Dynamic Configuration Processing and Optimization of Forms (Exploring Truss-bridges)

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ABSTRACT

The main objective of this research is to demonstrate a form exploration technique based on parametric form generation and evolutionary optimization. Accordingly, the design process of a truss bridge is considered, and two types of form-finding methods are presented, numerical modeling with computational analyses on one hand versus physical modeling on the other hand. The focus of this research is on form determination using the first method to indicate its ability to explore and evaluate forms based on multiple goals and offering arrays of comparable, good solutions instead of a single "optimal" form. Additionally, the physical modeling of the truss bridges is considered in order to draw a comparison between the form finding techniques that designers use to comprehend, evaluate or describe the performance of a typical structure.

The geometric configuration processing of the truss bridges is based on a mathematical system known as Formex algebra and the respective parametric formulations of the forms are provided by the algebra's associated programming software, Formian. The next step of form generation is implemented using the ParaGen method, based on genetic algorithm (GA) concepts. This method provides arrays of solutions that are structurally evaluated and mutated or recombined through an iterating cycle. In the case of the existence of multiple design criteria or cases which cannot be explicitly defined in terms of quantitative objectives, ParaGen provides visual representation of the solutions and allows the designer to have a suitable interaction and make decisions regarding personal preferences. The ParaGen framework uses a non-destructive, dynamic population to fill a database with solutions linked to a variety of performance characteristics. The database of solutions can then be explored for any multi-objective performance criteria. A detailed search can also be carried out by either choosing solutions based on visual criteria or by performance criteria.

Ultimately, the explained procedure demonstrates how designers can expand their design perspective and be provided with arrays of appropriate solutions, instead of simply one best solution, using a dynamic process of form generation and optimization.

Keywords: Topology Optimization, Genetic Algorithm, Formex Configuration processing, Truss Bridges.

1- INTRODUCTION

Designing a form is broadly considered as a creative procedure within which certain goals are purposefully sought. The designer usually sets some parameters such as topology or geometry of forms, material properties, architectural functions and load cases. Then, the design goals are generally defined by means of some criteria and the extent to which

solution(s) can meet them. In order to expand the designer's perspective, facilitate modifications of the forms and explore more possibilities of appropriate solutions in the early stages of design, the couple of parametric form generation and evolutionary optimization techniques can be applied [1].
In this research work two methods of form exploration are used to study the relation between the geometry and structural performance of specific types of spatial structures; one which is based on physical modeling and the other which is derived from the coupling of a parametric formulation and the application of a genetic search process. A case study of a two-lane truss bridge is opted for in this paper, since it allows one to consider structural performance as well as other design concerns like visual characteristics, compatibility with the surrounding environment and constructability. The truss bridge is given a width of 8 m and span of 48 m and is expected to be composed of two 2D trusses at the two sides that are braced together laterally. The trusses may be situated above or below or on both sides of the deck. The trusses can also have positive, negative or zero curvature (figure 1).

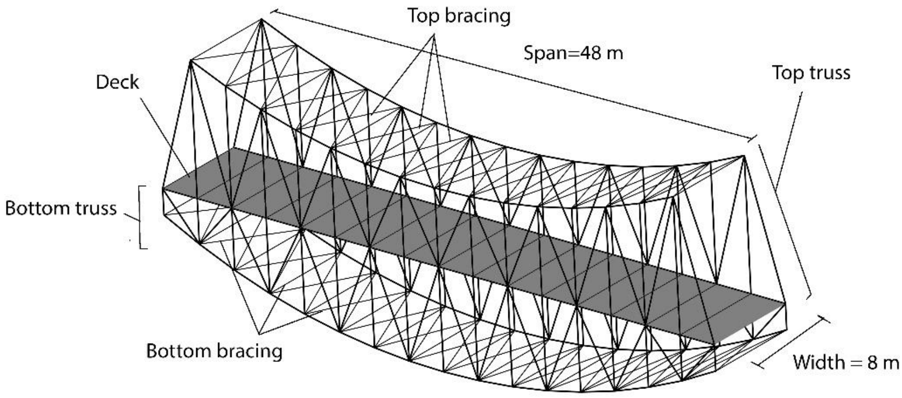


Figure 1: A typical form of the truss bridges that are to be explored.

The question is raised at the beginning of this study: what are appropriate solutions regarding the structural performance, visual appearance and a designer's individual preference, and how can such a set of suitable solutions with different geometrical and structural features be found.
The configuration of a bridge is first processed using Formex algebra and Formian programming software [2]. The geometrical concepts used within this step are described in the following section. Next, having produced a geometry, a DXF file is sent to STAAD.Pro for structural analyses and evaluation. The obtained information including graphic depictions is stored in a database which is linked to a visual exploration interface. In the next step pairs of bridges are selected based on the design objectives to breed further bridges. The new generations of truss bridges emerge through the iteration of this cycle to yield an array of suitable solutions. Ultimately, a fitness function is used to pull out the desirable solutions from the pool of generated forms. This process is described in detail in section 3 (see figure 8). Finally, a comparison with the results of form exploration through physical modeling of the truss bridges, accompanies the computational study at the end.

2- FORMEX CONFIGURATION PROCESSING

The configuration processing of truss bridges is described through geometrical concepts of Formex algebra [2]. Formex algebra is a mathematical system that allows a designer to define the geometrical formulation of forms through concepts that effect movement, propagation, deformation and curtailment (figure 2) [3]. The creation of any type of spatial structure, such as space trusses, domes, vaults, hypar shells, polyhedric and free forms, can be carried out by using this mathematical system and its associated programming language Formian.

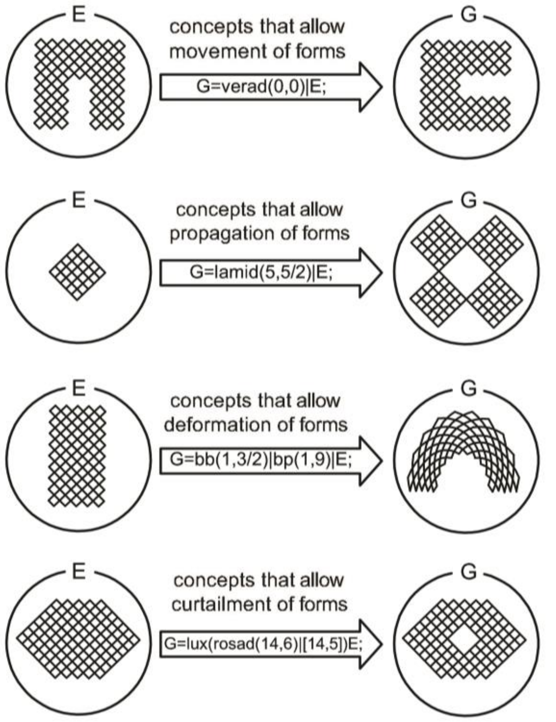


Figure 2: Some of the basic concepts of Formex algebra, [3].

In the first step, constant parameters, variables and also their acceptable intervals, described in table 1, are set. Additionally, sketches of truss patterns, illustrated in figure 3, are provided to assist the designer choosing the desired pattern more conveniently.

Table 1: Geometrical parameters on which the configuration processing of truss bridges are based.

