Proceedings of the IASS-SLTE 2014 Symposium
"Shells, Membranes and Spatial Structures: Footprints"
15 to 19 September 2014, Brasilia, Brazil
Reyolando M.L.R.F. BRASIL and Ruy M.O. PAULETTI (eds.)

Form Exploration and GA-Based Optimization of Lattice Towers Comparing with Shukhov Water Tower

A. KHODADADI*, P. VON BUELOW[a]

*University of Michigan
2000 Bonisteel Blvd. Ann Arbor, Michigan
anahitak@umich.edu

[a] University of Michigan

Abstract

The main objective of this research is to develop a form exploration technique based on parametric form generation using concepts of Formex algebra and evolutionary optimization based on ParaGen approach [1]. Accordingly, the design process of the lattice towers with polygon bases is studied. The focus of this research is to demonstrate the ability of a computational form-finding method in multi-objective design, and to offer arrays of comparable good solutions instead of a single "optimal" form. In addition, the Shukhov water tower is considered in order to draw a comparison between the results of the presented form finding technique and a well known successful design.

First, different tower configurations are described through geometrical concepts of Formex algebra [2]. Formex algebra is a mathematical system that allows the designer to define geometrical formulation of forms. The geometrical parameters used in formulations are the base shape of the towers, frequency of elements along the height of the tower, diameter of bottom base and the mesh patterns. The constant parameters, such as the height of the tower and diameter of the top are set to match the values of the Shukhov water tower.

Then, the ParaGen framework uses a non-destructive, dynamic population GA (NDDP GA) to fill a database with solutions linked to a variety of performance characteristics [1]. The database of solutions can then be explored for any single or multi-objective performance criteria. Because the solutions are linked to descriptive images, the exploration process takes place at both a visual qualitative level as well as a performance driven quantitative level. For the purpose of comparison, the properties of A-36 structural steel pipe sections are used. Using STAAD.Pro (Bentley Systems) for the analysis, it was also possible to size all members using AISC steel code as well as collect additional performance parameters such as deflection and modal frequency.

At last, results are entered into a SQL database which is linked to visual images of the designs. This allows for the comparison of designs both visually and using quantitative data. Pareto front graphs were produced based on the computational study, and the best performing results are plotted on these graphs in which the Shukhov water tower is also located for comparison. In conclusion, the strengths and concerns of applying the proposed method are also discussed, and it is explained 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, Lattice Towers

1. Introduction

Designing a form is broadly considered as a creative and purposeful procedure. In structural design usually some concerns are defined in terms of parameters such as topology or geometry of the structural form, material properties and load cases. Then, it is tried to achieve the best solution(s) that can meet the requirements. Within this process of design and optimization two main challenges may be raised. First, there are multiple criteria through the procedure which make the decision making more complicated. Second, using a trial-and-error method to seek one single best solution demands a huge amount of time and effort, and at last it may decline the designer's tendency to explore all the possibilities. Hence, in order to expand the designer's perspective,

Copyright © 2014 by the authors.
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

facilitate modifications of the forms and explore more possibilities of appropriate solutions in the early stages of design, the combination of parametric form generation and evolutionary optimization techniques can be applied [3].

In this paper, the topology of some lattice tapered towers are explored and an array of optimized solutions are obtained. The towers are geometrically and structurally compared to Shukhov's water tower built in 1896 for the All-Russian Exposition, in Nizhny Novgorod, Russia. Thus, the height and the top base diameter of the towers are determined to be 37 m and 8 m respectively, as the same values as that of Shukhov. The other variable parameters which are to define the topology of the towers are shown in Fig. 1 and listed in Fig. 2.

