# Computing Diagrid Structural Systems in Free-Form High-Rise Designs

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Recent years have seen the use of diagrid structural systems becoming widespread in architecture. Diagrids are advantageous mostly for cutting down on the number of structural elements used. However, the use of diagrid structural systems is still not common in free-form high-rise designs. Most high-rise designs are symmetrical and orthogonal structures whereas free-form as a type of building geometry form implies asymmetric configurations, without a fixed order or a central rotation axis. Among the difficulties observed in free-form high-rise designs is efficiency in the analysis and synthesis of structural solutions and in the physical realization of the structural elements. Overcoming these difficulties requires computational support. However, most of the existing software up to the task are protected by copyright and expensive, hence inaccessible to many small firms and individual designers. Addressing the problems of affordability and accessibility, the study presents a computational support system for preliminary design proposals of diagrid structures in free-form high-rise designs. This support takes place in an algorithmic design interface, and the biggest advantage is that designers can integrate the design and analysis phases in a single interface. The model has three main phases. These phases are the creation of a free-form high-rise geometry, structural analysis of this geometry when modelled as a diagrid structural system, and the numbering and sequencing of the most important structural element that is node connector so that it is suitable for the prefabrication. Based on the structural assessment of the model, the study also discusses the alternatives of diagrid structural systems to see whether the potential structural element may be added to the diagrid structural system.

**Keywords:** diagrid structural systems, free-form high-rise designs, node connector, preliminary design, structural analysis.

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# Diagrid Strüktür Sistemlerinin Serbest Biçimli Yüksek Tasarımlarda Hesaplanması

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Mimarlıkta diagrid strüktür sistemlerinin kullanımı son yıllarda yaygınlaşmıştır. Diagridler tasarımda kullanılan yapısal elemanların sayısını azalttıkları için avantajlıdırlar. Bununla birlikte, diagrid strüktür sistemlerinin serbest biçimli yüksek katlı tasarımlarda kullanımı yaygın değildir. Yüksek katlı tasarımların çoğu simetrik ve ortogonal yapılardır, fakat bir bina geometrisi biçim türü olan serbest biçim, sabit bir düzen ve merkezi bir dönme ekseni olmayan asimetrik konfigürasyonlardır. Serbest biçimli yüksek katlı tasarımlarda gözlenen zorluklar arasında yapısal çözümlerin analiz ve sentezindeki verimlilik ile yapısal elemanların fiziksel gerçekleştirilmesi vardır. Bu zorlukların üstesinden gelmek için hesaplamalı yaklaşımların desteğine ihtiyaç vardır. Bununla birlikte, bu çalışmaya kadar var olan yazılımlar telif hakkı ile korunmaktadır ve pahalıdır, bu nedenle birçok küçük firma ve bireysel tasarımcı bu yazılımlara erişemez. Bu yazılımların satın alınabilirlik ve erişilebilirlik problemlerini ele alan tez, serbest biçimdeki yüksek katlı tasarımlarda diagrid yapıların ön tasarımları için hesaplamalı yaklaşım ile bir destek sistemi sunmaktadır. Bu destek, algoritmik bir tasarım arayüzünde gerçekleşir ve en büyük avantaj, bütünleşik olarak tasarımcıların tasarım ve analiz aşamalarını tek bir arayüzde yapabilmeleridir. Model üç ana aşamadan oluşmaktadır. Bu aşamalar, serbest biçimli yüksek katlı bir geometrinin oluşturulması, bu geometrinin bir diagrid strüktür sistemi ile yapısal analizi ve en önemli yapı sistemi elemanını olan düğüm noktalarının ön üretim için uygun şekilde numaralandırılması ve sıralanmasıdır. Modelin yapısal değerlendirmesine dayanarak, tez, potansiyel yapısal elemanın diagrid strüktür sistemine eklenip eklenemeyeceğini görmek için diagrid strüktür sistemlerinin alternatiflerini tartışmaktadır.

**Anahtar Kelimeler:** diagrid strüktür sistemleri, serbest biçimli yüksek katlı tasarımlar, düğüm noktası, ön tasarım, yapısal analiz

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## 1. INTRODUCTION

Starting with Foster + Partners' prominent design 30 St Mary Axe (also publicly known as the "Gherkin"), diagrid structural systems are more and more utilized in contemporary architecture. Diagrid structural system is an innovative and flexible structural system where the structure is supported with diagonal structural elements on the periphery. Differently shaped and angled structural elements can be designed to a unique overall effect in each diagrid structural system.

There are two key lineages in research, namely those of Boake and Moon, that focus efforts on developing diagrid structural systems. Historically, Shukhov is designated as the pioneer in diagrid structural systems (Boake, 2014). Later, Foster + Partners disseminates the diagrid structural systems in contemporary architecture with the three unique designs that are the London City Hall, 30 St Mary Axe, and the Hearst Magazine Tower. Moon (2011) argues that, over the other more commonly used structural systems, diagrids, with the structural elements located on the façade, offer an advantage in powerful structural performance for unique high-rise designs.

Although diagrid structural systems are common in contemporary architecture, Capital Gate Tower in Abu Dhabi, ArcelorMittal Orbit Tower in London and CCTV Headquarters in Beijing are among the few examples of diagrid structural systems in free-form high-rise designs. Free-form as a type of building geometry form implies the condition of having or being an irregular or asymmetrical shape or design. A free-form mass has neither a fixed rule and homogeneous order, nor a symmetry or rotational central axis to rotate as. Some of the difficulties in free-form high-rise designs that prevent using diagrid structural systems in free-form high-rise designs frequently are in analyzing and defining structural solutions efficiently and the physical realization of structural elements.
Analyzing and defining structural solutions efficiently and the physical realization of structural elements are the two main difficulties in diagrid structural systems in free-form high-rise designs. These difficulties must be overcome with computational support, however, most of the existing software are unreachable expensive and protected by copyright so they are inaccessible to most designers. In order to overcome difficulties in the designing of diagrid structural systems in free-form high-rise proposals, developing a model for providing affordable and accessible computational support for preliminary design proposals is the main purpose of the study.

The study aims to design and analyze diagrid structural systems of the created free-form high-rise geometry and also prepare node connectors which are the most important structural element of diagrid structural systems for prefabrication. The study offers support to designers who are using diagrid structural systems in a free-form high-rise designs by avoiding the difficulties without struggling with unreachable expensive and protected software. This support takes place in an algorithmic design interface, and the biggest advantage is that designers can integrate the design and analysis phases in a single interface. This makes it extremely practical for designers.