Parameters	Sign	Constant/Variable	Acceptable interval/ value
Span of the bridge	L	Constant	48 m
Width of the bridge	W	Constant	8 m
Frequency of geometrical modules along the length of the bridge	m	variable	m should be an even integer. [4, 20] is recommended.
Total rise of the bridge at the top part	HX1	Variable	[0.5, 16] m
Total rise of the bridge at the bottom part	HX2	Variable	[0.5, 16] m
The rise of the arch at the top truss	X1	Variable	[0.01, 16] m
The rise of the arch at the bottom truss	X2	Variable	[0.01, 16] m
The top rise in non-arched part of the truss	H1	H1 = HX1 - X1	[0.49, 16) m
The bottom rise in non-arched part of the truss	H2	H2 = HX2 - X2	[0.49, 16) m
Curvature sign of the top truss	Sign1	Variable	1= positive curvature -1 = negative curvature 0 = none
Curvature sign of the bottom truss	Sign1	Variable	1= positive curvature -1 = negative curvature 0 = none
Pattern of top truss	Top	Variable	D1, D3, D5, D7, D9, D11, D13, D15, D17 (see figure 3)
Pattern of bottom truss	Bottom	Variable	D2, D4, D6, D8, D10, D12, D14, D16, D18 (see figure 3)

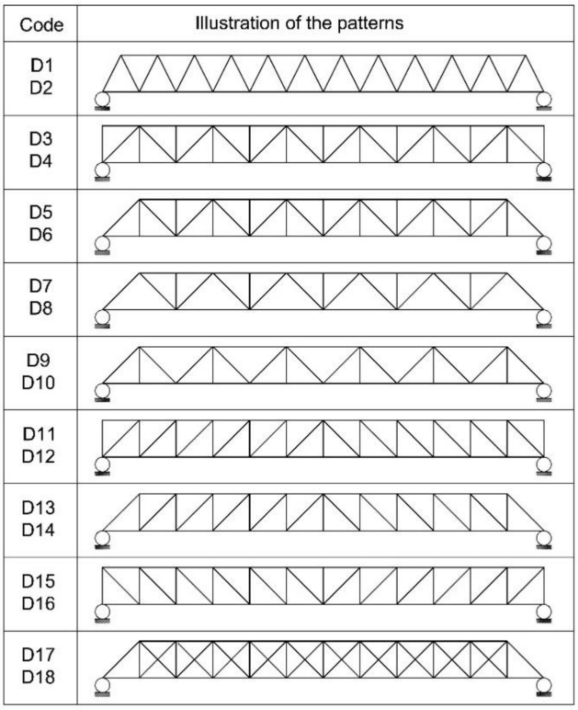


Figure 3: The truss patterns that are used for the top and the bottom parts of the bridges

The configuration of trusses can be processed using a 3-directional reference system similar to the global Cartesian system. Truss elements and deck members of the bridge are defined in terms of lines, and surfaces respectively. Figure 4 shows some parts of a simple truss bridge given in an appropriate reference system. Trusses are expected to have curvature at the top and bottom parts. The related parameters, used to define such bridges, are also demonstrated in figure 4.

Curved trusses can be created using the "pellevation" function which starts with a non-curved truss and deforms it by pushing the elements up or down, along the z axis, to the prescribed shape, see figure 5. The concept of pellevation has been presented in diverse ways that each can be applied to propagate different forms. In this study, "circular barrel pellevation" is used, [4] (figure 6). The configurations generated by Formian can be exported in DXF format and used in the next stage of study which includes a full structural analysis and design of members.

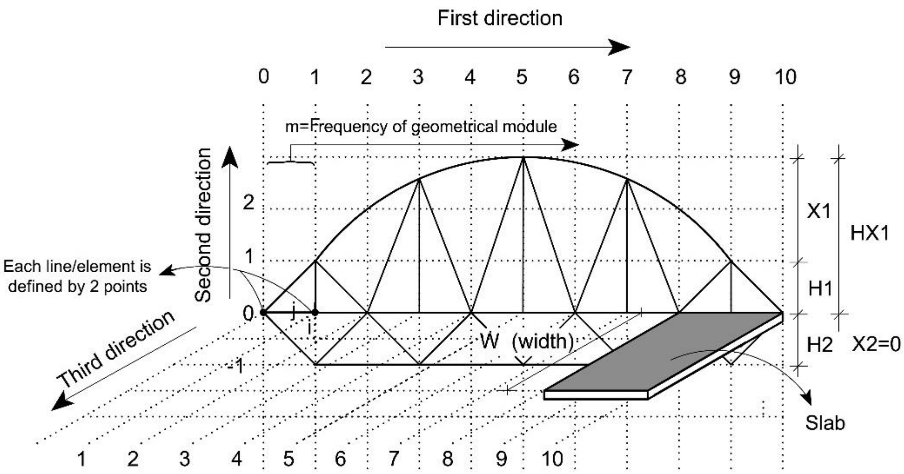


Figure 4: A part of a curved bridge configuration and the related parameters within a 3-direcional reference system

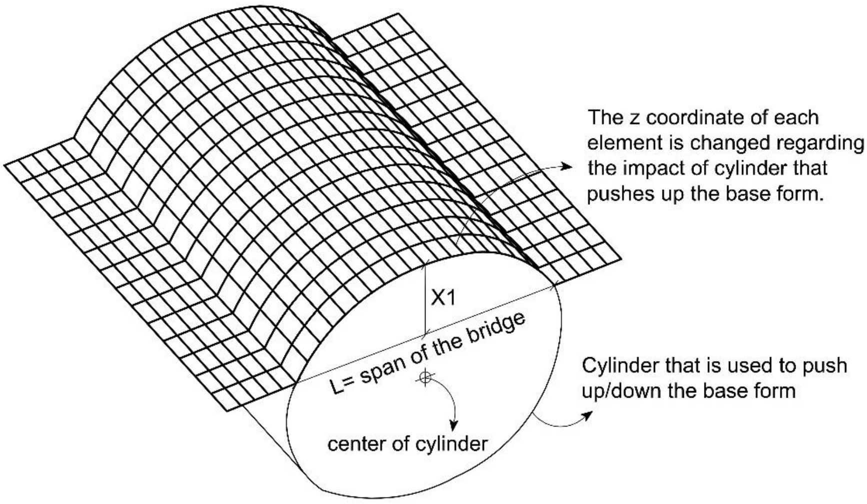


Figure 5: Illustrative example of the circular barrel pellevation with rectangular base.

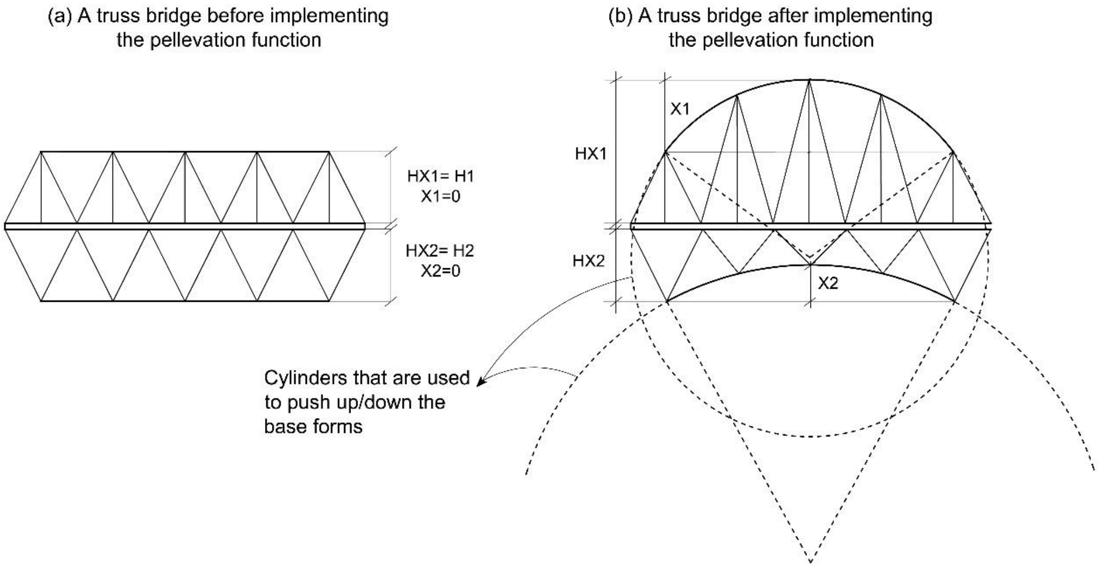


Figure 6: Configuration of a truss bridge before and after implementing pellevation function

