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Article *in* Journal of the International Association for Shell and Spatial Structures · December 2009

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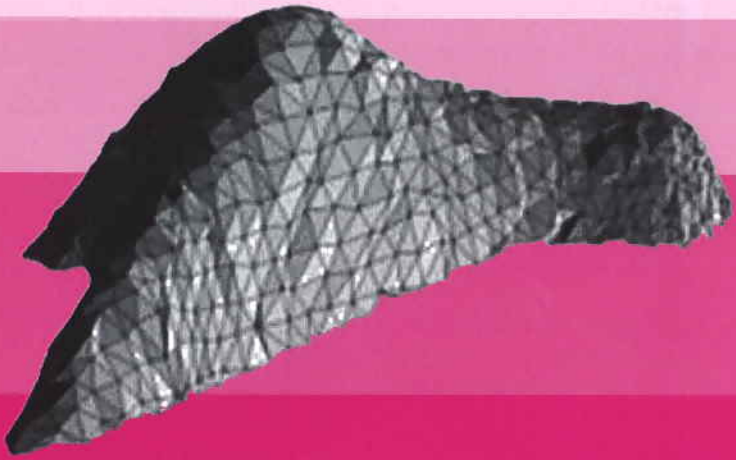

Vol. 50 (2009) No. 3

December n. 162

ISSN: 1028-365X

Journal

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COVER: *Photo from paper by P. Basso, A. E. Del Grosso, A. Pugnale and M. Sassone*

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SODEGRAF ISSN: 1028-365X Depósito legal: M. 1444-1960

JOURNAL OF THE INTERNATIONAL ASSOCIATION FOR SHELL AND SPATIAL STRUCTURES: **J. IASS**

COMPUTATIONAL MORPHOGENESIS IN ARCHITECTURE: COST OPTIMIZATION OF FREE-FORM GRID SHELLS

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Editor's Note: The first author of this paper is one of the four winners of the 2009 Hangai Prize, awarded for outstanding papers that are submitted for presentation and publication at the annual IASS Symposium by younger members of the Association (under 30 years old). It is re-published here with permission of the editors of the proceedings of the IASS 2009 Symposium: "Evolution and Trends in Design, Analysis and Construction of Shell and Spatial Structures" held in October 2009 in Valencia, Spain.

ABSTRACT

The optimization problem related to the tessellation of free-form grid shells is presented in this paper. This kind of structure is generally composed of a supporting grid that defines the geometry of a large number of cladding elements that are always different from each other. From the construction point of view this means that each single piece needs to be designed and produced "ad hoc", then marked and positioned with the aid of an assembling table. In order to reduce the heterogeneity of grid shell elements, several optimization strategies, referring both to evolutionary and gradient-based techniques, have been tested and compared. All the free-form geometries are defined and handled with a commercial NURBS based software, while the development of all the optimization procedures has been made thanks to the VB based programming language implemented inside the NURBS based software. Due to the smoothness of the solution domain of this specific problem, gradient based procedures seem to be the most efficient for the rapid convergence to the optimal solution. Finally a multi-objective procedure, that involves static analysis combined with the discussed geometrical optimization, is proposed in view of future developments.

Keywords: *computational morphogenesis, form finding, multi-objective optimization, cost optimization, grid shells, genetic algorithms, force density method.*

1. INTRODUCTION

The development of CAD-CAM applications and their widespread diffusion in architecture is changing the traditional relationship between design and construction, from two different points of view. First, architectural construction relies more and more on the industrial production of components and elements, which are merely assembled on the building site. Secondly, a large set of problems, related to manufacturing and assembling, need to be dealt with almost completely at the design stage. The manufacturing and industrial production of elements then become a part of the design process.

Back in 2004, a series of projects, based on this new trend, were grouped together at the Centre Pompidou in Paris under the name "Architectures non standard" [1]. The heterogeneity of the proposals ranged from the alteration of all the compositional, static and constructive principles to the total dematerialization to obtain a virtual architecture, the so called "Trans-architecture" of Marcos Novak. However, other designers did not restrict themselves to using commercial software, they customized it in order to create suitable tools to solve specific problems.

In short, on one hand information technology allows designers to develop their formal expression, leading to the "blob" as the extreme reference of their thinking, but, on the other hand, the solution of new problems connected to free-forms is approached by creating new shape generation and optimization tools which are developed "ad hoc".