## 2. THE MODEL

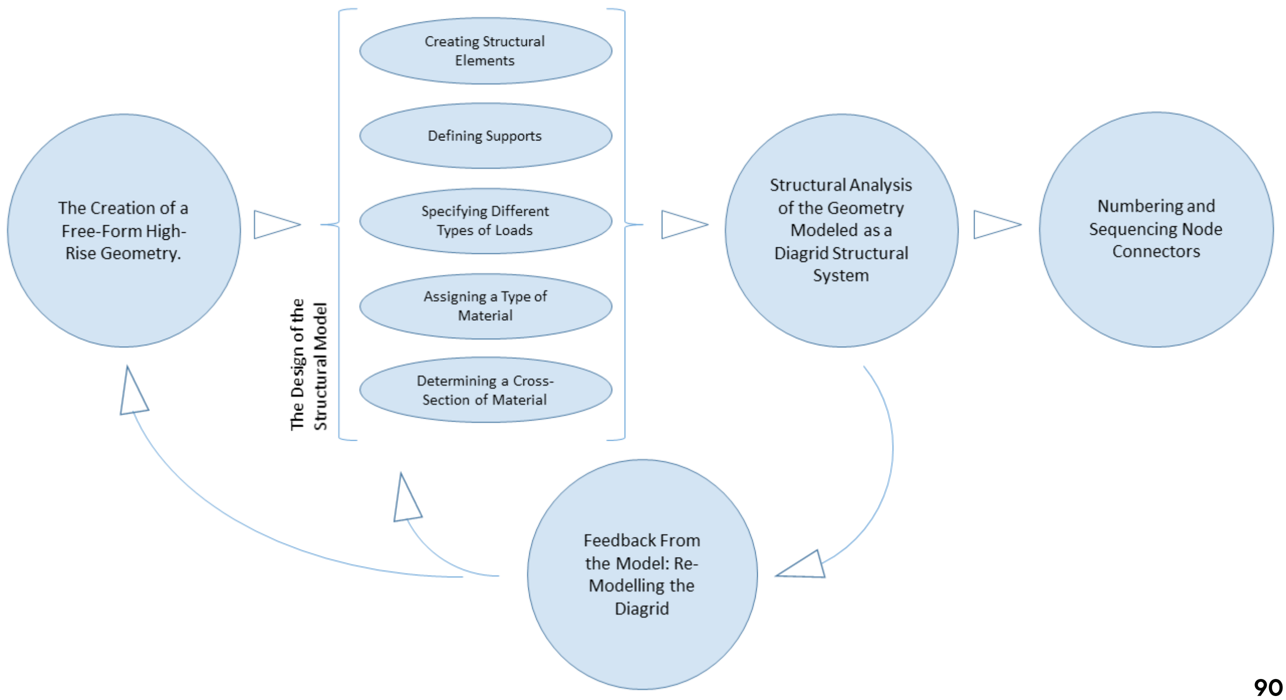
The study focuses on a model that creates a free-form high-rise geometry, designs a diagrid structural system, analyzes it and prepares node connectors which are most important structural element of a diagrid structural system for prefabrication in order to provide computational support for many small firms and individual designers.

In this section, the model that has been developed and designed in three phases as seen in the workflow diagram in Figure 1 is explained in detail. These phases are the creation of a randomly formed free-form high geometry, structural analysis of this geometry when modeled as a diagrid structural system, and the numbering and sequencing of the most important structural element that is node connector so that it is suitable for the prefabrication. Creating structural elements, defining supports, specifying different types of loads, assigning a type of material, determining a cross-section of selected material are the main steps of the design. The whole model has been constructed in the Grasshopper as shown in Figure 2, and the diagrid structural system has been designed and analyzed with the Karamba plugin for the Grasshopper program.

### THE CREATION OF A FREE-FORM HIGH-RISE GEOMETRY

The first step of the model is creating a free-form geometry for further phases. Free-form implies asymmetric configurations, without a fixed order or a central rotation axis.

**Figure 1 :** The workflow diagram of the model.



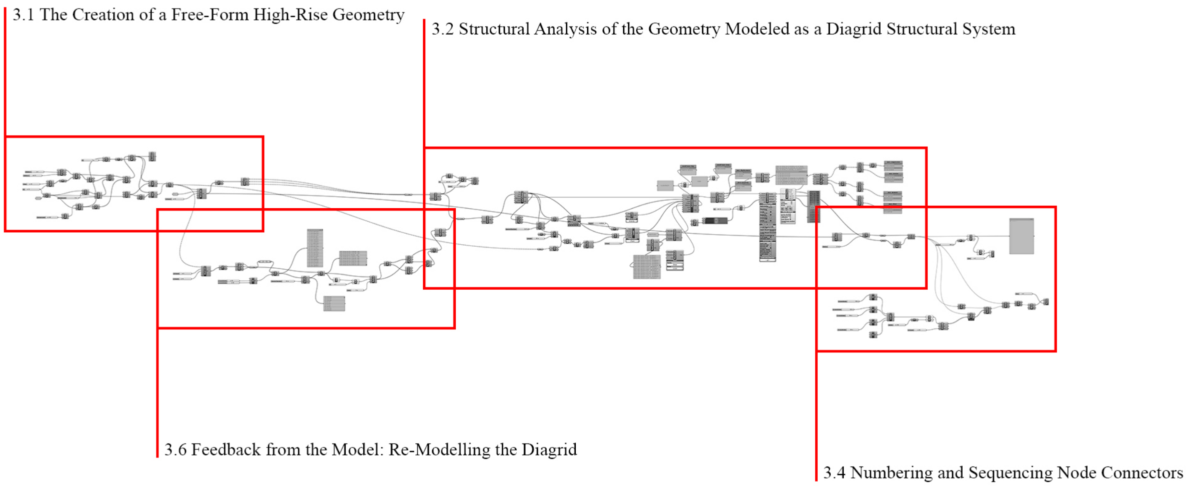


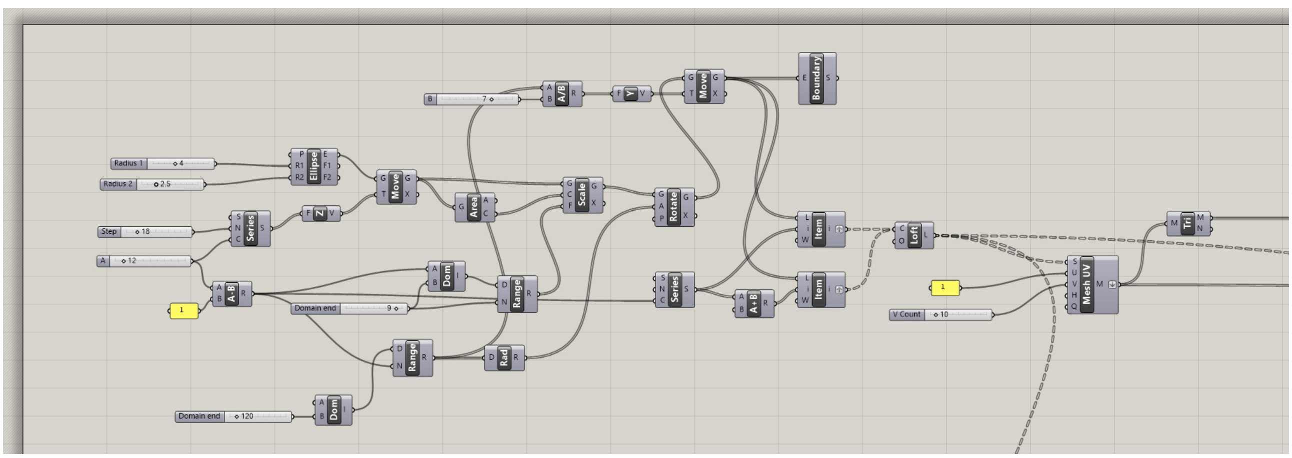

**Figure 2 :** The layout of the model in the Grasshopper.

The free-form geometry can be considered as a random geometry obtained in the digital design environments. In order to obtain the geometry, some parameters are required. A free-form is modeled with parameters such as the length and width of the base geometry in x and y direction and movement, rotation angle and the number of series in z direction.

The layout of parameters can be seen in Figure 3. The first step to create a geometry is about controlling circles and ellipses via parameters such as length and width of the base geometry in x and y direction. These parameters can be controlled by a user of the software, e.g. designer.

Then, series of various circles or ellipses which are already created in the first step listed in the z-direction. In order to get high-rise design, the lower limit of geometry height is set at 100 meters. According to the parameter of the number of series, desired height of the geometry is achieved. Movement and rotation angle of various circles or ellipses allow geometry to take the final shape.

**Figure 3 :** The layout of parameters for a free-form high-rise geometry.



Finally, using the loft component in the Grasshopper creates a free-form high-rise geometry from these series of circles and ellipses. There is only a search for form finding, no other input is addressed. As shown in Figure 4, via the triangulate component some alternatives for free-form high-rise geometries has diagonal lines over façade simply. The number of these lines can be controlled with the number of series in u-direction and the number of quads in v-direction.

