - Y Direction central sides	Length element (m)	Allowed max. Displacement beams (m)	Allow Max displacement beams	U_max < U_max_allow ?
1	**s275**	0.064856	5	7	0.021193	45	8.070	0.04035	6	8.000	0.0400	42	10.3671429	0.05183571	14	10.3671429	0.05183571	0.04000	OK
2		0.329934	3	5	0.012056	21	13.450	0.06725	4	8.000	0.0400	20	14.514	0.07257	10	14.514	0.07257	0.04000	OK
3		0.294949	3	12	0.009759	42	13.450	0.06725	4	8.000	0.0400	48	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
4		1.107277	2	14	0.014698	32	20.175	0.10088	3	8.000	0.0400	42	5.18357143	0.02591786	28	5.18357143	0.02591786	0.02592	OK
5		0.294962	3	10	0.009695	36	13.450	0.06725	4	8.000	0.0400	40	7.257	0.036285	20	7.257	0.036285	0.03629	OK
6		0.294995	3	11	0.00975	39	13.450	0.06725	4	8.000	0.0400	44	6.59727273	0.03298636	22	6.59727273	0.03298636	0.03299	OK
7		1.116553	2	5	0.014616	14	20.175	0.10088	3	8.000	0.0400	15	14.514	0.07257	10	14.514	0.07257	0.04000	OK
8		1.10779	2	11	0.014676	26	20.175	0.10088	3	8.000	0.0400	33	6.59727273	0.03298636	22	6.59727273	0.03298636	0.03299	OK
9	º	0.29517	3	6	0.01058	24	13.450	0.06725	4	8.000	0.0400	24	12.095	0.060475	12	12.095	0.060475	0.04000	OK
10		1.1081	2	12	0.014682	28	20.175	0.10088	3	8.000	0.0400	36	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
11		0.108249	4	11	0.010835	52	10.088	0.05044	5	8.000	0.0400	55	6.59727273	0.03298636	22	6.59727273	0.03298636	0.03299	OK
12		1.1089	2	9	0.014674	22	20.175	0.10088	3	8.000	0.0400	27	8.06333333	0.04031667	18	8.06333333	0.04031667	0.04000	OK
13		1.113359	2	6	0.014647	16	20.175	0.10088	3	8.000	0.0400	18	12.095	0.060475	12	12.095	0.060475	0.04000	OK
14		1.111067	2	7	0.014658	18	20.175	0.10088	3	8.000	0.0400	21	10.3671429	0.05183571	14	10.3671429	0.05183571	0.04000	OK
15		0.295068	3	8	0.010028	30	13.450	0.06725	4	8.000	0.0400	32	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
16		0.108188	4	9	0.016735	44	10.088	0.05044	5	8.000	0.0400	45	8.06333333	0.04031667	18	8.06333333	0.04031667	0.04000	OK
17		0.294908	3	14	0.009273	48	13.450	0.06725	4	8.000	0.0400	56	5.18357143	0.02591786	28	5.18357143	0.02591786	0.02592	OK
18		0.108232	4	13	0.012058	60	10.088	0.05044	5	8.000	0.0400	65	5.58230769	0.02791154	26	5.58230769	0.02791154	0.02791	OK
19		1.108728	2	10	0.01468	24	20.175	0.10088	3	8.000	0.0400	30	7.257	0.036285	20	7.257	0.036285	0.03629	OK
20		0.10818	4	8	0.014926	40	10.088	0.05044	5	8.000	0.0400	40	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
21		0.108229	4	10	0.011955	48	10.088	0.05044	5	8.000	0.0400	50	7.257	0.036285	20	7.257	0.036285	0.03629	OK
22		0.295249	3	7	0.009809	27	13.450	0.06725	4	8.000	0.0400	28	10.3671429	0.05183571	14	10.3671429	0.05183571	0.04000	OK
23		0.388885	3	4	0.011422	18	13.450	0.06725	4	8.000	0.0400	16	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
24		1.119293	2	4	0.014579	12	20.175	0.10088	3	8.000	0.0400	12	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
25		0.108162	4	7	0.015177	36	10.088	0.05044	5	8.000	0.0400	35	10.3671429	0.05183571	14	10.3671429	0.05183571	0.04000	OK
26		1.107412	2	13	0.014697	30	20.175	0.10088	3	8.000	0.0400	39	5.58230769	0.02791154	26	5.58230769	0.02791154	0.02791	OK
27		1.109989	2	8	0.014671	20	20.175	0.10088	3	8.000	0.0400	24	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
28		0.29502	3	9	0.010713	33	13.450	0.06725	4	8.000	0.0400	36	8.06333333	0.04031667	18	8.06333333	0.04031667	0.04000	OK
29		0.2949	3	13	0.009154	45	13.450	0.06725	4	8.000	0.0400	52	5.58230769	0.02791154	26	5.58230769	0.02791154	0.02791	OK
30		0.157972	4	5	0.014554	28	10.088	0.05044	5	8.000	0.0400	25	14.514	0.07257	10	14.514	0.07257	0.04000	OK
31		0.170862	4	4	0.011429	24	10.088	0.05044	5	8.000	0.0400	20	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
32		0.10824	4	12	0.011426	56	10.088	0.05044	5	8.000	0.0400	60	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
33		0.137617	4	6	0.012259	32	10.088	0.05044	5	8.000	0.0400	30	12.095	0.060475	12	12.095	0.060475	0.04000	OK
34		0.108242	4	14	0.008113	64	10.088	0.05044	5	8.000	0.0400	70	5.18357143	0.02591786	28	5.18357143	0.02591786	0.02592	OK
35		0.082663	5	6	0.013468	40	8.070	0.04035	6	8.000	0.0400	36	12.095	0.060475	12	12.095	0.060475	0.04000	OK
36		0.050644	5	9	0.026351	55	8.070	0.04035	6	8.000	0.0400	54	8.06333333	0.04031667	18	8.06333333	0.04031667	0.04000	OK
37		0.058982	5	8	0.020834	50	8.070	0.04035	6	8.000	0.0400	48	9.07125	0.04535625	16	9.07125	0.04535625	0.04000	OK
38		0.044529	5	11	0.015368	65	8.070	0.04035	6	8.000	0.0400	66	6.59727273	0.03298636	22	6.59727273	0.03298636	0.03299	OK
39		0.083341	5	5	0.019319	35	8.070	0.04035	6	8.000	0.0400	30	14.514	0.07257	10	14.514	0.07257	0.04000	OK
40		0.044599	5	10	0.026465	60	8.070	0.04035	6	8.000	0.0400	60	7.257	0.036285	20	7.257	0.036285	0.03629	OK
41		0.044486	5	12	0.017211	70	8.070	0.04035	6	8.000	0.0400	72	6.0475	0.0302375	24	6.0475	0.0302375	0.03024	OK
42		0.294976	3	15	0.009153	51	13.450	0.06725	4	8.000	0.0400	60	4.838	0.02419	30	4.838	0.02419	0.02419	OK
43		0.08209	5	4	0.016352	30	8.070	0.04035	6	8.000	0.0400	24	18.1425	0.0907125	8	18.1425	0.0907125	0.04000	OK
44		0.04454	5	13	0.015535	75	8.070	0.04035	6	8.000	0.0400	78	5.58230769	0.02791154	26	5.58230769	0.02791154	0.02791	OK
45		0.044505	5	14	0.011752	80	8.070	0.04035	6	8.000	0.0400	84	5.18357143	0.02591786	28	5.18357143	0.02591786	0.02592	OK
46		0.108229	4	15	0.010378	68	10.088	0.05044	5	8.000	0.0400	75	4.838	0.02419	30	4.838	0.02419	0.02419	OK
47		0.044479	5	15	0.013939	85	8.070	0.04035	6	8.000	0.0400	90	4.838	0.02419	30	4.838	0.02419	0.02419	OK
48		1.107224	2	15	0.014695	34	20.175	0.10088	3	8.000	0.0400	45	4.838	0.02419	30	4.838	0.02419	0.02419	OK

APPENDIX D - 3 : MODEL B - 2

MODEL B - 2 Optimization process (Results 48 variables)

Parameters considered:	Structural mat	Steel s275
	Cladding mate	Glass
	Load case	4 & 5

Height	m	22.63	Z direct	Unit: Appartment - Canopy - Appartment			
Lenght	m	72.57	Y dirct	Height	m	22.63	Z direct
Width	m	28.25	X direct	Lenght	m	72.57	Y dirct
Appartment measurements				Width	m	52.45	X direct
Height	m	22.63	Z direct	(roof) - low eave	m	8	
Lenght	m	72.57	Y dirct	Desnivel	m	5	
Width	m	12.1	X direct	angle	m	3	

B - 2 : Step 9 - After cross section opt.

