The Average Best Solution

A Generative Design Tool for Multi-Objective Optimization of Free-Form Diagrid Structures

by

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AUTHOR’S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

This research describes the generative modeling method implemented in an open-source program (Grasshopper) as a computational tool for performance evaluation and multi-objective optimization. It explores the initial steps of the design process to find the most fit design, based on goals defined by the designers, from among all possible solutions. In this context, this thesis uses the computational tool to propose a form-finding model for maximizing structural efficiency and constructability of diagrid structures with complex geometries.

In architecture and related disciplines, such as structural engineering, the complexity of the both project and the defined goal, that is caused by several design variables and the myriad of relationships between them, play crucial roles in the design process. For the successful handling of such complicated design processes, the consideration of specific goals, requirements, and overall design quality is central. Therefore, this thesis addresses the need for identification and application of computational methods to effectively handle several issues in this design process: the complexity of parametric modeling of diagrid structures, of those computational modeling issues related to analyzing, evaluating, scoring the performance objectives, and of making the decisions needed for the process of multi-objective optimization. To achieve such a goal, this thesis proposes a generative algorithm that includes a parametric model, computational model and a feedback loop. This kind of form-finding method deployed in the generative algorithm draws from existing research on multi-objective optimization. Most importantly, established articles from the Arup team make up the core concepts used in the algorithm-design process.

This thesis uses the generative algorithm as an integrally researched computational tool in its formal and operational research. As such, it proposes a conceptual design for a steel diagrid structure with fixed joints of the New National Gallery in Budapest. Such a form-finding method is based not only on structural efficiency, but also on constructability and architectural goals. In the decision-making process, the complicated relationships between considered objectives make it impossible to find the absolute best design solution that has the best performances in all of them. Instead of finding just one result, the generative algorithm eliminates a number of possible solutions based on their performances. The final decision "average best solution," which scores high in all objectives but that does not score the highest in all of them, needs to be made by the designer from the limited number of design solutions.

ACKNOWLEDGEMENTS

I would like to thank my thesis supervisor Philip Beesley for making my Master's such an incredibly rich and inspiring experience. Thank you also to my committee members, Maya Przybylski and Terri Meyer Boake, whose advice and expertise allowed me to explore areas outside my comfort zone.

DEDICATION

For my parents; Mehdi and Zahra.

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http://www.arch.ttu.edu/courses/2013/fall/5334/Students/Zuefeldt/Presentation02/default.htm

In.1

INTRODUCTION

In recent years, the use of steel diagrid structural systems has increased for free-form tall and mid-rise building designs such as the capital gate tower (Figure In.1). In such complicated structures, the form of the building, in addition to the architectural concept, significantly influences the structural efficiency and constructability of the whole project. Small modifications in the form of the schematic design have a huge impact on the performance of the design solution. In this way, all efficient design processes need to consider form as a variable in all steps of the design process to achieve the highest performance solution in the various objectives of a project.

Architects and engineers have used form-finding methods based on the optimization of the structural efficiency and material consumption for many years. However, more recently, computer technology has influenced different aspects of the building industry, causing beneficial developments in optimization techniques. Considering several aspects of a project in the design process increases the complexity of the decision-making process because of the huge number of variables and possible solutions in any project, especially those with complex geometries. Dealing with such design processes has been made possible by the shift from traditional experiment-based techniques to a new multi-objective optimization method.

For instance, the Arup team developed an algorithm that computationally encodes construction-related parameters and desired performances according to client, architectural, engineering, fabrication requirements. In this optimization process, the computation tool rapidly generates, evaluates, and mediates among thousands of design variations. The output is a set of optimized design solutions; subsequently, the final design needs to be selected by designers based on the evaluated performances of the solutions [1].

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[1] Chris Luebkeman, K. S. (2005). CDO: Computational design + optimization in building practice. The Arup Journal,

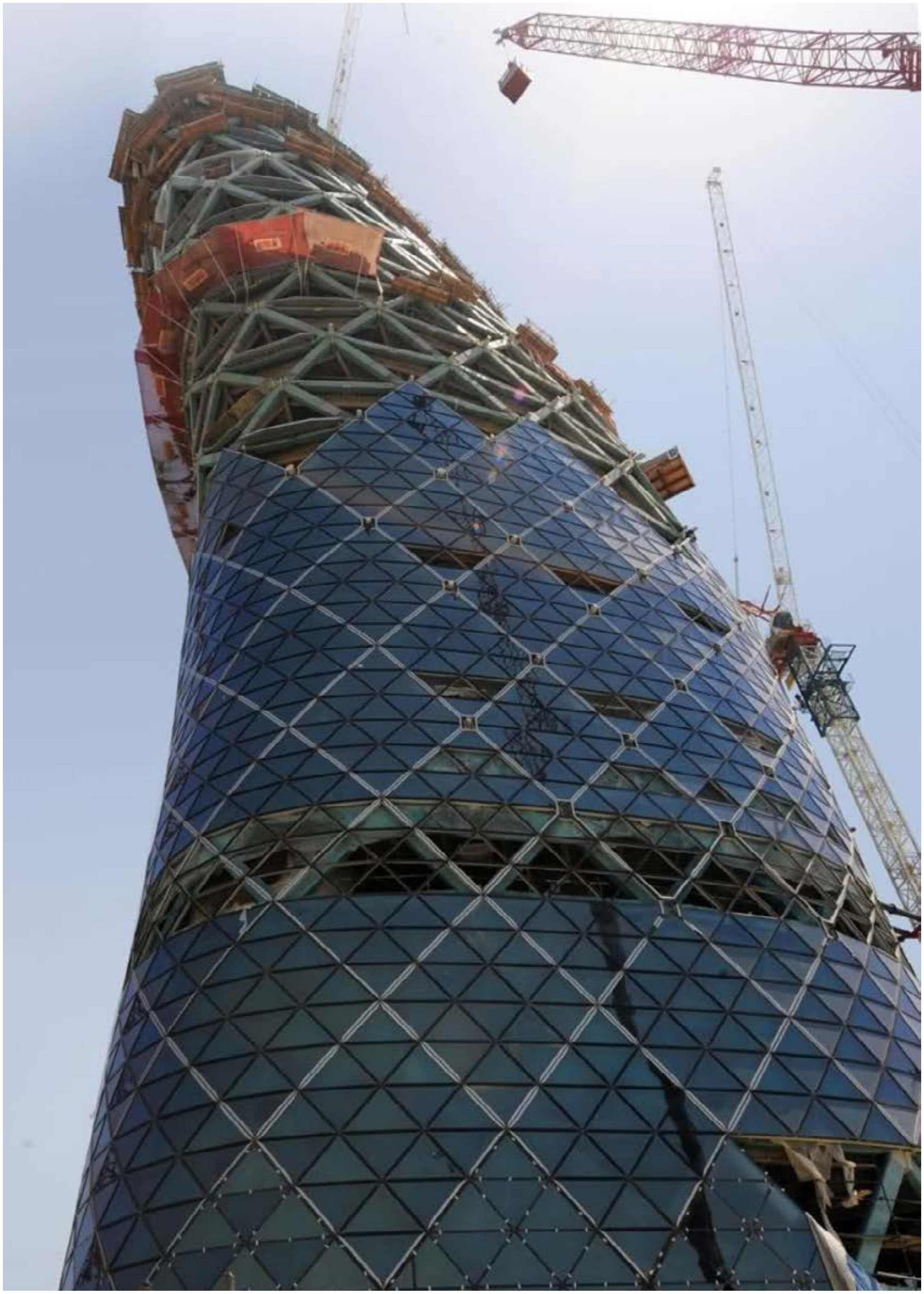

Figure In.1: Capital Gate tower

This thesis proposes a form-finding model to deal with such a complicated process and to find the most desirable form for the diagrid structure of the New National Gallery in Budapest. To achieve its goal, this thesis addresses the need of a generative algorithm to effectively handle two major concerns: the complexity issue of parametric modeling of diagrid structures and the computational modeling issues, which are related to analyzing, evaluating performances, scoring objectives, and making decisions for the process of optimizing performances.

In.2 MAIN RESEARCH QUESTION

- How can a performance driven free-form diagrid structure be developed by a generative modeling system in order to achieve the best quality in structural efficiency and constructability?

In.3 SUB QUESTIONS

- Which computation tools are developed to handle the complexity of the steel design process?
- Is the generative algorithm suitable to model multi-objective optimizations?
- What are effective variables in designing diagrid structures and how can they influence the structural design or construction process?
- Which kind of numerical analysis can be used to evaluate performances of the design proposal in different fields?
- How can objectives be converted, such as constructability to measurable parameters?
- What is the designer’s role in making decisions?
- How can developments in computation tools for analyzing and evaluating performances influence the design process?

DESIGN ASSIGNMENT

In.4

The design project proposed in this thesis is the New National Gallery in the Liget Budapest Project, which is currently one of the biggest museum projects being carried out in Europe. The focus will be the design of a performance-based complex geometry for diagrid structures. Performance of variables will be taken into account and the generative modeling system will be used to reach the highest performing designs.

THESIS ORGANIZATION

In.5

The thesis is structured in six chapters. The first presents the Liget Budapest competition as a design project, with some details about the proposed steel diagrid structure. In this chapter, different kinds of computation tools for designing and evaluating the performance of steel structures are introduced. The second chapter provides relevant background information for understanding the influence of different objectives and optimization methods in form-finding processes. The third chapter introduces the method of implementing multi-objective optimization in a generative algorithm and its computational requirements. The fourth chapter introduces the diagrid structure system, its design variables and related experiences in optimization. This chapter includes the Bishopsgate Tower as a case study that shows the advantages of using a generative algorithm in optimizing diagrid structures. The fifth chapter implements the practical application of the form-finding system in the proposed project to achieve the highest performance design and the final chapter concludes the work and presents potential areas for future research.

In.6

LITERATURE REVIEW

In recent years, the diagrid structural system has become more and more interesting for designing tall buildings, because of its structural efficiency and aesthetic potential, arising from the unique geometric configuration of the system [1]. In this way, several studies and projects by architects and engineers have been made in the field of diagrid structures to examine the parameters that led to the initial design process of diagrid structures. Background knowledge about the influence of these factors assists designers in the process of decision-making to achieve the highest performances.

K. Moon from Yale University, who has several articles about diagrid structures, determines the influence of the grid geometry on the structural efficiency of the whole proposed diagrid structure in his paper "Design and Construction of Steel Diagrid Structures." [2] Moreover, architect Terri Boake [1] has studied and used a wider range of parameters including geometrical and technical factors to determine their role in different objectives. Such a study, from a point of view of an architect, can be really helpful in the design process.

The aim of this thesis is to learn and use a set of these parameters in a form generating system to achieve the most efficient diagrid structure. However, "One of the most difficult aspects of understanding designing has always been that too many divergent acts occur simultaneously, defying simple description." [3] Because of this fact, the generation of form is a complex process that brings up the need of a computation method, a method that generates a broad range of non-

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[1] Terri Meyer Boake. (2014). Diagrid Structures: Systems, Connections, Details. Birkhauser,
[2] Kyoung-Sun Moon, Jerome J. Connor, John E. Fernandez. (2007). Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design. Department of Architecture, University of Illinois at Urbana–Champaign, Illinois, USA,
[3] Habraken, NJ & Gross, MD, 1988, "Concept Design Games", Design Studies, 9(3), pp. 150-158.

standard designs and assists designers in the process of decision-making, such as generative algorithms.

Generative algorithms as a tool for optimizing forms have been used in architecture from the 1950s, but the idea was first proposed by industrial engineers in transportation industry. However, it has not until recently been a practical method because of limitations in hardware and software.

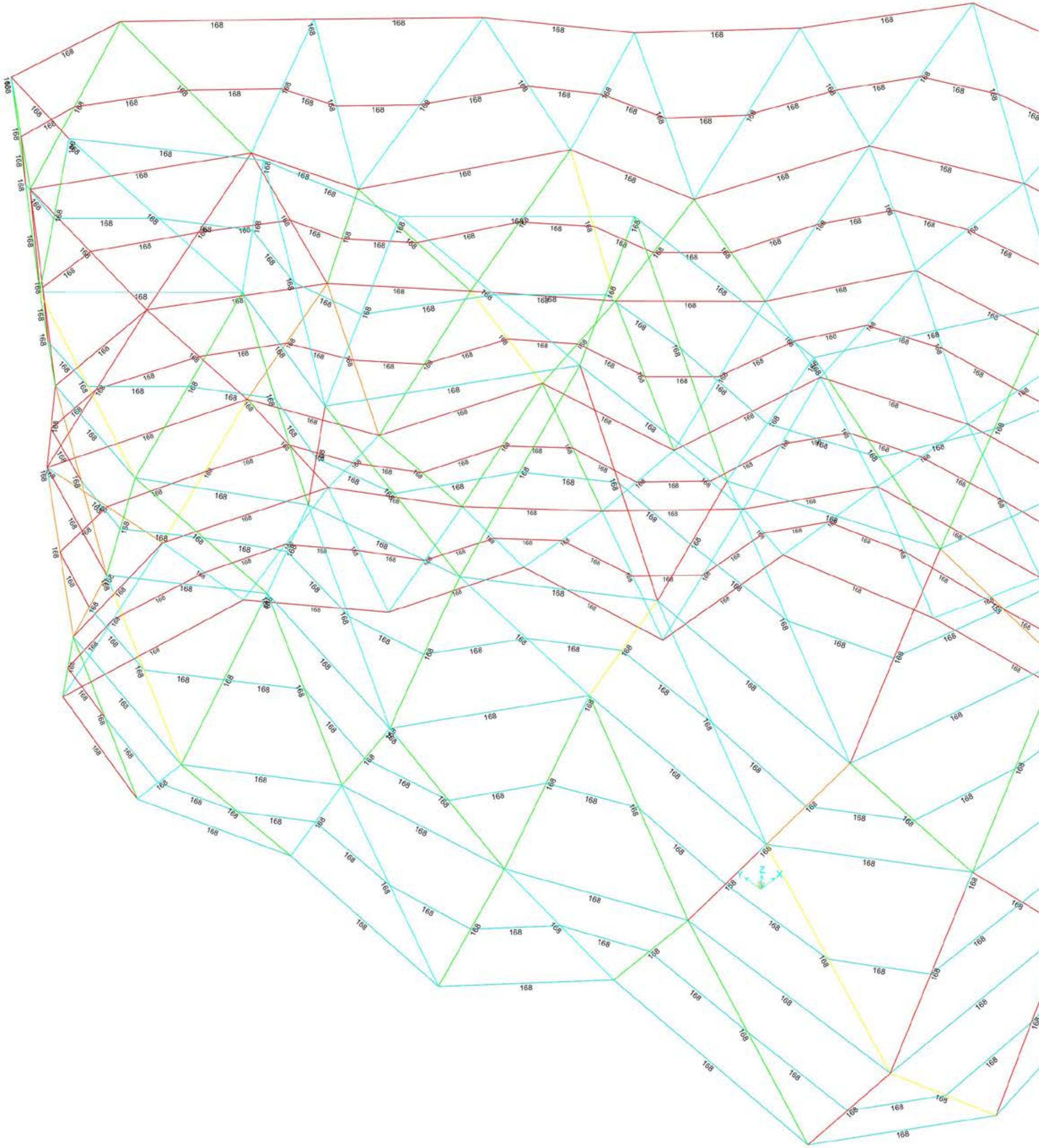
A number of designers such as John Frazer have worked on generative algorithms as tools in the design process. He had experienced the generative idea in several projects and published a book “An Evolutionary Architecture” in 1995 to explain the new role of designers and tools in both design and construction processes [1].

Furthermore, and specifically in the field of diagrid structures, the Arup team developed generative algorithms that computationally encode construction-related parameters and desired performances according to client, architectural, engineering and fabrication requirements.

Inspired by the above-mentioned projects and studies, this thesis proposes a form-finding model to deal with a complicated process and to find the most desirable form for the diagrid structure of the New National Gallery in Budapest.

[2] http://www.johnfrazer.com/research.html

CHAPTER 1
STEEL DESIGN AND COMPUTATION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1.1 DESIGN PROPOSAL

The main goal of this thesis is twofold: handling the complexity of free- form steel diagrid structures and proposing the best fit geometry for the structure of the New National Gallery, as part of the Liget Budapest Project, to offer the highest performances including the structural efficiency and constructability. A new Fine Arts Museum, part of the Liget Budapest Project, was announced as a design competition for the City Park of Budapest. As the most important building in this competition, the New National Gallery includes a public collection that preserves and displays artifacts from European and Hungarian art history, from the beginning of the 19th century up to the present day. The museum presents its works to visitors at a high professional level, with a solid scientific and international context, in a way that allows for an independent analysis of the Hungarian processes.

An initial design is proposed based on the architectural needs of the Gallery and its site, which are explained in Appendix 1. Figure 1.1 illustrates the different steps of the design process and the initial form that is used for further development. In this thesis, the focus will be the design of the highest performing steel diagrid structure for the proposed complex geometry.

Designers are more interested in using typical steel sections such as Rectangular HSS and Round HSS for diagrid structures. Thus, this thesis proposes a diagrid structure, in which the steel Round HSS, with limited variation in cross-section, is used for diagrid elements. In the design of joints, which is the most critical aspect of any diagrid structure, the Hearst Magazine Tower is used as a reference project (Figure 1.5). Moreover, Some modifications are applied to this joint technology to simplify fabrication and erection processes by maximizing shop fabrication. Figure 1.2 to 1.4 illustrates the proposed geometry for joints and the flooring system.

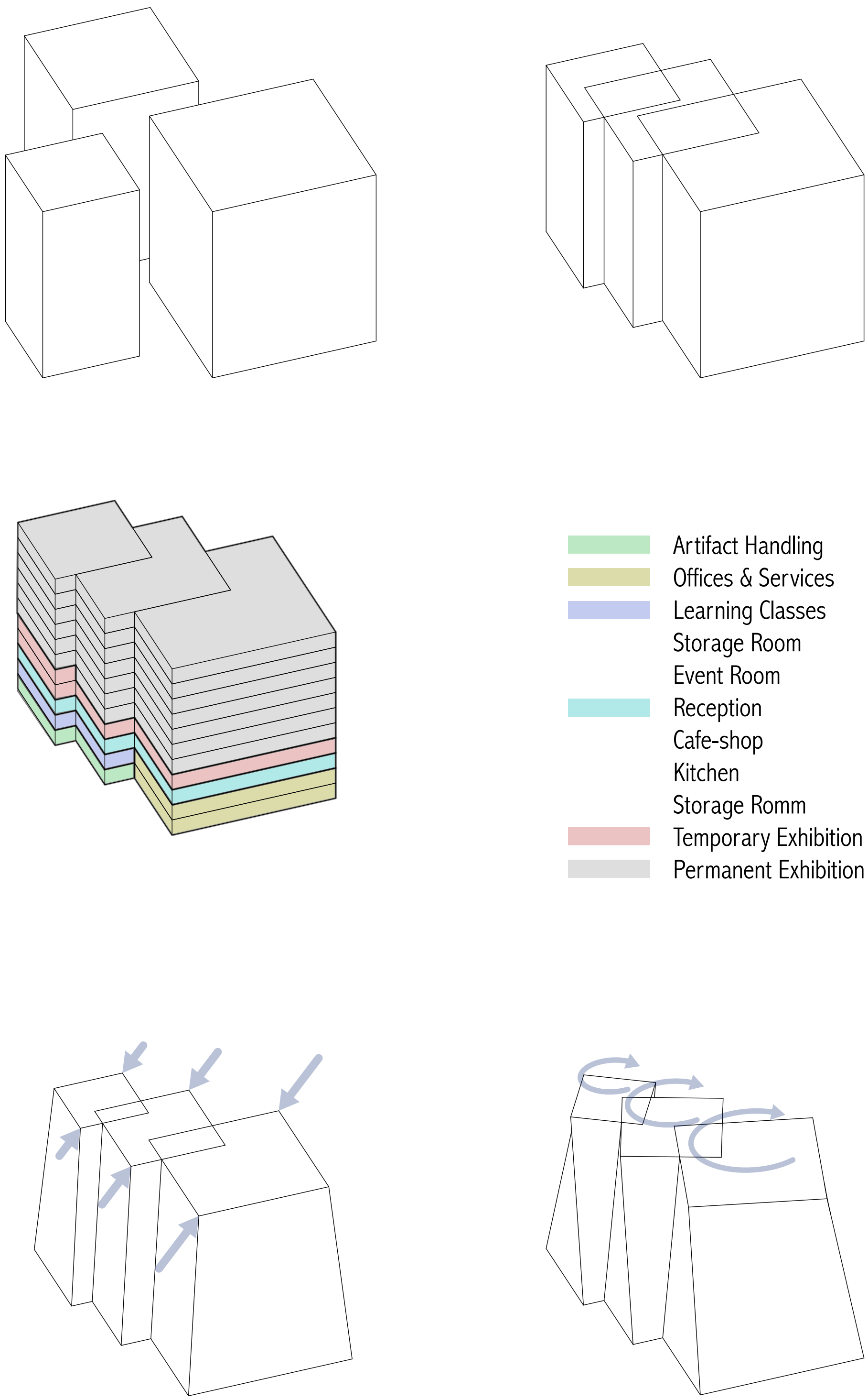
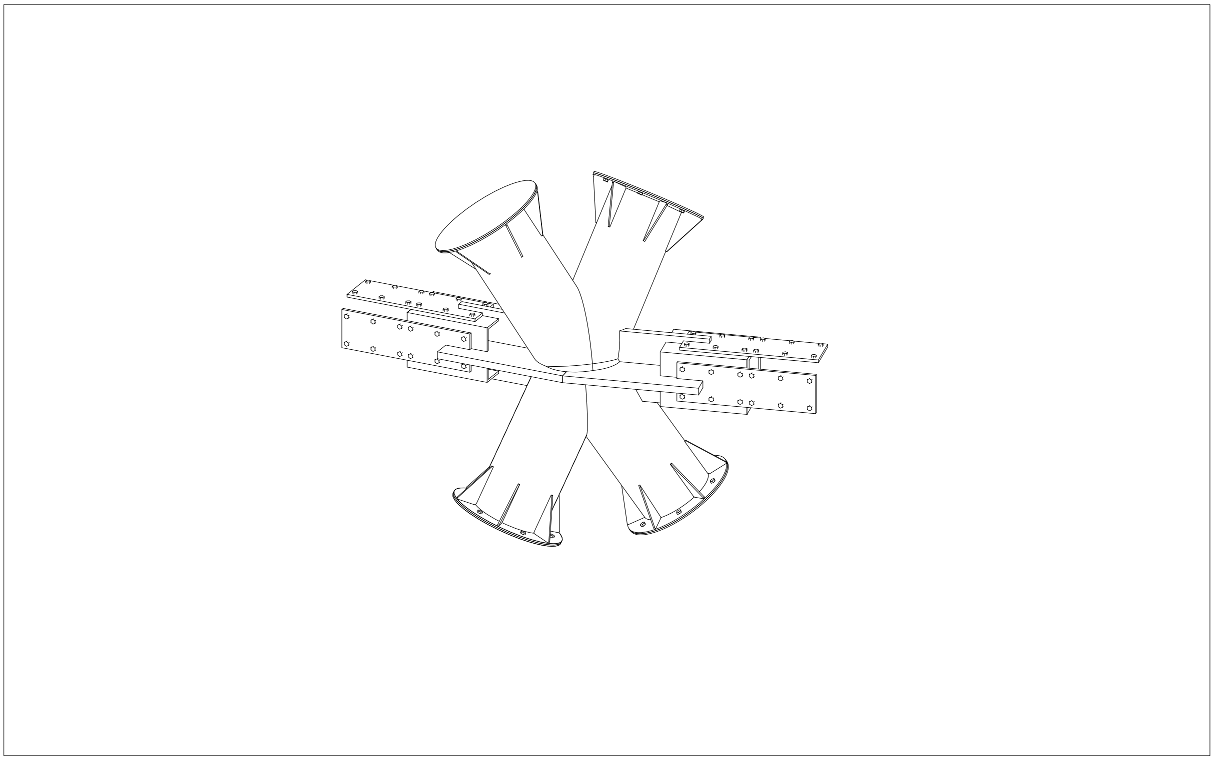


Figure 1.1: Schematic Design



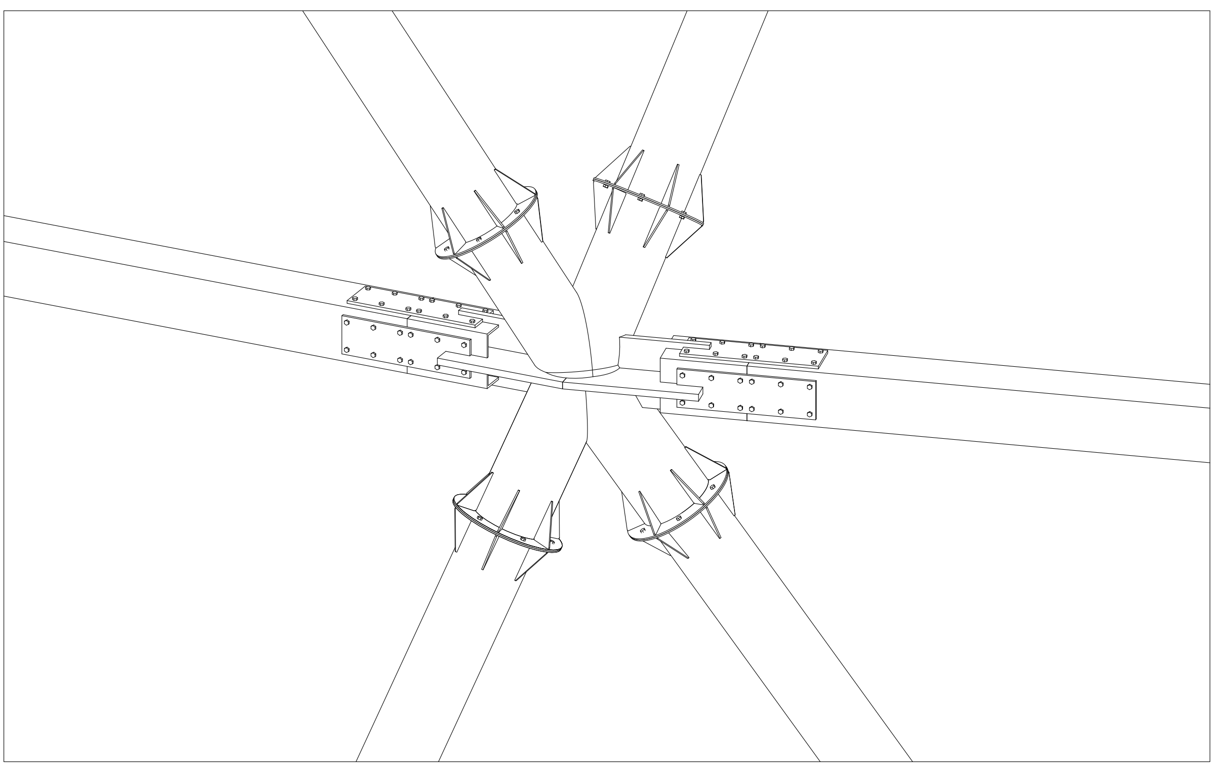
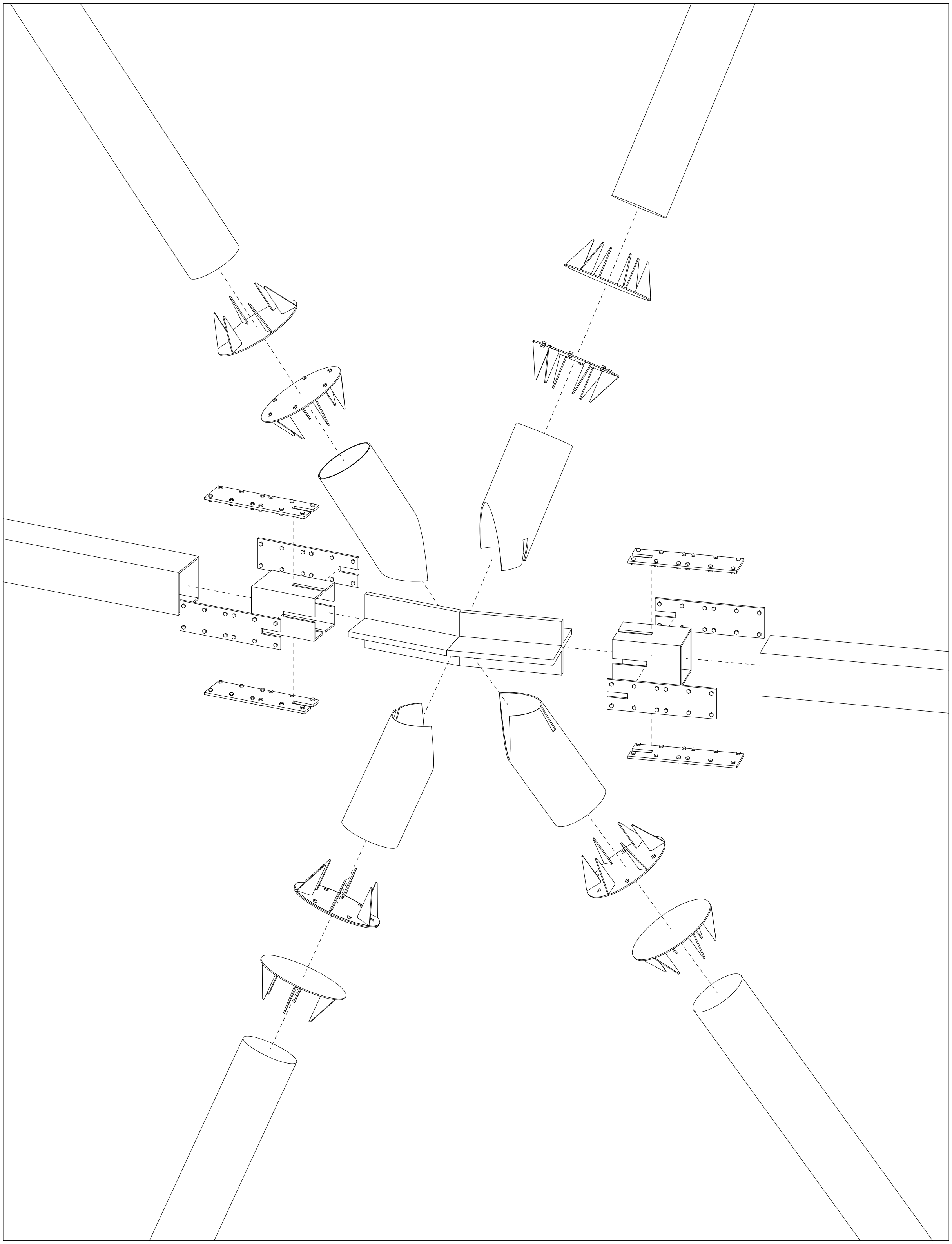


Figure 1.2: Proposed joints
and structural elements.