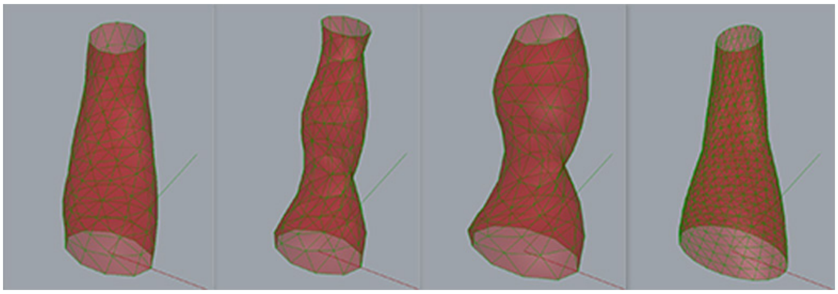


**Figure 4 :** Some alternatives for free-form high-rise geometries.

There has been a search for basic convenience for diagrid when creating alternatives. Larger floor width in lower parts, the lean angle at maximum 20° and providing a suitable space for the core of the building every level are some criteria for creating alternatives. Moreover, since a unique form will create inestimable value, and will be a prestigious icon in its environment, there are four individual unique forms are created in alternatives.

Between the alternatives the most proper one is selected because it provides an efficient interior area in every floor level and a more balanced structure while presenting a unique free-form high-rise geometry.

The selected geometry over the alternatives is ready to move to the next phase, where structural analysis of this geometry when modeled as a diagrid structural system is taking a place as represented in Figure 5.

## THE CREATION OF A FREE-FORM HIGH-RISE GEOMETRY

In this phase of the model, the diagrid structural system on the selected free-from high-rise geometry is designed and analyzed over simple diagrid layout that is already achieved in the previous phase by selecting particular parameters with the help of using the Karamba plugin for the Grasshopper program.

In order to perform structural analysis, firstly designing the structural model is essential. For the design of the structural model, creating structural elements, defining supports, specifying different types of loads, assigning a type of material, determining a cross-section of selected material are main steps. Then, the basis for the structural analysis are, evaluating and visualization of stress levels, displacements of structural elements, total weight of the structure. The main branches of the design and structural analysis of the diagrid structural system can be seen in the Grasshopper layout as shown in Figure 6.

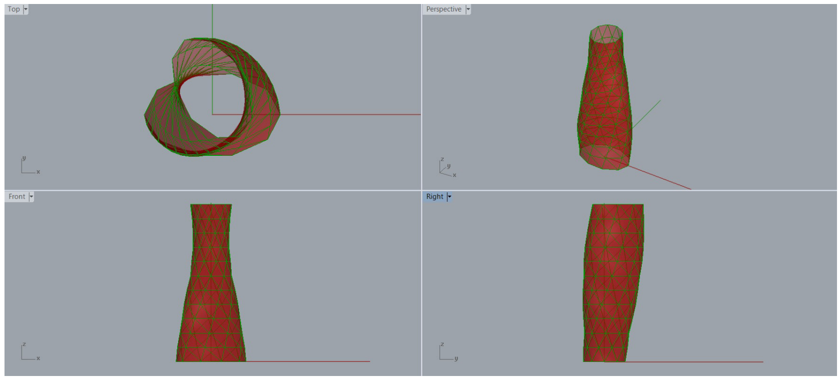



**Figure 5 :** Diagonal lines of the selected free-form high-rise geometry.

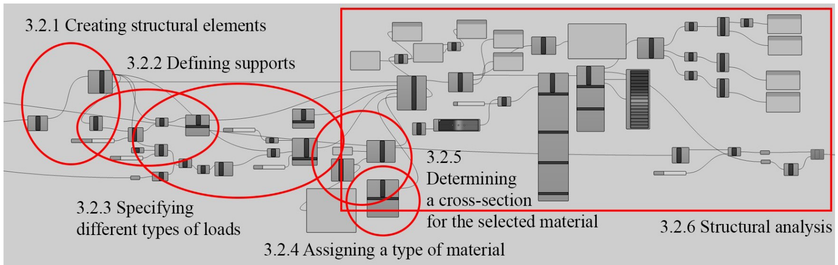



**Figure 6 :** The main branches of the design and structural analysis.

## CREATING STRUCTURAL ELEMENTS

Structural elements of the model are important to be defined in the first step of the designing diagrid structural system for a structural analysis. In the diagrid structural system, structural elements are located on the building façade divided by diagonal lines.

The assembly component in the Karamba library as shown in Figure 7, collects basically all required data for structural analysis from the model so that converts lines to the structural elements. Initially, future structural elements, in this case, the diagonal lines of the model, must be prepared for the assembly component in order to be converted to beams.

In the selected model, there are 340 diagonal lines of free-form high-rise geometry. This number is calculated by parameters such as the step size of series in u direction and the number of quads in v direction. The model is designed with the parameters of the step size of series in u direction, which is 12, and the number of quads in v direction, which is 10. For u direction, since the horizontal beams are located on the both ground and roof levels, 12 times 10 yield to a total of 120 lines. For v direction, the step size of series in u direction, which is 11 (excluding the roof) multiplied by 20 make a second total of 220 lines. There are four lines at one single module of diagrid. The module divided by horizontal beam from the half has two lines so the number of 20 is used rather than 10 in the calculation for v direction. The total for the model is 340 lines.

The number of the parameters can be changed according to the user of the model designer. If the numbers of the step size of series in u direction and the number of quads in v direction are changed by designer, so eventually, the number of the lines and beams will be affected and generated automatically through the model. Joining these lines to the assemble component make them to serve as structural elements of the model. Thus, there are basically 340 structural elements in the model of the diagrid structural system in free-form high-rise designs.

## DEFINING SUPPORTS

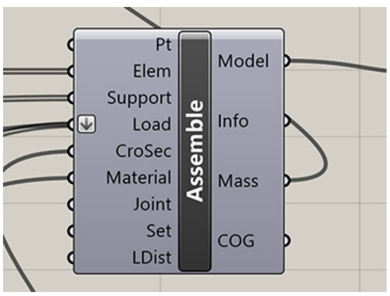
Once structural elements are set, defining supports of the structure is the next goal in the model. The support component in the Karamba library, convert selected points to fixed points for supporting the structure. The main challenge here, defining those selected points. Points as serving supports should be located both in the ground level and at the connection point of the lines which are converted to the beams of the structure as explained in the previous stage.

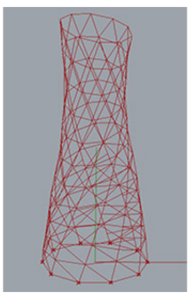
Since there are 10 quads in v direction in the model, these 10 points in the ground level are defined as supports of the structure as seen in Figure 8. In the end, by joining these supports to the assemble component, they are serving as support elements of the model. Essentially, the number of defined supports has to be enough to support the structure.

## SPECIFYING DIFFERENT TYPES OF LOADS

Thirdly, specifying single or more loads in the structure is another essential step to complete structural analysis. This is possible by using the loads component in the Karamba library. The loads component is a multi-use component where single or various types of more loads can be specified for the structure.

Gravity is the main load for all structures and is the simplest type of load because it does not require any parameter other than a crude information on the location on earth. Additional to the gravity load, wind load is a significant type of load for high-rise designs. Since wind direction and load is an environmental factor, according to the geographical conditions of where the model is located, wind direction is defined. As illustrated in Figure 9, for the model which located where wind direction is from north in most of the days of a year, vectors are defined from the north direction. These vectors are creating load conditions for the wind load and they can be set up according to the parameters such as the force of the vector and direction of the vector.



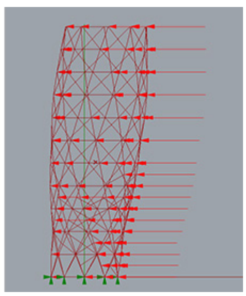


**Figure 7 (Left):** The assembly component in the Karamba library.
**Figure 8 (Middle) :** Support points of the structure.
**Figure 9 (Right):** Wind loads and supports of the structure.

Additional loads can also be defined since the load component in the Karamba library allows multiple types of loads to be set. For example, there are different values for live loads according to various functions of structures whether it is for residential or office. The values of live loads differ according to the function of the building and the country where the building is located but eventually they are fixed numbers so the live load does not require any parameter.