Number of iteration	Max displacement columns	Columns Laterals left short	Length element (m)	Allowed max. Displacement beams (m)	Columns Laterals rigth short	Length element (m)	Allowed max. Displacement columns (m)	Columns front	Length element (m)	Allowed max. Displacement columns (m)	Columns back	Length element (m)	Allowed max. Displacement columns (m)	Columns Front Ablock	Length element (m)	Allowed max. Displacement columns (m)	Allow Max displacement columns	U_max < U_max_allow ?	max. Allow displacement	U_max < U_max_allow ?	Total number of elements	Total mass (kg)	Utilization ratio cross section (%)
1	0.071539	7	8.00	0.026666667	7	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	2	22.63	0.0754	0.0921	OK	0.12252	OK	135	309788.5449	53
2	0.031474	5	8.00	0.026666667	5	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	3	22.63	0.0754	0.0921	OK	0.12252	Not	84	355054.4843	269
3	0.030409	12	8.00	0.026666667	12	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	4	22.63	0.0754	0.0921	OK	0.12252	Not	162	376742.489	241
4	0.045561	14	8.00	0.026666667	14	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	5	22.63	0.0754	0.0921	OK	0.12252	Not	150	394445.1161	904
5	0.030464	10	8.00	0.026666667	10	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	6	22.63	0.0754	0.0921	OK	0.12252	Not	142	351859.0044	241
6	0.030414	11	8.00	0.026666667	11	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	7	22.63	0.0754	0.0921	OK	0.12252	Not	154	363379.1453	241
7	0.047123	5	8.00	0.026666667	5	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	8	22.63	0.0754	0.0921	OK	0.12252	Not	72	360486.2798	911
8	0.04561	11	8.00	0.026666667	11	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	9	22.63	0.0754	0.0921	OK	0.12252	Not	127	385484.9248	904
9	0.031124	6	8.00	0.026666667	6	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	10	22.63	0.0754	0.0921	OK	0.12252	Not	102	336648.9998	241
10	0.045592	12	8.00	0.026666667	12	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	11	22.63	0.0754	0.0921	OK	0.12252	Not	138	399896.2179	904
11	0.045473	11	8.00	0.026666667	11	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	12	22.63	0.0754	0.0921	OK	0.12252	OK	188	343727.3775	88
12	0.045815	9	8.00	0.026666667	9	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	13	22.63	0.0754	0.0921	OK	0.12252	Not	113	359639.9573	905
13	0.046629	6	8.00	0.026666667	6	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	14	22.63	0.0754	0.0921	OK	0.12252	Not	87	350824.9106	909
14	0.046204	7	8.00	0.026666667	7	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	15	22.63	0.0754	0.0921	OK	0.12252	Not	97	355933.0745	907
15	0.030687	8	8.00	0.026666667	8	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	16	22.63	0.0754	0.0921	OK	0.12252	Not	130	330866.0468	241
16	0.045703	9	8.00	0.026666667	9	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	17	22.63	0.0754	0.0921	OK	0.12252	OK	167	325910.2412	88
17	0.030406	14	8.00	0.026666667	14	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	18	22.63	0.0754	0.0921	OK	0.12252	Not	198	372617.8305	241
18	0.045451	13	8.00	0.026666667	13	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	19	22.63	0.0754	0.0921	OK	0.12252	OK	221	338860.8076	88
19	0.045707	10	8.00	0.026666667	10	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	20	22.63	0.0754	0.0921	OK	0.12252	Not	129	372745.8944	905
20	0.045857	8	8.00	0.026666667	8	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	21	22.63	0.0754	0.0921	OK	0.12252	OK	158	318644.4054	88
21	0.045569	10	8.00	0.026666667	10	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	22	22.63	0.0754	0.0921	OK	0.12252	OK	185	334033.3579	88
22	0.030805	7	8.00	0.026666667	7	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	23	22.63	0.0754	0.0921	OK	0.12252	Not	126	343576.2159	241
23	0.032183	4	8.00	0.026666667	4	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	24	22.63	0.0754	0.0921	OK	0.12252	Not	94	365234.1614	317
24	0.048116	4	8.00	0.026666667	4	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	25	22.63	0.0754	0.0921	OK	0.12252	Not	80	358485.6501	914
25	0.046015	7	8.00	0.026666667	7	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	26	22.63	0.0754	0.0921	OK	0.12252	OK	150	328675.025	88
26	0.045593	13	8.00	0.026666667	13	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	27	22.63	0.0754	0.0921	OK	0.12252	Not	163	382708.038	904
27	0.046022	8	8.00	0.026666667	8	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	28	22.63	0.0754	0.0921	OK	0.12252	Not	119	348473.7971	906
28	0.030569	9	8.00	0.026666667	9	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	29	22.63	0.0754	0.0921	OK	0.12252	Not	154	342497.6587	241
29	0.030428	13	8.00	0.026666667	13	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	30	22.63	0.0754	0.0921	OK	0.12252	Not	199	364263.8535	241
30	0.046739	5	8.00	0.026666667	5	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	31	22.63	0.0754	0.0921	OK	0.12252	Not	129	355599.4375	129
31	0.047653	4	8.00	0.026666667	4	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	32	22.63	0.0754	0.0921	OK	0.12252	Not	117	383790.671	139
32	0.04549	12	8.00	0.026666667	12	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	33	22.63	0.0754	0.0921	OK	0.12252	OK	222	354026.1183	88
33	0.046334	6	8.00	0.026666667	6	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	34	22.63	0.0754	0.0921	OK	0.12252	Not	145	336486.2619	112
34	0.045424	14	8.00	0.026666667	14	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	35	22.63	0.0754	0.0921	OK	0.12252	OK	250	346217.5516	88
35	0.053918	6	8.00	0.026666667	6	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	36	22.63	0.0754	0.0921	OK	0.12252	OK	166	314925.1156	67
36	0.077302	9	8.00	0.026666667	9	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	37	22.63	0.0754	0.0921	OK	0.12252	OK	212	304113.6977	41
37	0.077438	8	8.00	0.026666667	8	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	38	22.63	0.0754	0.0921	OK	0.12252	OK	198	298337.5567	48
38	0.077181	11	8.00	0.026666667	11	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	39	22.63	0.0754	0.0921	OK	0.12252	OK	244	322065.326	36
39	0.054213	5	8.00	0.026666667	5	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	40	22.63	0.0754	0.0921	OK	0.12252	OK	155	325751.3827	68
40	0.077219	10	8.00	0.026666667	10	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	41	22.63	0.0754	0.0921	OK	0.12252	OK	231	312577.0581	36
41	0.07716	12	8.00	0.026666667	12	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	42	22.63	0.0754	0.0921	OK	0.12252	OK	262	332393.7607	36
42	0.030379	15	8.00	0.026666667	15	3.000	0.0100	8	27.630	0.0921	8	27.630	0.09210	43	22.63	0.0754	0.0921	OK	0.12252	Not	234	381621.1031	241
43	0.058264	4	8.00	0.026666667	4	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	44	22.63	0.0754	0.0921	OK	0.12252	OK	144	353392.1821	67
44	0.077204	13	8.00	0.026666667	13	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	45	22.63	0.0754	0.0921	OK	0.12252	OK	280	313873.3165	36
45	0.077188	14	8.00	0.026666667	14	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	46	22.63	0.0754	0.0921	OK	0.12252	OK	296	320847.1995	36
46	0.045433	15	8.00	0.026666667	15	3.000	0.0100	10	27.630	0.0921	10	27.630	0.09210	47	22.63	0.0754	0.0921	OK	0.12252	OK	275	354026.8363	88
47	0.077164	15	8.00	0.026666667	15	3.000	0.0100	12	27.630	0.0921	12	27.630	0.09210	48	22.63	0.0754	0.0921	OK	0.12252	OK	313	327799.5753	36
48	0.045561	15	8.00	0.026666667	15	3.000	0.0100	6	27.630	0.0921	6	27.630	0.09210	49	22.63	0.0754	0.0921	OK	0.12252	Not	203	406375.0333	904

APPENDIX D - 3 : MODEL B - 2

MODEL B - 2 Optimization process (Results 48 variables)

Parameters considered:	Structural material	**Steel s275**
	Cladding material	**Glass**
	Load case	**4 & 5**

Height	m	22.63 Z direct
Lenght	m	72.57 Y dirct
Width	m	28.25 X direct
Appartment measurements		
Height	m	22.63 Z direct
Lenght	m	72.57 Y dirct
Width	m	12.1 X direct

Unit: Appartment - Canopy - Appartment		
Height	m	22.63 Z direct
Lenght	m	72.57 Y dirct
Width	m	52.45 X direct
(roof) - low eave	m	8
Desnivel	m	5
angle	m	3

COMPARISON			
Reducction of mass (kg)	Reducction of mass (%) respect the initial value	Reducction of mass (%) respect the initial value	Nº of iteration
103388.0265	25	25	1
-14290.65643	-4	0	2
33888.1018	8	8	3
-8438.024014	-2	0	4
31483.46394	8	8	5
33569.24855	8	8	6
-36717.98349	-11	0	7
-5605.186095	-1	0	8
7630.996301	2	2	9
-6401.834625	-2	0	10
95605.40265	22	22	11
-6729.613097	-2	0	12
-23461.75068	-7	0	13
-12635.85431	-4	0	14
25553.89282	7	7	15
86740.26876	21	21	16
30133.96236	7	7	17
96479.88769	22	22	18
-6398.957663	-2	0	19
80836.11746	20	20	20
91906.45394	22	22	21
16753.8004	5	5	22
-32986.06155	-10	0	23
-43233.08184	-14	0	24
74144.16354	18	18	25
-7496.7095	-2	0	26
-8886.780882	-3	0	27
27329.52157	7	7	28
27646.94349	7	7	29
27761.73389	7	7	30
-8945.22762	-2	0	31
98789.63339	22	22	32
50617.06384	13	13	33
99840.07549	22	22	34
82317.39553	21	21	35
118675.9977	28	28	36
111128.8107	27	27	37
127693.7639	28	28	38
67896.26492	17	17	39
123649.2298	28	28	40
130979.9738	28	28	41
32010.091	8	8	42
31739.73743	8	8	43
131217.3632	29	29	44
135039.2438	30	30	45
102786.8441	23	23	46
138921.704	30	30	47
-9533.105196	-2	0	48

	Before cross section optimization			After cross section optimization		
Nº of iteration	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)	Total mass (kg)	Utilization ratio cross section (%)	Utilization ratio cross section (%)
1	413176.5714	26	26	309788.5449	65	65
2	340763.8279	23	23	355054.4843	32	32
3	410630.5908	22	22	376742.489	33	33
4	386007.0921	53	53	394445.1161	53	53
5	383342.4683	22	22	351859.0044	30	30
6	396948.3939	22	22	363379.1453	31	31
7	323768.2964	45	45	360486.2798	44	44
8	379879.7387	48	48	385484.9248	47	47
9	344279.9961	21	21	336648.9998	30	30
10	393494.3832	49	49	399896.2179	49	49
11	439332.7801	30	30	343727.3775	41	41
12	352910.3442	44	44	359639.9573	43	43
13	327363.1599	45	45	350824.9106	44	44
14	343297.2202	45	45	355933.0745	43	43
15	356419.9396	22	22	330866.0468	29	29
16	412650.5099	30	30	325910.2412	46	46
17	402751.7929	24	24	372617.8305	34	34
18	435340.6953	30	30	338860.8076	46	46
19	366346.9367	46	46	372745.8944	45	45
20	399480.5229	30	30	318644.4054	44	44
21	425939.8118	30	30	334033.3579	41	41
22	360330.0163	21	21	343576.2159	29	29
23	332248.0998	30	30	365234.1614	32	32
24	315252.5683	45	45	358485.6501	44	44
25	402819.1885	31	31	328675.025	44	44
26	375211.3285	51	51	382708.038	51	51
27	339587.0162	44	44	348473.7971	43	43
28	369827.1803	21	21	342497.6587	30	30
29	391910.797	23	23	364263.8535	33	33
30	383361.1714	36	36	355599.4375	44	44
31	374845.4433	44	44	383790.671	40	40
32	452815.7517	30	30	354026.1183	44	44
33	387103.3257	33	33	336486.2619	40	40
34	446057.6271	30	30	346217.5516	40	40
35	397242.5112	28	28	314925.1156	46	46
36	422789.6954	25	25	304113.6977	75	75
37	409466.3674	25	25	298337.5567	68	68
38	449759.09	25	25	322065.326	65	65
39	393647.6476	31	31	325751.3827	54	54
40	436226.2879	25	25	312577.0581	78	78
41	463373.7345	25	25	332393.7607	70	70
42	413631.1941	24	24	381621.1031	35	35
43	385131.9195	40	40	353392.1821	52	52
44	445090.6797	25	25	313873.3165	70	70
45	455886.4433	25	25	320847.1995	65	65
46	456813.6804	31	31	354026.8363	46	46
47	466721.2793	25	25	327799.5753	71	71
48	396841.9281	55	55	406375.0333	55	55

APPENDIX E: OUTPUT FROM GRASSHOPPER. SECTION FORCES AND VERIFICATIONS

APPENDIX E- 1 : MODEL A

1st Loop - MODEL A - Verifications Step 9

MODEL A - step 9 - verification of the most unfavorable element

'Most optimal cases" Iteration Nº		25	X = 4 Y = 6				Results - Input from grasshopper				
Element_ID	Span direction	Material	Type of profile	Nº of frames	Span of elements [m]	Nº Elem	Deflection [m]	Max Normal Force	Max Shear force	Max Bending moment	Max. Stress
							u [m]	Nd [KN]	Vd [KN]	Md [KNm]	σ [kN/cm2]
Beams Top - X direction	X direction	S235	HEB 220	7	7.06	28	0.006059	0	41.120432	50.284216	13.673
Beams Top - Y Direction	Y direction	S235	HEB 550	5	12.10	30	0.041762	0	96.46713	195.660239	7.872

							Results - Input from grasshopper				
Element_ID	Span direction	Material	Type of profile	Number of frames	Length [m]	Nº Elem	Deflection [m]	Max Normal Force	Max Shear force	Max Bending moment	Max. Stress
							u [m]	Nd [KN]	Vd [KN]	Md [KNm]	σ [kN/cm2]
Columns Laterals	z direction	S235	HEB700	7	22.63	14	0.008472	-15.229993	6.567251	33.822428	0.921592044
Columns front/back	z direction	S235	HEB160	5	22.63	6	0.023459	-13.422006	16.613963	70.707307	21.71584462

Verifications

Axial Buckling Resistance		Shear resistance		Flexural resistance		Flexural resistance (V+M)		Lateral Buckling Resistance		Allow Max. Stress		Max.Def		Element_ID
N_{RD} [kN]		V_{RD} [kN]		$M_{C,RD}$ [kN]		$M_{V,RD}$ [kN]		$M_{RD,LT}$ [kN]		σ [kN/cm2]		u_max [m]		
752.7319642	OK	236.3046539	OK	194.345	OK	Not needed	-	60.81220998	OK	27.5	OK	0.0353125	OK	Beams Top - X direction
3814.358746	OK	932.7815287	OK	1313.885	OK	Not needed	-	746.2092612	OK	27.5	OK	0.060475	OK	Beams Top - Y Direction