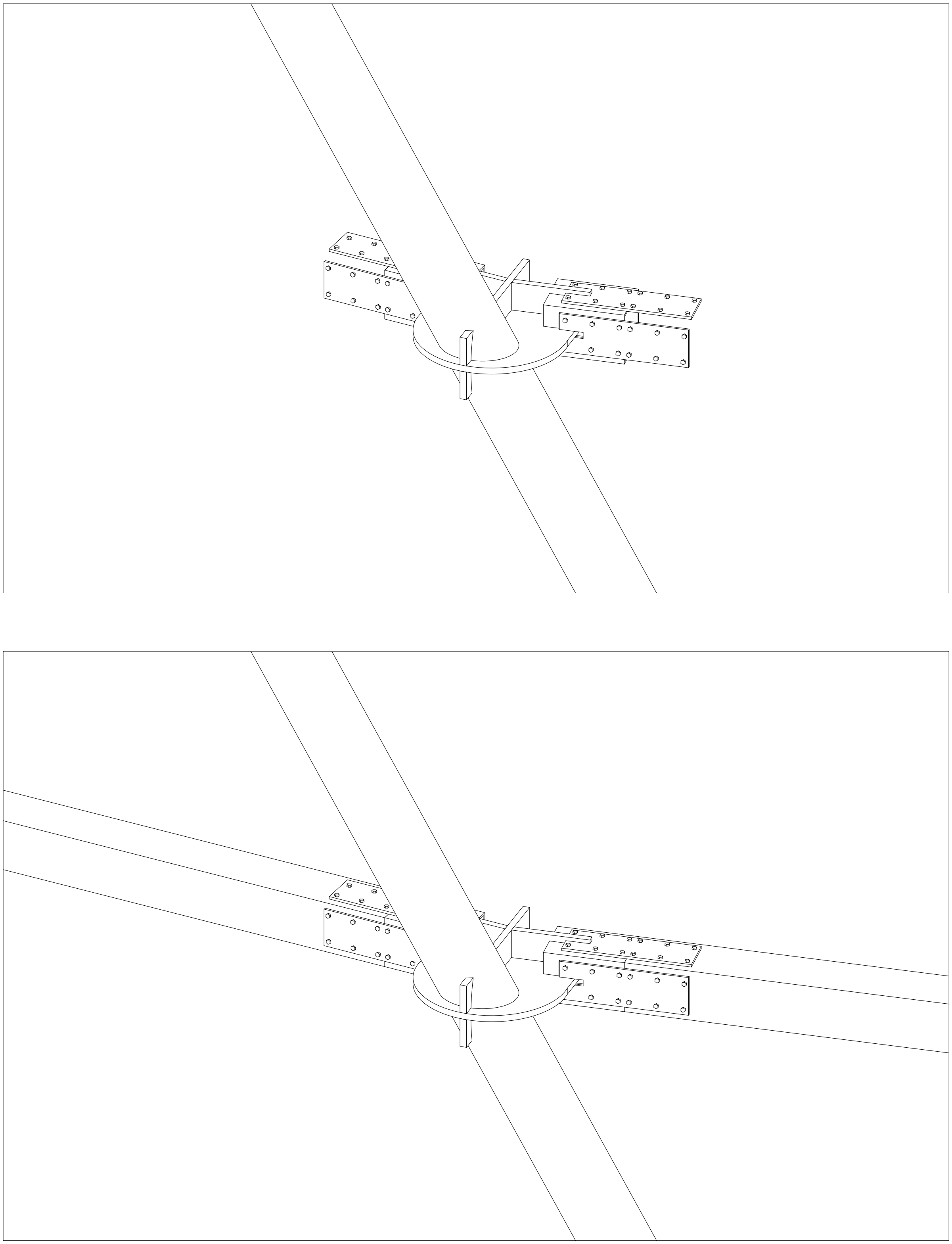
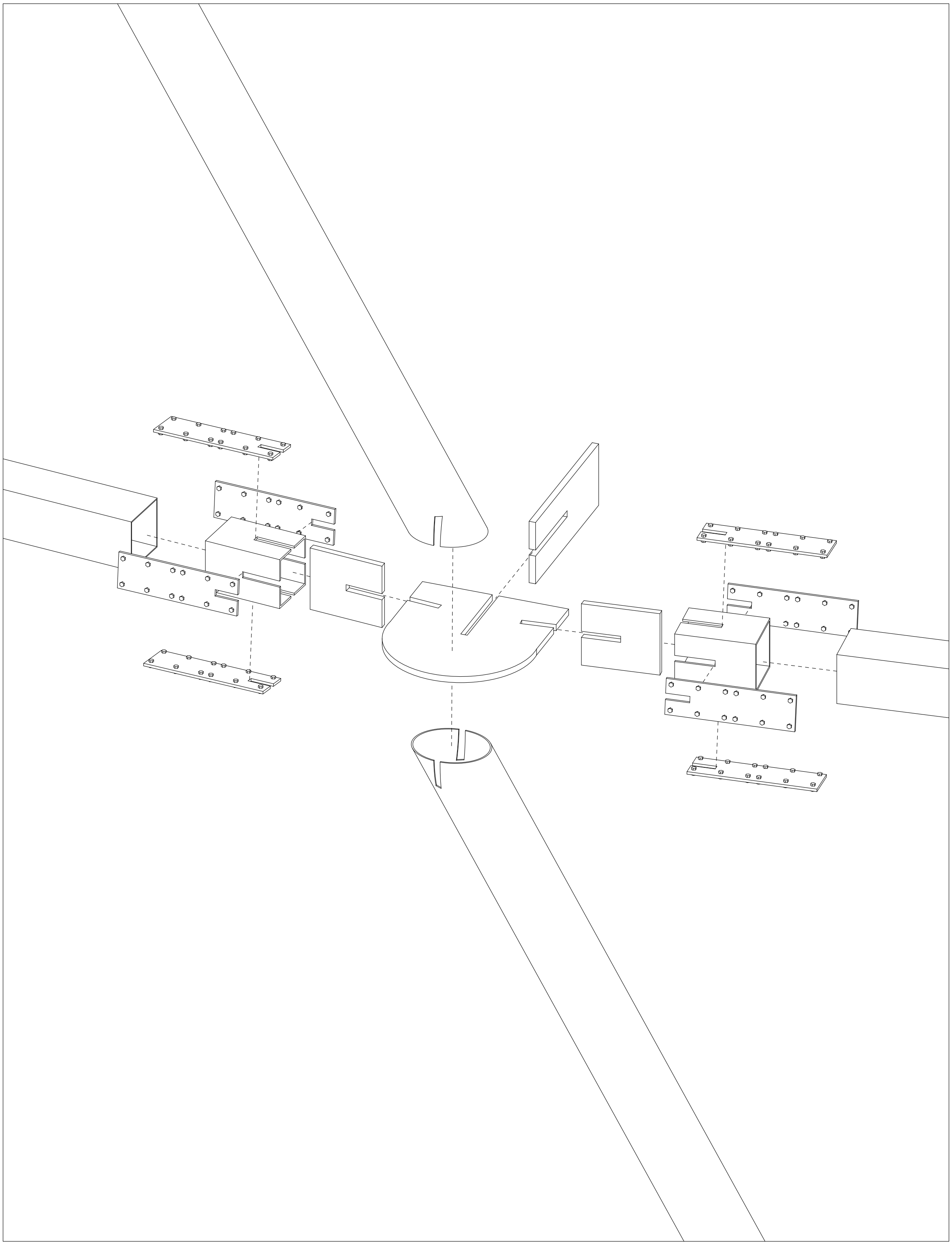


Figure 1.2: Proposed Mid- Span joint



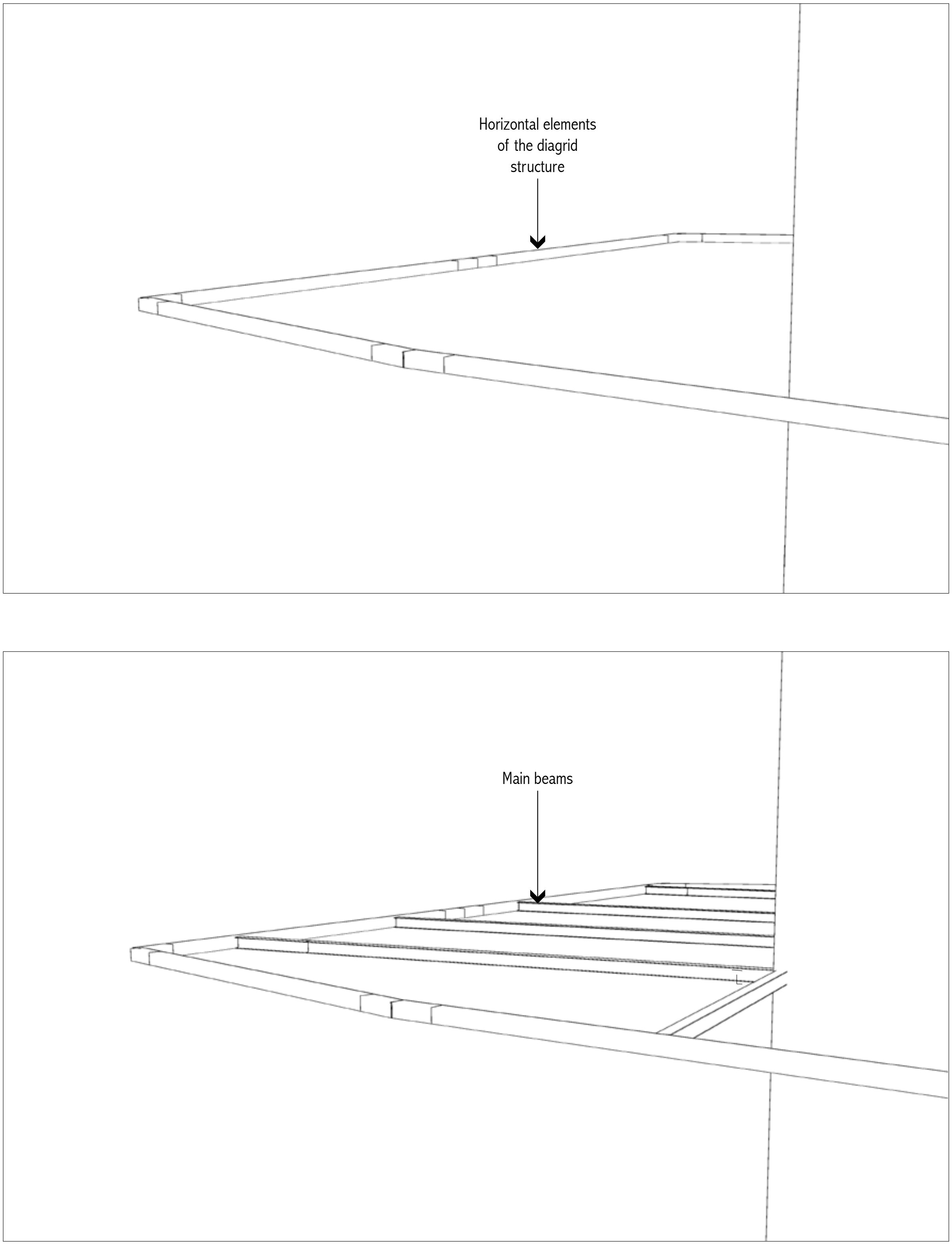
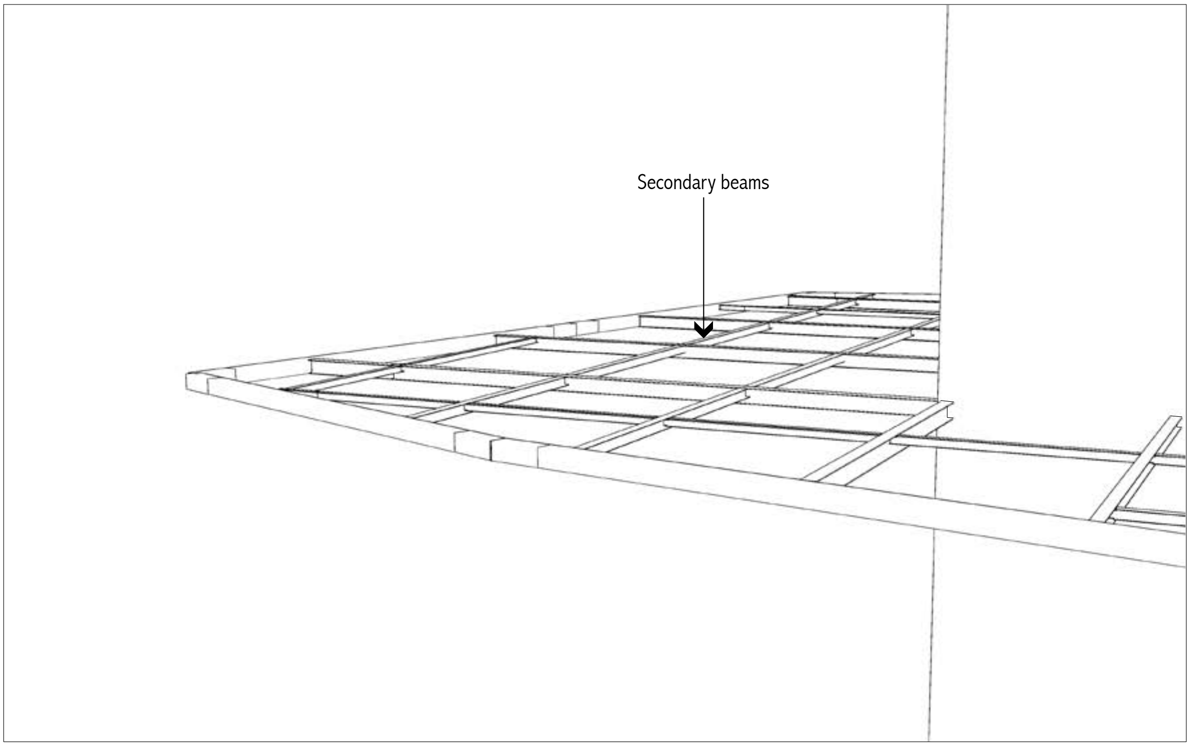
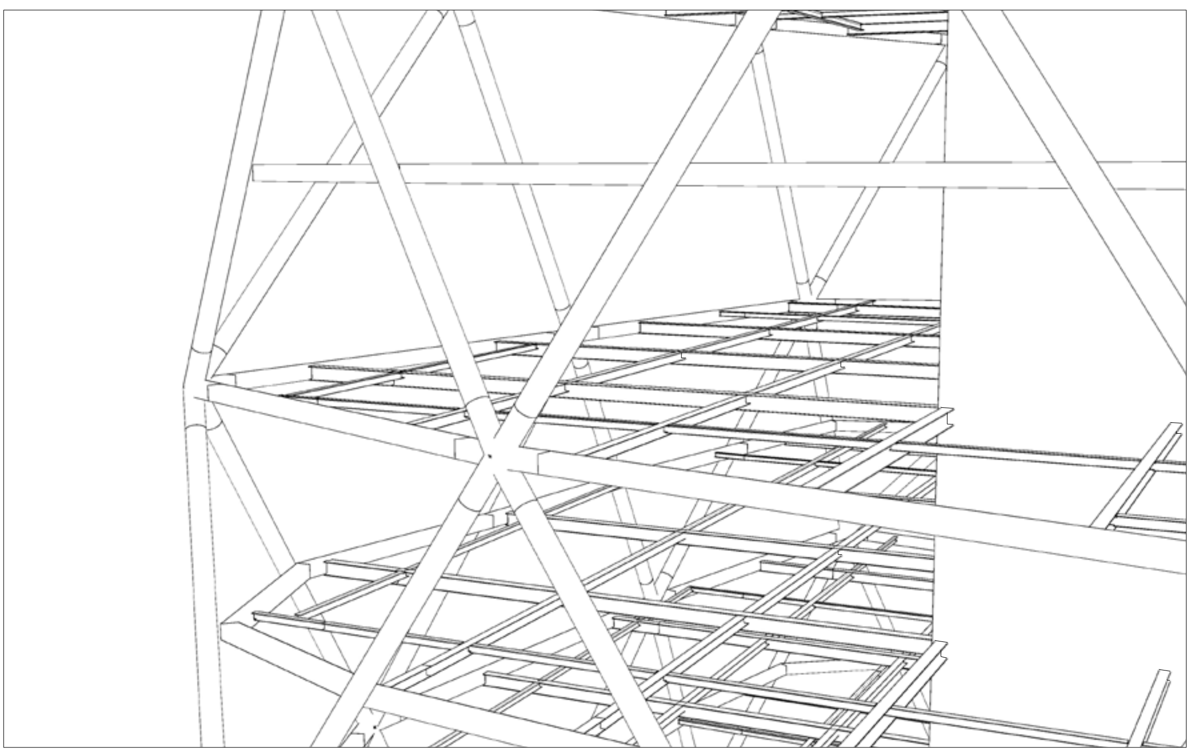


Figure 1.3: Flooring system


Secondary beams



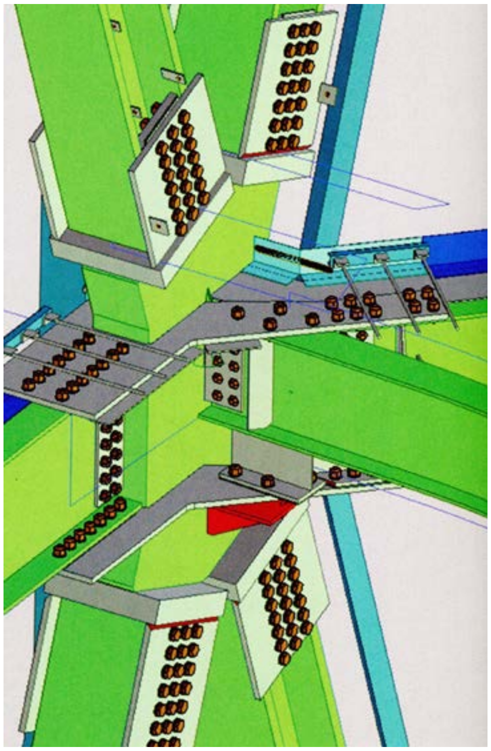


Figure 1.5: Detailing Hearst tower

The proposed geometry for the structure needs to provide the maximum adaption to the initial design, in addition to maximum structural efficiency and constructability. Such a design process is affected by several design variables with non-linear relationships that increase the complexity of the whole process for designers. Different combinations of variables produce different results. Moreover, in complex design processes, the relationships between the design variables are usually not linear, which means any variable can affect several aspects of the design process in different ways. Under such conditions, in order to achieve the best design, the influence of variables on all aspects of the design needs to be considered. Most often, in complex design processes, the fact of having the absolute minimum or maximum amount variables does not offer the optimum solution for all aspects of a project. Such a non-linear relationship increases the complexity of the decision- making process. In other words, as long as any part of a complex system is incomplete, partial, and dependent, the system is much more complex than its parts [1]. These days, computation helps designers to deal with such complexity. Computers are much faster and more efficient in processing a large number of inputs with complicated relationships.

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[1] Batty, A., Torrens, P. M. (2005). Modelling and prediction in a complex world. Futures(37), , 745-766.

COMPLEXITY AND COMPUTATION

Improvements in the field of digital drawing, parametric design and, more general, the role of computation in design and fabrication over the last decade have radically improved possibilities in developing complex geometries and design strategies.

In developing a complex geometry, design and fabrication processes are affected by several design variables that increase the complexity of the whole design process. In a simple design process with limited variables and predictable roles, designers can still handle the complexity of the process without any computation; however, in more complex design cases, it is impossible for designers to manually consider all design variables and make the best decision. Moreover, the second aspect of complexity is the non-linear relationship between the design variables. It is difficult to isolate and define variables that only influence one aspect of the design. There are conflicting variables and not all of them influence a given aspect of the design to the same extent. For example, angles of structural elements in diagrid and orthogonal structural systems play different roles in the structural efficiency. In orthogonal framing systems, columns close to 90 degrees are more efficient because they are designed for axial loads alone. However, grid elements in diagrid structures are designed for both axial and lateral loads. For this reason, changing their angles has the opposite influence on the efficiency of the structure, in providing stiffness against lateral and axial loads. Such variables have non-linear relationships and increase the complexity of the whole system.

These days, computation helps designers to deal with such complexity. New digital design technologies have been developed to assist designers from conceptual design development to construction management. Such a digital design includes algorithms that can handle the complexity of design projects by simulating design and construction processes virtually.

Recently, two major trends of using algorithms in an architectural context have been created. The most common trend is related to programs that can be used in the construction phase of a project, such as in the automation of hugely repetitive tasks to increase efficiency and accuracy, or in the translation of a proposed schematic design into detailed fabrication information for use in digital fabrication. However, a second group of algorithms has been developed to handle the whole design strategy of schematic design in its many different forms, including generative form-finding processes, optimization responding to defined goals, and algorithmic design processes that focus on the use of algorithms as a strategic stance.

1.2.1 COMPUTATION FOR THE CONSTRUCTION PHASE

The first groups of algorithms, which can be used in construction phase, prepare construction documents from initial structural analysis to detailing, shop drawings, digital fabricating, and erection. These lists of information let architects to evaluate the efficiency of the proposed solution in different steps of the construction process and to make the best decision before any on-site operations.

Current advances allow algorithms to work with any 3D geometry with any degree of complexity that can be invented by designers. For instance, software programs such as Matlab [1] and SAP2000 [2] are able to structurally analyze any form with any level of complexity. Advanced analytical techniques allow engineers to develop the structural design step-by-step and propose the best performing structure.

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[1] MATLAB is a high-level language and interactive environment fornumerical computation, visualization, and programming.http://www.mathworks.com
[2] SAP2000 follows in the same tradition featuring a very sophisticated, intuitive and versatile user interface powered by an unmatched analysis engine and design tools for engineers working on transportation, industrial, public works, sports, and other facilities. http://www.csiamerica.com/products/sap2000

In the next step, fabricators create 3D models of the proposed structure to clarify all details, including joints and structural elements with software programs such as Tekla [1] and Bentley Systems [2]. They are powerful tools for detailing and modeling the whole workflow including fabrication and erection. Such software programs can increase productivity and minimize possible errors in the fabrication and erection processes. Next, information from the 3D model needs to be converted to essential information for fabrication processes including the automatic cutting and welding machines. Different robot arms or machines use different software programs to apply the plasma torch on steel components. Such a system can simplify shop layout, increase speed and accuracy and address a growing shortage of skilled workers.

All above-mentioned computation methods improve possibilities in design and fabrication of steel structures and help designers deal with recent complexities in form and design strategies. For example, two design solutions with different forms and geometry are proposed for the gallery's diagrid structure (Figure 1.6). The first option is geometrically more of a match with the initial design; on the other hand, the second option has more regular grid modules and angles that can be beneficial in its structural efficiency and constructability. Most importantly, SAP2000 and Tekla are used to evaluate the performance of design solutions. These two software programs can evaluate the performance of two options in the fields of structural efficiency and constructability. The most structurally efficient must employ the least amount of steel for the same load bearing, whereas the highest performance in constructability means the minimum of cutting, welding and errors in construction.

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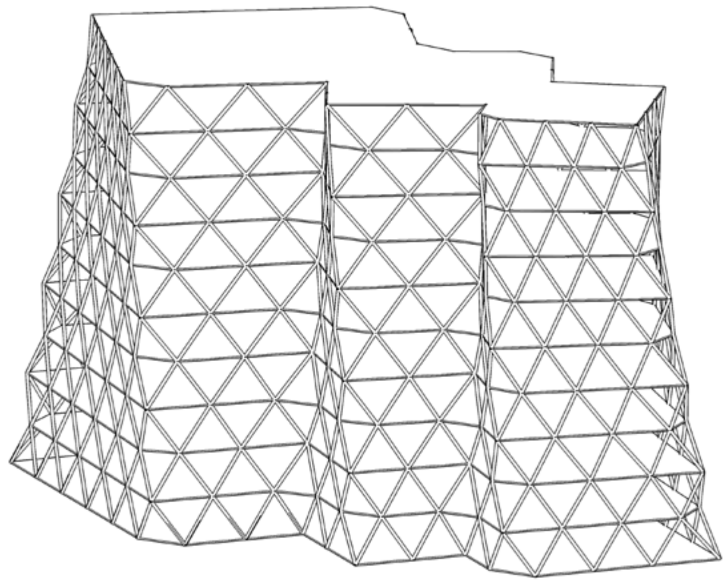
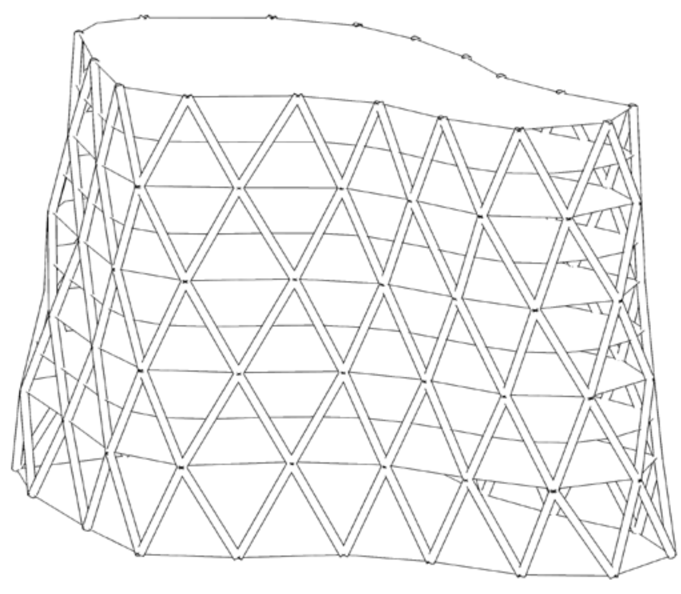
[1] Tekla provides model-based software for customers in construction, infrastructure and energy industries worldwide.
http://www.tekla.com
[2] Bentley's flexible and scalable software allow seamless workflow of analysis, design, detailing, documentation and BIM data.
www.bentley.com



Solution 1



Solution 2

Figure 1.6: Design Solutions

STRUCTURAL EFFICIENCY

In the fist step, SAP2000 structurally analyzes two forms and applies the minimum required cross-section to each element. Cross-sections are selected from the list below (Table 1.1) (Figure 1.7):

Section	d mm	t mm	Mass kg/m
HFCHS 139	139.7	6.1	21.7
HFCHS 168	168.3	7.4	31.3
HFCHS 219	219.1	7.6	42.6
HFCHS 273	273	8.6	60.5
HFCHS 355	355.6	8.9	81.1
HFCHS 457	457	11.8	139.2
HFCHS 508	508	11.8	155.1

Table 1.1: Selected Cross-sections

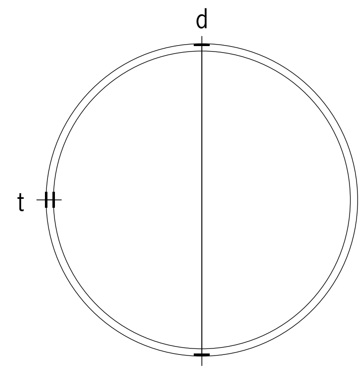


Figure 1.7: HFCHS Cross-section

The design process includes checking the structure with the smallest section for all elements and replacing those with bigger sections that cannot pass the structural analysis. This process will continue to find a solution in which all elements pass the structural needs (Figure 1.8). The final result is the lightest structure for each option that is able to provide enough stiffness. The material consumption can be easily calculated from the list of elements (Table 1.2).

Solution 2

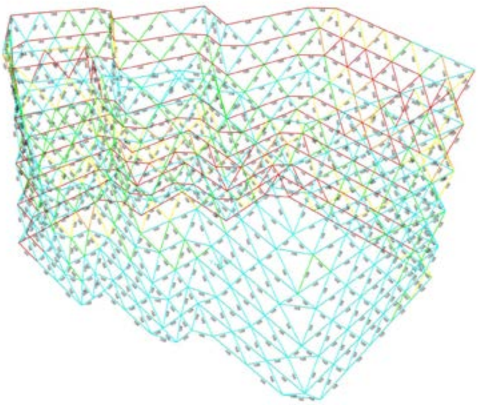
Section	Quantity	Length
HFCHS 139	-	-
HFCHS 168	80	32
HFCHS 219	23	12.5
HFCHS 273	43	33.3
HFCHS 355	17	17.7
HFCHS 457	7	12.5
HFCHS 508	-	-
Total Weight		108 ton

Solution 1

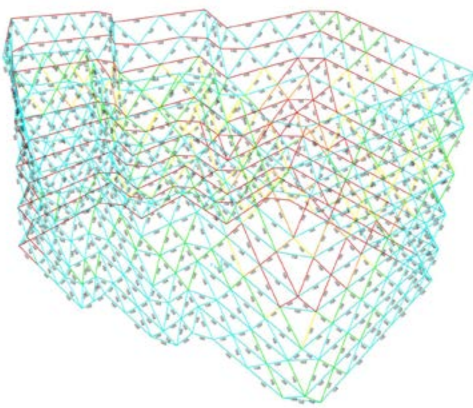
Section	Quantity	Weight ton
HFCHS 139	-	-
HFCHS 168	535	112.2
HFCHS 219	95	27.1
HFCHS 273	63	25.5
HFCHS 355	13	7
HFCHS 457	-	-
HFCHS 508	-	-
Total Weight		171.8 ton

Table 1.2: List of minimum elements for solutions

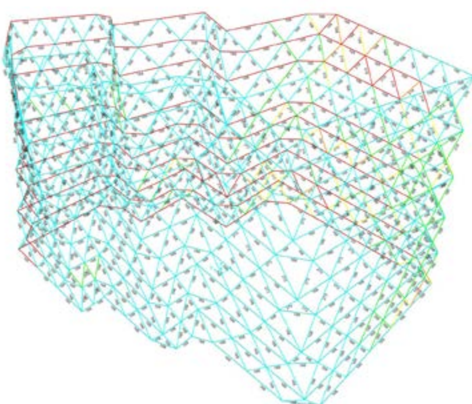
The minimum material consumption for solution 1 is 171 tons of steel; however, it is 108 tons for solution 2. As such, option 2, with170 structural elements, is more structurally efficient.



Step 1



Step 2



Step 3

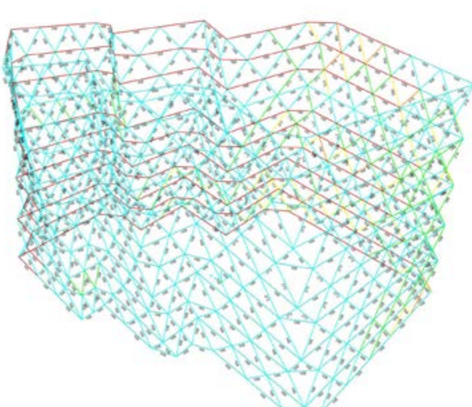
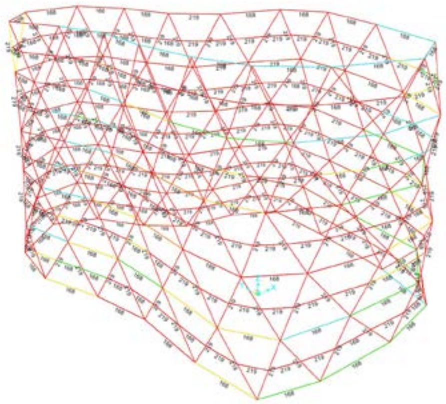


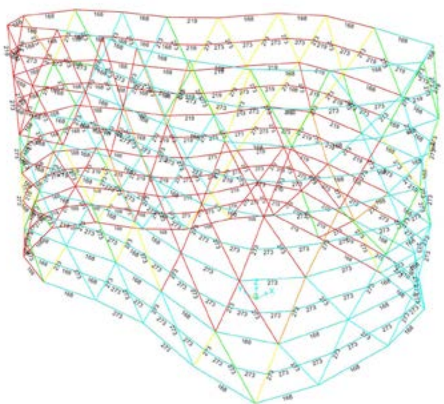
Figure 1.8: Structural analysis by SAP2000

Step 4

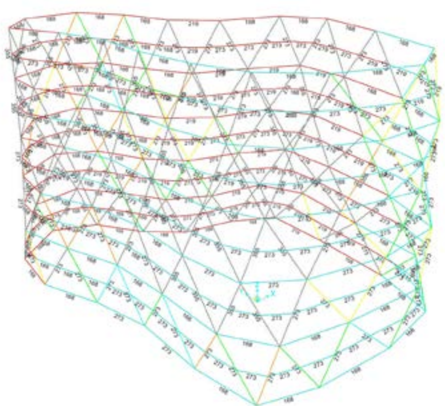
Solution 1



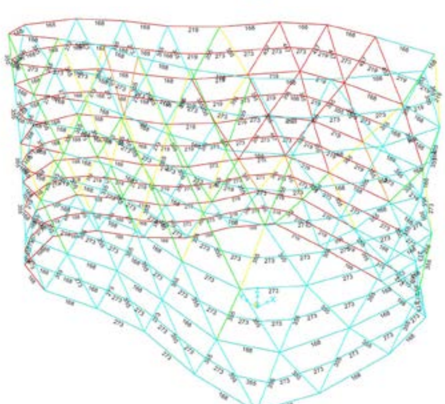
Step 1



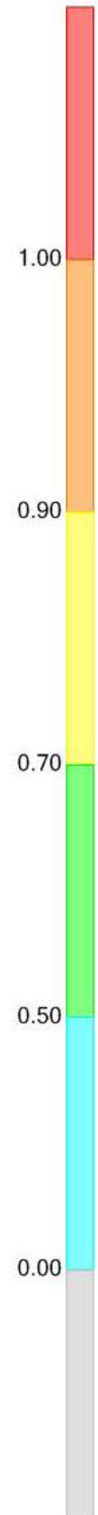
Step 2



Step 3



Step 4



Solution 2

1.2.1.2 CONSTRUCTABILITY

To find the possible errors in constructing details, the structure from the SAP2000 is modeled in Tekla. The Tekla model is developed manually based on information from the parametric model and the structural design by SAP 2000. The parametric model shows the location, direction and length of structural elements; and yet, the structural analysis determines the minimum required cross-section for each element. With such a list of information, the only part of the design that needs to be determined is the geometry of the joints. Tekla has the ability to draw connections automatically based on designers' decisions. Such a model is essential for ensuring the constructability of joints, which is especially critical in structures with complex geometries.