1.1 Free-form grid shells

The development of computer technologies has played an important role in the conceptual design of grid shell structures, a constructive typology that was initially studied and developed by engineers mainly from the constructive point of view (Schlaich and Shober [2]) in order to improve structural efficiency. In the last few years, many designers, stimulated by the potential of new parametric design tools capable of handling free-form surfaces, have gradually replaced regular shapes with more complex geometries, generating a set of new problems related to the constructive rationality of these structures.

The long covering for the trade fair in Milan (2005) and the roof structure for the MyZeil shopping centre in Frankfurt (2009, Figure 1), both designed by the Italian architect M. Fuksas, the Docks de Paris project by Jakob and MacFarlane (2009), the Bmw Museum in Munich designed by Coop Himmelb(l)au (2007) and the roof structure for the Cour Visconti at the Louvre Museum in Paris, designed in 2005 by Bellini and Ricciotti, are all examples of this new interest in free-form grid shells. In these cases, structural elements, which are always different from each other, might be optimized from the constructive point of view in order to obtain a limited number of pieces, avoiding the risk of dealing with a puzzle of numbered parts on the building site. Even though, in the case of cladding glass plates, a limited typology of elements may not be a decisive requirement, due to the computer-aided manufacturing processes known as mass customization, it becomes dramatically important when more complex materials or devices are used such as photovoltaic panels or dynamic shading systems.

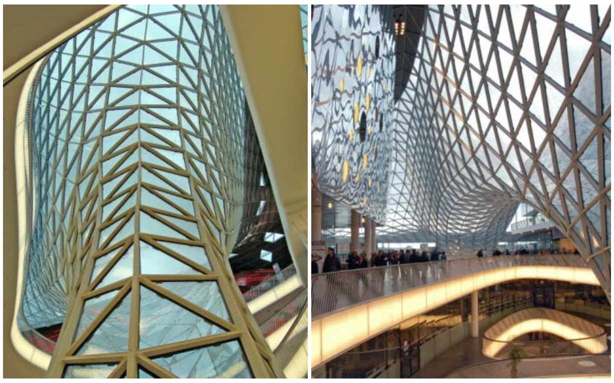


Figure 1. *MyZeil shopping centre in Frankfurt.*

1.2 Towards a low-cost free-form design

Starting from these considerations, there are basically two ways of reducing the costs of high tech structures with arbitrary shapes: one concerns manufacturing, the other design. In manufacturing, CAD-CAM systems are currently capable of simplifying the construction process by reducing human presence at the machines. In many cases, the direct link between drawings and production allows components to be worked with different shapes almost at the same cost as standard serial elements. This makes the designer relatively free in the definition of the architectural and structural form because the optimization strategies are present mainly at the production level. Nevertheless, a further reduction in costs can be obtained if the optimization philosophy is introduced right back at the early design stages.

For these reasons, four grid shell structure tessellation optimization procedures have been developed and compared in this research: first a discussion on the limits of an analytical approach is presented, then the solution method has been changed in a shape improvement way and dealt with using classical optimization methods and evolutionary techniques.

The aim of this paper is not to present a detailed comparison of different strategies but to focus on the most significant advantages and disadvantages of each procedure in a sort of “step by step” solution process.

Algorithms have been carried out by customizing the Rhinoceros™ NURBS modelling software through its implemented VB programming language.

2. ANALYTIC APPROACH: SPHERE PACKING ALGORITHM

This first developed algorithm, named “sphere packing”, is based on a recursive generation of spheres over a given surface in order to build a triangular mesh characterized by element lengths that always belong to a limited and desired fixed list.

A well defined set of radius measures, that we call the ‘reference database’, defines the number of possible sphere typologies involved in the algorithm.

