Topology and Form Finding via Genetic Algorithms

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Senior Project
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Abstract

The following presents an approach to early applications of the Galapagos program as a means to optimize structural forms. The process was conducted with Rhino's Grasshopper program, the structural analysis plug-in, Karamba, and the genetic algorithm solver, Galapagos. This topological form finding process was based on flexible parameters that modified brace and column locations, and diaphragm size and positions.

This process worked by having Galapagos modify a parametric model which had initial randomly generated variables for the genomes. After structural analysis, Galapagos was tasked with changing the form in order to minimize overall displacement of the structure. Being an evolutionary solver, Galapagos creates a "population" of solutions and eliminates non-effective offspring to continue breeding effective offspring through multiple generations. This means that solutions found through Galapagos were best fit to the program, but were not necessarily an absolute perfect solution, as that could take hundreds of generations to find. This also means solutions vary based on the beginning placement of genomes before populations are created. However, after comparing Galapagos to what was intuited and what are known structural solutions, there is a strong case to be made that Grasshopper, Karamba, and Galapagos can be used effectively in engineering practice to create both beautiful and efficient structures.

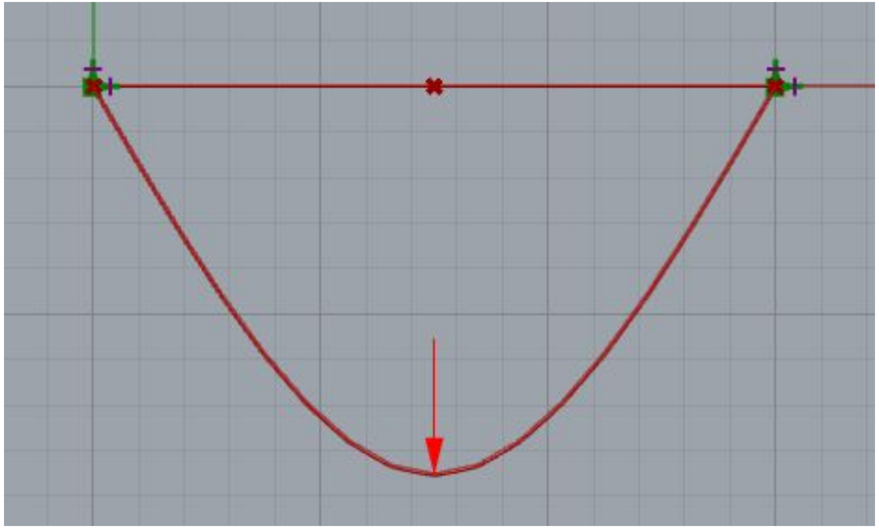
Grasshopper and Karamba for Structural Analysis

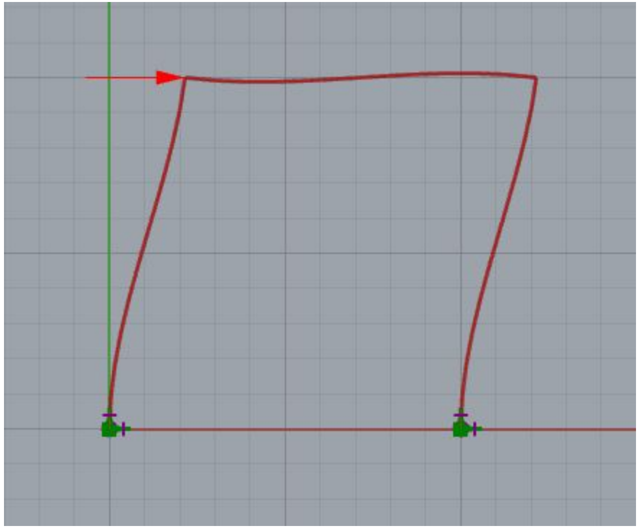
Grasshopper and Karamba

Grasshopper is a visual coding environment within Rhino3D composed of pre-coded components placed on a canvas that interact with the Rhino modeling space. Grasshopper is unique in that there is no traditional code writing and there is no code to “run.” Instead all components are constantly running, so any changes can be seen in real time within Rhino.

Karamba is a structural analysis plugin for Grasshopper that can perform many of the same tasks as a traditional analysis program. The main benefit of Karamba is that it can be used to find and create more optimal forms and material placement.

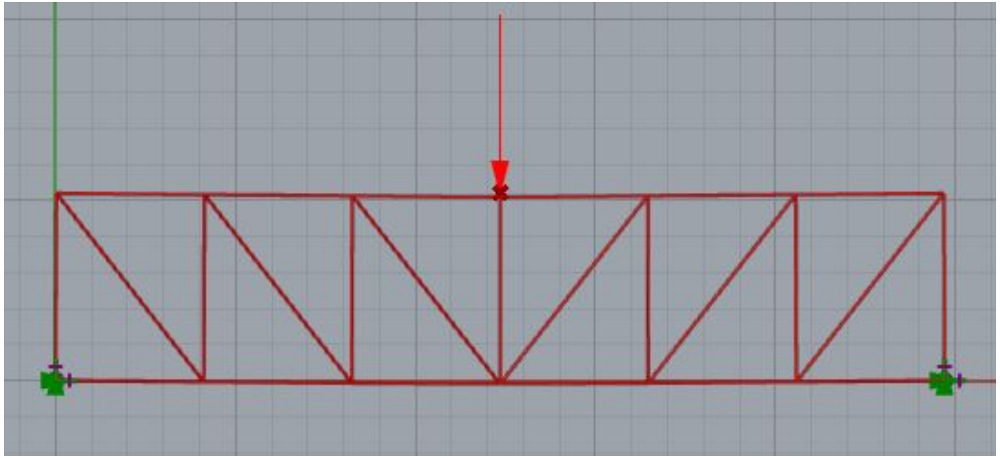
Basic Structural Elements

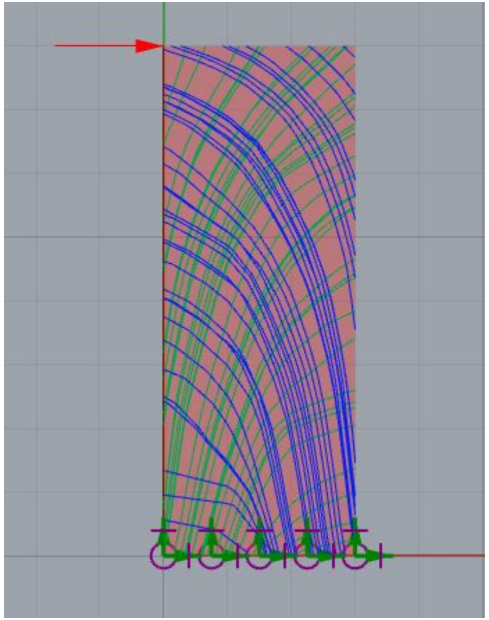




A simply supported beam and a portal frame modeled with Grasshopper and analyzed using Karamba. The results are what we would expect to see based on given loads. Both the geometry and load placement of both elements can be changed and results will be shown in real time.

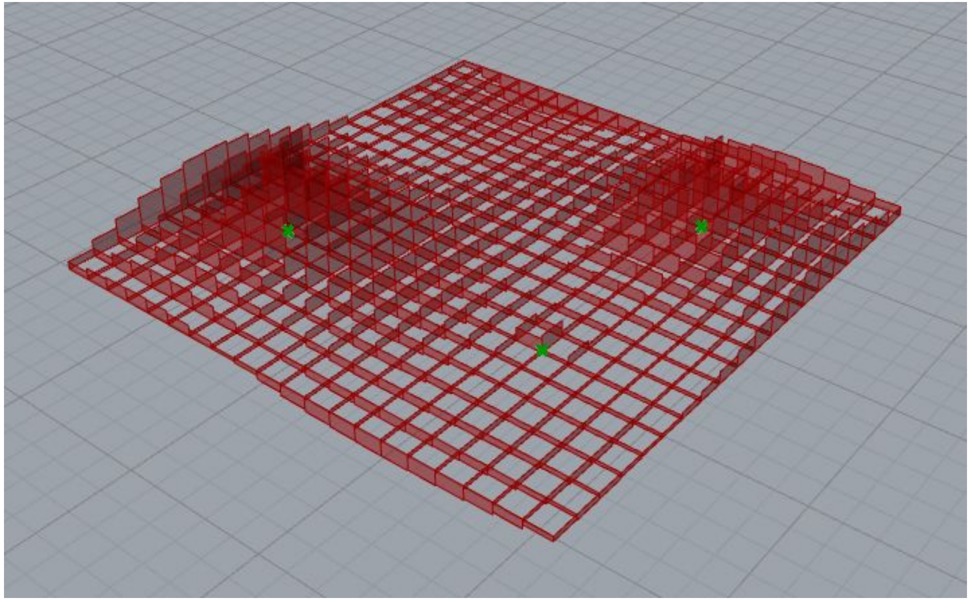
Basic Structural Elements





A truss and a shear wall are shown here. Dimensions and the number of bays for the truss can be changed instantly. Karamba was used to paint the principal stress lines shown on the shear wall; blue for compression and green for tension.