3- GENETIC ALGORITHM

Form exploration and *traditional optimization* can both be used in form finding, however, optimization generally is carried out to search for *one* single best solution and exploration seeks *a set* of significantly *different good* solutions. Exploration can be used at the early stages of design to study a wider range of possibilities for reasonably *good* or even *unexpected* solutions. Form exploration usually can be accomplished efficiently using parametric tools. Evolutionary computation methods provide means to search a range of generated solutions in a directed way [1].

Form optimization can be accomplished in different stages. Topology, geometry and determination of member sections. This can take place recursively or all at once. Topology is the highest level at which forms can be explored. An instance of a topology will have a specific geometry which can either be explored in a range under a single topology or linked to differing topologies. Solutions can be sorted in an array which can be inspected visually in a relevantly easy way. Specific solutions of a certain topology and geometry are further composed of members which can be optimized as well, but with which designers usually have less direct interaction in terms of form finding. In this research work, form exploration is accomplished at topology and geometry levels.

A genetic algorithm, originally described by John Holland, is a search method that progresses through iterating cycles to find solutions that meet certain goals [5]. Using mechanisms like recombination and mutation, good solutions may be found which are not anticipated by designers. The solutions which are inherently parametric, are described in terms of a list of variables which are analogous to genes on chromosomes. These chromosomes are bred to form children that inherit characteristics through the genes of their parents.

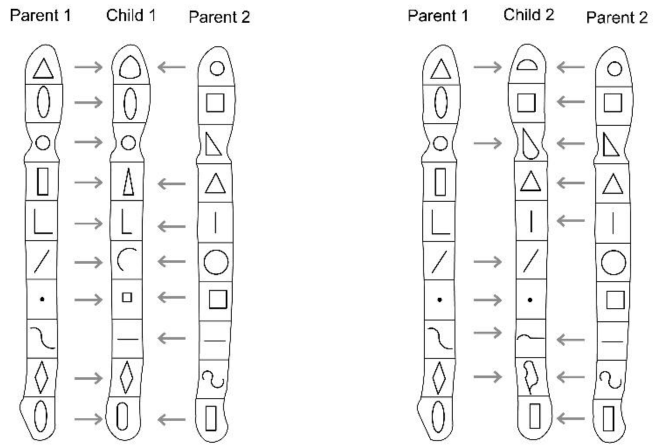


Figure 7: Half Uniform Crossover (HUX): The characteristics of parents 1 and 2 are described in terms of some shapes. The child may inherit some exact characteristics of parent 1 or exactly that of parent 2 or a combination of that of both may emerge through its chromosome.

ParaGen uses a non-conventional genetic algorithm called a Non-Destructive Dynamic Population GA (NDDP GA). It incorporates HUX as described above in the breeding step. ParaGen incorporates the following steps:

1. The problem is described in terms of parametric variables: a chromosome.
2. An initial pool of solutions is generated and stored in a database.
3. A population of parents is dynamically pulled from the full solution pool based on given criteria (the fitness function).
4. Two parents are randomly selected from the population.
5. A child is bred (HUX) from the selected parents.
6. The chromosome (variable values) of the child is translated into a geometric solution.
7. The performance of the solution is evaluated based various simulation software.
8. The resulting performance values along with the parametric values are uploaded to the database. Images are also included and linked to the solution.

Steps 3 through 8 form an iterative cycle which continues until satisficing solutions are found. ParaGen is designed to run using a parallel cluster of PCs linked to a web server through the internet. The solution database and design interface are placed on the web server (the interface is a www site), and steps 3-5 run on that web server. Each child is downloaded to a PC linked to the server simply by connecting to the ParaGen website.

In a traditional GA approach, any defective or poor performing solutions are usually removed from the breeding population (killed off). However, in the NDDP GA all solutions, both well performing and poorly performing solutions are stored in the database. ParaGen simply stores all performance values and defers any ranking of these values to the moment of breeding (thus “dynamic” selection). By retaining data on all solutions, the designer is able to learn from ill solutions and increase the knowledge of what would make a good solutions [6].

Furthermore, in case of any modification of criteria, the poor performing solutions can also be re-considered and re-used in the breeding process to form new solutions.