Verifications

Axial Buckling Resistance, y		Axial Buckling Resistance, z		Flexural resistance		Flexural resistance (V+M)		Column Buckling Resistance		Allow Max. Stress		Max.Def		Element_ID
$N_{RD,y}$ [kN]		$N_{RD,z}$ [kN]		$M_{C,RD}$ [kN]		$M_{V,RD}$ [kN]		$M_{RD,LT}$ [kN]		σ [kN/cm2]		u_max [m]		
2853.861876	OK	403.3273402	OK	-	OK	Not needed	-	631.8293756	OK	27.5	OK	0.07543	OK	Columns Laterals
505.2937559	OK	9.70679923	not	-	OK	Not needed	-	1.327816101	not	27.5	OK	0.07543	OK	Columns front/back

APPENDIX E - 1 : MODEL A

1st Loop - MODEL A - Section forces (Output from GH) - Step 9 (1st Loop)

		X	Y
First model - before Cross optimization			
First model - after Cross optimization		4	6
Parameters considered:	Structural mater		**Steel s275**
	Cladding materia		**Glass**
	Load case		**4**
	Iteration Nº		**25**

Beams top X direction

Normal forces	Bending moment	Shear Force
0	19.55473	15.526804
0	19.554725	15.526801
0	17.497318	14.822915
0	17.497319	14.822916
0	46.667647	37.710775
0	46.666551	37.708857
0	46.640831	33.471043
0	46.636256	33.470514
0	50.284216	40.678182
0	49.42504	41.120432
0	50.281543	36.072387
0	49.425848	35.951101
0	50.28374	40.678661
0	49.423872	41.119041
0	50.28373	36.072646
0	49.423881	35.950892
0	50.283756	40.678649
0	49.423888	41.11903
0	50.283651	36.072619
0	49.423826	35.950873
0	50.291197	40.676464
0	49.433909	41.11892
0	50.260496	36.068055
0	49.407918	35.947216
0	24.67075	19.626014
0	24.669547	19.624943
0	22.253541	17.920452
0	22.25164	17.92019

Beams top Y direction

Normal forces	Bending moment	Shear Force
0	89.861794	43.258937
0	89.699056	40.419795
0	93.794233	45.358691
0	93.807542	45.520806
0	94.23069	40.397607
0	94.47902	45.635476
0	89.861732	43.258929
0	89.698994	40.41977
0	93.792751	45.358525
0	93.808054	45.520729
0	94.229856	40.397644
0	94.48053	45.635606
0	195.656346	93.230283
0	195.660239	90.277425
0	188.165609	96.46713
0	165.614152	74.354259
0	245.839688	104.736061
0	245.829795	114.289748
0	173.688927	82.07746
0	173.686971	76.772031
0	178.886663	86.417906
0	178.898145	86.668704
0	179.168526	76.354156
0	179.174524	86.685502
0	195.656391	93.23028
0	195.660283	90.277444
0	188.165084	96.46696
0	165.613614	74.354271
0	245.84034	104.735939
0	245.828097	114.289595

Columns laterals

Normal forces	Bending moment	Shear Force
-15.229993	33.822428	6.56725
-4.388199	2.339347	0.155021
-4.388199	2.523963	0.167255
-4.388199	2.522621	0.167166
-4.388199	2.525563	0.167361
-4.388199	2.532059	0.167792
-10.827493	19.106087	3.113566
-15.229993	33.822428	6.567251
-4.388199	2.338424	0.15496
-4.388199	1.923265	0.127448
-4.388199	1.920629	0.127274
-4.388199	1.924494	0.12753
-4.388199	1.934837	0.128216
-10.827493	19.102232	3.113459

Columns Front/back

Normal forces	Bending	Shear Force
-31.297584	70.707	16.613963
-17.456779	53.759	12.390569
-31.297584	70.707	16.613961
-13.422006	31.694	7.42684
-12.094106	24.88	5.593712
-13.422006	31.694	7.426835

APPENDIX E- 1 : MODEL A

2nd Loop - MODEL A - Verifications

MODEL A - step 9 [2nd loop] (11b - after modifications) - verification of the most unfavorable element

'Most optimal cases''	Iteration Nº	25	X = 4 Y = 6				Results - Input from grasshopper				
Element_ID	Span direction	Material	Type of profile	Nº of frames	Span of elements [m]	Total number of elements	Deflection [m]	Max Normal Force	Max Shear force	Max Bending moment	Max. Stress
							u [m]	Nd [KN]	Vd [KN]	Md [KNm]	σ [kN/cm2]
Beams Top - X direction	X direction	S275	HEB180	7	7.06	28	0.013	0	24.440	28.994	13.623
Beams Top - Y Direction	Y direction	S275	HEB360	5	12.10	30	0.026	0	83.275	174.768	14.567

							Results - Input from grasshopper				
Element_ID	Span direction	Material	Type of profile	Nº of frames	Length [m]	Total number of elements	Deflection [m]	Max Normal Force	Max Shear force	Max Bending moment	Max. Stress
							u [m]	Nd [KN]	Vd [KN]	Md [KNm]	σ [kN/m2]
Columns Laterals	z direction	S235	HEB450	7	22.63	14	0.009389	-22.267863	13.325585	51.226479	4.750955499
Columns front/back	z direction	S235	HEB340	5	22.63	6	0.003957	-17.456779	18.736635	74.659846	6.924262859

	Verifications					
Element_ID	**Axial Buckling Resistance**	**Shear resistance**	**Flexural resistance**	**Lateral Buckling Resistance**		**Max.Def**
	N_{RD} [kN]	V_{RD} [kN]	$M_{C,RD}$ [kN]	$M_{RD,LT}$ [kN]	σ [kN/cm2]	u_max [m]
Beams Top - X direction	442.929 OK	202.433 OK	132.385 OK	32.678 OK	27.5 OK	0.035 OK
Beams Top - Y Direction	1054.740 OK	595.392 OK	737.825 OK	214.720 OK	27.5 OK	0.060 OK

	Verifications					
Element_ID	**Axial Buckling Resistance, y**	**Axial Buckling Resistance, z**	**Flexural resistance**	**Column Buckling Resistance**		**Max.Def**
	$N_{RD,y}$ [kN]	$N_{RD,z}$ [kN]	$M_{C,RD}$ [kN]	$M_{RD,LT}$ [kN]	σ [kN/m2]	u_max [m]
Columns Laterals	983.6066639 OK	562.92504 OK	- OK	229.0277405 OK	27.5 OK	0.07543 OK
Columns front/back	771.093481 OK	263.86749 OK	- OK	154.6333907 OK	27.5 OK	0.07543 OK

MODEL A - Section Forces (Output from GH) - step 9 [2nd loop] (11b - after modifications)

		X	Y
First model - before Cross optimization			
First model - after Cross optimization		4	6
Parameters considered:	Structural ma		**Steel s275**
	Cladding mat		**Glass**
	Load case		**4**
	Iteration Nº		**25**

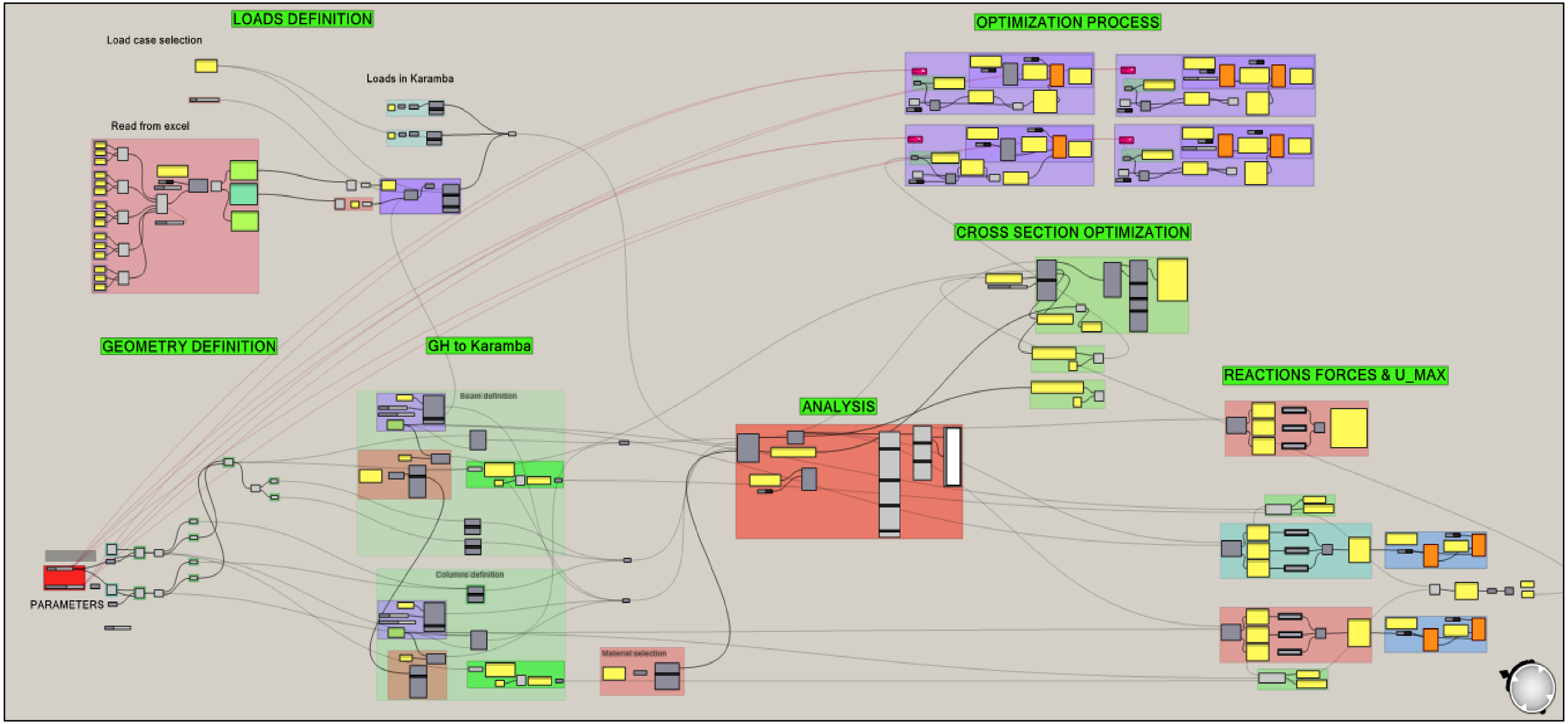
Beams top X direction			Beams top Y direction			Columns laterals			Columns Front/back		
Normal forces	**Bending moment**	**Shear Force**	**Normal forces**	**Bending moment**	**Shear Force**	**Normal forces**	**Bending moment**	**Shear Force**	**Normal forces**	**Bending moment**	**Shear Force**
0	6.980397	5.604381	0	45.705069	20.933342	-22.267863	51.226479	13.325585	-17.46	74.659846	18.736635
0	6.980397	5.604381	0	61.819497	29.215155	-22.267863	19.508662	1.290535	-17.46	53.686577	13.657517
0	8.828845	7.426909	0	65.810048	32.130934	-22.267863	24.747564	1.637008	-17.46	74.659838	18.736633
0	8.828846	7.426909	0	66.220951	32.475674	-22.267863	24.746041	1.636906	-17.46	74.659846	18.736635
0	21.379609	18.0643	0	67.749792	29.187793	-22.267863	24.87474	1.645452	-17.46	53.686577	13.657517
0	21.379605	18.064295	0	73.626021	35.017341	-22.267863	25.426014	1.682058	-17.46	74.659838	18.736633
0	21.375703	17.858869	0	45.705069	20.933341	-22.267863	33.744921	7.36045	-17.46	47.919386	10.308147
0	21.375699	17.858867	0	61.819497	29.215155	-22.267863	51.226479	13.325585	-17.46	44.371715	8.812853
0	28.992376	24.440022	0	65.810048	32.130934	-22.267863	19.508655	1.290535	-17.46	47.919381	10.308146
0	28.992369	24.440015	0	66.220951	32.475674	-22.267863	24.747557	1.637007	-17.46	47.919386	10.308147
0	28.991465	24.035365	0	67.749792	29.187793	-22.267863	24.746033	1.636906	-17.46	44.371715	8.812853
0	28.991458	24.03536	0	73.626021	35.017341	-22.267863	24.874731	1.645452	-17.46	47.919381	10.308146
0	28.991978	24.439964	0	101.145083	44.67901	-22.267863	25.426005	1.682058			
0	28.991971	24.439957	0	145.118408	67.487665	-22.267863	33.744921	7.36045			
0	28.991975	24.035474	0	145.117999	70.266135						
0	28.991968	24.03547	0	116.256209	53.053196						
0	28.991973	24.439958	0	174.768395	74.388639						
0	28.991969	24.439952	0	174.763883	83.275375						
0	28.991959	24.035463	0	85.422545	39.161767						
0	28.991955	24.035462	0	116.334154	54.590346						
0	28.99413	24.440355	0	123.874995	60.197483						
0	28.994126	24.440348	0	123.8833	60.856232						
0	28.989538	24.034958	0	119.479227	53.240184						
0	28.989535	24.034957	0	119.481882	58.427395						
0	15.42439	12.914685	0	101.145074	44.679006						
0	15.424387	12.914681	0	145.1184	67.487661						
0	15.050439	12.689115	0	145.117991	70.266132						
0	15.050438	12.689114	0	116.256203	53.053192						
			0	174.768377	74.388631						
			0	174.763865	83.275367						