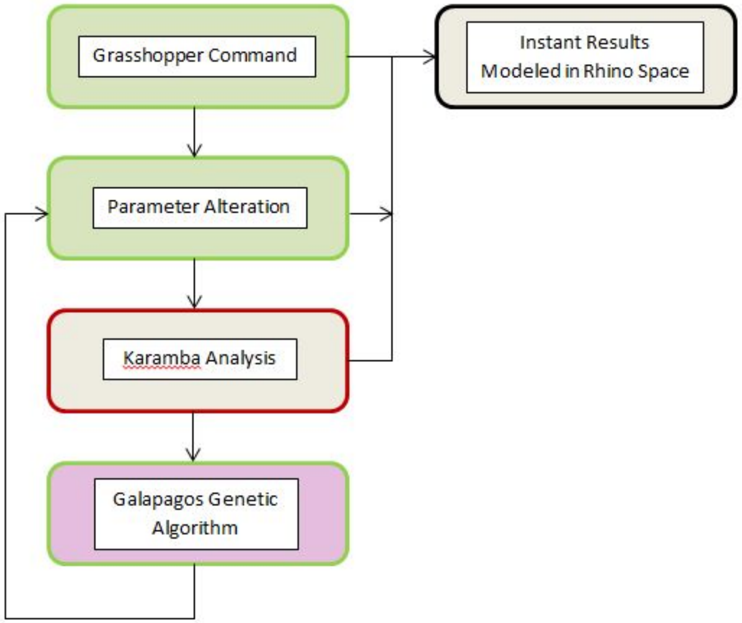
Karamba Form Finding



Here is a grid of beams supported at the green points shown and subjected to a simply gravity load across the whole structure. Using Karamba, the moment at each point along the beam was calculated. From the moment diagram, rectangles were extruded along the length of the beam. This can be translated to the idea that the most material should be placed where the rectangles are the tallest. This is a basic example of form finding and topology optimization, and moving forward the goal was to automate this process.

Topology Process

Graphic of Analysis Process

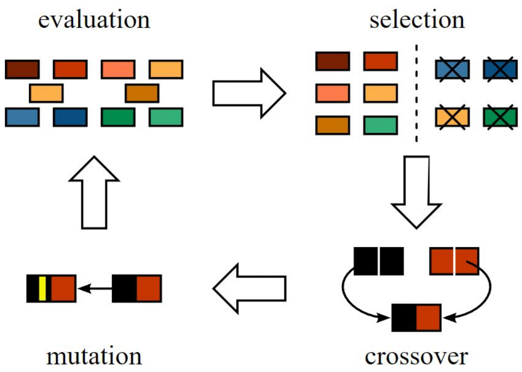


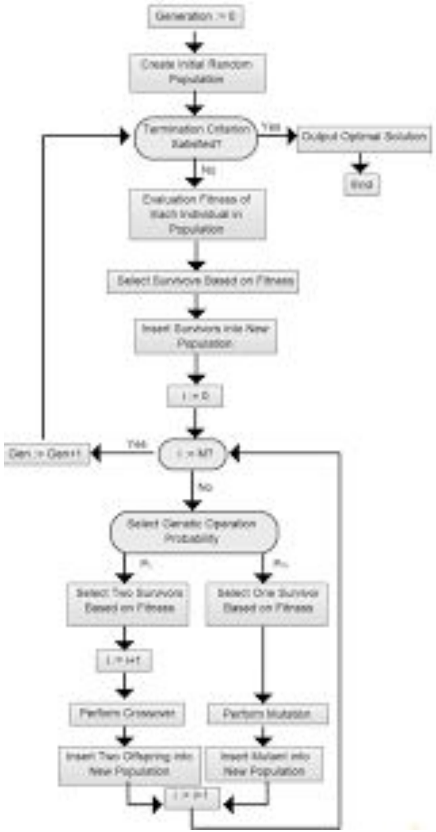
> Grasshopper Input creates a visual model in Rhino space, changes seen in real time

> Karamba plugin allows model to be structurally analyzed

> Galapagos uses Karamba output and geometric input to change parameters and find what it deems the most fit solution

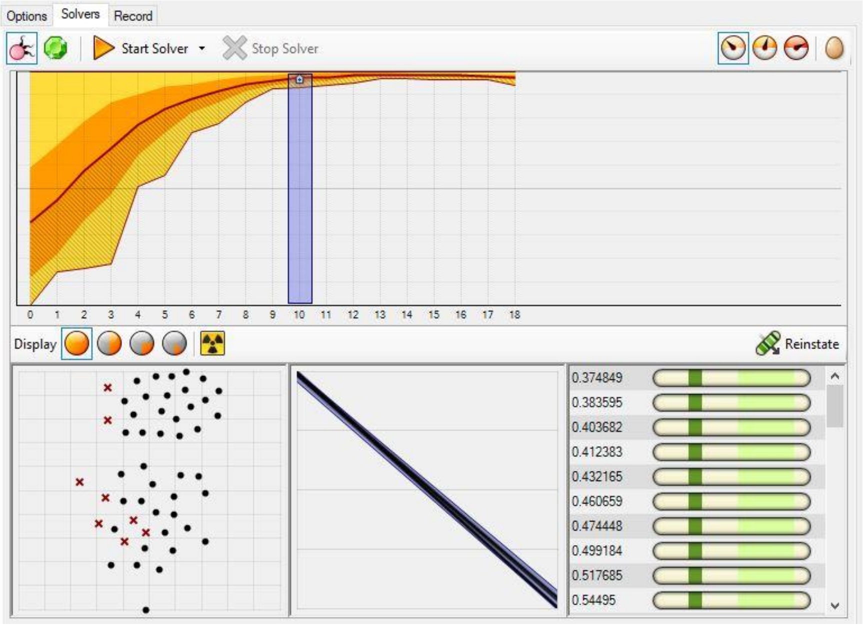
Genetic Algorithm Explanation





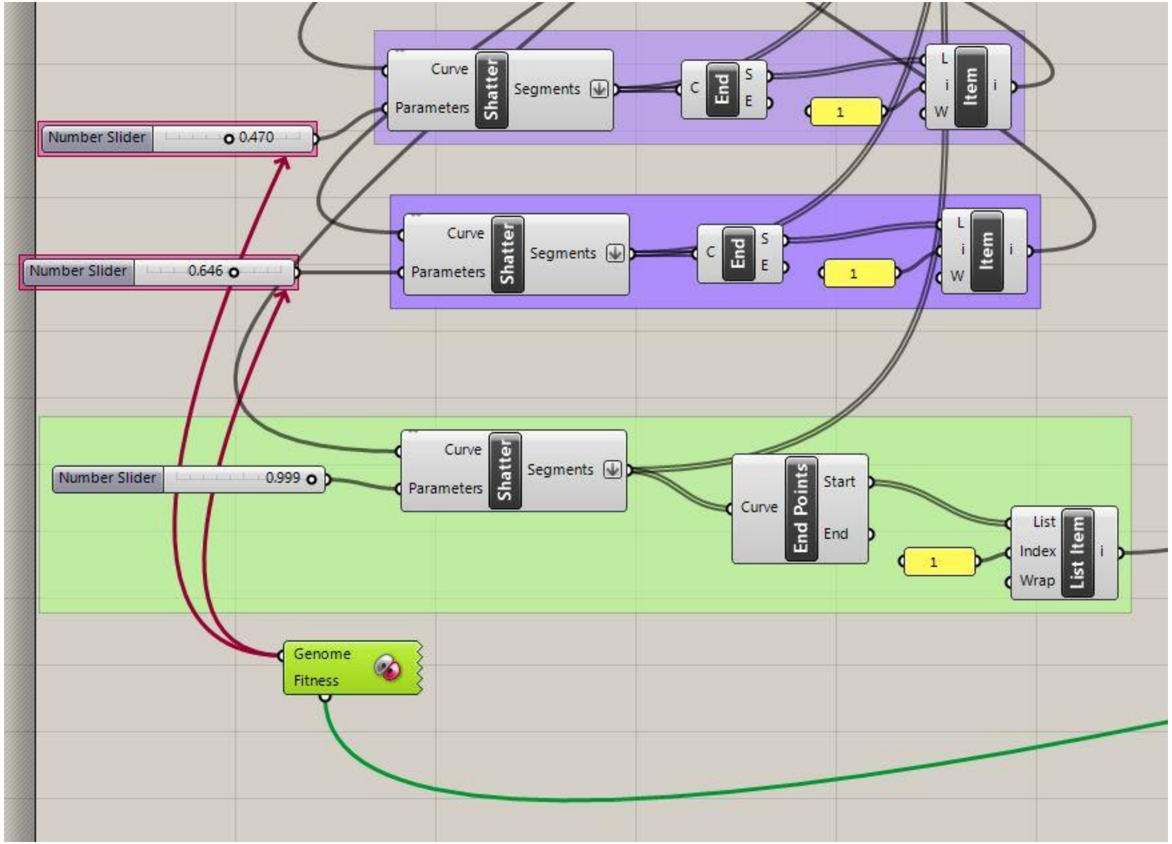
A genetic algorithm is solver that uses “evolutionary techniques.” This is done by generating a population of solutions based on genomes (variable subject to change) reacting to a fitness (desired parameter to be minimized or maximized). An effective solution is found, keeping “fit” genomes in a generation and breeding them with other favorable genomes in the following generation, as well as eliminating non-favorable solutions.This process is very similar to natural selection in the real world since Galapagos iterates, or breeds, multiple generations of solutions until it finds what it believes to be the fittest solution. The image to the left shows the basic genetic algorithm process while Pugnale’s flowchart on the right delves more into Galapagos’ specific process.