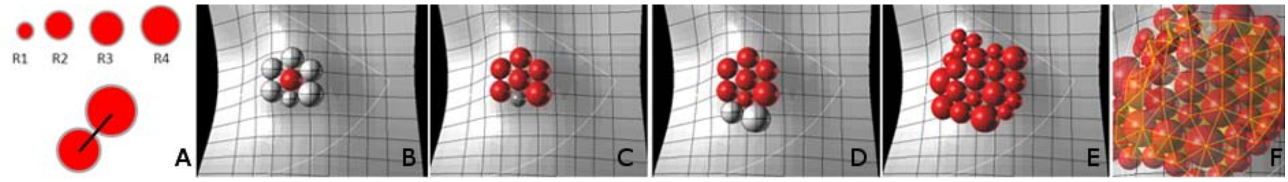


Figure 2. *A sequence of the "sphere packing" algorithm. From left to right: A – four spheres representing the four radius measures composing the database. The final length of the mesh frames results from the combination of the four possible frame typology measures (*$\boldsymbol{C_{4,2} + 4 = \frac{4!}{2!\cdot(4-2)!} + 4 = 10}$*). B – at each step, the algorithm develops around a reference sphere (red). Only the last sphere which closes the circle must be tangent to the other three spheres, consequently it is not possible to set the position of its centre but, at this step, it is only possible to choose a sphere with the centre as close as possible to the original surface. C – When the circle around a reference sphere is complete, another reference sphere is chosen (dark grey) and in D – another circle around this sphere begins. E – Once the original surface is covered by the spheres. F – The final mesh is made by connecting each sphere centre to the centres of the surrounding spheres.*

Each sphere has to be tangent to all the others around it and the centre of each sphere has to be as close to the primitive surface as possible. The generation procedure, as shown in Figure 2, starts from a chosen point on the surface and develops in a radial way. The final mesh is generated by the connection of all the tangent sphere centres and the number of frame typologies derives from the combinations of radius measures. Consequently the database plays a very important role for both the algorithm efficiency and for the result accuracy and shape. The larger the number of radius measures the longer the time the algorithm takes and the smoother the resulting mesh. Moreover, the final pattern dimensions derive from the range of measures chosen by the designer.

The results of this first approach (see section 5) highlight problems that are mainly connected to computational speed. In particular, an increasing number of database measures leads to many more possible combinations of spheres. Moreover the necessity of taking care of many particular cases does not fit well with a smart algorithm structure.

3. FROM GENERATIVE TO IMPROVING PROCEDURE

Apart from the creation of new meshes from scratch, it is possible to start from a given mesh and adapt the mesh frame lengths to a set of chosen measures. In fact, commercial modeling software offers internal procedures to mesh generic surfaces and the results are always an optimal approximation of the starting NURBS. Another advantage is the possibility of deciding on "a priori" constraints for the mesh vertices. It is important to remember that the mesh is a representation of the aimed for structure; Supposing the structure is, for example, a covering, it is obviously important to consider the position of the columns during the optimization process.

Three different new algorithms have been developed, one "ad hoc" and the other two taken from literature and suitably adapted to this problem. The "ad hoc" algorithm, named Progressive Move Rotate and Fix (PMRF), is a simple translation of the sphere packing concept to the case of a given starting mesh: the algorithm develops from a chosen mesh knot in a radial way changing a frame length at each step with the nearest one taken from the database. The first procedure taken from literature is a Genetic Algorithm (GA), a meta-heuristic optimization method based on the concept of human evolution. This is a consolidated method therefore only references about this technique (Goldberg [3], Koza [4] and Mitchell [5]) and its usage (Pugnale and Sassone [6]) are provided here. The last procedure is a particular implementation of the gradient-based technique called Force Density Method. A brief description of this method, considered the most suitable for the previously set goal, is given in section 4. All the presented algorithms have been tested on the benchmarks explained in section 5.

3.1 Objective function

The improving process of the starting mesh can be analyzed as a comparison between the frame lengths at each step of the optimization process and a set of referential measures, strategically chosen on the basis of economical parameters for the construction of the final grid shell tessellation of the desired shape.

The fitness function that allows the effectiveness of the developed algorithms to be monitored is:

$$f = \sum_{i=1}^{n}(l_i - l_{dat}^{*} \backslash) \to 0 \qquad (1)$$

$where$:

$n = number\ of\ frames$;

$l_i = length\ of\ frame\ i$;

$l_{dat}^{*} = the\ nearest\ database\ measure\ to\ l_i$

The convergence of the fitness function f to zero is the optimal searched for solution.

3.2 Optimum database

A particularly effective step, in order to improve the previously illustrated procedures, has been the development of an auxiliary algorithm, whose function is to optimize the database by choosing a set of “smart” measures. A database of element lengths can be generated starting from a tentative mesh laid on the reference surface. From such mesh, which can be automatically generated, it is possible to group the elements with similar lengths and to evaluate the mean value of each group. These values are a good starting point for the definition of an element database.

The fitness calculation is improved by assuming these mean values as database measures and, moreover, this improvement occurs if groups are chosen in order to contain as many original elements as possible. A standard “divide et impera” algorithm has been implemented to perform this process. It should be noticed that avoiding a direct choice of database measures does not mean a loss of control of the final result as the lengths of the starting mesh frames are managed by the designer.