APPENDIX F: SCRIPT IN GRASSHOPPER DEFINITION

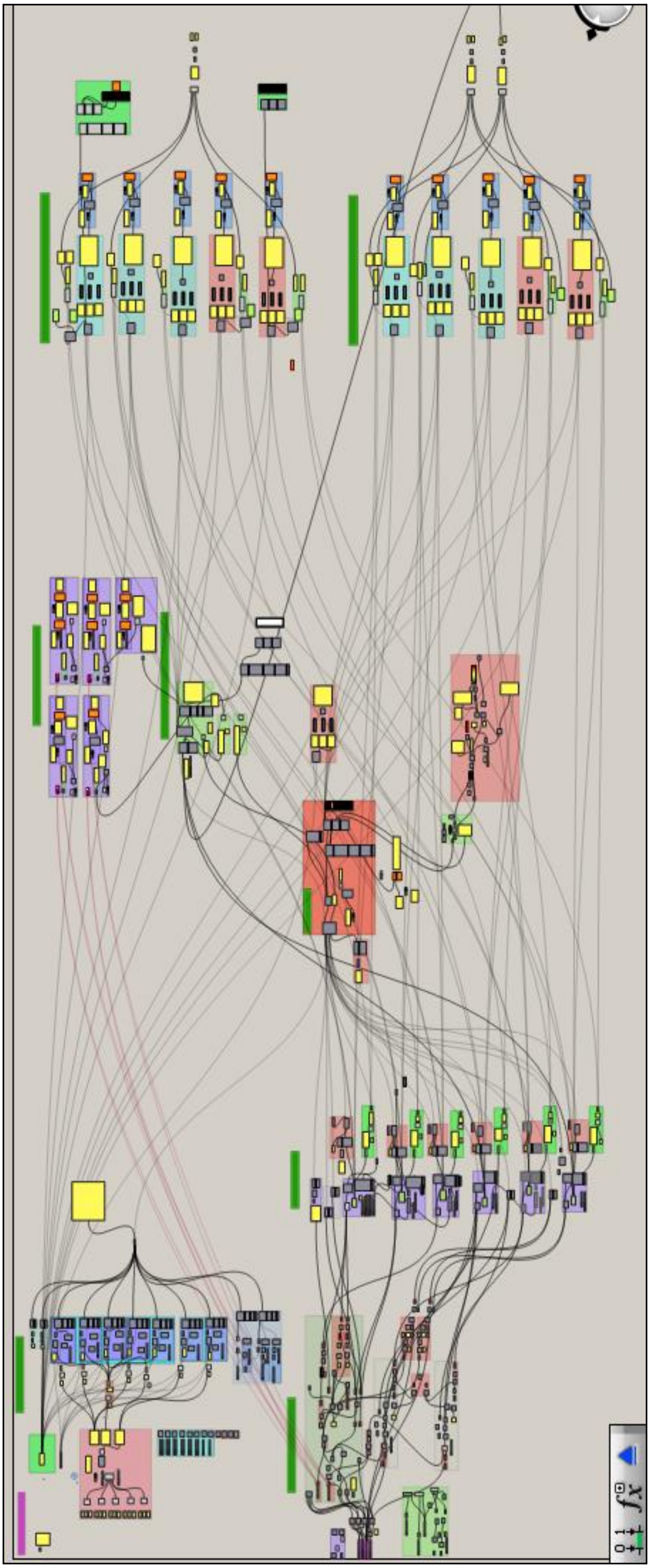
OVERVIEW OF SCRIP DEFINITION (EXAMPLE)

Scripts defined in GH:

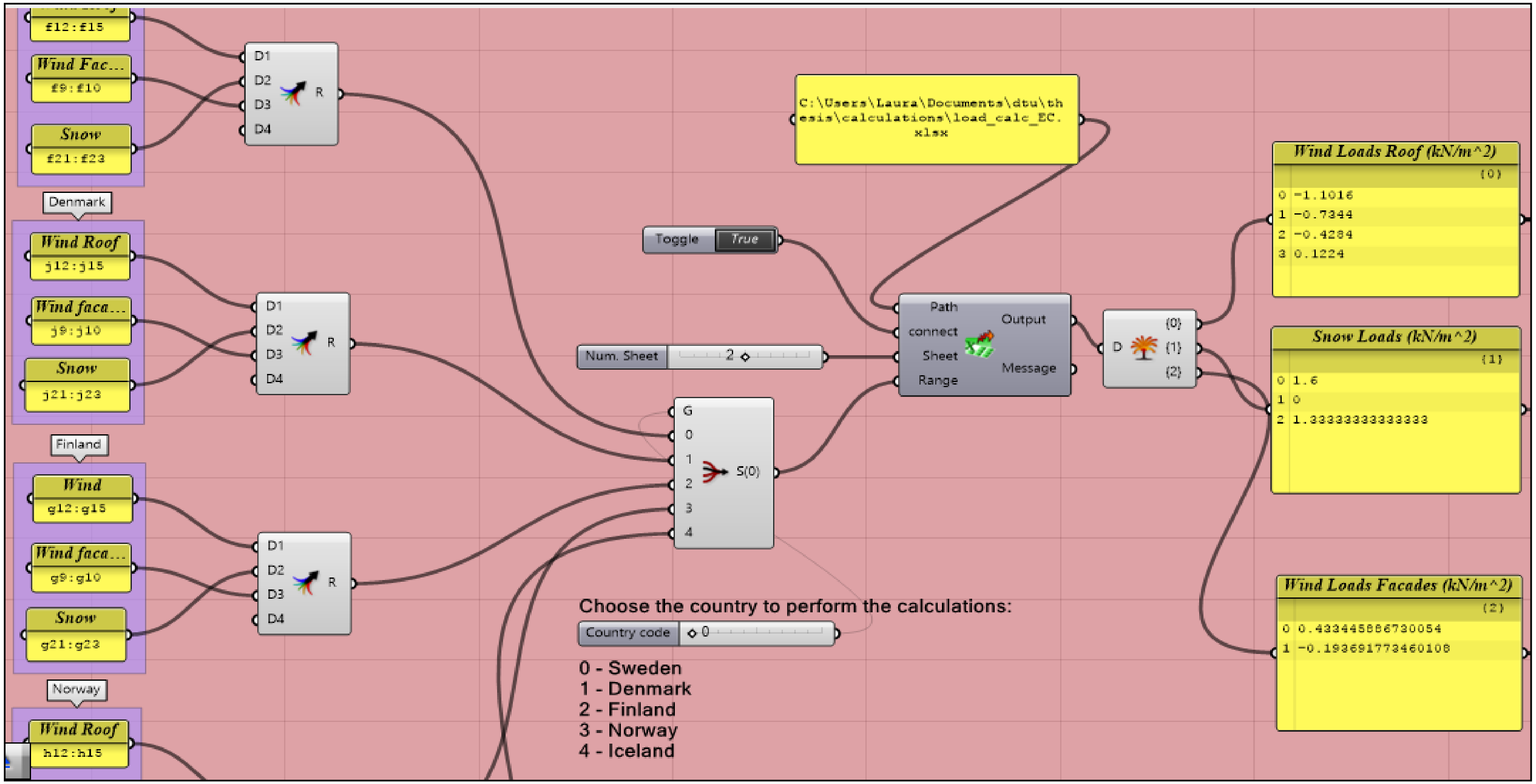
- Model A
- Model B – 1
- Model B – 2
- Model B – 3



MODEL A – overview of the script



MODEL A – Read from excel : Loads definition



```
C:\Users\Laura\Documents\dtu\thesis\calculations\load_calc_EC.xlsx
```

```
Wind Loads Roof (kN/m^2)
{0}
0 -1.1016
1 -0.7344
2 -0.4284
3 0.1224
```

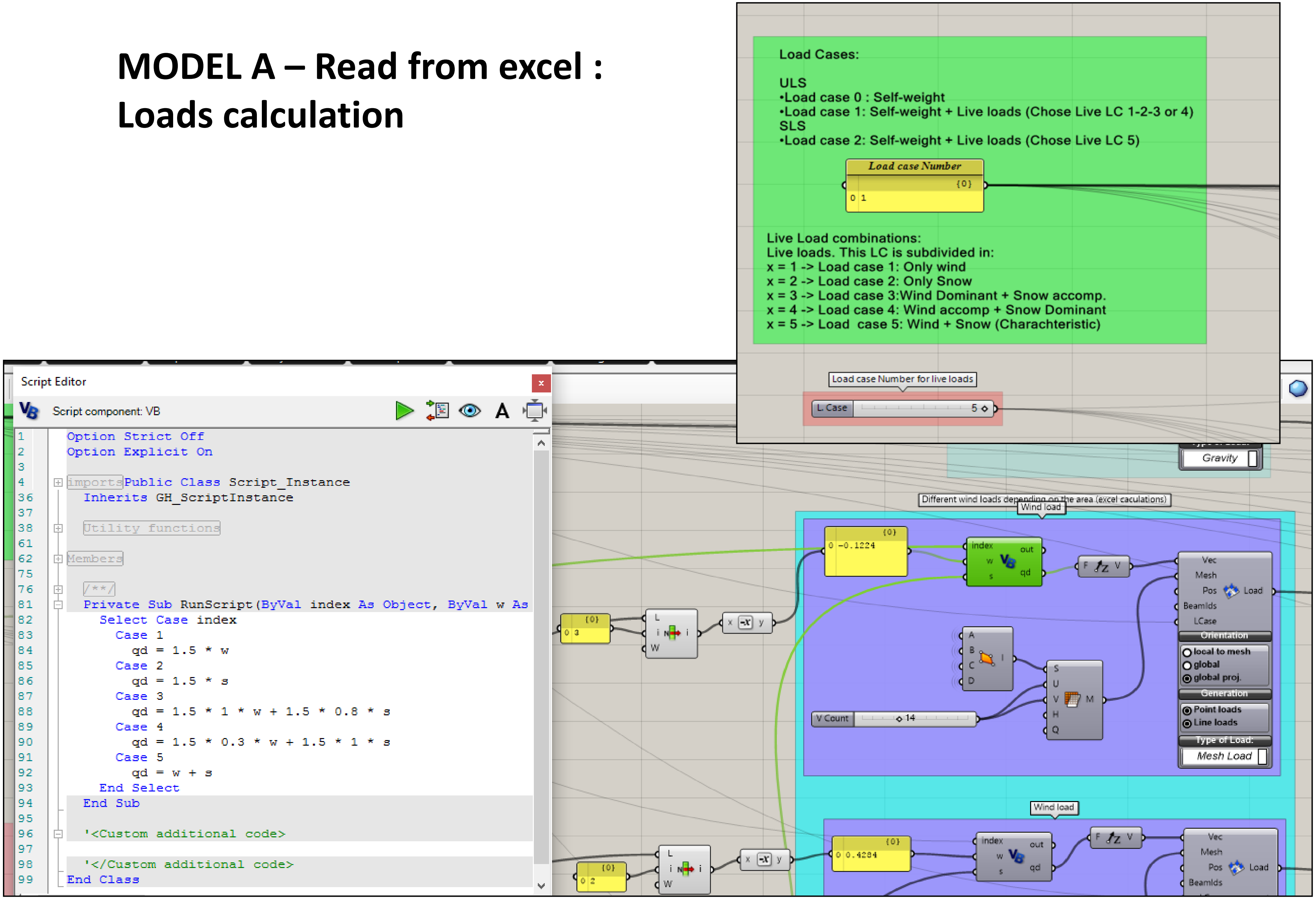
```
Snow Loads (kN/m^2)
{1}
0 1.6
1 0
2 1.33333333333333
```

```
Wind Loads Facades (kN/m^2)
{2}
0 0.433445886730054
1 -0.193691773460108
```

