SPACE
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BIM INITIATIVE

Parametric Modeling of Diagrids

DIAGRIDS

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.

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.

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)

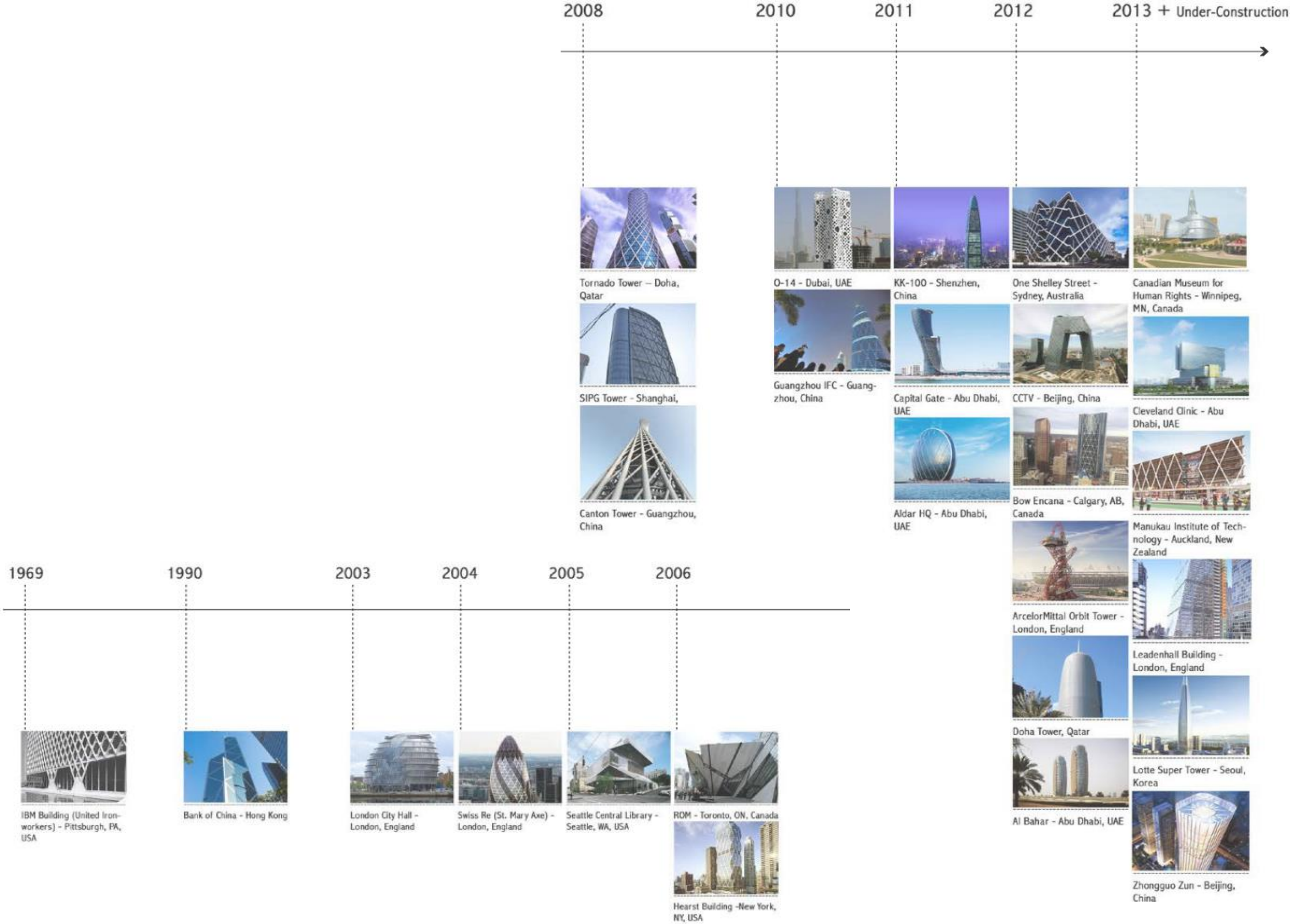
and the Hearst Headquarters (Figure 4.3)

After the above-mentioned pioneers, the diagrid structural system got more popular because of recent developments in fabrication technologies and structural simulations

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

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

the diagrid timeline *– a good source for following the development of this structural system.*



1969

IBM Building (United Ironworkers) - Pittsburgh, PA, USA

1990

Bank of China - Hong Kong

2003

London City Hall - London, England

2004

Swiss Re (St. Mary Axe) - London, England

2005

Seattle Central Library - Seattle, WA, USA

2006

ROM - Toronto, ON, Canada

Hearst Building -New York, NY, USA

2008

Tornado Tower – Doha, Qatar

SIPG Tower - Shanghai,

Canton Tower - Guangzhou, China

2010

O-14 - Dubai, UAE

Guangzhou IFC - Guangzhou, China

2011

KK-100 - Shenzhen, China

Capital Gate - Abu Dhabi, UAE

Aldar HQ - Abu Dhabi, UAE

2012

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

2013 + Under-Construction

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

WHY DIAGRID

Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design.
Kyoung-Sun Moon, Jerome J. Connor, John E. Fernandez. (2007)
A Computational Approach to the Design of Free Form Diagrid Structures, Jessica Nicole Sundberg. (2009).
The Bow: Unique Diagrid Structural System for a Sustainable Tall Building. Barry Charnish and Terry McDonnell. (2008)

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. 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. 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 stiffness of equivalent rigid frame or braced frame structure shows ***how the diagrid structural system provides the same stiffness with less material consumption.***

THE BOW

The Bow: Unique Diagrid Structural System for a Sustainable Tall Building. Barry Charnish and Terry McDonnell. (2008)

Diagrid Structures: Systems, Connections, Details. Terri Meyer Boake. (2014)

Studies 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.

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.

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/

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.

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.

The Application Of Non-Routine Structural Patterns To Optimise A Vertical Structure.

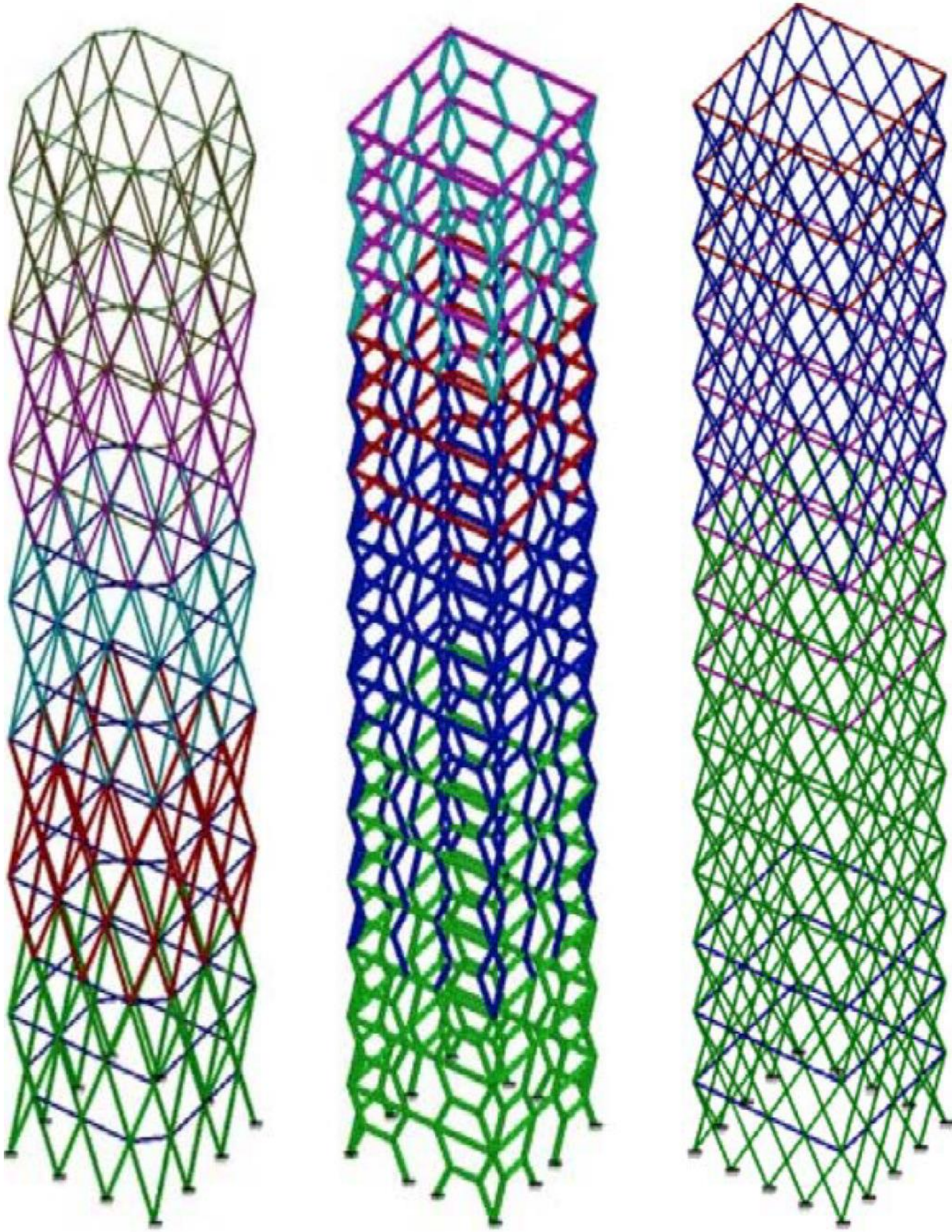
Eunike Kristi Julistiono. (2009).

The paper 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. Three non-routine structural patterns

– **triangular**, **hexagonal** and **diamond**

were chosen for examination based on their benefits. 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**.



DIAGRID ANGLES

Diagrid Structural Systems for Tall Buildings: Characteristics and Methodology for Preliminary Design.

Kyoung-Sun Moon, Jerome J. Connor, John E. Fernandez. (2007)

555m Tall Lotte Super Tower, Seoul, South Korea.

William F. Baker, Charles M. Besjak, Brian J. McElhatten, Preetam Biswas. (2009)

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. 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 . 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.

Illustrated in Figure 4.8,

the form-finding process **controls the angle of elements** based on structural analysis to achieve the optimum design.

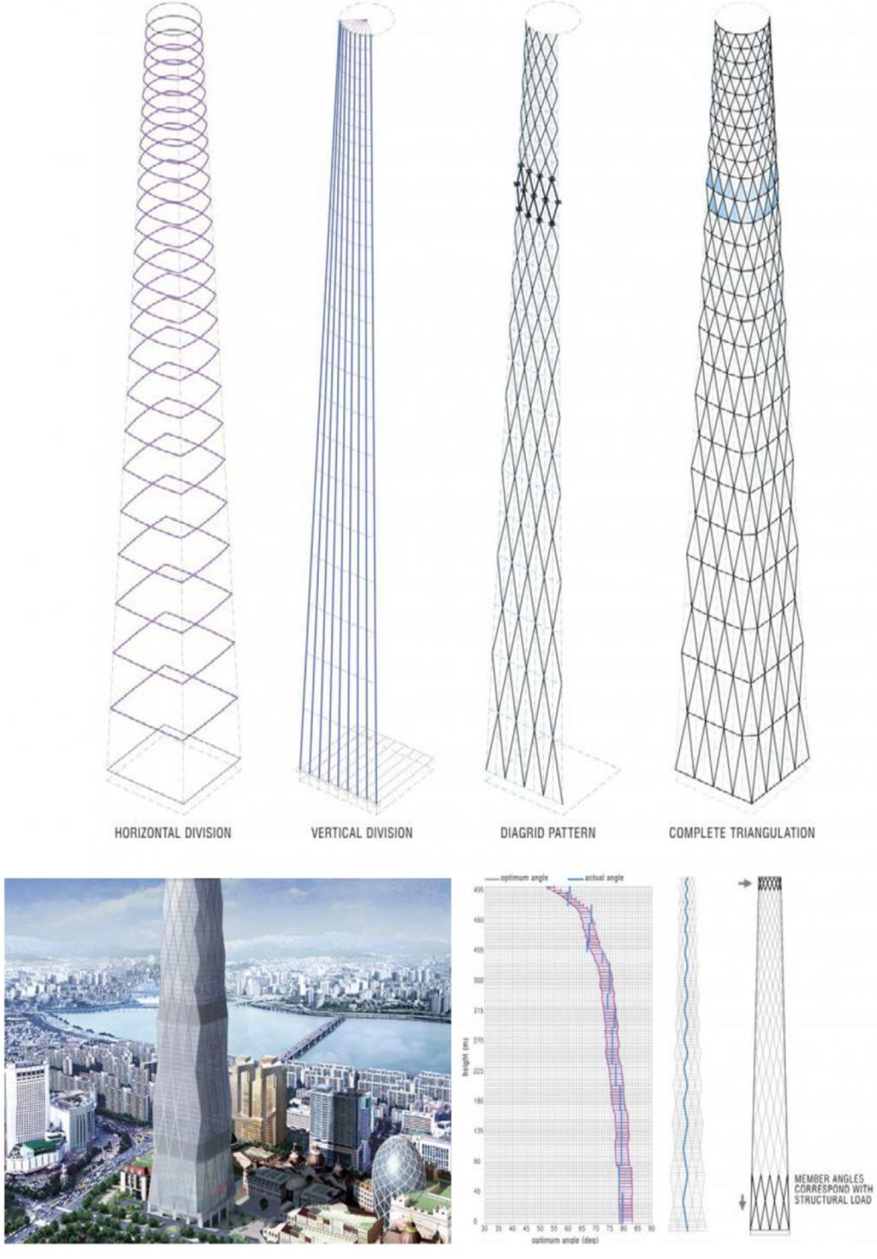


Figure 4.8: Lotte Super tower in Seoul, http://valueofdesign.

HEIGHT OF THE GRID ELEMENTS

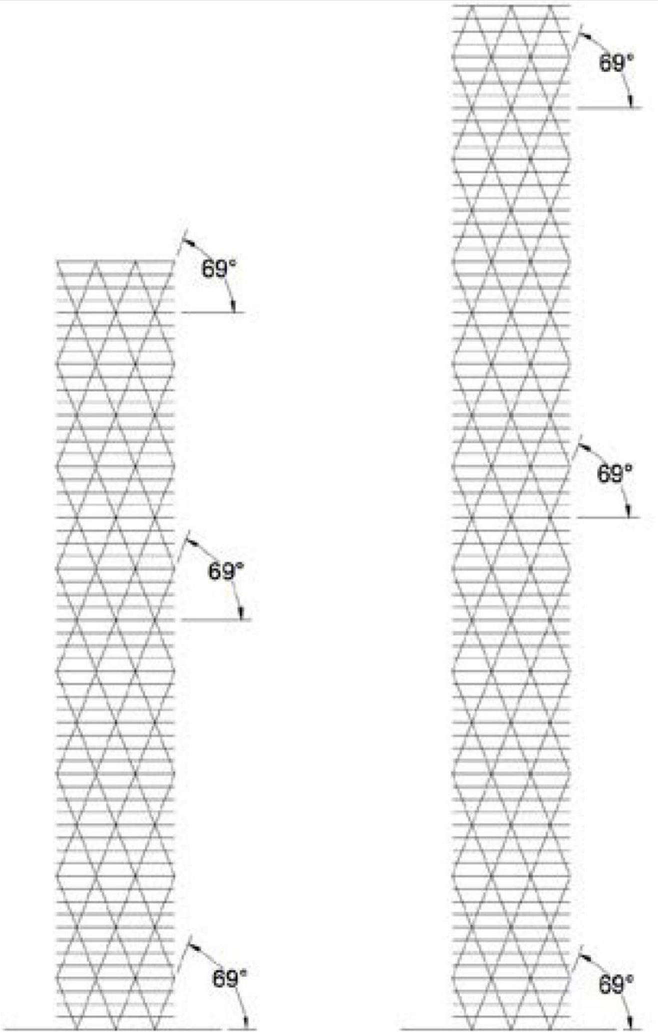
Diagrids, The New Stablity System: Combining Architecture With Engineering, Terri Meyer Boake, 2013

Design and construction of steel diagrid structures K. Moon. (2009).

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. 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



(a) 60-Story Uniform Angle Diagrids

(c) 80-Story Uniform Angle Diagrids

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

INTENSITY

CCTV Headquarters, Beijing, China:
Structural engineering design and approvals.
The Arup Journal, (2005).

One of the most common methods for structural optimization is to use a regular pattern with same proper ties 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.

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

Optimization runs several times to achieve the efficiency required for the project.