More loads can be considered for other design related choices. If the design has a swimming pool or mechanical systems on the rooftop, extra point load in the z-direction should be specified in addition to the gravity, wind load and live load.

## ASSIGNING A TYPE OF MATERIAL

Next step for structural analysis is assigning a type of material for the structural elements (beams). This choice will have an effect on the cross-section, the overall mass and the structural analysis.

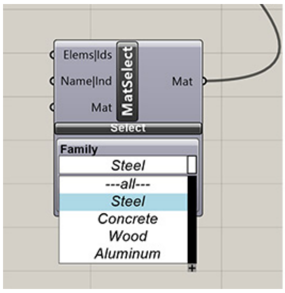
The MatSelect component in the Karamba library helps to assign a type of material, there are certain standards and numbers for each type of material inside the component. Therefore, the user must only select the material of beams, i.e. steel, concrete, wood and aluminum as seen in Figure 10.

Steel has certain advantages over other types of materials in high-rise designs, such as strength, dimensional stability and easy prefabrication (Wells, 2005). Strength and stability is important in high-rise designs and prefabrication is essential in diagrid structural systems, so steel is selected as a type of material of beams in this example.

## DETERMINING A CROSS-SECTION FOR THE SELECTED MATERIAL

The final step is determining a cross-section of selected material in the previous step which is steel for complete structural analysis. The CroSecSelect component in the Karamba library, as shown in Figure 11, provides various type of cross sections with different thickness and selected one is assigned to the beams of the structure.

In order beams to behave structurally, 1-dimensional objects which are beams at present must have 3-dimensional characteristics. The cross-section is 2-dimensional shape, i.e. rectangle, square, round, and when they extruded along the length of the beam, the 3-dimensional characteristic is achieved. It is possible with CroSecSelect component in this step. Type of cross sections starting with “RO” represents round extrusion along the length of the beam. Since the geometry is free-form, selecting round cross-section is rational due to the convenience it provides in the combination details. Once the cross-section is determined, the input of the nodes is also defined simultaneously according to information that also defines cross-section.



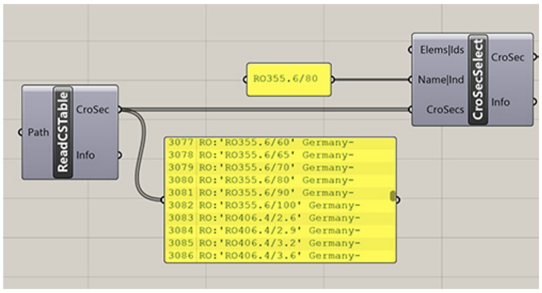




**Figure 10 (Left):** The MatSelect component in the Karamba library and material types.
**Figure 11 (Right):** The CroSecSelect component in the Karamba library.

## STRUCTURAL ANALYSIS

Following the above steps, the model is assembled, and structural analysis through finite element analysis can be performed with selected inputs. Finite element analysis also called FEA, is representing structural elements as separated and calculate how loads and forces distribute themselves throughout each structural element. Evaluating and visualization of stress levels, displacements of structural elements, total weight of the structure are the basis of the structural analysis. At the end of the structural analysis, a structural assessment is discussed as feedback and alternatives are offered.

The selected inputs are representing just one case for this example dedicatedly and these inputs can be changed anytime potentially via parameters which results with different case and outputs. Constructing a model with computational approach has parameters and parameters have this potential. Therefore, comparative examples will be discussed with different inputs in this step in order to benefit from this potential so that provide better and economical structural conditions and solutions.

The assembly component in the Karamba library collects all inputs from previous steps and then the AnalyzeThI component analyzes mostly the building-scale models with small deflections. Placing inputs to these components performs the structural analysis for diagrid structural systems in high-rise designs.

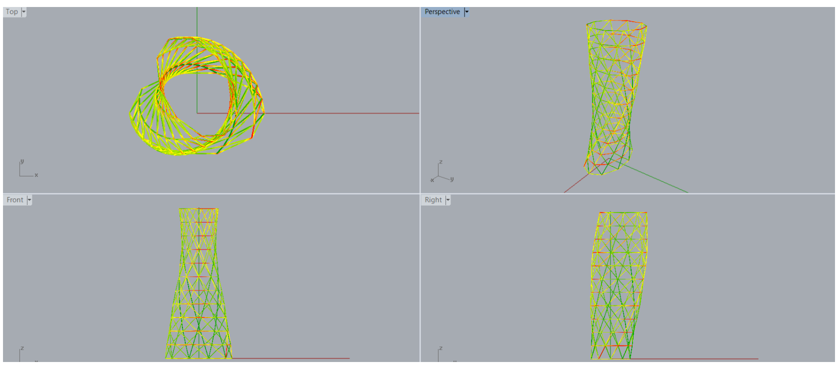



**Figure 12:** Structural analysis of free-form high-rise geometry.

As represented in Figure 12, visualization with a color range from green to red can represent displacement, utilization and axial stress of structural beams as structural analysis. Displacement is a term that how much stress beams experience under loading. However, utilization demonstrates stress in terms of its percentage of the maximum stress capacity of the material, but axial stress shows stress information directly.

Percentages of current stress to the maximum stress capacity of different type of materials, concrete (C20/25), wood, concrete (C80/95) and steel are shown in Figure 13 respectively. Thus, type of the concrete has a significant effect on the utilization diagram, C20/C25 concrete has a weaker performance comparing wood, whereas C80/95 has better. For instance, if the chosen safety factor is %10, the only material that provides it is steel. On the whole, the percentages of current stress to the maximum stress capacity of different type of materials show that steel has a better and balanced performance than wood and any type of concrete in terms of stress capacity while designing diagrid structural system in free-form high-rise designs.

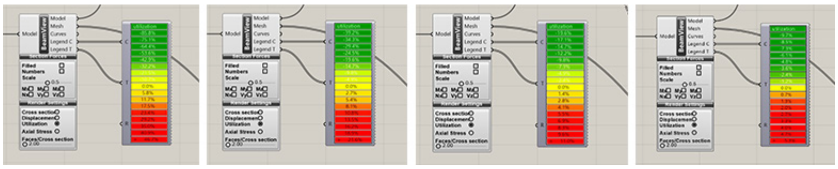


**Figure 13 :** Percentages of current stress to the maximum stress capacity.

This visualization is an effective way to understand general behavior and performance of the structure under defined loads in the previous steps, yet it is not complete enough to perform a structural analysis. In addition, there are three main quantitative measures that need to be considered if a complete structural analysis is desired. Mass of the whole model, maximum displacement of any structural element of the model and the maximum stress of any structural element of the model can experience is based on the limits of the material.

The mass of the model is the total weight of the whole structure and is impacted directly by the cross-sectional dimensions of the beams and the type of the materials that beams have. Moon (2009) studies the different height of diagrid structure with a variable angle of node connectors in terms of mass, and his study shows that 60-floor building has average 3500-ton steel mass. In the example, the structure has an approximately 200-meter height of 45 floors, and a 2600-ton steel mass. This value compares well to the 2400-ton steel mass of 30 St Mary Axe with 40 floors (Munro, 2004).

Displacement measure refers to the maximum distance any structural element of the structure moves under load. Although all structures move under loading, there are limits for how much the structure can move according to the national and international regulations. The output of the displacement of this model is about 0.04 meters as seen in Figure 14.


**Figure 14 :** Model mass and maximum displacement.

Stress is calculated based on the force in each structural element. In the model, stress levels of the model represent a range between maximum and minimum values under loading and are experienced based on the limits of the material. Forces are given as negative values for compressive forces and positive values for tensile forces. Thus, in order to minimize the overall force both the largest number (highest tensile force) as well as the absolute value of the smallest number (highest compressive force) has to be decreased. Stress levels can be represented via both raw stress level or utilization of the material, utilization shows stress in terms of its percentage of the maximum stress capacity of the material, whereas stress shows stress level directly.