Figures 1.9 and 1.10 show errors in construction for both options. However, all constructible joints are not equally efficient to fabricate. In buildings with regular geometries, the fabrication process can be easy and economically compatible with other structural techniques. This compatibility is a result of the limited variation in configuration of structural elements, such as the Hearst Headquarters in New York, a structure that is constructed by typical modules. However, irregular building forms create the need for variation in joint geometries, which generally increases the difficulty of the fabrication process. In the gallery project, similar to the Capital Gate Tower, the geometry of any node and diagrid module is unique because of the complex geometry of the whole structure. Nevertheless, this is not to say that building forms are no longer important. Generally, elements with extremely high or low angles make the process of welding or bolting more complex, and increase the chance of errors in both fabrication and assembly processes. Therefore, grid models that are geometrically closer to equilateral triangles are more efficient in construction processes and cause minimum errors in construction (Figure 1.11).

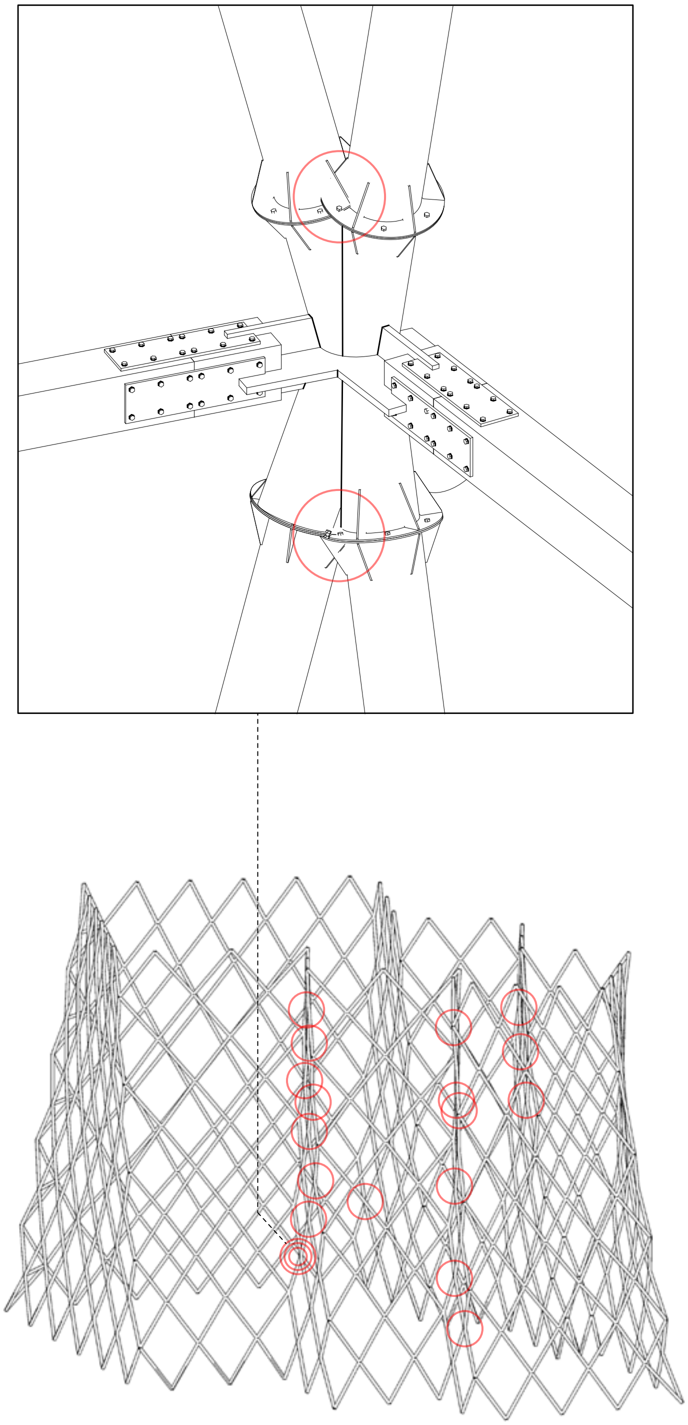
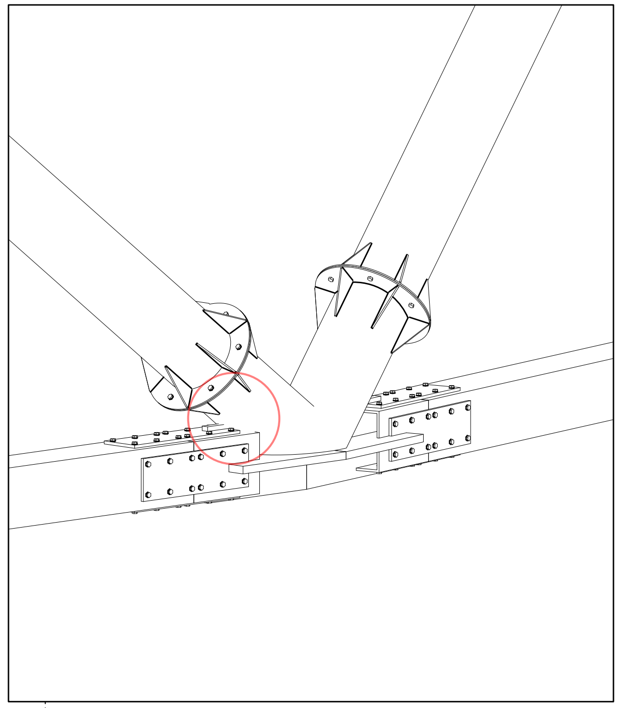
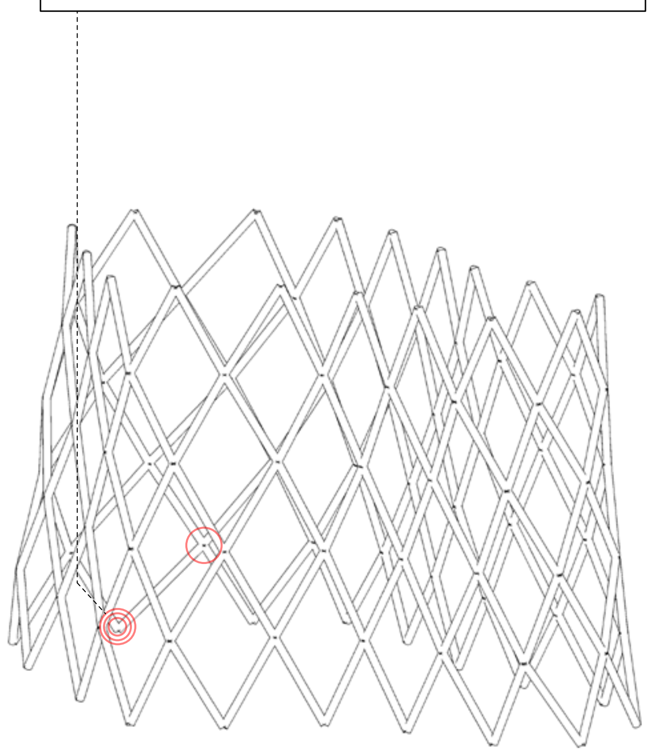


Figure 1.9: Error in construction, Solution 1





Solution 2

Figure 1.10: Error in construction, Solution 2

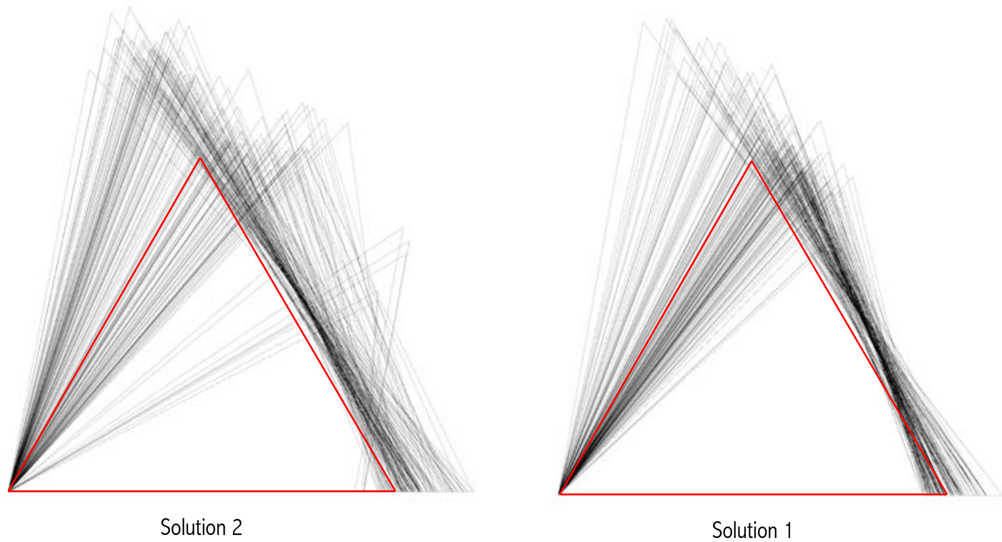


Figure 1.11: Adaption with equilateral triangles

FORM-FINDING ALGORITHM

1.2.2

The above-mentioned software programs can increase the efficiency of the decision-making process by applying several types of analysis and simulations on each design solution to evaluate its performance. However, the designer can never claim that the proposed design solution is the best fit because of the significant influence of the building's form and the structure's geometry in final performances, such as structural efficiency and constructability. In other words, as long as the designer does not consider all effective parameters during the design process, including form, the final solution does not necessarily have the highest performance.

This group of software has an absolute limited ability to consider the form of the building in the design process. Thus, a second group of computations is developed to explore the use of computation in the larger context of the scheme as a strategic stance by generative form-finding processes. Such an algorithm can propose a form-finding process that considers the structure's geometry as a design variable to achieve the best possible solution in defined performances.

For many years, architects and engineers have been using form-finding methods based on the optimization of structural efficiency and material consumption. That said, computer technology has recently influenced different aspects of the building industry, and so has caused beneficial developments in optimization technics. It has been possible to shift from traditional experiment-based techniques to a new method that is inspired by combining computer modeling and mathematics for multi-objective optimization (Figure 1.12).

To confront such a complicated process and find the most desirable form for the diagrid structure, a computational model is designed which rapidly generates, evaluates, and scores performances of different objectives. In this thesis, such a multi-objective optimization is done by a generative algorithm.

Thus, the thesis addresses the need for the identification and application of computational methods that will effectively handle both the complexity issue of parametric modeling of diagrid structures and the computational modeling. This latter modelling is related to analyzing, evaluating, scoring performances objectives, and then making decisions for the process of multi-objective optimization.

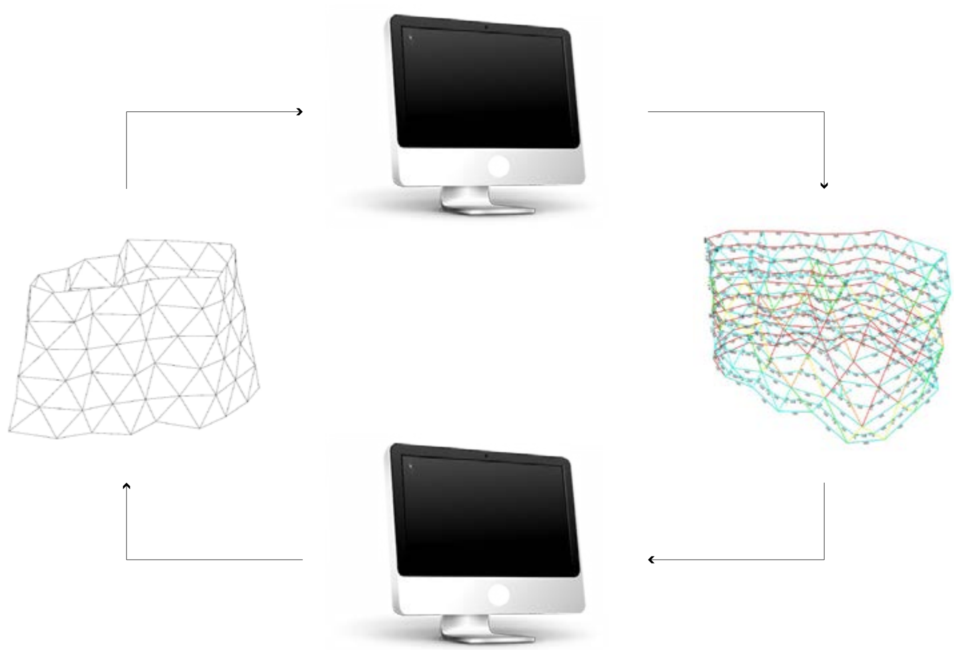


Figure 1.12: Form-finding Algorithm

CHAPTER 2
FORM-FINDING

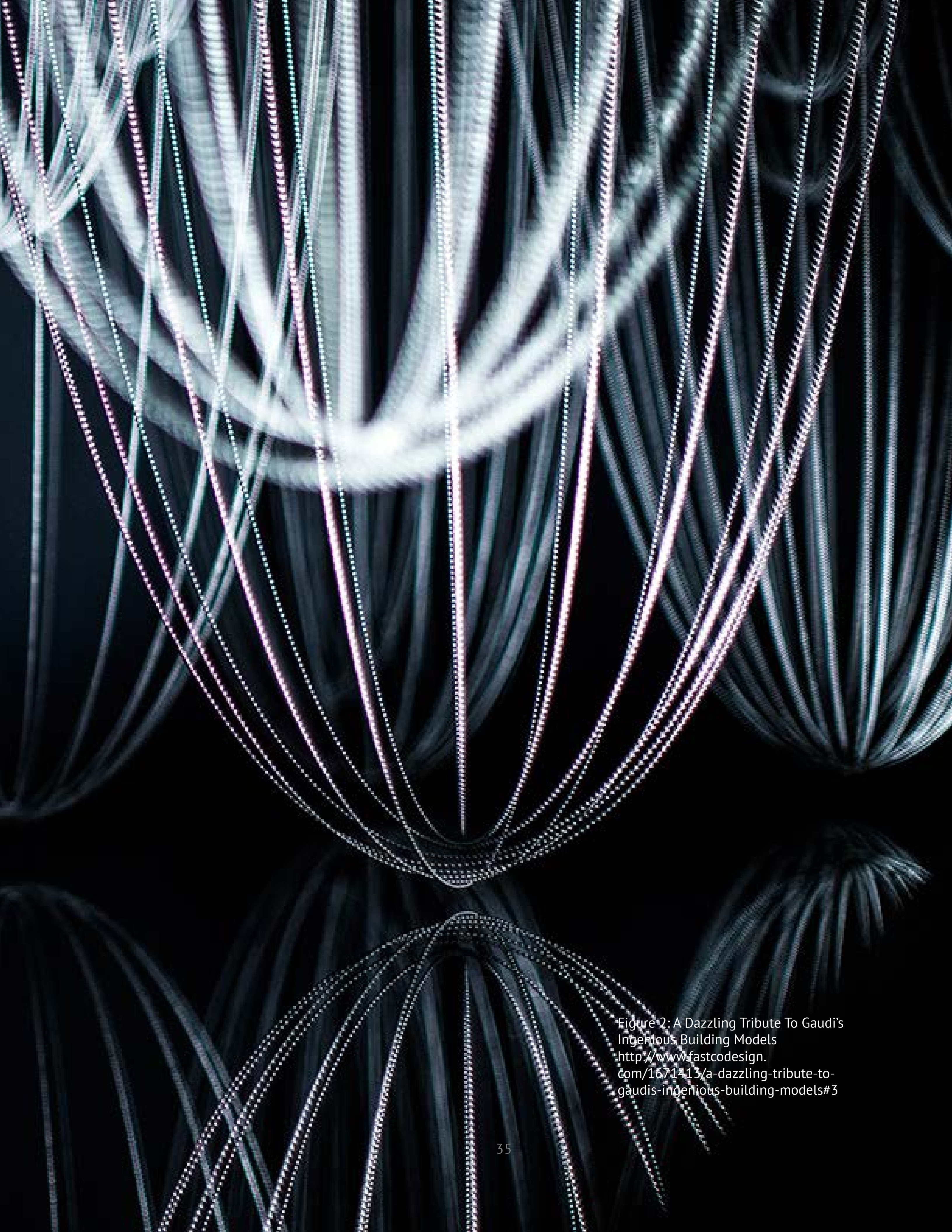


Figure 2: A Dazzling Tribute To Gaudi's Ingenious Building Models http://www.fastcodesign.com/1671413/a-dazzling-tribute-to-gaudis-ingenious-building-models#3

2 FORM-FINDING

Historically, structural efficiency governed the form of buildings, but recently, with developments in computational simulators, several aspects have been taken into consideration regarding a form-finding process, from architectural intent to construction efficiency. This method of form-finding brings designers into closer contact with engineers and fabricators to determine the highest performance design in all objectives. To identify the potential of geometries in the optimization of a design proposal, this chapter focuses on historical and contemporary methods of form-finding models for structural designs.

2.1 HISTORICAL USE OF FORM-FINDING MODELS FOR STRUCTURAL DESIGN

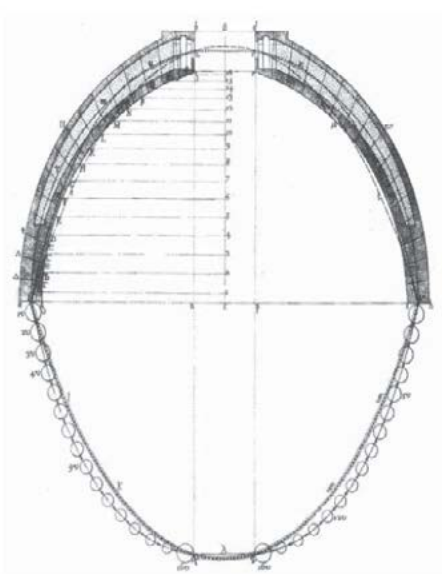


Figure 2.1: Saint Peter's dome. Hanging chain model. Poleni, 1748, http://automaticoroboticocodificado.masterproyectos.com/wp-content/uploads/2010/06/14.pdf

Historically, the form of the structure has been used as a variable to achieve the optimum structure design. In 1675, Robert Hooke was the first to use flexible chain to propose a form-finding method for making arches. Based on that experience, he stated the inverted catenary theorem: since they are simple compression structures, the stability of masonry arches and domes is independent from their scale, and every dimension of a structural model can be increased proportionately to erect the real structure [1]. The idea of hanging chain has been used for several architectural experiments and projects; for instance, in 1748, Poleni applied this system in his attempt to prove the stability of Saint Peter's dome (Figure 2.1). Furthermore, two architects and a new material played important roles in the process of form-finding developments: the work of Antonio Gaudí, the development of concrete shells and the innovative, lightweight structures

[1] Heyman, J. (1999). El esqueleto de piedra. Mecánica de la arquitectura de fábrica. Madrid: Instituto Juan de Herrera. [The stone skeleton] Cambridge University Press,

created by Frei Otto [1].

Antonio Gaudí improved the method of hanging chain to make very complex three-dimensional structures. For example, he made a three-dimensional funicular model using strings and small bags of shot pellets for the Colonia Güell chapel. With this experiment, he offered a new method that used nature and geometry as inspirational sources for making unique forms for structures (Figure 2.2).

Gaudí stated: "I calculate everything: first, I consider some weights to find the funicular, I cover it with forms and materials and readjust the weights, and then sometimes I change slightly the funicular. This way the logical form emerges from necessity. [2]"

Next, the invention of reinforced concrete let designers apply more complex form finding systems to structures. Pioneer engineers of the 20th century such as Pier Luigi Nervi, Eduardo Torroja, the architect Felix Candela, Ove Arup, Nicolas Esquillan and Heinz Isler proposed new structural forms suitable for the characteristics and potential uses of concrete, with firm criteria of structural efficiency [1]. For example, the project Torroja's Frontón de Recoletos in Madrid with a 55 meter long shell illustrates how new possibilities can be applied to new materials (Figure 2.3).

This development generally showed the influence and importance of materiality in the process of form-finding without relying on concrete. Every material has a different and specific personality and every shape imposes its own tensional state. The natural solution to a problem, optimal in relation to the pre-conditions from which it emerges, conveys an impressive message, satisfying

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[1] Alejandro Bernabeu Larena. (2009). Shape Design Methods Based on the Optimisation of the Structure. Historical Background and Application to Contemporary Architecture. Third International Congress on Construction History, Cottbus,
[2] Giralt Miracle. (2002). Gaudí. La búsqueda de la forma. [Design towards convergence.] Dickson, M.,

Figure 2.2: Funicular model for the Colonia Güell. Antonio Gaudí, 1889-1914, http://arewebeautiful.blogspot.ca/2013/04/se-voce-quer-enlouquecer-digita-

the requests both of the engineer and the artist [1].

The third important development in the field of form-finding and structural efficiency is related to the work of the architect Frei Otto in collaboration with the engineer Edmund Happold. They had the biggest influence in contemporary architecture and structural engineering by way of their form-finding methods. Frei Otto's methodology is related to the natural forms and their origin,

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[1] Alejandro Bernabeu Larena. (2009). Shape Design Methods Based on the Optimisation of the Structure. Historical Background and Application to Contemporary Architecture. Third International Congress on Construction History, Cottbus,

to achieve forms with maximum structural efficiency and minimum material consumption. Thus, many form finding models such as soap films and hanging chains, have been used to design lightweight structures to minimize tension of the surface structures. In the German pavilion in the Montreal Universal Exhibition or the aviary for the Munich zoo, Frei Otto used different form finding techniques. For instance, in the Garden Festival in Manheim, a complex timber shell was created based on soap bubble-foam structures (Figure 2.4).

Figure 2.3: Concrete shells. Frontón de Recoletos, Madrid. Eduardo Torroja, 1935, http://veredes.es/blog/monumentos-de-hormigon-inigo-garcia-odiaga/

Figure 2.4: Manheim Garden Festival. Interior view. Frei Otto and Edmund Happold, 1973, http://commons.wikimedia.org/wiki/File:Multihalle07.jpg

FORM FINDING MODELS AND STRUCTURAL EFFICIENCY IN CONTEMPORARY ARCHITECTURE

Over the last four decades, with the ongoing development in computation, new optimization techniques have emerged, such as evolutionary structural optimization and performance based optimization. These methods have permitted designers to move from traditional techniques to new computational methods in which digital modeling, mathematical algorithms, and simulators are used.

are used. Several experiments have been made in this field for optimizing shape, topology and/or member sizes. In the following sections, the two most current optimization techniques, evolutionary structural optimization and performance based optimization, are briefly identified.

2.2.1 EVOLUTIONARY STRUCTURAL OPTIMIZATION

Evolutionary structural optimization (ESO) generates a form-finding process to minimize bending efforts of the structural elements by removing or shifting inefficient material units.

Step-by-step, as the process evolves, the structure becomes more similar to the optimal form. In the optimal form, bending efforts are minimized, and all elements are affected by axial loads (compression or tension stresses) without almost any mechanical wastage. Moreover, the developed version of ESO is able to add materials where needed. In order to multi-objective optimization, the algorithm needs to be modified to consider more objectives in removing or shifting material units.

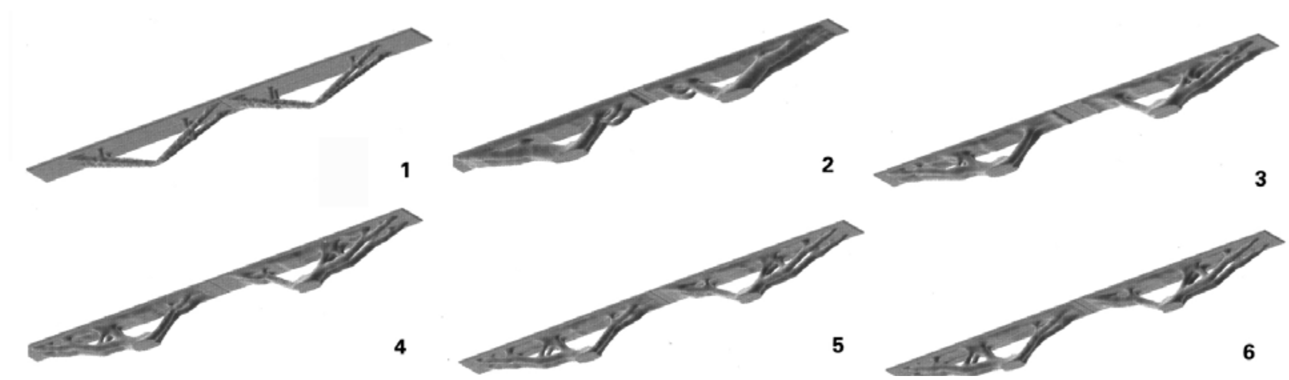

Figure 2.5: QEC Convention Centre. Arata Isozaki and Mutsuro Sasaki. Doha, 2003, http://www.dezeen.com/2013/08/22/qatar-national-convention-centre-by-arata-isozaki/

[1] Xie, Y.M., Steven, G.P. (1997). Evolutionary Structural Optimization. Springer,

ESO is used for several projects to achieve the maximum structural efficiency. For instance, Arata Isozaki, in collaboration with engineer Mutsuro Sasaki, has applied this method for the new Florence station and in the QEC Convention Centre in Doha (Qatar). The Convention Centre is a structure with 250 m long by 30 meters wide and 20 m high, with only two support points. Figure 2.5 shows some of proposed forms by the ESO.

PERFORMANCE BASED OPTIMIZATION 2.2.2

In this context of architectural freedom, some engineers propose applying form-finding methods based on the optimization of the structure to create or modify architectural shapes, a process which is called performance based optimization. In such a method, the goal is mathematically defined and an algorithm searches for the best performing design, according to the logic related to the architectural shape and its structural support with the maximum focus on reducing the waste of materials.

As Mike Cook states: “We need form-generation models that recognize the laws of physics and are able to create ‘minimum’ surfaces for compression and bending as well as tension. And we need to extend the virtual building model to virtual construction – not just conception – so that the way a building is fabricated and erected becomes as important a part of design as its efficient use of materials. This will help us create buildings that will conserve material and energy and hence go some way towards meeting today’s pressing need – conservation of our global resources [1].”

The performance based optimization has been used in several projects and experiments. For example, Norman Foster, in the project the Great Court roof at British Museum in London, used this idea to design the most invisible and light structure that meets other architectural needs too. The geometry of the roof needed to follow the museum’s edges and was also limited by the lack of flexibility in the height of the structure.

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[1] Xie, Y.M., Steven, G.P. (1997). Evolutionary Structural Optimization. Springer,

Thus, engineers used a form-finding system that began with the geometry that would adopt a soap-film stretched between the inner circle and the outer rectangle, inflated into an undulating shell [1]. Then the algorithm was used to assist designers in controlling the stress level in structural elements. Thus, the result would be a bubble with limited convexity and small structural elements to meet the need of maximum structural efficiency and transparency (Figure 2.6).

Figure 2.6: British Museum. Roof of the Great Court. Norman Foster and Buro Happold. London, https://www.flickr.com/photos/chrisk1982/5887091968/ 2000

2.3 OPTIMIZATION BEYOND STRUCTURAL EFFICIENCY

The last two sections show how some structural optimization related to the field of form finding structures has been well-known for centuries. However, the modern building industry undertakes a complex task, including various approaches, parameters, and conflictive objectives that can play roles in the form-finding process.

Recently, in addition to structural optimization, designers have focused on different aspects of projects and their affects on the geometry of the building, such as environmental impact, efficiency in construction, energy consumption and economy. Evaluating the influence of all these design parameters needs new developments in form-finding methods, tools, and strategies. New fields of optimization can be used in the design process, with recent developments and the introduction of computer technologies, simulators, and analyzers in architecture and engineering.

[1] Williams C. (2004). Design by algorithm. Wiley-Academy,

OPTIMIZATION FOR ENVIRONMENTAL IMPACTS

Environmental conditions can influence the design process, form, and structure. However, understanding these conditions can help designers to modify their designs to receive the maximum benefits and minimum negative impact from the surrounded environment. In other words, designers can use form-finding systems to optimize environmental impact on the building.

These days, the need of such optimization in the design process is more essential than in the past because of the increasing costs of energy for construction and maintaining the buildings. The optimization includes controlling the flow of heat, light, and noise. Modeling these parameters needs expert simulators, because they are not static. Therefore, such a form-finding system is used instead of following the function of the static forces of energy.

“We have shifted from the mechanical age to a ‘solid state’ era. The world of the 21st century will be a ‘solid state’ world. ‘Solid state’ techniques are based upon materials which can alter their properties or transmit information merely due to electronic or molecular proceedings. Hence we can dispense with mechanical systems in many cases.[1]”

Recent developments in computational simulations of environmental impacts allow new experiments in optimization of energy flow by controlling the form of the building. For example, one of the most important parameter that can influence the design process in any project is Light. In the project Triton office building in Frankfurt, variable complex geometry for the facade was developed in order to maximize natural lighting and to minimize heat gain in summer for different sun conditions (Figure 2.7).

[1] Davies, M. (1990). Eine Wand für alle Jahreszeiten. Arch+, 104

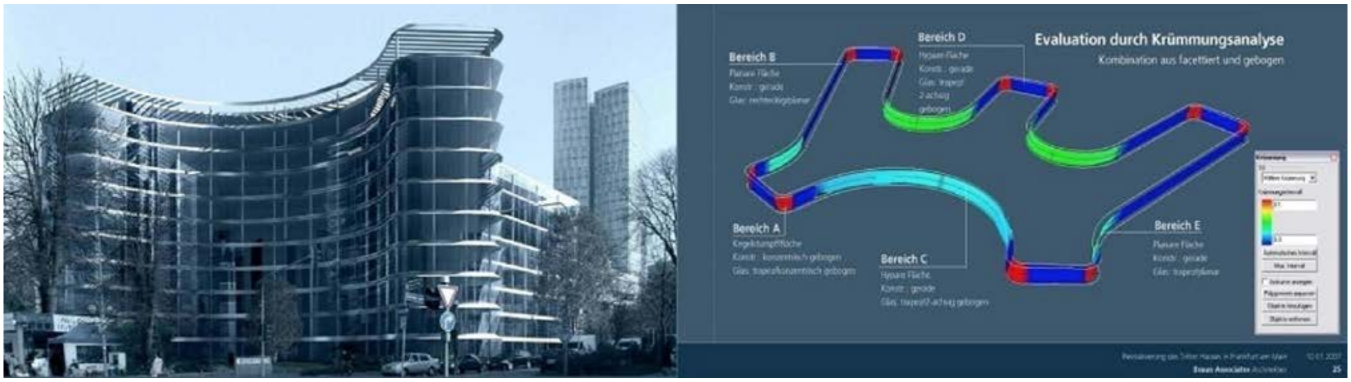

Figure 2.7: Triton office building Frankfurt, Arch.: Braun Associates, Eng.: TEC/ Transsolar

However, other objectives are considered in generating the final form of the façade, such as economical and constructability issues[1].

2.3.2 OPTIMIZATION OF CONSTRUCTION PROCESS

The construction process is always a challenge for designers especially in designing free-form structures. Difficulty in construction is the one of the main reasons for wasting money, time, and material in the building industry. Designers with current technologies are able to consider different aspects of the construction process, including fabrication, transportation, and assembly in the design processes. The goal of optimization in each project can be different. For example, minimizing the material wasted in the fabrication process is the main goal in a project, but minimizing the assembly process is the goal in other one because of the labor-intensive process of assembly.