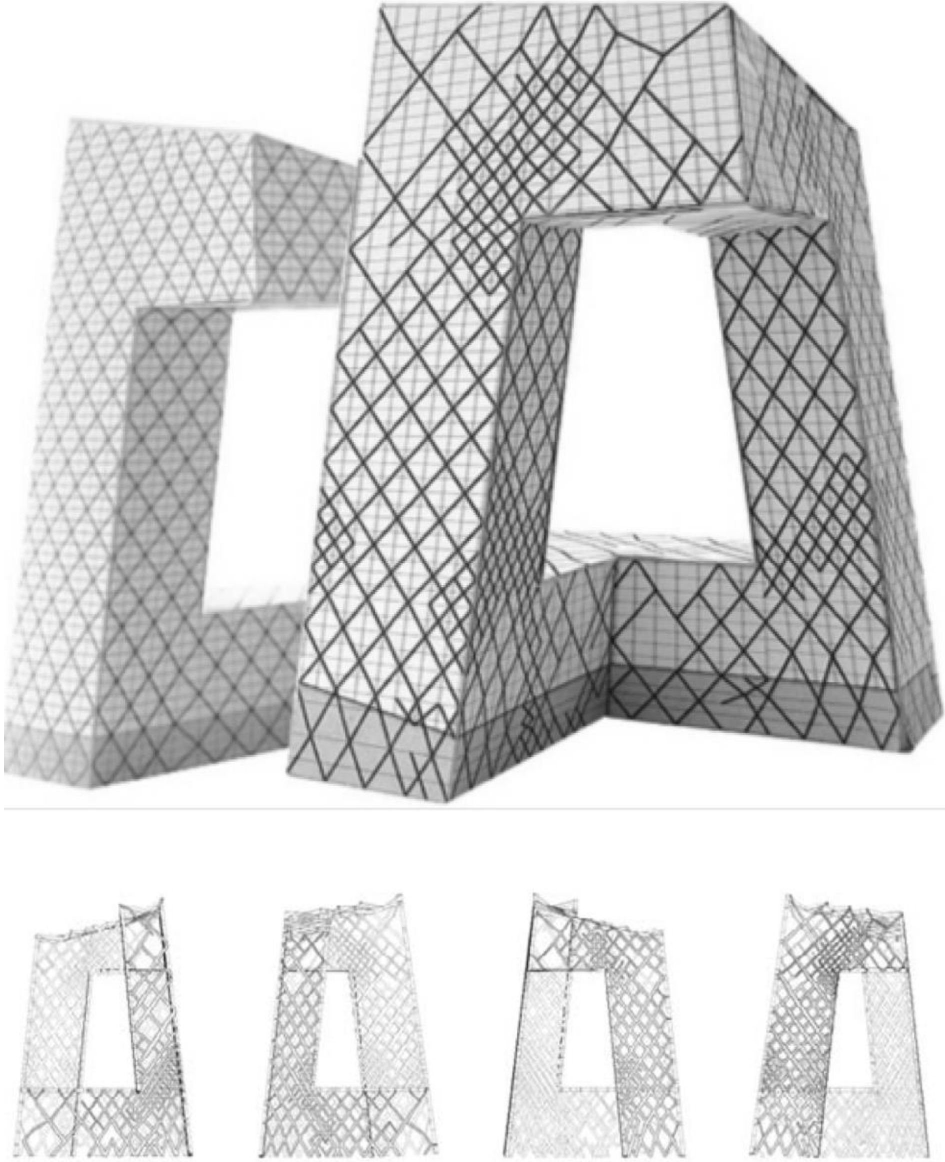
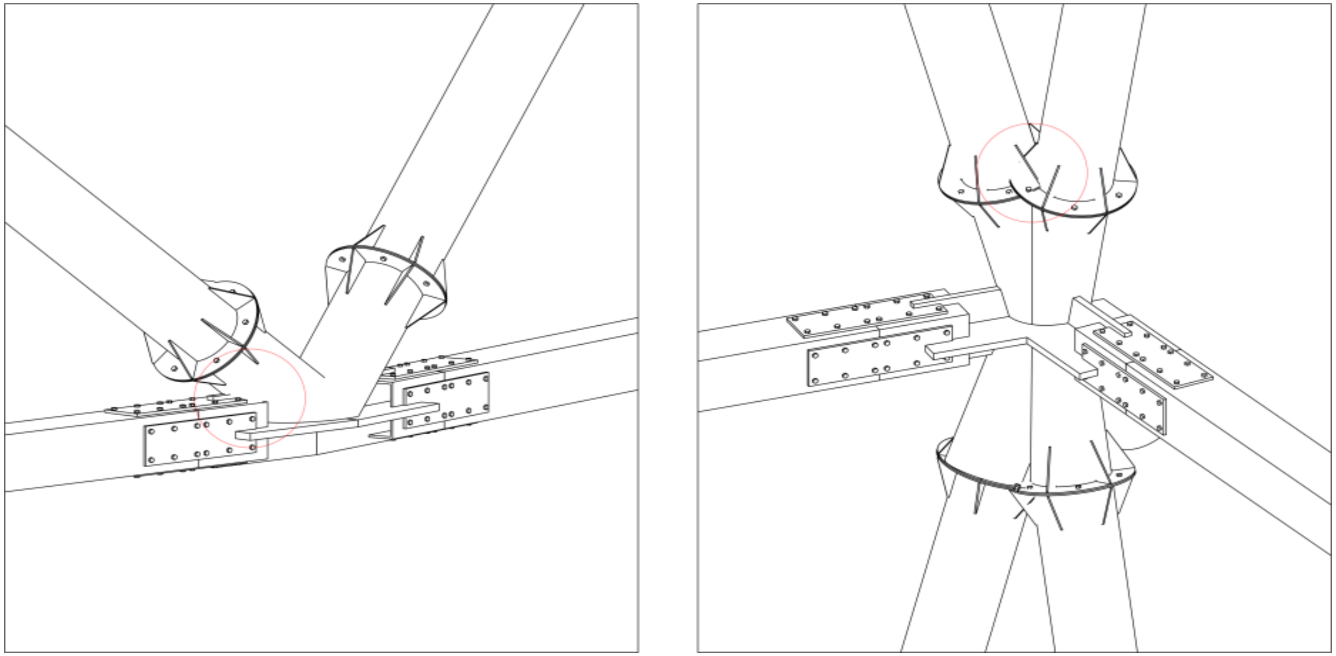


Figure 4.10: CCTV Headquarters by Rem Koolhass

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



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.

OPTIMIZATION OF CONSTRUCTION PROCESS

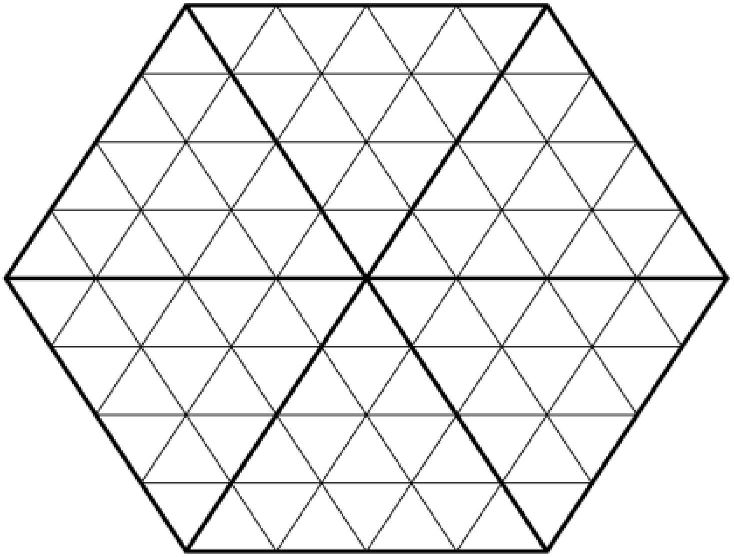
Constructability is always a serious issue that must be considered in the design process of diagrid structures. That said, it does not mean all constructible design solutions are equally efficient. For buildings with regular geometries, the fabrication process can be easy and economically compatible 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.

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.

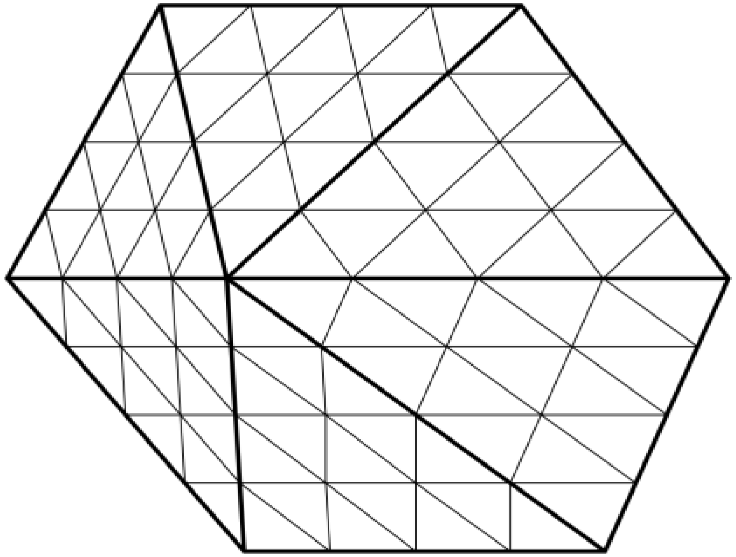
GRID GEOMETRY & CLADDING SYSTEMS

Diagrids, The New Stablity System: Combining Architecture With EngineeringTerri Meyer Boake. (2013).

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.



Equilateral triangle grid modules



Grid modules with extremely high or low degrees

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.

the issue

In recent years, the use of **steel diagrid structural systems** has increased for free-form **tall and mid-rise building designs**

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 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, **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.

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

For instance, the Arup team **developed an algorithm**

- that computationally encodes construction-related parameters and desired performances according to client, architectural, engineering, **fabrication requirements**.

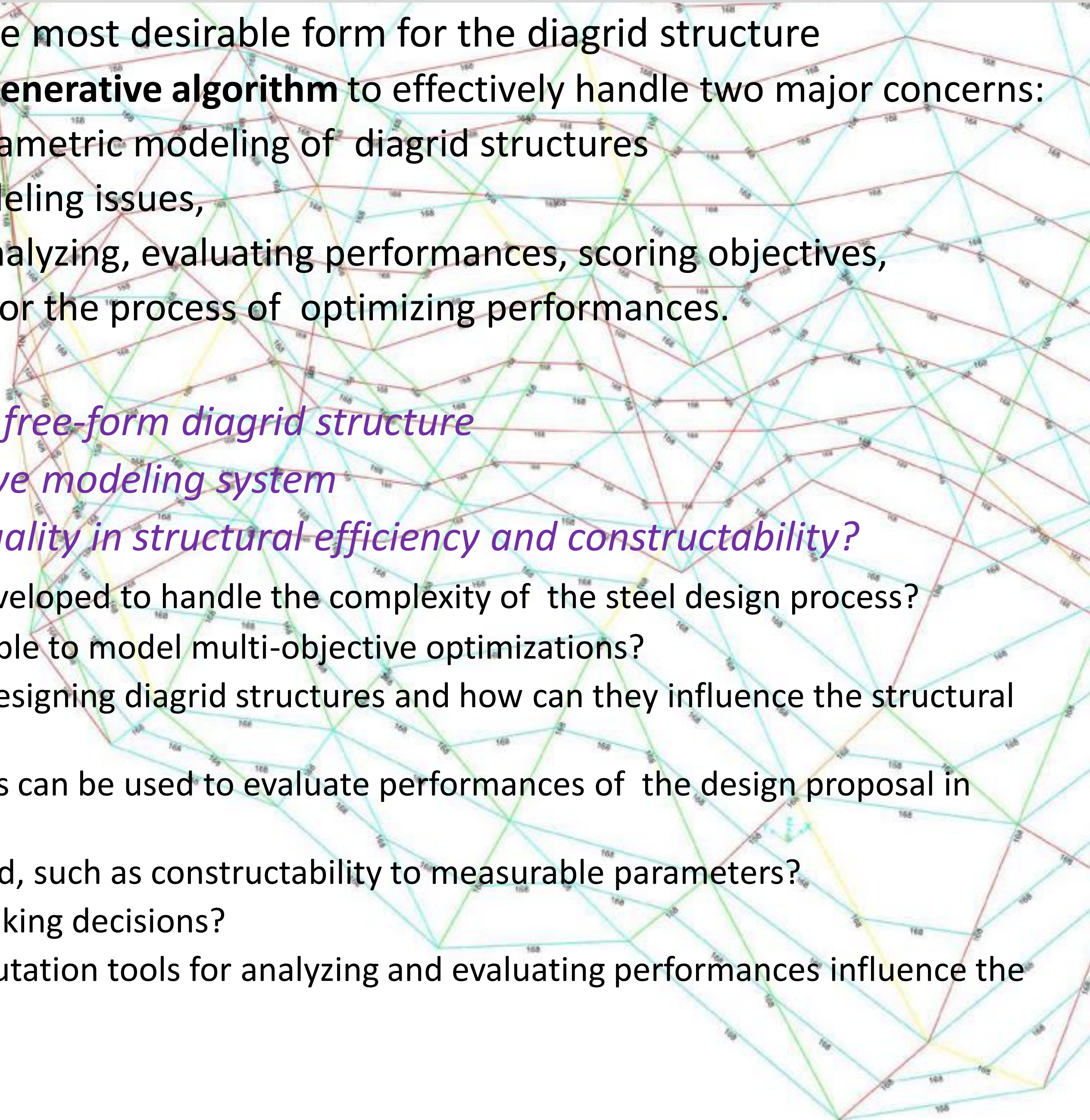
In this optimization process, the **computation tool**

- 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

the proposal



a form-finding model to find the most desirable form for the diagrid structure
which addresses the need of a **generative algorithm** to effectively handle two major concerns:

1. the complexity issue of parametric modeling of diagrid structures
2. and the computational modeling issues,
   which are related to analyzing, evaluating performances, scoring objectives,
   and making decisions for the process of optimizing performances.

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

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?

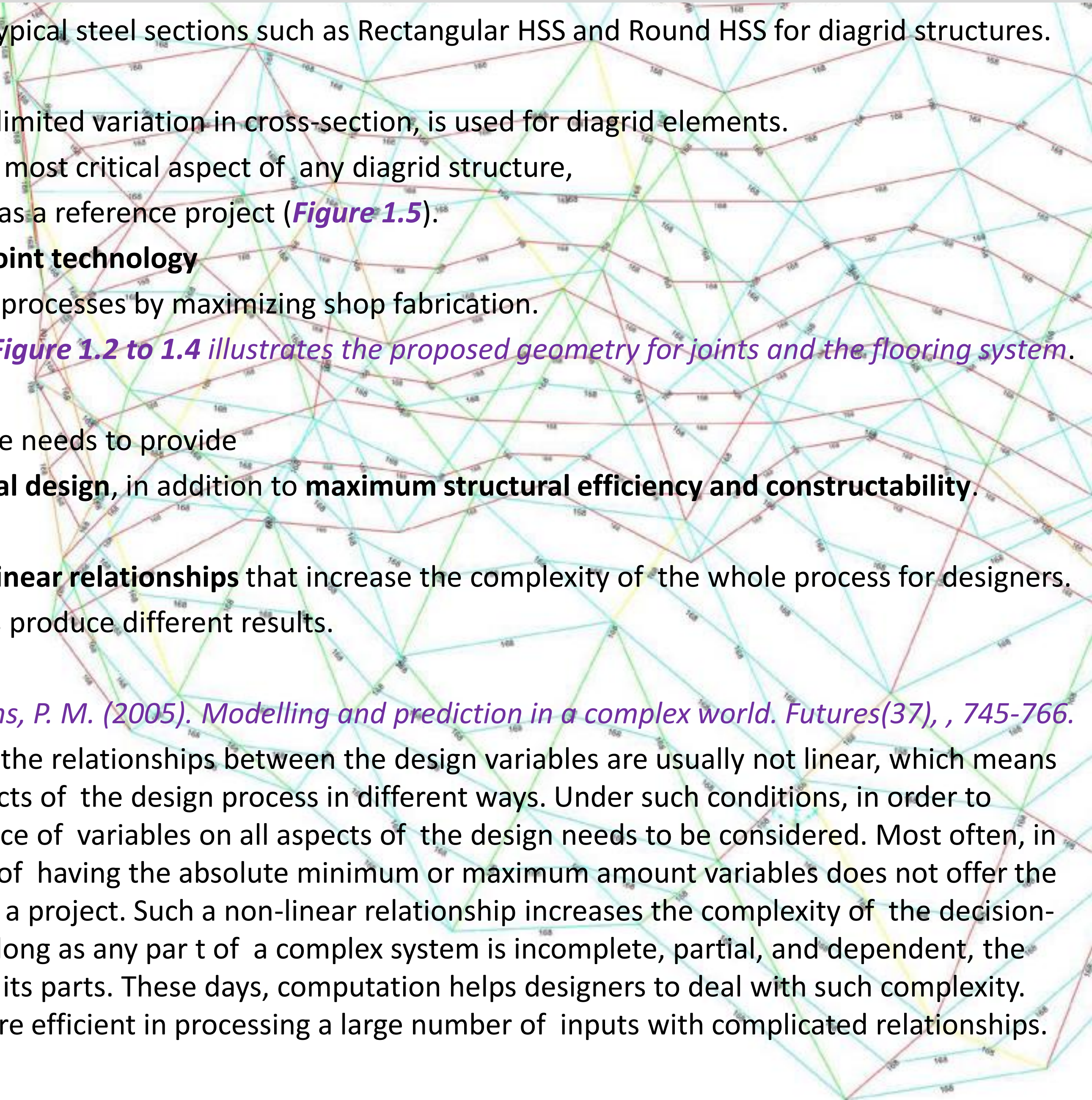
Which kind of numerical analysis can be used to evaluate performances of the design proposal in different fields?

How can objectives be conver ted, 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 PROPOSAL



Designers are more interested in using typical steel sections such as Rectangular HSS and Round HSS for diagrid structures.

*Thus, 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***).

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*.

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.

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

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 par t of a complex system is incomplete, partial, and dependent, the system is much more complex than its parts. 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.

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 or thogonal structural systems play different roles in the structural efficiency. In or thogonal 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.

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.

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 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** and **SAP2000** 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.

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** and **Bentley Systems**.
    - They are powerful tools for detailing and modeling the whole workflow including fabrication and erection. Such software 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.

