

# Combining parametric form generation and design exploration to produce a wooden reticulated shell using natural tree crotches

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## Abstract

LIMB is a project recently carried out at the University of Michigan, Taubman College to explore the potential use of natural tree crotches as bifurcation elements in the construction of a reticulated, wooden shell. The use of these natural tree elements offers advantages of both economy in using waste material (the crotches) as well as an aesthetic offered by the organic elements which have been formed over time by the flow of bifurcating forces. The project explores replacing mortise and tenon joinery methods common in historic heavy timber construction with a single bifurcated piece of wood. Because of their low economic value, tree crotches are often not harvested for commercial purposes. This project proposes using these natural pieces to design connections in timber construction. Through the design and fabrication of a full-scale reticulated shell, this research shows how organic variations in tree limb bifurcation can bring about valuable and sustainable opportunities for generative, architectural timber design. ParaGen, a design exploration method developed at the University of Michigan, was used to develop the form of the final shell. The method combines form generation based on a parametric model with analysis using simulation software, and stores all solutions in a Structured Query Language (SQL) database. The database can then be explored using a variety of data acquisition methods. New solutions can be generated to target desired criteria using genetic algorithm techniques. An example of a realized design is presented.

**Keywords:** wood structures, timber joinery, reticulated shells, form exploration, topology optimization

## 1. Introduction

Historic precedents for the use of tree crotches in wood structures can be found in both 17th century framing for naval vessels as well as joinery in timber barn construction [1]. Presumably, this technique offered angular joints without complex mortise and tenon details. In addition, a degree of moment resistance could be achieved that exceeded other joining techniques. Figure 1 shows examples of the described use of natural tree bifurcations. In these cases, the wood grain naturally follows the shape of the piece. More recently Claus Mattheck at the University of Karlsruhe has carried out extensive physical testing of the behavior and strength of natural forked tree sections [2]. In his work he also gives guidelines for the selection and defect detection in these pieces in nature.

The goal of the work presented here is to make use of these naturally forked tree sections as joining elements in architectural, structural systems. In this effort we focus on the design of reticulated dome structures. The raw tree crotches are cut to size and milled to final form and dimensions in a 5-axis CNC router (see Figure 2.). The design intent is to produce standardized nodal elements that can be joined easily to connective strut elements. By using the CNC router, exact final angular and linear dimensions can be precisely attained.

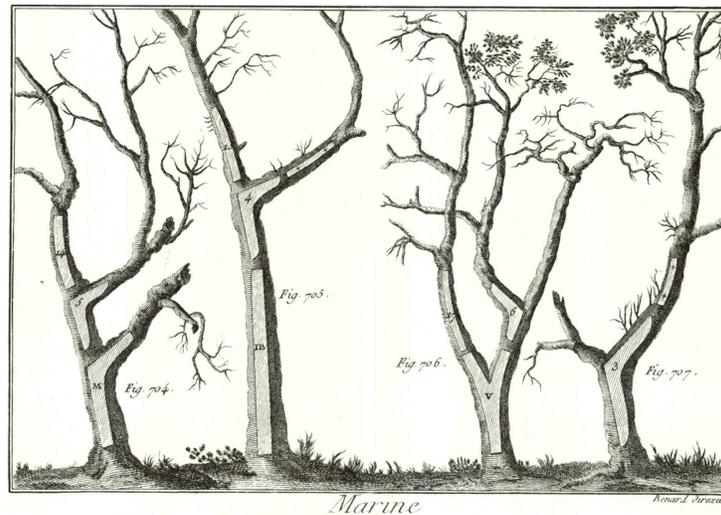


Figure 1: Example bent and bifurcated elements taken from natural tree sections. [1]

Part of the design intent is to limit the number of different joint elements in order to achieve a standard set of parts that could be produced and used in different circumstances.



Figure 2: left) Component parameters and assembled parts right) Milling jig.

## 2. Design process

The form generation model is constructed using Rhino/Grasshopper. The model executes the following steps in the generation of each solution:

1. Selection of a base topology grid
2. Dynamic relaxation of the grid to find a compression shell (with Kangaroo)
3. Analysis of the shell under gravity loading (with Karamba)
4. Export of images (with Ladybug)

In addition, as a post process, the chosen form can be adjusted to use a preselected set of joints. This allows for economy using either fewer different pieces or pieces from an available stockpile.