4. VIRTUAL FORCE DENSITY METHOD

Since Linkwitz and Schek’s first development in 1970’s [7] the Force Density Method (FDM) has been well known as a powerful tool for analytical form-finding and static analysis of self-stressed structures, such as tensile membranes and cable networks (Southwell [8]).

At present, FDM is always associated to a real stress state of the structure under a field of applied forces which, combined with other boundary conditions (constraints, etc.), allows the shape to evolve and improve. However, looking at the problem from the mathematical point of view, it can be realized that the method works by replacing the real cable stress state with a fictitious vector related to the mesh geometry.

For the defined purpose, the fictitious stress state has been defined for each frame element using geometrical vectors that represent the difference between the length of the element and the nearest measure of the database (Figure 3 and Equations 2).

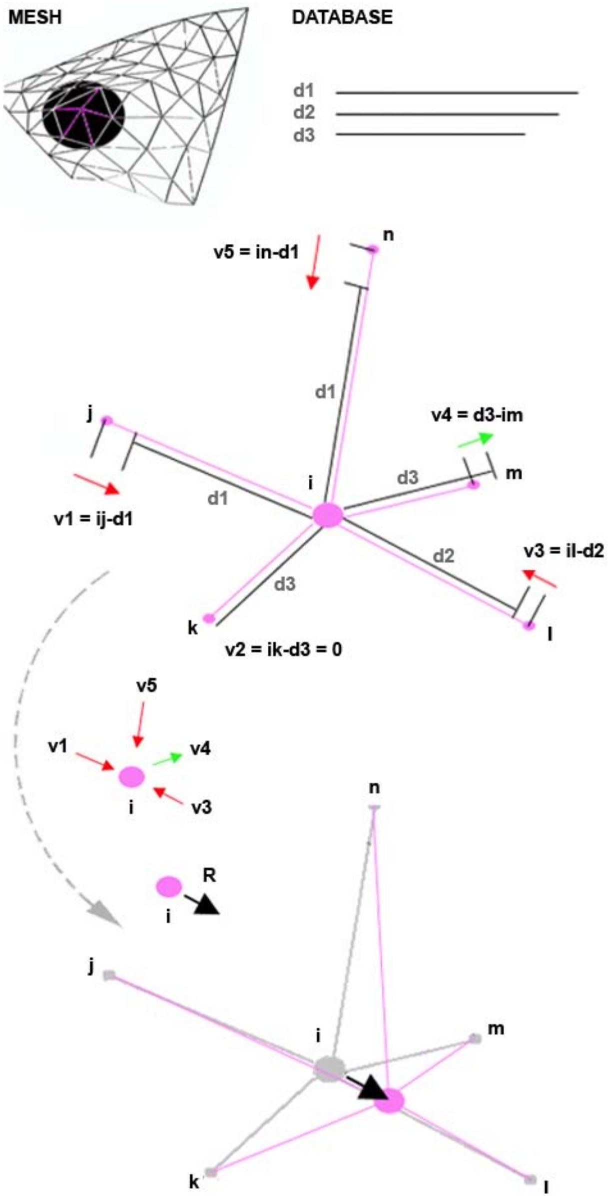


Figure 3. VFDM concept.

Referring to node *i* in Figure 3, the equations read:

$$\begin{aligned} &\frac{v1_x}{d1}+\frac{v2_x}{d3}+\frac{v3_x}{d2}+\frac{v4_x}{d3}+\frac{v5_x}{d1}=R_x \\ &\frac{v1_y}{d1}+\frac{v2_y}{d3}+\frac{v3_y}{d2}+\frac{v4_y}{d3}+\frac{v5_y}{d1}=R_y \qquad (2) \\ &\frac{v1_z}{d1}+\frac{v2_z}{d3}+\frac{v3_z}{d2}+\frac{v4_z}{d3}+\frac{v5_z}{d1}=R_z \end{aligned}$$

The only fundamentals for the optimization algorithm are:

1. A set of *n* points (nodes) $\mathbf{p} \in \mathbb{R}_3^n$ where $\mathbf{p}_k$ is a 1x3 array representing point k coordinates for k = 0,1…, *n*.
2. A connectivity matrix **M**
3. Boundary conditions **C**
4. A vector's generation rule *r*
5. An objective function *f*

Points 1 and 2 together give the geometry definition of the network. However, it should be underlined that the shape of M in the algorithm can vary in function of the set goal. Point 3 is not strictly necessary because, from the mathematical point of view, the initial position of the nodes could in itself represent a sufficient boundary condition. However, defining constraints or restraints for the node coordinates cannot practically be avoided when dealing with real projects. In this case, point 4 only depends on the geometry of the mesh at each step. Point 5 represents the controller of the algorithm: the fitness evaluation at each step is the way the iterations can be stopped. It is possible and, sometimes, convenient to use the objective function itself as a vector generation rule. Therefore, in this case, points 4 and 5 would be merged (*r* = *f*).