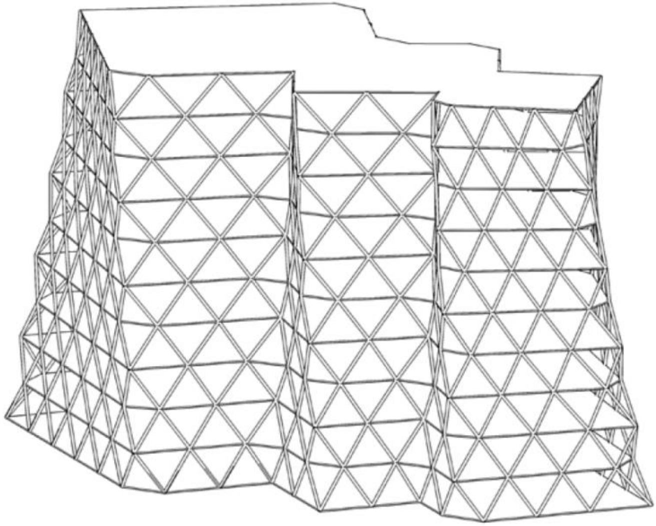
design solutions

For example,

two **design solutions** with different forms and geometry are proposed for the gallery's diagrid structure

1. The first option is geometrically more of a match with the initial design;
2. on the other hand, the second option has more regular grid modules and angles

   that can be beneficial in its structural efficiency and constructability.

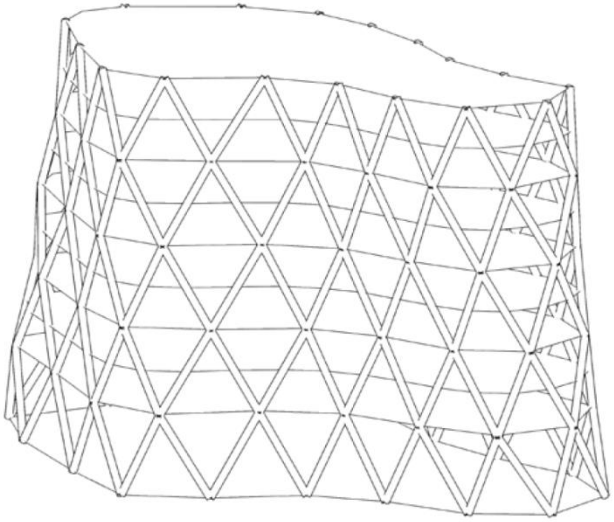


Solution 1

Most imporantly, **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.



Solution 2

structural analysis in SAP2000

In the fist step,

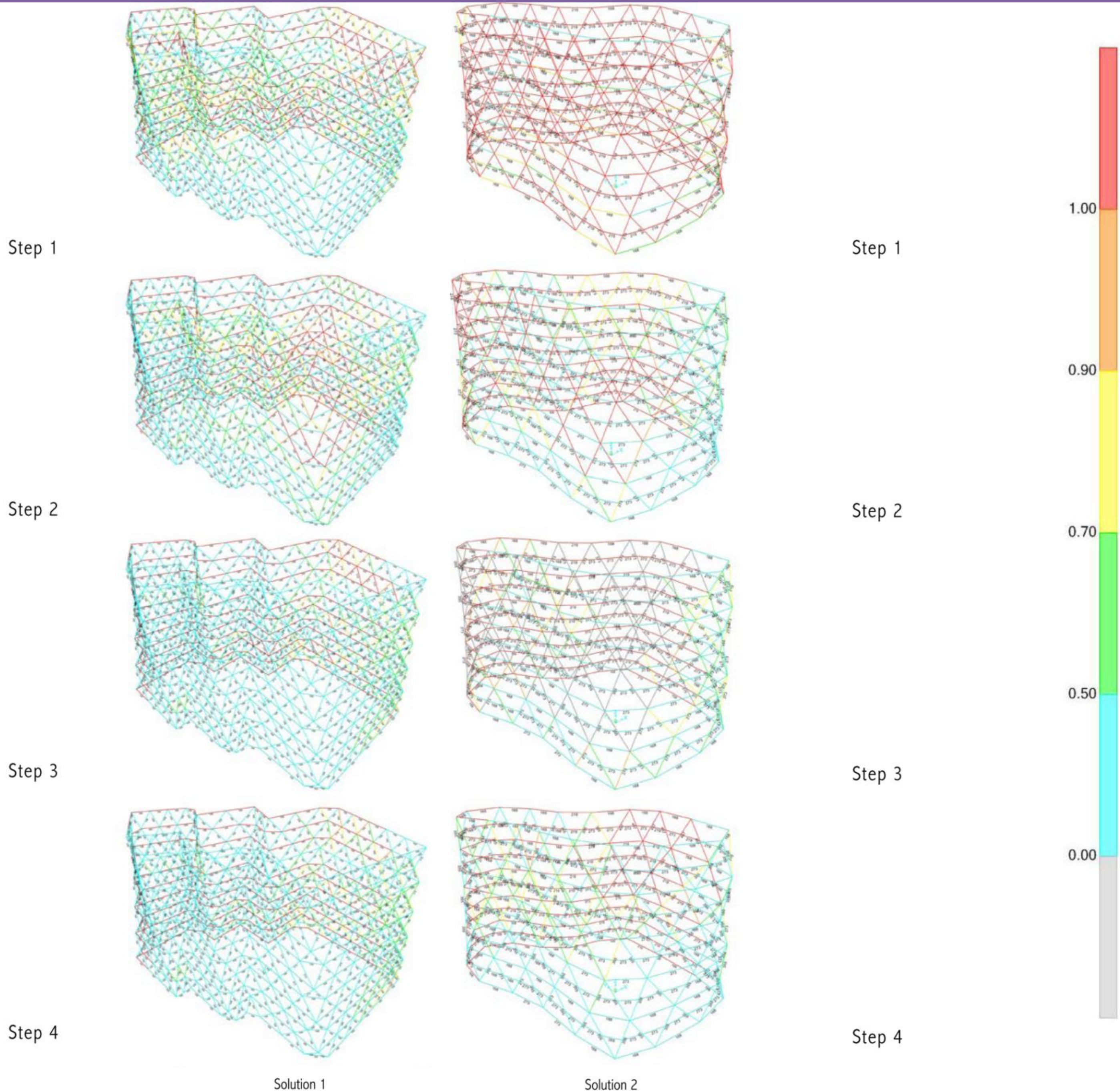
SAP2000 structurally analyzes two forms and applies

the minimum required cross-section to each element.

The material consumption can be easily calculated from the list of elements

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



STRUCTURAL EFFICIENCY

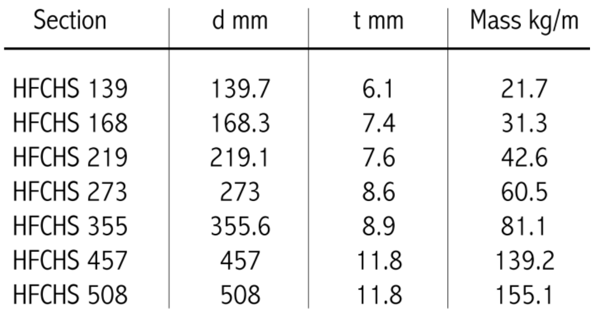
The **final result is the lightest structure** for each option that is able **to provide enough stiffness**.

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.



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

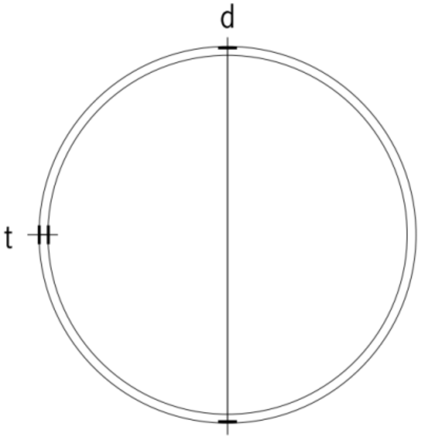
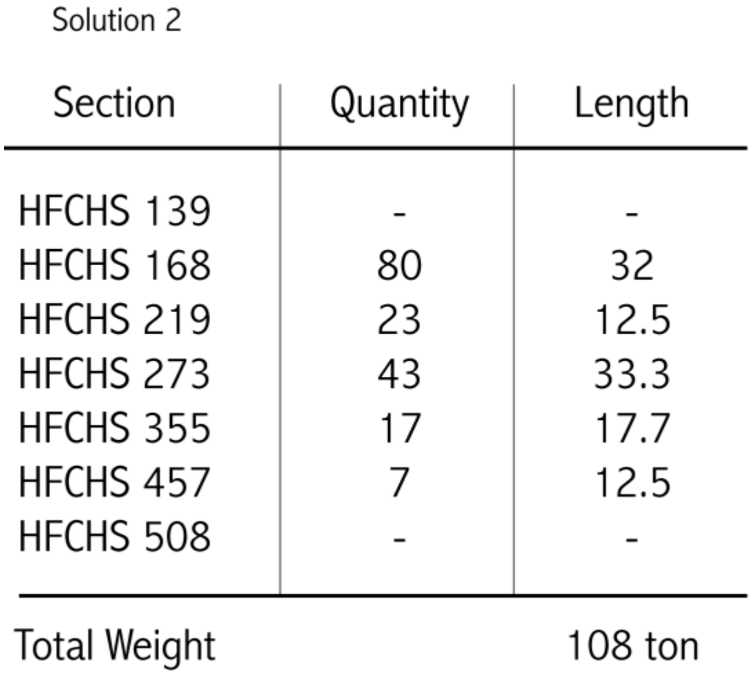
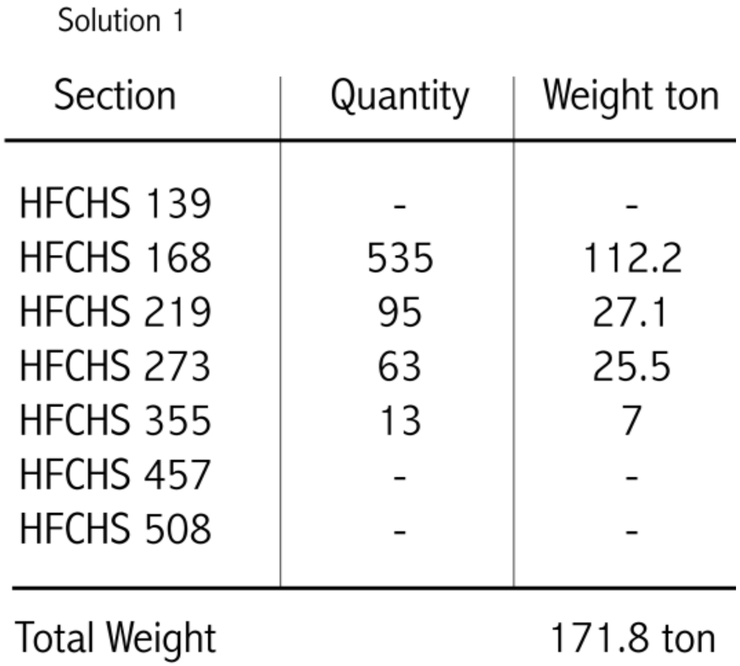


Figure 1.7: HFCHS Cross-section



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

errors in construction for both options

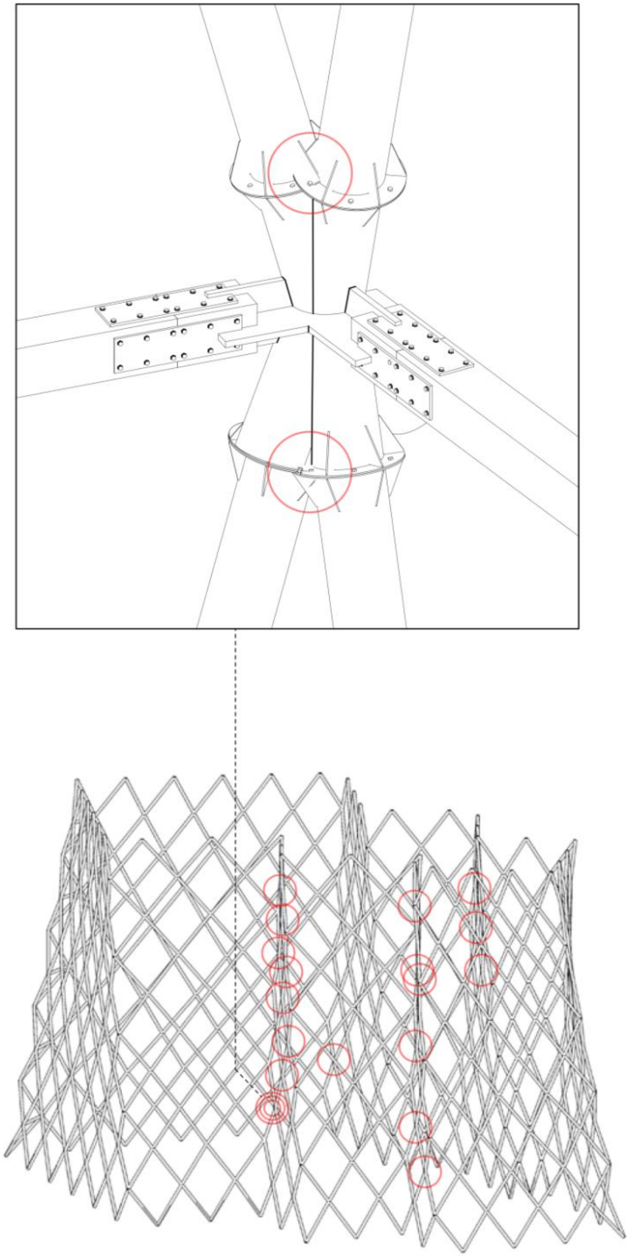
To find the possible errors in constructing details, the structure from SAP2000 is modeled in **Tekla**.

The Tekla model is developed manually based on information from the parametric model
and the structural design by SAP 2000.

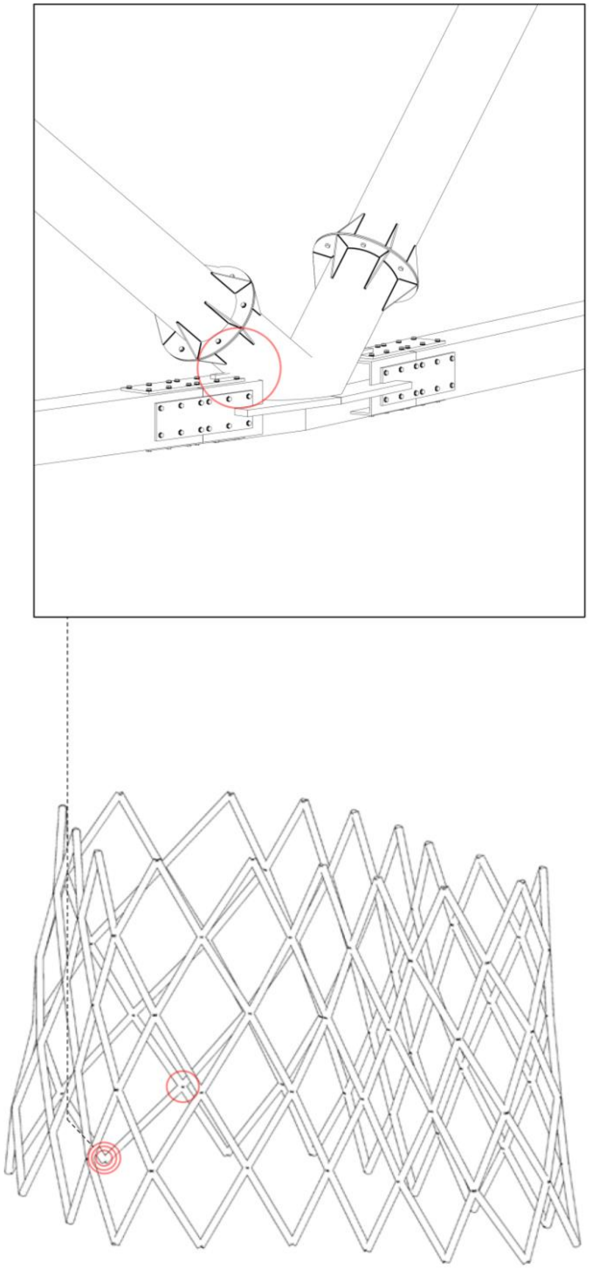
The **parametric model** shows the location, direction and length of structural elements;
and yet, the **structural analysis** determines the minimum required cross-section for each element.

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.



Solution 1



Solution 2

CONSTRUCTABILITY

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 structural variation in configuration** of elements, such as 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.

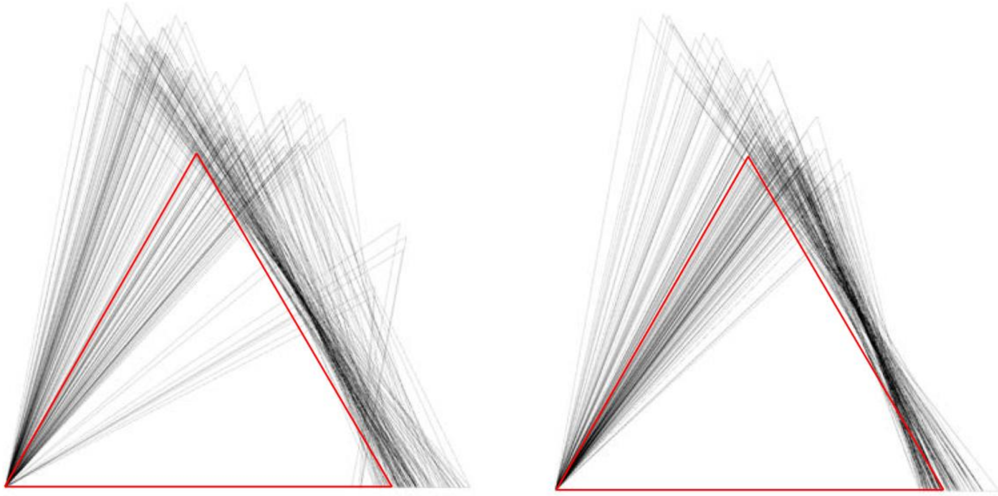
Generally, ***elements with extremely high or low angles make the process of welding or bolting more complex***,

and ***increase the chance of errors in both fabrication and assembly processes***.