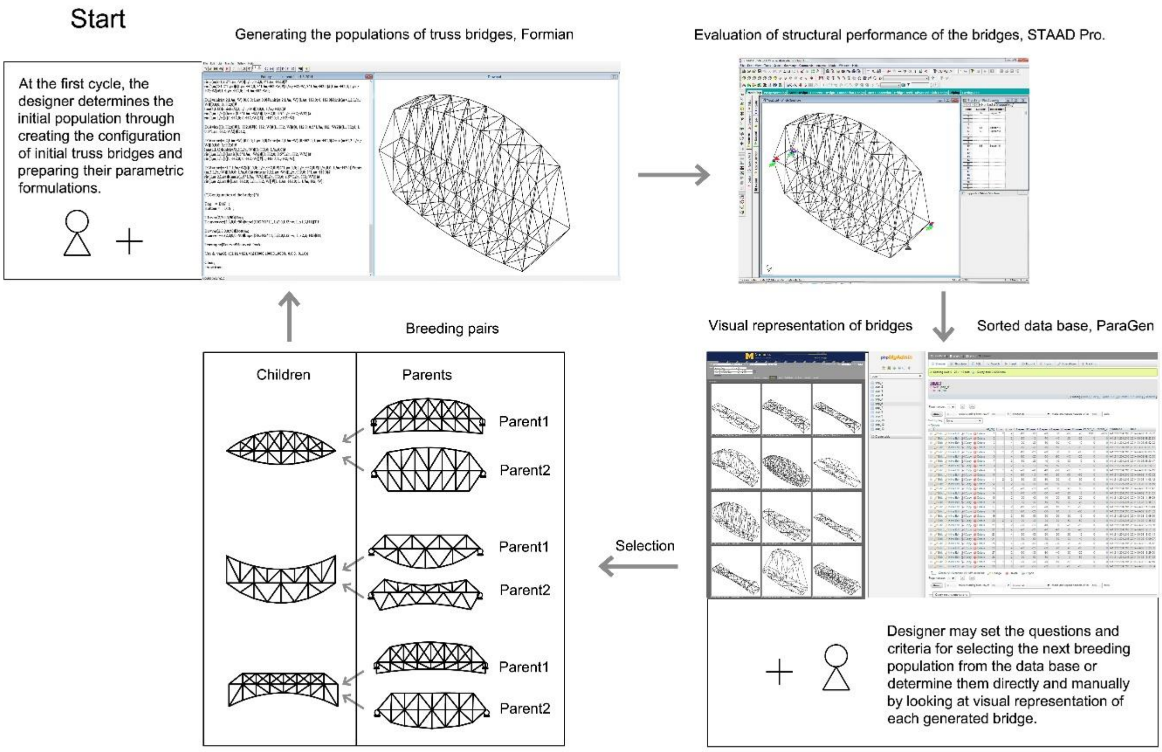


Figure 8: Schematic of the cyclic method of IGDT

ParaGen guided by the multi-objective performance criteria set by the designers, concentrates the generation of new solutions in the area of the solution space defined by the fitness function of the GA, and the focus of the exploration becomes more defined. Within a productive exploration, thousands of solutions are evaluated by the program. The designer uses the ParaGen web interface to filter and sort these solution based on any combination of geometry or performance data. In this way, a well performing set of solutions is defined as a manageable quantity, which is reasonable for the designer to visually inspect and possibly make selections for further breeding. The web interface provides interaction between the designer and the form exploration system which eventually leads to choosing the final desirable solutions. The designer's interaction can be also based on a totally aesthetic preference.

4- FORM EXPLORATION AND OPTIMIZATION PROCESS

This section describes in more detail the 8 step process enumerated in section 3 as the ParaGen method. In step 1. Formian was used to describe a wide range of truss bridge types and geometries. In the parametric formulation, 11 independent variables plus 2 additional values were used - (Total Top Height and Total Bottom Height) which are depended on others, but useful in formulating constraints. These 13 parametric input variables for Formian are listed in table 1.

For this trial, Span was set to 48 m and Width set to 8 m. These 13 variables constituted the "chromosome" description of a solution which is eventually downloaded to Formian for processing into a geometry (step 6). This "chromosome is bred from two parents in step 5 using a GA crossover technique called HUX [7]. The two parents are randomly selected from

a limited population (step 4), which is gleaned from the full database using a SQL query (step 3). This SQL query formulates the search objective or fitness function for the GA.
Once the input variables (the "chromosome") are passed to Formian, Formian processes the variables to produce one instance of the parametric bridge geometry. Formian generates a visual perspective view as well as a numeric DXF description which can be read by other simulation software. In this example a finite element analysis (FEA) was carried out using STAAD.Pro (step 7). The process makes use of scripts written in each software used plus a general Windows interface script (AutoHotkey) to automate the process. Steps 6 and 7 are performed in parallel using a cluster of PCs. At the completion of the analysis, the original input data (the "chromosome") plus all of the associated performance data collected through the simulation software, plus any number of descriptive images and files, are all uploaded to the server through the web site interface (step 8). On the server all numeric data is placed in a database and tagged to the images. The ParaGen web site then offers a graphic window into this database by displaying the images and associated performance values. The ParaGen web interface also allows the designer to sort and filter the displayed images and data in a variety of ways to enhance the exploration of the solution space. Figure 9 shows the query boxes that allow the designer to display different ranges of the solutions. In this example, the solutions which are filtered according to the properties described in Table 2 are displayed. This demonstrates how the website can display a set of solutions for any particular list of requirements and preferences. Finally, any solution can be choosen regarding the designer's preferences.

Table 2: Filtering properties of a series of solutions in ParaGen web - Example 1.

Properties	Desired value
Number of panels	>= 8
Total length of members	=< 2000
Max deflection	=< 10
Total weight	=< 300
Number of joints	=< 180
Total top height	>= 300

In addition to solution displays, the ParaGen website provides graphs in which the designer can compare two specific properties and choose the most desirable solution. Figure 10, shows a graph in which solutions are distributed regarding the maximum deflection and total length of members. For example the designer may look for a solution which has the least maximum deflection and the least total length of members. It is possible to click on the specific chosen solution and find out more detail regarding the other geometrical and structural properties. Figures 11 and 12 illustrate the chosen solution and the diagram of the modal shape. Table 3 shows a sample of detailed information from this same solution.

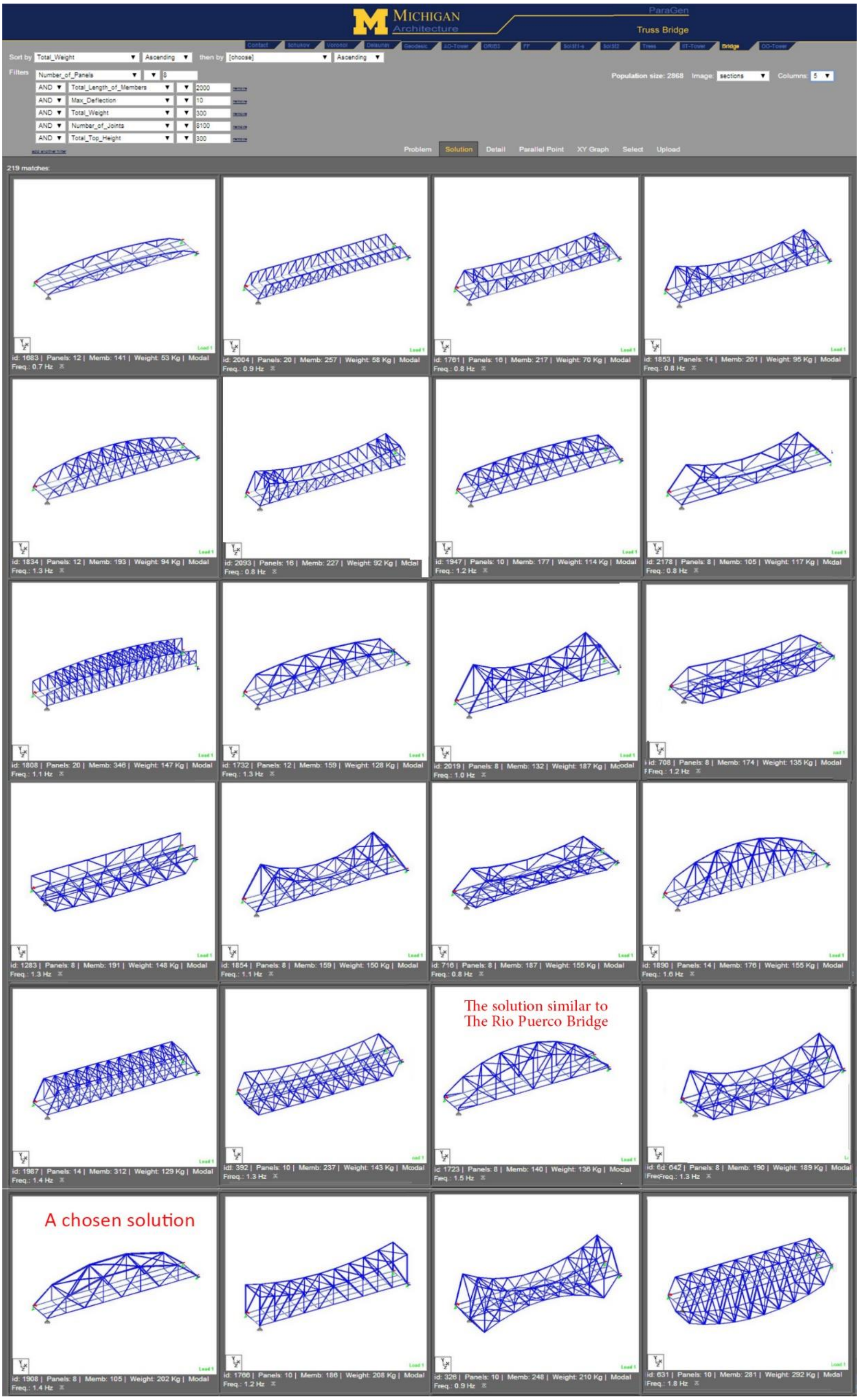


Figure 9: Example 1 – Display of solutions according to the properties of a filter mentioned in table 2.