There is a direct link between the cross-section of selected material and the model mass, displacement, and the stress levels. Thicker cross-section yields to higher values of model mass, smaller displacement and smaller absolute values of largest and smallest stress levels. Therefore, the cross-section of the beams can be thicker if it is necessary in terms of structural behavior. However, it is always important to provide economical solutions by keeping the cross-section of the beams thinner as lighter model mass is preferred. In the Figure 15, 16 and 17, different cross-sections are studied which are RO273/80, RO406.4/80 and RO711/80 respectively and it is observed that when model mass is getting heavy, the maximum displacement is decreasing. On the other hand, as the cross-section thickens, maximum moment and shear forces in the model and the both stress levels (compressive force and tension force) are increased considerably. However, percentages of current stress to the maximum stress capacity is slightly decreased. Providing a less the maximum displacement, smaller and balanced absolute values of largest and smallest stress levels with less model mass is the target, so finding balance between all is essential. It is also not preferred having thicker cross-section of the beams and heavier model mass.

Through structural analysis of the designed diagrid structural system, it is observed that there may be a need for potential structural elements that may be added to the diagrid structural system as well as the suitability of the designed diagrid structural system instead of making a cross-section of the structural elements of the whole model thicker. As a result of any need, feedback that structural system can be re-modeled restarts the design and analysis. This situation is examined in detail in the next section of the study.

## DESIGNING NODE CONNECTORS

Diagonal structural elements and horizontal beams connect to one another at the node connectors. The first input while designing node connectors is the number of the nodes. The number of nodes of the model vary based on the parameters of the step size of series in u direction and the number of quads in v direction. The parameters determine the number of the level of horizontal beams and the conjunction points of diagonal structural elements and horizontal beams in each level eventually. The number of

Figure 15 : RO273/80, model is 1847 tons, max. displacement is 0.05 m.

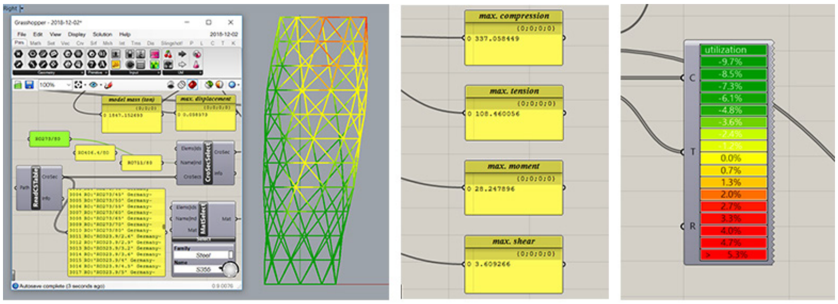



Figure 16 : RO406.4/80, model is 3123 tons, max. displacement is 0.03 m.

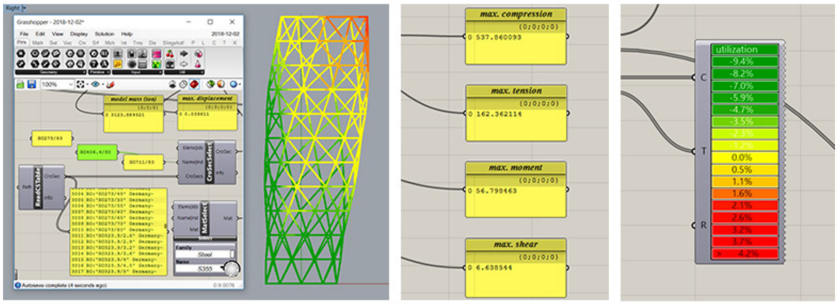
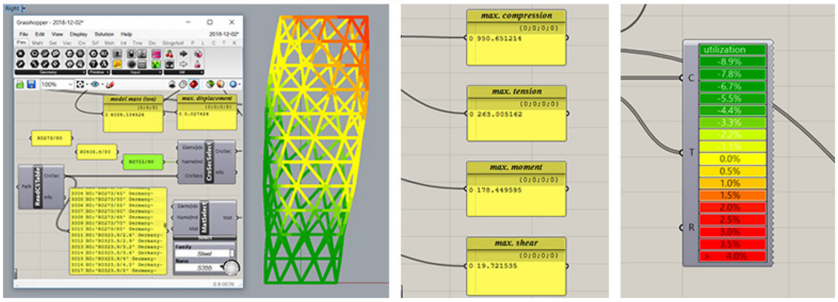



Figure 17 : RO711/80, model is 6039 tons, max. displacement is 0.02 m.




the level of horizontal beams and the conjunction points of diagonal structural elements and horizontal beams in each level eventually. The number of the level of horizontal beams times the conjunction points yield to a total number of node connectors. For instance, 12 levels of horizontal beams with 10 conjunction points in each level gives 120 node connectors whereas 23 levels of horizontal beams with 21 conjunction points in each level gives 483 node connectors.

In addition, the decision of the cross-section and size of node connectors are other parameters in designing node connectors. The cross-section of node connectors is linked to the cross-section of the structural elements. Once the cross-section of the structural elements is determined, the input of the nodes is also defined simultaneously. The size of node connectors is affected from the parameter of the length of each branch of node connector. In Figure 18, via the parameter some alternatives for node connectors are shown with different sizes. The selected node connector (left) has almost 4-meter length provides both effective connection work in the construction area due to space between branches and is cheaper for fabrication because it has less surface area comparing to taller alternatives.

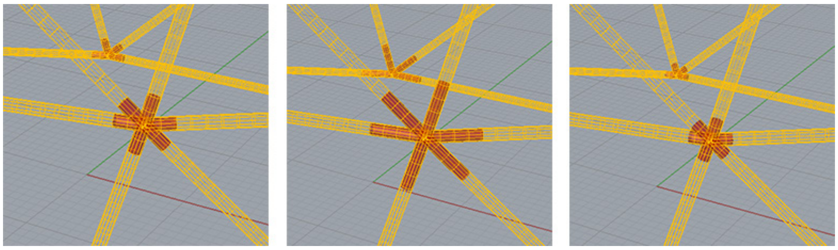


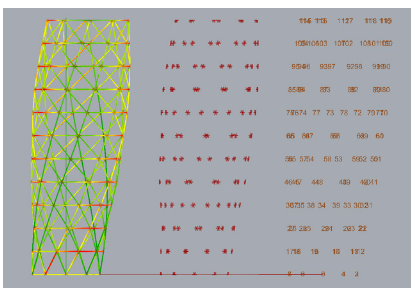
**Figure 18 :** Some alternatives for node connectors.

## NUMBERING AND SEQUENCING NODE CONNECTORS

In the last step of the model, node connectors, which are the most critical structural element of the diagrid structural system, are separated from the geometry, numbered first, and then sequenced on a surface, ready for prefabrication.

Having numbers and being sequenced for node connectors are essential for prefabrication and effective in decreasing the number of works in the construction area. This allows node connectors to be listed according to the parameters such as number of floor level, floor height so that provides better organization and eases follow-up tasks for construction. Moreover, machines and robots are likely to read these numbers and work in order according to the sequence in case of any automated construction processes.

In the model, the model has 12 levels of horizontal beams including roof, 45-floor levels with 4,5m height and 10 conjunction point in each level, so there are essentially 120 node connectors. Initially, as illustrated in Figure 18, node connectors are distinguished from the whole geometry and starting from ground level, numbers are given to each node connector in order. Node connectors in ground and roof level have 4 branches whereas the others have 6. In other words, there are basically 19 node connectors which have a different number of the branch than others in the model.



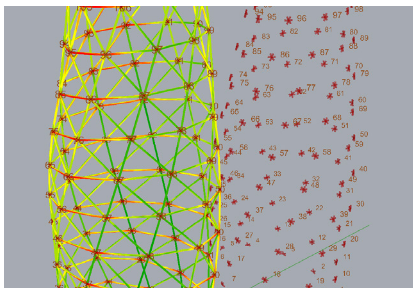


**Figure 19 (Left):** Node connectors are numbered.
**Figure 20 (Right):** Node connectors in the geometry and separated from the geometry.