## 2.1. Selection of a base topology grid

Because tree crotches generally join three members, a hexagonal grid is chosen for the shell mesh. Also, for this initial study, it is desired to limit the total number of joints and members so as to reduce fabrication time. For this reason the grid topologies are limited in overall size and complexity. In addition, some topologies contain a central oculus that further reduces the number of joints and members. Figure 3 shows the seven topologies included in the form finding search.

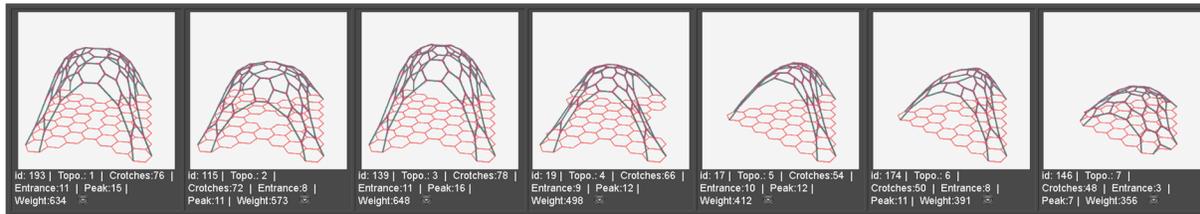


Figure 3: The seven different topologies included in the form finding search.

## 2.2. Dynamic relaxation of the grid

The next step is to use the Grasshopper plugin Kangaroo [3] to apply dynamic relaxation coupled with an upward force to find a compression controlled shell. The force level (rest/length ratio) which drives the height extension is taken as a variable, and spring tensions are set over three ranges of the surface – the supporting legs, the edges and the central portion. This has an influence on the final curvature in the different regions. The examples in Figure 3. all show an uplift force of 1. Figure 4 shows topology 3 with upward forces applied ranging from 0.5 to 1.8.

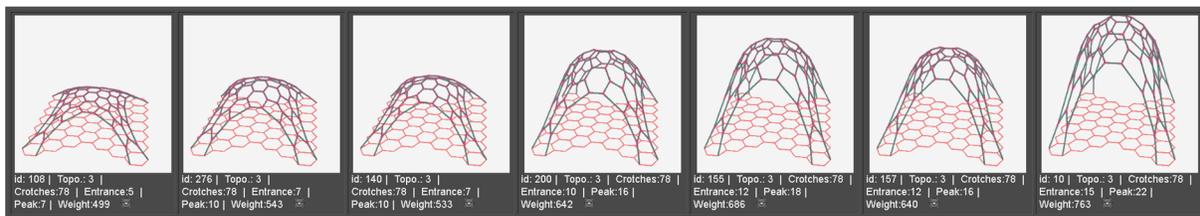


Figure 4: Topology 3 shown with an upward force ranging from 0.5 to 1.8.

## 2.3. Analysis of the shell

Two basic categories of data are collected on each shell solution: geometric parameters and structural parameters. Key geometric values that are useful in choosing a solution include: clear height of the side arches, center maximum height, number of joints and members, longest and shortest members, defining crotch angles, as well as the base topology type. Since the member sections and wood density are preset, the overall weight is also calculated. With the geometry of the shell determined, a structural analysis is performed using Karamba [4]. Values recorded from the analysis include maximum axial force, moment and deflection as well as utilization factors of members in tension and compression. All quantitative values are uploaded to a SQL server as well as images of the geometry and structural plots. In addition, a catalog view showing each joint with all defining angles is included (see Figure 5).

## 2.4. Export of images

A selected range of images is generated and exported from Grasshopper using Ladybug. All of the generated images can be viewed along with the quantitative data, and printed as a one-page description for any solution. Figure 5. shows such a description sheet for one solution. These summary sheets are very useful in making a design selection among a specified set of solutions. Using ParaGen a final selection set can be

defined by solutions that meet chosen criteria. Then the final selection can be made based on both visual quality and a combination of other criteria. Quantitative data can of course be graphed and compared (e.g. with Pareto sets), but qualitative aspects are often best shown by visual depictions.