Mostly, optimization in construction of complex geometries is related to minimizing the variety of geometries or construction processes. They are experiments in order to simplify fabrication and assembly process by modifying the overall shape or patterns

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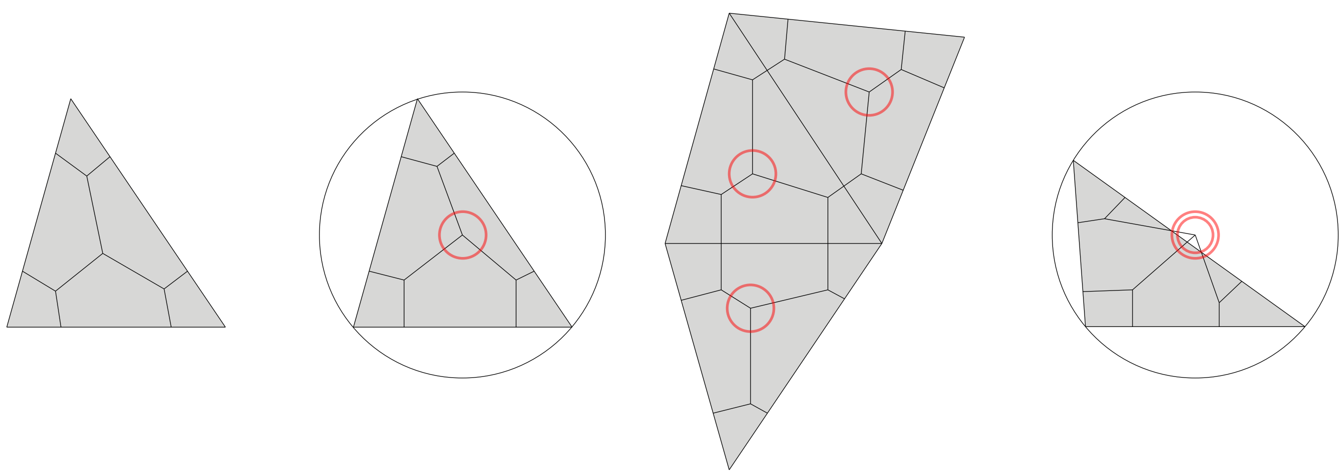
[1] Patrick Teuffel. (2008). Responsive Building Envelopes: Optimization for environmental impact, Senior Lecturer in Architectural Engineering School of Civil Engineering, University of Leeds. The 6th International Conference on Computation of Shell and Spatial Structures,

of structures. For example, in the project Historical Museum of North Jutland, in Denmark, different aspects of design including structure, construction and assembly are all considered to design the optimum free-form roof shell, which includes timber structural triangular panels. In the parametric definition of the roof structure a geometrical issue arises when a triangular component has obtuse angles because, in that case, the circumcircle center of a triangle does not lie inside the triangle. In this geometrical condition, the circumcircle center will land outside the triangle, causing the subdivision algorithm to give an output that is not suitable for structural purposes, because of the non-perpendicular meeting components [1](Figure 2.8).



Optimization techniques need to be used as a form-finding process to solve the construction problem. The goal of the optimization is to find the minimum distance between the circumcircle centroid and the area centroid to avoid the circumcircle centroid falling outside the triangle boundary by modifying the form of the structure [1]. Such a complex optimization process is modeled in a generative algorithm. (Figure 2.9)

Figure 2.8: The perpendicular meeting achieved by using circumcircle, and the problem when the corner angle exceeds 90 degree.

[1] Alberto Pugnale.Parametric Design and Construction Optimization of a Freeform Roof Structure. Department of Civil Engineering, Aalborg University, Aalborg, Denmark,

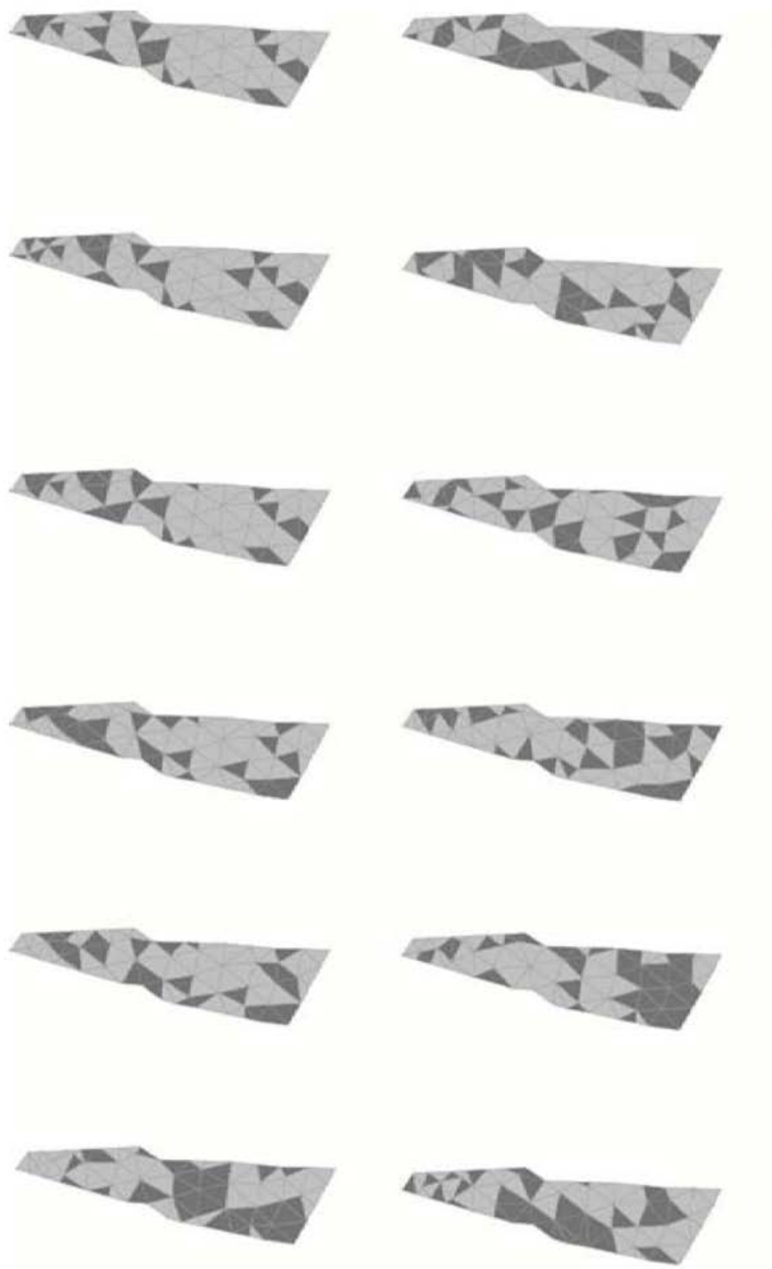
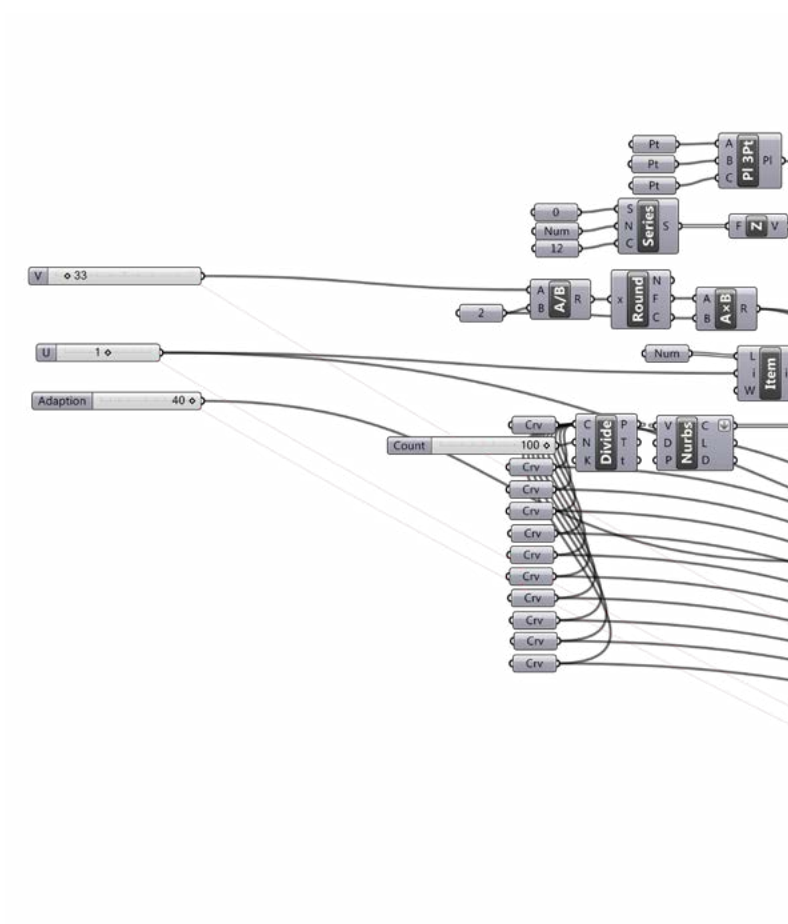
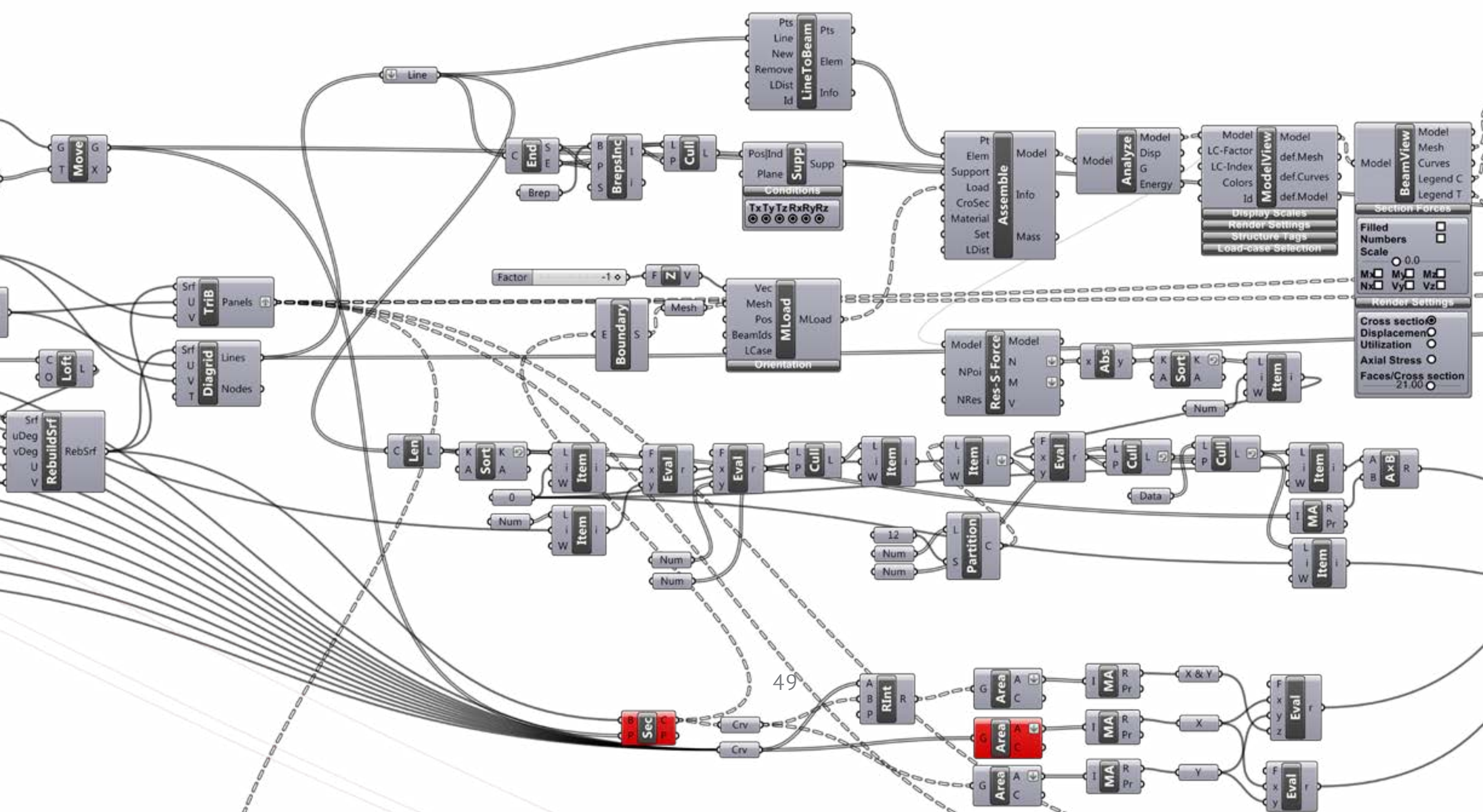


Figure 2.9: Process of optimization, dark facets is the non-successful triangles

CHAPTER 3
GENERATIVE MODEL




LineToBeam
Line
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End
BrepsInc
Brep
Cull
Supp
Conditions
TxTyTzRxRyRz
Assemble
Analyze
ModelView
Display Scales
Render Settings
Structure Tags
Load-case Selection
BeamView
Section Forces
Filled
Numbers
Scale
Render Settings
Cross section
Displacement
Utilization
Axial Stress
Faces/Cross section
Factor
Z
TriB
Panels
Boundary
Mesh
MLoad
Orientation
Loft
Diagrid
Lines
Nodes
Res-S-Force
Abs
Sort
Item
RebuildSrf
RebSrf
Len
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Partition
Data
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X
Y

3

3.1

GENERATIVE MODEL
FORM FINDING AND OPTIMIZATION

The main goal of a form-finding algorithm is reaching a design that can provide the highest performance in the related objective. Such an algorithm may be considered as an optimization process because it is defined as a decision-making process to maximize benefits out of available resources [1]. From the mathematical point of view, optimization is the process of checking the defined possible values as inputs to maximize or minimize the function f(x). In this way, the form that offers best function, which can be minimum or maximum based on our needs, is defined as the optimum or the best design solution.

$$\begin{array}{lll} minimize & F(\bar{x}); & \bar{x} \in R^n \\ such\ that & g_i \leq 0; & i = 1, \cdots, p \\ & h_j = 0; & j = 1, \cdots, q \\ where & F(X) = \begin{bmatrix} f_1(\bar{x}) \\ \cdots \\ f_n(\bar{x}) \end{bmatrix} & \end{array}$$

Where:

F(x): object function
gi: inequality restriction functions
hj: equality restriction functions
fi(x): i-th object function
x: parameters

In more complex problems, the number of variables and objectives can be higher. These kinds of problems that include several objectives are called multi-objective (MO) problems and the optimization processes are known as multi-objective optimization. Such a complexity is common in the field of architecture because designers usually must confront many objectives to make a successful design. It may be, for instance, finding the design that

[1] Goh Chi Keong. (2007). Evolutionary Multi-Objective Optimization In Uncertain Environments. Department of Electrical & Computer Engineering National University of Singapore,

meets the regulation requirements and saving the maximum money, while offering the lowest energy consumption and providing the highest thermal comfort [1].

In multi-objective optimization, a solution that has the highest performance in one objective does not necessarily produce the best scores in other objectives too. In that case, the average best solution is defined instead of the optimum solution. The average best solution is scored high in all objectives; however, it is not necessarily the best in any of them. Usually, the designer needs to make the final decision from a list of good solutions.

To make an optimization algorithm for MO problems, the parametric model of the design is first needed to describe the design mathematically and make all possible solutions. Secondly, objectives and the computational logic, which can evaluate and score the performances of solutions, need to be defined in a very practical way.

The most important step in optimization MO problems is related to defining the problem in a mathematical way and translating results into understandable design solutions, because translating concepts that are not measurable to a mathematical parameter can be a critical problem. For example, constructability of a diagrid structure is not a measurable parameter by itself. To translate the problem into an understandable way, a measurable parameter first needs to be defined instead of the constructability, which can be different according to the different project. Next, the designer has to determine the best result and define a scoring system to compare design solutions with the best result and evaluate constructability of a diagrid structure.

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[1] Laurent Magnier. (2008). Multi-objective Optimization of Building Design Using Artificial Neural Network and Multi-objective Evolutionary Algorithms. The Department of Building, Civil and Environmental Engineering, Concordia University Montreal, Quebec,

3.2

GENERATIVE MODELLING

A generative model includes a parametric model, computational model and a feedback loop. The algorithm processes, in several steps, different sets of inputs and finds a list of results, which are considered as the possible solutions. It helps architects to consider more possible solutions (Figure 3.1).

"A generative model describes an iterative and dynamic process, which finds solutions to the design problems through the repetition of design development cycles [1]."

A generative model has inputs and outputs, which are considered to be design solutions, during every step of the process. In the next step, the algorithm scores solutions based on defined computational logic that monitors the designer's needs. This step is called performance evaluation. Then, to complete the feedback loop, the evolutionary optimization algorithm translates those scores in relation to the initial variables. After many steps of processing, the model finds the best design option as the final output. This process allows finding design solutions for complex design tasks that cannot be found using a traditional design process [2].

Even more importantly, "The model can also be seen as a design in itself, because the programmer carefully creates the process of coming to a building. The generative model is therefore an abstract design solution [3]."

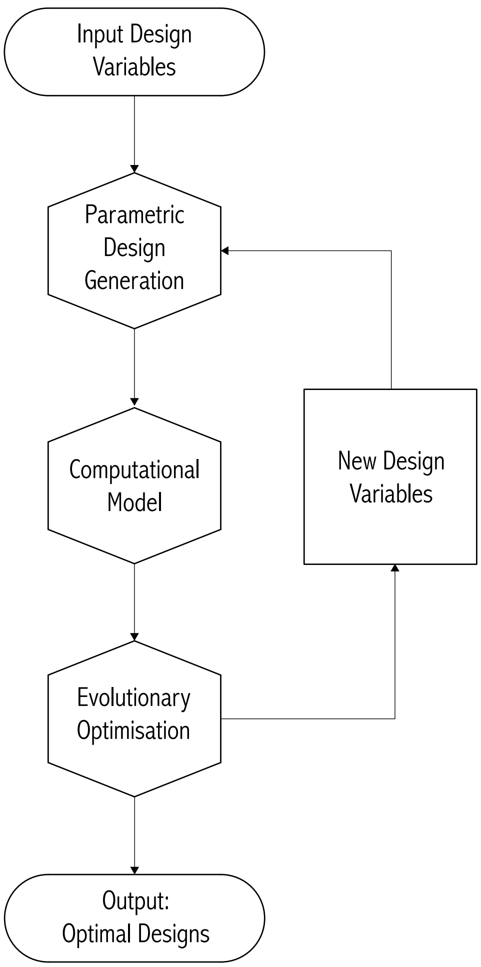

Figure 3.1: Generative Model Flowchart

[1] Puusepp, R. (2011). Generating circulation diagrams for architecture and urban design using multi- agent systems. (Doctor of Philosophy). University of East London,
[2] Zee, A. v. d., Vries, D. d. (2008). Design by Computation. The Generative Art Conference, Milan,
[3] Frazer, J. (1995). An Evolutionary Architecture. Architectural Association Publications. Garibaldi,

COMPUTING GENERATIVE MODEL

In this thesis, the whole design process, including all stages, is modeled in Grasshopper. Figure 3.2 is an example of a generative design process developed in Grasshopper. In such an algorithm, any kinds of objectives can be chosen, such as climate, functionality, and structural efficiency.

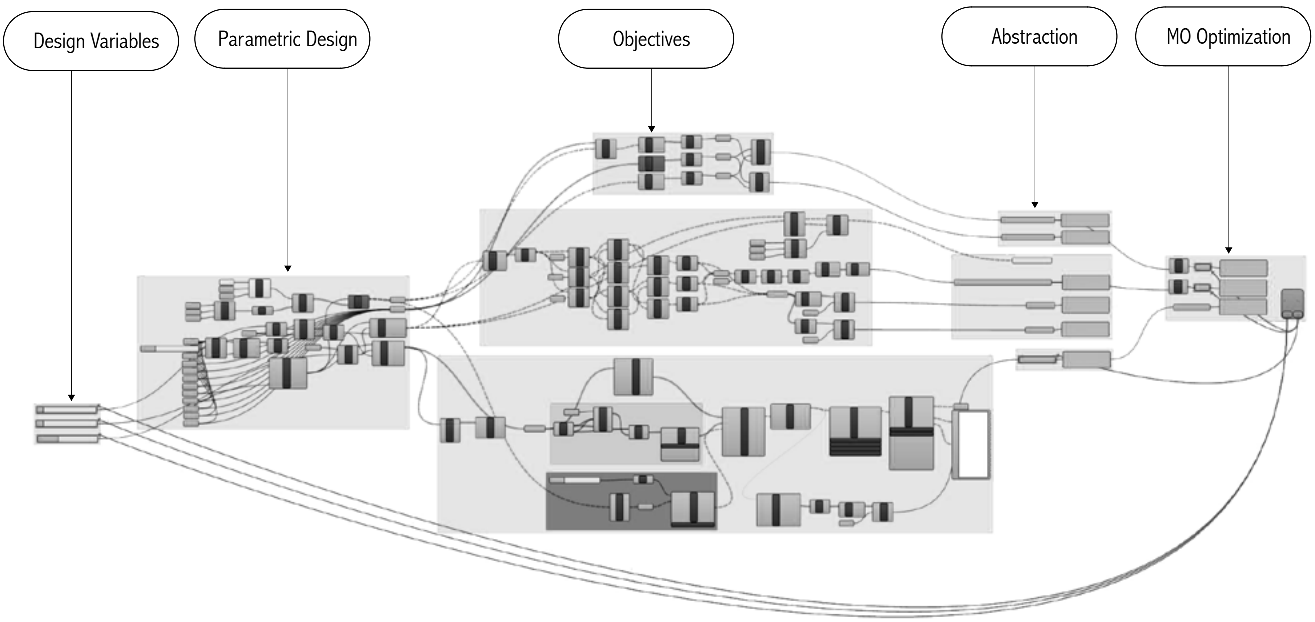

Figure 3.2: Generative Model in Grasshopper with the Different Stages

Any generative model has four different stages. The first two stages are related to the parametric modeling, including its variables and the parametric design that generates design solutions. The variables, in the first stage, are used as inputs for the second stage. The parametric design, in the second step, generates several solutions for different sets of variables. The output can be a pattern, structure, a massing model or anything else that can be considered as the design proposal.

In the third stage, the parametric model is checked and scored by design objectives. This stage can include simulators and several analyses to evaluate the performances of any possible solutions. In the last stage, the abstraction illustrates the scores, which can be in percentages, between zero and one, or in any unit. Next, the multi-objective optimization is applied to the scores and records them based on related variables. Then, the algorithm learns from the results and picks new values for variables input in the first stage. This design process will continue in a loop to find the optimally performing design.

3.2.1.1 PARAMETRIC MODELLING

The first couple of steps, in generative modeling, are part of the parametric model. Such a modeling system can be developed to quickly generate various design solutions. Next, the final design proposal can be picked from all possible solutions manually or by computational logic.

The values of the design variables can be determined by modifying number sliders in Grasshopper to visually check different possibilities in the designed model. In the optimization process, it can be done by a genetic algorithm that will be discussed later in this chapter.

The computation process is not able to make new solutions; it is just able to pick one from all proposed options from the parametric model. Thus, the parametric model's components, including variables and the logic, need to be defined carefully to produce the maximum possibilities.

COMPUTATIONAL MODEL AND DECISION-MAKING PROCESS

3.2.1.2

The generative models, after any step of processing, produce a set of design solutions that is considered as a new generation. The performances of different solutions need to be mathematically evaluated and scored by the computational model. Results are illustrated in a graph such as that in Figure 3.3. Any point represents a design solution, and its location in the graph shows its performances in objectives. If the algorithm is designed to minimize the scores, the solutions on the bottom left have the best performances in both objectives. However, the solutions in the top-left and bottom-right corners have good performances in just one of them. At the end of the design process, designers need to check all dominant solutions and make the final decision. It is true that the generative system plays an important role in the decision-making process, but still it is the designer who sets the logic behind the algorithm:

"The architect is recast as the controller of processes, who oversees the formation of architecture [1]."

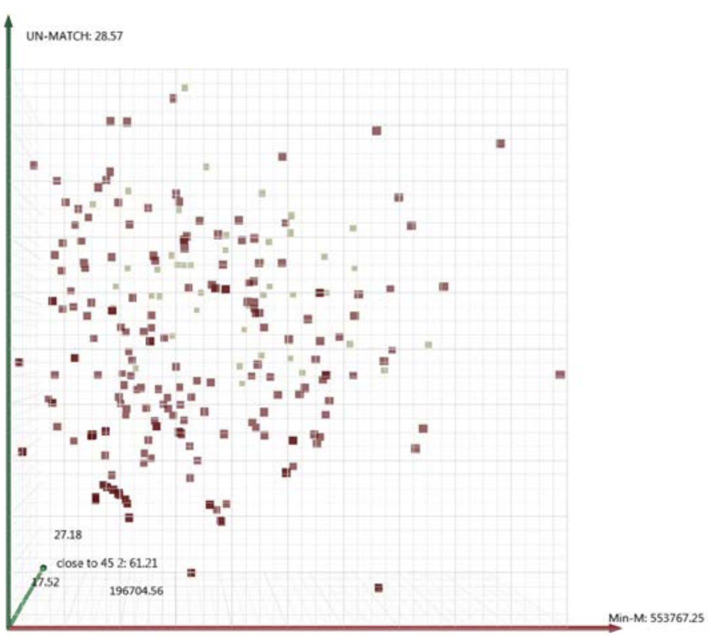

Figure 3.3: The Generative Solutions

[1] Neil Leach, David Turnbull, Chris Williams. (2004). Digital Tectonics. Wiley-Academy,

3.2.1.3 EVOLUTIONARY OPTIMIZATION

In complex systems with several variables, the big number of possible solutions makes it slow, sometimes impossibly slow, to check all possibilities, even when powerful computers are used. Thus, genetic algorithms (GA), based on biological evolution mechanisms, are proposed to find the best answer in a faster and more efficient way. With such a system, designers can deal with multiple-objective systems with more and more complex variables[1].

In any step of processing, a set of variables is called and the solution is recorded with its genes (design variable). The first solution set is generated randomly. The algorithm produces the next generations by mimicking biological reproduction and paring solutions. After any step the genes of two of the best performing solutions are paired to produce a new set of genes. These genes are used as variables for the next step. The solution that is the best match for design needs best will be proposed as the final result [2].

[1] Ciftcioglu, Ö., Bittermann, M. S., Sariyildiz, I. S. (2007). A Neural Fuzzy System for Soft Computing. from http://www.bk.tudelft.nl/fileadmin/Faculteit/BK/Onderzoek/Projecten/Computational_Intell igent_Design/doc/205.pdf
[2] Deb, K., Pratap, A., Agarwal, S., Meyarivan, T. (2002). A fast and elitist multi-objective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2), 182-197.

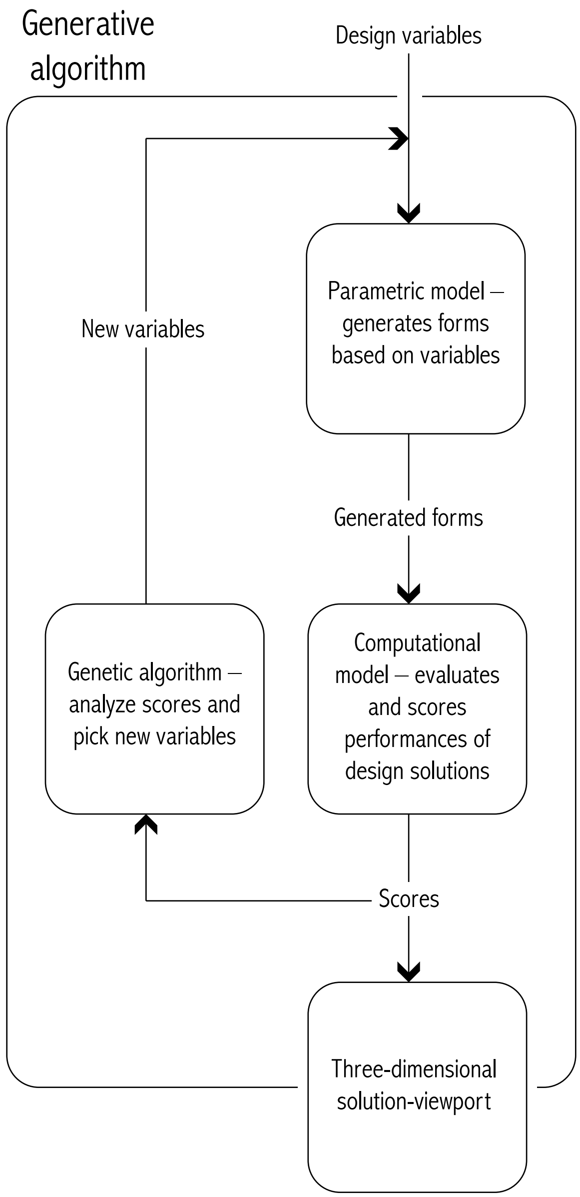

Figure 3.4: Generative algorithm overview

3.3 TOOLS

Generative design is becoming more popular because of recent developments in programming environments such as Open Frameworks[1], Quartz Composer [2], Vvvv [3], Scriptographer [4] and Rhinoceros 3D [5] that are easy to use even for users with limited programming knowledge and experience.

In this thesis, different software programs are used together, but the main one used is Grasshopper [6]. It is a visual programming language designed for Rhino. Rhino is a 3D modeling tool, and Grasshopper works as a plug-in. It can be used to make parametric models, computation models and general generative algorithms. Grasshopper has many advantages in meeting architects' needs. For example, many computational components and plugins are made for Grasshopper that can help designers to analyze different aspects of projects and design algorithms for multi-criteria optimization. In this thesis, plugins such as Octopus[7], for Multi-objective optimization, Lunch Box [8], for parametric design, and Karamba [9], for structural analysis integration, are used in modeling and analytic processes.

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[1] http://www.openframeworks.cc/
[2] http://quartzcomposer.com/
[3] http://vvvv.org/
[4] http://scriptographer.org/
[5] http://www.rhino3d.com/
[6] http://www.grasshopper3d.com/
[7] http://www.food4rhino.com/project/octopus
[8] http://www.grasshopper3d.com/group/lunchbox
[9] http://www.karamba3d.com/

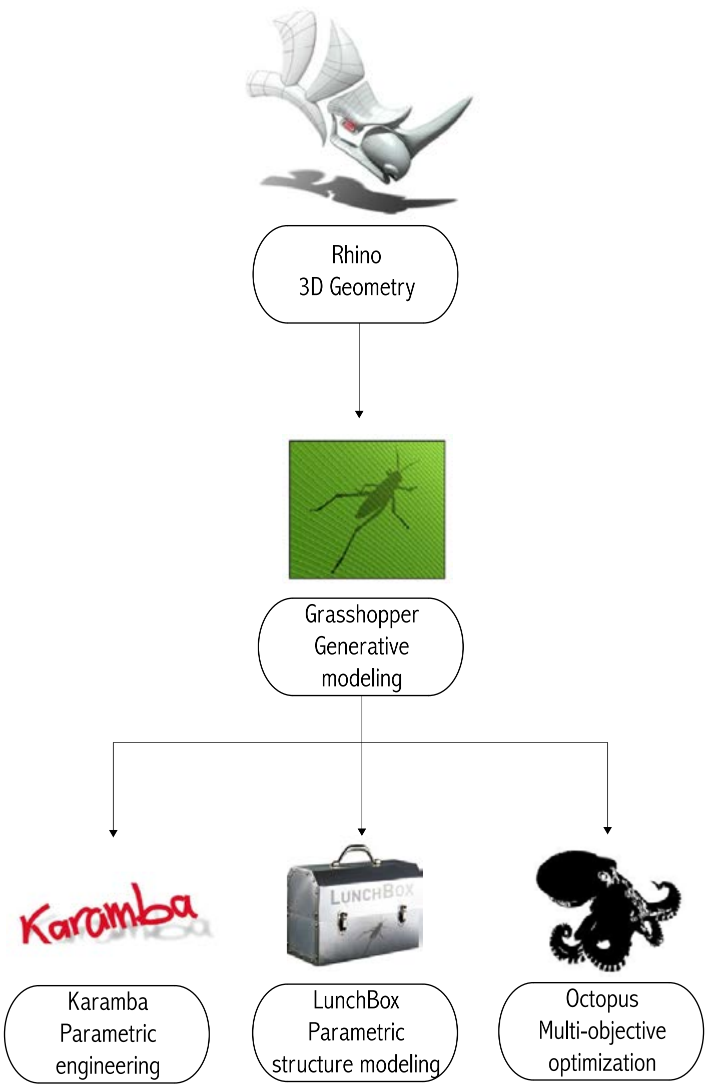
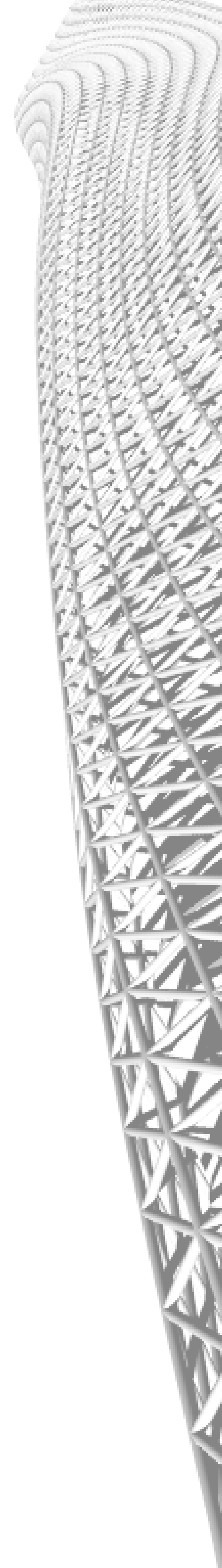


Figure 3.5: Collaboration between different softwares

CHAPTER 4
DIAGRID STRUCTURE



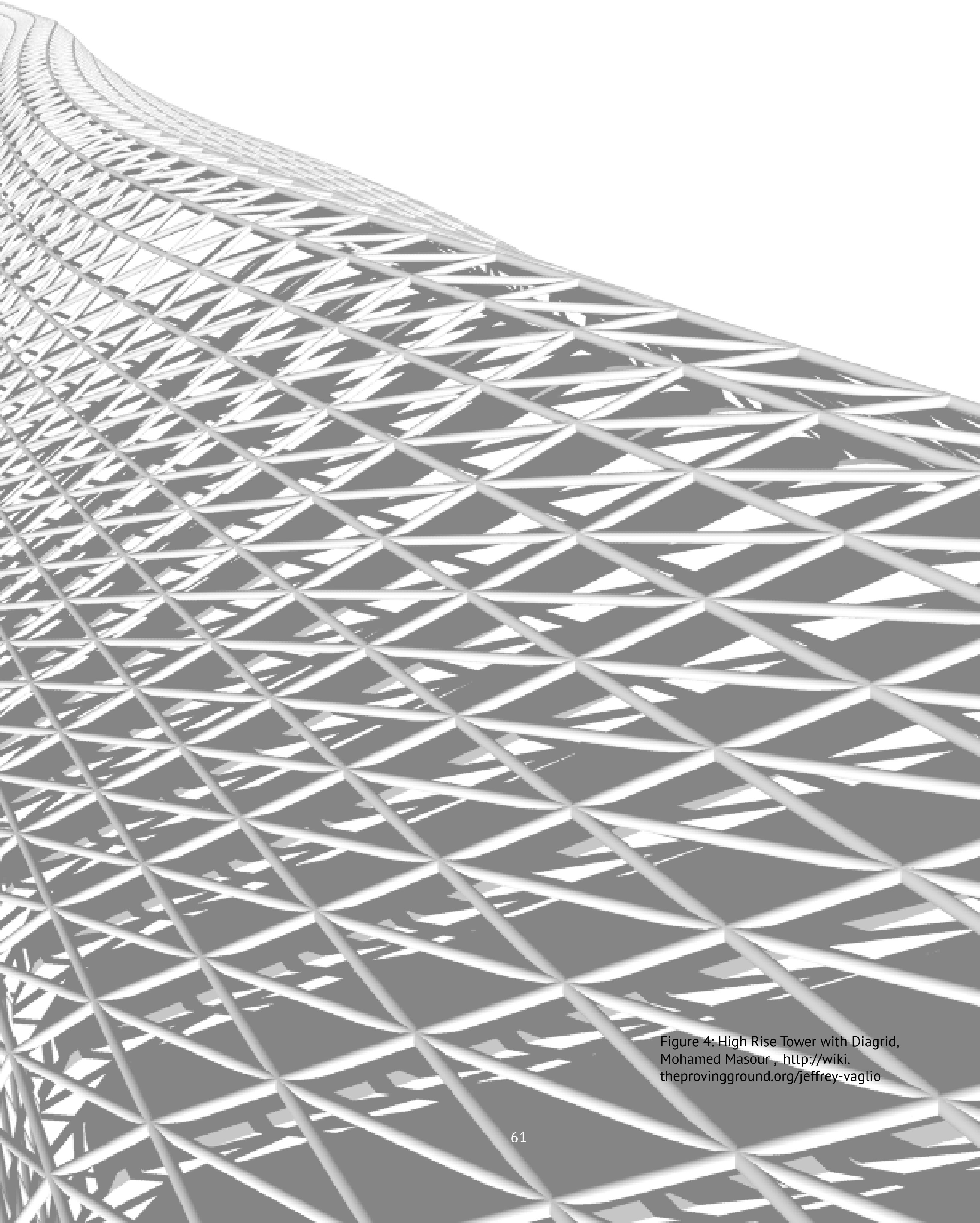


Figure 4: High Rise Tower with Diagrid, Mohamed Masour , http://wiki.theprovingground.org/jeffrey-vaglio

4.1 DIAGRID

The aim of this thesis is to learn and use a generative computational design approach that permits architects to achieve the most efficient diagrid structure.

