Specialised algorithms for different project stages in a post-formed timber gridshell design

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ABSTRACT: This paper forms part of broader research collaboration between the design firm *Gridshell.it*, and the Department of Architecture, University of Naples that investigates the use of digital design tools in timber-based structures. This paper reports on the development of a digital-based application for form finding of timber post-formed gridshells. It provides the background to the current stage of development and outlines the mapping and code structure of the application. The tool is seen as a response to *Gridshell Form Finding Tool* or GFFT (Pone et al, 2013); its objectives are two-fold:

1) Perform a fast geometrical and structural optimisation to transform an arbitrary freeform into a viable timber gridshell structure;

2) Support conceptual design of timber gridshells in the heuristic stage of the design process;

The enhancement application, integrated with Grasshopper software, promotes optimisation capacity for structurally verified form finding at the early design phase of project development. It addresses earlier shortcomings of the tool to improve usability and accuracy. A reverse-engineering procedure has also verified the outcomes of this method, which effectively corresponds to the gridshell form obtained through a classical dynamic relaxation.

1 INTRODUCTION AND BACKGROUND

Timber gridshells commonly define a small domain of structures which gain their strength from their double-curved shape, and are made of a grid of wooden laths instead of a continuous surface (Happold, 1975). As Richard Harris explains (2003), a gridshell is “a shell with large openings in it in a manner that allows the remaining strips or grids to behave, structurally, as a shell”, thus allowing minimum use of material with structural efficiency for large span architectures. In recent years, a number of digital tools has been developed or scripted, to simplify the design and drawing of gridshells or to optimise their characteristics (Adriaenssens 2013, 2014; D’Amico et al, 2014; De Peloux et al, 2013; Kuijvenhoven and Hoogenboom, 2012; Li and Knippers, 2011; Bouhaya et al., 2009, Pugnale Sassone, 2007) or to design more general form-active structures (Roithmayr, 2003; Dimcic, 2011).

This paper forms part of a wider research on digital design (Pone et al, 2013) and new construction methods (Colabella et al, 2015) of timber post-formed gridshells, conducted by an Italian firm specialising in timber special structures (*Gridshell.it*) together with the Department of Architecture, University of Naples.

1.1 *Classical gridshell form-finding*

The general goal of this research is to investigate the uptake of digital technologies in timber-based buildings. To date, *Gridshell.it* has built thirteen timber gridshells, eight of which were defined through the *Gridshell Form Finding Tool* or *GFFT*, developed by the same group of researchers. This tool, written in *Grasshopper*™ with *Kangaroo Physics* simulates, through dynamic relaxation (Linkwitz, 1971), the real process of assembly and bending of a post-formed gridshell, and supports viable form analysis and qualitative structural performance of the structure. However, its utility is limited in the advanced stage of the design process, and cannot easily manage complex shapes. The accuracy and precision of *GFFT* has been tested through a reverse engineering process on two full scale prototypes built at the Department of Architecture of Naples: *Toledo Gridshell 1.0* and *2.0.* In testing conducted by *Gridshell.it* and *Suor Orsola Benincasa University*, the structure in both cases displayed a discrepancy of maximum 4cm in height and width between the 3D model and the prototypes. This observed gap between the digital model and the built structure can be attributed to the inaccuracy of the particle spring system used, despite its materials properties being calibrated with *FEM* software. The first version of this tool (2012) was implemented with a curvature analysis sector that warns the designer against any odd bending condition, in order to minimise rods damage. This simulator allows the designer to verify a designed shape, through a trial and error process. Some critical issues, encountered in the last three years of this development process, required an upgrade of the entire design tool. This paper outlines the last elaborations of an enhanced digital tool for form-finding of feasible timber post-formed gridshells at early stage of design.

1.2 *An enhanced method*

A number of issues were identified which compromised *GFTT's* ease of use and accuracy application in its uptake during the concept design phase of a project. The first is the high level of experience required in the use of the tool; and its limitation in being efficient and useful only with simple forms. Furthermore, the use of the *GFFT*, in the early stage of design, as a form-finder, poses a problem in the determination of the correct flat grid configuration and the boundary conditions, able to fit the desired three-dimensional shape.