5. APPLICATIONS AND RESULTS

5.1 General comparison

A first comparison of the four developed algorithms has been made over three simple benchmarks, representing three surfaces with different Gaussian curvatures. This test (Figure 4) highlights that the VFDM is the most effective algorithm as for as both the computational speed and the number of elements adapted to the database (in red in Figure 4).

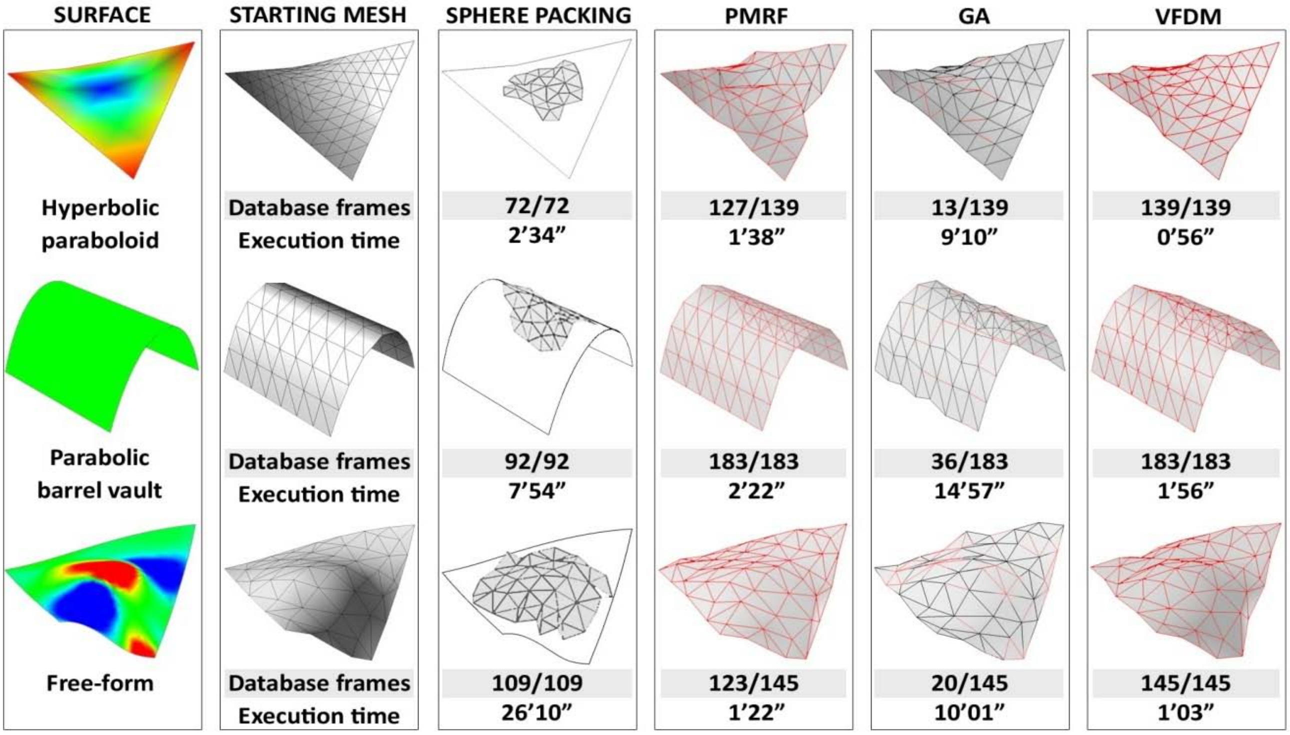


Figure 4. *Comparison of the developed algorithms on benchmark surfaces with different Gaussian curvatures. For both the first two benchmarks database is made by 4 measures while for the free-form surface 12 database measures are used.*

5.2 Tuning of the VFDM

In order to better analyze the behaviour of the VFDM algorithm, another two applications are presented. The first one (Figure 5) shows the consequences of using different databases in the same optimization process: increasing the number of database measures allows a time saving in terms of computation and also a better approximation of the original surface and consequently smoother shapes. However, a different choice of database measures also affects the final result.