Choose the country to perform the calculations:

0 - Sweden
1 - Denmark
2 - Finland
3 - Norway
4 - Iceland

MODEL A – Read from excel : Loads calculation



Load Cases:

ULS
- Load case 0 : Self-weight
- Load case 1: Self-weight + Live loads (Chose Live LC 1-2-3 or 4)

SLS
- Load case 2: Self-weight + Live loads (Chose Live LC 5)

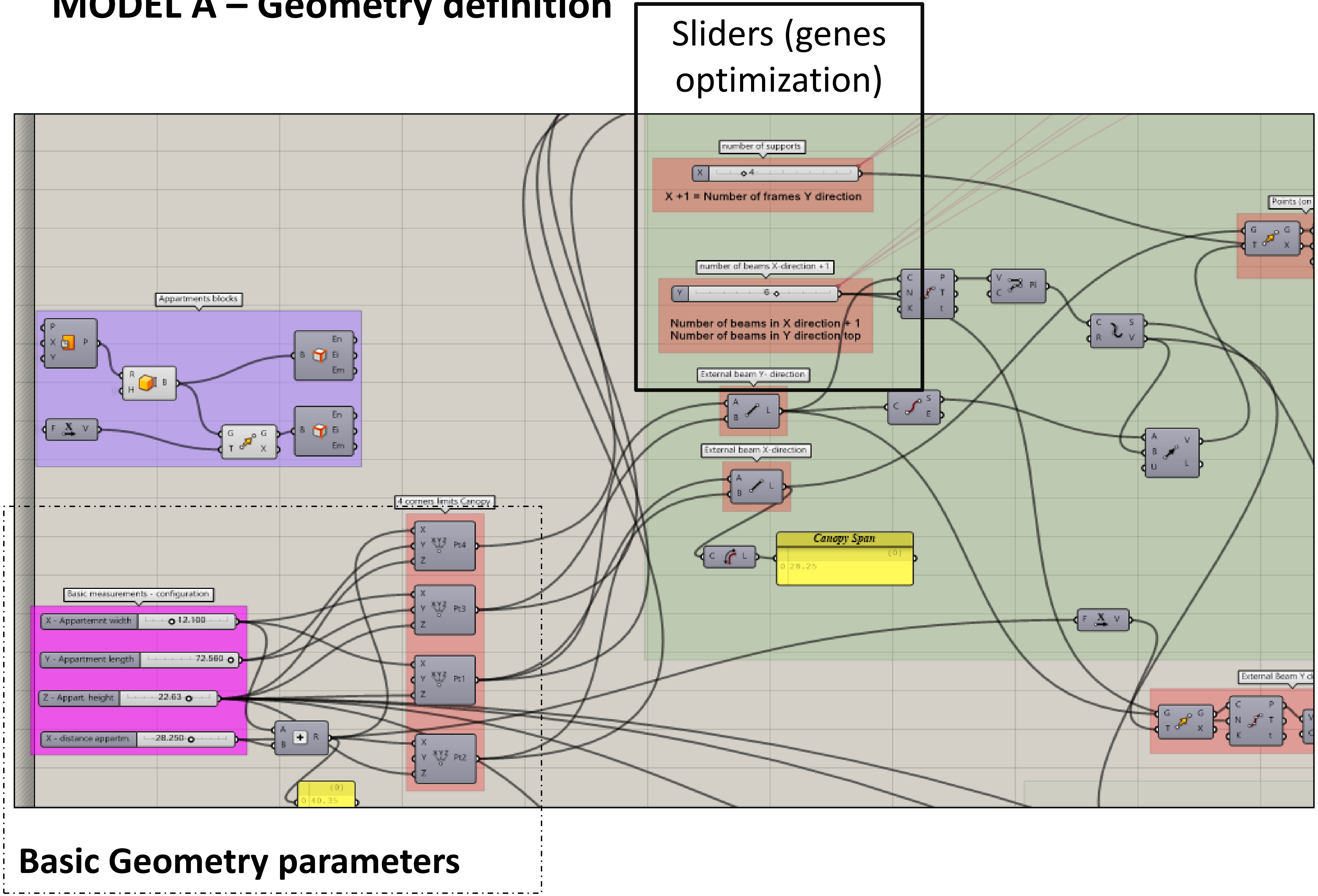
Live Load combinations:
Live loads. This LC is subdivided in:
x = 1 -> Load case 1: Only wind
x = 2 -> Load case 2: Only Snow
x = 3 -> Load case 3:Wind Dominant + Snow accomp.
x = 4 -> Load case 4: Wind accomp + Snow Dominant
x = 5 -> Load case 5: Wind + Snow (Charachteristic)

Script Editor

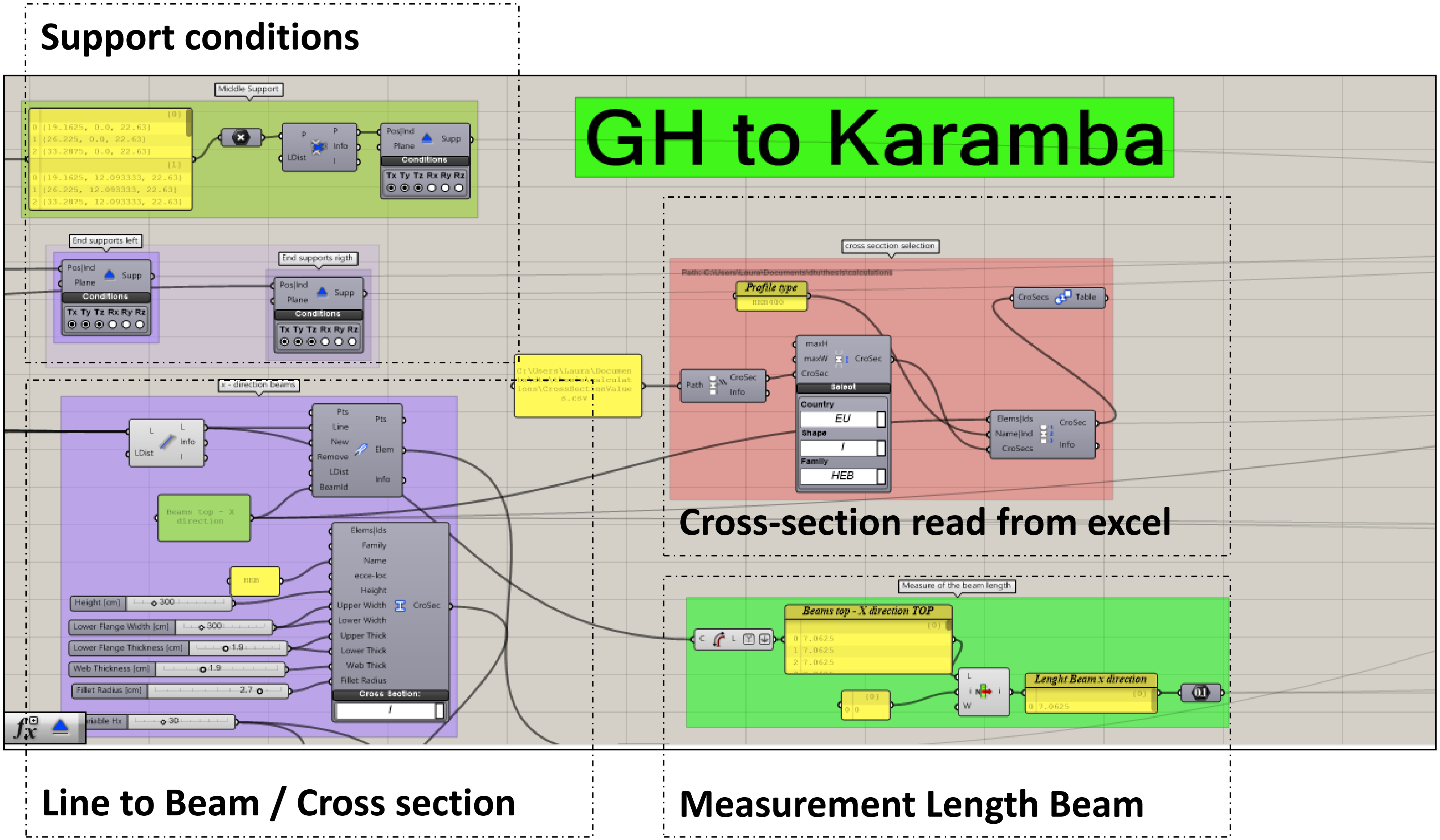
Script component: VB

```
Option Strict Off
Option Explicit On

importsPublic Class Script_Instance
  Inherits GH_ScriptInstance

  Utility functions

Members

  /**/
  Private Sub RunScript(ByVal index As Object, ByVal w As
    Select Case index
      Case 1
        qd = 1.5 * w
      Case 2
        qd = 1.5 * s
      Case 3
        qd = 1.5 * 1 * w + 1.5 * 0.8 * s
      Case 4
        qd = 1.5 * 0.3 * w + 1.5 * 1 * s
      Case 5
        qd = w + s
    End Select
  End Sub

  '<Custom additional code>

  '</Custom additional code>
End Class
```

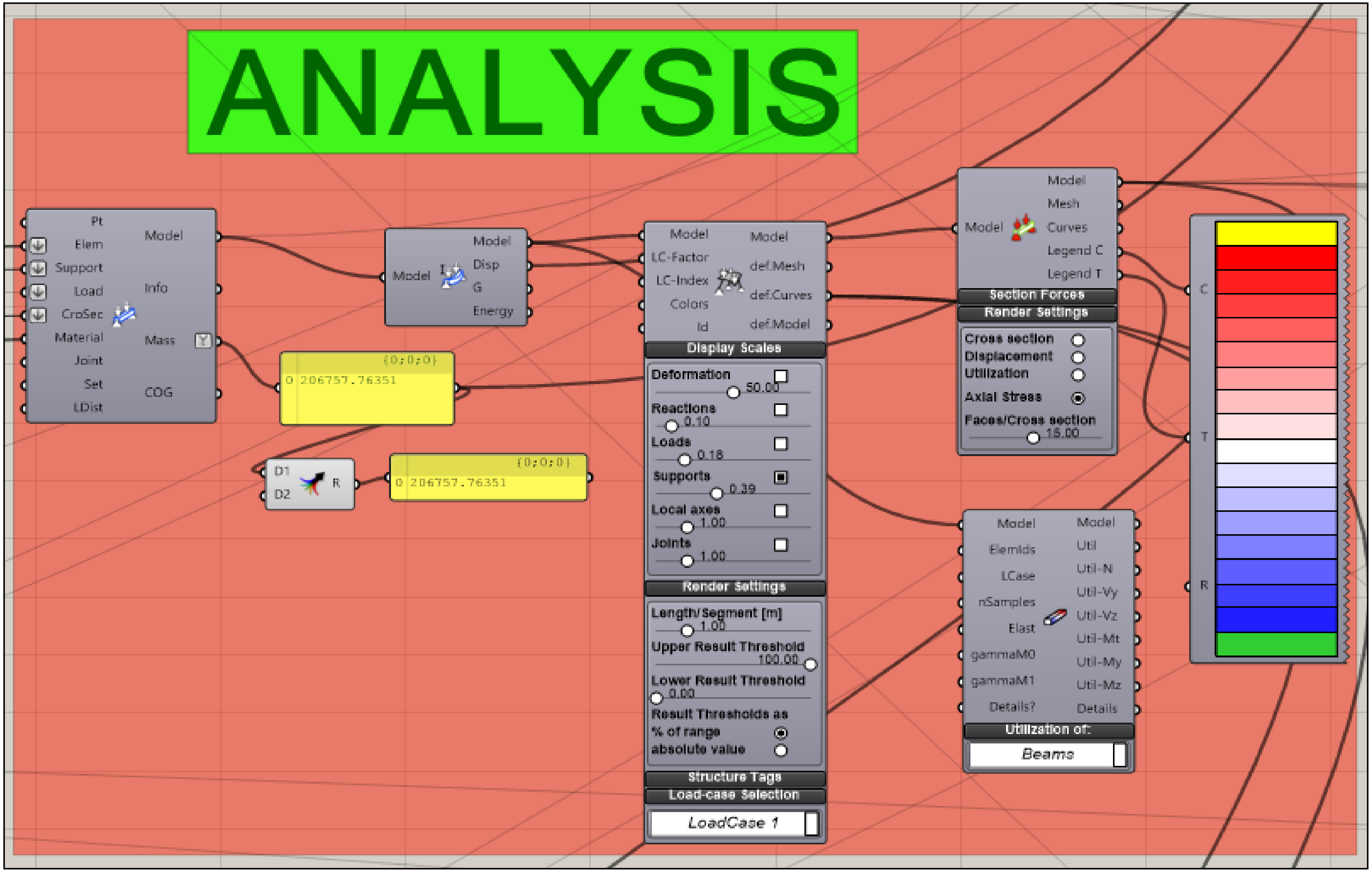
MODEL A – Geometry definition



MODEL A – Grasshopper to Karamba



MODEL A – Analysis



Deformation ☐ 50.00
Reactions ☐ 0.10
Loads ☐ 0.18
Supports ☒ 0.39
Local axes ☐ 1.00
Joints ☐ 1.00