In addressing these shortcomings, a new tool, called *GridMaker*, based on geometry principles rather than physical ones, has been developed, implementing the *Netfish Method* (Otto 1974), through a process of optimization. This method has been proposed for the first time by Klaus Linkwitz for the Mannheim Multihalle Gridshell (Otto 1974), and more recently described by Toussaint (2007), Bouhaya (2009) and Basso (2009). Crucial for the analogies with the issues of this paper is the work on the planar tessellation of gridshells by means of the "sphere packing" algorithm (Basso et al, 2009), here utilised as the generator of the net to be further optimized in order to minimise the curvature of timber laths. Its aim is to facilitate a deeper control of the design through the management of the lath orientation and the consequent minimisation of their active bending stresses.

The new process, which combines the two tools together, follows four main phases (Fig. 1):

1. Input of a freeform surface, derived from an architectural concept;
2. Mapping the surface with a gridshell-feasible network of rods, that is, the transformation of the surface into a gridshell through the sphere method;
3. Unroll the three-dimensional canopy into a flat lattice;
4. Performing a dynamic relaxation through *GFFT* to convey the flat lattice into its spatial configuration.

At phase 4, the contour of the flat grid becomes the new input of the *GFFT* in order to reinstate the gridshell from a geometrical-dependent input to a physical-dependent output.

This method does not intervene in the definition of the input *NURBS Non-Uniform Rational Basis spline*, intended as an arbitrary choice, nor in the final dynamic relaxation procedure. It follows the phases summarised in Figure 1, focusing on the characterization of the mapping process and the unrolling phase. The undescribed parts are fully explored in Pone et al. (2013).

This method can be applied recursively, to render the final physically-viable shape of the gridshell.

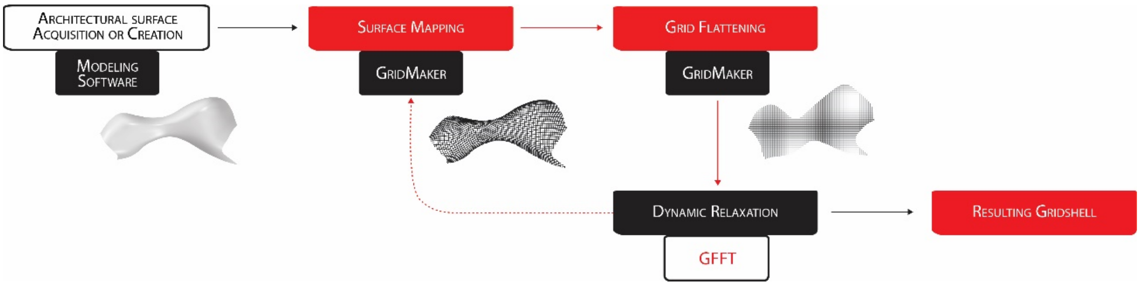

Figure 1. Flowchart describing the form-finding process, from *GridMaker* to *GFFT*.

2 GRIDMAKER – CODE STRUCTURE

2.1 *Overview*

Algorithm *GridMaker* is implemented by *Python*™ within *Grasshopper*™. It performs the following operations:

1. Definition of the input *NURBS*;
2. Extension of the *NURBS* domain;
3. Mapping of the extended surface through the *Netfish method* and drawing of the grid-shell;
4. Intersection between the shape boundary edges and the gridshell;
5. Redrawing of the gridshell inside the domain;
6. Development of the gridshell on a plane;
7. Drawing of the flat grid contour.

2.2 *Mapping process and first application*

The core of the *GridMaker* tool is the mapping process that leads to the capacity to model a gridshell from a freeform surface.

In this method, the surface is divided into four quarters defined by two orthogonal axes, split at the intersection point, which are projected onto the surface. The projected semi-axes, that are the generative curves, are divided into points by a fixed distance that correspond to the grid size.