Galapagos Function



The top graph shows the total number of generations being bred (x-axis) vs the total spread of genome solutions being tested (yellow region/y-axis). The red line shows the average solution in each generation and the orange region is the standard deviations away from the average solution. The bottom left image shows the total spread of solutions in relation to each other and the bottom middle similarly is the disparity between values on sliders compared to other solutions.

Galapagos Connections

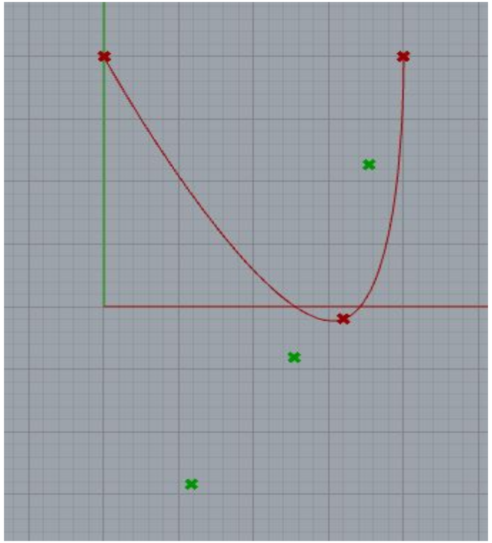


The left image shows Galapagos connecting to sliders (maroon arrows) which alter parameters in this file. The fitness connection (green arrow) decides what parameter should be minimized or maximized. In our case, fitness connected to deflection of the structure.

Galapagos Testing

Curve to Point Optimization

Before



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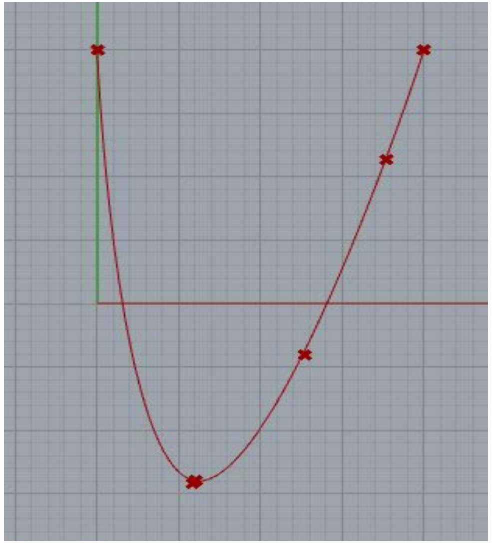
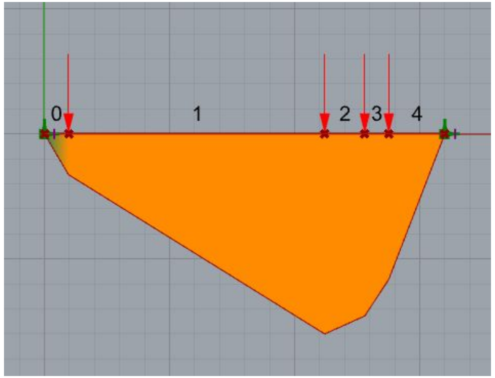


In our first test utilizing Galapagos we created random points and a simple parabolic curve, and had galapagos match the curve to the points by minimizing the distance from the curve and the points. In this case the fitness output of Galapagos connects to a component outputting the distance between the curve and the points, and the genomes are the X and Y coordinates of the vertex. This was completed without using any of Karamba's structural analysis to get a basic understanding of Galapagos.

Combining Galapagos with Karamba Analysis

Before



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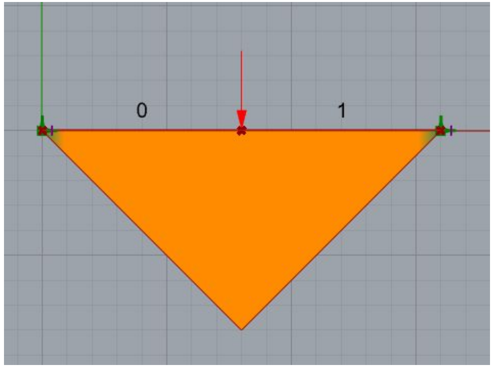
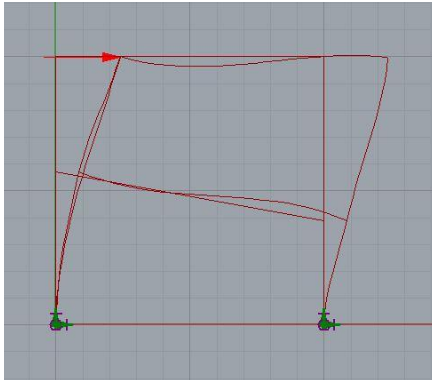


Although not a practical application, we next tasked Galapagos with moving point loads to find a maximum moment in a beam. This was our first attempt at combining Galapagos with Karamba and was to verify that we could trust the program. As would be predicted, Galapagos ended up placing all loads on top of each other at the center of the beam, so we felt comfortable moving forward.

Simple Braced Frame

Before



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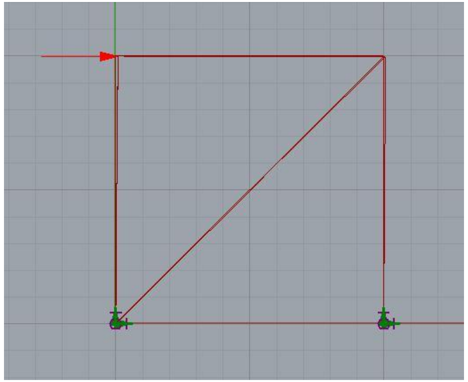
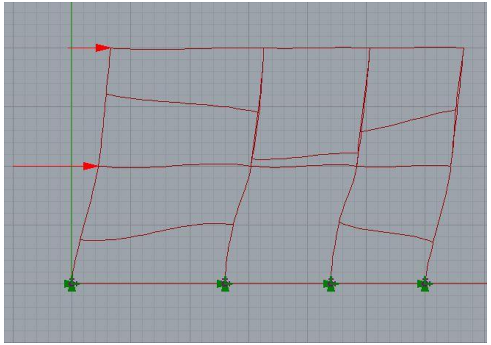


Next we began testing on a simple braced frame, now with two adjustable variables: the location of either end of the brace along the frame. Fitness is minimization of deflection. Again the results are what we would expect, as Galapagos created the basic braced frame we see everyday.

Complex Structural Elements

Complex Frame

Before



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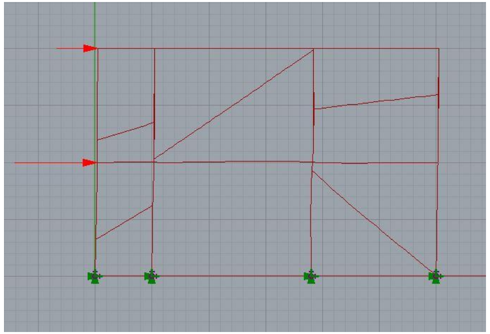
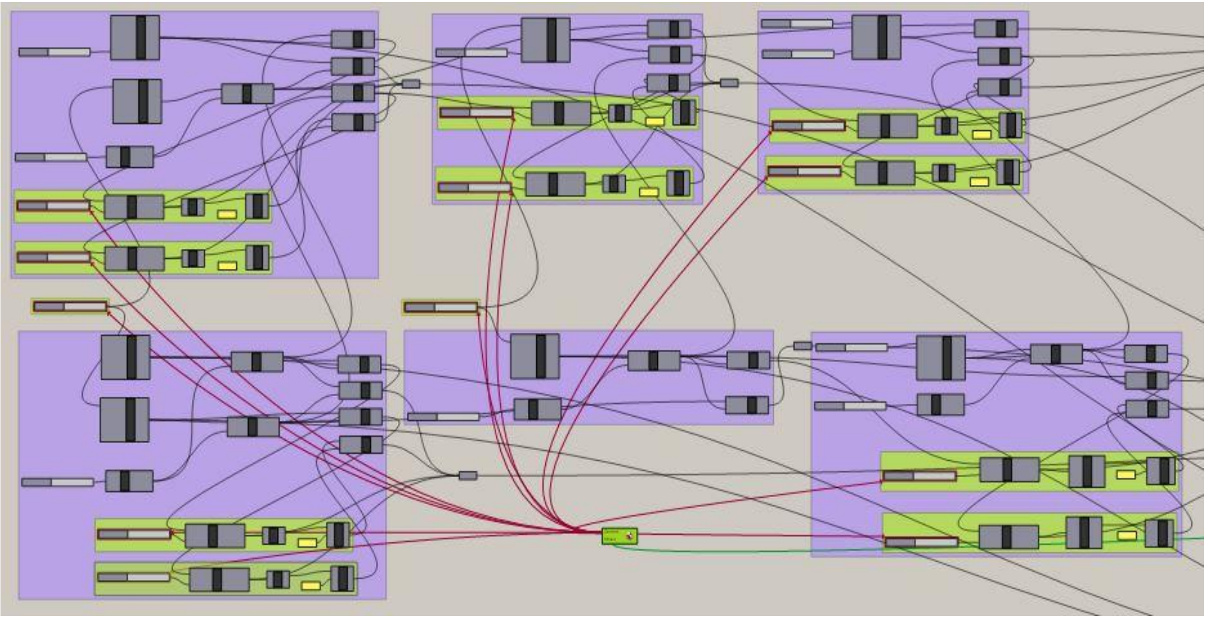