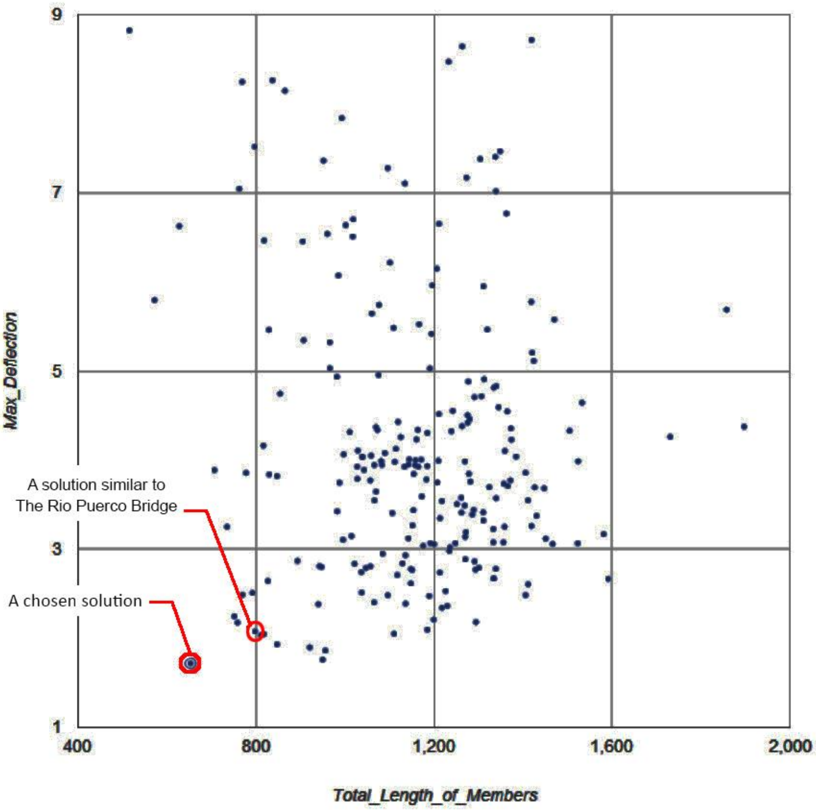


Figure 10: The graph of total length of members versus maximum deflection.

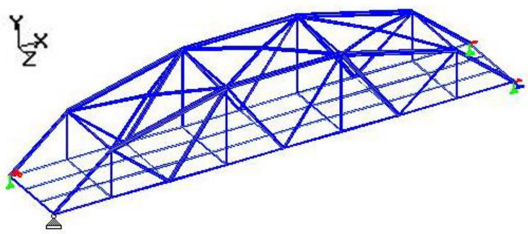


Figure 11: Diagram of truss sections

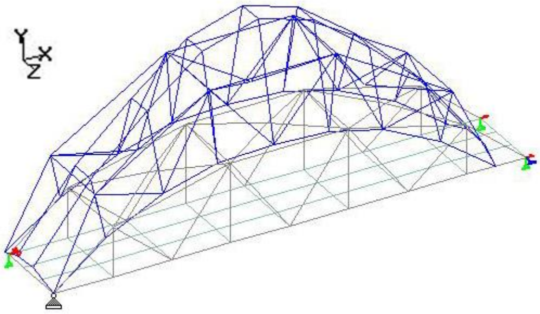


Figure 12: diagram of modal shape

Table 3: Geometrical and structural properties of a chosen solution – Example 1

Properties	Value	Properties	Value
ID_tag	1908	Number of Panels	8
Span	4800 cm	Top Truss Pattern	9
Width	798 cm	Bottom Truss Pattern	0
Height of Top Base Truss	219 cm	Total Top Height	847 cm
Height of Bottom Base Truss	0 cm	Total Bottom Height	0 cm
Top Rise	628 cm	Parent_1	0
Bottom Rise	0 cm	Parent_2	0
Number of Joints	47	Number of Members	105
Longest Length Member	12.38 cm	Weight/ Deflection	3.47
Total Length of Members	653.08 cm	Modal Frequency	1.43 Hz
Top Curvature Sign	1 = upward +	Total Weight	202.02 Kg
Bottom Curvature Sign	0 = no curve	Max Deflection	1.718 cm

Figure 13: The Rio Puerco Bridge, located on U.S. Route 66, with a 76m span across the Rio Puerco River, 1933. Photo by Alex Tucker

Figure 14: The Liberty Bridge, Pittsburg, US, built between 1926 and 1928, with a span of 811 m. Photo by Mark Yashinsky.

The other example shown in figures 15 to 17 indicates that filtering and sorting can be carried out differently with some other properties that are presented in table 4.