For each quarter, two spheres located at the first two points of the corresponding semi-axis, are created with a radius equal to the grid size (Fig. 2a). The intersection between the spheres and the surface defines two closed curves whose further intersection (Fig. 2b) will trace a new node on the surface (Fig. 2c).

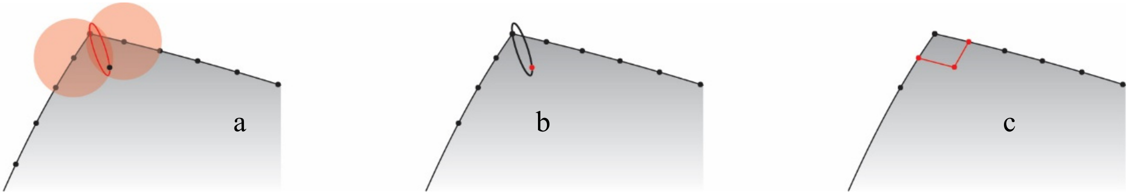

Figure 2 a, b, c . Key frames of the *Netfish* method.

A recursive process for each quarter allows the mapping of the whole surface.

A limit of the described method is the inability to cover the whole surface. This depends on two main issues: 1) The edges of the surfaces cannot be mapped because the points are defined discreetly on each axis and they never exactly fall on the boundary curve (Figure 3a) and 2) When the length of one or both of the projected semi-axis, is lower than the length of the quarter section curves in the same direction, there will be shadow zones that cannot be mapped (Figure 3b).

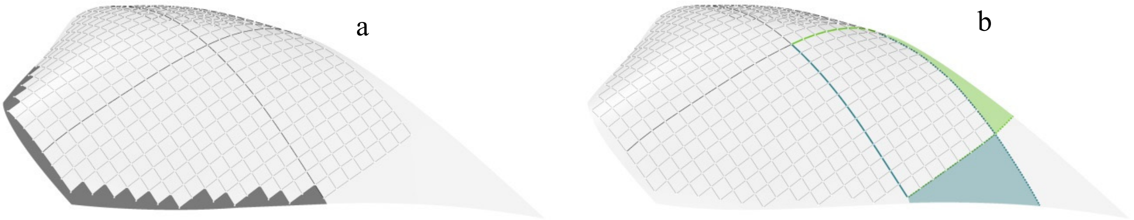

Figure 3a and b. Main issues encountered during the mapping process.

This issue has been identified by Bouhaya (2009) where ex-post cutting of the surface undermined the aim of the algorithm to preserve the input information. The first section of the *GrdiMaker* code addresses this first issue where the domain of the input surface is extended by a defined value and is restricted to the original one after the mapping process is completed, thereby trimming all the Gridshell elements outside the shape.

In order to verify the accuracy and functionality of the tool, *GridMaker* has been tested via the prototype *Toledo Gridshell 2.0* (Figure 4), a doubly symmetrical gridshell built in Naples in 2014 (D'Amico et al, 2015). Originally designed from the relaxation of a planar grid via *GFFT*, the two orthogonal axes have been placed with the intersection point at the surface centre and oriented according to the symmetrical axes of the surface. The results show a perfect match between the prototype and the gridshell generated through the new tool.

Further attempts on asymmetrical and unrelaxed surfaces, (geometrical-dependent surfaces that present high curvature degrees), reveal the limits of the initial assumption: where problems are related to the arbitrary location of mapping the start point and the two generative curves.