All node connectors of the diagrid structural system as shown in Figure 20 has already numbers, but they are not sequenced on the surface yet. In diagrid structural systems in free-form high-rise designs, since the geometry in the model is asymmetric, every node connector has a various angle in each branch. Thus, prefabrication is essential for node connectors due to the economic reason which aims less amount of work in the site and various type of node connectors. For prefabrication, it is important to have both separated and sequenced node connectors in a surface

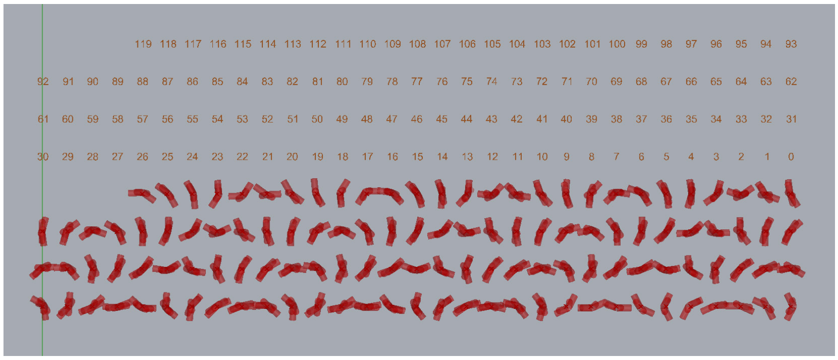



**Figure 21 :** Node connectors are sequenced.

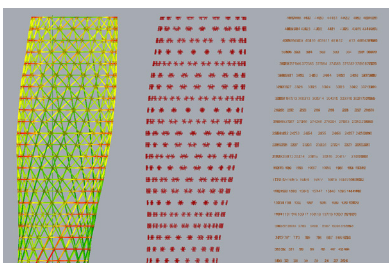
and as seen in Figure 21, on a separated surface, all node connectors are sequenced and ready for prefabrication.

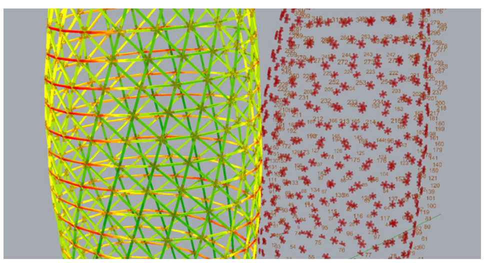
Using the potential of the model, since it contains parameters that can give outputs according to the various inputs, an alternative model has designed which has 23 levels of horizontal beams including the roof and 21 conjunction point in each level, so there are essentially 483 node connectors in this case. Initially, as illustrated in Figure 22, 23 and 24 node connectors are distinguished from the whole geometry and starting from ground level, numbers are given to each node connector in order.

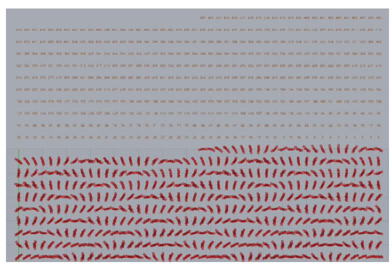
Several cases can be studied and analyzed in the model, comparative examples can be also discussed with different analysis in this step in order to benefit from the potential of the parametric design so that provide efficient conditions and solutions which satisfy alternative design ideas. Through various inputs, it should not be forgotten that selected inputs are representing just one case for this example dedicatedly and these inputs can be changed anytime potentially via parameters which results with different case and outputs, in other words, constructing a model with computational approach has parameters and parameters have this potential.

For instance, in this step of the study two alternatives are represented with 120 and 483 node connectors respectively. In other words, preliminary design for planning and an opportunity and flexibility for changing requirements are two key subjects for efficient design and construction. Therefore, in the preliminary design stage, the stakeholders can have the flexibility to realize several alternatives and discuss them in order to find aesthetic, efficient and most importantly the agreed solution for everyone, so that there are not any problems due to inaccurate planning and changing requirements.

**Figure 22 (Left):** Node connectors are numbered.
**Figure 23 (Middle) :** Node connectors in the geometry and separated from the geometry.
**Figure 24 (Right):** Node connectors are sequenced.







## FABRICATING NODE CONNECTORS AS PROTOTYPES

In this step, node connectors of the diagrid structural system in free-form high-rise designs are indicated in Figure 25. And ideally, every node connector has to be prefabricated for the construction. The node connectors selected randomly from the sorted ones are produced as prototypes with a three-dimensional printer in order to create a model for the process of node connectors of diagrid structural system in free-form high-rise designs from design to prefabrication with the help of the model and the three-dimensional printer.

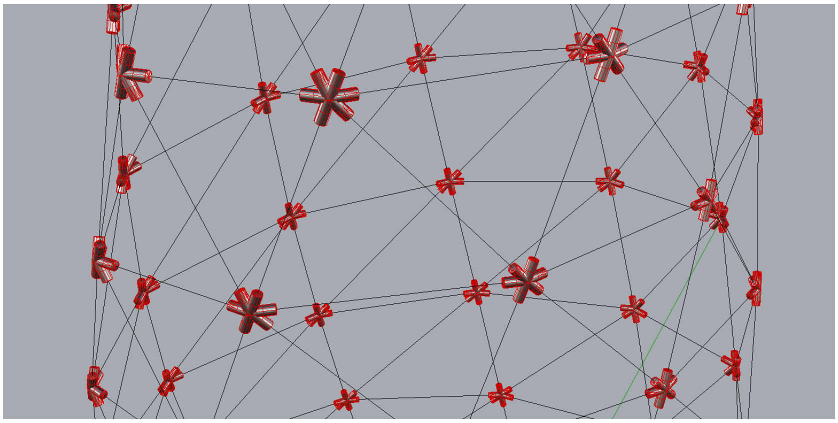
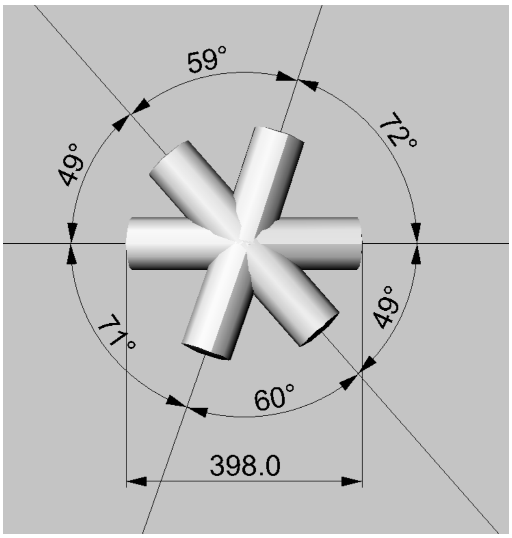


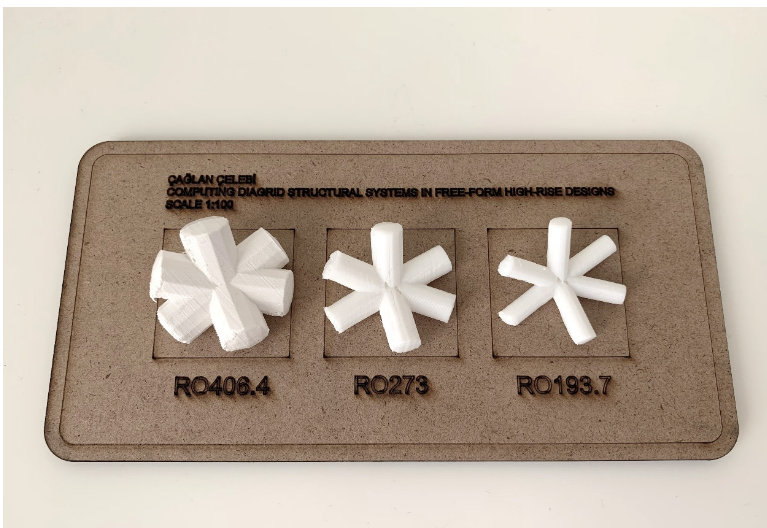
**Figure 25 :** Node connectors of the diagrid structural system.