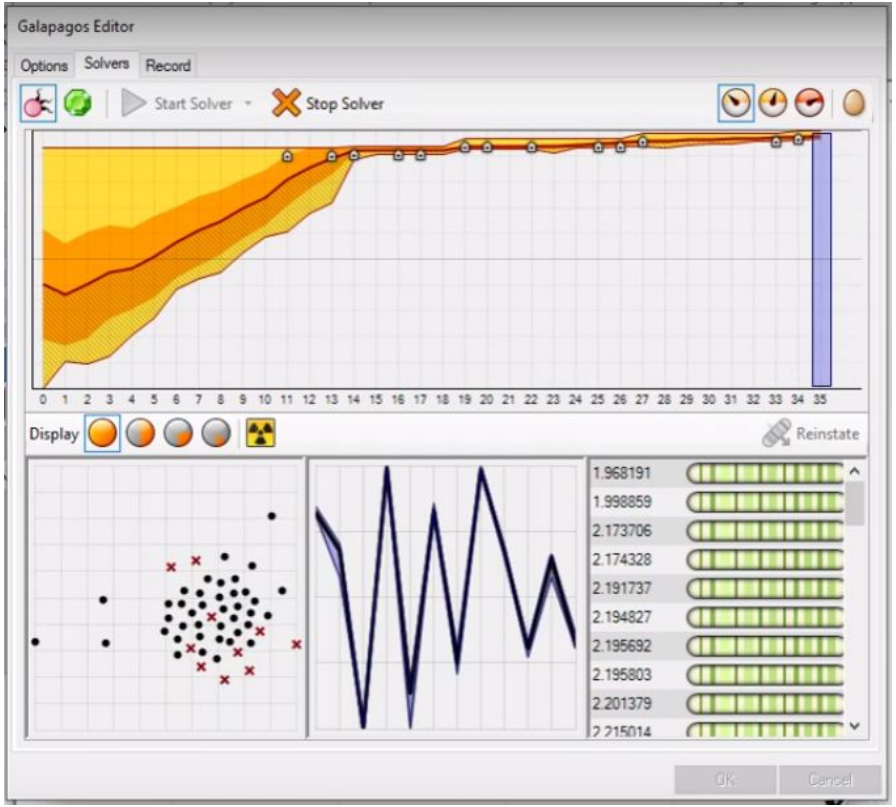
Next we moved to a more complex structural form: 2 stories, 5 editable braces, a central opening, as well as moving interior supports and columns. This type of form was to expand on the original, simple form while still utilizing increased amount of genomes on top of incorporating a hypothetical opening an architect/designer might task an engineer to design around. This showed us how many more iterations it takes for Galapagos to find a reasonable solution when given a multitude of variables to adjust. This also was our first example of seeing how an automated, genetic solver found a solution that doesn't seem logical if an engineer was tasked with reducing deflection in this system with the same parameters.

Galapagos Connections



Here you can see that Galapagos attaches to many more variables than in the simple frame. This not only caused the program to run slower, but also caused many more generations to be required to find the final solution.

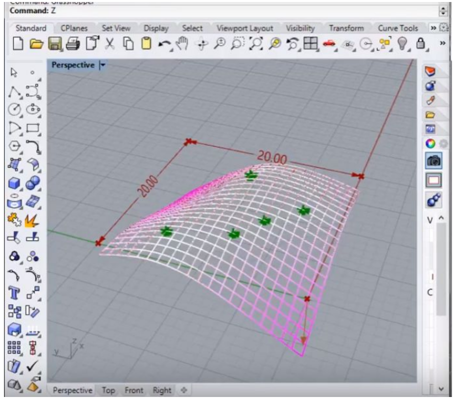
Galapagos Output



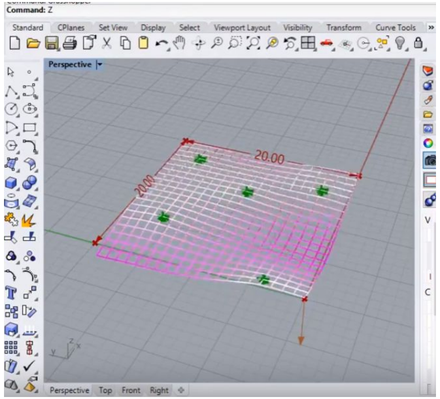
This image of Galapagos' output during its runtime shows the program converging to a common solution. With this semi-complex structures with multiple variables, Galapagos took about 14 generations just to converge. Even after that, Galapagos did not stop running for about 45 generations before its final "fittest" solution was found.

Diaphragm w/ 5 Supports

Before



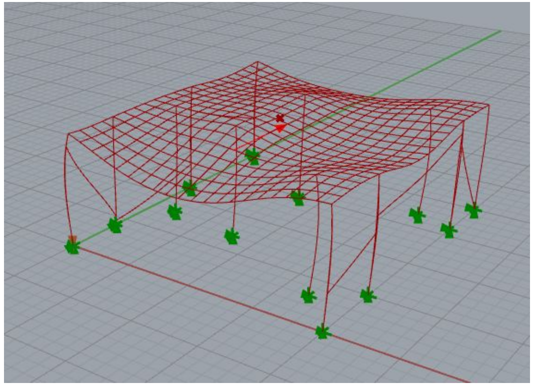
After



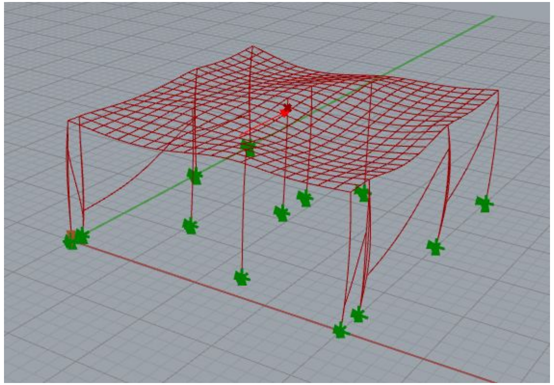
From the LFRS, we then transitioned to diaphragms. In this instance the variables being altered are the location of the supports with the goal of reducing overall deflection in the system. This again led to a very long converging process and a large total amount of generations produced before a “fittest” solution was found. This was because each support counted as two variables since they could be translated along the x and y axis. Once the fittest solution was found we saw that the structural element came to a logical finding for deflection reduction as the supports moved towards the four outward corners with one moving to the center as seen in the bottom right image.

First 3D Structure/First Building Optimization

Before



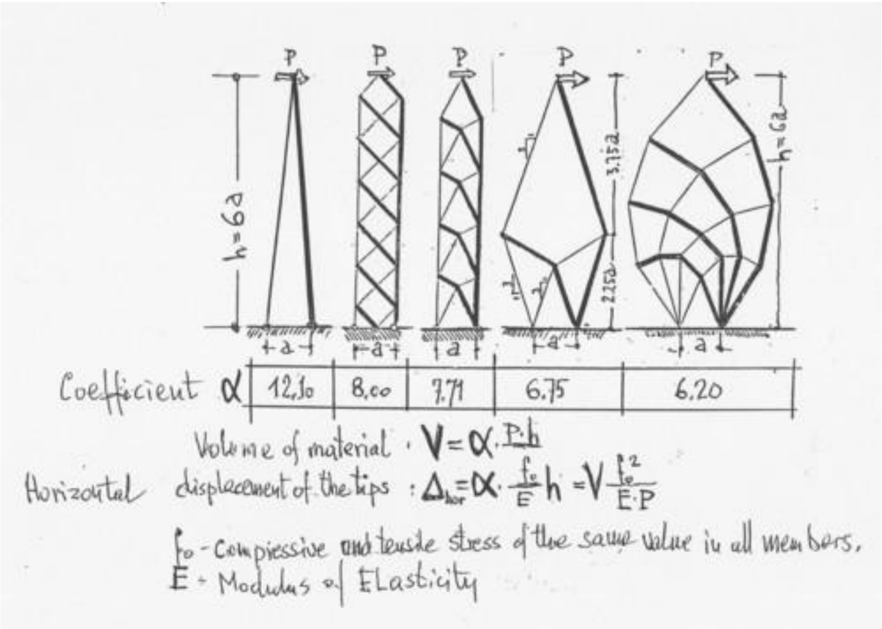
After



Now having tested all of those structural elements, we combined them to create our first test in optimizing a three dimensional structure. From the last structural element we extruded the supports into columns which could move along the diaphragm, as well as adding mobile braces with sliding supports on the sides of this structure. Galapagos was tasked with reducing deflection in this system from both a vertical gravity load as well as a lateral load placed at the center of the diaphragm. This final solution showed an instance in which Galapagos found a very effective solution, although it may not seem as a logical form that an engineer would design with.