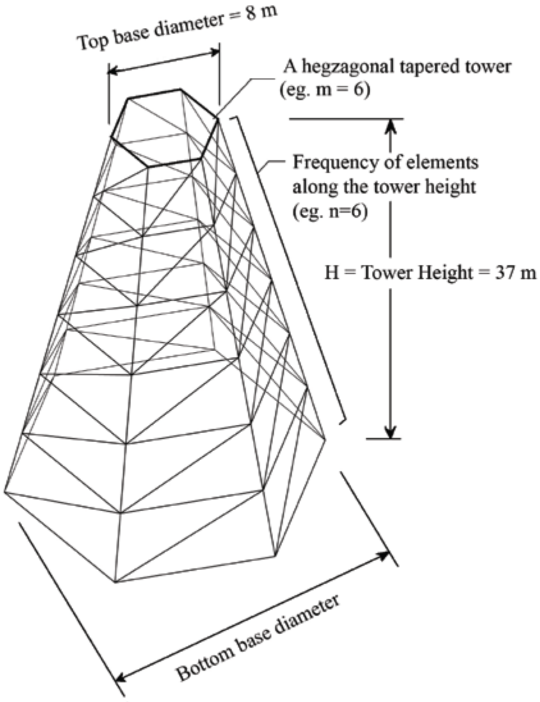

Figure 1: A typical form of the lattice towers that are to be explored and its geometrical parameters.

Parameters	Symbol	Constant/Variable	Acceptable interval/ value
The height of the tower	H	Constant	37 m
The top diameter	D1	Constant	8 m
The bottom diameter	D	Variable	[8, 24] m
Frequency of elements along the height of the tower.	n	Variable	[4, 37] m
Number of sides of the tower polygonal base	m	Variable	[3, 12]
Pattern of the towers	Top	Variable	D1, D2, D3, D4, D5, D6, D7, D8

Figure 2: Geometrical parameters on which the configuration processing of the lattice tapered towers are based.

In this paper, first, the geometrical configuration processing of the towers is described through the concepts of Formex algebra and using Formian programming software [2]. Having processed the topology of the towers, the DXF file of a tower is sent to STAAD.Pro. for structural analyses and evaluation. The obtained structural data and graphic depictions are stored in a database which is linked to a visual exploration interface. In the next step pairs of towers are selected regarding the design objectives to breed further solutions. The new generations of towers are produced within the iteration of these steps 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 Fig. 6. Finally, the series of suitable solutions are presented through which the designer can chose the desirable ones regarding their structural performance, visual appearance.

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

2- Formex configuration processing of the lattice tapered towers

The configuration processing of towers is described through geometrical concepts of Formex algebra. 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 [4]. The creation of any type of spatial structures, such as space trusses, domes, vaults, hyperbolic forms, polyhedric and free forms, can be carried out by using this mathematical system and its associated programming language Formian.

Having determined constant parameters, variables and also their acceptable intervals (Fig. 2 and 3), the Formex formulations can be defined using a cylindrical coordinate system, (Fig. 4) [2]. For more information about the cylindrical coordinate system and how to define the tower elements with appropriate configuration of lines, see Nooshin et al, 2001. Additionally, sketches of patterns used in designing the towers, illustrated in Fig. 3, are provided to assist the designer choosing the desired pattern more conveniently. 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.