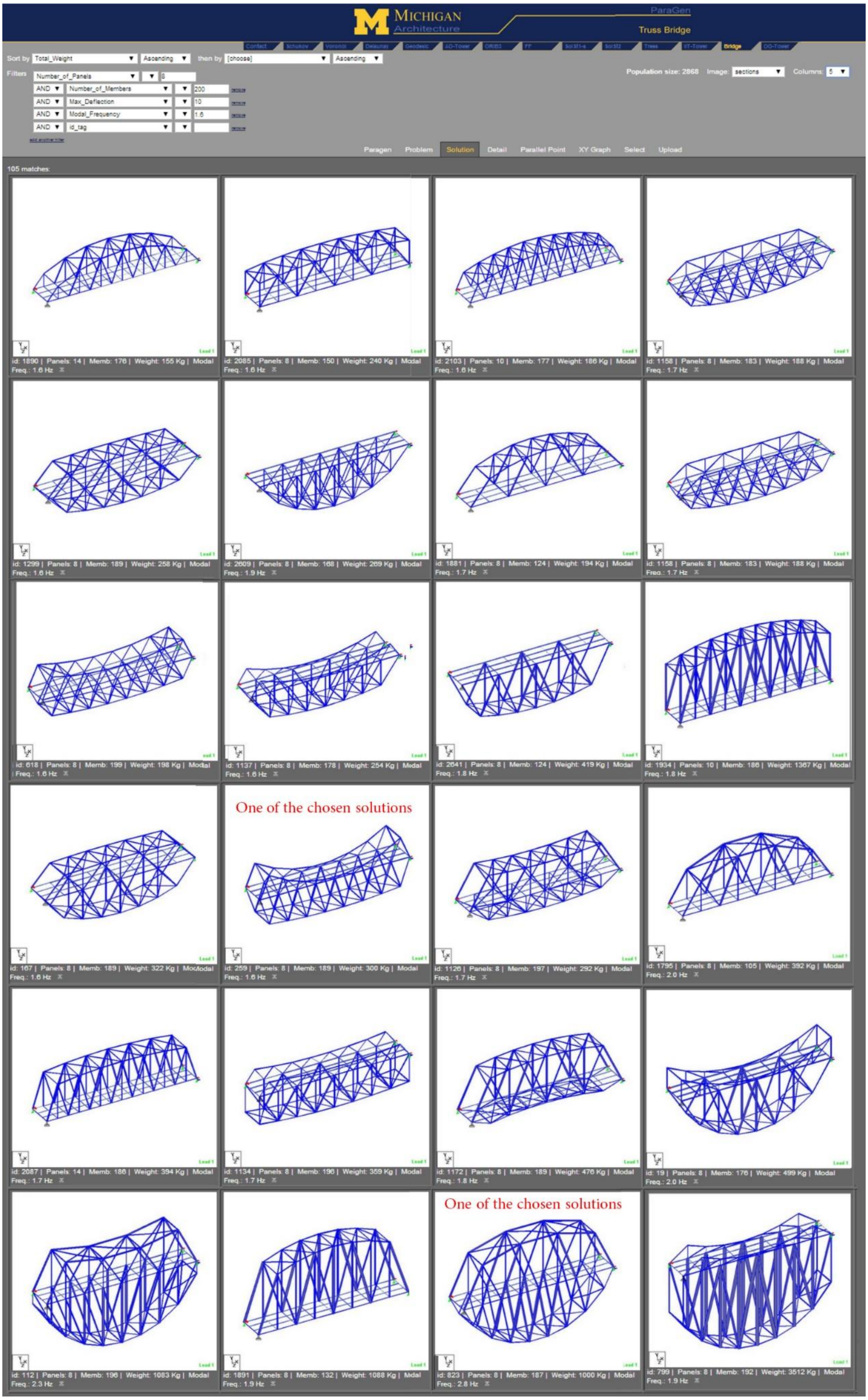


Figure 15: Example 2 – Display of solutions according to the properties of a filter mentioned in table 3.

Table 4: Filtering properties of a series of solutions in ParaGen web - Example 2.

Properties	Acceptable value
Number of panels	>= 8
Number of members	=< 200
Max deflection	=< 10
Modal frequency	>= 1.6

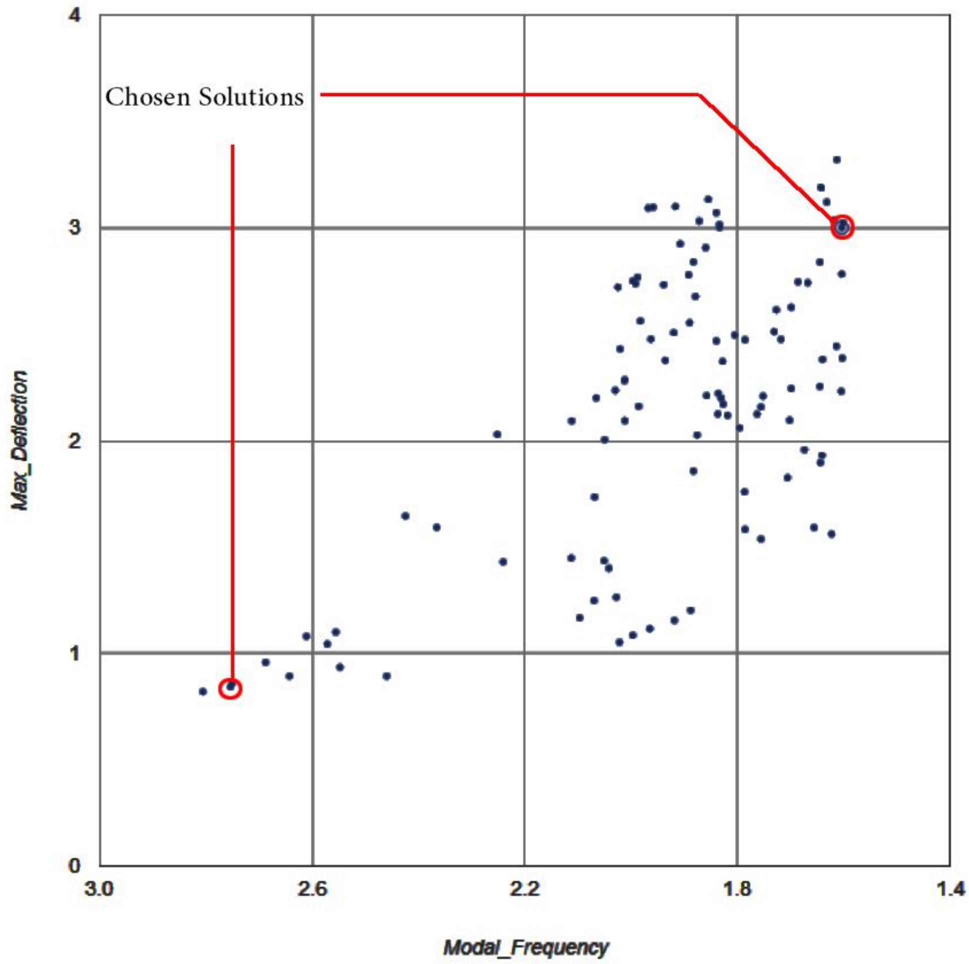
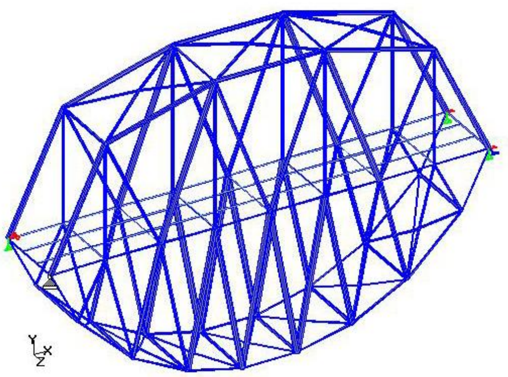


Figure 16: The graph of modal frequency versus maximum deflection.



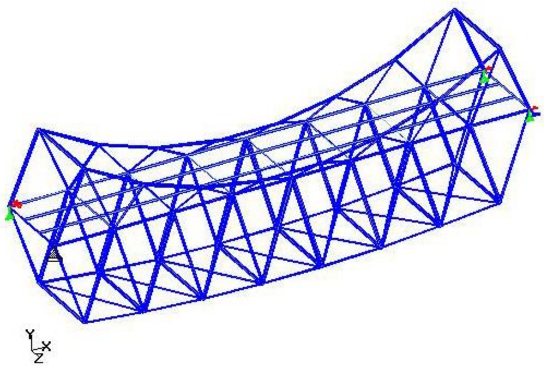


Figure 17: A solution with 0.858 cm maximum deflection and 2.751 Hz modal frequency.

Figure 18: A solution with 3.001 cm maximum deflection and 1.064 Hz modal frequency.

5- PHYSICAL MODELING

The physical modeling and testing of truss bridges was carried out in the context of a structures course at University of Michigan, School of Architecture. Groups of students were asked to make a 1/64 scale model of a bridge using balsa wood, and to the best of their knowledge choose a suitable geometrical pattern to reach a high strength-to-weight ratio. The variables in this exercise are the number of elements, the truss patterns, the number of joints, the number of truss panels and the height of the trusses.