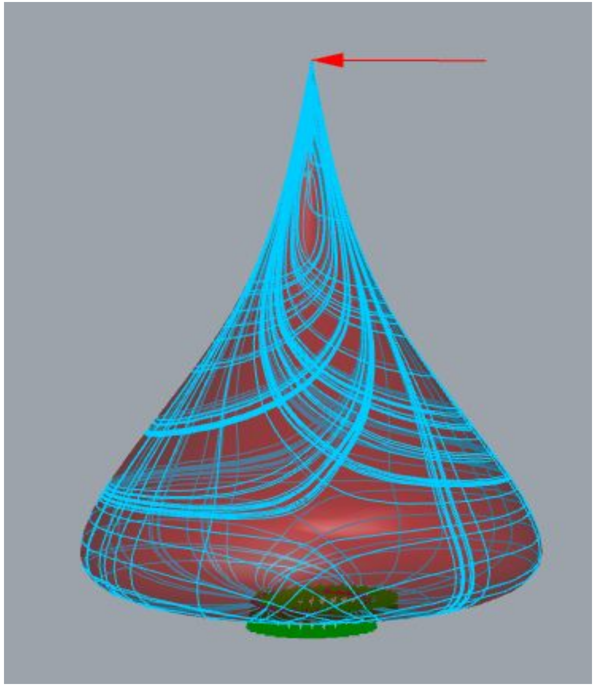
Tower

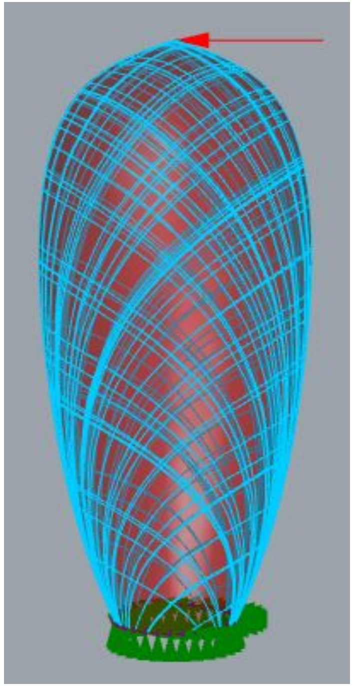
Michell Structure



The image on the right shows a michell structure after several iterations of form finding. A michell structure is a well known benchmark solution to the problem of the optimal form of a cantilever with a point load at the top. The fully realized michell structure is on the far right of the image, and we attempted to recreate this form within Grasshopper.

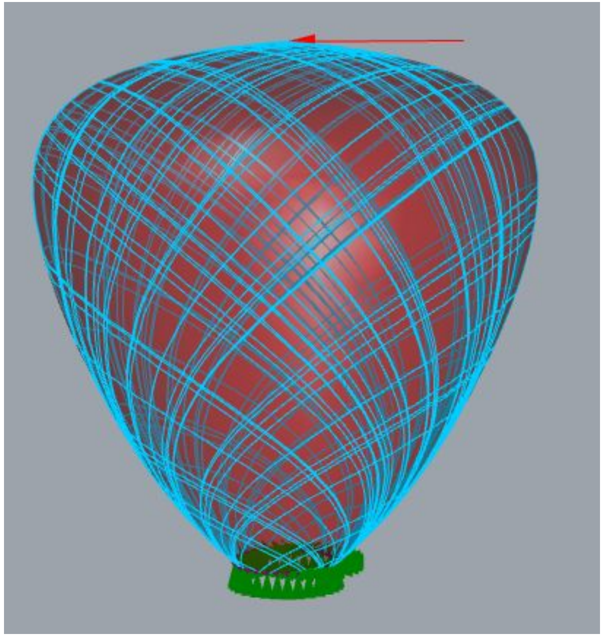
Tower 1

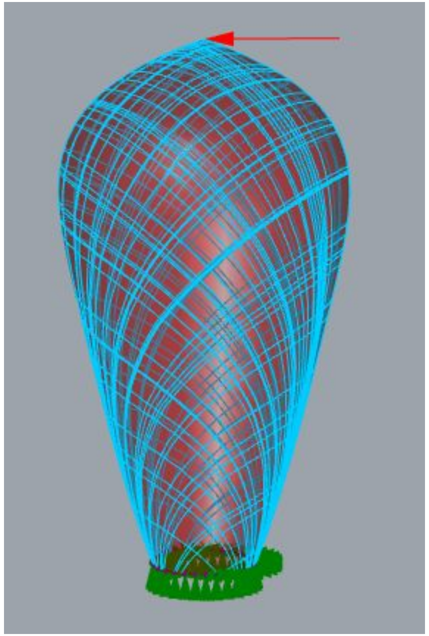




The image on the left shows a randomly generated cantilever form created by Galapagos, supported at the base and subjected to a point load at the top. Galapagos was tasked with changing the form in order to minimize displacement, and the image on the right is its final solution, with a clear michell structure seen in the principal stress lines.

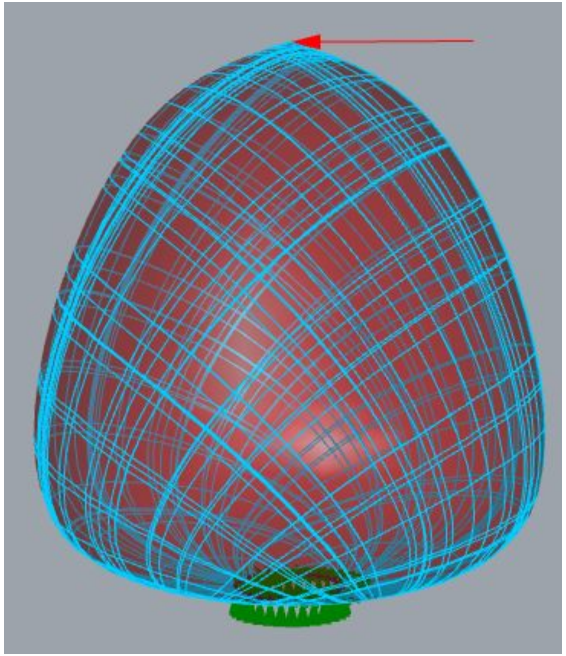
Tower 2

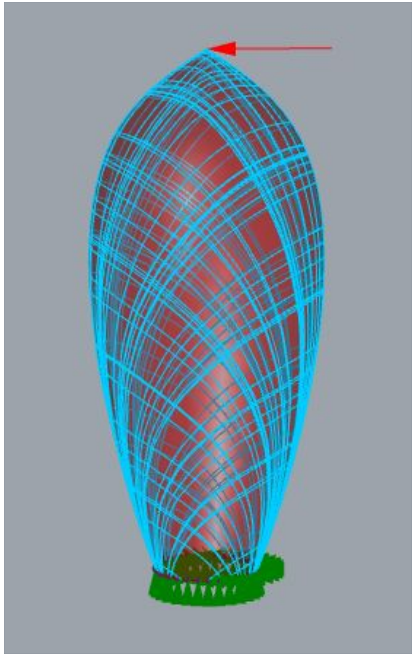




As we ran the same process in Galapagos multiple times, we noticed slightly different results depending on the form that Galapagos started with. The left image is another random form generated by Galapagos, and the right image is the optimized form. It is slightly different from the one shown previously, but still has the michell structure shape.