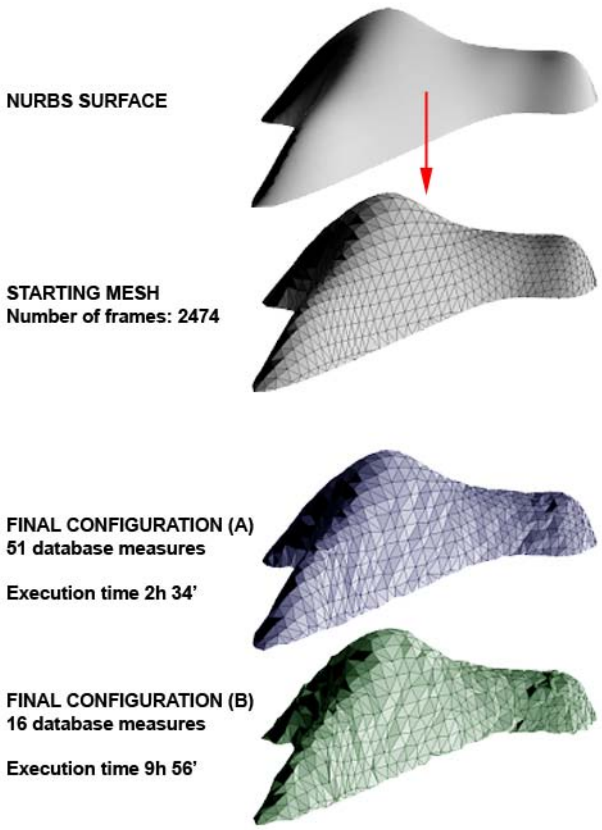
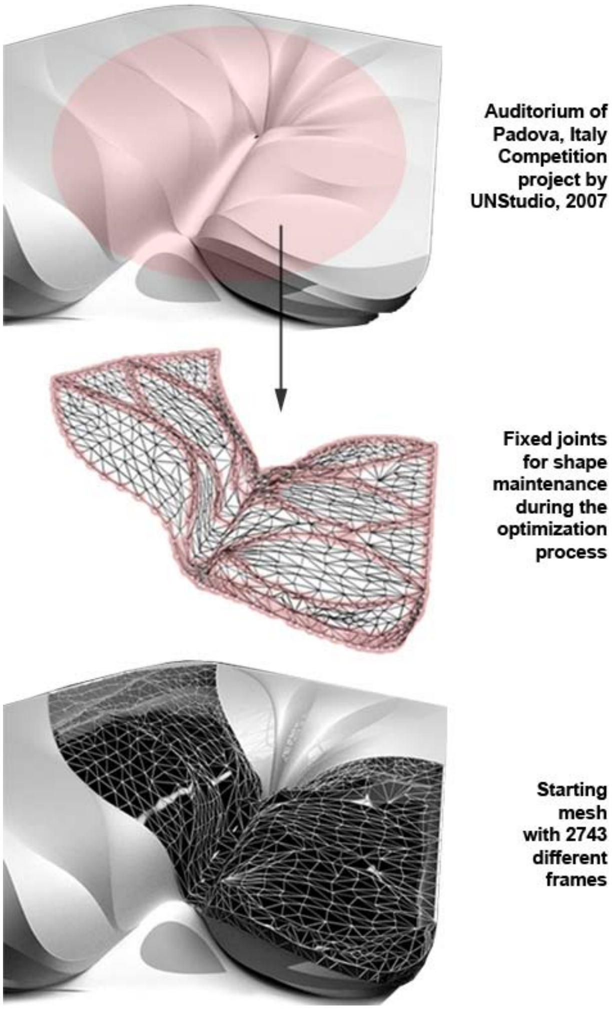


Figure 5. *VFDM appl.1: shape smoothness evaluation.*

The algorithm seems to work quite well, and all the frame lengths are adapted to the database measures, even though the database is ‘small'.

The second application shows the consequences, in algorithm efficiency, of a significantly high number of constrained joints. When the original shape that has to be approximated has a very irregular geometry or there are characteristic lines whose maintenance is of primary importance, the possibility of fixing some joints or of linking their movement to curves or surfaces during the optimization process is necessary. On the other hand, if the boundary conditions are too rigid, the total convergence of the algorithm would be impossible, as in the real case study shown in Figure 6.