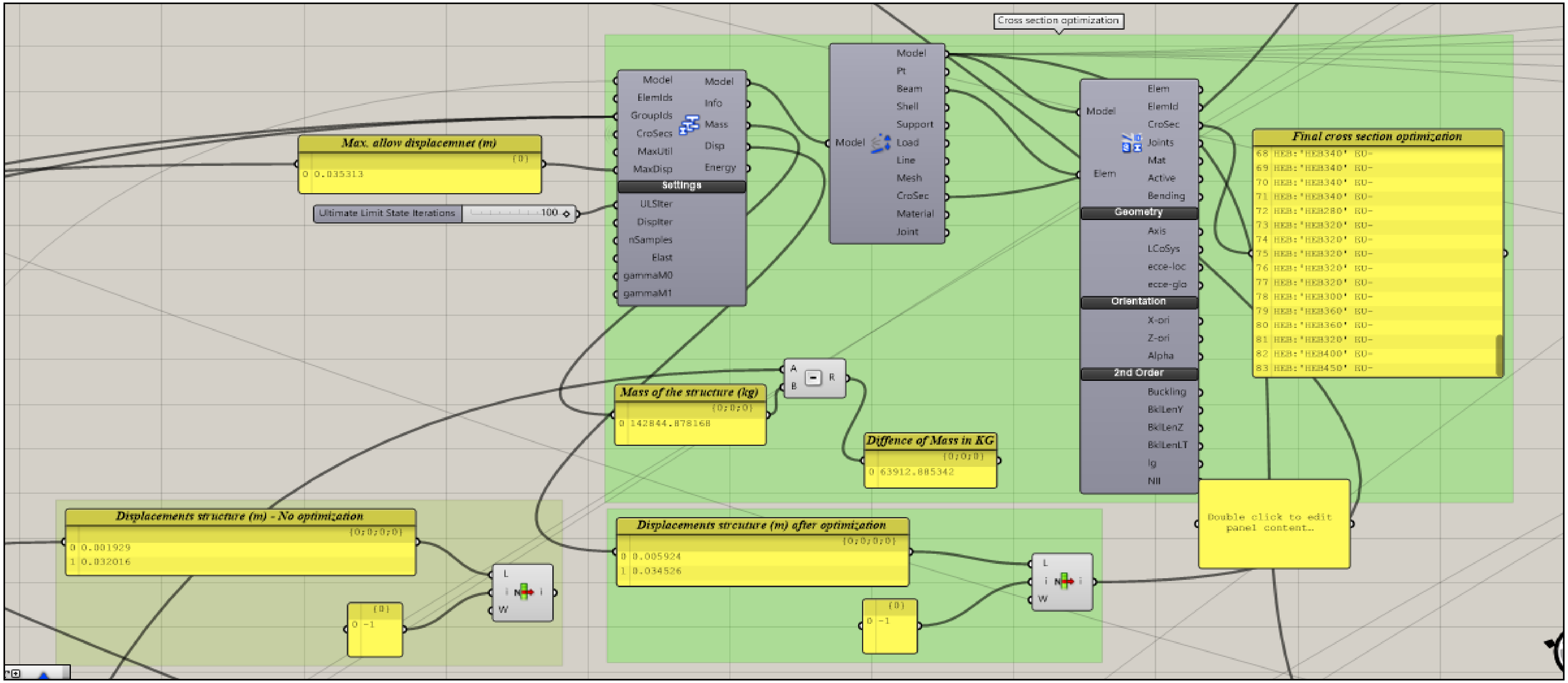
Length/Segment [m] 1.00
Upper Result Threshold 100.00
Lower Result Threshold 0.00
Result Thresholds as
% of range ●
absolute value ○

LoadCase 1

Cross section ○
Displacement ○
Utilization ○
Axial Stress ●
Faces/Cross section 15.00

Beams

MODEL A – Cross Section optimization



Max. allow displacemnet (m)

```
{0}
0 0.035313
```

Mass of the structure (kg)

```
{0;0;0}
0 142844.878168
```

Diffence of Mass in KG

```
{0;0;0}
0 63912.885342
```

Final cross section optimization

```
68 HEB:'HEB340' EU-
69 HEB:'HEB340' EU-
70 HEB:'HEB340' EU-
71 HEB:'HEB340' EU-
72 HEB:'HEB280' EU-
73 HEB:'HEB320' EU-
74 HEB:'HEB320' EU-
75 HEB:'HEB320' EU-
76 HEB:'HEB320' EU-
77 HEB:'HEB320' EU-
78 HEB:'HEB300' EU-
79 HEB:'HEB360' EU-
80 HEB:'HEB360' EU-
81 HEB:'HEB320' EU-
82 HEB:'HEB400' EU-
83 HEB:'HEB450' EU-
```

Displacements structure (m) - No optimization

```
{0;0;0;0}
0 0.001929
1 0.032016
```

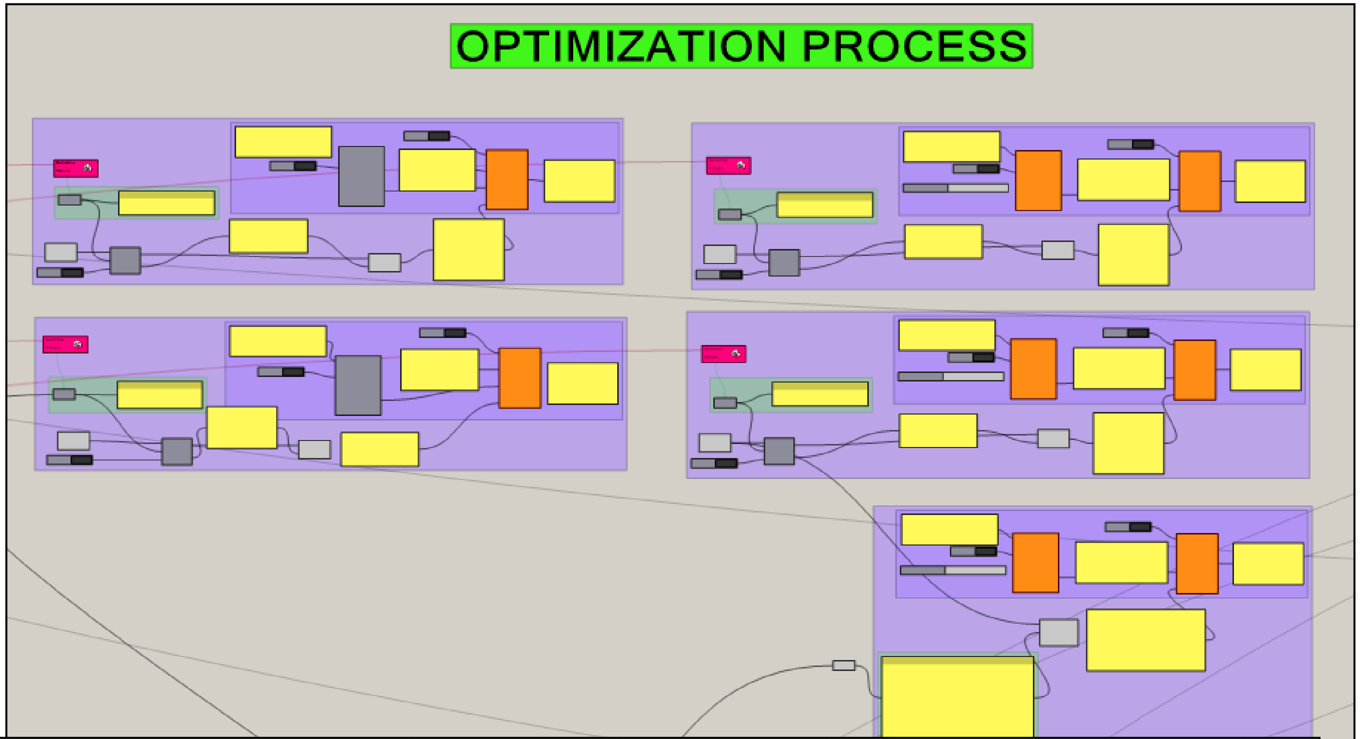
```
{0}
0 -1
```

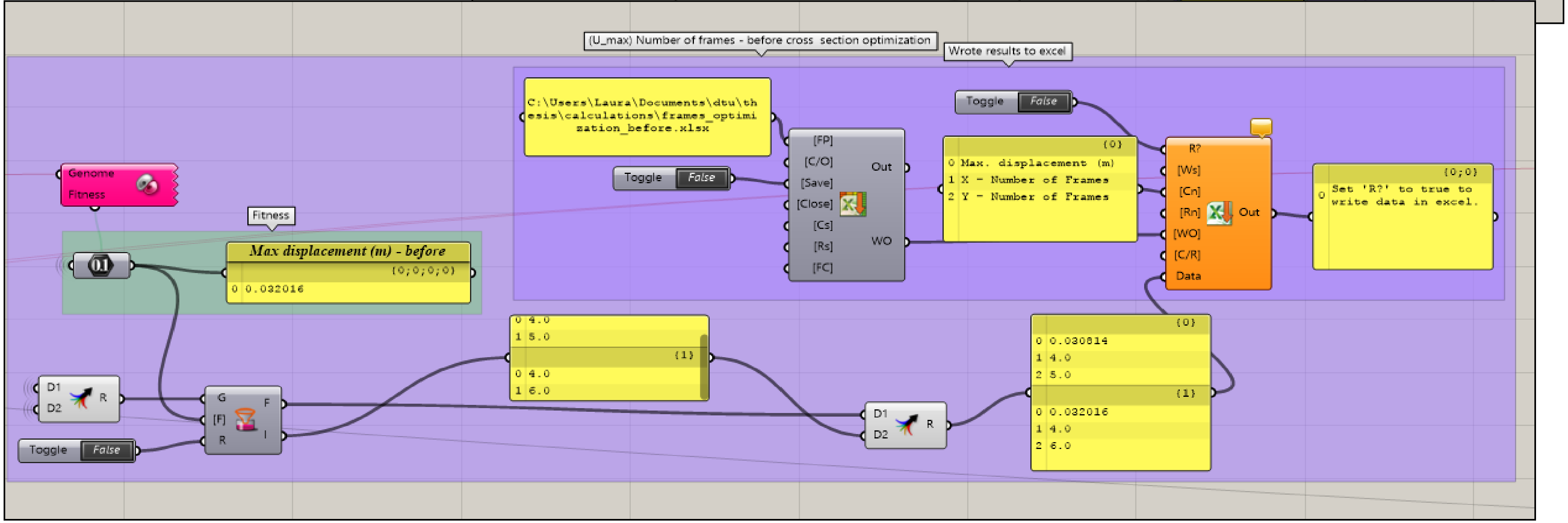
Displacements strcuture (m) after optimization

```
{0;0;0;0}
0 0.005924
1 0.034526
```