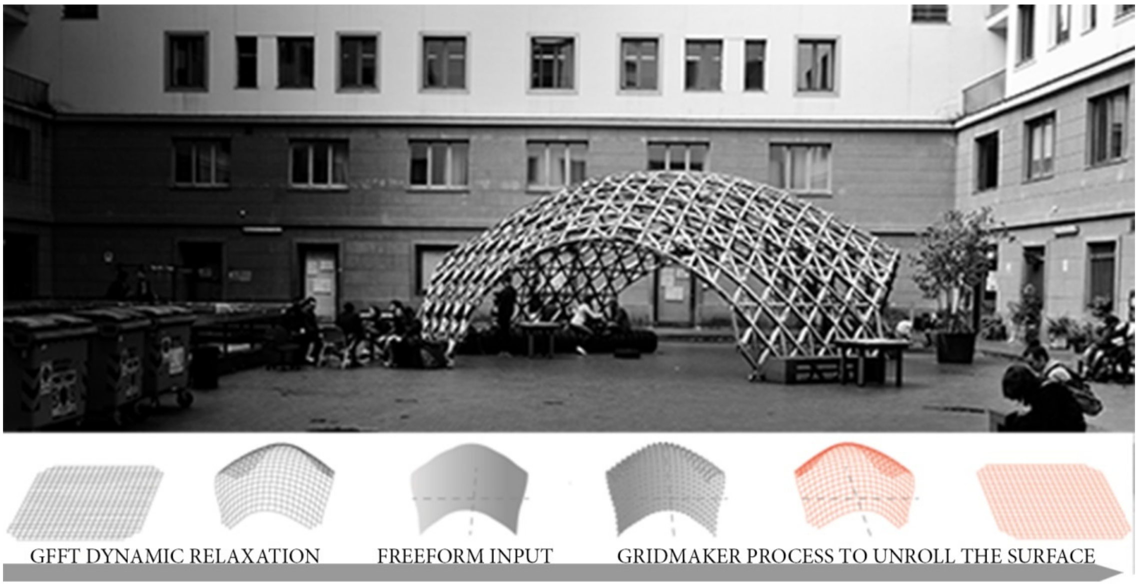

Figure 4. Toledo 2.0, first validation of *GridMaker* through the comparison between the real flat lattice and the one derived from the Genetic Algorithm *GridMaker*. The result is an identical flat lattice. Photo by Daniele Lancia

2.2.1 *Applications on freeform surfaces – The definition of the generative curves and the kinematic compatibility issue*

The shape and the orientation of the axes represent a constraint for the mapping process. If the form of the projected axes does not represent a feasible configuration of a loaded rod that lies on the surface, the result may be wrong and complete mapping may not be achieved. This issue becomes apparent for highly curved surface, where a curvature inversion event happens, where the unviable straight shape of the axes will cause the shrinkage of the net and the overlapping of the following parts (Figure 5).

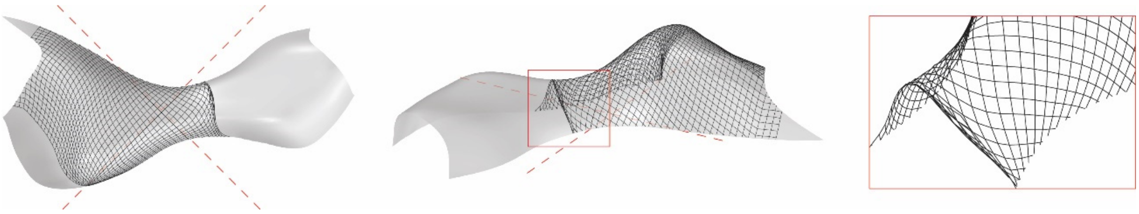

Figure 5. Shrinkage and overlapping of the net from an unsuccessfully mapped surface.

The imposition of a straight shape for the axes will result in planar curves, when projected along the Z direction.

A parametric definition to generate the starting curves allows the overcoming of this issue. Using this method, each semi-axis is divided into a number of points depending on the complexity of the surface to map and each point is moved along a vector lying on the axes plane, normal to the semi-axis direction by a variable value. Finally, a curve is interpolated through these points and projected to the surface (Figure 6). The difficulty to control such a large number of variables using a trial and error procedure led to the incorporation of an optimisation process.

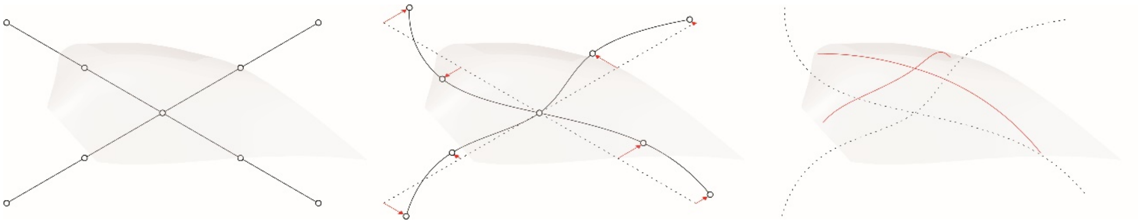

Figure 6. Axes parametric definition and its graphic domain.