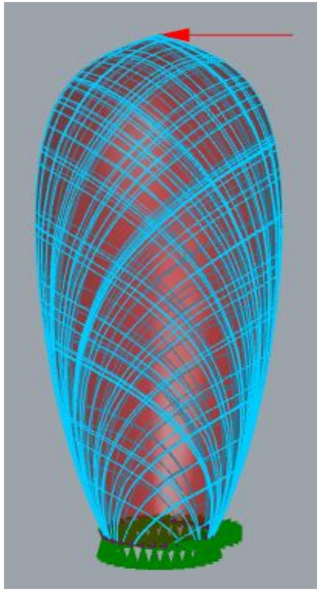
Tower 3

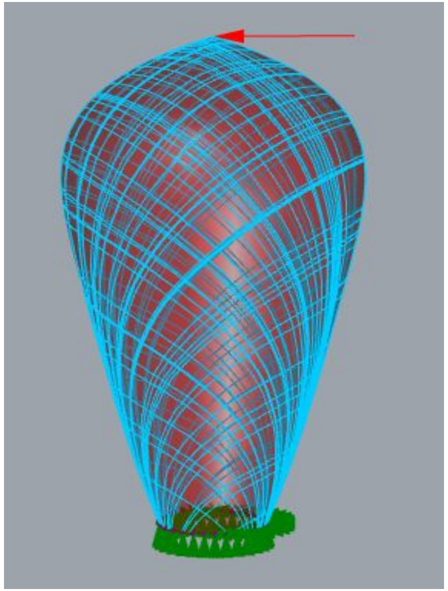


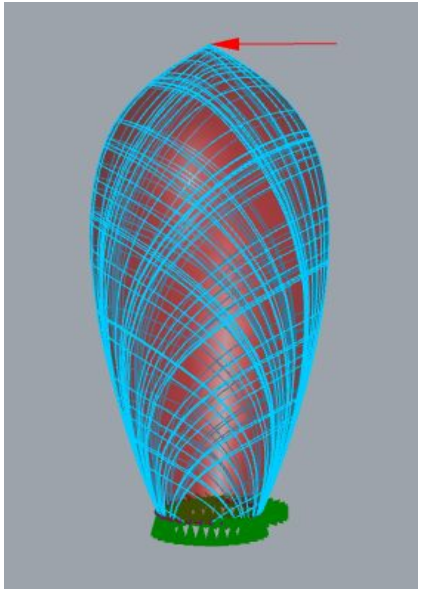


Shown here is the third iteration of the same process, with again a slightly different final form. This was run to test the variance among solutions and to make sure Galapagos was still giving us adequate results.

Genetic Differences







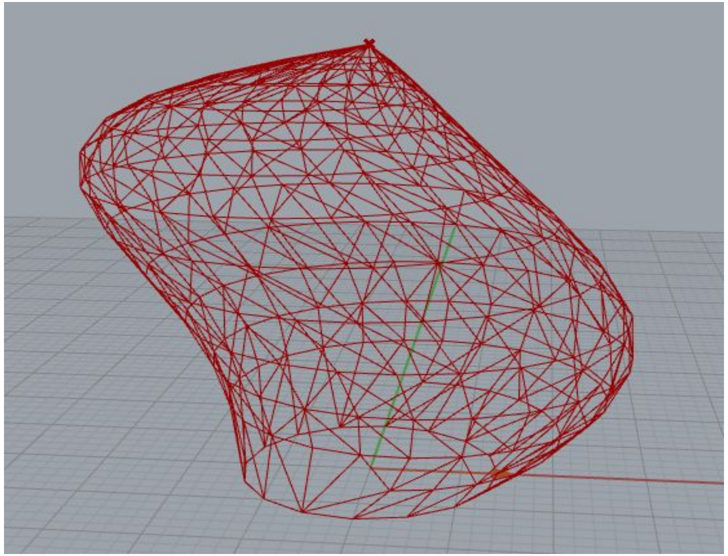
Here, a comparison of all final results is shown. The variance in form is due to how Galapagos finds a solution to the problem it is given. Much like how nature may come up with different solutions to the same problem, Galapagos will also choose which genes (variables) to cull and breed based on what is currently available to it. As we can see, all three final forms are viable solutions as they all give the michell structure form that we were looking for.

High Rise

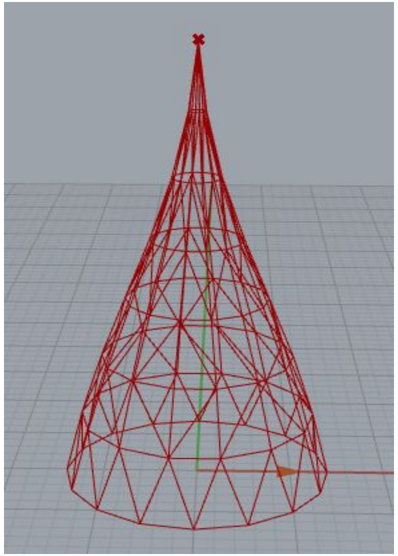
High Rises

The following slides show three iterations of a high rise structure, each with a randomly generating starting form and each subjected to different loading patterns. All structures were created the same way, all had the same modifiable parameters, and Galapagos optimized all structures with the intent of minimizing overall deflection of the structure. Rather than modeling a smooth shell form as seen previously, these structures were modeled with individual beams for more in depth analysis purposes rather than pure form finding. Karamba was also used to show the material utilization of each element in the structure, with red showing more utilization, and blue showing less.