For instance, the node connector selected randomly has a various angle in each branch and almost 4-meter length in the y-direction as shown in Figure 26.

As prototypes, randomly selected three node connectors with three different cross-sections are fabricated with a three-dimensional printer in 1:100 scale as an outcome of a model for the process of node connectors of the diagrid structural system in free-form high-rise designs from design to prefabrication (Figure 27).

**Figure 26 (Left):** Dimensions of the node connector selected randomly.
**Figure 27 (Right):** Three-dimensional fabricated node connectors in 1:100 scale.



Node connector is the center of the concept of the diagrid structural system and they are often parts of the diagonal structural elements. Node connectors play both aesthetical and functional roles as three-dimensional connections.

Fabrication as prototype is important in order to observe both aesthetical and functional role of node connectors better as designer. Thicker cross-section of selected material leads to a layout with larger spans and slightly less percentages of current stress to the maximum stress capacity whereas thinner cross-section leads to a denser layout and slightly more percentages of current stress to the maximum stress capacity. Moreover, selecting thicker cross-section in same layout provides less displacement but more total mass so an expensive model.

Experimenting and perceiving different prototypes in real rather than on computer, gives an idea to designers about diagrid designs and proportions of node connectors. Comparing alternatives of different cross-sections in prototypes helps designers while deciding the cross-section of structural elements and node connectors and the size of node connectors. Moreover, there is also the possibility to study and discuss preliminary connection details on these alternative prototypes.

**FEEDBACK FROM THE MODEL: RE-MODELLING THE DIAGRID**

In this part of the study, in the structural analysis of the model in the previous part, the remodeling of the diagrid structural system is discussed whether the potential structural element that may be added to the diagrid structural system are efficient. Moreover, it has been observed that the structural element in the diagrid structural system can be used more densely regionally, for instance in CCTV Headquarters. Diagrid structural system can be strengthened regionally as a solution to the structural strength requirements of the free-form high-rise designs. Therefore, as a result of any need, the diagrid will be re-modelled according to the feedback.

The main goal of adding potential structural elements is providing an alternative and possible more efficient solution to the problematic structural performance than the costly thickening of the cross-section of all the structural elements. Moreover, aesthetical concerns may also play a role in shaping geometrical patterns of the diagrid structural system. Montuori et al. (2014) study various geometric patterns of diagrid structural system in a regular geometry, emphasizing that different geometric patterns of the building façade that are almost comparable in terms of structural performance.

After the design and structural analysis of the model, whether a diagrid structural system in free-form high-rise designs is satisfying conditions efficiently or not will be observed clearly. There may be a need or a potential for adding structural elements to the diagrid structural system. In other words, if the system is efficient, but there is a desire for a various geometrical pattern or if the system is not efficient and there is an intention for the different design aspect, firstly, the weakest regions where the structure is weak and unstable will be detected according to the structural analysis of the structure.

Location of additional structural elements are defined respectively according to the analysis: Locations where there are extreme positive and negative stress levels and maximum displacement are the main target. Moreover, adding structural elements closer to the support points has a positive contribution to the structural behavior. Then, defined weak regions will be strengthening regionally as a part of the design process. Increasing the number of structural elements in these regions instead of the whole system as an economical and efficient solution is the main step of this process.

Total weight of the structure is always controlled and compared with previous results while adding structural elements as the aim is to find an economical and efficient solution. The structural system will be remodeled according to the feedback from the analysis until the satisfactory result is achieved.

**DETECTING WEAK REGIONS**

In this step, the regions where the structure is weak and unstable will be detected according to the structural analysis of the structure. Since, stress is calculated based on the force in each structural element and stress levels of the model represents a range between maximum and minimum values under loading and is experienced based on the limits of the material, where the overall force leads the largest number (highest tensile force) and the absolute value of the smallest number (highest compressive force) are the weak regions of the structure. In addition, in the displacement visualization diagram, the unstable regions of the structure can also be observed. However, the much distance beams move under loading is observing in the top part of the structure because where is the farthest point from support. The critical point here is that the overall strength of the structure is affecting directly to the most unstable region where displacement is maximum, more strength less displacement.

In the weak regions starting from the bottom and foundation of the structure, additional structural elements are proposed as seen in Figure 29 with two alternatives through the parameters in the model in order to support the whole structure with both decreasing the gap between the largest number (highest tensile force) and the absolute value of the smallest number (highest compressive force) and maximum displacement, this proposal is studied in the next step.

**SUPPORTING WEAK REGIONS**

Next step for re-modeling diagrid is supporting the weak regions according to the inputs from the previous step. Since the geometry is asymmetric, where the bending happens the region is indicated as a weak region in both utilization and stress visualization diagram. Additional structural elements placed in this region provides more efficient structural conditions as decreasing the gap between the largest number (highest tensile force) and the absolute value of the smallest number (highest compressive force) compared to former geometry as represented in both utilization and stress visualization diagrams in Figure 30 and Figure 31.

The strategy for adding potential structural elements is uncomplicated. Potential structural element is added as a line from the midpoint of randomly selected diagonal structural element that is located exactly in the weak regions to another midpoint of the side diagonal structural element. This happens for the indicated number of times in the specified regions which are the weak regions of the whole structure. There are a few parameters in order to control these additional structural elements. For instance, the density of these elements can be controlled via inputs such as the number of potential structural element and random seed generator, but the center of gravity of these elements is always around the center of the already detected weak regions.

Moreover, while making additional structural elements to provide improved structural conditions, it is also important to examine the displacement diagram as well as stress diagram. It is not surprising that the model mass is increasing when structural elements are added. But the displacement diagram is affected positively. As shown in Figure 32 and Figure 33, after the addition of new structural elements, the maximum displacement is decreased by almost 1 cm and the displacement diagram changes from red color range to orange range which represents the most unstable structural elements.

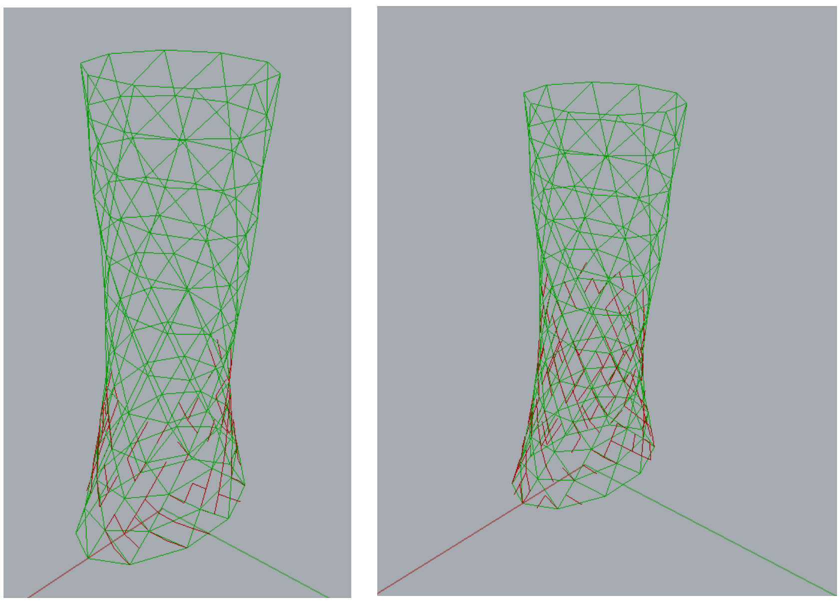
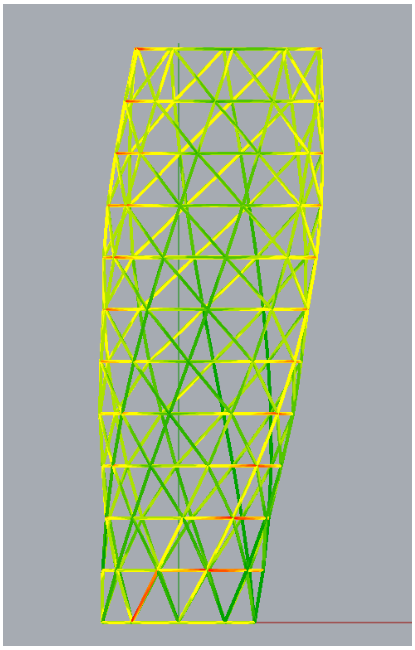