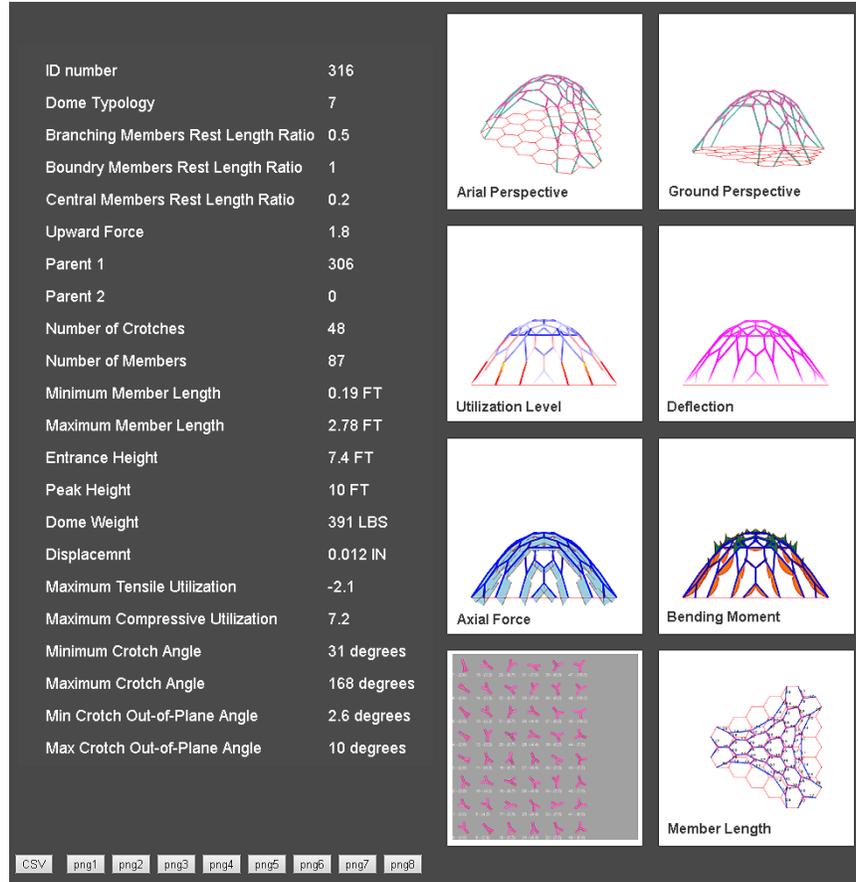


Figure 5: Detail summary sheet for one solution showing both quantitative data and visual form.

### 3. Design generation/exploration with ParaGen

The generation of the solution space, along with the exploration to find the best solutions is accomplished using ParaGen, a design aid developed at the University of Michigan. Details of the ParaGen method have been discussed in several previous IASS papers [5]. Basically, the system couples some parametric form generation, (in this effort the Rhino/Grasshopper combination was used with Kangaroo), with a simulation and analysis tool, (for this Karamba is being used). The results are uploaded to a SQL server, which uses a genetic algorithm (GA) to search for more solutions that fit specified criteria. The process is cyclic and can run on a single machine or on any number of clients in parallel. All that is required is for the clients to be able to each access the software and the SQL server through an interactive web page. Figure 6. shows the basic ParaGen cycle as well as the steps in the process.

ParaGen is based on a Non-Destructive Dynamic Population GA (NDDP-GA) [5]. It is non-destructive in the sense that every solution generated is saved in a SQL database. The breeding populations are then drawn from this database dynamically at the moment breeding takes place. This offers several advantages over conventional GAs. Whereas traditional GAs remove unfit solutions from a population, the NDDP-GA stores

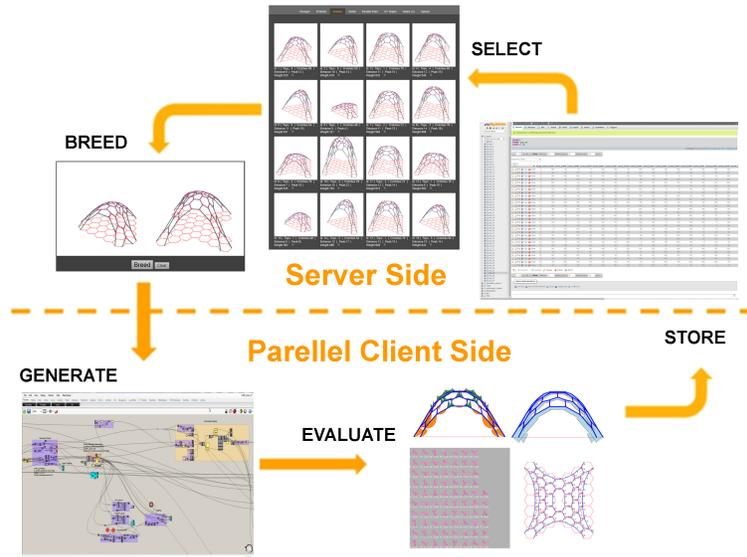


Figure 6: The basic ParaGen cycle showing the steps used to generate a range of solutions.