High Rise 1 - Form Differences



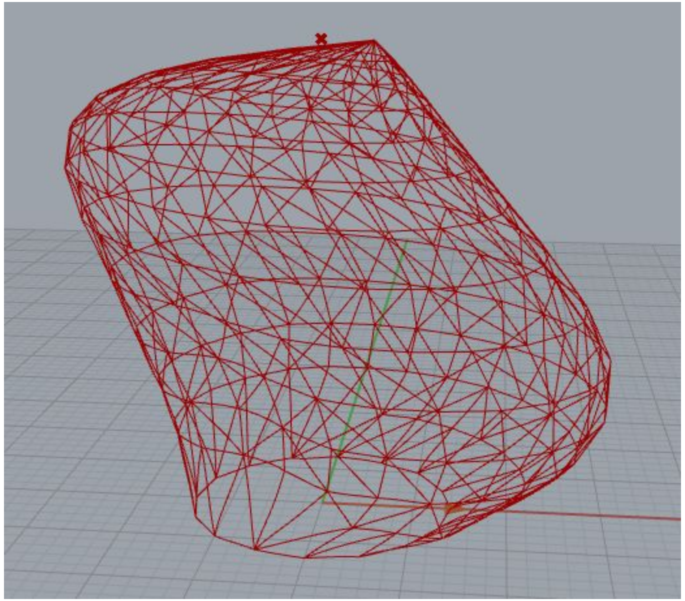
Before



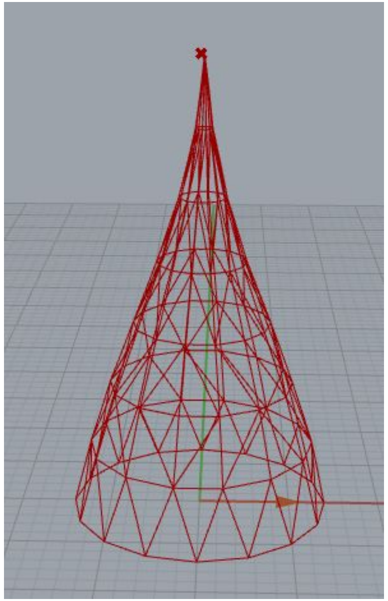
After

Loading: Gravity load thrown laterally at the structure

High Rise 1 - Deflection Differences



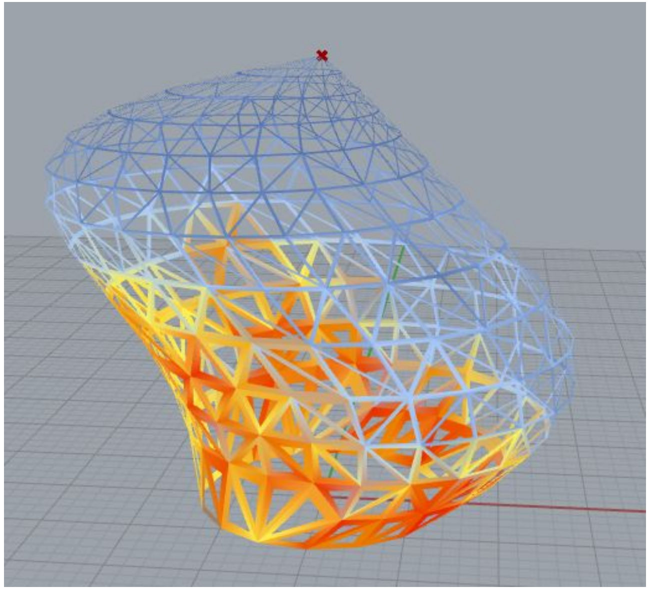
Before



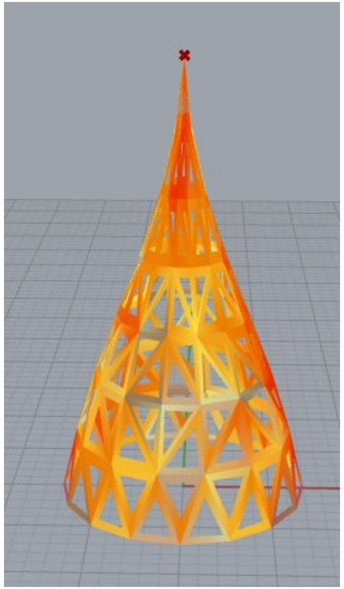
After

Loading: Gravity load thrown laterally at the structure

High Rise 1 - Material Utilization Differences



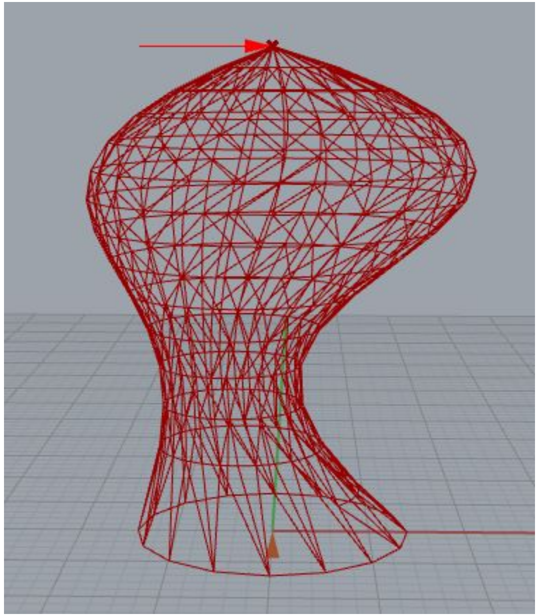
Before



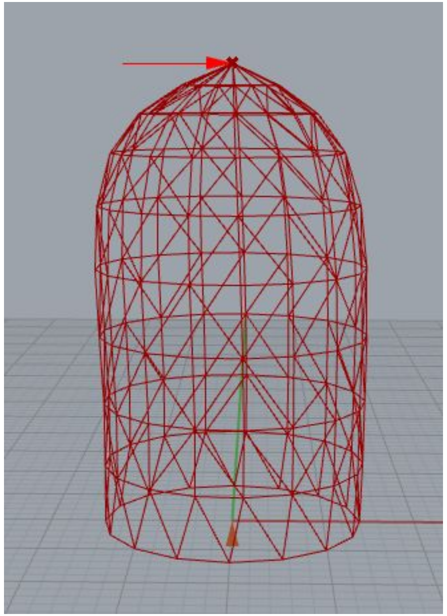
After

Loading: Gravity load thrown laterally at the structure

High Rise 2 - Form Differences



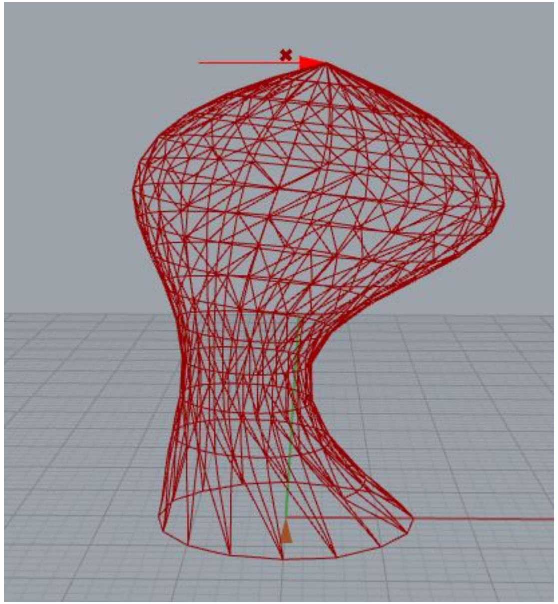
Before



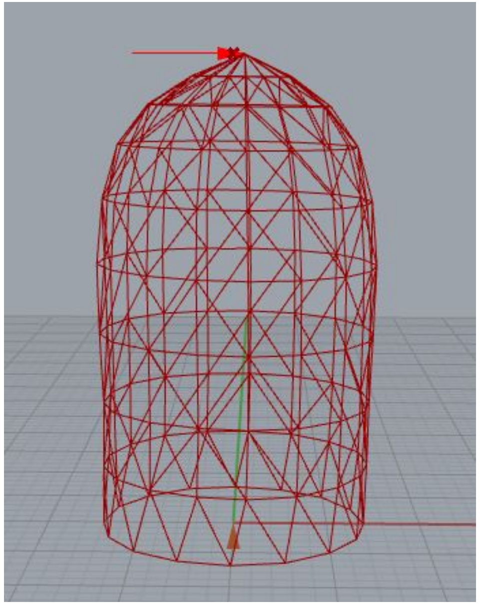
After

Loading: Gravity load downwards, lateral point load at peak

High Rise 2 - Deflection Differences



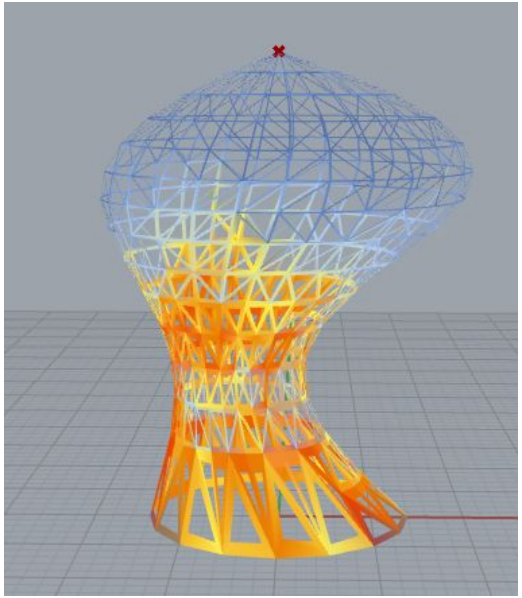
Before



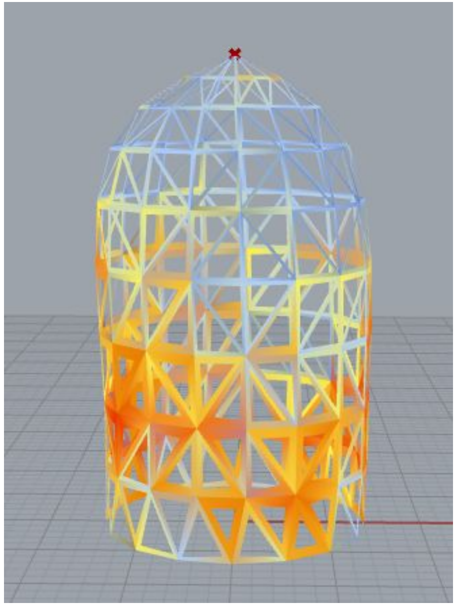
After

Loading: Gravity load downwards, lateral point load at peak

High Rise 2 - Material Utilization Differences



Before



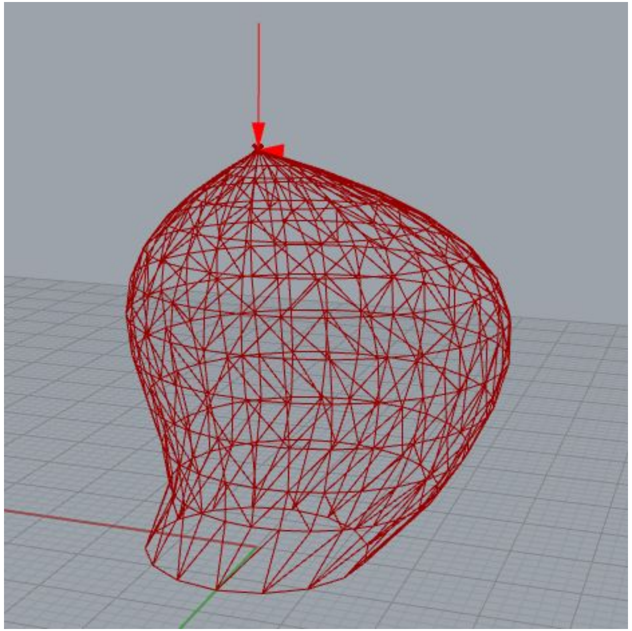
After

Loading: Gravity load downwards, lateral point load at peak

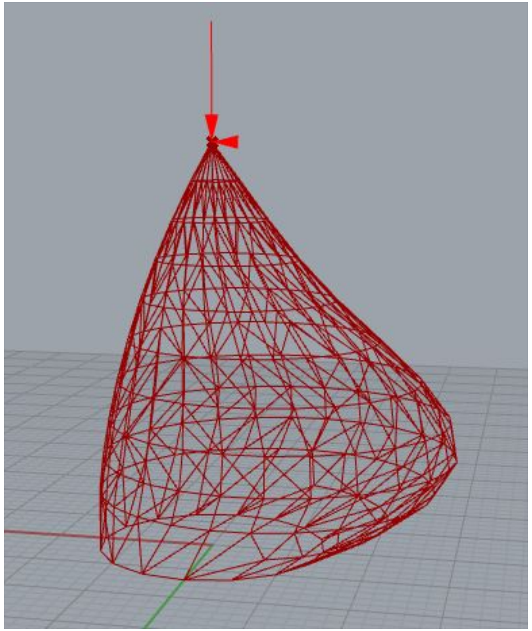
High Rise 3

Our final iteration on optimizing a high rise led us to this final form for the structure. This final test was done as we noticed that using gravity as a load affected how Galapagos came to a solution. Since Galapagos can alter the size of the structure, the mass was changing, and therefore the total load on the structure was changing. In the first high rise with gravity being thrown laterally, Galapagos makes the logical decision of coming to the smallest shape possible as it reduces the total load the structure experiences. In the second high rise, Galapagos comes to an ordinary uniform shape, even with a lateral force at the top, since gravity is acting vertically now. In this final iteration with Galapagos not being able to alter the load, we see an unnatural, unpredictable, yet very effective solution.