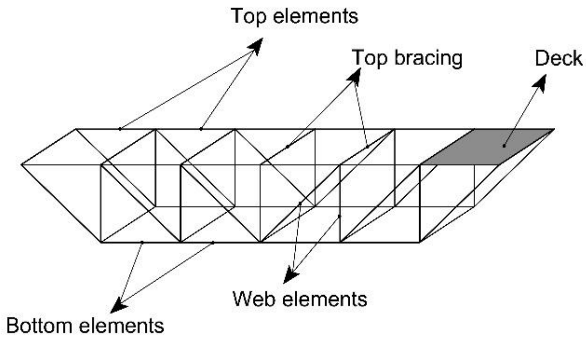


Figure 19: Different parts of a typical model of a truss bridge

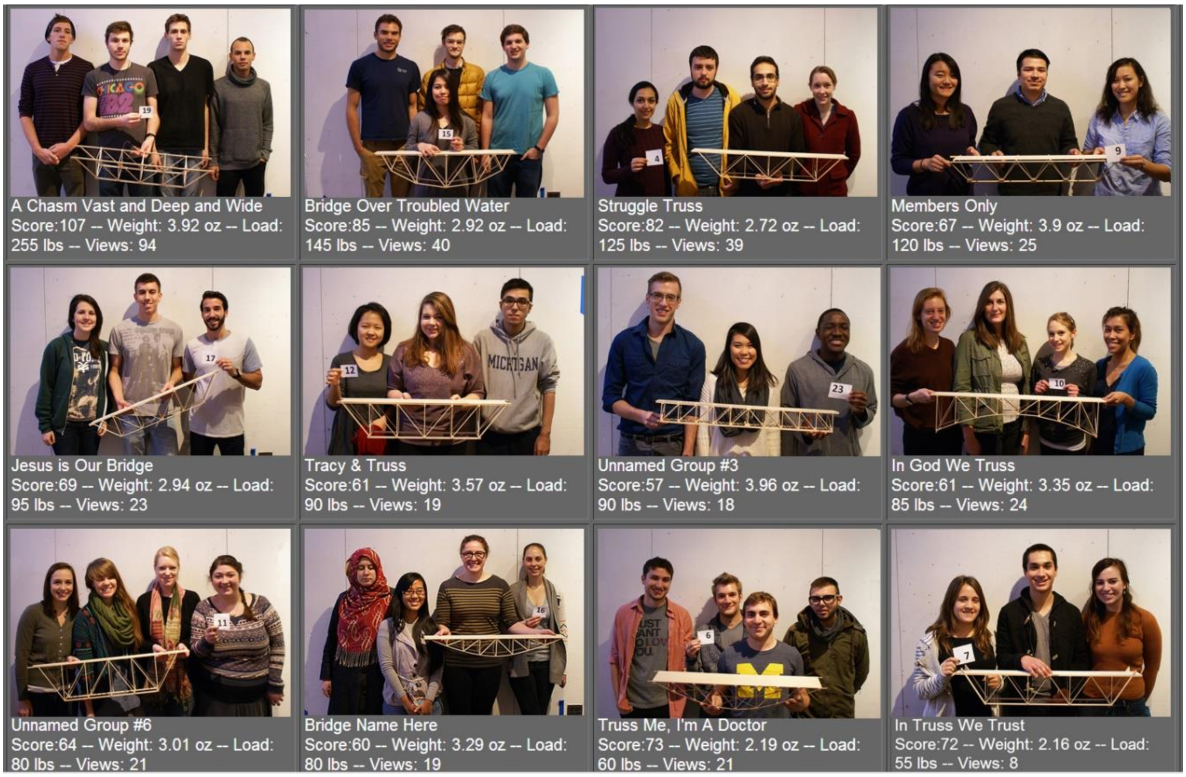


Figure 20: Some of the physical models of the bridge trusses that groups of students made of wood **[8]**