“Diagrid (diagonal grid) refers to a supporting framework system in which structural elements of metal or concrete are diagonally intersecting. In this framing system, unlike in triangulated systems such as space frames, space trusses or geodesic structures, lattices that include angled structural elements are used as vertical components instead of the usual vertical columns [1].“

Figure 4.1: IBM building in Pittsbugh in the early 1960s, http://www.andrew.cmu.edu/user/ma1f/ArchArch/postwarPGHarchbibliography.html

[1] Han Xiaolei, Huang Chao, Ji Jing, Tang Jiamin,. (2008). Experimental research on the CFST space intersecting connections. State Key Laboratory of Subtropical Architecture Science, School of Civil and Transportation Engineering, South China University of Technology, Guangzhou 510640, China,

In recent years, the diagrid structural system has become more and more interesting for designing tall buildings, because of its structural efficiency and aesthetic potential, arising from the unique geometric configuration of the system [1]. The first building constructed with this structural system was the IBM building in Pittsburgh in the early 1960s (Figure 4.1). Diagrid was not then used again for years until the early 1980s. Norman Foster proposed such a structural system for the Humana Headquarters competition. Unfortunately, this project was never constructed. Later, Norman Foster used a diagrid system in the Swiss Re Building (Figure 4.2) in London and the Hearst Headquarters (Figure 4.3) in New York. After the above-mentioned pioneers, the diagrid structural system got more popular because of recent developments in fabrication technologies and structural simulations [2]. Figure 4.4 illustrates the diagrid timeline, which is a good source for following the development of this structural system.

Figure 4.2: Swiss Re Building, London
http://www.coroflot.com/isabelinfantes/architecture

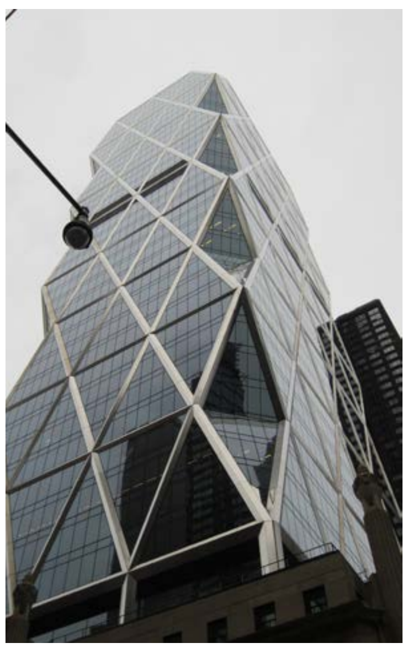


Figure 4.3: Hearst Headquarters, New York
http://macaulay.cuny.edu/eportfolios/ugoretz11/2011/10/03/nyc-art-everywhere/

[1] Terri Meyer Boake. (2014). Diagrid Structures: Systems, Connections, Details. Birkhauser,
[2] K. Moon. (2009). Design and Construction of Steel Diagrid Structures. School of Architecture, Yale University, New Haven, USA,

Figure 4.4: The diagrid timeline
Terri Meyer Boake. (2014). Diagrid Structures: Systems, Connections, Details. Birkhauser,

2008 | 2010 | 2011 | 2012 | 2013 + Under-Construction


Tornado Tower – Doha, Qatar


SIPG Tower - Shanghai,


Canton Tower - Guangzhou, China


O-14 - Dubai, UAE


Guangzhou IFC - Guangzhou, China


KK-100 - Shenzhen, China


Capital Gate - Abu Dhabi, UAE


Aldar HQ - Abu Dhabi, UAE


One Shelley Street - Sydney, Australia


CCTV - Beijing, China


Bow Encana - Calgary, AB, Canada


ArcelorMittal Orbit Tower - London, England


Doha Tower, Qatar


Al Bahar - Abu Dhabi, UAE


Canadian Museum for Human Rights - Winnipeg, MN, Canada


Cleveland Clinic - Abu Dhabi, UAE


Manukau Institute of Technology - Auckland, New Zealand


Leadenhall Building - London, England


Lotte Super Tower - Seoul, Korea


Zhongguo Zun - Beijing, China

4.2 WHY DIAGRID

In tall buildings, the main problem that governs the design is lateral loads, instead of the gravitational loads in shorter building. Thus, systems that are more efficient in achieving stiffness against lateral loads are considered better options in designing tall buildings. The diagrid system is one of the most efficient lateral resisting systems, and this feature is caused by its triangular configurations [1]. Diagonal elements in this system are able to resist both gravity and lateral loads, while diagonal elements in other systems, such as conventional braced frame structures, can resist only lateral loads. Thus, the structure can be stable with minimum or even no vertical elements [2]. Such elimination of structural elements causes some architectural advantages such as more flexibility on the floor plan and less obstruction of the outside view. These are the most important differences between diagrid and other exterior-braced frame structures.

In addition to the above-mentioned architectural advantages, the diagrid system increases the efficiency of material consumption. For instance, in stiffness-based design methodology, the horizontal stiffness of a regular diagrid is calculated by the following formula:

$KH \approx (AE/h) \sin\theta \cos2\theta$

And the vertical stiffness is calculated by the following formula:

$KV \approx (AE/h) \sin3\theta$

Comparing these formulas and the stiffness of the equivalent rigid frame or braced frame structure shows how the diagrid structural system provides the same stiffness with less material consumption[3].

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[1] Kyoung-Sun Moon, Jerome J. Connor, John E. Fernandez. (2007). Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design. Department of Architecture, University of Illinois at Urbana–Champaign, Illinois, USA,
[2] Jessica Nicole Sundberg. (2009). A Computational Approach to the Design of Free Form Diagrid Structures. Massachusetts Institute of Technology,
[3] Barry Charnish and Terry McDonnell. (2008). "The Bow": Unique Diagrid Structural System for a Sustainable Tall Building. CTBUH 8th World Congress,

Studies, such as "The Bow" by Barry Charnish and Terry McDonnell, have concluded that, if a diagrid system is properly engineered, its final weight can be 20% less than other systems such as braced tube structures. In "The Bow", two systems, one a diagrid, the other a moment-frame one, both in steel, are used to design a 59-story tower in Calgary. Comparing the steel consumption from these two systems proves that the diagrid system is 20% more efficient than the conventional moment-frame structure for such a tall building (Figure 4.5)[1]. In addition to its technical advantages, the configuration of the diagrid system can make a unique appearance for the building and provide additional aesthetic value to the building itself. But aesthetic and structural efficiency are not the main reasons that make this system interesting; rather it is its potential in making free-form structures that is the most important reason. Diagrid technology has been used for several projects with complex geometries such as CCTV in China (Figure 4.6) and the Capital Gate in the UAE [2].


Figure 4.5: The Bow, Calgary, http://www.josienicolephotography.com/?_escaped_fragment_=commercial/c1cwu


Figure 4.6: CCTV, China, http://www.fromthebaytobeijing.com/day-45-in-beijing-cctv-tower/

[1] Barry Charnish and Terry McDonnell. (2008). "The Bow": Unique Diagrid Structural System for a Sustainable Tall Building. CTBUH 8th World Congress,
[2] Terri Meyer Boake. (2014). Diagrid Structures: Systems, Connections, Details. Birkhauser,

4.3 STRUCTURALLY OPTIMIZED DIAGRIDS

In recent years, several studies and projects have been made in the field of optimization diagrid structures. They mostly have one purpose: achieving the most efficient structural system. In these studies, efficiency is defined as the ratio of the load carried by a structure to its total weight (strength to weight ratio). A structure is efficient if it has the maximum strength with the least weight (Sandaker 2007). To achieve this goal, different aspects of the diagrid structure that act as variables in the optimization process are considered: the structural pattern, diagrid angles, height of the grid elements, and intensity of the structures. One or a set of these features of a diagrid structure can be considered as the variable in the optimization process.

4.3.1 STRUCTURAL PATTERNS

The geometry of structural patterns can play an important role in the form-finding process to achieve the most efficient structure. Several geometries have been used for high-rise or mid-rise buildings. For example, the paper "The Application Of Non-Routine Structural Patterns To Optimize A Vertical Structure" by Eunike Kristi Julistiono presents the use of non-routine structural patterns to replace the orthogonal pattern mostly used in other vertical buildings to create an optimum design of perimeter structure for vertical buildings [1]. Three non-routine structural patterns – triangular, hexagonal and diamond – were chosen for examination based on their benefits (Figure 4.7).

According to this paper, the triangular pattern is the most efficient for both medium-rise and high-rise buildings; however, the hexagonal- pattern is the least efficient design. A structure with triangular pattern is almost five times lighter than a hexagonal one.

---

[1] Eunike Kristi Julistiono. (2009). The Application Of Non-Routine Structural Patterns To Optimise A Vertical Structure. Department of Architecture, Faculty of Civil Engineering and Planning, Petra Christian University,

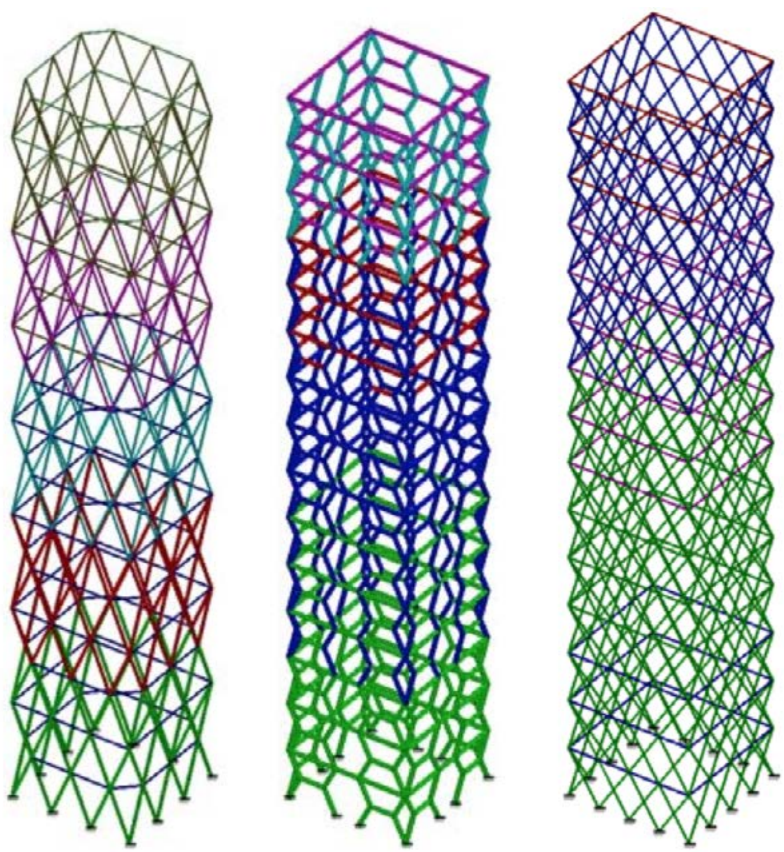

Figure 4.7: 3D models of high-rise structural solutions.

4.3.2 DIAGRID ANGLES

Any building is under shear and axial loads. If the axial loads govern the design, structural elements need to be more vertical. Nevertheless, more horizontal elements are more efficient in resisting stress from shear.

According to the study by Moon et al. [1], to achieve the maximum shear rigidity, the typical module angle should be 35 degrees; however, it is 90 degrees for bending stiffness. In diagrid structures, without any vertical columns, elements should be designed for both shear and bending stiffness. Thus, to achieve the optimal design, both conflicting requirements need to be considered in the optimization process.

Thus, the angle of the structural elements plays a significant role in the optimization process. Moreover very tall buildings do not need same shear and bending stiffness along elevation. Thus, diagrid elements with more vertical elements towards the base and more horizontal elements for upper levels provide more efficiency than uniform grid modules [1]. As a result, to achieve the most optimal diagrid for such tall building, we need more vertical elements at the base and more horizontal elements at the top of the building. The same optimization process influences the diagrid structure for the Lotte Super Tower in Seoul [2].

Illustrated in Figure 4.8, the form-finding process controls the angle of elements based on structural analysis to achieve the optimum design.

[1] Kyoung-Sun Moon, Jerome J. Connor, John E. Fernandez. (2007). Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design. Department of Architecture, University of Illinois at Urbana–Champaign, Illinois, USA,
[2] William F. Baker, Charles M. Besjak, Brian J. McElhatten, Preetam Biswas. (2009). 555m Tall Lotte Super Tower, Seoul, South Korea. American Society of Civil Engineers,

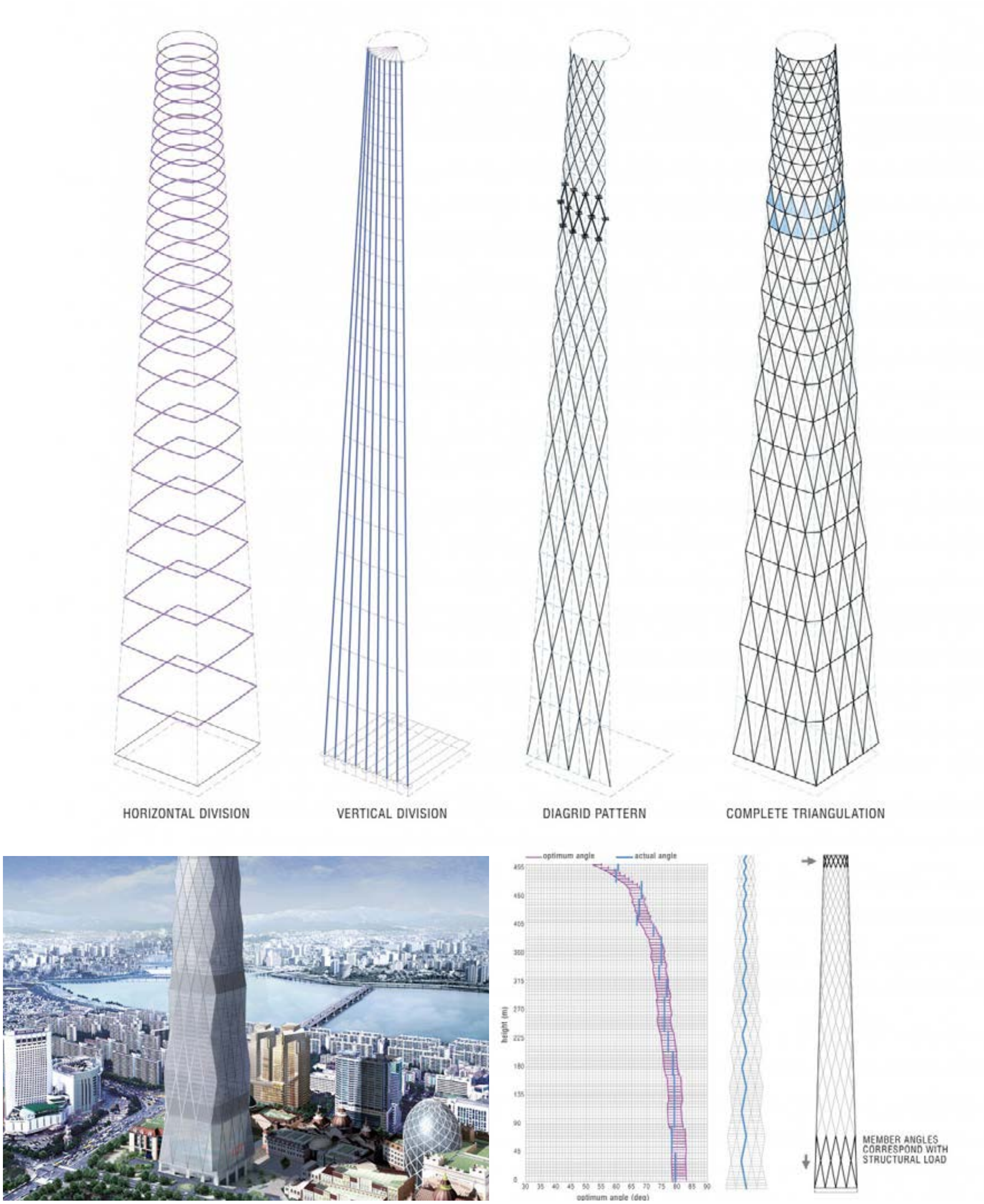

Figure 4.8: Lotte Super tower in Seoul, http://valueofdesign.

4.3.3 HEIGHT OF THE GRID ELEMENTS

In recent years, developments in fabrication technologies have made irregular grids such as the Lotte tower more affordable, although the fabrication process of this kind of structure system is still more expensive than other systems [1]. Therefore, many designers, to save a large amount of money in the construction phase, usually attempt to minimize variety in their proposed nodes. Besides angles, the height of grid elements can be optimized based on the height of the building in this way.

For example, the paper “Design and Construction of Steel Diagrid Structures” by K. Moon from Yale University presents a stiffness-based design method to specify diagrid members’ sizes for tall buildings. This method is used in the design processes of a set of diagrid structures, 40, 50, 60, 70 and 80 stories tall, to find the optimal grid geometries in which the typical floor plan dimensions are 36 m x 36 m with story heights of 3.9 m.

In the case of uniform angle diagrids, studies show that the 6-storey module needs an angle of 63 degrees to achieve the most efficient design for 40- and 50-storey buildings; however, the optimal model is the 8-story with an angle of 69 degrees for 60-storey and taller diagrids [2] (Figure 4.9).

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[1] Diagrids, The New Stablity System: Combining Architecture With Engineering, Terri Meyer Boake, School Of Architecture, University Of Waterloo, 2013
[1] K. Moon. (2009). Design and construction of steel diagrid structures. School of Architecture, Yale University, New Haven, USA,

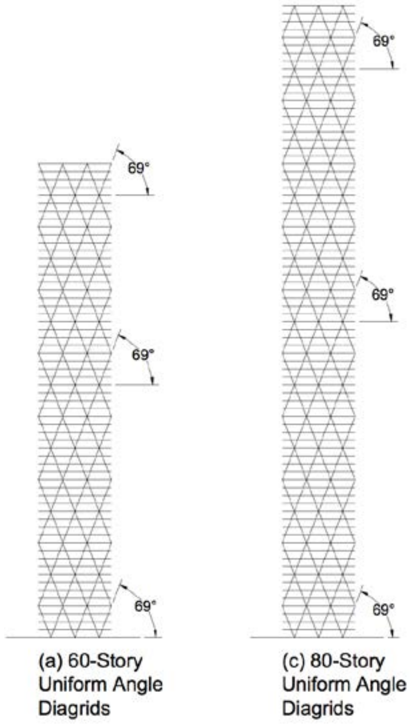

Figure 4.9: 60- and 80-story diagrid structures with diagonals placed at uniform angles

INTENSITY

4.3.4

One of the most common methods for structural optimization is to use a regular pattern with same properties and elements and to control the intensity of the pattern. Altering the existing structural elements or implementing new ones can modify the intensity of the structure.

For instance, in the CCTV Headquarters by Rem Koolhaas, this structure is supported by a bracing system all around the building. First of all, a regular pattern with similar intensity in all points is proposed for the bracing system. Subsequently, the distribution of forces is calculated and different actions are applied on the bracing members based on their categories:

• Adding bracing members
• Keeping them the same
• Removing bracing members

The optimization process runs several times to achieve the efficiency required for the project. [1] (Figure 4.10)

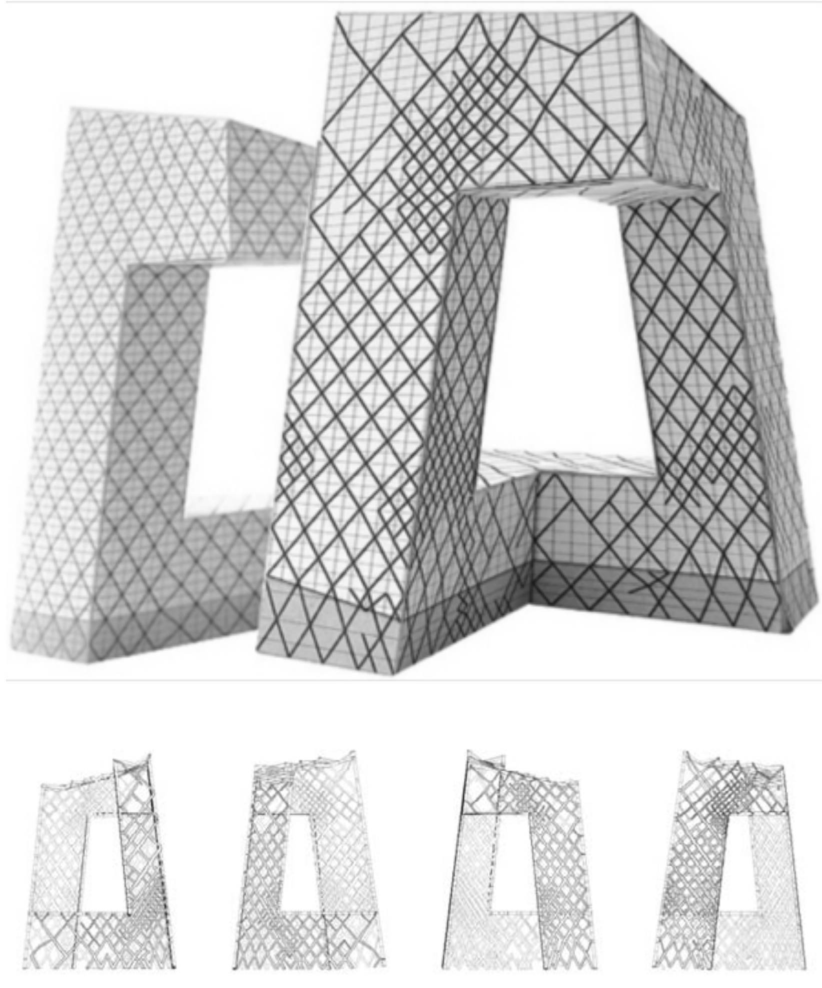

Figure 4.10: CCTV Headquarters by Rem Koolhass

[1] Chris Carroll, Paul Cross, Xiaonian Duan, Craig Gibbons, Goman Ho, Michael Kwok, Richard Lawson, Alexis Lee, Andrew Luong, Rory McGowan, Chas Pope. (2005). CCTV Headquarters, Beijing, China: Structural engineering design and approvals. The Arup Journal,

OPTIMIZATION OF CONSTRUCTION PROCESS

The construction process of diagrid structures, because of the complexity of joints, is critical. Fabricating such joints, especially with a wide range of differentiation in angles, is an expensive and time-consuming process.

In the design process, a simple parametric model is able to draw diagrid structures on any free-form mesh. But without any control in the geometry of grids, the final structure probably includes some unsuitable geometry in which angles of grid elements are extremely high or low.

Generally, elements with extremely high or low angles make the process of welding or bolting more complex, and increase the chance of errors in both the fabrication and assembly processes (Figure 4.11).

Thus, the shape of joint grids, or in other words, the angles of grid elements, plays an important role in constructability of the project. Although it is possible to fabricate almost any complex geometry by using today's CAD/CAM technology, such geometries with unsuitable angles are not the most efficient and economical solution.

Constructability is always a serious issue that must be considered in the design process of diagrid structures. That said, it does not mean all constructible design solutions are equally efficient. For buildings with regular geometries, the fabrication process can be easy and economically compatible with other structural technics because of the limited variation in configuration of structural elements such as the Hearst Headquarters in New York, a building constructed by typical modules. However, irregular building forms create the need for variation in joint geometries, which generally increase the difficulty of the fabrication process.

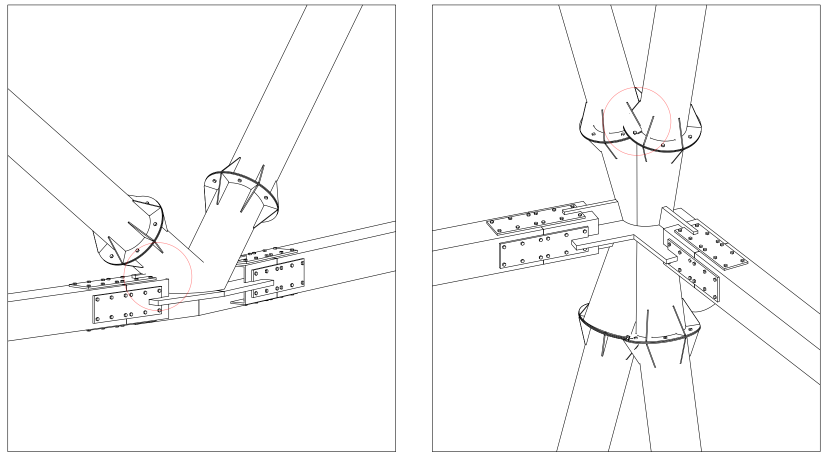

Figure 4.11: Errors in fabrication because of high or low angles

In addition to the fabrication process of the diagrid structure, unsuitable geometries of models can also cause problems in fabrication of cladding systems. Different from usual orthogonal structural systems, which are mostly clad with rectangular shaped curtain wall units, diagrid structures are clad with triangular or diamond shapes that usually follow the geometry of the grid modules [1]. For this reason, in designing a cladding system for diagrid structures, rectangular curtain wall units are used to enhance constructability, performance, structural efficiency and aesthetic expression. However, grid modules with extremely high or low degrees can also cause difficulties in the construction of cladding systems. Figure 4.12 illustrates the influences of grid geometries on cladding systems.

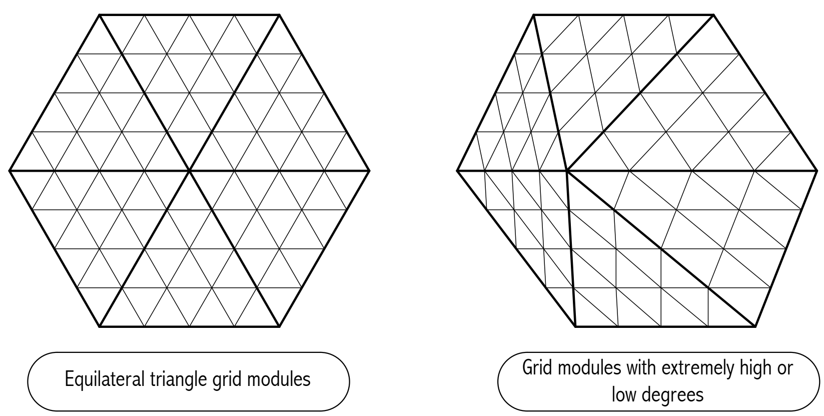

Figure 4.12: The influences of grid geometries on cladding systems.

[1] Terri Meyer Boake. (2013). Diagrids, The New Stablity System: Combining Architecture With Engineering. School of Architecture, University of Waterloo,

All in all, to achieve the most efficiency in the construction process, grid module geometries need to be developed to provide minimum variation and maximum adaptation to equilateral triangles to prevent extremely high or low angles.

CASE STUDY: GENERATIVE ALGORITHM AND OPTIMIZATION OF DIAGRIDS

As mentioned above, diagrid structure variables, including element angles, lengths and the structure intensity, influence the structural efficiency and constructability of the project. Thus, the best design solution is the result of a process in which all of these variables are considered. According to the study in chapter two, such a form-finding process can be developed by a complete generative algorithm.

To make a generative algorithm, the parametric model must first be designed to describe the design mathematically based on defined variables. Input can be one or a set of variables. Other features of the model have to be considered as fixed input that cannot be changed in the process of optimization.

Secondly, the computational model must be established: it provides the main logic that evaluates solutions. A generative model has different inputs and outputs during every step of the process. These outputs can be checked with the definition of the best design in fields of structural efficiency, architectural intent and constructability, and consequently scored. These scores in relation to the initial diagrid design can be interpreted by the evolutionary optimization algorithm to extract new design variables for next the step of processing. After several iterations, the generative model presents the highest performing designs as a final output. As an example, Arup, in collaboration with architects Kohn Pedersen, designed a generative model to propose a bracing system, that provides the maximum efficiency and architectural intent, for Bishopsgate Tower in London.

This tower, more than 300m tall, needed a bracing system of steel tubular cross-sections. To achieve the maximum efficiency, the variable density for the bracing pattern on the façade was considered. Thus, as the tower rises the bracing system needs to be denser.

The form-finding method generates and compares $3x10^{48}$ possible design solutions, which is not possible manually. The algorithm looks for the minimum number of bracing elements necessary to provide enough structural stiffness (Figure 4.13).

For this tower, a new tool was developed to automate the process of decision-making by generating, analyzing, and evaluating performances. In fact, the mentioned method is based on a pattern design that was first proposed in 1961[1]. In this method, the algorithm follows the process of adding and removing bracing elements to achieve the requested efficiency, which is not possible by traditional optimization methods [2].