Therefore, **grid models that are geometrically closer to equilateral triangles**

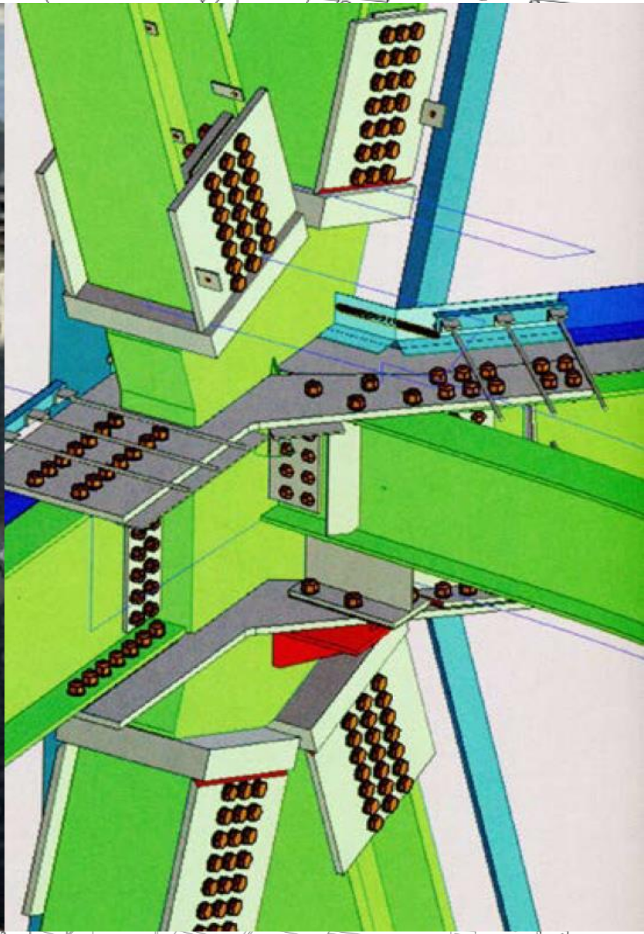
are more efficient in construction processes and cause minimum errors in construction (Figure 1.11).

adaptation with equilateral triangles



Solution 2

Solution 1



FORM-FINDING ALGORITHM

For many years, architects and engineers have been using **form-finding methods** based on the optimization of structural efficiency and material consumption. Computer technology has recently influenced different aspects of the building industry, fostering **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**

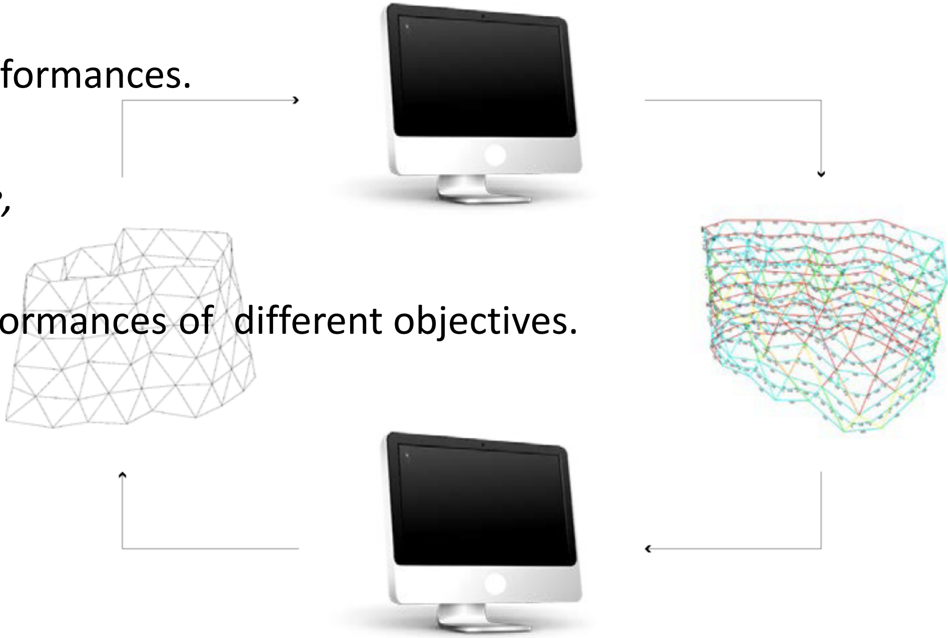
Software programs can increase the **efficiency of the decision-making process** by applying several types of analysis and simulations on each design solution to evaluate its performance.

Algorithmic software has an absolute limited ability to consider the form 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.

to find the most desirable form for the diagrid structure,
a **computational model** is designed
which rapidly generates, evaluates, and scores performances of different objectives.
using a generative algorithm.



OPTIMIZATION BEYOND STRUCTURAL EFFICIENCY

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.

Several experiments have been made in this field **for optimizing shape, topology and/or member sizes**.

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.

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

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.

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.

ESO is used for several projects **to achieve the maximum structural efficiency**.

PERFORMANCE BASED OPTIMIZATION

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.

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

The **performance based optimization** has been used in several projects and experiments.

For example, Norman Foster, in the project the Great Cour t 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. 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. 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).

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

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 exper t 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 proper ties or transmit information merely due to electronic or molecular proceedings. Hence we can dispense with mechanical systems in many cases.

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 façade was developed in order to maximize natural lighting and to minimize heat gain in summer for different sun conditions. However, other objectives are considered in generating the final form of the façade, such as economical and constructability issues.

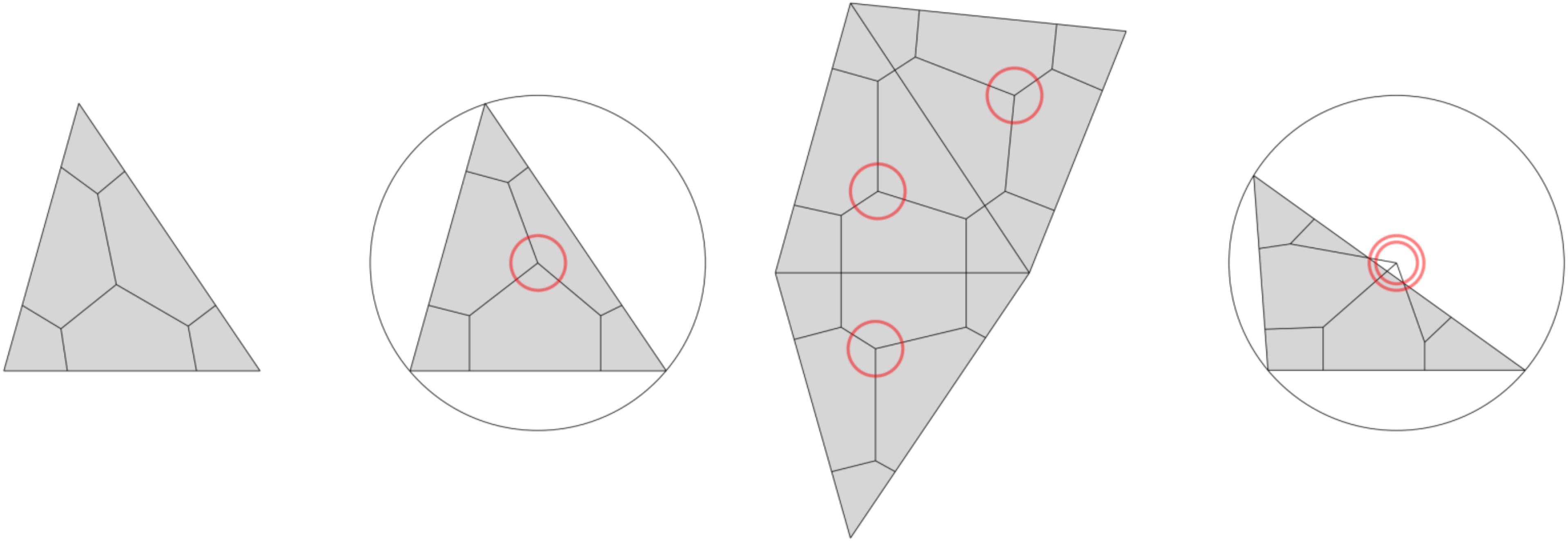
Patrick Teuffel. (2008). Responsive Building Envelopes: Optimization for environmental impact, Senior Lecturer in Architectural Engineering School of Civil Engineering, University of Leeds. The 6th International Conference on Computation of Shell and Spatial Structures,

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.

perpendicular meeting achieved by using the circumcircle and the problem when the corner exceeds 90 deg

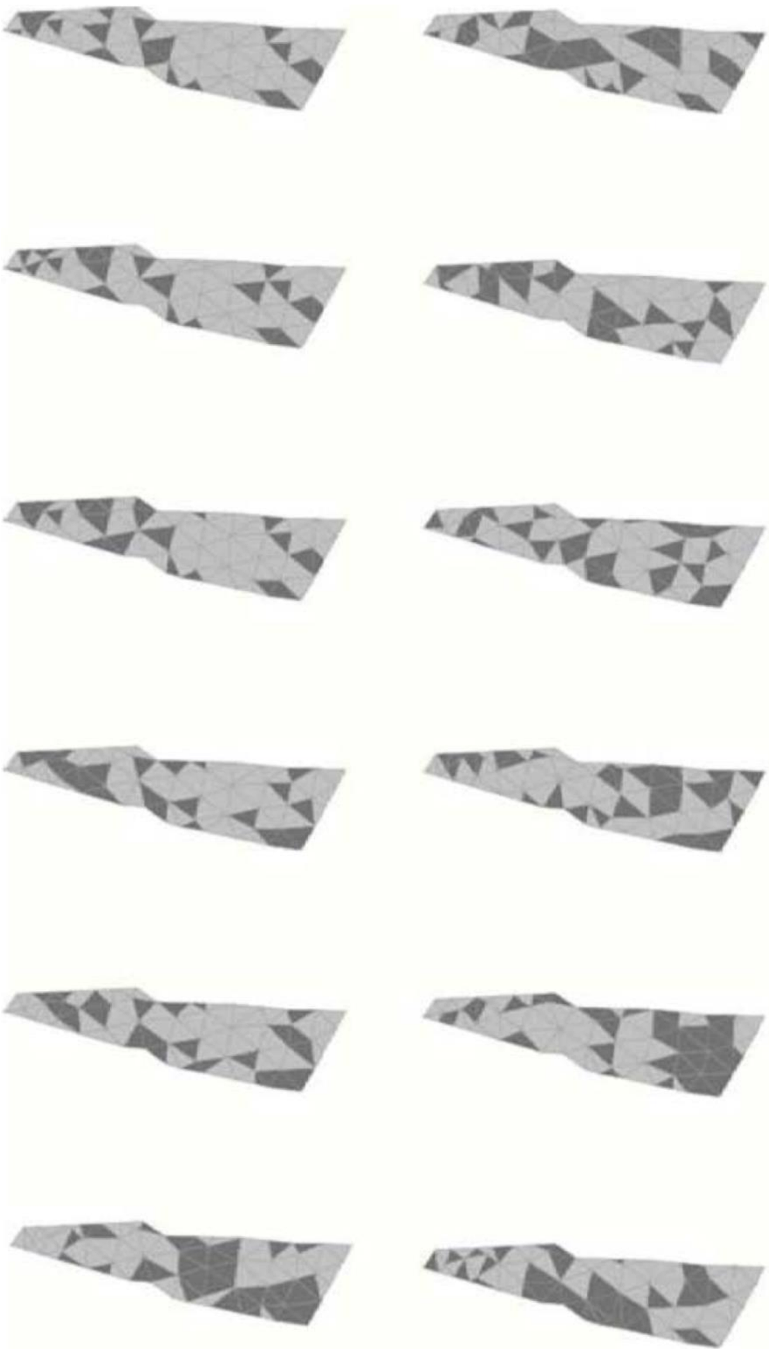
They are experiments in order to simplify fabrication and assembly process by modifying the overall shape or patterns of structures. For example, in the project Historical Museum of North Jutland, in Denmark, different aspects of design including structure, construction and assembly are all considered 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



optimization process where the dark facets represent non-successful triangles

Parametric Design and Construction Optimization
of a Freeform Roof Structure.
Alberto Pugnale

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 . Such a complex optimization process is modeled in a generative algorithm.



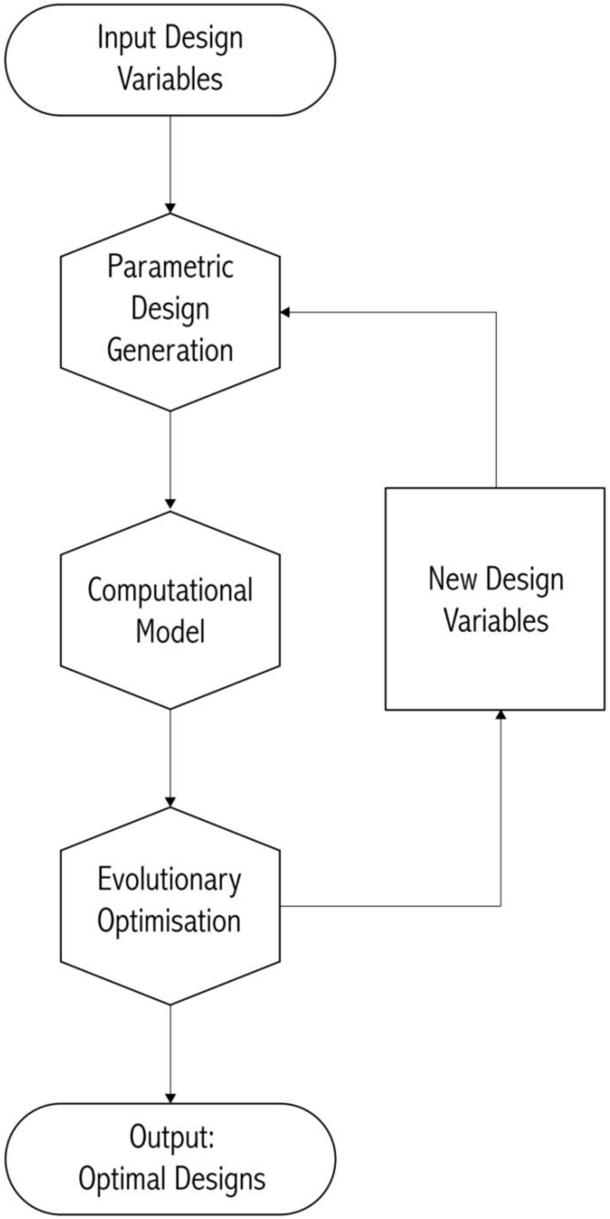
GENERATIVE MODELLING

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.

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

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 .

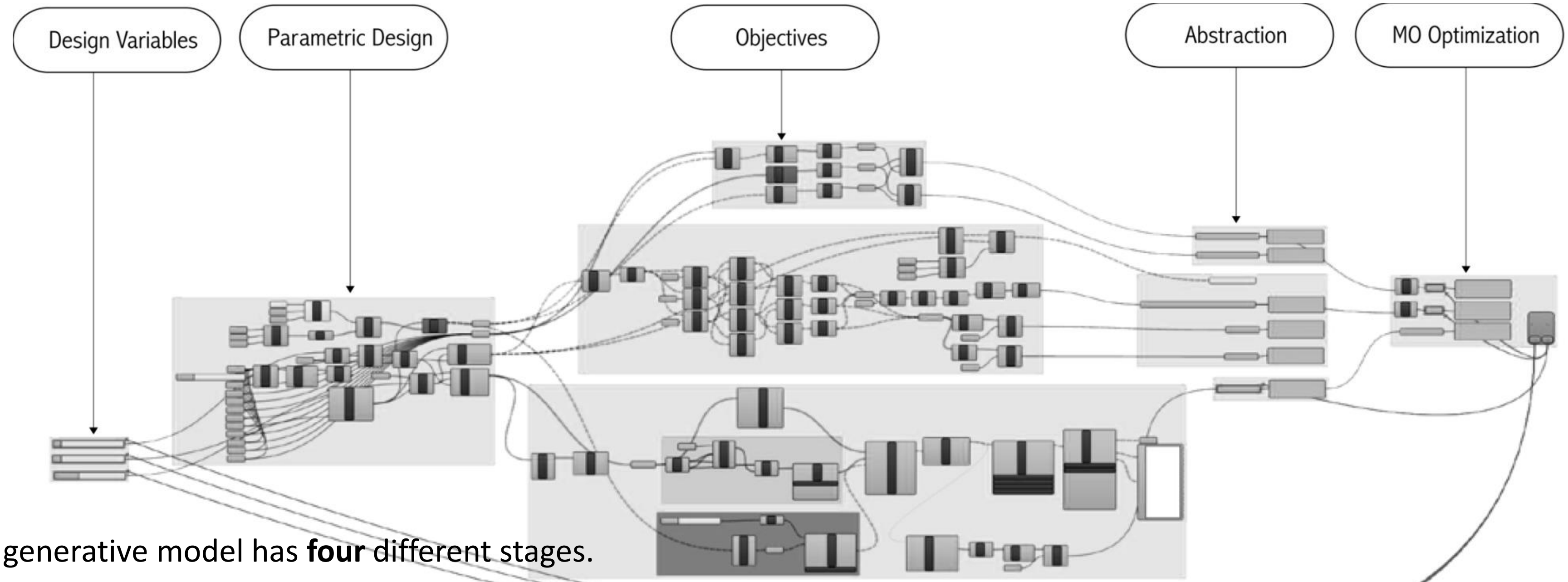
The model can also be seen as a design in itself, because the programmer carefully creates the process of coming to a building. The generative model is therefore an abstract design solution.



COMPUTING GENERATIVE MODEL

*In a **generative design process developed in Grasshopper**.*

any kinds of **objectives** can be chosen, such as **climate**, **functionality**, and **structural efficiency**.



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.