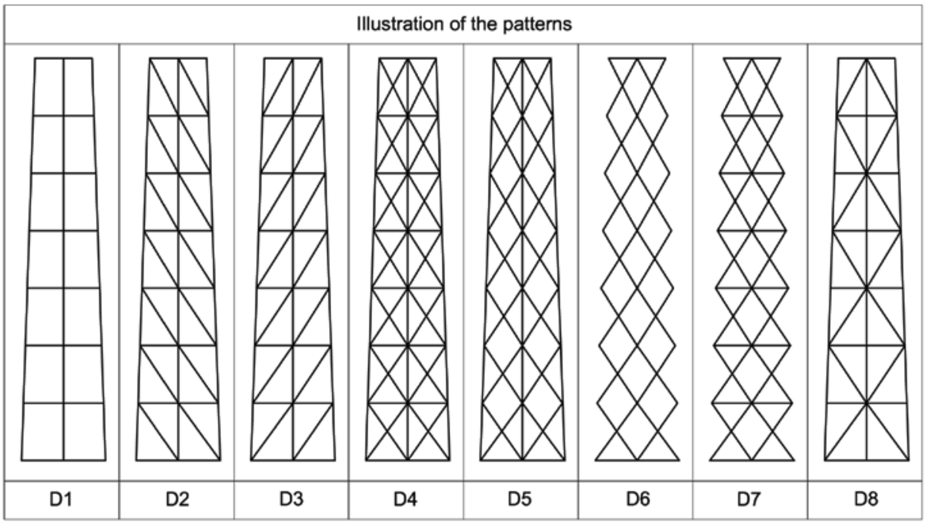

Figure 3: The patterns that are used in designing the lattice tapered towers

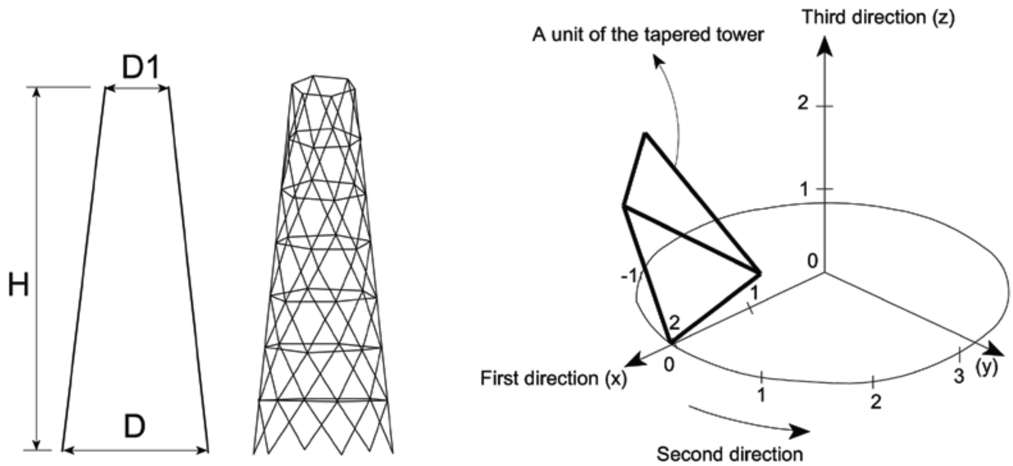

Figure 4: The cylindrical reference system used to define the configurations of the lattice towers [2]

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

3- Genetic Algorithm

Form exploration and *traditional optimization* can both be used in form finding, however, optimization generally is carried out to search *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 [3].

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 (see Fig. 5).

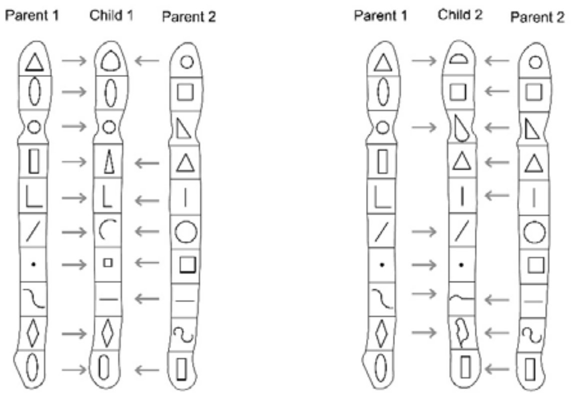

Figure 5: Half Uniform Crossover (HUX): The characteristics of parents 1 and 2 are described in terms of some shapes. The child may inherit some exact characteristics of parent 1 or exactly that of parent 2 or a combination of that of both may emerge through its chromosome.

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.

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 solution pool.
4. Two parents are randomly chosen from the population.
5. A child is bred (HUX) from the 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 and a web server. The solution database and design interface is placed on the web server (the interface is a www site) and steps 3-5 (the GA) are likewise a program

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

on that server. Each child is downloaded to a PCs linked to the server simply by connecting to the ParaGen website (see Fig. 6).

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 rating of these values to the designer. 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 of form of new solutions.