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[1] Hooke, R and Jeeves, TA. (1961). Direct search solution of numerical and statistical problems. Journal of the Association for Computing Machinery, 8, 212-229.
[2] Chris Luebkeman, K. S. (2005). CDO: Computational design + optimization in building practice. The Arup Journal,

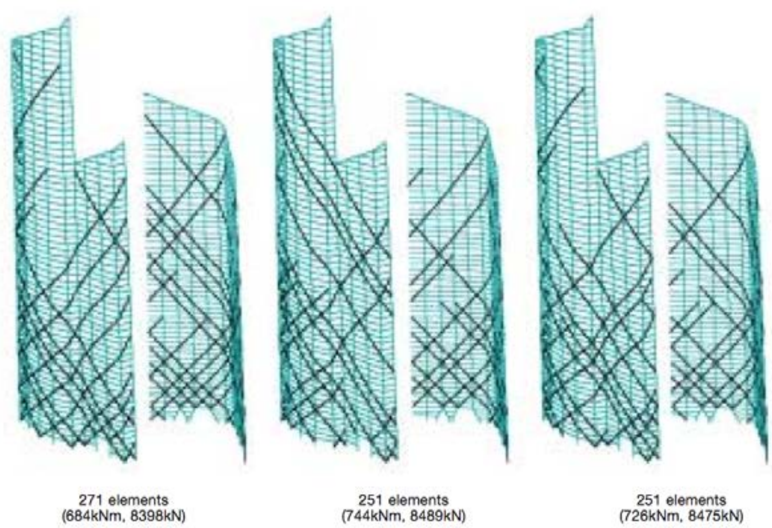
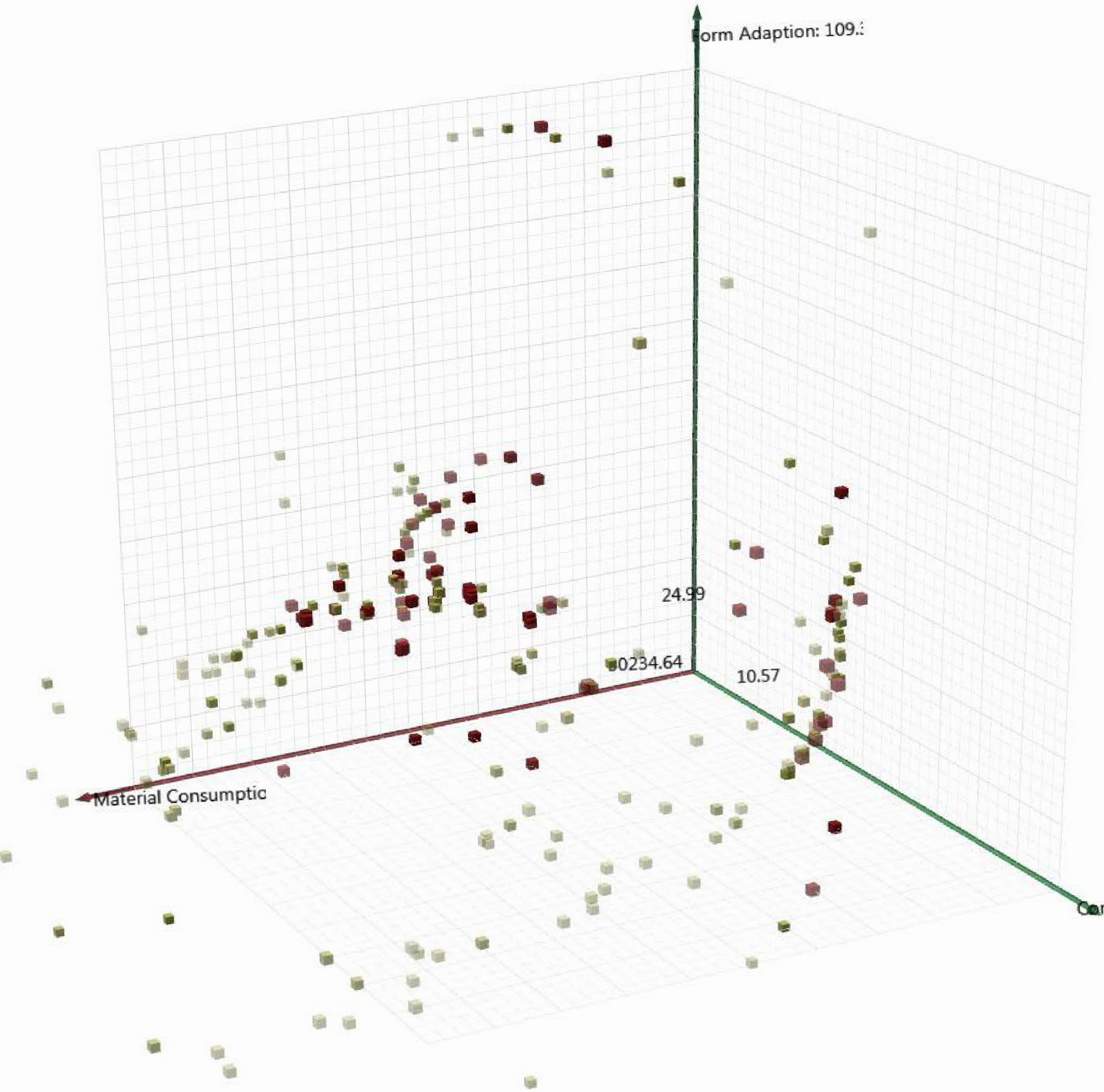


Figure 4.13: Planning application schemes for the bracing system of the Bishopsgate Tower. http://www.futureglasgow.co.uk/extra/pinnacle4.jpg

CHAPTER 5

FINAL DESIGN



Form Adaption: 109.3
24.99
10.57
0234.64
Material Consumptio

5.1 PROPOSED FORM-FINDING METHOD

In this thesis, the focus will be the design of a performance-based complex geometry diagrid structure for the New National Gallery. The performance of a number of objectives is considered in the proposed form-finding process. The objectives include structural efficiency, architectural design intent and constructional performance. Furthermore, a multi-objective optimization process will be used to reach the highest performing design solution. The input of this process is the initial designed form (Figure 5.1) and some external information for drawing grid geometries and the output of this process is a diagrid structure that proposes the highest performances.

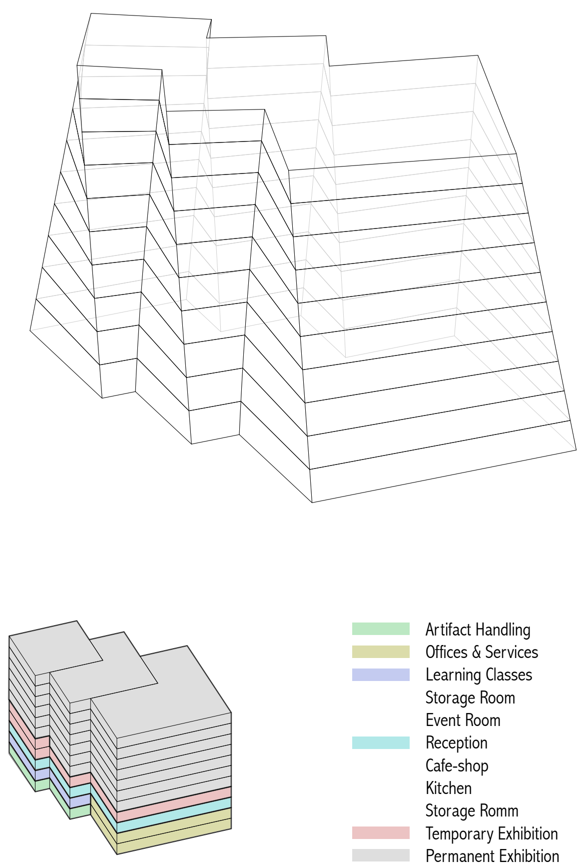


Figure 5.1: Initial Design Form

FORM-FINDING MODEL 5.2

A generative algorithm is designed to generate the defined form-finding process. In this generative model, a parametric model of a diagrid structure is first designed based on defined variables. Secondly, a computational model is designed that can evaluate the performances of objectives. Then a set of new design variables is offered by the genetic algorithm to make a loop in the design process. This process is continued to achieve the highest-performing design. Figure 5.2 illustrates the whole form-finding process.

PARAMETRIC MODEL 5.2.1

The first step of the form-finding process is related to the parametric model of the diagrid structure. In this model, different variables are used as inputs, including the form of the structure and the grid geometry for the diagrid system. These two aspects of the design are parametric independent, but using different sets of inputs can make a wide range of possible solutions.

FORM OF THE STRUCTURE 5.2.1.1

The initial form of the building is designed based on architectural needs such as minimum space necessary for programs and the best arrangement for programs in the building. The result of the design process is an irregular geometry that can be modified by the form-finding system to achieve the highest performance. For example, the form of the building, in addition to the grid geometry, defines the angle of structural elements that play an important role in its structural efficiency and constructability. Figure 5.3 shows how small modifications in the form can structurally influence the grid elements.

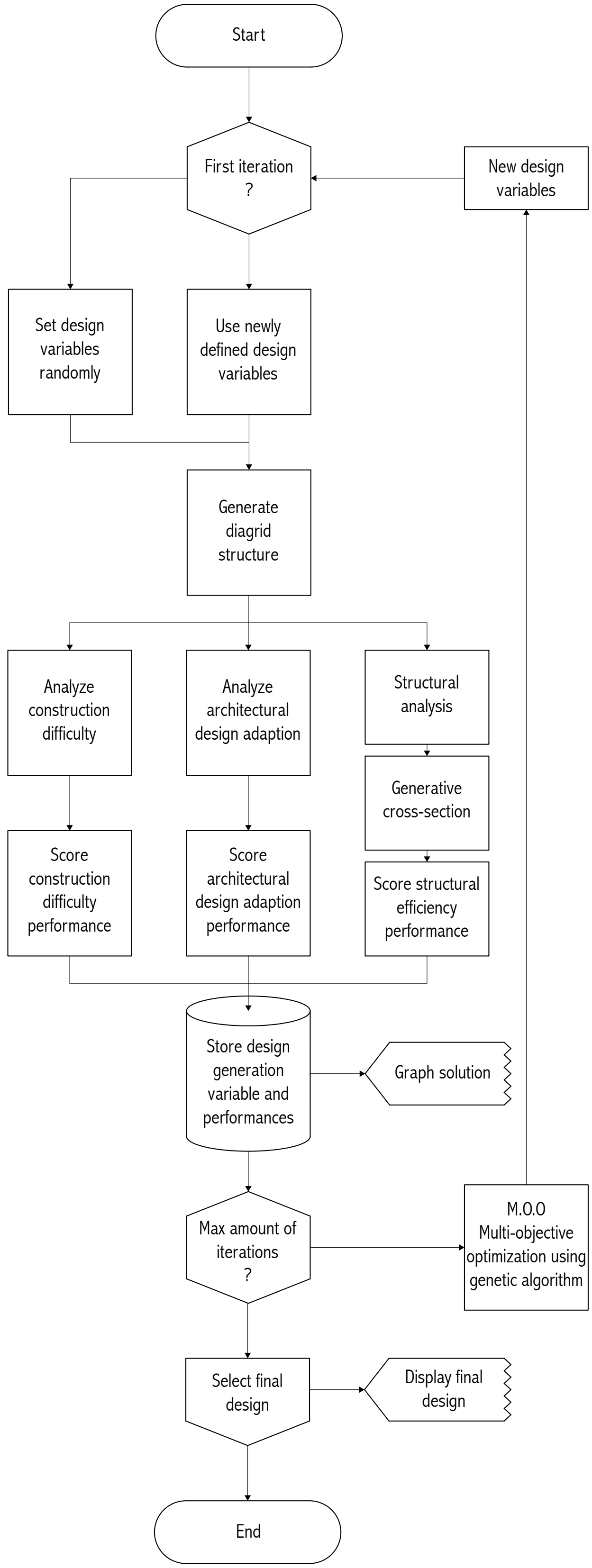


Figure 5.2: Generative model components

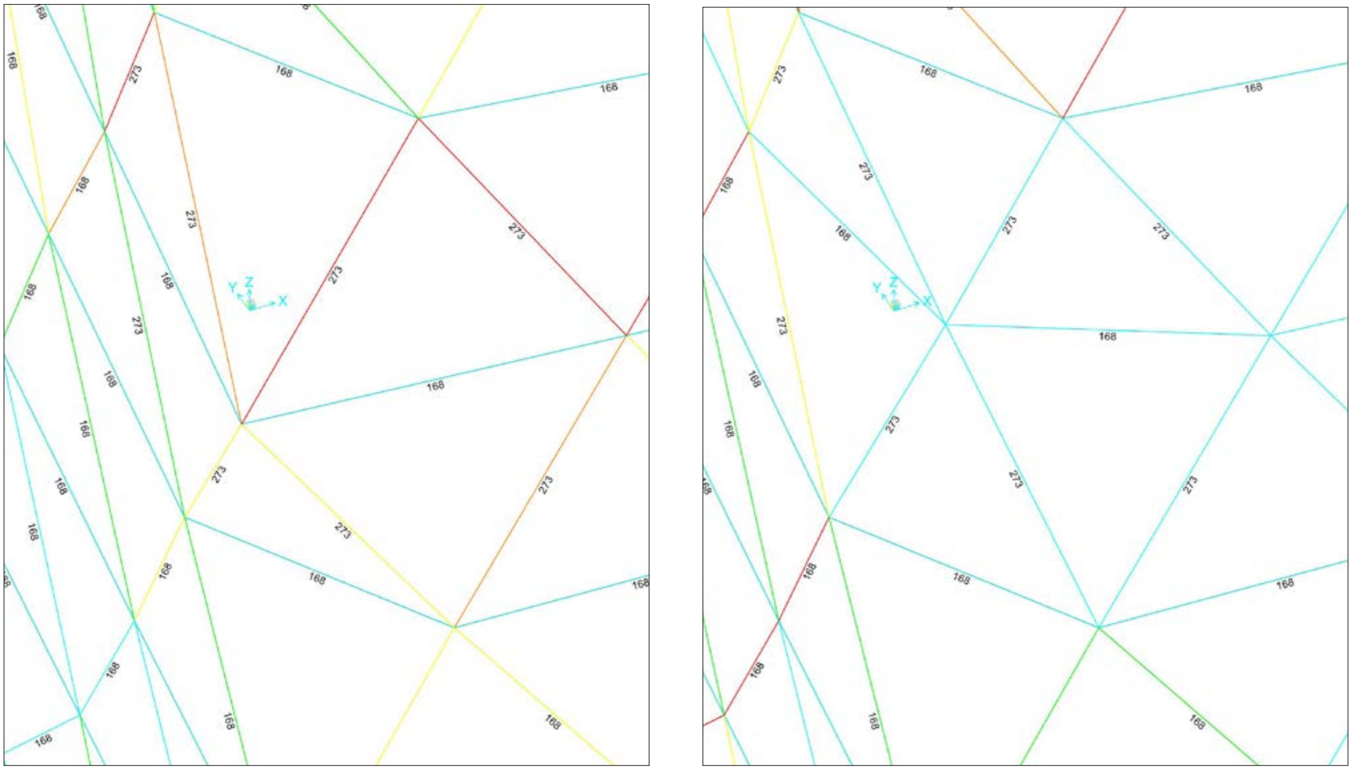
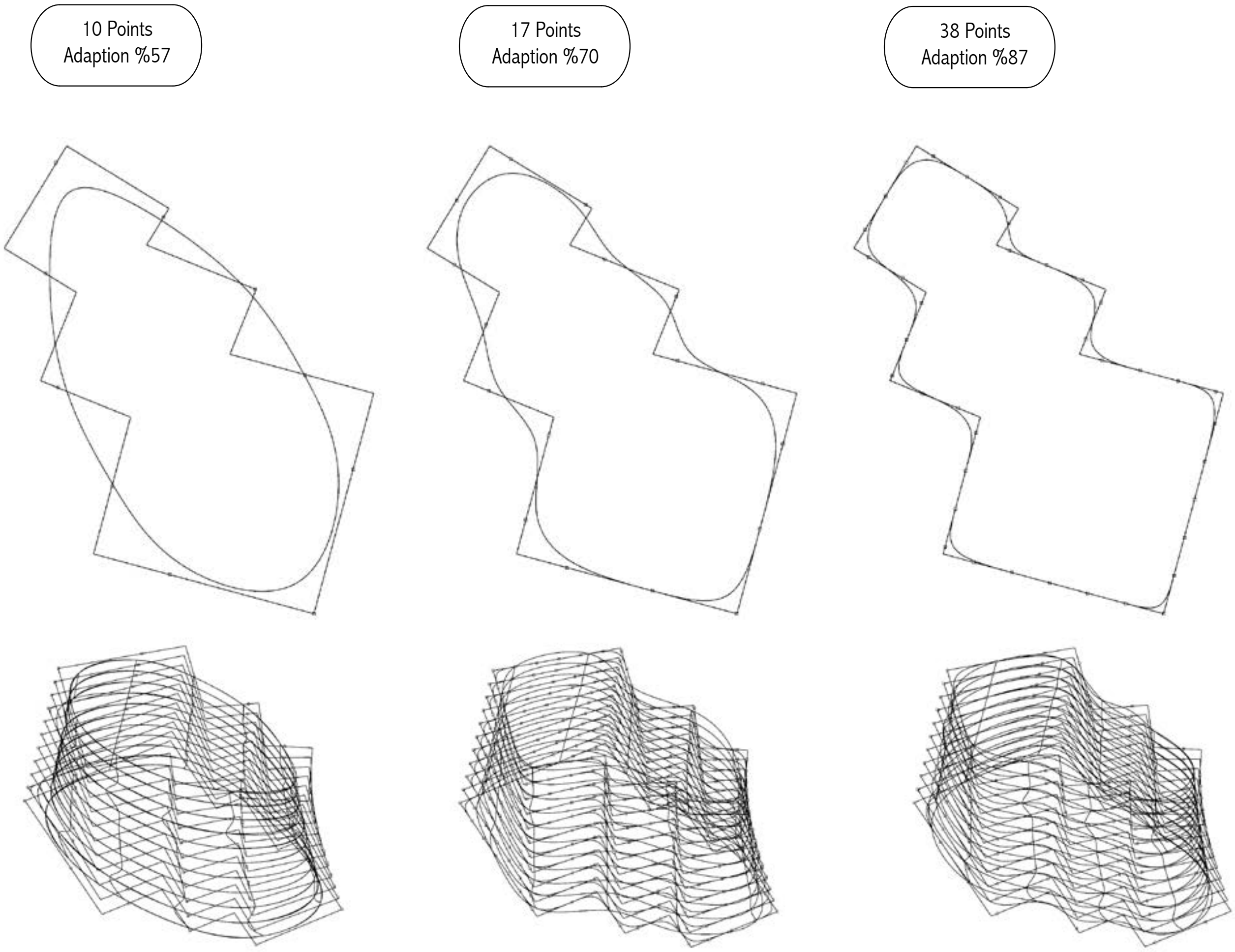


Figure 5.3: Modification in the form and its structural influence on grid elements

The designed method for simplifying the form of the structure is specifically designed for this project to make new solutions by minimizing concavities on the form. It can help to achieve the better performances in constructability and structural efficiency.

In the proposed parametric model, the curves around the slabs are considered as variables. Any curve is defined by a number of points that can be changed. The number of points, at each level, shows how close the proposed geometry is to the initial form or how much the form is simplified. More points mean more adaption, whereas fewer points mean greater simplification. In the next step, curves make a loft that shows the form of the façade and diagrid structure. Thus, the degree of simplification is considered a variable in the parametric model used to define the form of the building. Figure 5.4 illustrates the method of transforming the building's basic form from the initial proposal into more possible solutions.



5.2.1.2 GRID GEOMETRY

Figure 5.4: The method of transforming and simplifying the building's form

The parametric model, in the second step, draws a diagrid structure for the designed form. In this parametric model, the number of elements in each row (diagrid angle) and the height of the rows are considered as variables.

As mentioned in chapter four, the structural pattern, diagrid angles, height of the grid elements and intensity of the structures all need to be determined for each diagrid structure. In this project, to simplify the parametric modeling system, the structural pattern and intensity of the structure are not considered as variables. The triangular pattern is used for all possible solutions and the intensity of the structures would not change in any design solution.

More elements in each row and taller rows mean more vertical triangles, while fewer elements in each row and shorter rows mean more horizontal triangles. More elements in each row and shorter rows cause fewer loads on each element and thinner cross-sections, but fewer elements in each row and taller rows cause more loads on each element and thicker cross-sections (Figure 5.5).

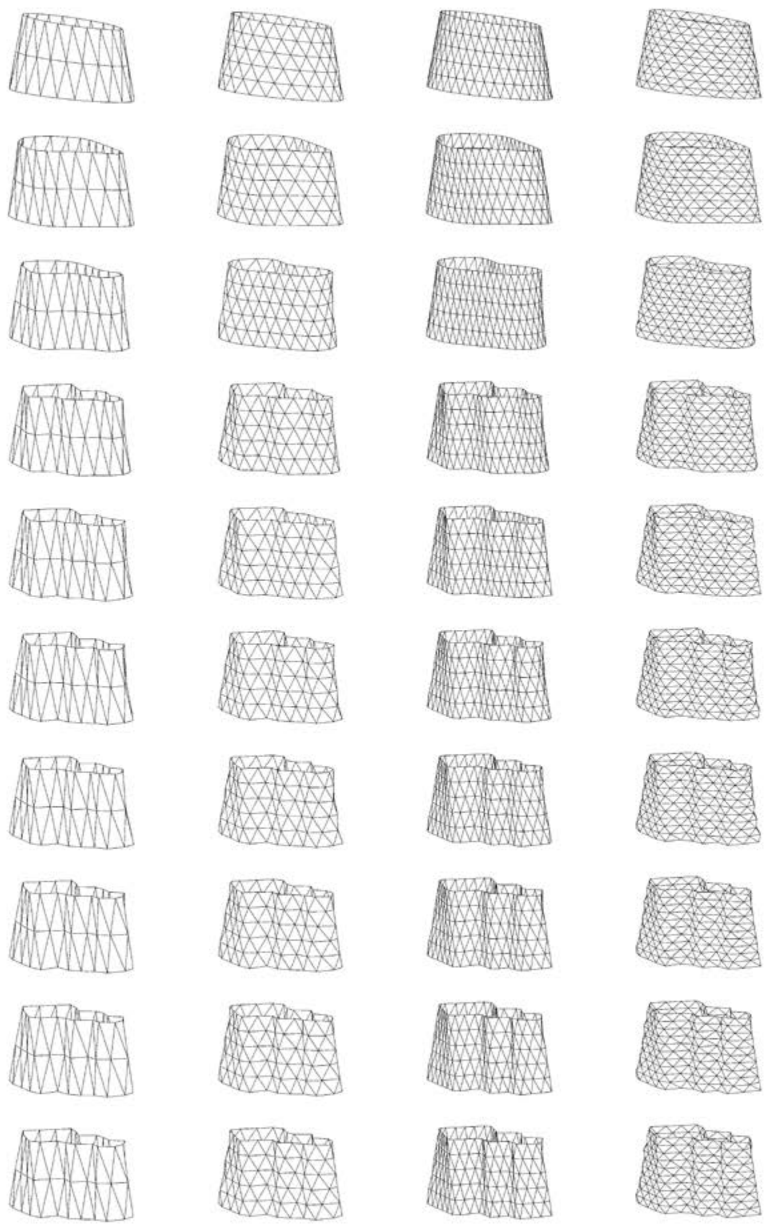


Figure 5.5: Variation in Form and Grid Geometry

5.2.2 COMPUTATIONAL MODEL

The second step of the form-finding process is the computational model. The result from the parametric model is used as input for this step. The proposed computational model is able to evaluate the performance of design solutions and score them. Then, these scores are used for evolutionary multi-objective optimization to find the most desirable solution. Three main aspects will be evaluated: architectural design adaption, structural efficiency and construction difficulty. These objectives are further explained in this chapter.

5.2.2.1 ARCHITECTURAL DESIGN ADAPTION

The first variable, in the parametric model, is the form of the building. The algorithm modifies the base form, which is designed by architects, to achieve the optimum performances. But from a designer's point of view, minimum modification, which means maximum adaptation between the final result and the initial design, is more desirable. Thus the optimum solution in this objective is the exact initial form and any modification is unwelcome. The algorithm compares the initial form and the proposed form by evaluating four areas:

- A: slab areas of the initial form,
- B: Slab areas of the proposed form,
- C: common areas of two sets of slabs,
- D: Different areas of two sets of slabs. (Figure 5.6)

Based on these four values, two variables are defined:

- Form Adaption In Percent 100 x (C - D) / A
- Area Adaption In Percent 100 x B / A

If the variable 'Area Adaption' shows 100 percent, the proposed form provides enough space for, but it does not mean the proposed form is geometrically adapted to the initial design.

On the other hand, if the variable ‘Form Adaption’ shows 100 percent, it means that the proposed form has the highest geometrical adaption to the initial form.

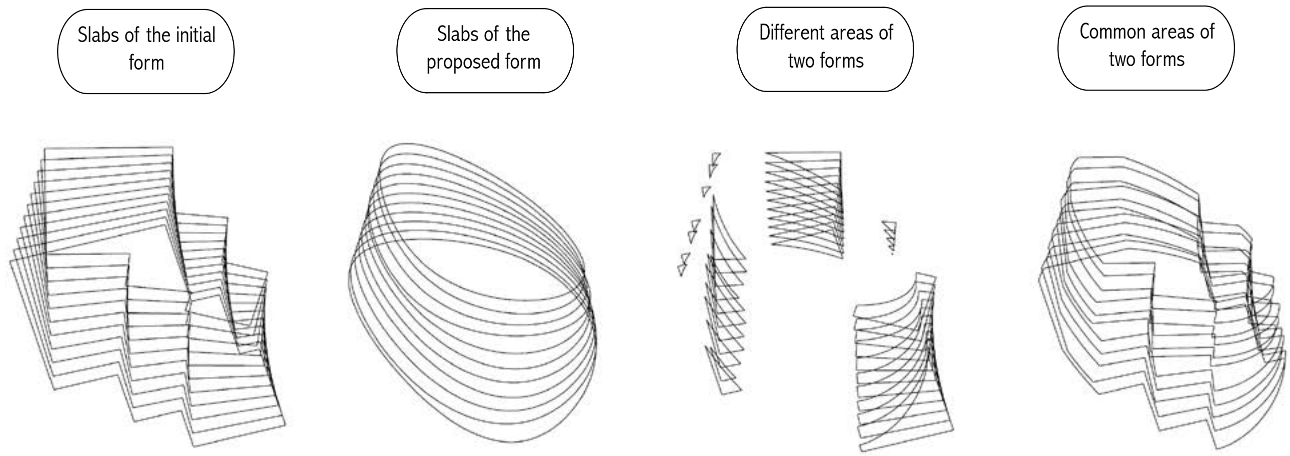


Figure 5.6: Variables for Evaluating the Architectural Design Adaption

STRUCTURAL EFFICIENCY 5.2.2.2

In this thesis, similar to most structural optimization studies, structural efficiency is defined as the ratio of the load carried by a structure to its total weight (strength to weight ratio). The algorithm modifies the form and the number of the elements in the diagrid structure to achieve the minimum material consumption. Karamba, as a structural analyzer, is used in this generative algorithm.

Many software programs are developed for structural analysis that mostly provide better facilities with more accurate analysis than Karamba, such as SAP2000. For example, Karamba is not the best tool for analyzing dynamic loads like wind or earthquake loads. However, none of them are as adapted to Grasshopper as Karamba. This feature makes it the best choice for form-finding processes. Many projects have included Karamba in their form finding processes such as the Music Pavilion in Salzburg Biennale 2011 (Figure 5.7).

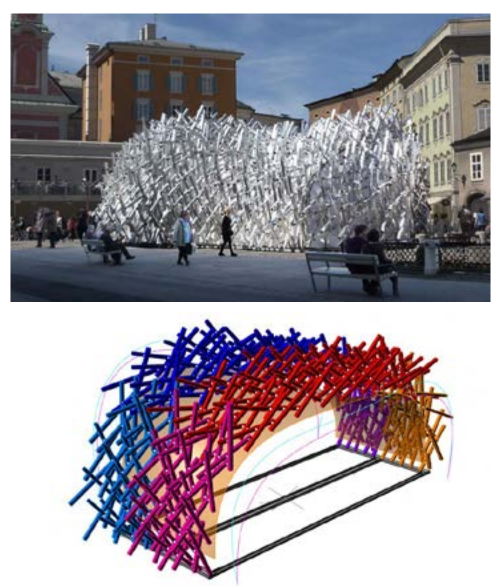
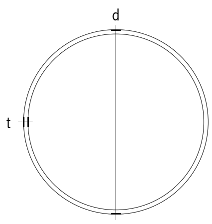


Figure 5.7: Music Pavilion in Salzburg Biennale 2011 by Soma

To simplify the evaluation process, only the axial capacities of steel sections are considered in the structural analysis. Thus, the algorithm, based on a structural analysis (by Karamba plugin) that can determine maximum axial load for each element, calculates the minimum needed cross-section from the Table 5.1. The actual material consumption is equal to calculated cross-sections in kg/m multiplied by length of all the elements in meters. The material consumption will be calculated for all solutions, and the optimum result is the least consumption. The cross-section design is based on the following formula and cross-sections in Table 5.1.

$$C_r = \phi A F_y \left(1 + \lambda^{2n}\right)^{-1/n} \qquad \lambda = \frac{KL}{r}\sqrt{\frac{F_y}{\pi^2 E}}$$



where:
n=2.24 for HSS Class H (stress-relieved), and WWF members
n=1.34 for other hot-rolled, fabricated sections and HSS Class C
k=0.65 for joints fixed against rotation and translation

Table 5.1: Round Hollow Section, Factored Axial Compressive Resistances, r_y

Section: Effective length KL (ft) with respect to least radius of gyration, ry	HFCHS 508	HFCHS 457	HFCHS 355	HFCHS 273	HFCHS 219	HFCHS 168	HFCHS 139
16	866	767	429	299	145	98.1	60.1
17	859	760	423	291	139	91.6	54.4
18	853	753	416	284	133	85.2	49.0
19	846	746	409	275	128	78.9	43.9
20	839	738	402	267	122	72.7	39.7
21	831	729	395	259	116	66.8	36.0
22	823	721	387	250	110	60.9	32.8
23	815	712	379	242	104	55.7	30.0
24	807	703	371	233	98.6	51.2	27.5
25	798	693	363	224	93.0	47.2	25.4
26	789	684	355	215	87.4	43.6	23.5
27	780	674	346	207	82.0	40.4	21.8
28	770	664	338	198	76.8	37.6	20.2
29	761	653	329	189	71.6	35.1	18.9
30	751	643	321	181	66.9	32.8	17.6

CONSTRUCTION DIFFICULTY

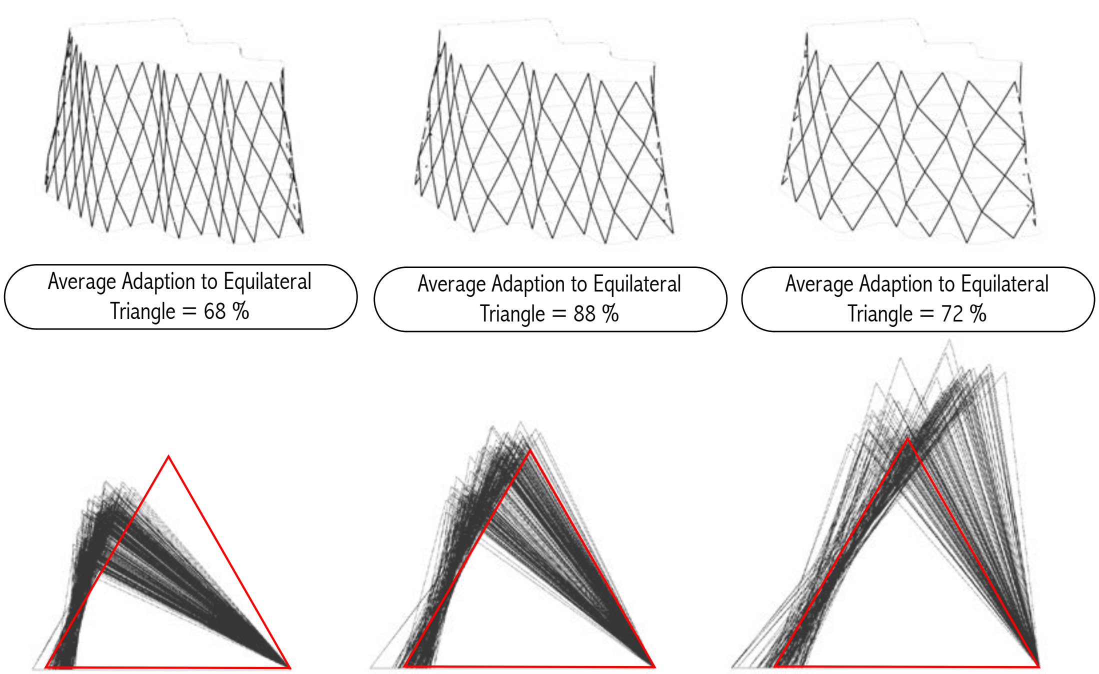
5.2.2.3

According to the above-mentioned studies, grid models that are geometrically closer to equilateral triangles are more efficient in construction processes. Thus, this algorithm, to optimize the construction process, calculates all angles of modules and finds the best possible solution in which angles have the minimum differentiation, with 60 degrees. The algorithm defines three variables including:

- Average Adaption to Equilateral Triangle in Percent
  $100 - (|(D1+D2+...+Dn) - 60n| \times 100) / 180$
- Max Angle — Max $[D_1, D_2, \ldots D_n]$
- Min Angle — Max $[D_1, D_2, \ldots D_n]$

Information from ‘Max Angle’ and ‘Min Angle’ shows the worst elements in case of constructability. If these elements are technically constructible, all elements can be fabricated as well. However, it does not mean all constructible solutions are equally easy to fabricate. The variable ‘Average Adaption to Equilateral Triangle’ can show the best solution between all possible ones (Figure 5.8).