2.2.2 *The optimisation process*

The objective of the genetic algorithm optimisation process is to explore all the possible generative curves derived by the initial axes, in order to maximise the mapped area and consequently minimise any overlapping event. Furthermore, the minimisation of the curvature radii variation in both directions is taken into account to prevent cusp formation. A preliminary fitness function was coded or written as:

$$f_1(\alpha, \gamma) = \alpha + \gamma \tag{1}$$

$$\alpha(F, a) = A - \sum_{k=0}^{F} a_k \tag{2}$$

$$\gamma(M, N, R^{xz}, R^{xy}) = \left\{ \left[\sum_{i=0}^{N} \frac{\sum_{j=1}^{(M_{(i)}-1)} \Delta R_j^{xz}}{(M_{(i)}-1)} \right] + \left[\sum_{i=0}^{N} \frac{\sum_{j=1}^{(M_{(i)}-1)} \Delta R_j^{xy}}{(M_{(i)}-1)} \right] \right\} \cdot \frac{1}{N} \tag{3}$$

Where:

- N is the number of gridshell rods;
- M is the number of nodes at the ith rod;
- $\Delta R_j = R_{j-1} - R_j$;
- R_j^{xz} and R_j^{xy} are the curvature radii, calculated respectively in XZ and XY local planes – with z the axes along the element, and x the surface normal -, of an arc constructs from the nodes j-1, j, j+1;
- A is the surface area;
- F is the number of the gridshell rhombuses;
- a_k is the area of the kth rhombus.

The design variables, coded as the genome of the genetic algorithm are defined by:

1. The axes origin location on a fixed rail under the surface;
2. The global rotation of the axes;

3. The distance between the straight axes points, and their relative vertices on the new-bent planar axes.

First results showed the possibility to complete the mapping process without overlaps, but the solution was not considered as acceptable: the excessive shrinkage of the grid squares, indeed, was not compatible with the deformation of post-formed timber gridshells.

Therefore, a new fitness function is defined below to include the global shrinkage level of the grid. Considering the smallest angle for each rhombus of the gridshell, the shrink factor can be calculated as:

$$\sigma(N,\Theta) = \sum_{i=0}^{N} 90 - min(\Theta_i, 180 - \Theta_i) \tag{4}$$

Where:

- N is the number of the gridshell rhombus;
- Θ_i is the angle in degrees between any two consecutive segments of the ith rhombus.

The new fitness function becomes:

$$f_2(\alpha,\sigma) = \alpha + \sigma \tag{5}$$

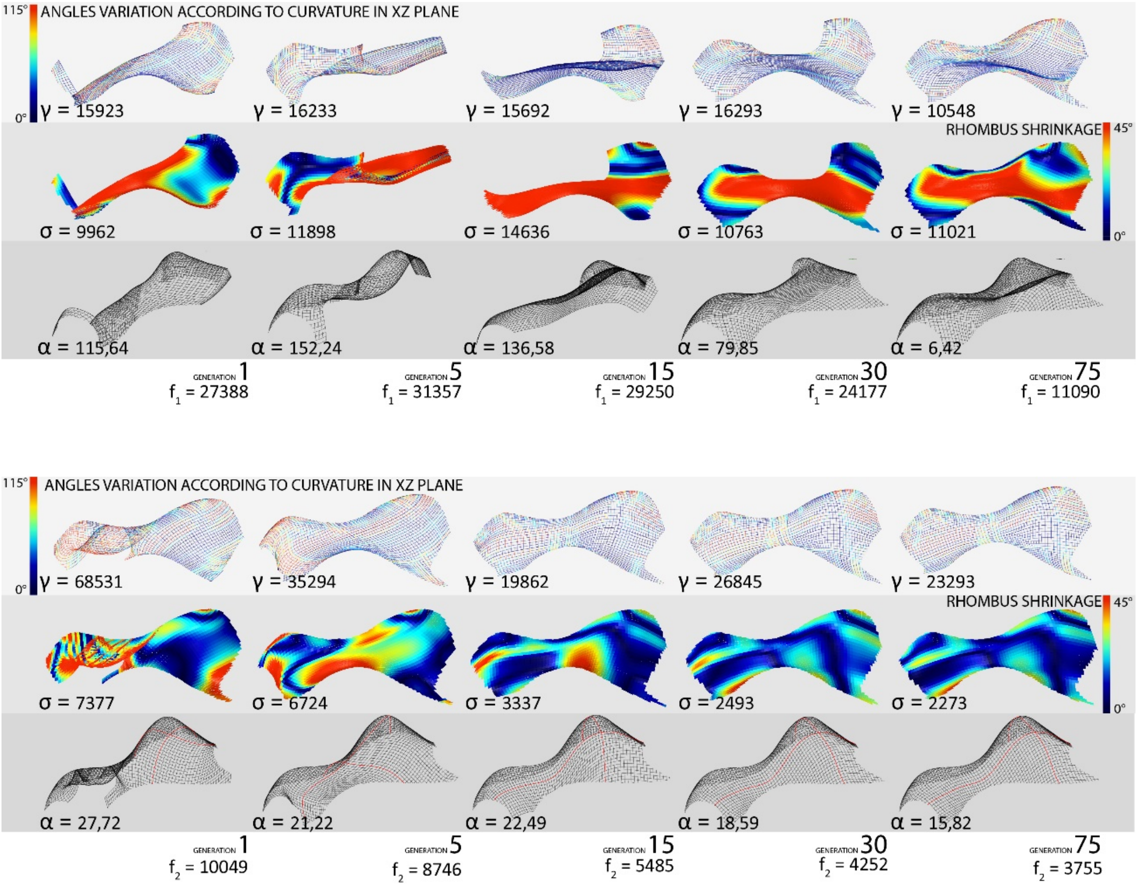

Figure 7. Overview of the two optimization process, performed with the two different fitness functions, respectively, f_1 and f_2, showing the two optimization process in terms of curvature, angles variation, and phenotype.

The optimisation results show that the contribution of the shrinkage level function helps the whole process to converge earlier, providing better results in terms of curvature variation, despite absent in the fitness function (Figure 7). Furthermore, the minimisation of the squares deformation corresponds to the maximisation of the surface area, then covered with the minimum material cost.

2.3 *The unrolling phase*

Once the gridshell geometry is defined, the flat grid can be generated. The process follows these steps:

1. Assignment of a reference system in XY plane oriented according to the gridshell axes rotation;
2. Extraction of the information about the grid nodes;
3. Construction of the new points matrices for each quarter and drawing of the boundary curve.

The flat grid is processed by GFFT, to rebuild the gridshell through dynamic relaxation and achieve a real physical-dependent form.

3 CONCLUSIONS

This paper describes a design procedure for freeform timber gridshells which combines the *Netfish method*, developed to discretise a generic surface in a grid of quads, with a GA and used to find the optimal orientation of such a grid to minimise the lath's curvature. The relevance of this parameter for the design of timber gridshells comes from the experience gained by the authors who, through prototyping, identified each single issue to be related to the simulator.

The *Netfish method*, indeed, is a simple geometrical tool implemented in *Rhino/Grasshopper*, which assumes a great importance when optimized according to the three parameters used as the design variables of the procedure, i.e. the axes, the rotation and the diagonal of the rhombus. That is the opportunity to bind together architecture and structural typology, already at the concept stage, without shrinking too much the possibility of freeform and, at the same time, without kicking the structure out of the design process.

The optimisation procedure can be easily used as a drafting tool for conceptual design. Ongoing research work is aiming at reducing the time consuming phase of the concept stage, also to encourage designers to directly find a feasible freeform gridshell already at the early step of design, rather than adjust it according to structural instances in a further phase.

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