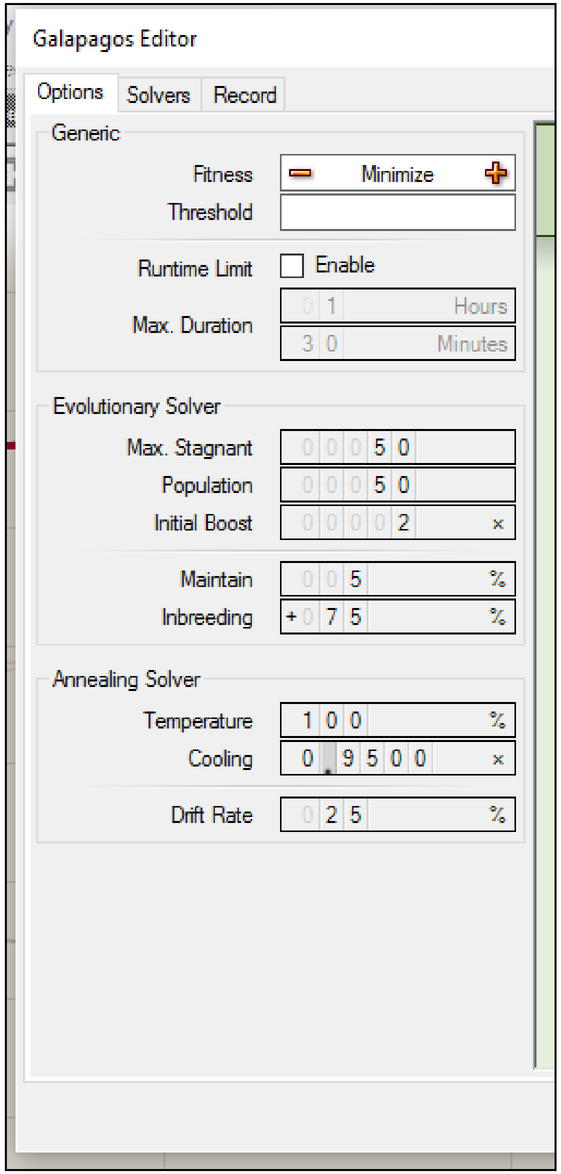
```
{0}
0 -1
```

MODEL A – Optimization process





MODEL A – Optimization process input Galapagos



Galapagos Editor

Options | Solvers | Record

Generic

Fitness: Minimize

Threshold:

Runtime Limit: ☐ Enable

Max. Duration: 0 1 Hours; 3 0 Minutes

Evolutionary Solver

Max. Stagnant: 0 0 0 5 0

Population: 0 0 0 5 0

Initial Boost: 0 0 0 0 2 ×

Maintain: 0 0 5 %

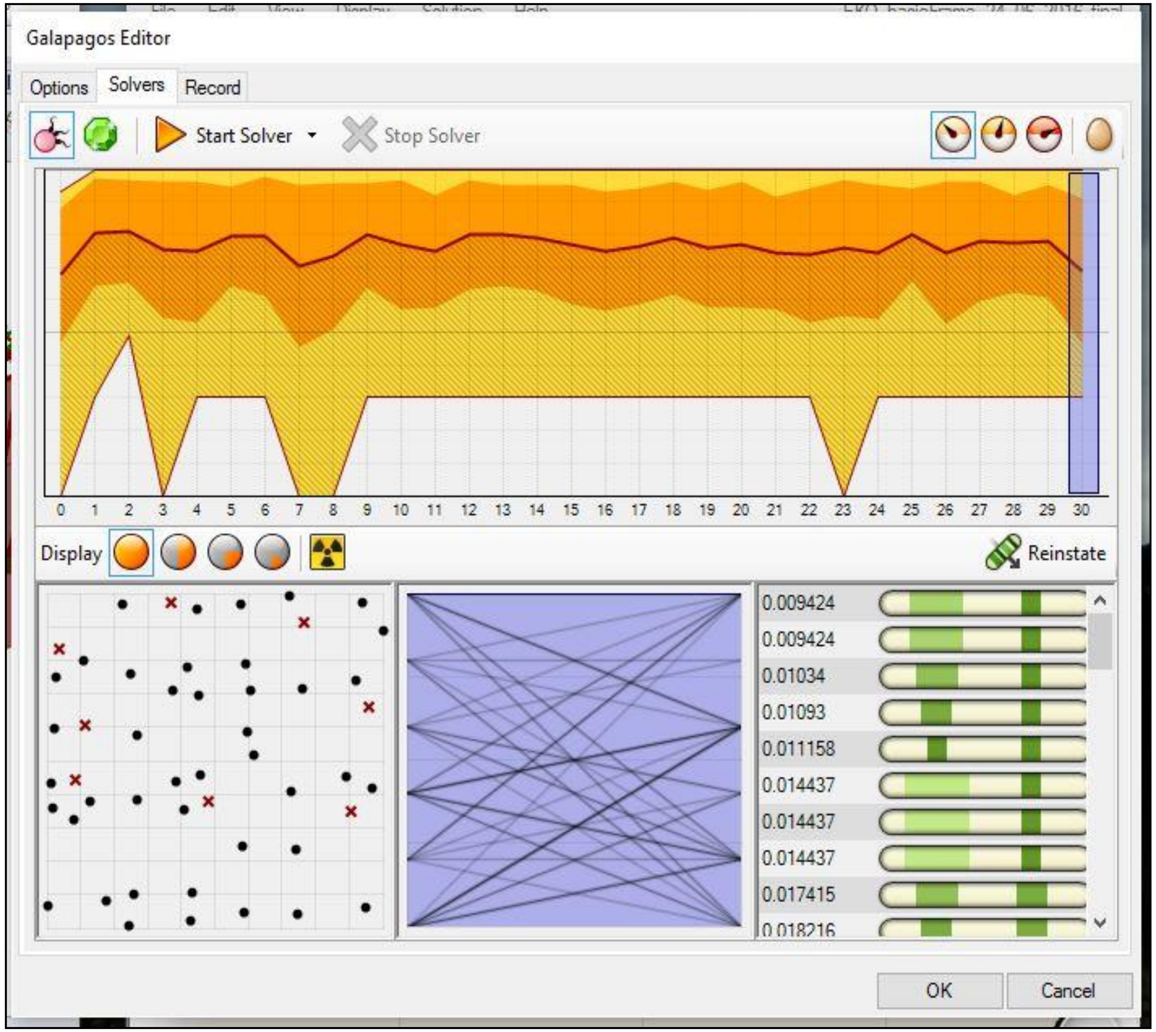
Inbreeding: + 0 7 5 %

Annealing Solver

Temperature: 1 0 0 %

Cooling: 0 . 9 5 0 0 ×

Drift Rate: 0 2 5 %

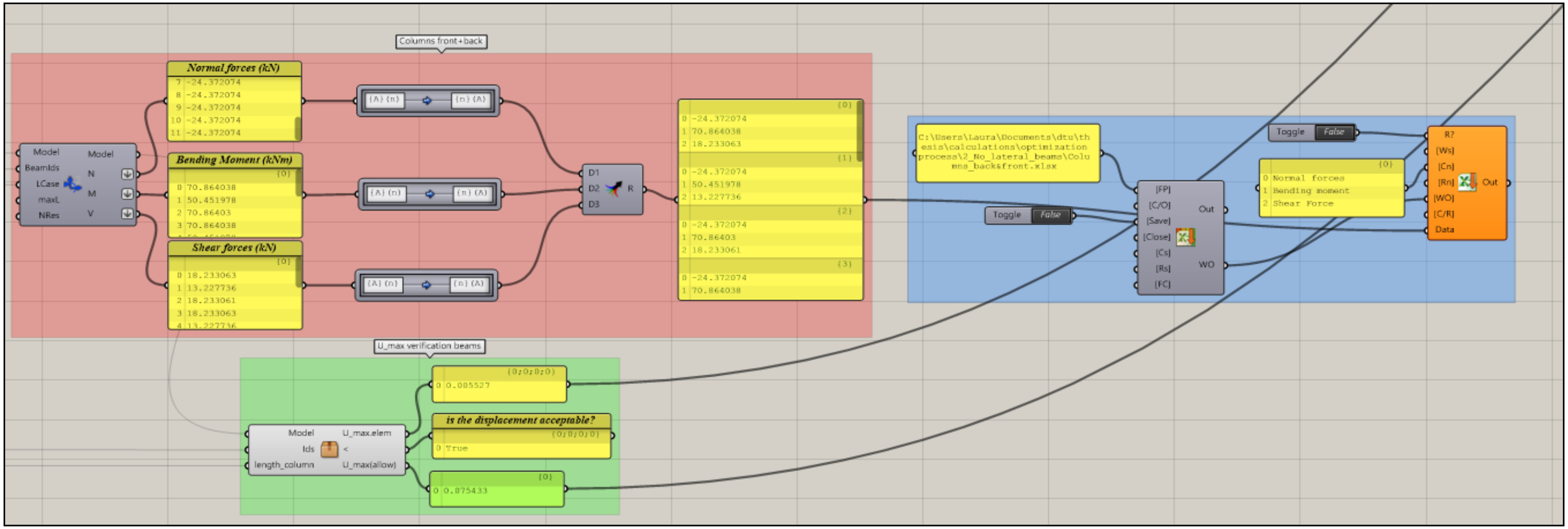


Galapagos Editor

Options | Solvers | Record

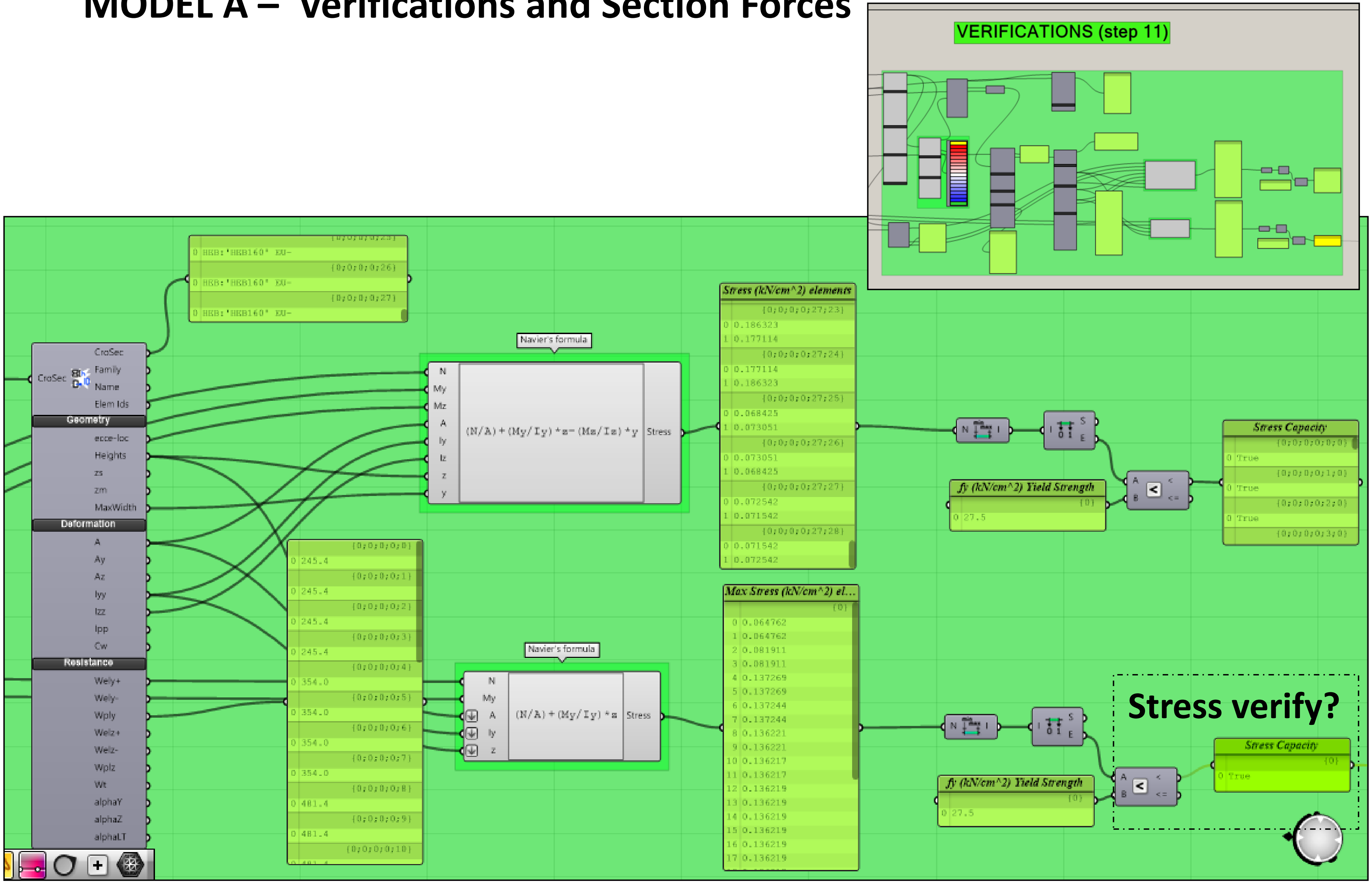
0.009424
0.009424
0.01034
0.01093
0.011158
0.014437
0.014437
0.014437
0.017415
0.018216