Figure 5.8: Average Adaption to Equilateral triangle



5.3 MULTI-OBJECTIVE OPTIMIZATION

For multi-objective optimization, the Octopus plugin is used in this thesis. This tool looks for the best solution for defined objectives by producing a set of possible optimum solutions that ideally reach from one extreme solution to the other by genetic algorithms. Octopus totally satisfies our needs in this project. It is developed to replace the only tool in Grasshopper for genetic modeling. The most important development is related to its ability to handle up to six objectives and show results in a two- to six-dimensional solution-viewport.

After any step of processing the genes of two of the best performing solutions are paired to produce a new set of genes. These genes are used as variables for the next step. Finally, Octopus shows results from each step of a computation in a solution-viewport such as the Figure 5.9. Any axis illustrates scores for related objectives. Octopus reduces the number of possible solutions and allows designers to make the final decision between limited options.

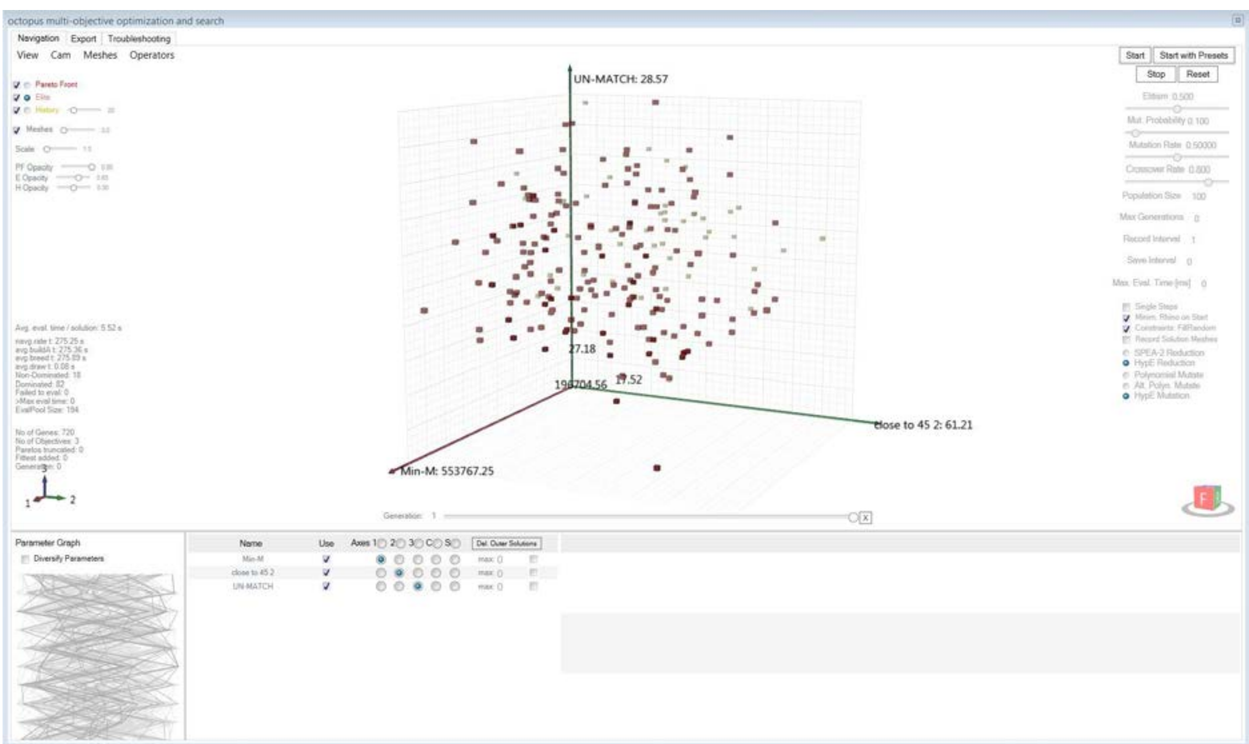


Figure 5.9: Octopus interface

THE FINAL SOLUTION

In evolutionary multi-objective optimization, to find the best fit solution, different solutions are compared. The defined loop ran 70 generations, with 10 solutions each, to compare 700 design solutions. In Figure 5.10, all 700 solutions are shown as points in the 3D graph. No green points survived because they were overcome by better solutions. These points are mostly far from the axis because closer points have better performances in related objectives. Dark red points show non-dominated solutions, which means these solutions provide better performances and have a chance to be chosen as the optimum design by a designer.

The final decision needs to be made by the designer. To make the best decision, the designer has to check all dark red points and compare them based on scores of objectives and any additional

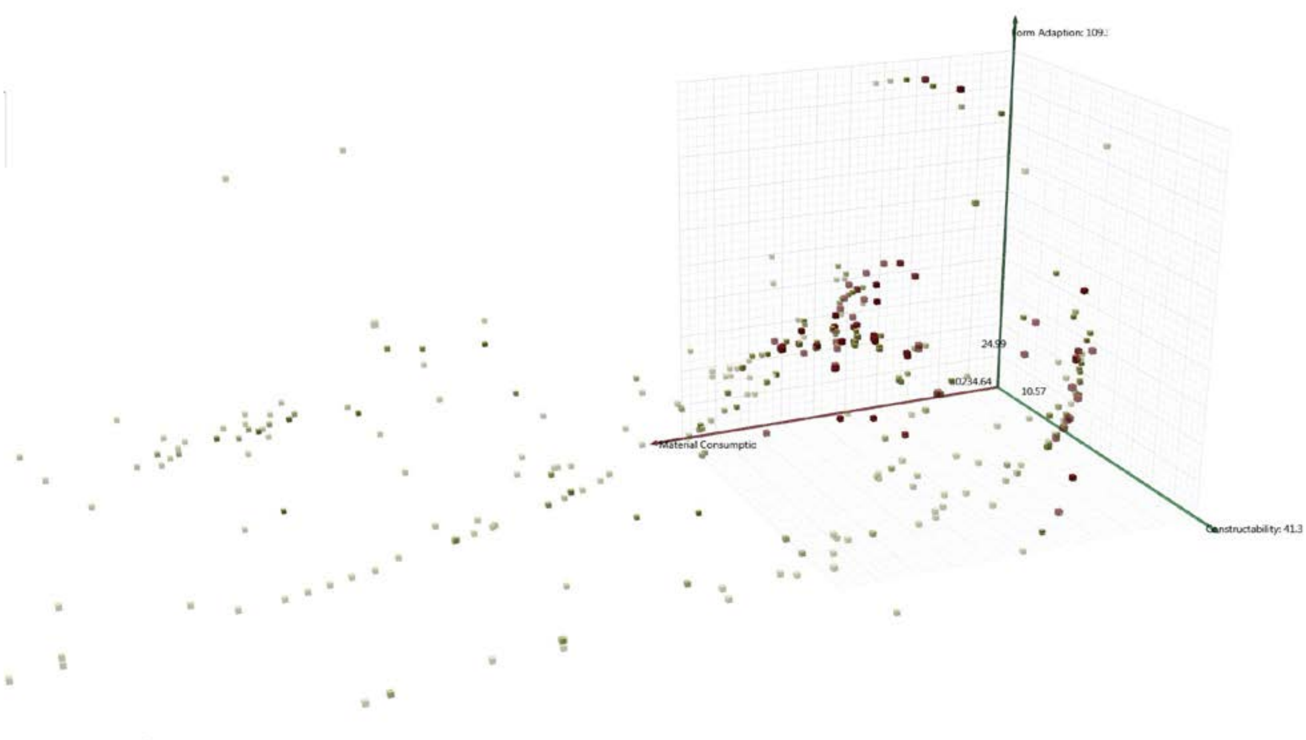


Figure 5.10: All generated design solutions

parameters such as aesthetics. All chosen solutions have high scores in two objectives and moderately high ones in the other. Designers, based on the importance of the objectives, can make different decisions. For example, if the structural efficiency is more important for the designer, the solution that has the highest performance in structural efficiency is the answer; however, it does not necessarily have the best performances in other objectives.

That said, designers usually choose the average best solution: a design that is the point nearest to the origin. This solution is scored high in all objectives. Nonetheless, it is the best in none of them. Usually, a non-average solution is more interesting, because of the benefits in one aspect – but obviously it is not the best decision.

The final design solution, in this thesis, is the average solution. It is the design nearest to the origin. All aspects perform high, but not the highest. As it can be seen in Figure 5.11, all three aspects clearly perform high.

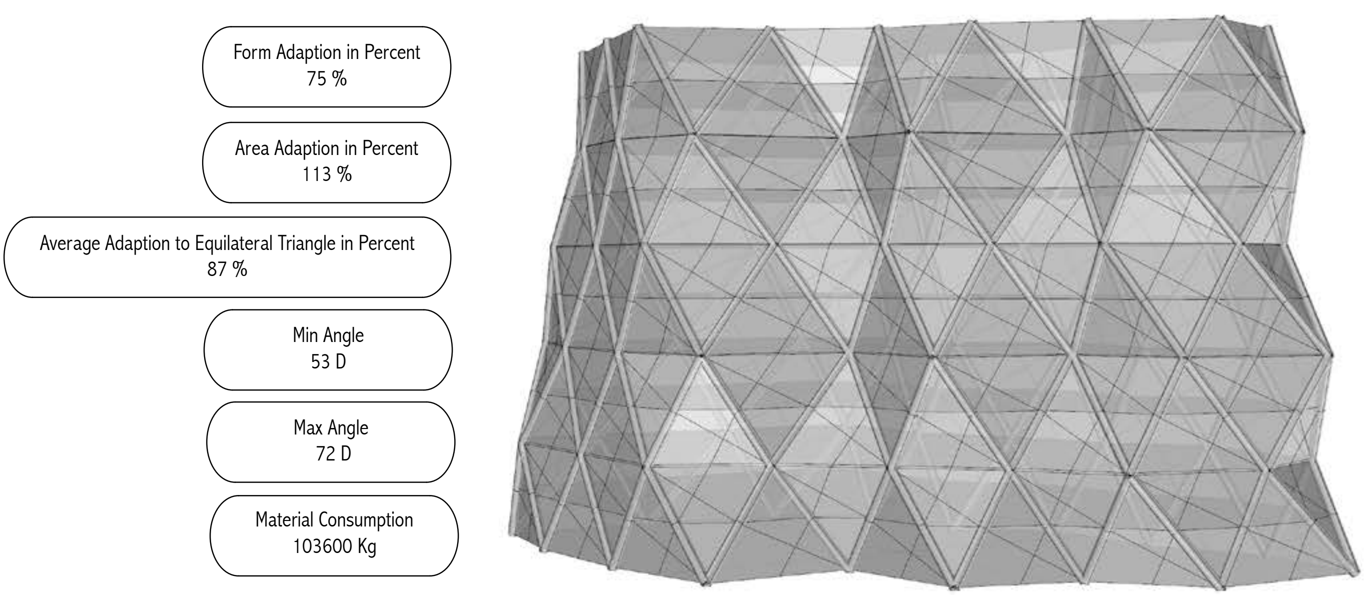
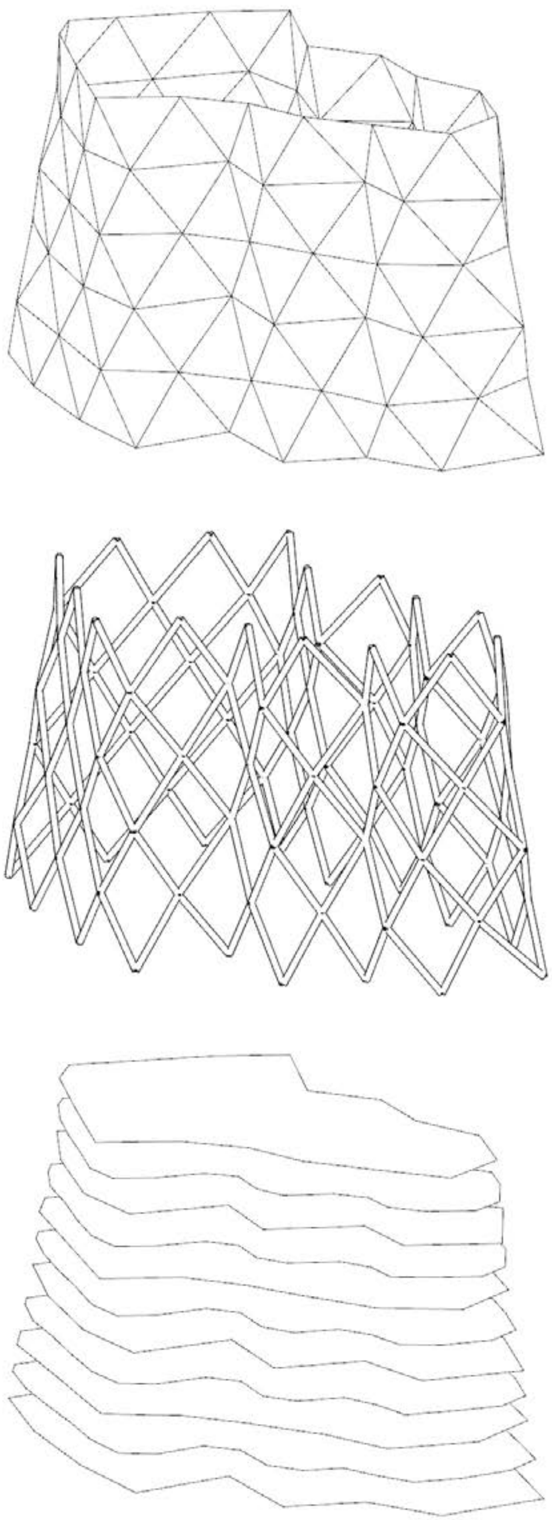


Figure 5.11: Performances of the Final Design



Cladding System

Diagrid Structure

Slabs

Figure 5.12: Final Design Expanded

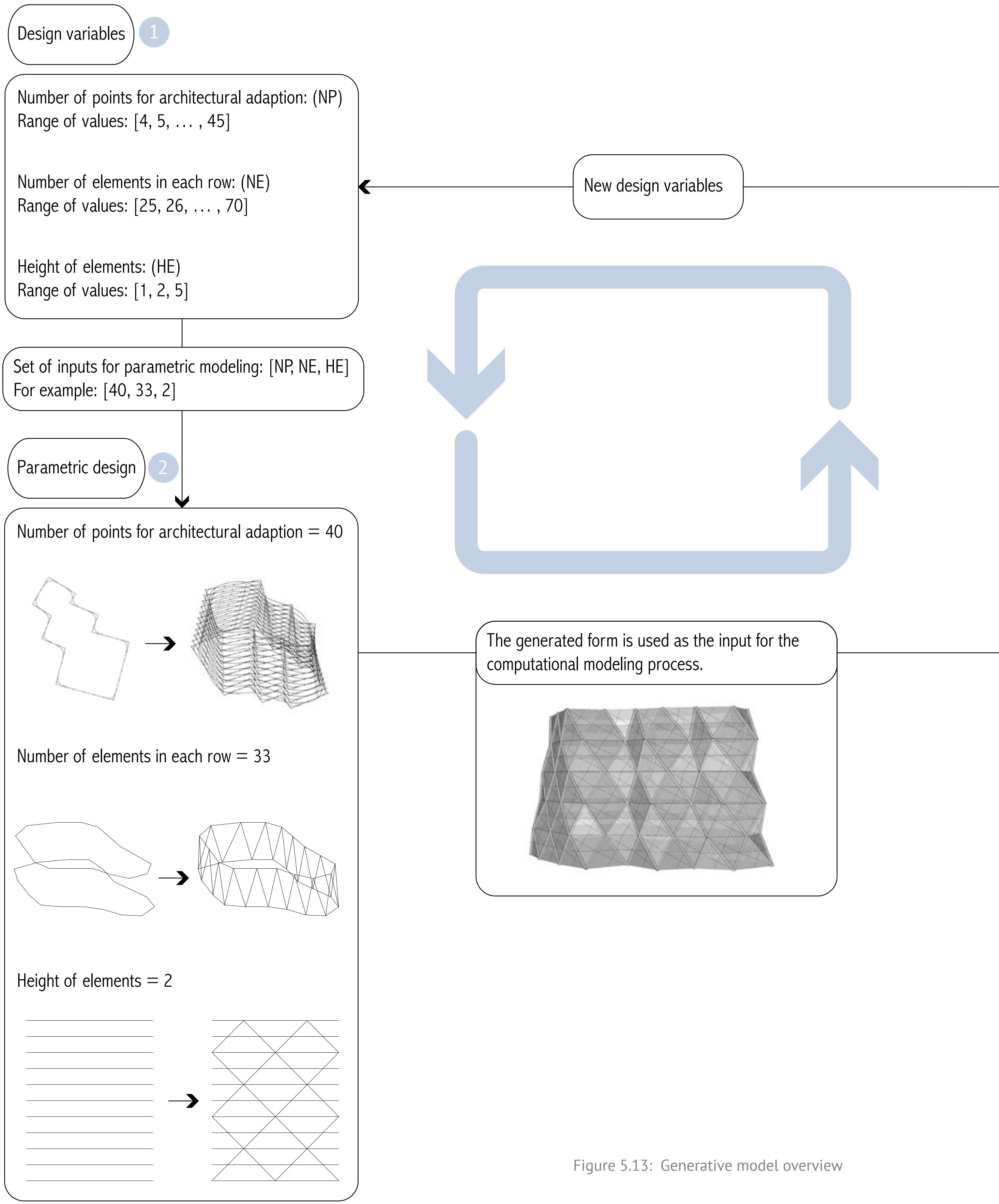
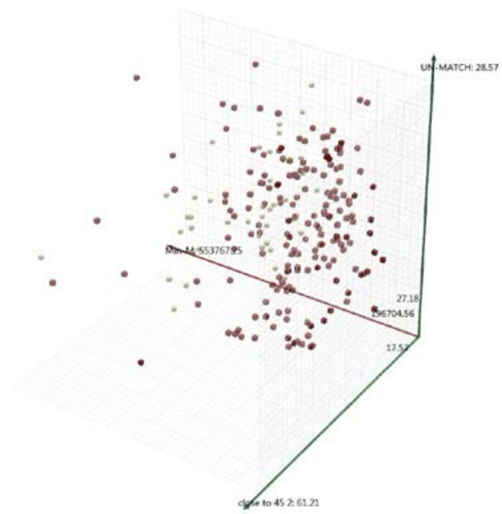


Figure 5.13: Generative model overview

M.O.O Multi-objective optimization using genetic algorithm 4

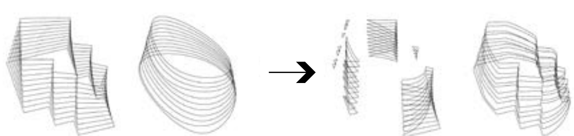
Store design generation variable and performances: [NP, NE, HE]-[MC, FA, AA]

5 All generated design solutions



Parametric design 3

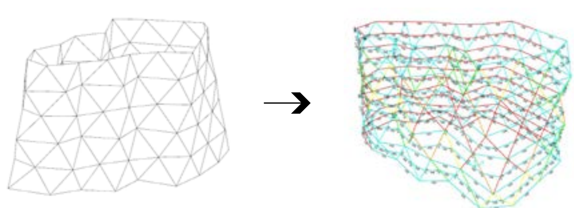
Architectural design adaption: (ADA)



Calculate form adaption in percent: (FA)
100 x (C - D) / A

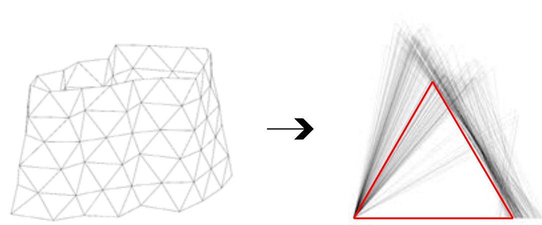
A: slab areas of the initial form,
C: common areas of two forms slabs,
D: Different areas of two forms slabs.

Structural efficiency: (SE)



Calculate the material consumption: (MC)

Construction difficulty: (CD)



Calculate the average adaption to equilateral triangle in percent: (AA)
100 - (|(D1+D2+...+Dn) - 60n| x 100) / 180

5.5 PERFORMANCES OF THE FINAL SOLUTION

All computation techniques and scoring systems, in the generative algorithm, are designed to simplify the actual process of performance evaluation by computation tools such as Tekla and SAP2000. The generative model translates the concept of constructability to an easy way by comparing the angle of diagrid elements, but the designer can never be sure about the result without testing the final design solution by professional software such as Tekla. The structural analysis, in the proposal algorithm, does not have enough accuracy as well. Thus, the final design is modeled in SAP2000 for more accurate analysis and results.

The output from further developments can be compared with the result from two initial solutions in the first chapter. This comparison shows whether or not the form-finding process is able to find better proposals. In this way, the design from the algorithm is developed by Tekla for evaluating the constructability and SAP2000 to determine material consumption and structural efficiency.

Figure 5.15 shows the analysis steps and results. According to them, the minimum cross-sections, which are needed for the proposed diagrid structure, are listed below:

Section	Quantity	Weight - ton
HFCHS 139	-	-
HFCHS 168	-	-
HFCHS 219	82	47.1
HFCHS 273	54	44
HFCHS 355	15	16.4
HFCHS 457	8	15
HFCHS 508	1	2
Total Weight		124.5 ton

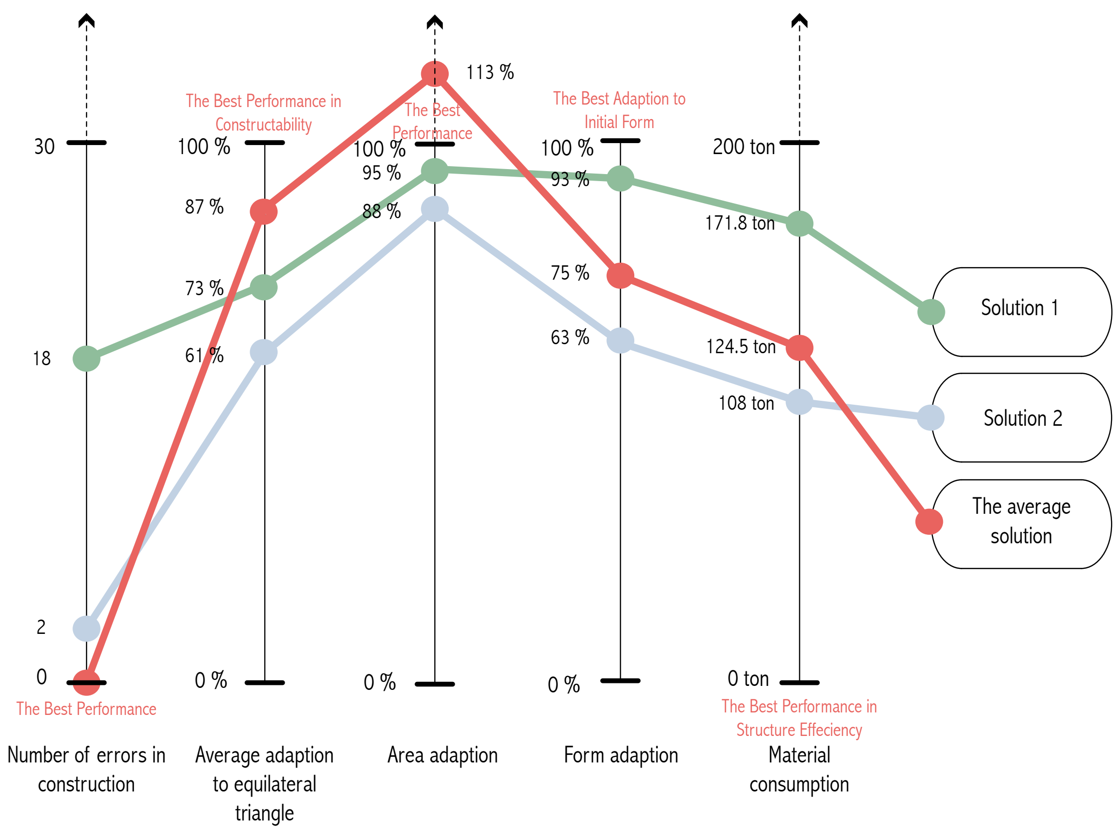
Table 5.2: List of minimum elements for the proposed solution

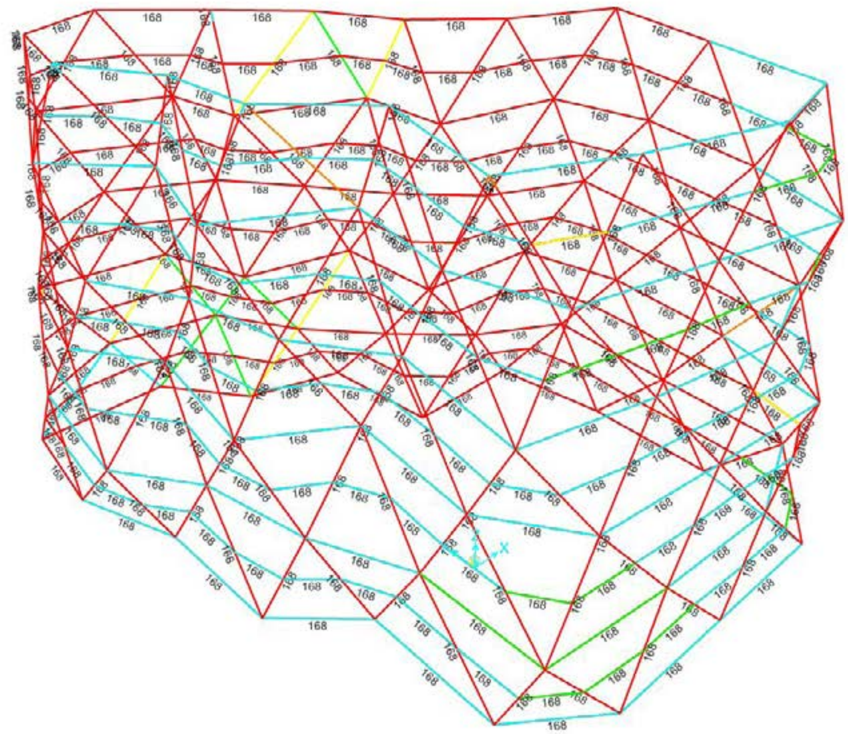
Thus, the material consumption is 124.5 tons – that is 27 percent less than solution 1 and 15 percent more than solution 2.

Figure 5.16 illustrates the model of the proposed result in Tekla. According to initial analysis, it has no error in construction because of high or low angles. This means that the structure is physically constructible. For further analysis, the length of needed cutting and welding operation can be determined by Tekla. These parameters, in addition to material consumption, show which solution is more cost efficient in the fabrication process.

Overall, the form proposed from the generative algorithm is easier to be constructed than solutions 1 and 2. However, it is just 18 percent less architecturally adaptable to the initial form than solution 1, and uses 15 percent more steel than solution 2 (Figure 5.14). As such, the proposed solution is not the absolute best answer but the average best solution, which has high performances in all objectives but not the best in all of them.