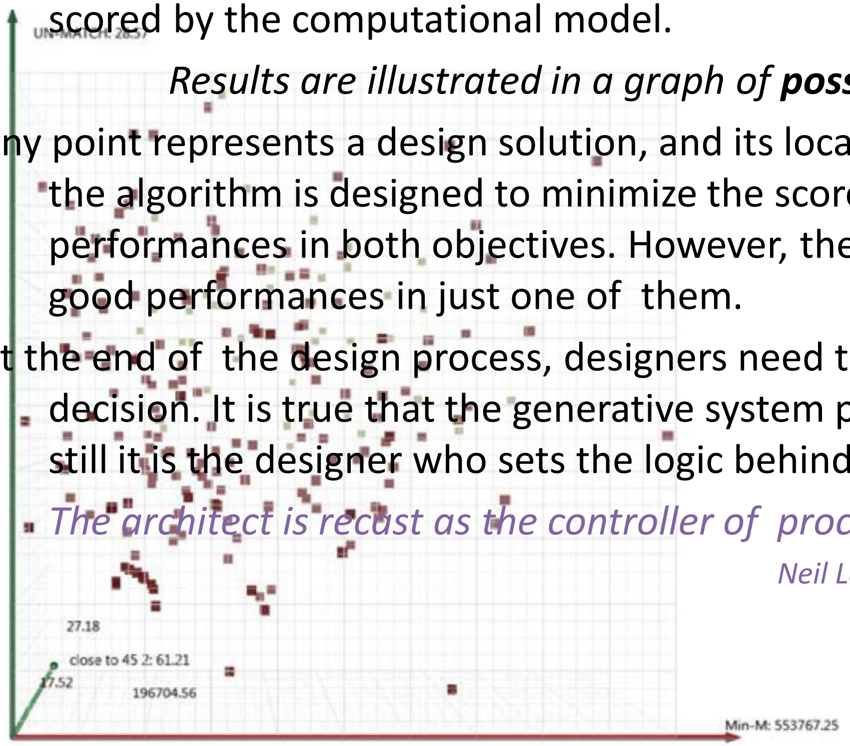
Then, the algorithm learns from the results and picks new values for variables input in the first stage. This design process will continue in a loop to find the optimally performing design.

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.

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.

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 of ***possible generative solutions***

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

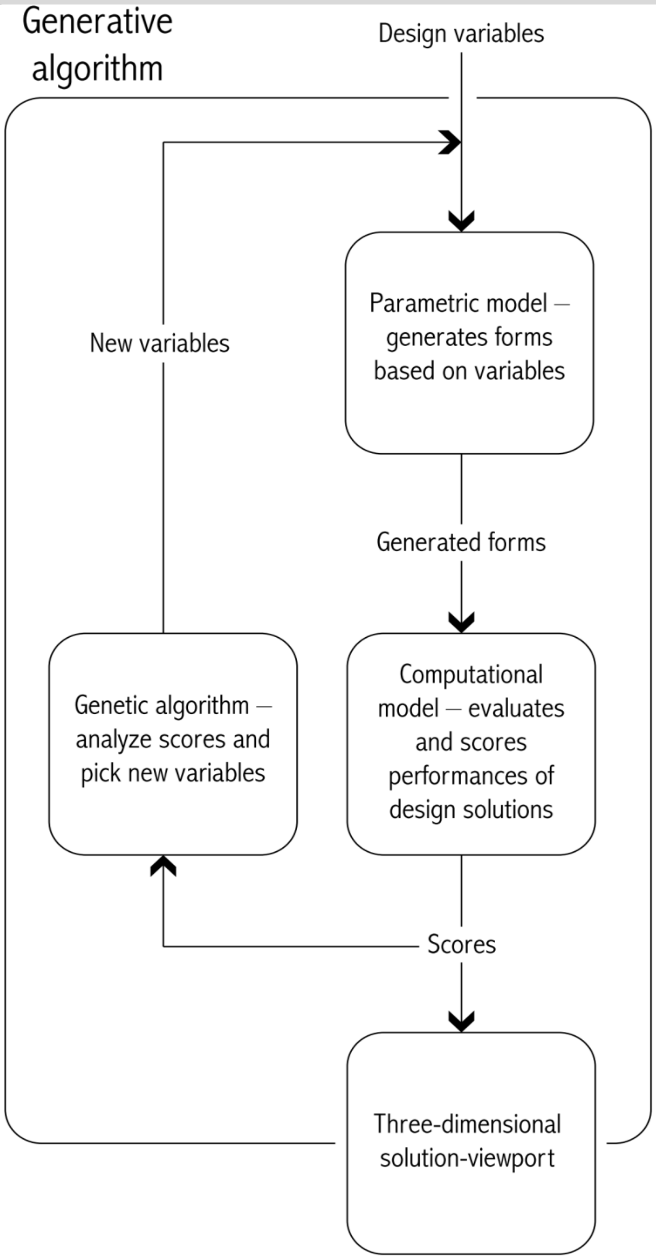
Neil Leach, David Turnbull, Chris Williams. (2004). Digital Tectonics. Wiley-Academy,

EVOLUTIONARY OPTIMIZATION

A Neural Fuzzy System for Soft Computing.
A fast and elitist multi-objective genetic algorithm
NSGA-II. IEEE Transactions on Evolutionary Computation, 6(2), 182-197.

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

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.



Generative algorithm

Design variables

Parametric model – generates forms based on variables

New variables

Generated forms

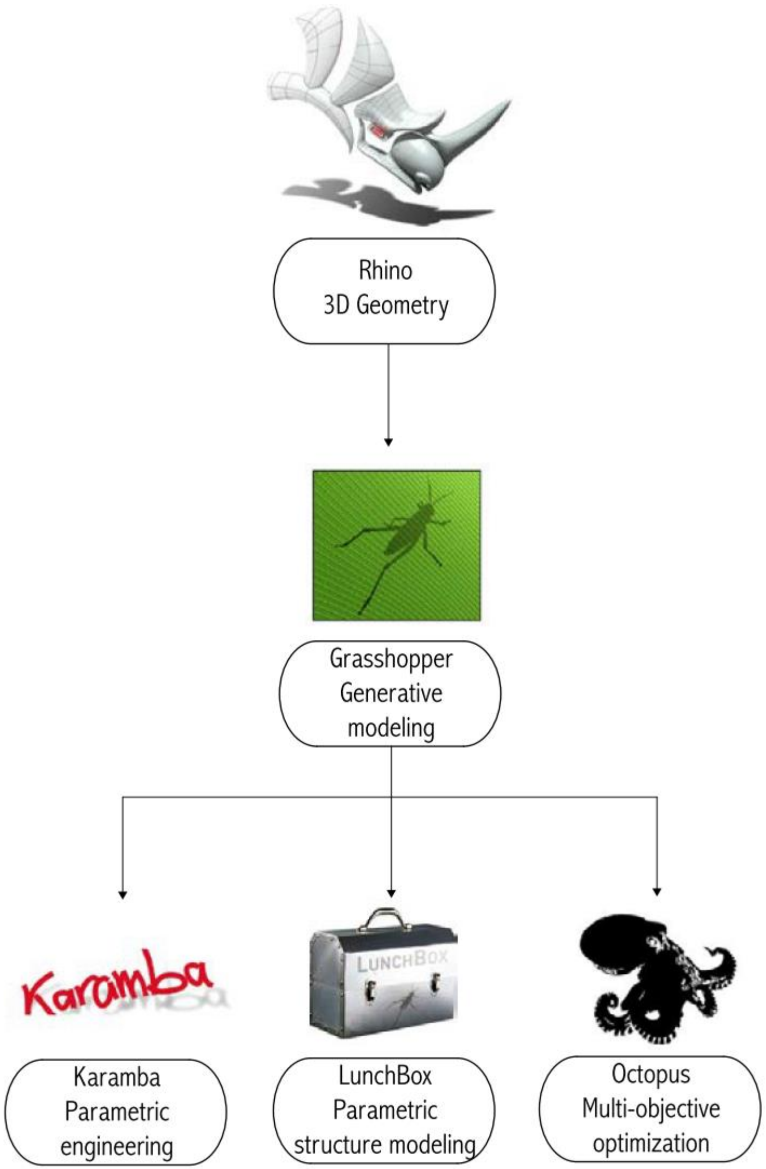
Genetic algorithm – analyze scores and pick new variables

Computational model – evaluates and scores performances of design solutions

Scores

Three-dimensional solution-viewport

TOOLS



Generative design is becoming more popular because of recent **developments in programming environments .**

[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

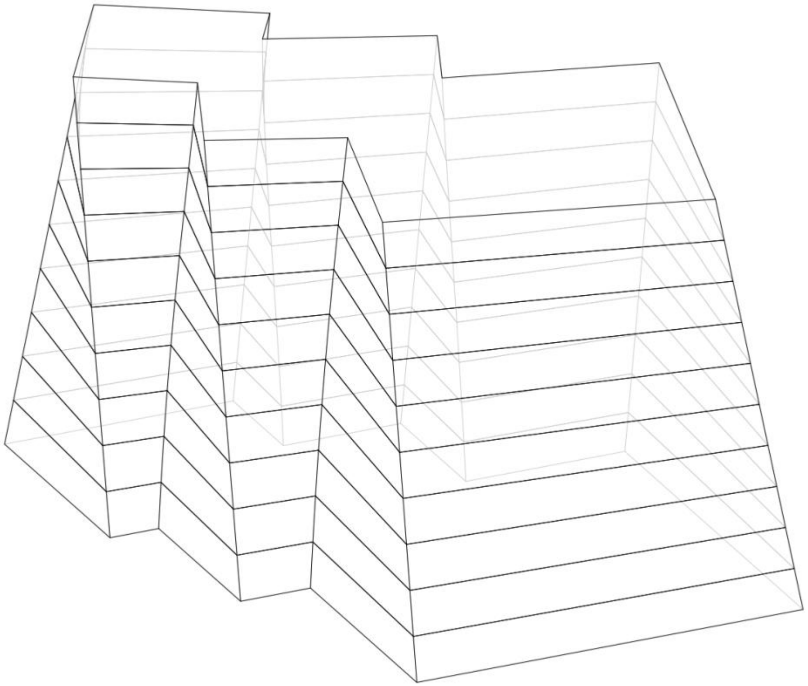
[8] http://www.grasshopper3d.com/group/lunchbox

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

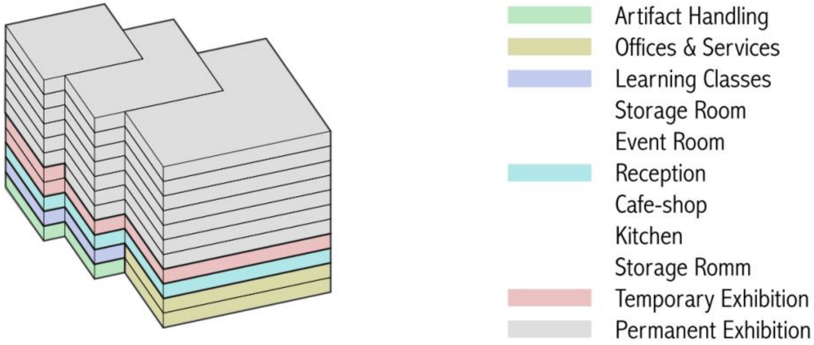
For example, many computational components and plugins are made for Grasshopper that can help designers to analyze different aspects of projects and design algorithms for multi-criteria optimization using plugins such as

- Octopus, for Multi-objective optimization,
- Lunch Box, for parametric design,
- and Karamba, for structural analysis

PROPOSED FORM-FINDING METHOD



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.



FORM-FINDING MODEL

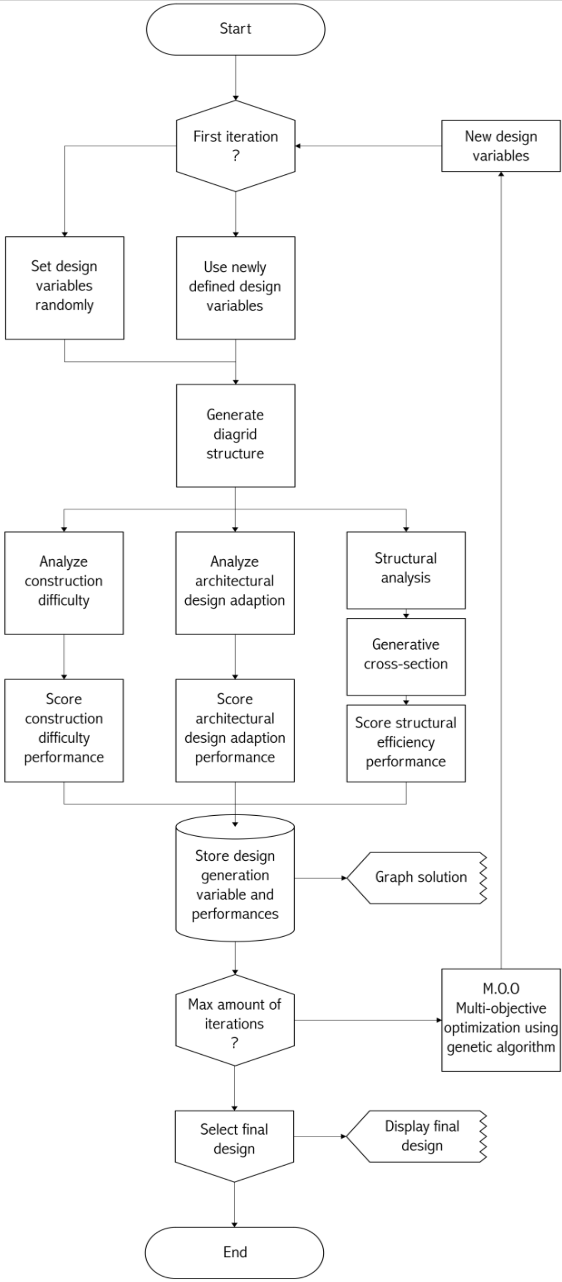
A generative algorithm is designed

- 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.



FORM OF THE STRUCTURE

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.

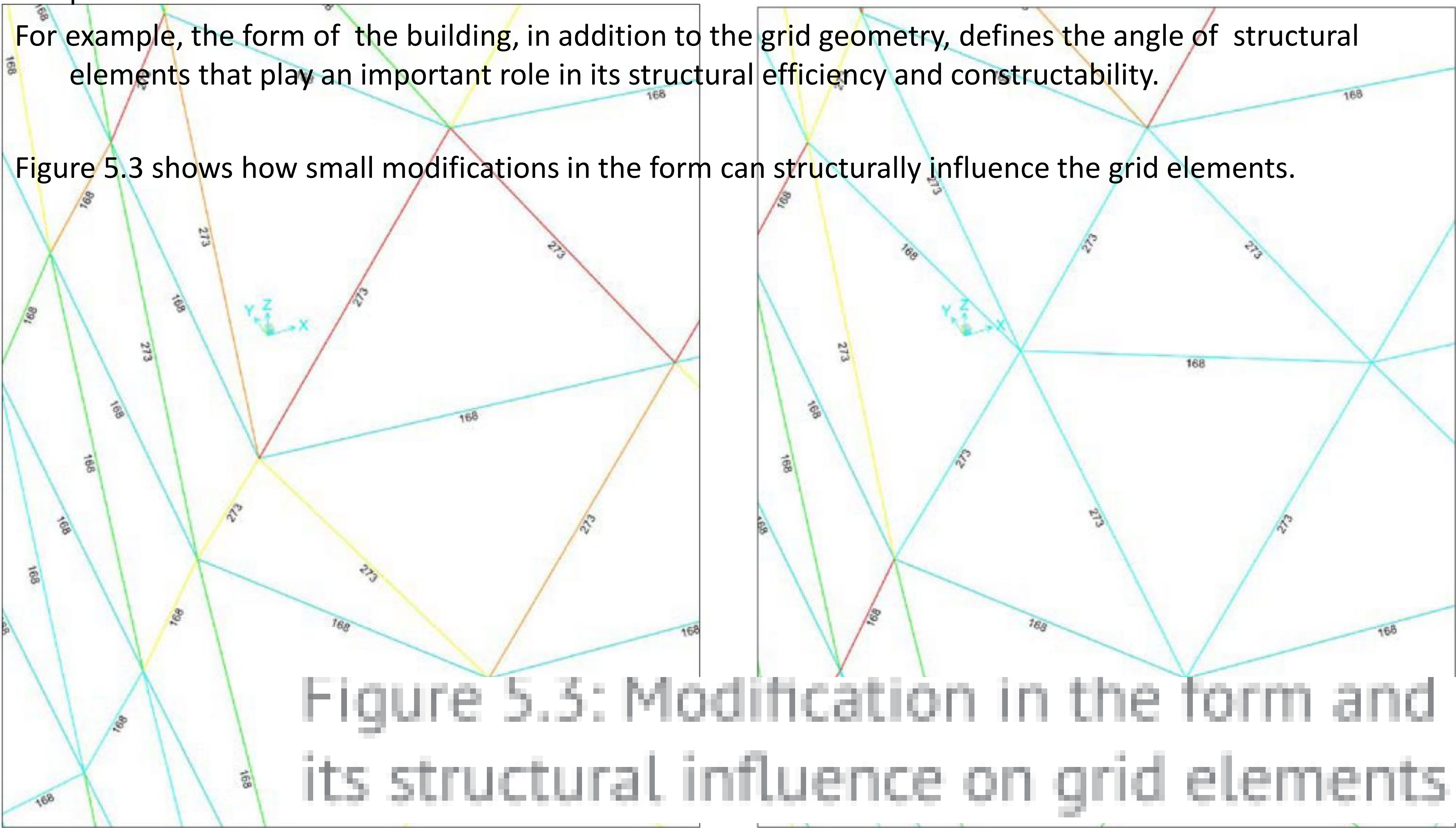
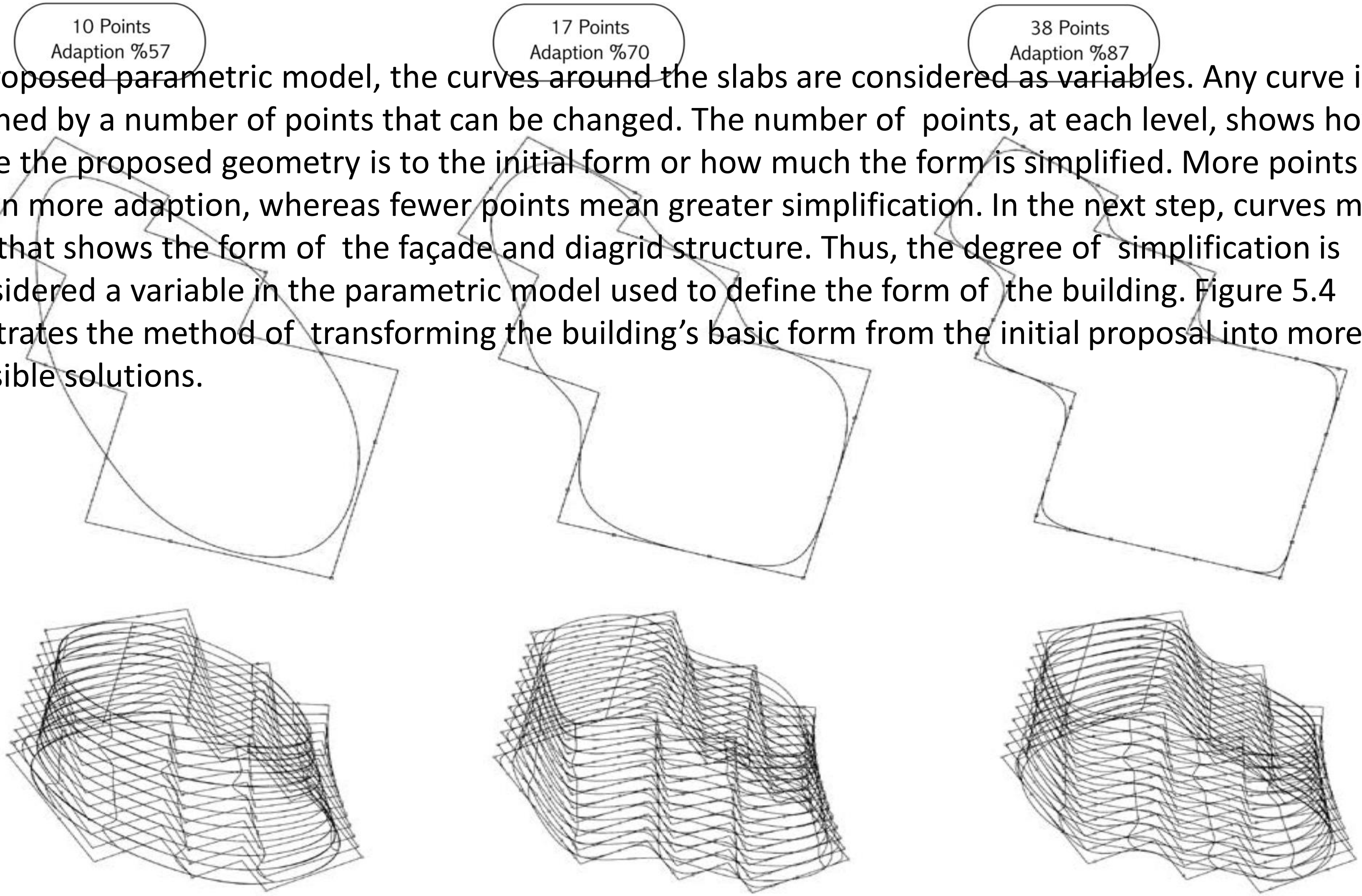