Mesh frames	**2743**
Database measures	**36**
Database frames	**2326**
% of database frames	**85**
Execution time (min)	**47**
No. of constrained joints	**392**
% of constrained joints	**15**

Figure 6*. VFDM appl. 2: shape maintenance evaluation.*

5.3 Best algorithm

The VFDM algorithm seems to be an effective optimization procedure to deal with the discussed geometrical problem. It should be noticed, in particular, that the greater the number of elements composing the structure that has to be optimized, the better the solution. In fact, a significantly increasing number of elements does not usually require a similar increase in database measures to achieve a smooth approximation of the initial shape. Consequently, the number of database measures becomes a smaller percentage of the total number of elements.

6. MULTI-OBJECTIVE OPTIMIZATION

The possibility of a combination of the presented geometrical optimization process and a static enhancement of a structure, starting from the research by Pugnale and Sassone [6], has been tested. The procedure, written in VB, sees the interaction of a commercial NURBS modeler, such as Rhinoceros™, with a FEM software, such as Ansys™, through a Memetic Algorithm (MA) (Elbeltagi *et al.* [9]) that is implemented inside the previously shown VFDM algorithm.

The MA implements the evolution of a NURBS surface acting on the vertical movement of 16 control points into a square base parallelepiped volume. All the NURBS surfaces are then changed into a corresponding mesh, which is automatically generated by the software and geometrically optimized before the static performance evaluation. The shell performance evaluation of the shell is based on the strain energy of the structure under a uniform force field (Sasaki [10]). Table 1 shows the chosen boundary conditions for this multi-objective benchmark, while Table 2 refers to the Memetic Algorithm parameter setting.

Table 1. *Boundary conditions for a multi-objective application.*

Domain	**Square base parallelepiped volume (9m x 9m x 6m)**
No. of NURBS control points	**16**
Constraints	**4 fixed joints (the 4 corners of the square base of the p.v.)**
Restraints	**No relative rotations of the frames**
Material	**Steel (ρ=7850 kg/m^3, E=210000 N/mm^2, ν=0,3)**
Frame section	**Pipe D101.6 mm x 3.6 mm (A=11,1 cm^2, J=133 cm^4)**
Load pattern	**1kN/m^2**

Table 2. *Memetic Algorithm (MA) parameters.*

No. of generations	**60**
Population size	**15**
No. of élite individuals	**1**
No. of individual for the local search	**2**
No. of individuals to be discarded	**2**
% of population mutation	**30**
% of individual mutation	**20**

The first results obtained from this simple case study are shown in Figure 7. The graph represents the fitness of the best individual (dark grey) and the mean fitness trend (light grey) generation after generation.

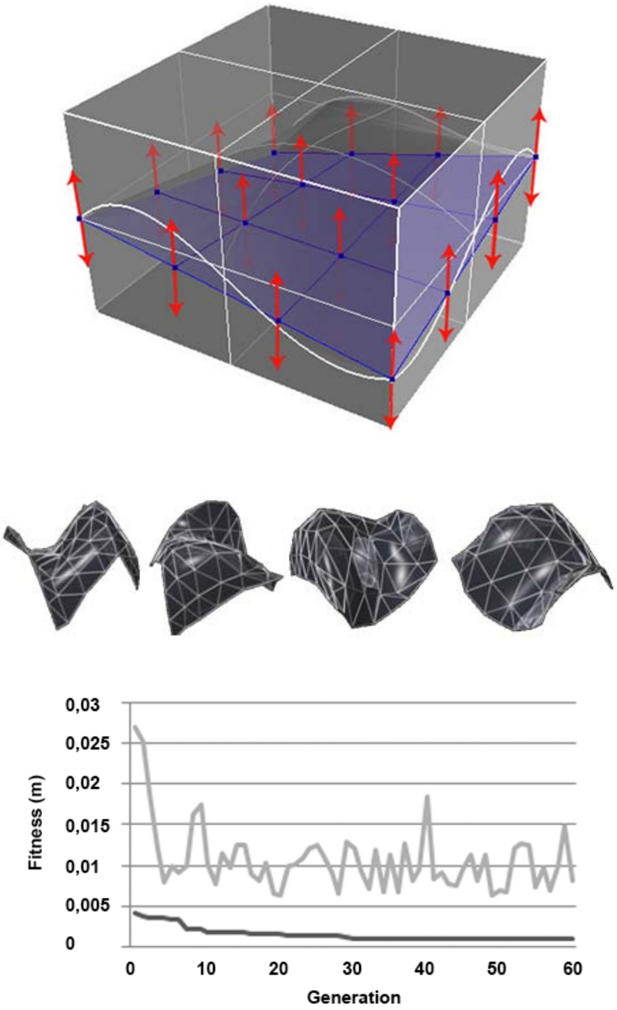


Figure 7. *From the top: solutions domain; mesh configurations after optimization process; analysis results (grey line=mean fitness, black line =best fitness).*