**Figure 28 :** The first alternative (left) and second alternative (right).



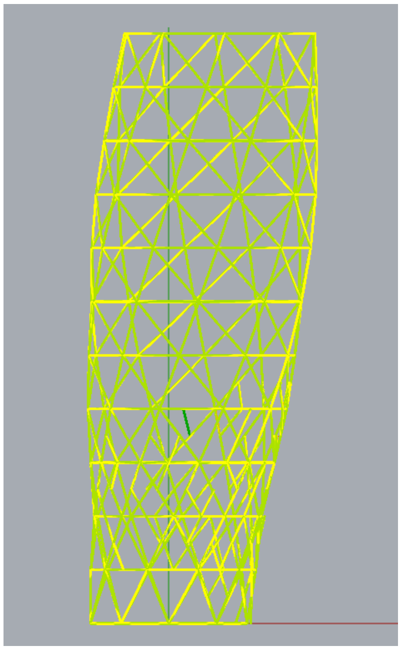


**Figure 29 (Left):** Stress diagram before adding structural elements.
**Figure 30 (Right) :** Stress diagram after adding structural elements.

A final observation is that it is possible to provide a more economical alternative solution by adding structural elements in specific regions instead of modifying the whole structure. This is not the only and correct way for providing a structural solution, yet it is an experimental alternative solution that opens up opportunities for alterations on the façade that can incorporate new considerations of functional and aesthetic terms.

## FABRICATING DIAGRIDS AS PROTOTYPES

Three alternatives of diagrids that designed through the model are fabricated in 1:2000 scale as prototypes (Figure 34). The difference between alternatives is the structure: a layout with larger spans with a thicker cross-section of selected material (alternative 1), a layout where structural elements are added locally (alternative 2) and a denser layout with a thinner cross-section of selected material (alternative 3).

Designer can select a denser layout with a thinner cross-section of selected material if more closure and privacy is desired or select a layout with larger spans with a thicker cross-section of selected material if seeking more open space on façade or sun light. Moreover, a layout where structural elements are added locally is an experimental alternative in between them and provides alterations on the façade. The functions of interior space can be designed and adapted according to this alteration.

Fabrication is important in order to experiment different diagrid layouts as designer. Comparing different alternatives of diagrid layouts in prototypes shows that the structure affects the architectural characteristic of the diagrids. Discovering alternatives of diagrids in real rather than on computer, support designers for deciding alternative layouts.

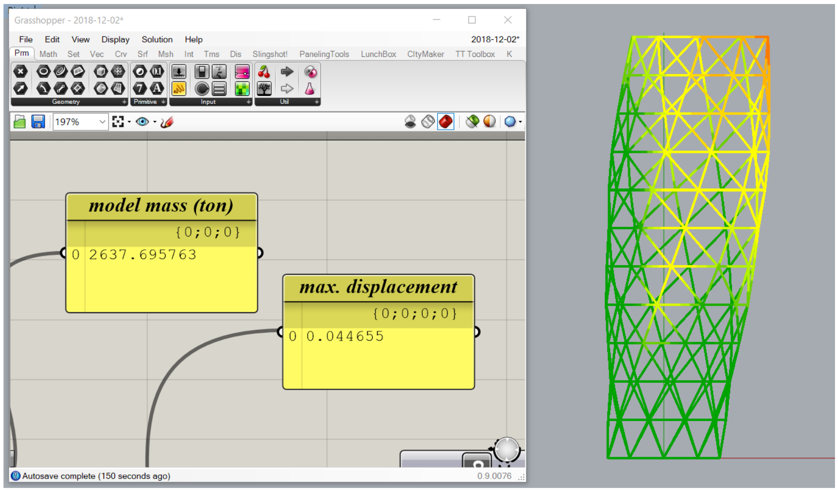



**Figure 31 :** Displacement diagram before adding structural elements.

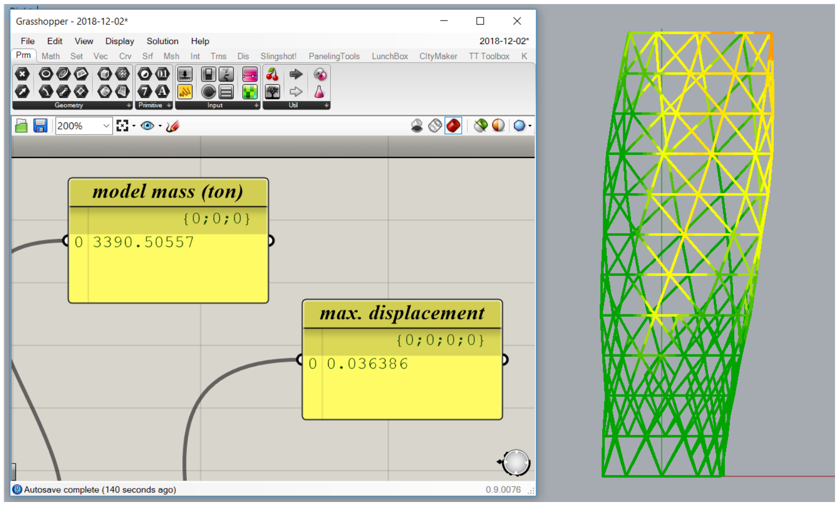



**Figure 32 :** Displacement diagram after adding structural elements.

## 3. CONCLUSION

This study focuses on diagrid structural system in free-form high-rise designs by constructing a model with a computational approach that designs a diagrid structural system, analyzes it and prepares node connectors which are most important structural element of a diagrid structural system for prefabrication in order to support designers to design it. In other words, this study presents a methodology to design and produce parametrically customizable node connector components of diagrid structural system in free-form high-rise designs by a computational approach. Consequently, designers will have a chance to determine a range of structural configurations of diagrid structural system in free-form high-rise designs and merely use the designed model on a computer to fine tune them.

The study offers a holistic perspective to the diagrid structure in free-form high-rise designs develops an affordable and accessible computational support for the preliminary design. This support takes place in an algorithmic design interface, and the biggest advantage is that designers can integrate the design and analysis phases in a single interface. This makes it extremely practical for designers.

The model has been designed and developed via using accessible open-source software: The Grasshopper and the Karamba plugin (free version). The model has been constructed in Grasshopper and the diagrid structural system has been designed and analyzed with the Karamba plugin for the Grasshopper program. It is also open to further developments and this emphasizes the potential of using open-source software: the expanding of the knowledge additively.

In addition, the model is flexible due to its parametric characteristic and can be adapted to various individual projects so that designers benefit from it particularly but understanding potentials and having essential knowledge of predictability of the model give way to a more efficient gain. The model developed in this study offers that. Through the development of possibilities and opportunities of computational approaches, this study aims to support the use of diagrid structural systems in free-form high-rise designs among small firms. Thus, by the help of achievements of the study, it is assumed that when the diagrid structural system is used in a free-form high-rise designs, the complexities and difficulties occurring during the design and prefabrication phases will be avoided.


**Figure 33 :** Three-dimensional fabricated diagrids in 1:2000 scale.

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I am indebted to the committee members Prof. Dr. Gülen Çağdaş and Asst. Prof. Dr. Sevil Yazıcı for their constructive suggestions that contribute to the development of the study.

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