Figure 5.3: Modification in the form and its structural influence on grid elements

PARAMETRIC MODEL

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.

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.



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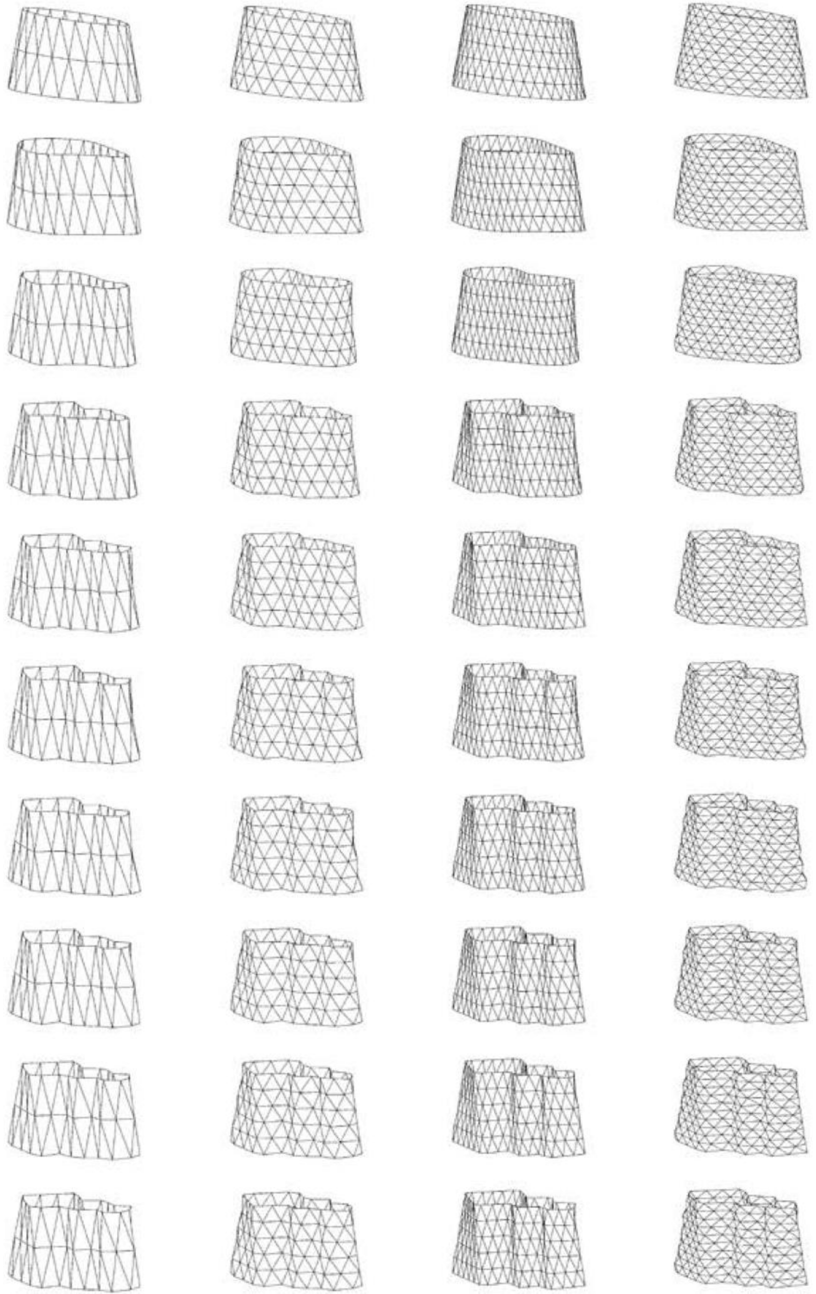
GRID GEOMETRY

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.

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.



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.

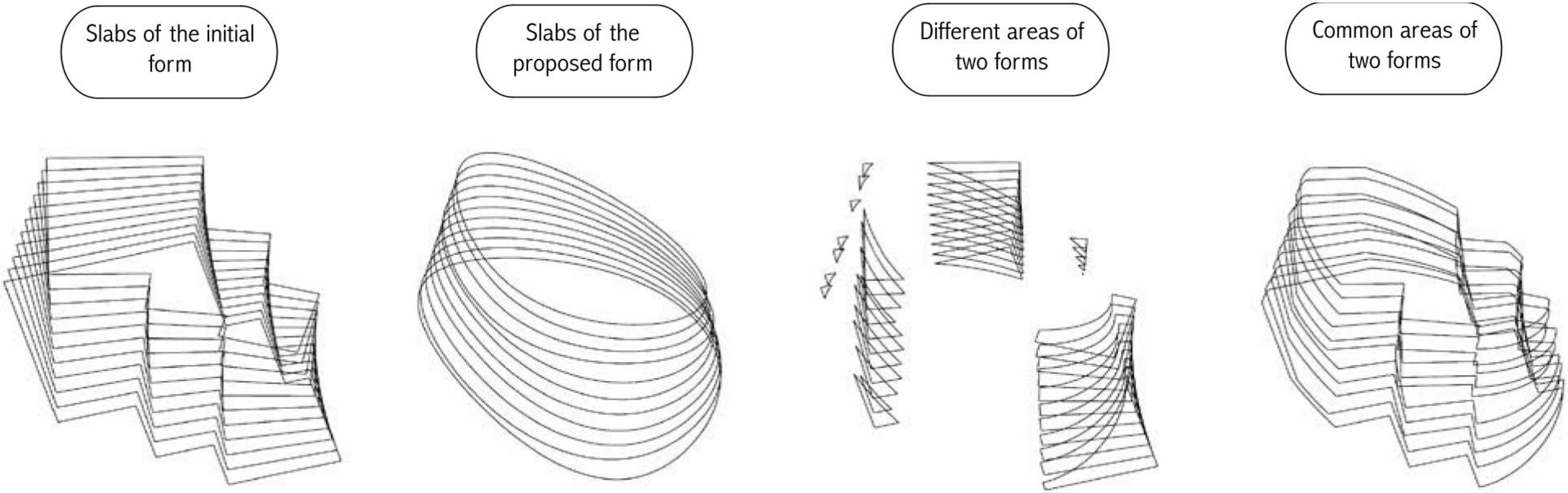
Three main aspects will be evaluated:

- architectural design adaption
- structural efficiency
- and construction difficulty

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.



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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%,

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%,

it means that the proposed form has the highest geometrical adaption to the initial form.

STRUCTURAL EFFICIENCY

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

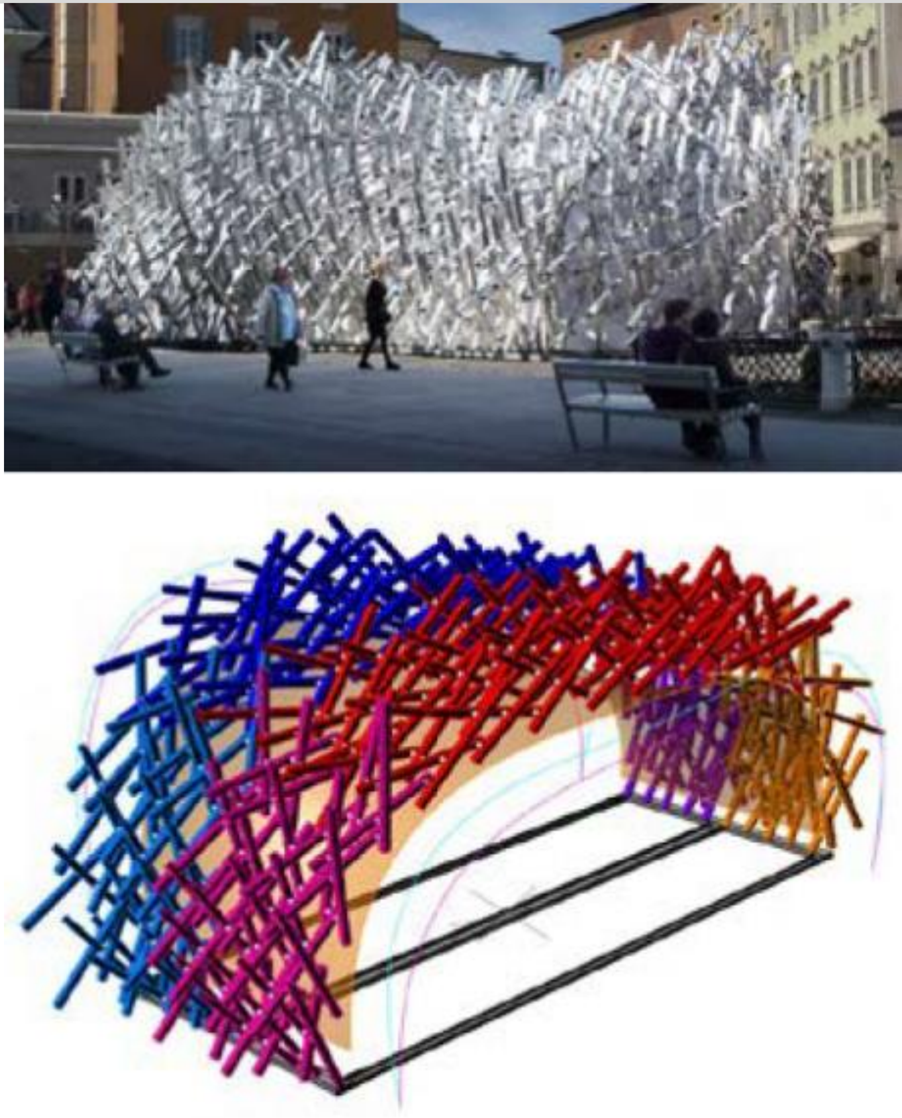


Figure 5.7: Music Pavilion in Salzburg Biennale 2011 by Soma

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.

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.

$$C_r = \phi A F_y \left(1+\lambda^{2n}\right)^{-1/n}$$

$$\lambda = \frac{KL}{r}\sqrt{\frac{F_y}{\pi^2 E}}$$

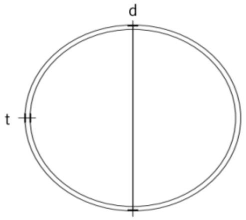


Table 5.1: Round Hollow Section, Factored Axial Compressive Resistances, r_y

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

Section		HFCHS 508	HFCHS 457	HFCHS 355	HFCHS 273	HFCHS 219	HFCHS 168	HFCHS 139
Effective length KL (ft) with respect to least radius of gyration, ry	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

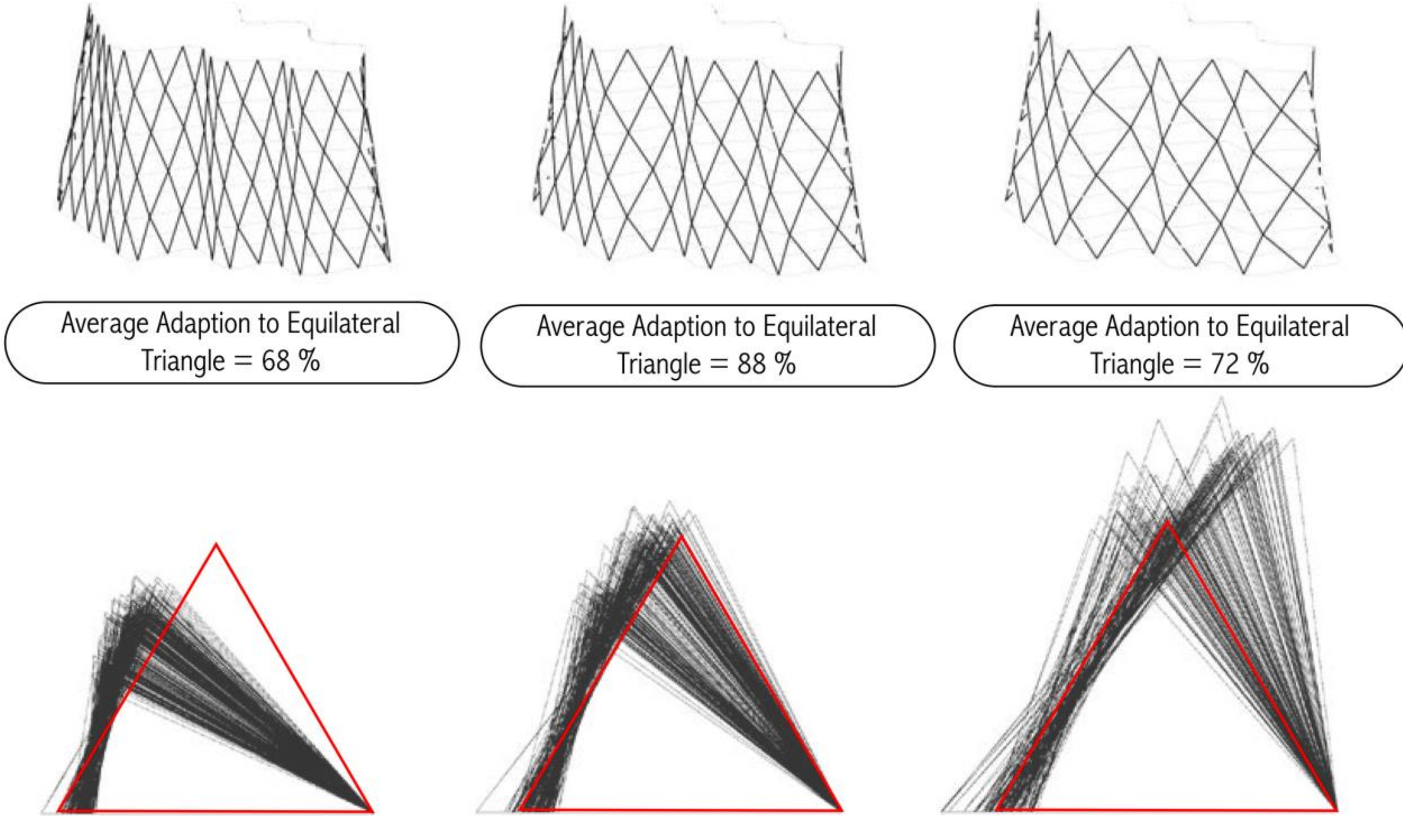
Grid models that are geometrically closer to equilateral triangles are more efficient in construction processes. Thus, this algorithm, to optimize the construction process, calculates all angles of modules and finds the best possible solution in which angles have the minimum differentiation, with 60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