all solutions permanently in a database. One advantage in this approach is that as each new child is generated, a check can be made in the database to ensure that the child has not already been developed. This is not possible in a traditional GA, and as a result, the same solution is often repeated causing wasted computational effort. Also in a traditional GA, the population evolves slowly and progressively with each new cycle of breeding. This means that if the breeding criteria (the fitness or objective function) changes, the entire process must be restarted to again slowly evolve a fit population. A dynamic population, however, is drawn immediately from the database of all solutions so far. So rather than starting over entirely, the criteria are merely redefined, and the best population for the new criteria is drawn from the database of all solutions found to that point. This gives an NDDP-GA a great deal more flexibility in exploring a large solution space for multiple criteria.

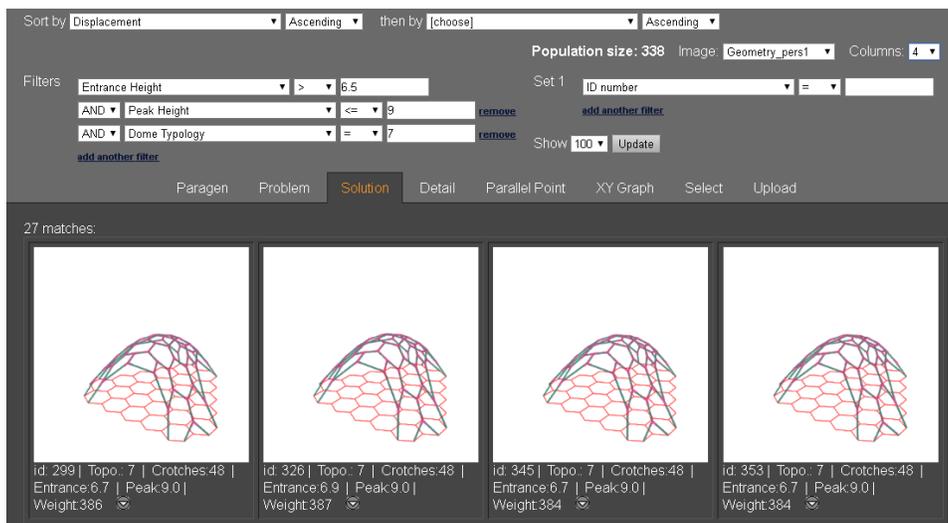


Figure 7: SQL filters for search and breeding criterion.

The use of an NDDP-GA gives ParaGen a distinct advantage in solution *exploration* as opposed to traditional *optimization*. Classic optimization generally searches for a single best solution for some given criteria. ParaGen, on the other hand, is focused more on exploration. It searches for a range of pretty good solutions for differing criterion. This might be a traditional Pareto set (ParaGen can perform Pareto optimization too) or it might simply be a set of solutions that respond well to different criteria. Because ParaGen also provides images of the solutions, it is possible to consider qualitative considerations as well which include form, aesthetic appearance or spatial qualities.

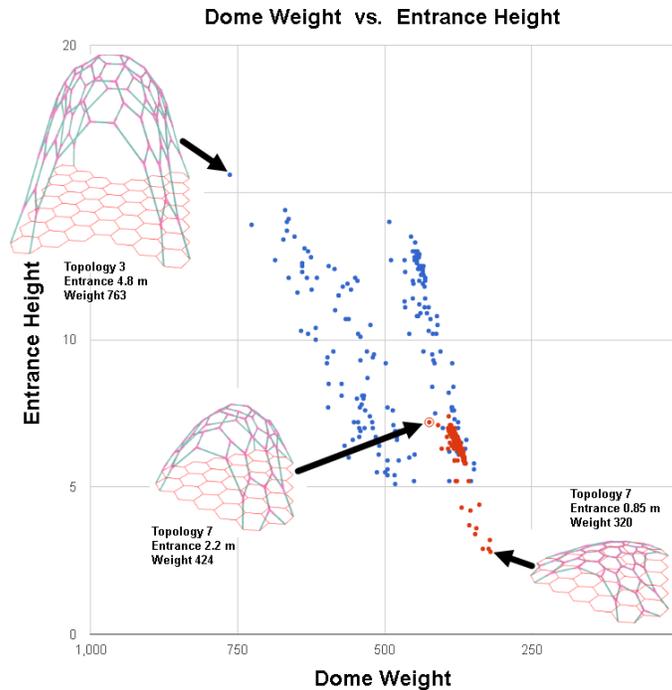


Figure 8: A plot showing the relation of dome topology set 7 (red dots) to the other topologies with respect to entrance height vs. total weight.