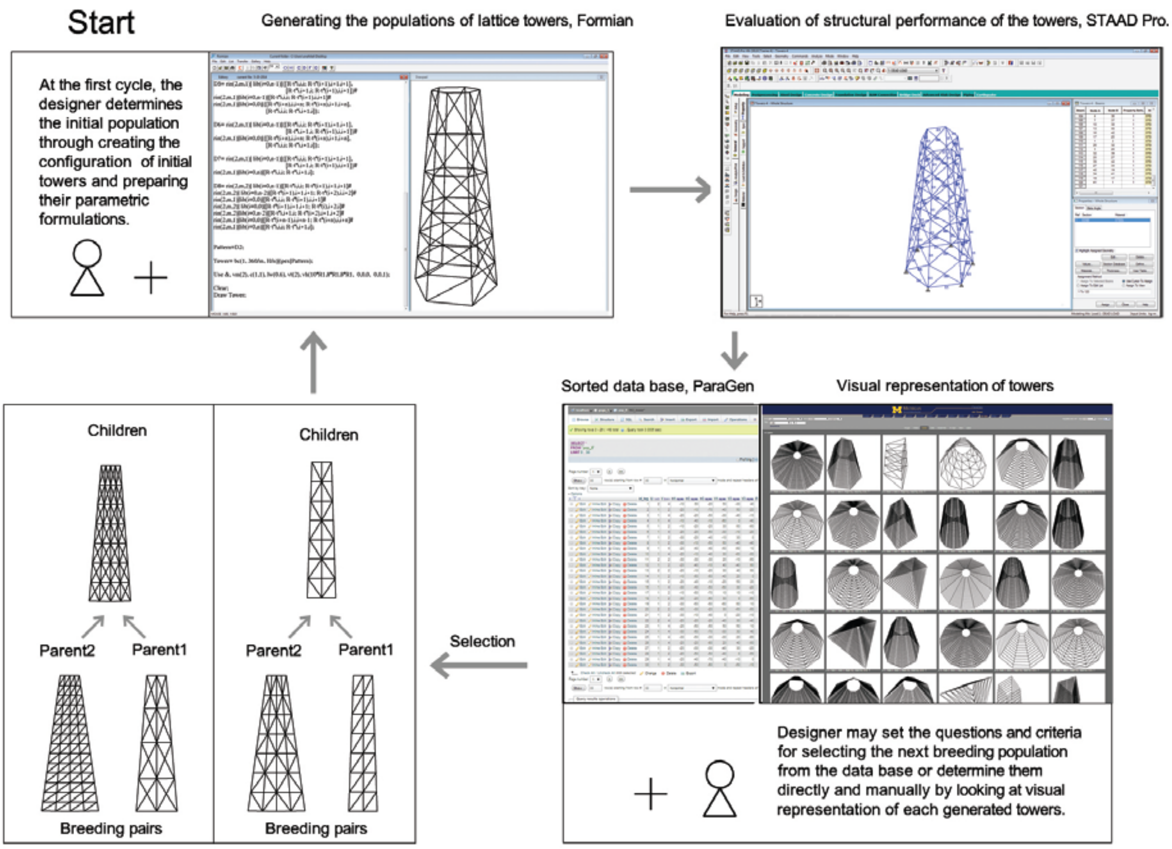

Figure 6: Schematic of the cyclic method of IGDT

ParaGen guided by the multi-objective performance criteria set by the designers, concentrates 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 choose the final desirable solutions. The designer's interaction can be also based on a totally aesthetic reasons.

4- Form Exploration and Optimization Process

This section describes in more detail the 8 step process enumerated in section 2 as the ParaGen method. In step 1, Formian was used to describe the geometry of a wide range of lattice tapered towers. In the parametric formulation, 4 independent variables are used, (see Fig. 2).

For this trial, height of the tower was set to 37 m and top base diameter set to 8 m. The 4 variables constituted the "chromosome" description of a solution which is eventually downloaded to Formian for processing into a

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

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 tower 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 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 website 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 7: Shukhov Water Tower, Polibino, photo by Arssenev

In this study, the Shukhov water tower is set as the design target to determine the fitness function and filtering combinations. The first series of solutions have the geometrical properties which seem to be more suitable than that of design target. Fig. 8 shows the query boxes that allow the designer to survey different ranges of the solutions which are filtered according to the geometrical properties displayed in Fig. 9.