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

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



Average Adaption to Equilateral Triangle = 68 %

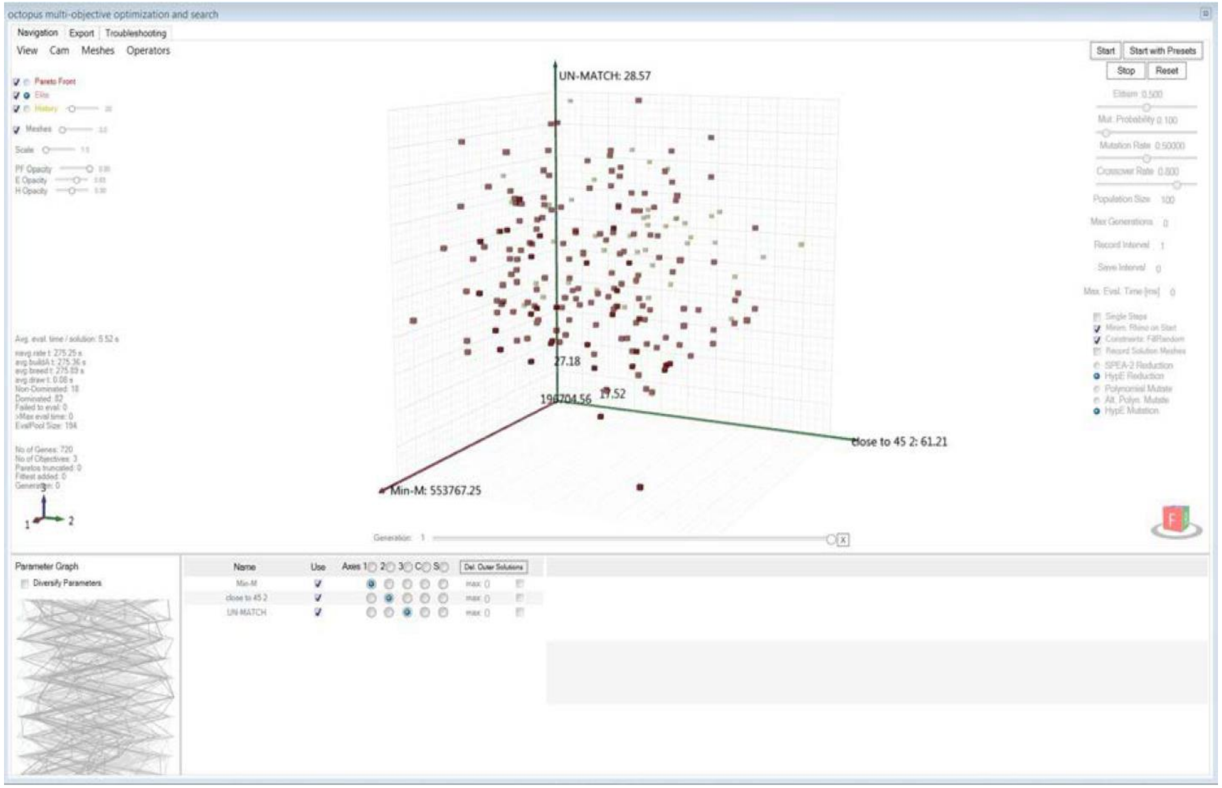
Average Adaption to Equilateral Triangle = 88 %

Average Adaption to Equilateral Triangle = 72 %

the octopus interface

this **MO-tool's utility** lies in ***its ability to handle up to six objectives***
and show results in a two- to six-dimensional solution-viewport.
the **Octopus 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.
It is ***developed to replace the only tool in Grasshopper for genetic modeling***.

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. 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.



Avg. eval. time / solution: 5.52 s
navg rate t: 275.25 s
avg buildA t: 275.36 s
avg breed t: 275.89 s
avg draw t: 0.08 s
Non-Dominated: 18
Dominated: 82
Failed to eval: 0
>Max eval time: 0
EvalPool Size: 194

No of Genes: 720
No of Objectives: 3
Paretos truncated: 0
Fittest added: 0
Generation: 0

Elitism 0.500
Mut. Probability 0.100
Mutation Rate 0.50000
Crossover Rate 0.800
Population Size 100
Max Generations 0
Record Interval 1
Save Interval 0
Max. Eval. Time [ms] 0

☐ Single Steps
☑ Minim. Rhino on Start
☑ Constraints: FillRandom
☐ Record Solution Meshes
○ SPEA-2 Reduction
● HypE Reduction
○ Polynomial Mutate
○ Alt. Polyn. Mutate
● HypE Mutation

☐ Diversify Parameters

Name	Use	Axes 1	2	3	C	S		
Min-M	☑	●	○	○	○	○	max 0	☐
close to 45 2	☑	○	●	○	○	○	max 0	☐
UN-MATCH	☑	○	○	●	○	○	max 0	☐

FINAL SOLUTION

In **evolutionary multi-objective optimization**,

to find the best fit solution,

different solutions are compared.

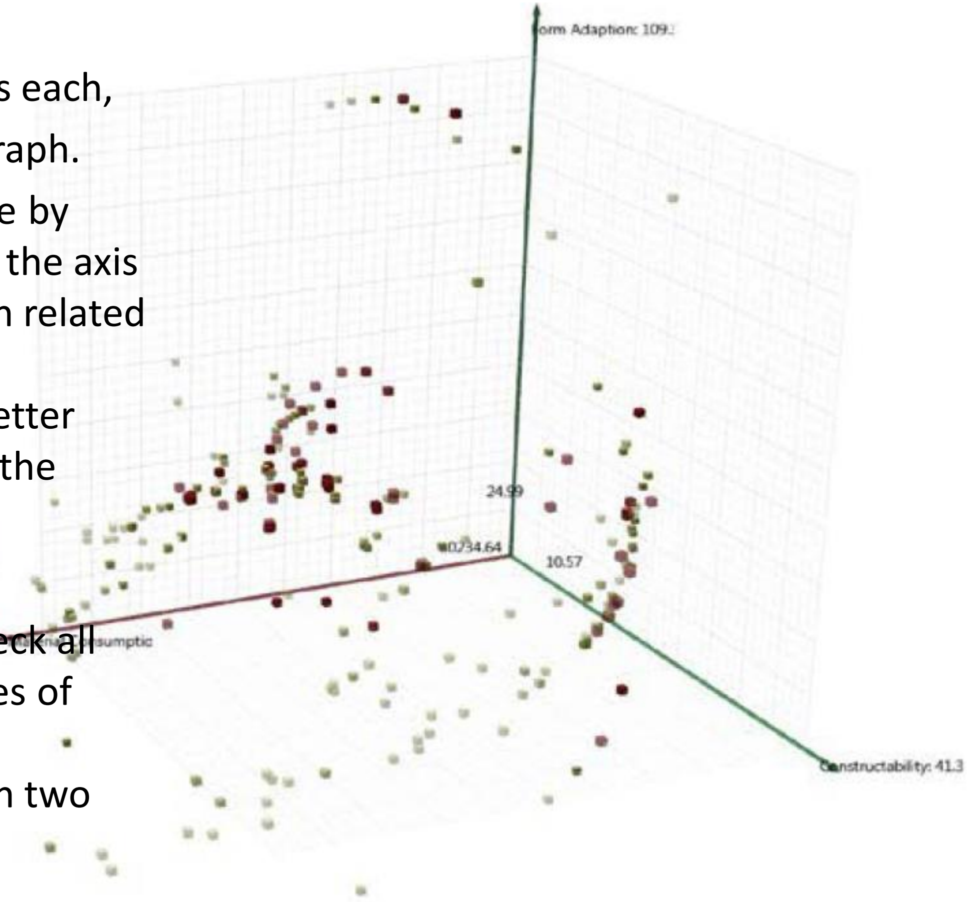
The defined loop ran 70 generations, with 10 solutions each,

to compare 700 design solutions 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 parameters such as aesthetics. All chosen solutions have high scores in two objectives and moderately high ones in the other.



FINAL SOLUTION

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**, is the average solution. It is the design nearest to the origin. All aspects perform high, but not the highest. As shown here, ***all three aspects clearly perform high***.

Form Adaption in Percent
75 %

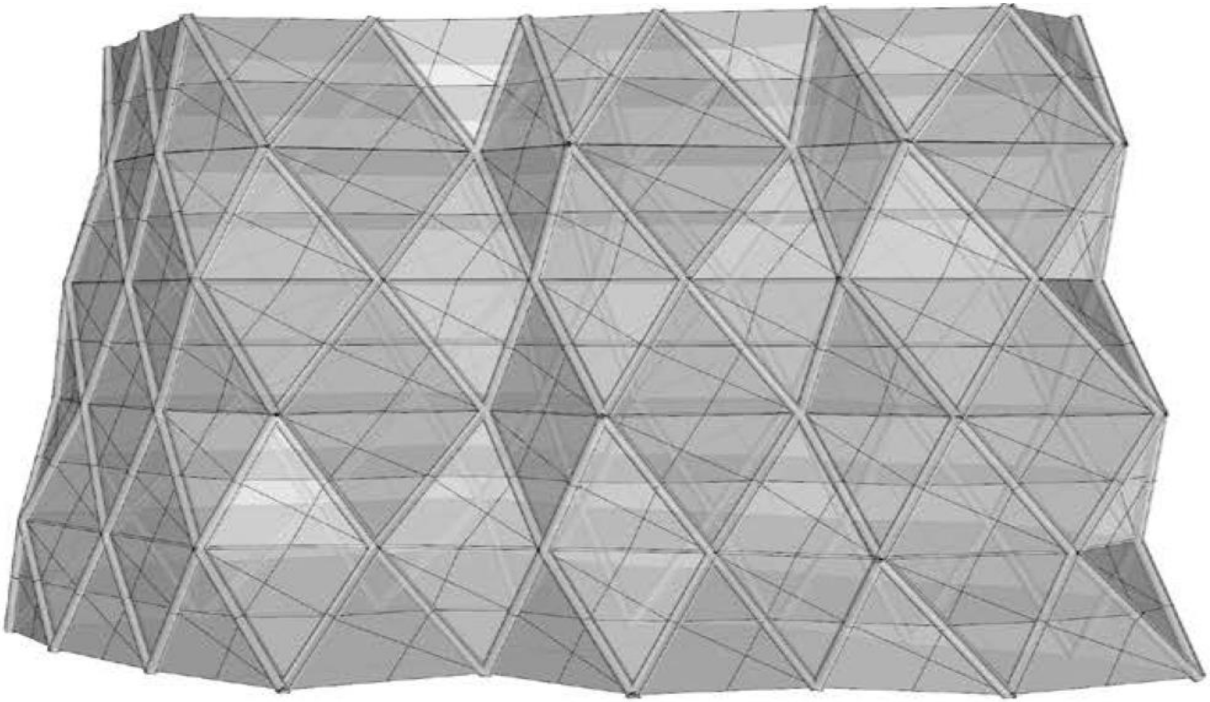
Area Adaption in Percent
113 %

Average Adaption to Equilateral Triangle in Percent
87 %

Min Angle
53 D

Max Angle
72 D

Material Consumption
103600 Kg



SOLUTION PERFORMANCE

All **computation techniques** and **scoring systems**

in the generative algorithm

are designed to simplify process of performance evaluation using computation tools in Tekla and SAP2000.

The **generative model** translates the *concept of constructability* easily by ***comparing** the angle of diagrid elements*,

but the designer can never be sure about the result

without testing the final design solution

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

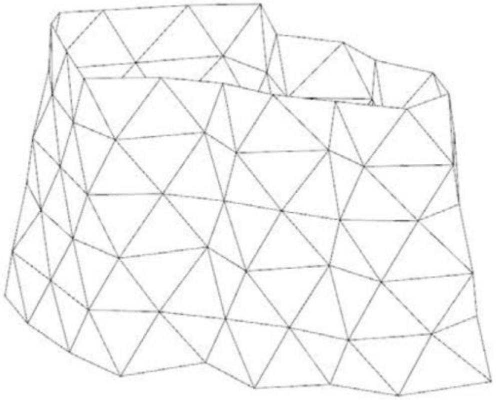
***compared** with the result from two initial solutions*

This comparison shows whether or not the form-finding process is able to find better proposals.

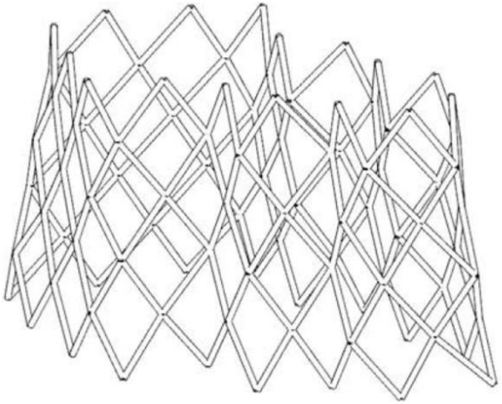
In this way, the design from the algorithm is developed by

Tekla for evaluating the constructability

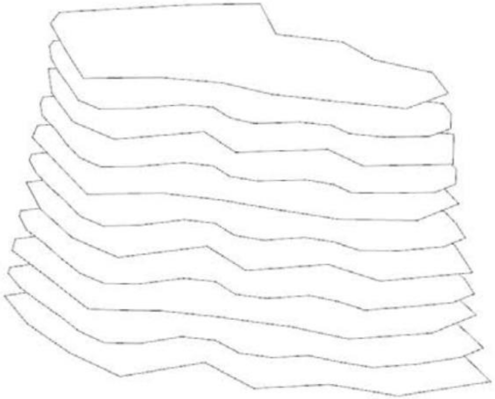
and **SAP2000** to determine material consumption and structural efficiency.