Exploration in ParaGen is further facilitated by a set of post-processing tools. First, since all of the defining data for each solution is maintained in the SQL database, the full range of SQL queries can be employed in searching for different combinations or ranges of criteria.

In Figure 7., a search is made for domes with an entrance height of at least 2 meters (6.5 feet) but with a peak center height limited to 2.7 meters (9 feet). The search set is restricted to topology type 7, and the results are displayed in ascending order of displacement (from least to greatest). Since the results are all contained in the database, they will be displayed instantly, thus making the search truly interactive and visual.

The quantitative parameters can also be searched using interactive graphing functions. Additional information can be displayed through the use of color. For example in Figure 8., the red dots show the relation of topology 7 as compared to the other topologies regarding entrance height and overall weight. Again because all data is stored in the database, the results are displayed instantly, making interactive comparisons quick and easy. Also, by running the cursor over any of the dots, the solution id and data is displayed, and by clicking on any dot, the solution image is immediately displayed. All of these post-processing options combine to make ParaGen a versatile design exploration tool.

Using the ParaGen exploration tools a final design was chosen from the generated options. Due to limits of space, time and resources the criteria for the initial prototype were set to give a smaller dome that still maintained a minimum entrance height of 2 meters. The number of nodes was also minimized which resulted in topology 7. The other factor considered was the range of crotch angles which was chosen to match the range of sizes that was available. The selected dome is shown in Figure 5. Also due to time constraints, the initial prototype was constructed from one third of the total dome. The constructed prototype is shown in Figure 9.



Figure 9: The constructed prototype of one third of the full dome

#### **4. Prototype construction**

The fabrication of the dome segment had three parts: the nodes, the members and the joining element between them.

##### **4.1. Grid nodes (tree crotches)**

The nodal points between members were fabricated from tree bifurcation pieces or crotches. The process included seven steps:

1. Collecting the crotches – sawn from waste timber
2. Scanning the crotches – photogrammetry with cameras using Agisoft Photoscan.
3. Fitting the desired finished geometry within the raw crotch
4. Producing the CNC mill path – using Mastercam
5. Milling the piece
6. Sealing the piece to retard drying and cracking
7. Milling the connection (hole for peg)

Figure 2 shows a piece mounted in the milling jig at the conclusion of the 3D routing operation. Each piece went through this process which takes several hours per piece. The milling time alone took about 2 hours.

##### **4.2. Member pieces**

The straight, strut elements between nodes were fabricated using 70 mm (2-3/4 inch) diameter billets. For these, rough turning maple blanks were used (commonly used to produce baseball bats). These are knot free pieces, and should have a strength comparable to select mixed maple (NDS allowable compressive stress of 6000 kPa (875 psi)).

### 4.3. Pegged connections

The connecting element between the crotch node and the straight struts was a simple 25mm (1 inch) wood dowel as a peg. In the original design the intention was to glue the peg in place with casein (wood) glue. The joint was tested in this form in flexure, and was found to develop the full tensile strength of the dowel, which was 276 Nm (204 ft-lbs). However, because the prototype needed to be disassembled, the pegs were fixed in place with screws rather than glue, which reduced the flexure capacity to about 100 Nm (73 ft-lbs). The allowable compressive capacity would still be based on the net section and was about 20 kN (4500 lbs).

### 5. Discussion

The erection process was easily accomplished with temporary bracing of the nodes. Due to a time limit to produce the prototype, only one third of the designed dome was fabricated and erected. Although the erection of the shell took less than one day, the production of the joints through the seven step process described above proceeded at a rate of about two per day. In the prototype, because disassembly would be necessary, the pegged joints were screwed and not glued which compromised the strength. This resulted in some joint slippage during erection. After a few weeks standing in the dry indoor environment, some cracking of the crotch pieces was also observed. As a means of crack prevention, tests are currently being run using Polyethylene Glycol (PEG) injection under pressure. Also, kiln drying techniques using controlled pressure, temperature and humidity to dry the lumber without cracking are being pursued.

### 6. Conclusion

The concept of repurposing the waste product of tree crotches did succeed, and a section of a dome was fabricated. Problems encountered include the time required to scan and mill each piece. This could be improved by standardizing the angles used, which would minimize the number of different sizes needed. Also, the grading of the wood was a concern. One approach would be to pre-shape pieces with a band saw, thus exposing potential defects in the wood, reducing milling time and expediting drying.

### Acknowledgements

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