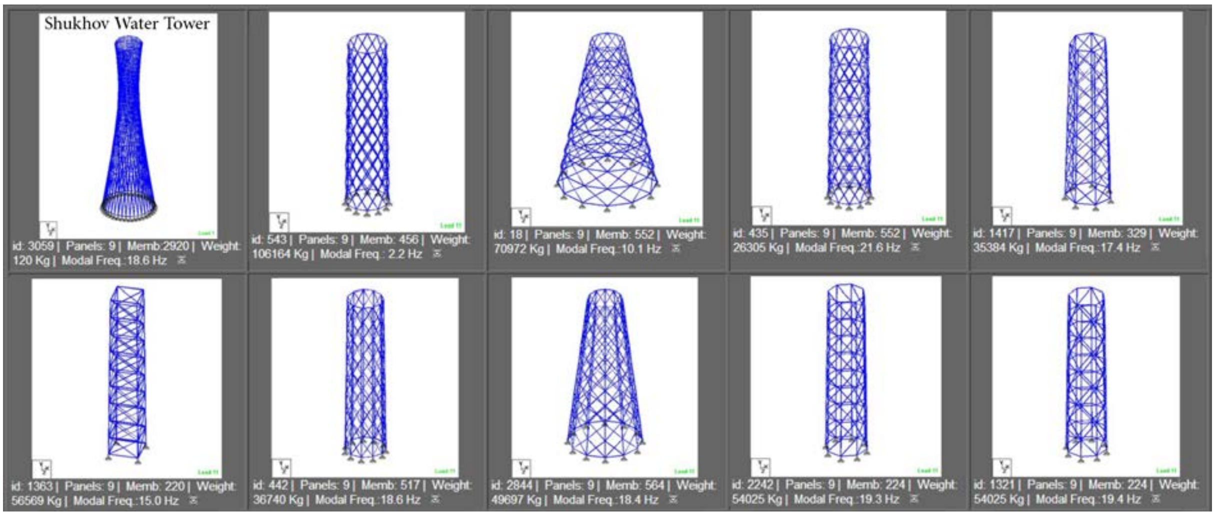

Figure. 8: ParaGen display of solutions filtered for better geometrical properties comparing to the Shukhov water tower mentioned in Fig. 9.

Properties	Acceptable value
Height section	= 9
Diameter of the base	> 8 m
Number of joints	=< 1000
Total weight	=< 120000 Kg

Figure 9: Filtering properties of solutions in ParaGen interface which have properties similar to the Shukhov water tower.

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

Additionally, the ParaGen website provides graphs in which the designer can compare two specific properties and choose the most desirable solution. Fig. 10, shows a graph in which solutions are distributed regarding the number of joints and the total weight. In this graph the points represent the solutions that have different properties and the designer may choose one of them regarding the personal preference or other criteria. This figure also indicates that although Shukhov water tower is significantly light, there are 920 joints that make the tower more labor intensive to construct. Other fabrication considerations such as required joint fixity can be quickly observed and taken into consideration by viewing the solution images. In this way trade-offs can be made regarding the various parameters. Graphs can be easily created for any geometric or performance values and limited to show any desired range of solutions.