Cladding System



Diagrid Structure



Slabs

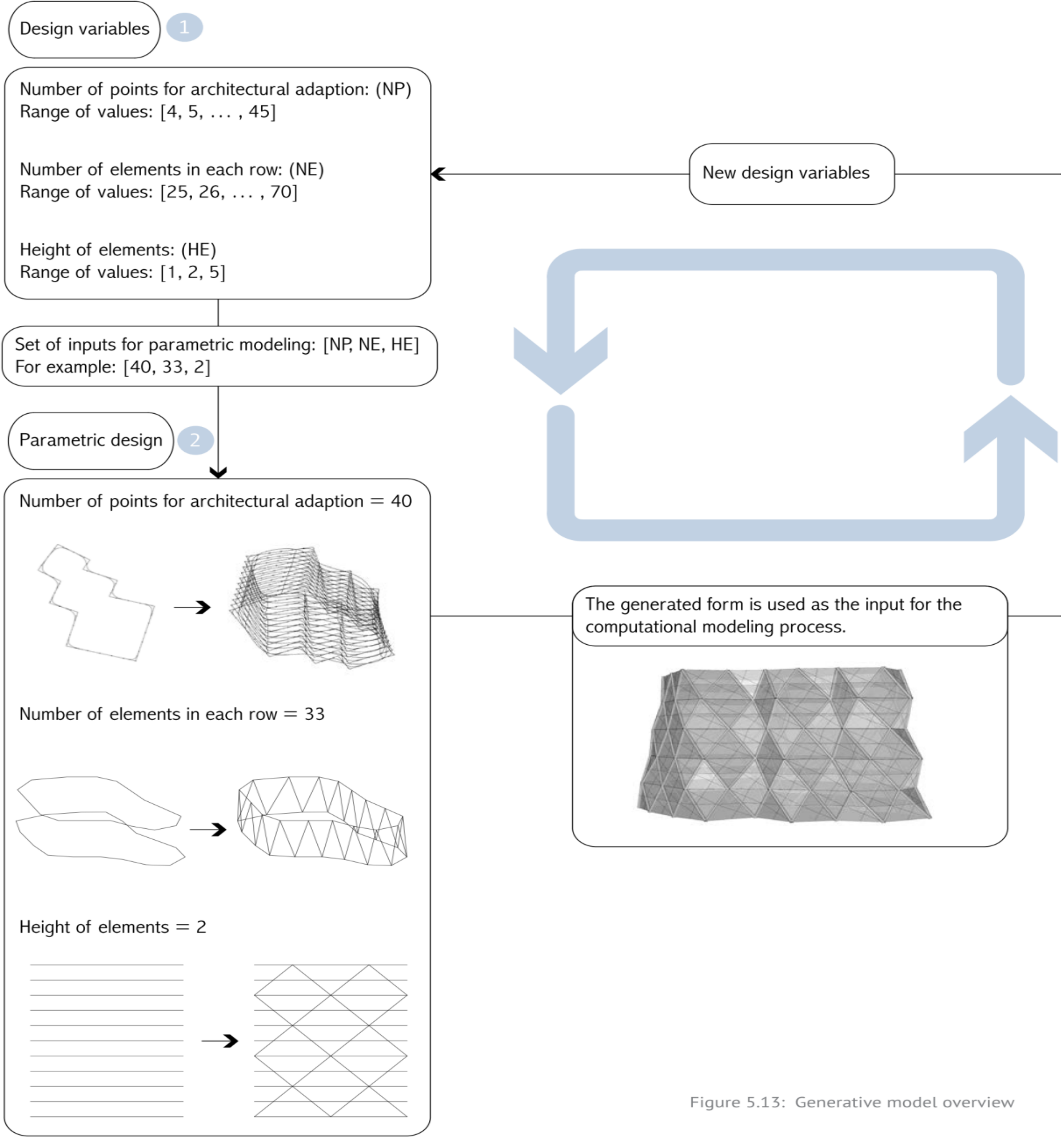
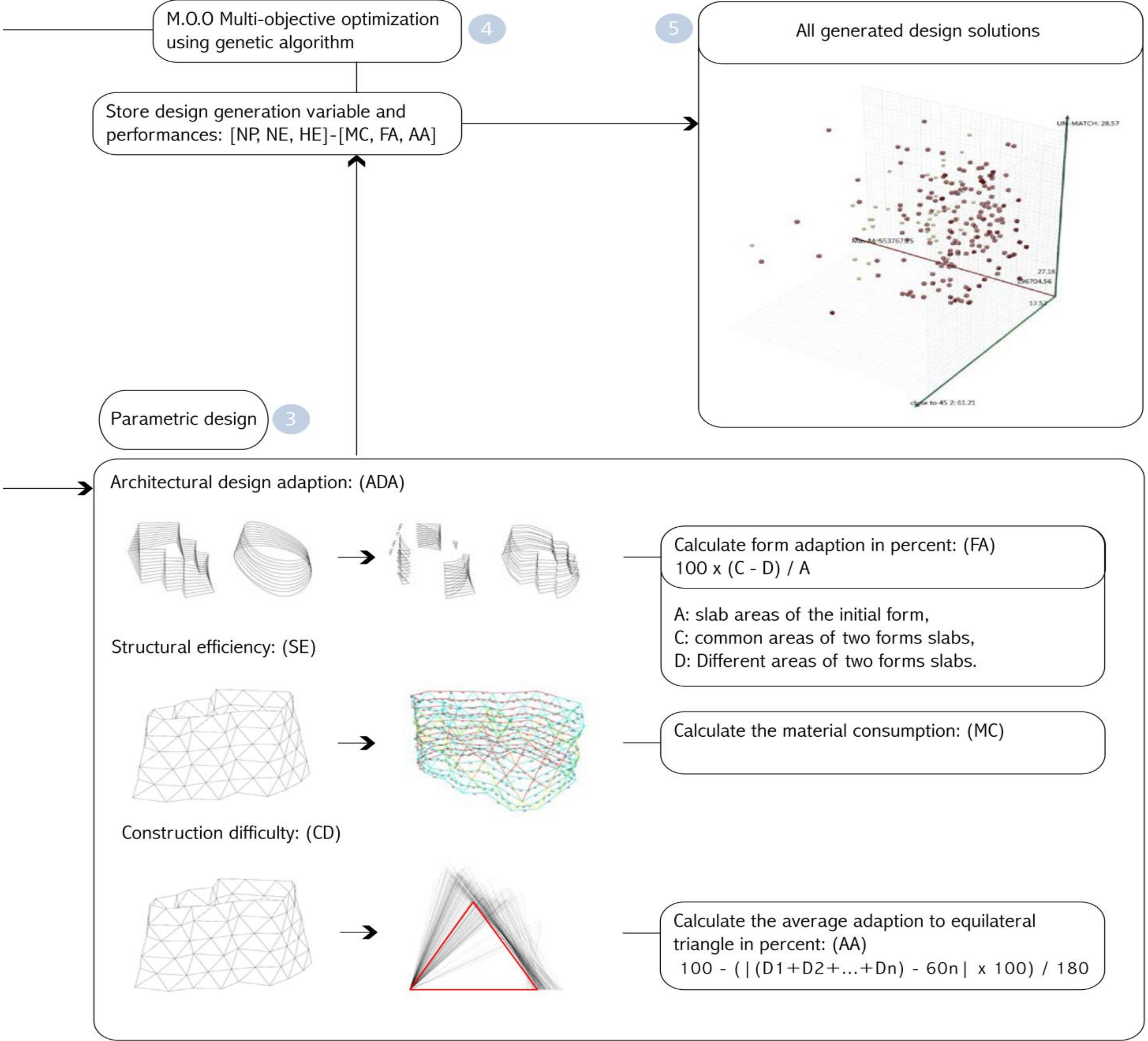
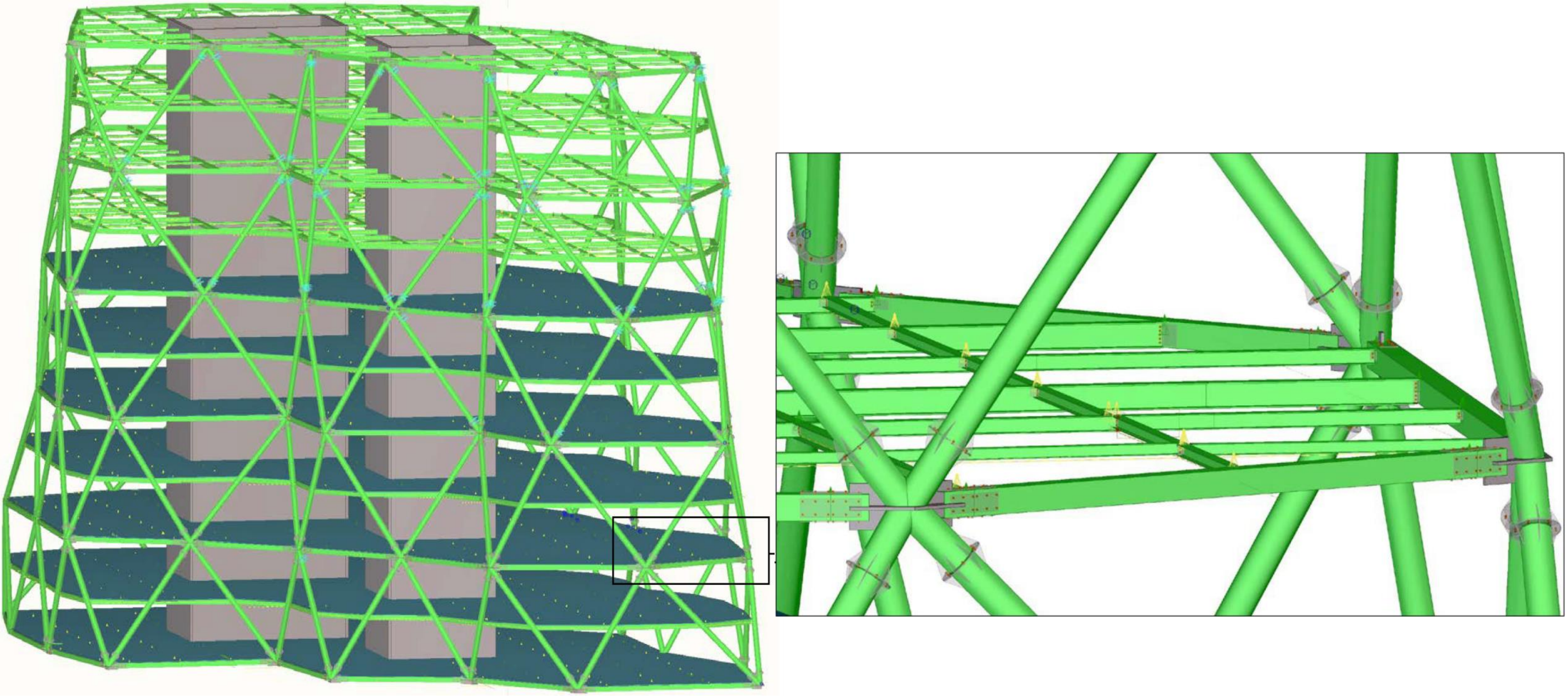


Figure 5.13: Generative model overview


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
UN-MATCH: 28.57
Min M: 55376795
27.18
196704.56
17.52
close to 45 2: 61.21
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

TEKLA MODEL



according to initial analysis in Tekla Structures,

it has **no error in construction** because of high or low angles.

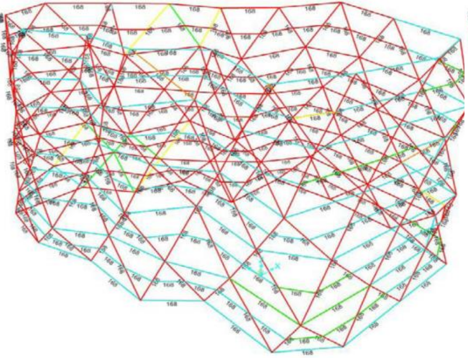
This means that the **structure is physically constructible**.

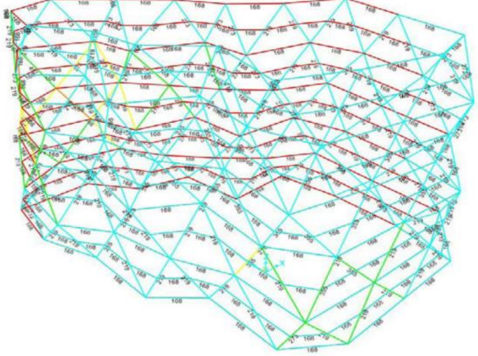
also the length of needed cutting and welding operation can be determined by Tekla.

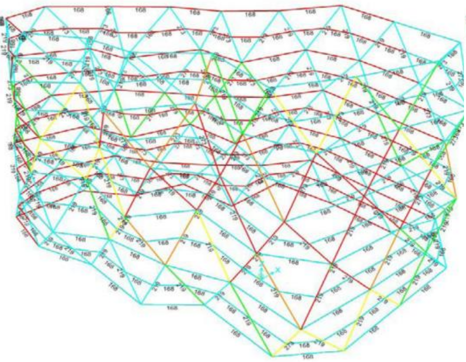
These parameters, in addition to material consumption,

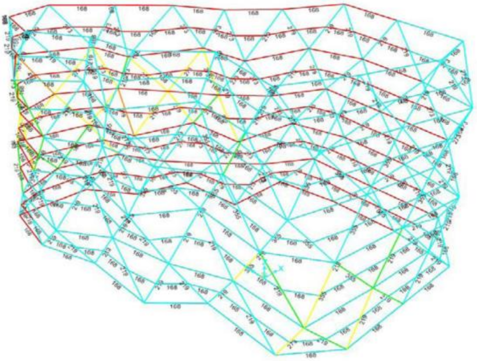
show ***which solution is more cost efficient in the fabrication process***.

PERFORMANCE RESULTS


Step 3


Step 3


Step 4


Step 4

shows analysis steps and results in SAP2000

minimum cross-sections

proposed for the diagrid structure,

material consumption is

124.5 tons

which is 27% less than solution 1

and 15% more than solution 2.

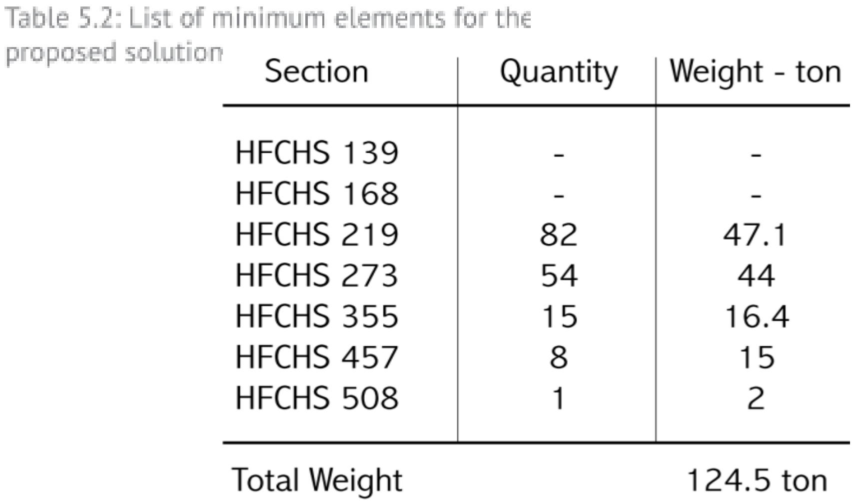
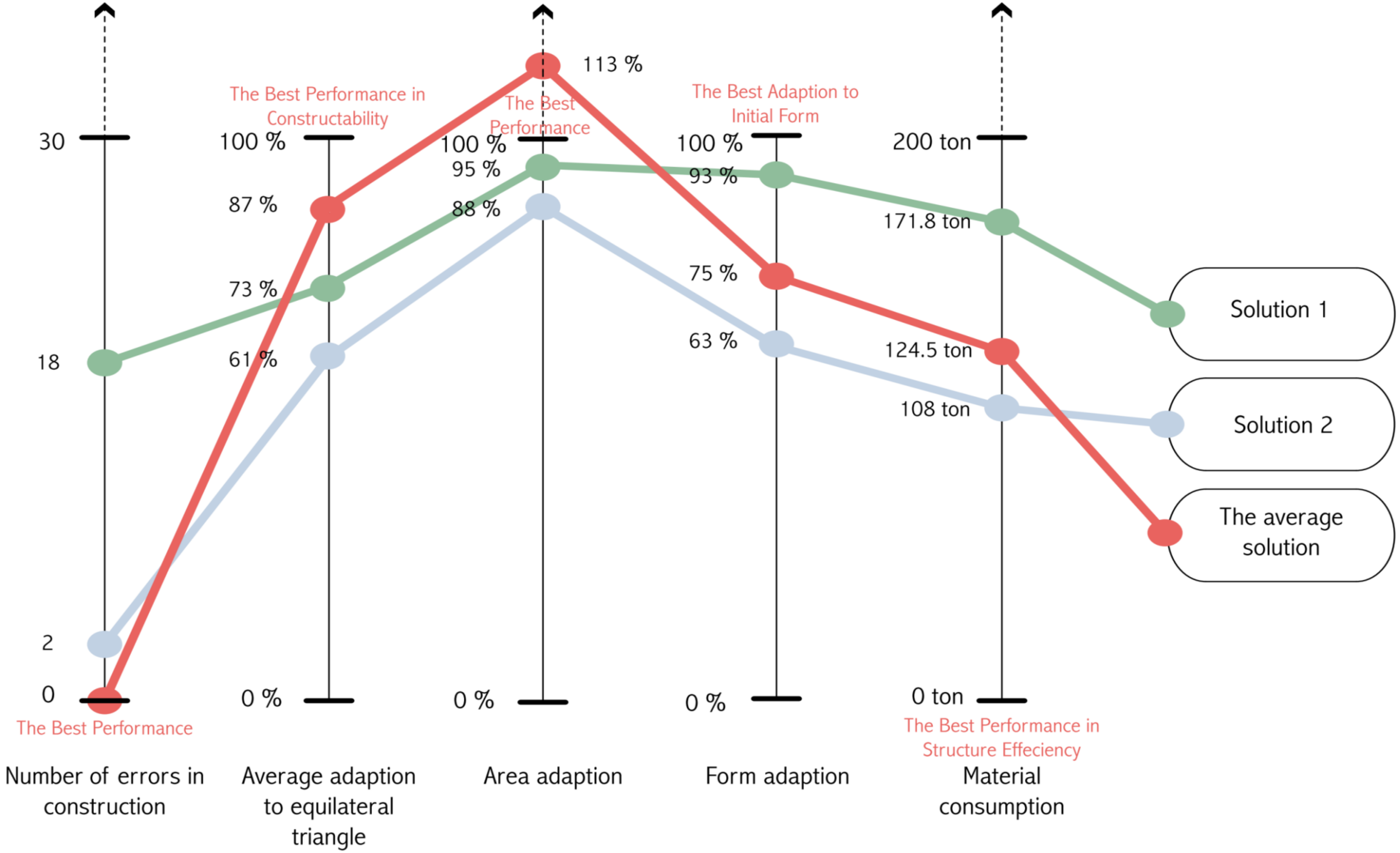


Table 5.2: List of minimum elements for the proposed solution

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



overall, the ***GA-proposed form is easier to build than solutions 1 and 2***.

albeit being **18% less architecturally adaptable** to the initial form than solution 1,

and **uses 15% more steel** than solution 2.

so it is not the absolute best answer but ***the average best solution***,

i.e high performances in all objectives but not the best in all of them.

CASE STUDY: GENERATIVE ALGORITHM AND OPTIMIZATION OF DIAGRIDS

Direct search solution of numerical and statistical problems. Chris Luebkeman, K. S. (2005)

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 the next iteration

After several iterations, the generative model presents the **highest performing designs** as a final output.

Computational design + optimization in building practice. The Arup Journal,

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.

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

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.

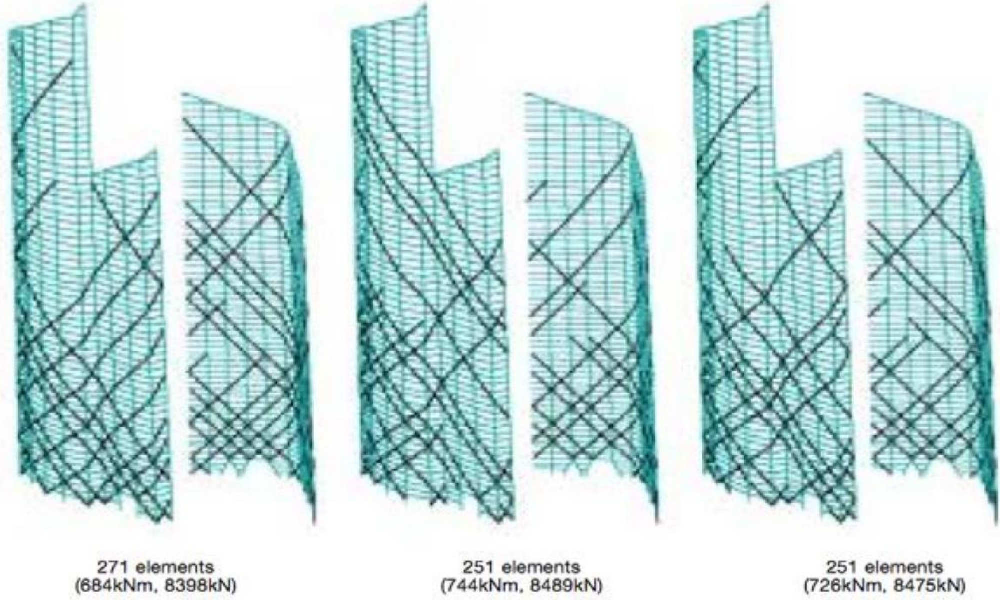


Figure 4.13: Planning application schemes for the bracing system of the Bishopsgate Tower. http://www.futureglasgow.co.uk/extra/pinnacle4.jpg

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