MODEL A – Verifications and Section Forces

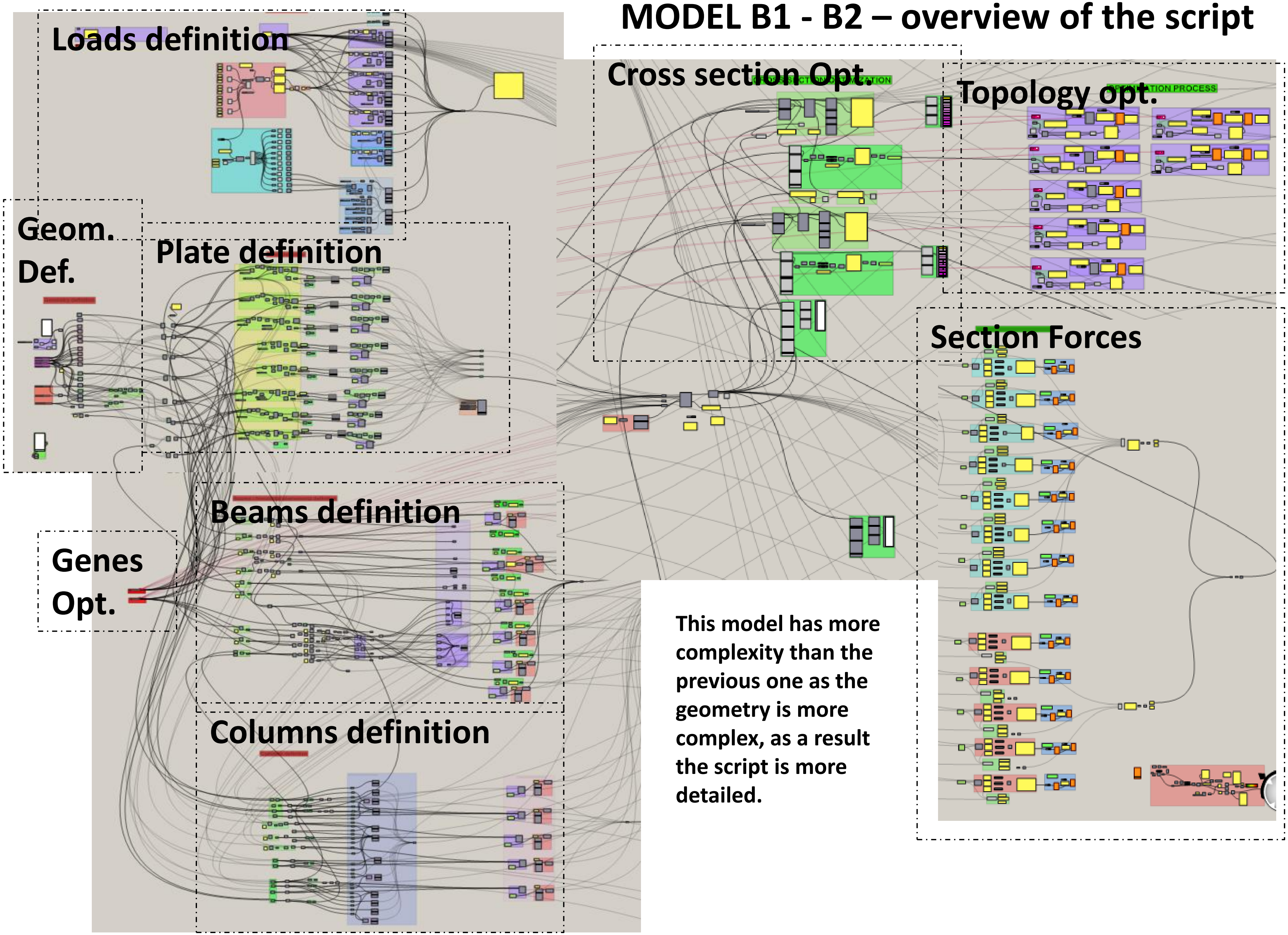


From each group of elements (Beams top X, Beams top Y, Columns Lateral and Columns Front & Back) are taken the maximum section forces : Maximum Bending Moment, Maximum Shear Force and Maximum Axial force, to carry out the corresponding verification according to Eurocode. → Export to Excel (Step 11)

MODEL A – Verifications and Section Forces



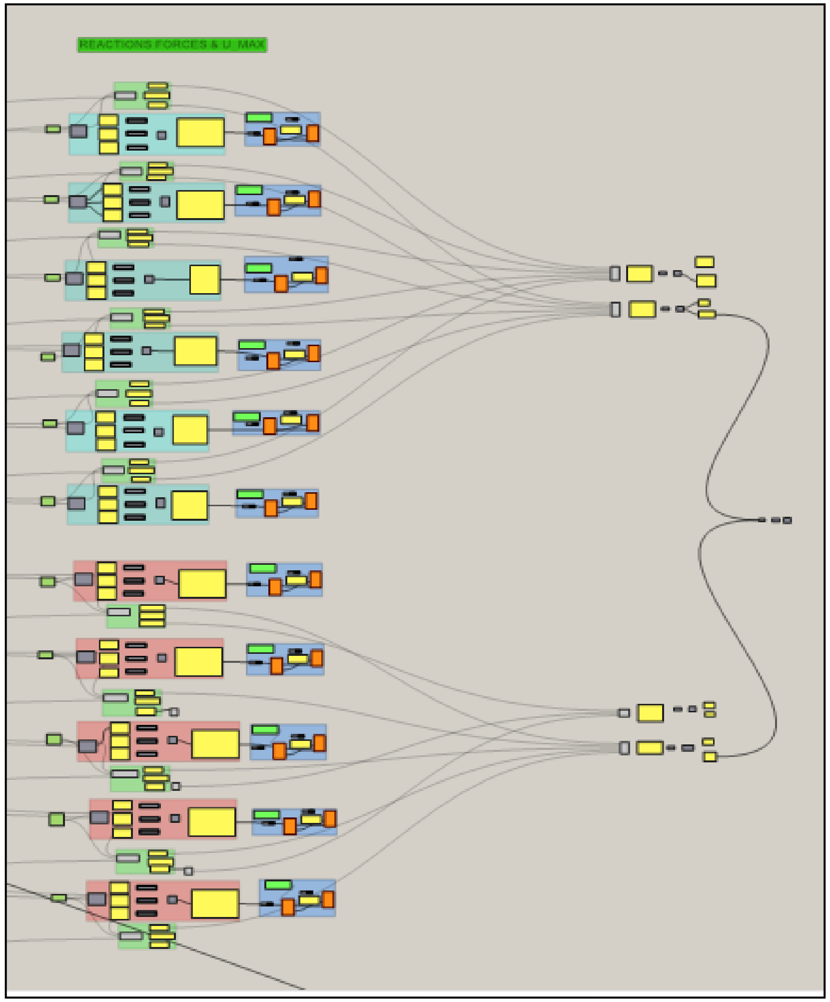
MODEL B1 - B2 – overview of the script



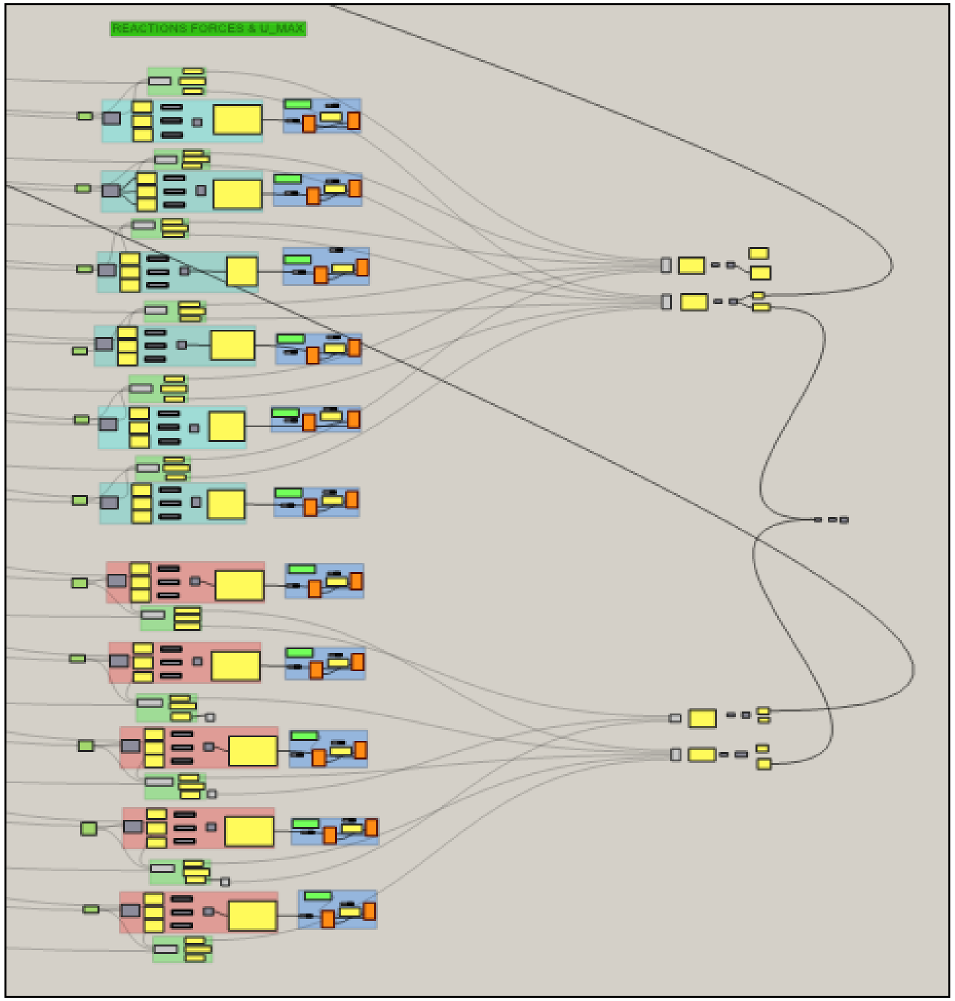
This model has more complexity than the previous one as the geometry is more complex, as a result the script is more detailed.

MODEL B2 – Section forces

The verifications have been divided in the different elements for the optimization step 7 and optimization step 9



Maximum section forces – Step 7



Maximum section forces – Step 9

MODEL B3 – overview of the script

Increase of complexity in the design means increase of complexity in the script, as every element should be perfectly defined for the post structural analysis .