Under a uniform load pattern of 1kN/m^2, the maximum vertical displacement for the structure ensued from the optimization process is equal to 9.97e-04 m. The static behavior of the resulting grid-shell is comparable to other traditionally effective configurations (on the right in Figure 8) and the free-form structure (139 elements) is made only with 8 frame typologies.

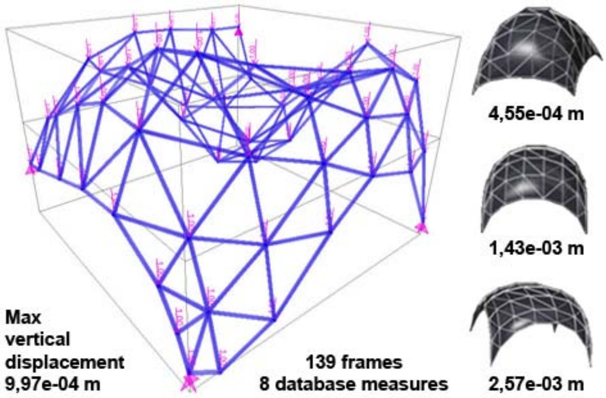


Figure 8. *Comparison of the three reference optimal configurations and the analysis result.*

7. CONCLUSIONS

Free-form structures are closely related to the grid shell typology, mainly because of its simplicity in fitting any starting arbitrary shape. Thus, the possibility of a simple interchanging of structural and cladding materials would encourage designers to find new original architectural proposals on every occasion.

Important improvements have been made on the rapidly diffused "file-to-factory" production procedures, which allows non-standard structures to be constructed with reasonable costs. However, a further reduction, in terms of the overall costs, can be obtained by introducing morphogenesis and optimization tools starting from the early design phases.

In conclusion, the development of four different optimization algorithms can be considered as a study related exclusively to the efficiency of tools and to the effectiveness of different procedures. The VFDM appears to be the algorithm that best satisfies the requirements of an optimization instrument as well as of a versatile design tool. At a deeper level, the aim of this research was to explore new ways for the conceptual design of low-cost free-form grid shells.

REFERENCES

[1] ***Ed. Migayrou, F.***, *Architectures non standard*, Centre Pompidou, 2003.

[2] ***Schlaich, J., and Schober, H.***, Glass-covered Lightweight Spatial Structures, Eds. Abel, J. F., Leonard, J. W., and Penalba, C. U., *Spatial, Lattice and tension structures: Proceedings of the IASS-ASCE International Symposium*, American Society of Civil Engineers, 1994, pp. 1-27.

[3] ***Goldberg, D. E.***, *Genetic algorithms in Search, Optimization & Machine Learning*, 1st ed., Addison-Wesley Professional, 1989.

[4] ***Koza, J. R.***, *Genetic Programming: On the programming of computers by means of natural selection*, 1st ed., The MIT Press, 1992.

[5] ***Mitchell, M.***, *An Introduction to Genetic Algorithms*, The MIT Press, 1998.

[6] ***Pugnale, A., and Sassone, M.***, Morphogenesis and Structural Optimization of Shell Structures with the Aid of a Genetic Algorithms, *Journal of the International Association for Shell and Spatial Structures*, Vol. 48, No. 155, 2007, pp. 161-166.

[7] ***Linkwitz, K., and Schek, H. J.***, Einige Bemerkungen zur Berechnung von vorgespannten Seilnetz-Konstruktionen, *Ingenieur-Archiv*, Vol. 40, 1971, pp. 145-158.

[8] ***Southwell, R. V.***, *Relaxation methods in engineering science: a treatise on approximate computation*, Oxford University Press, 1940.

[9] ***Elbeltagi, E., Hegazy, T., and Grierson, D.***, Comparison among five evolutionary-based optimization algorithms, *Advanced Engineering Informatics*, Vol. 19, No. 1, 2005, pp. 43-53.

[10] ***Sasaki, M.***, *Flux Structure*, TOTO, 2005.