Figure 5.14: Performance of three solutions





Step 3

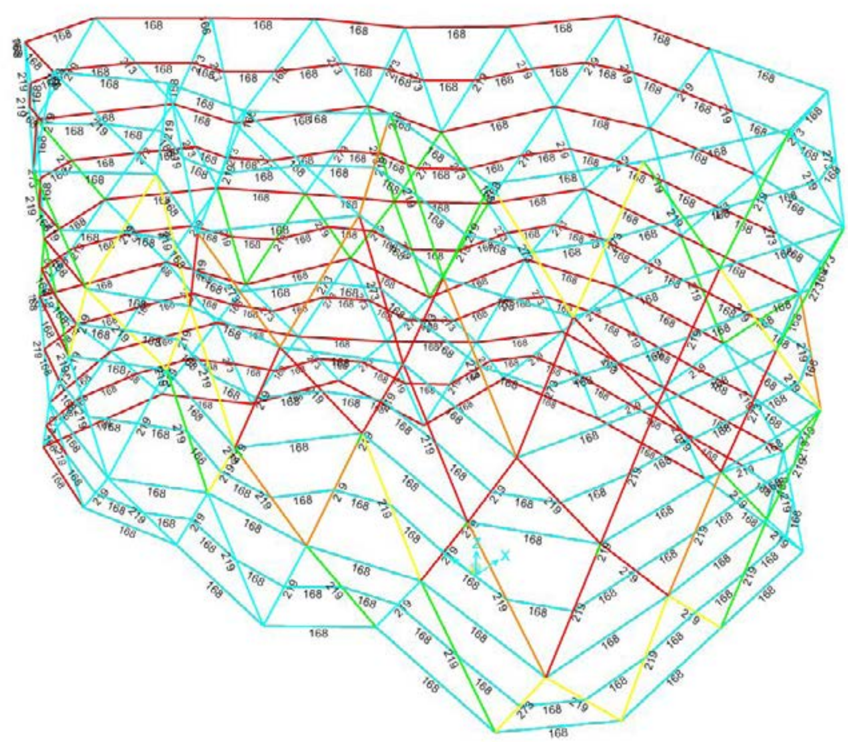
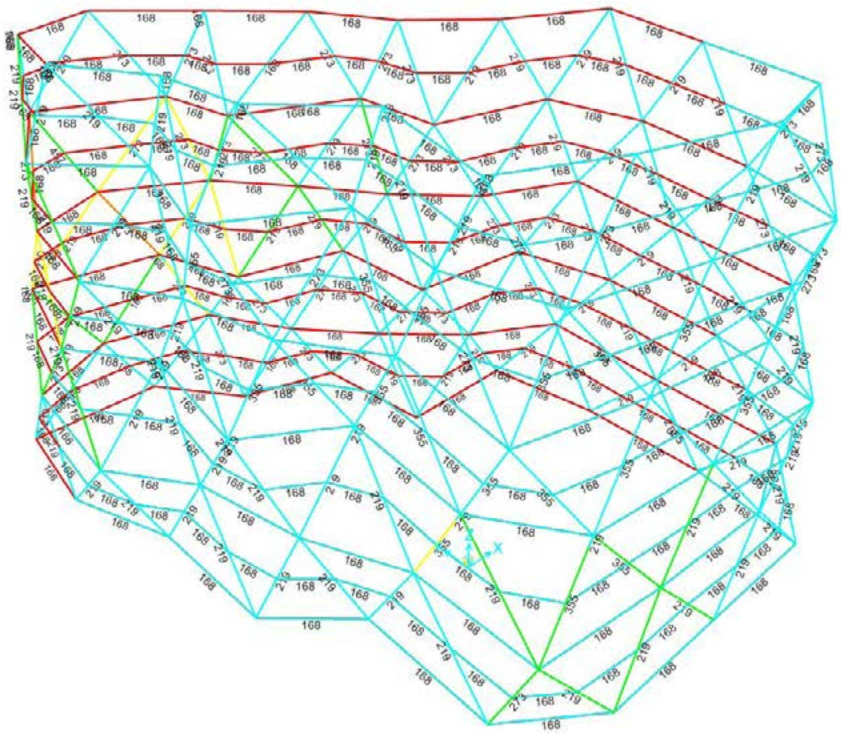
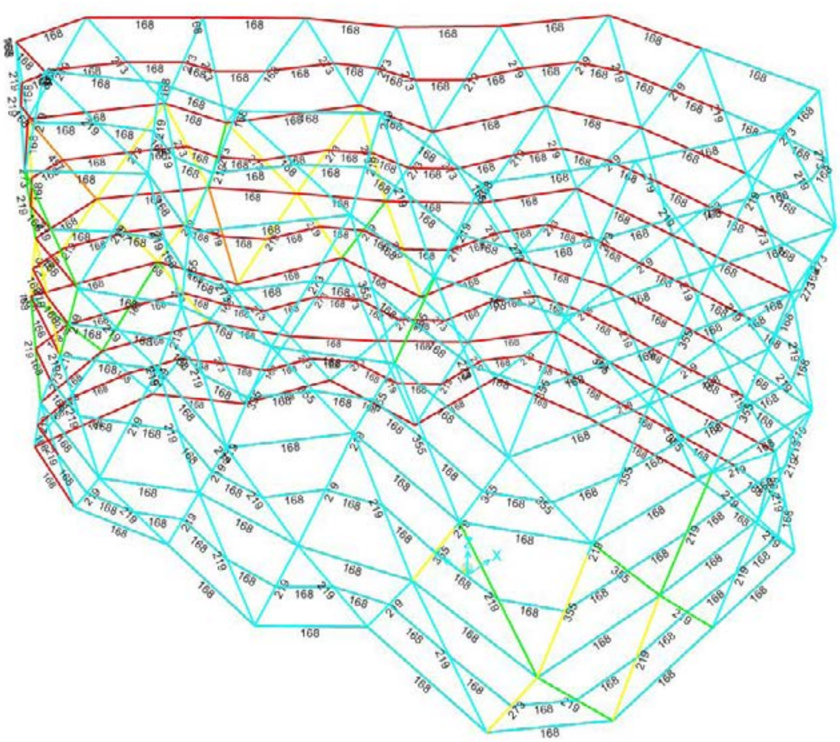


Figure 5.15: Structural analysis by SAP2000

Step 4



Step 3



Step 4

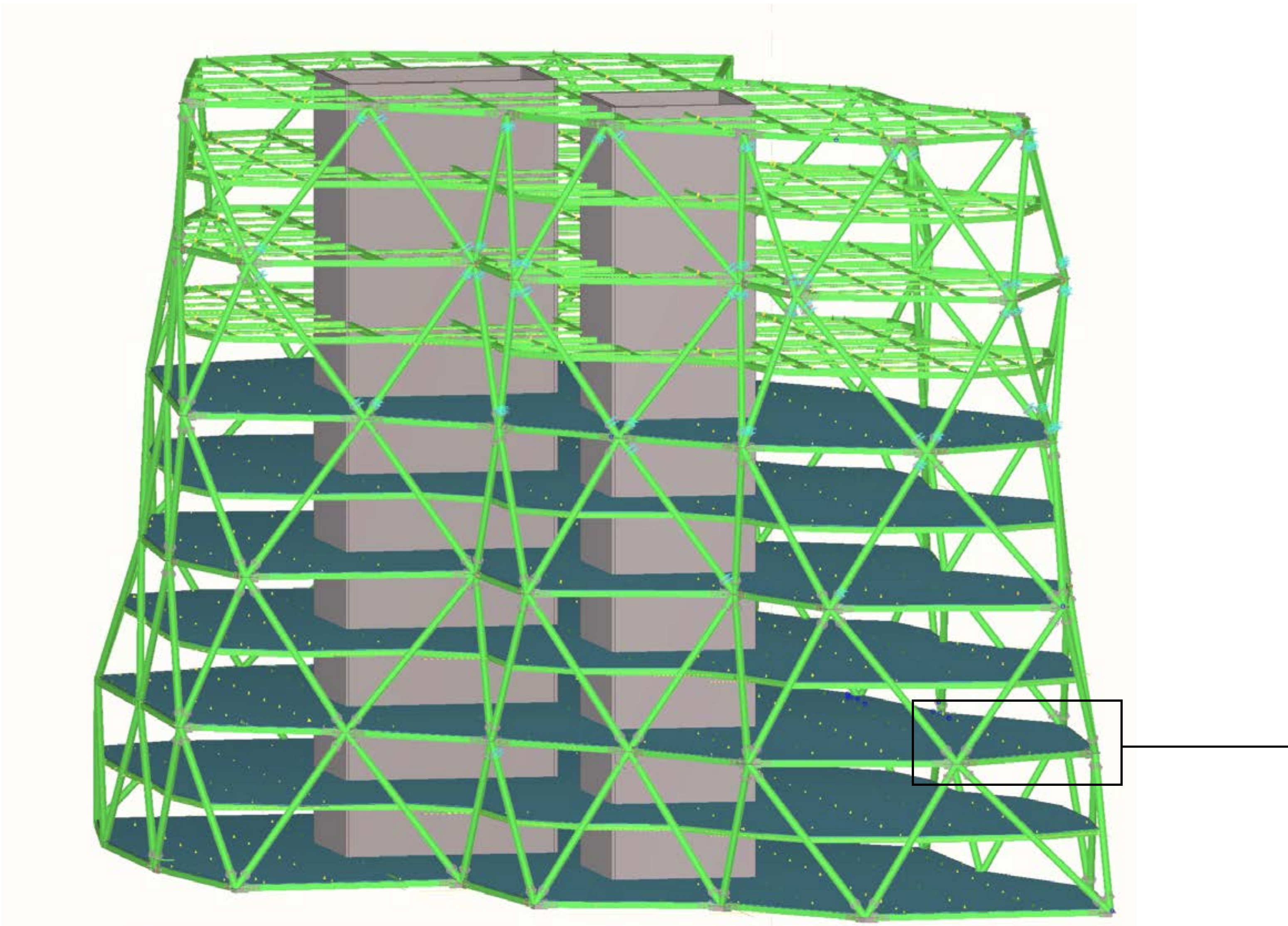


Figure 5.16: Tekla Model

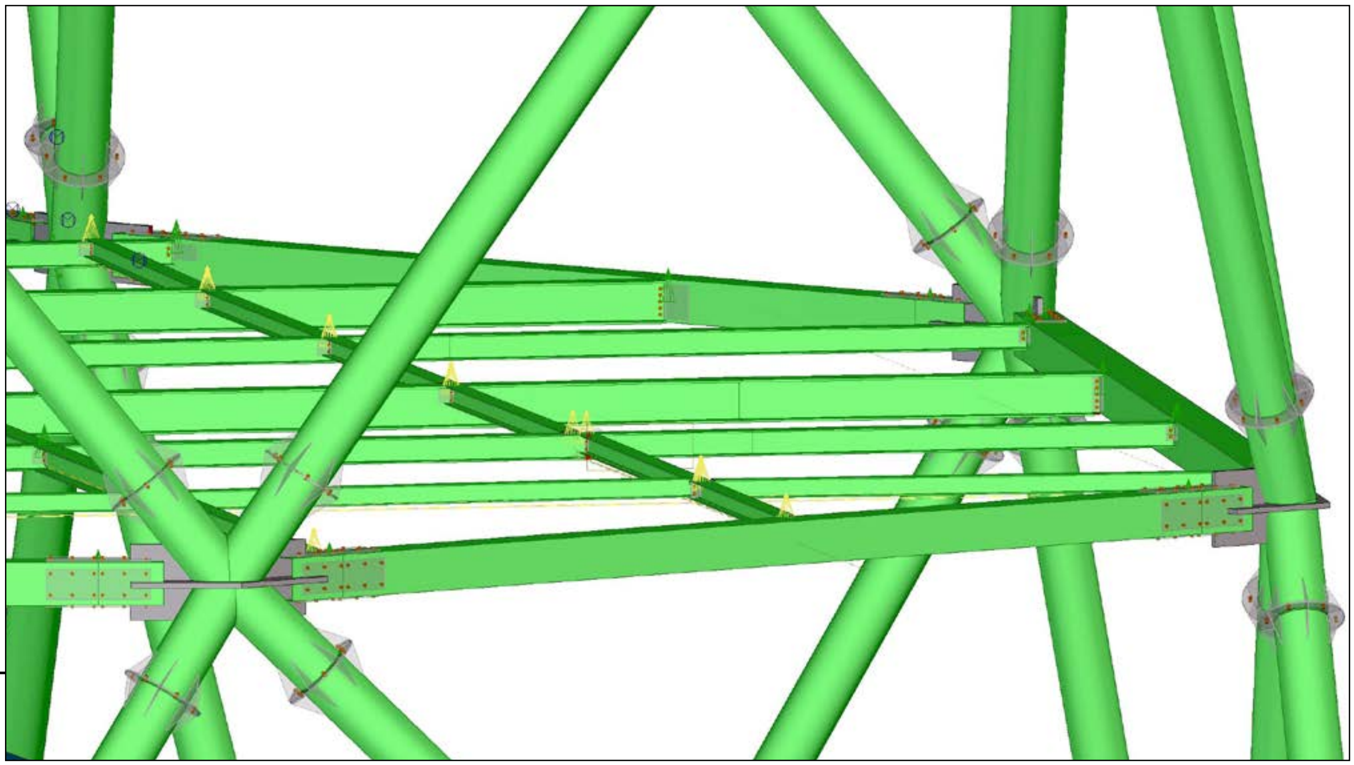


Figure 5.17: Render - under construction

CONCLUSION

This research is focused on using generative algorithms in the initial architectural design process to take performance of variables into account and reach a high-performing synthesis that accommodates multiple design criteria. Within this thesis, a generative algorithm has been developed to guide configuration and geometry of a complex free-form diagrid steel structure for design of the New National Gallery as part of the Liget Budapest Project.

For the past four decades, architects and engineers have been using form-finding methods based on increasingly precise analysis involving the optimization of structural efficiency and material consumption. Building upon this existing methodology, the research of this thesis includes limited analysis of constructability and correspondence to design models as parameters in designing a free-form diagrid. In order to achieve effective evaluating and scoring criteria for this analysis, practical knowledge of design variables of diagrid structures is necessary.

The generative algorithm developed here includes a parametric model, computational model and a feedback loop. The parametric model considers sets of inputs and generates a list of possible solutions. The shape and complexity of the proposed form is dependent on values of a range of design variables. The components of the parametric model include variables and logic that requires careful definition in order to produce maximum-performing solutions. Operation of the algorithm involves processing of potential solutions, filtering and selecting optimal choices amongst proposed options.

Selection addresses performance of multiple objectives. The computational model is designed to rapidly evaluate and score relative performance analyzed for these objectives. Evolutionary optimization is included within this algorithm, comparing different generated designs and their scores to make a list of potential solutions. This list is organized to reflect ‘average best’ scoring that synthesizes multiple objectives, determining the optimal performance based design.

A number of limits may be observed within the algorithmic analysis process illustrated within this thesis. These include simplified axial load analysis; use of pre-existing structural systems as assumed standards; generalized curvature smoothing with limited precision, and a requirement for relatively subjective assembly of a range of final scoring using different units of measurement.

The evaluation and scoring technique governing the structural analysis embedded within the algorithm is limited. In this analysis, axial loads are modeled without providing for other forces and vectors. In addition to objectives where quantifiable scoring is readily available, additional analysis is added involving relatively subjective analysis of the criterion of constructability. For this objective, the operation of the algorithm involves selection of a pre-existing high-scoring design solution as a goal, and calculating relative differences in geometric configuration between the form being analyzed and this goal.

In this thesis, the algorithm generates design solutions to average curvatures in multiple directions, with those values applied to criteria of structural efficiency and constructability. However, to produce increased precision, a ‘smart’ model embedded with automated smoothing curvatures could be employed.

Design solutions include different types of scores that require qualitative judgments in order to form a final synthesis. In this thesis, material consumption scores are expressed in units of mass, while constructability is scored in percentile values. Final decisions on optimal solutions may be presumed to vary widely based on the relative weighting of such criteria.

The analysis method described here could be enhanced by employing complex-systems analysis currently supported by commercial software programs such as Tekla, described earlier in this study. By investing in automated modeling using comprehensive variables identified within a well-developed parametric model, a Tekla analysis should be able to include fabrication and erection processes that could more directly support a quantative scoring of ‘constructibility’. Such an analysis could, in turn, be employed for comparison with the limited scoring provided within the current study.   The analysis of the structural system proposed here represents only a limited part of comprehensive architectural design. With more development, the functions covered by the present study could be expanded to include key objectives such as:

- Quality and organization of interior spaces
- Geometry of the cladding modules, joints, pieces and their influences on the construction process
- Sustainability features such as natural lighting and ventilation
- Location and geometry of structural cores

The computational approach studied within this thesis could be enhanced by development of specialized ‘plug-in’ software modules that could extend the current implementation of Grasshopper software. Specific areas of development could focus on fabrication details including torching and welding in steel construction. A well-designed plugin could calculate the energy and cost needed for shop fabrication of steel details based on designed joints and structural elements.

To further develop such an algorithm, a wide range experiences, skills, and research is necessary. This invites collaboration of a group of professionals with deep knowledge in different fields including engineers, fabricators, researchers, and programmers.

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APPENDIX

APPENDIX 1 Ap.1

(Documents of the international design competition for new museum buildings in Budapest, Hungary from its official website. http://www.ligetbudapest.org/index.php)

DESIGN PROJECT Ap.1.1

Instead of doing a theoretical research on diagrid structures design in relation to multi-objective optimization, this thesis proposes a design for the New National Gallery in Liget Budapest Project. The goal of this study is to put forward a form-finding method that can consider performances of different objectives in designing free-form diagrid structures, including parameters from both the design and construction process.

This project will focus on the design of a performance-based complex geometry diagrid structure. Following this reasoning, the performance of a number of objectives will be studied and a multi-objective optimization process will be used to reach the highest performing designs. The objectives include structural performance (focus on the material consumption), architectural design intent (focus on the resemblance of the initial designed and proposed structure) and constructability (focus on resemblance of grid geometries and equilateral triangles). Finally, the following chapter introduces the project, site, programs and architectural needs in context.

LIGET BUDAPEST COMPETITION PROGRAM Ap.1.2

1. New building of the New National Gallery
2. New building of the Museum of Ethnography
3. New building complex of the Hungarian Museum of Architecture and the Photo Museum, consisting of two separate buildings
4. New building of the House of Hungarian Music

Ap.1.3

THE NEW NATIONAL GALLERY

As one the most important public collections of its kind, the New National Gallery collects, preserves and displays artifacts from European and Hungarian art history, a collection which takes visitors from the beginning of the 19th century up to the present day. The museum displays the works at a high professional level, with a solid scientific and international context, in a way that allows for an independent analysis of the evolution of Hungarian art and cultural history. The period covered by the permanent exhibition of the New National Gallery spans from 1800 to 1950. In addition to maintaining and promoting cultural heritage, it is the mission of the New National Gallery to be widely available to the visitors based on the principles of an 'open Museum' and a 'Museum for everyone.' Its task is to become a venue for the development of national identities, a tourist destination and a primary basis for learning and the transmission of knowledge.

At the same time, the Museum is a scientific research point for art historians, where basic research work and contextualization of the artifacts take place; this objective explains the call for renewing the institution on the basis of art history and musicological methodologies. The results of this research are made available to the public in the form of exhibitions and publications. As such, the New National Gallery is an institution open to the latest trends in both international contemporary art and knowledge, while contemporary social and artistic dialogue is pursued via an independent workshop called the GAIA lab. Furthermore, the museum has close ties to international museums all over the world and takes part in discussions surrounding domestic and international art, art history and musicology.

Through its pedagogical activity, the New National Gallery plays an important role in the visual education of young people and supports the implementation of school and out-of-school programs belonging to institutions of public education. The museum also educates and orients visitors by attending to the diversified needs of the public and by facilitating complete access to its digital content. Disadvantaged populations and people with disabilities are treated as priority visitor groups in order to contribute to their social integration through the organization of special programs. Moreover, by presenting different fields of art, theatre, music and literature through its programs, the museum inspires the authors of the various arts to take part in a creative dialogue and contributes to raising the level and quality of public culture.

Figure Ap.1.1: City Park, Budapest

Ap.1.4

SITE

The selected site for the shared building of the New National Gallery and Ludwig Museum is on the Hungária körút side of City Park, to the Northeast of the building of Petőfi Hall, close to Hermina Street. The land site is bordered by Petőfi Hall, which has been marked for demolition, by Városligeti ring road and by Zichy Mihály Street.

The selected site for the building is situated in one of the important historical axis of the City Park. For this reason, the tender applicant is expected to show how the design reflects this cultural context and to take into account the appropriate dialogue that will be created by increasing the size of the field through the demolition of the Petőfi Hall. On the other hand, it is also important to remember that the planned building will have a view on Hermina Street; as a consequence, interesting facades should be designed in both directions.

Figure Ap.1.2: Site for New National Gallery

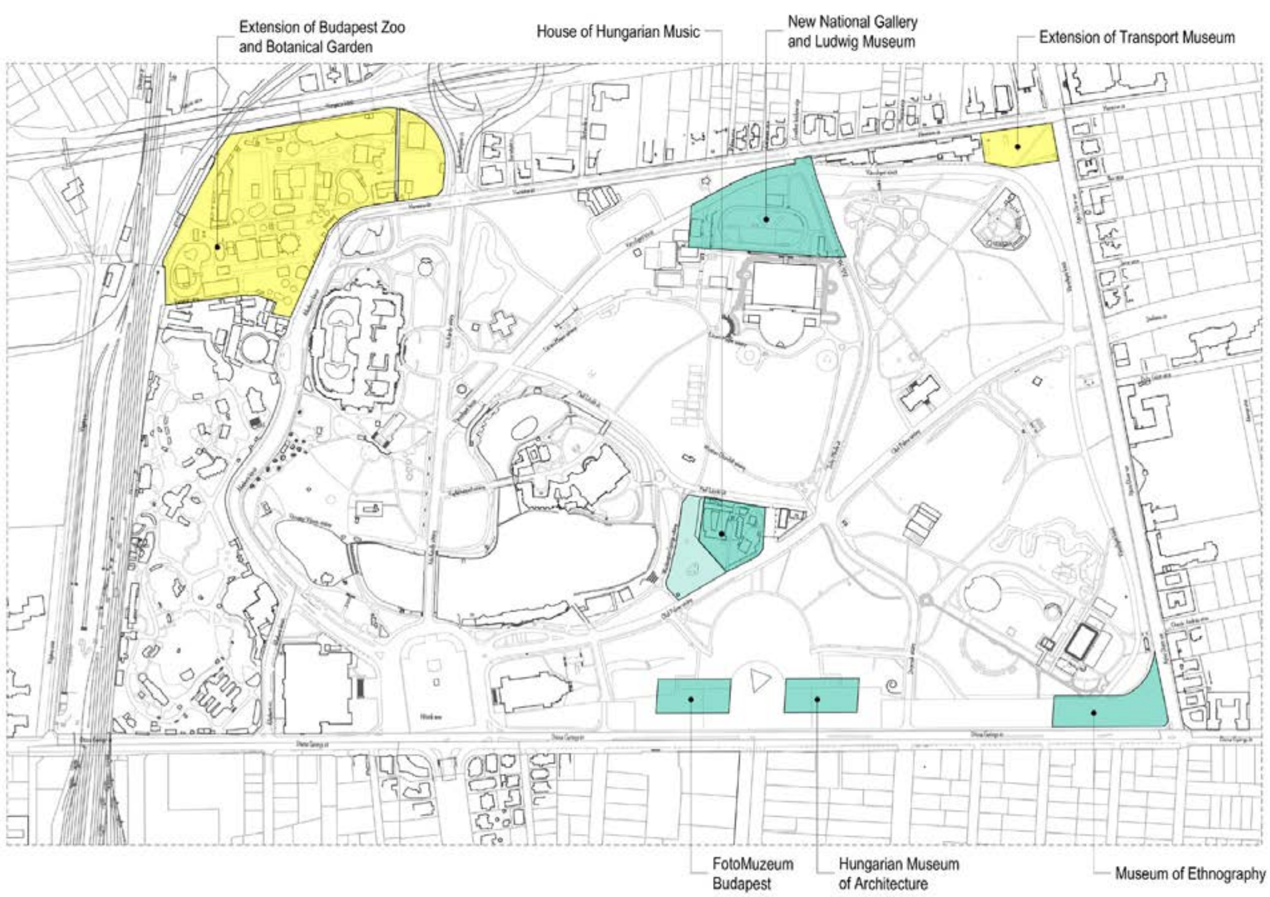


Figure Ap.1.3: Site - Bird view

Ap.1.5 PROGRAM OF REQUIREMENTS

Ap.1.5.1 OUTDOOR SPACES

The museum is in need of a well-located outdoor area that can host open-air programs. It can be located on any side of the building in agreement with the architectural concept. Nevertheless, the outdoor areas around the building are as much part of the City Park as the areas used by the institution; therefore, they must offer solutions for traditional outdoor activities (seating surfaces, solid surfaces, etc.).

Ap.1.5.2 ENTRANCE

The building will be accessible for most people from the direction of Hermina Street or in the line of the historical axis from the great meadow. In an optimal case, the entrance hall, the central information-orientation site of the building, may be approached from several directions. As such, enough space should be provided for the assembly of those arriving in groups close to the entrance.

Ap.1.5.3 EVENT ROOM

The most important event room of the building has 800 a square-meter floor surface with a representative interior design worthy of the rank of an important institution. The room should be well equipped for holding exhibition openings, amplified, projected or translated lectures, for showing films, chamber music and theatre performances and reading evenings (projector, sound and light technology). In order to meet these requirements, an 'invisible' studio (technical control room) is connected to the room, where sound reinforcing and projections are coordinated. The event room is directly accessible from the reception area and, if necessary, it can contribute to the upkeep of the institution through being rented out. It also has its own cloakroom and catering area. A room is needed for the storage of technical equipment, as well as a changing room, lavatory and place for the storage of artists' instruments. The event space should be easily accessible from the street and from the underground garage (parking in and out). Finally, a large inner space elevator with a stop on the parking level is needed close to the event room.

PERMANENT EXHIBITION

• Floor space of permanent exhibitions in the new building:	9,200 m2
• Permanent exhibition Hungarian and European	
• painting and sculpture	8,300 m2
• Visual store for sculptures	220 m2
• Medal cabinet	80 m2
• Glass roof atrium for the exhibition of statues	600 m2

The most important mission of the New National Gallery is the presentation of the core collection: a permanent exhibition of Hungarian and international painting and sculpture. In this 8,300 m2, a total elimination of natural lighting is expected. The visual store of sculpture is in good enough condition so that the display can be given a separate room too, but it can also be stored in one of the visitor traffic areas. The large-size sculptures would be exhibited in a glass roof covered atrium, which can only be placed on the ground floor due to the movement and weight of the objects.

Ap.1.5.5

TEMPORARY EXHIBITION

Floor space of temporary exhibitions in the new building: 3,500 m2. The temporary exhibition spaces should not be exposed to natural light.

• Temporary exhibition halls	2 x 1,500 m2
• Graphics cabinet	3x80 m2 = 240 m2
• Research exhibition space	160 m2
• Contemplative space (Shrine)	100 m2

In the building of the NNG, two big exhibition halls for temporary exhibitions and three smaller rooms for special functions will be built. In the two 1,500 square-meter halls, two big representative temporary exhibitions can be open simultaneously. Depending on the requirements of the exhibitions hosted, these spaces can be converted, narrowed down, or divided into smaller parts.
The temporary graphic exhibitions – this genre requires more intimate space as it invites closer inspection by the viewer – need three rooms of a lower internal height. They would open into each other, but if necessary they could be separated from each other, and are thus suitable for organizing small graphic and chamber exhibitions simultaneously.

In addition to above-mentioned programs, the museum includes pedagogical units, the GAIA LAB, a self-service restaurant and brasserie and collection-storage rooms.

GENERAL ARCHITECTURAL REQUIREMENTS

The New National Gallery gives a comprehensive overview of European culture and the Central European and Hungarian national identities by presenting the prominent European artworks of the modern age and the richest collection of Hungarian fine art. The museum building conveys the image of a dynamic and open institution that preserves with respect and interprets the artifacts assigned to it by the nation.

The New National Gallery is an institution open to contemporary intellectual trends, in the spirit of the altering perspectives and approaches and in the light of ongoing research. For this reason, the design must reinterpret its collection material and the publishing of these new interpretations. One outcome of the basic thesis of the continuous change of the artistic canon is architectural flexibility. In other words, the architectural concept should allow that continuous changes can be made to the permanent exhibitions and to the design of parallel narratives or emphatic surfaces at the intersection points of the exhibition halls. Furthermore, the outward design of the building, its floor plan arrangement and interior spaces should all reflect the fact that the museum openly welcomes all members of the public.
It should also demonstrate that it is equally open to the issues of the modern age, insofar as it acts as a venue for public social discourse. Consequently, the museum building cannot be archaistic in any way; rather, it should express the concept that the exhibitions do not mediate absolute standards, but merely evoke the past while simultaneously providing a contemporary interpretation of the present time.

APPENDIX 2

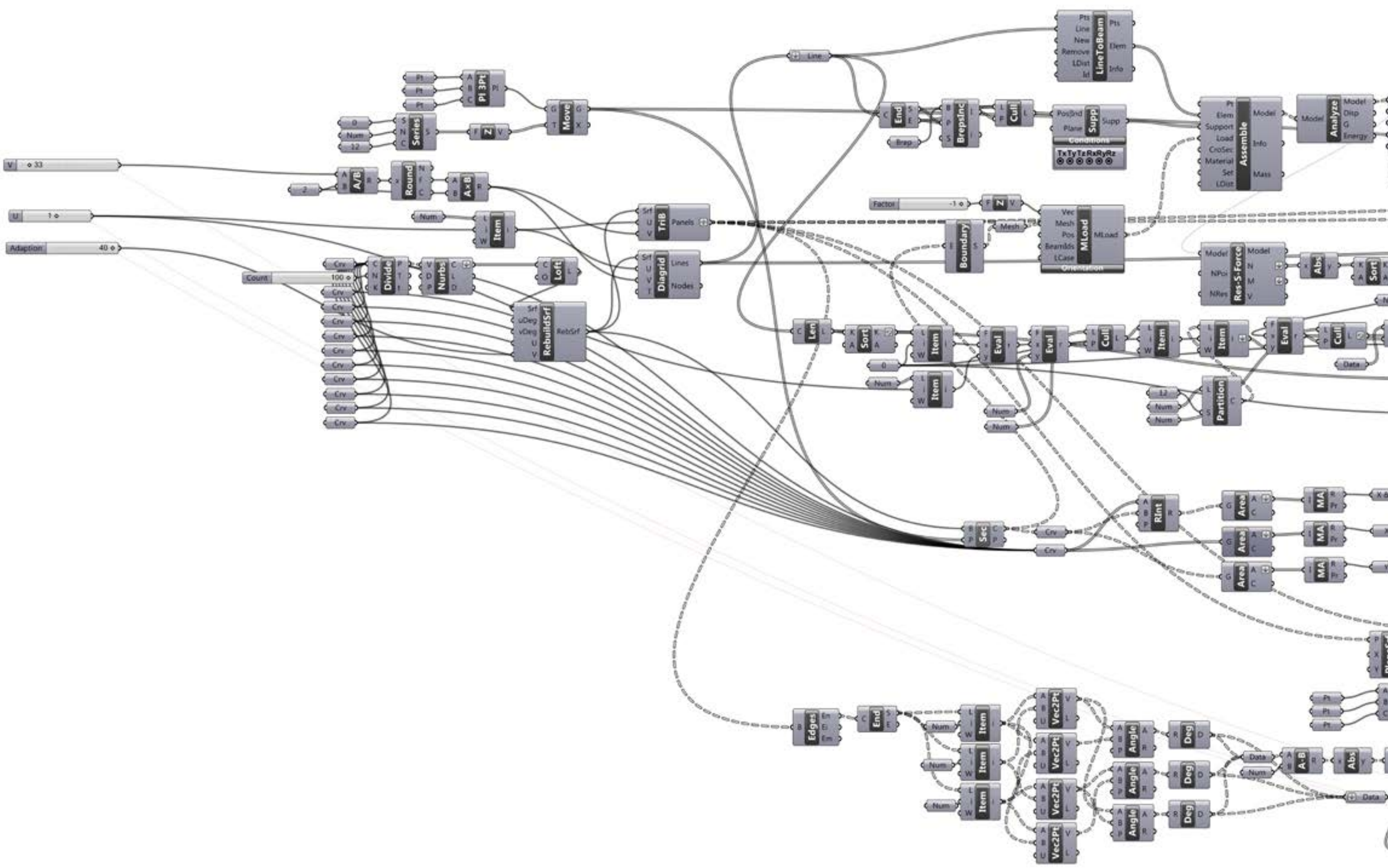
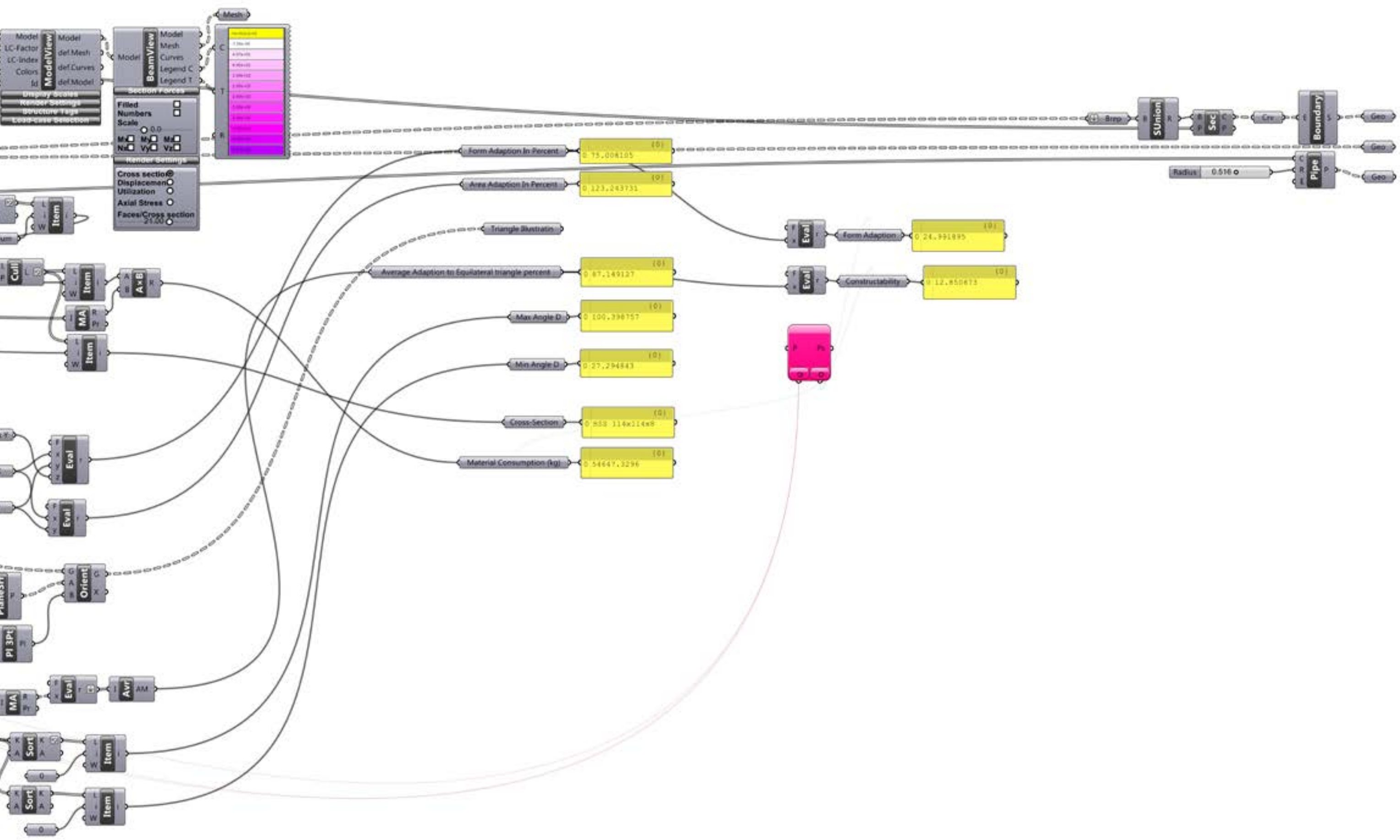


Figure AP.2: Proposed
Form-Finding Algorithm


Mesh
ModelView
BeamView
Form Adaption In Percent
Area Adaption In Percent
Triangle Illustratin
Average Adaption to Equilateral triangle percent
Max Angle D
Min Angle D
Cross-Section
Material Consumption (kg)
Form Adaption
Constructability
Brep
SUnion
Sec
Crv
Boundary
Geo
Radius
Pipe
Cull
Item
Eval
Orient
Sort