High Rise 3 - Form Differences



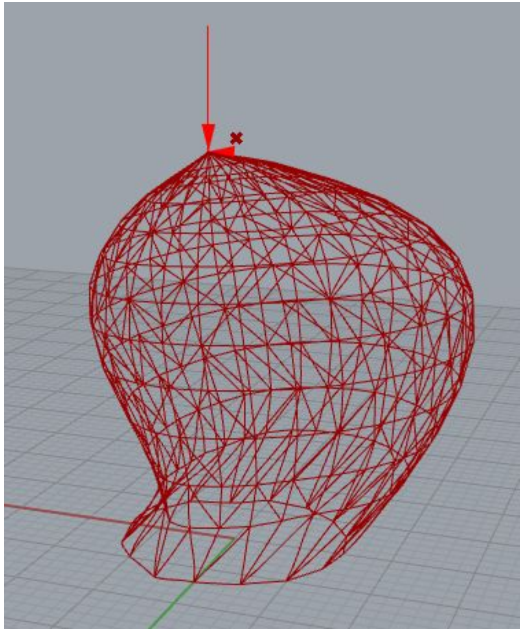
Before



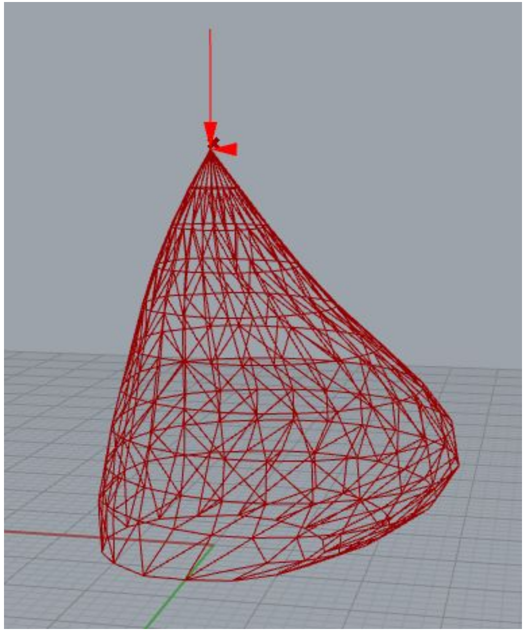
After

Loading: Point load downwards, lateral point load at peak at ⅙ gravity load

High Rise 3 - Displacement Differences



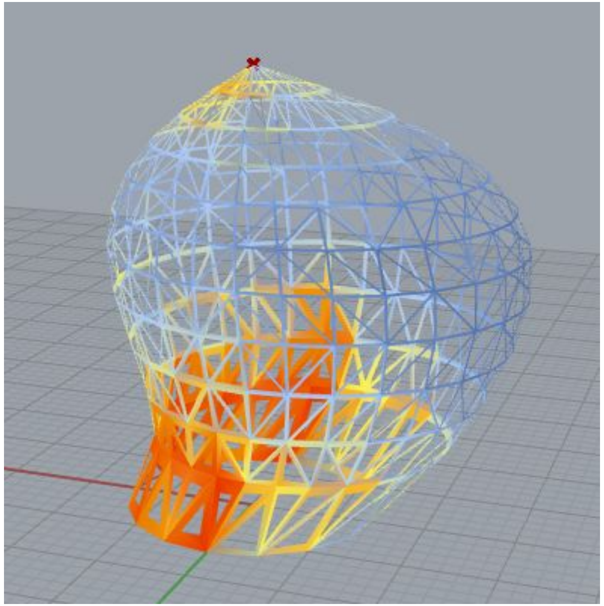
Before



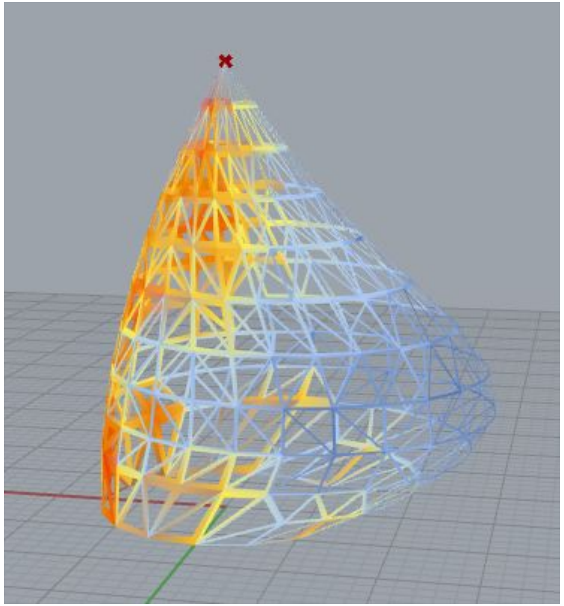
After

Loading: Point load downwards, lateral point load at peak at ⅙ gravity load

High Rise 3 - Material Utilization Differences



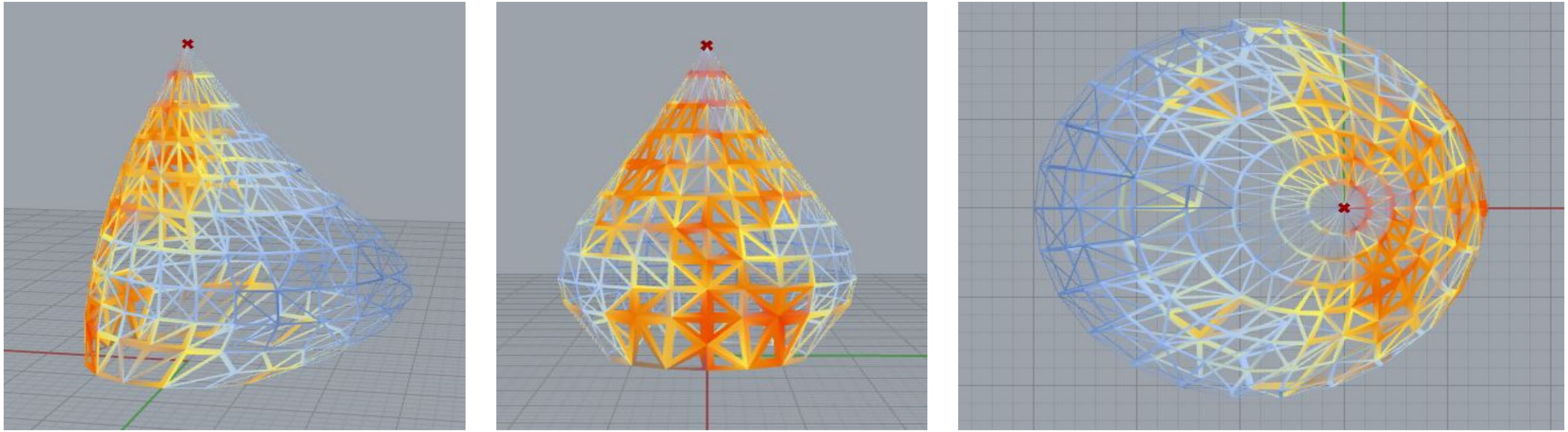
Before



After

Loading: Point load downwards, lateral point load at peak at ⅙ gravity load

High Rise 3



Differing views of the final structure are shown above. In plan view, on the far right, there is a clear line of symmetry parallel to the lateral load (not shown). Since this is somewhat expected, it gave us confidence that our solutions from Galapagos were meaningful and that the various tools used throughout our project can be used in the field to create complex, yet efficient and expressive structures.

Global, Cultural, Social, Environmental, Economic, & Constructability Considerations

While this project only scratches the surface of all the capabilities these programs have, it still manages to take in all of the above considerations. Using Galapagos as a design aid and Karamba for real time structural analysis is a tool being discovered and utilized more and more in structural engineering globally; this project sheds light on these programs and their usefulness to Cal Poly specifically as it is not explored in our major yet. Furthermore, the results that these programs output give efficient forms which save on economic cost of structures which in turn saves the amount of materials needed to be extracted out of the environment. These efficient designs are also aesthetically pleasing and bring about expressive forms which appeal to the modern culture seen in architecture today, as well as appealing to the evolving social forms which buildings are being designed for. The only issue this project poses, is how complex constructibility may be for some of the designs we found. This only helps prove the need for interdisciplinary work, as other forms of engineering can take on the complexity of connections as well as the coordinating of constructing a project as complex as this.

Files

Plugins Required:

Karamba (may have to simplify Grasshopper model if using free version of Karamba)

- https://www.karamba3d.com/

MeshEdit

- https://www.food4rhino.com/app/meshedit

Download Link to All Files:

- https://drive.google.com/open?id=1SzzswjOHVdMS8ye05-UgF5JggOYX5tH7