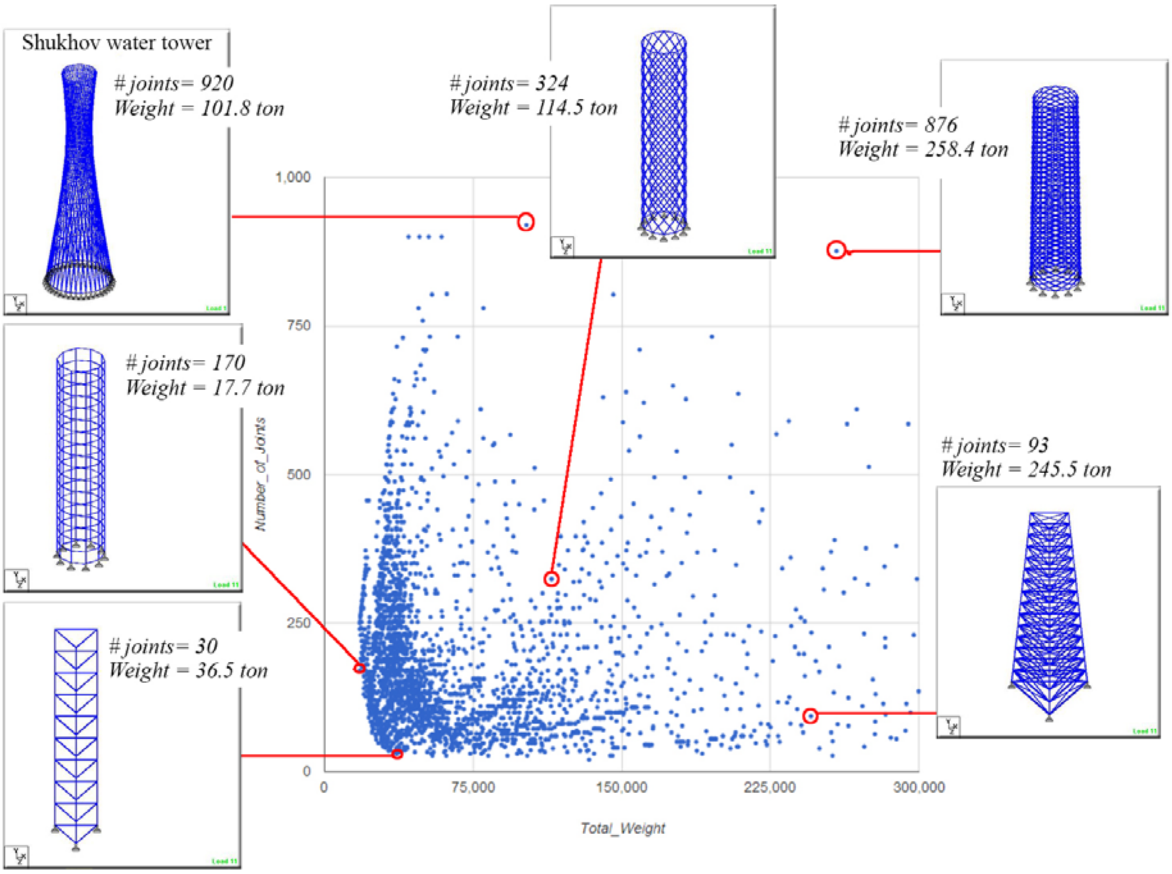

Figure 10: A graph that illustrate the number of joints vs. total weight of the solutions.

5- Conclusion

Coupling the Formex configuration processing and evolutionary optimization based on ParaGen concept has the following advantages:

1- It can expand the designers perspective by providing number of suitable solutions 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- Explicit structural data about the performance of each solution is provided;
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.

Using this method requires certain knowledge, skills and facilities and brings some concerns such as:

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;

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.

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.

However, 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.

References

[1] von Buelow, P., ParaGen: Performative Exploration of Generative Systems. *Journal of the International Association for Shell and Spatial Structures,* 53(4), 2012, 271-284.

[2] Nooshin, H. & Disney, P., Formex Configuration Processing II. *International Journal of Space Structures,* 16(1), 2001, 1-56.

[3] von Buelow, P., *Genetically Engineered Architecture: design exploration with evolutionary computation.* Saarbrücken: VDM Verlag Dr. Mueller e.K., 2007.

[4] Nooshin, H., Disney, P. L. & Champion, O. C., Computer-Aided Processing of Polyhedric Configurations. In: J. F. Gabriel, ed. *Beyand the Cube: The Architecture of Space Frames and Polyhedra.* New York, Chichester, Weinheim, Brisbane, Singapore, Toronto: John Wiley & Sons, Inc., 1997, 343-384.

[5] Holland, J. H., *Adaptation in Natural and Artificial Systems.* Ann Arbor: The University of Michigan Press, 1975.

[6] von Buelow, P., *Techniques for more Productive Genetic Design: Exploration with GAs using Non-Destructive Dynamic Populations.* Cambridge, Ontario, Canada, s.n., 2013, 24-26.

[7] von Buelow, P., *Improving Generative Design through Selective Breeding.* Poland, s.n., 2013.

Copyright © 2014 by the author(s).
Published by the International Association for Shell and Spatial Structures (IASS) with permission.