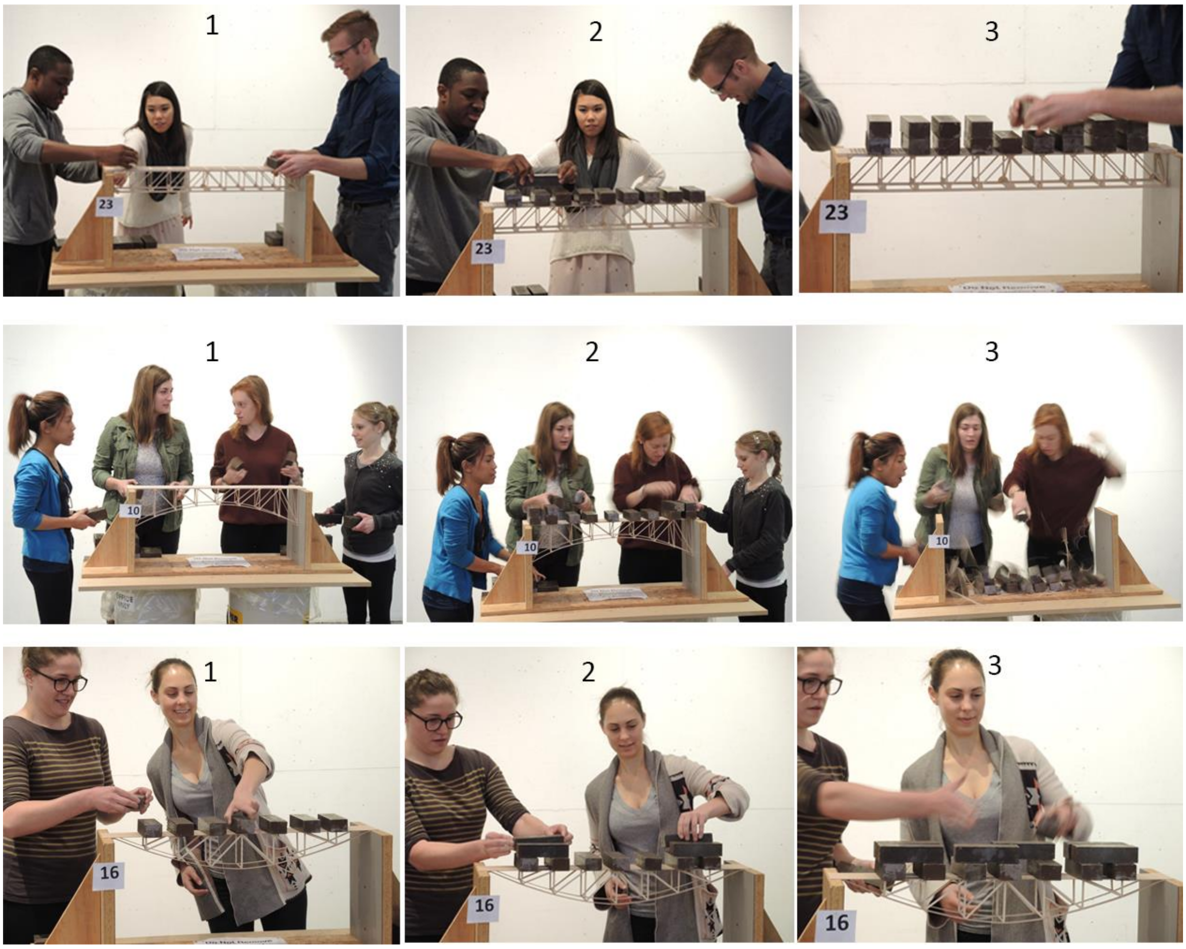


Figure 21: Testing the bridge models by loading them with steel weights **[8]**

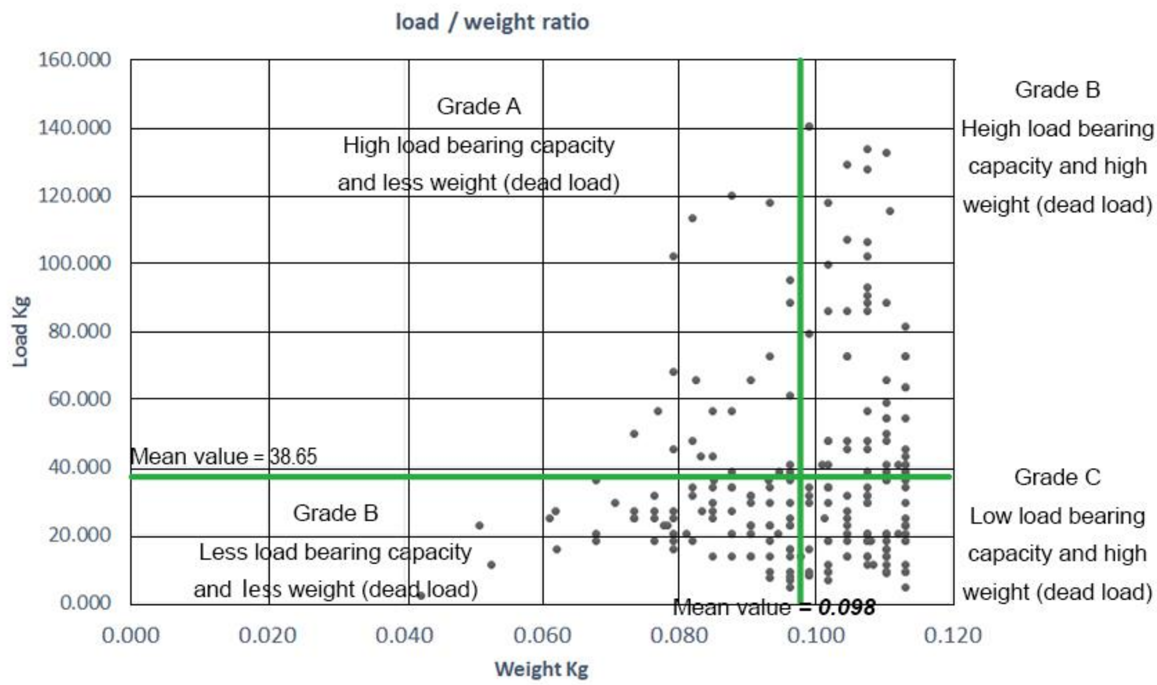


Figure 22: A plot of held load/ weight of the bridge models

Then, the models were loaded until the breakage point and the structural performance was presented in terms of weight to load capacity ratio (see table 5). The 217 models considered in this paper were tested and their strength-to-weight ratio recorded. The mean value of load capacity of models is 38.65 kg and their mean dead loads are equal to 98 gr. Regarding these two values, three grade levels can be defined, see figure 22. Grade A refers to each model with a load bearing capacity more than the average value and an amount of weight that is less than the respective mean which are the most desirable characteristics. Grade B indicates those models which either have high load bearing capacities or lighter weights. Grade C represents less desirable models that have high weight and low load bearing capacity.

Table 5: The specifications of some of the models that have an A grade

ID	Weight (kg)	Load (kg)	# elements	# joints	# panels	Height/Span
1029	0.088	120.178	74	32	8	[0, 0.10] *
1124	0.093	117.910	50	26	5	[0, 0.13]
1020	0.082	113.375	96	44	8	[0, 0.17]
1103	0.096	95.235	106	44	11	[0, 0.18]
1025	0.096	88.433	98	50	9	[0, 0.11]
1127	0.093	72.560	74	32	8	[0, 0.25]
1230	0.079	68.025	54	24	6	[0, 0.17]
1315	0.083	65.758	58	24	6	[0, 0.25]
914	0.091	65.758	90	44	12	0.15
1004	0.096	61.223	118	58	9	[0, 0.136]
1304	0.077	56.688	54	24	6	0.17
1109	0.085	56.688	118	46	8	[0, 0.25]
1034	0.088	56.688	104	44	10	0.1
1012	0.074	49.885	1046	80	14	[0, 0.21]

* The interval indicates on curved trusses whose height vary from 0 to a maximum rise.

Correlating the specifications of the yield results, following points can be concluded (see table 5):

- Those models which have curvature at top or bottom or at both parts perform better than those trusses that follow a non-curved pattern;
- The quality of construction, such as applied material or techniques used to build the joints, may influence the models' performance, and this may limit the designers' perspective in the form finding process;
- The pace and action of loading the bridges also has an effect on the experiment. Thus, some geometrically similar bridges perform differently;
- On one hand, the materials that can be practically used to do physical modeling by students are limited, and on the other hand, it may not make sense to use the actual construction material like steel in the form finding process. This may lead the study to inaccurate or different conclusions;
- Making 217 models consumes time and requires number of individuals to be involved. This may prevent the design team exploring diverse possibilities;
- Using physical modeling makes the form finding process more tangible and comprehensible. Therefore, in spite of all mentioned constrains, sometimes it helps

the designer to gain a firsthand sense of structural performance obtainable through such physical experiments.

6- CONCLUSION

According to the two different procedures of form exploration, the physical and digital procedures, their strengths and weaknesses are briefly described in table 6.

Table 6: Strengths and weaknesses of two different form exploration techniques

	Form exploration using physical modeling	Dynamic configuration processing and evolutionary optimization
Strengths	1- The process is comprehensible for most of the designers since they can have a close and direct interaction with the structural performance of the models. 2- The procedure isn’t limited to certain software or doesn’t require to use a specific license. 3- The procedure of model making doesn’t require a certain knowledge in structure or programming field.	1- The pool of solutions provides more than a thousand forms with different topology, geometrical and structural properties and the results are not limited to a single best solution. 2- Considering the number of solutions that are provided, this procedure is relevantly time efficient. 3- The actual materials, supports, joints and other properties can be considered through the process and the outcomes of the form exploration yield suitable and explicit information about the structural performance of the forms. 4- Visual displays of solutions allow the designer to have an appropriate interaction within the procedure and choose the final solution regarding personal preferences and concerns. 5- The designer can determine different fitness functions and sets of filtering to obtain the desired solutions. 6- Diverse graphs can be provided to assist the designer comparing the certain properties within an array of solutions.
Weaknesses	1- The processes requires time and number of individuals to be involved with the model making. The cost of model making should also be considered. 2- The actual materials usually can’t be used through the process. 3- Number of different models that can be made are relevantly limited. 4- The construction quality (eg. materials and method used to make the joints) and the pace and action of loading impact the performance of the models. 5- Form exploration should definitely be accompanied with precise structural analysis to obtain the numerical values of the properties.	1- Running the form exploration cycle requires certain knowledge in programming and working with some specific software. 2- License requirements and the availability of the software may be an issue. 3- Some bugs and problems with the compatibility of each used software may cause errors. 4- Certain digital facilities and machines are required to accomplish the study.

Ultimately, using a dynamic process of form generation and optimization expands the designer's perspective in form exploration, though it requires certain knowledge, skills and facilities. In cases of professional projects where multiple purposes like aesthetic issues, stability, costs and construction requirements should be considered, this form exploration technique seems more helpful. In contrast, although physical modeling has its own limitations in professional area, it provides some advantages in pedagogical practices.

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