DigitalBamboo_Algorithmic Design with Bamboo and Other Vegetable Rods

Stefan Pollak and Rossella Siani

Abstract Algorithmic design software is widely acknowledged as a tool to manage complex design tasks and to enhance material optimization, structural performance, ergonomic needs or similar aspects. The present paper investigates how these tools can be applied to projects that use an important amount of non-standardised, natural materials. The use of renewable and locally sourced materials is becoming mandatory if we accept the challenge of providing an appropriate built environment for a growing world population. A special focus is given to vegetable rods such as giant reed and bamboo. Building tradition provides uncounted examples of how humankind employs natural fibres to erect or ornate its shelters. Some of them can inspire new uses to be applied in contemporary architecture. The aforementioned digitally controlled design processes are normally meant to feed so-called computer aided manufacture processes. Such methods generally need highly standardised materials. The use of renewable materials in such a framework is often impossible due to intrinsic irregularities of natural resources. Can this gap be bridged? The present paper illustrates the design-and-build technology *DigitalBamboo* thought to conciliate the two realms of natural building materials and algorithmic design control. The method has been conceived for experimental projects made of Italian bamboo in the form of strips but can be applied to other vegetable fibres or rods and to other geographical contexts. The investigated technology includes appropriate communication tools to bridge the divide between designer and builder. The illustrated technology is based on manual assembly of digital data and includes ways of transposing geometric entities into topological textures, physical nodes and structures.

Keywords Natural materials · Algorithmic design · Appropriate fabrication · Gridshell · Assembly maps · Nodes

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United Nations' Sustainable Development Goals 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

1 Introduction

The fourth industrial revolution allows architectural design along with its workflow control, the construction itself, and the performance monitoring to be more and more implemented by computation and automatised processes [1].

DigitalBamboo is an experimental research that applies algorithmic design approaches to bamboo, a natural material with interesting structural and expressive features.

The inquiry is part of the broader research line *DigitalNature* [2], which investigates the meeting points between innovation and tradition, between advanced design and locally sourced natural materials.

The main challenge of this research is to adapt Industry 4.0 processes, which generally imply numerically controlled machines or robots [3] and highly standardised products, in order to make them cope with natural materials in their raw form. An original method is proposed to deal with this delicate step.

Using a material in its natural form, with a few processing steps to reach the assembly phase, reduces the impact of the product life cycle assessment [4, 5], both in the initial pre-production phase and in the disposal phase.

Traditional building models with regrowing, natural materials are implicitly circular and provide benefits both for the environment and the local economy. Such good practices can increase their effectiveness and multiply their positive effects on the ecosystem if associated with more complex control tools.

The increase in process-complexity that comes along with the combination of digital tools with physical production means can allow for an improvement in performance and hence for a better management of resources. This opens new perspectives with respect to sustainability, a concept that is transforming itself from a merely conservative approach as defined in the Brundtland Reports [6] or in concepts like *Décroissance Sereine* [7–9] towards a more active attitude as witnessed in the 17 UN Sustainable Development Goals. Similarly to what happens in mature living organisms, where a growth in complexity takes the place of a physical growth, this can be seen as a passage from a quantitative towards a qualitative growth [10].

The use of algorithmic generative design combined with construction processes that make use of natural materials endeavours a specific niche of this perspective.

2 Physical and Digital

2.1 *Fast Growing Plants as Building Material*

In a circular perspective, the use of vegetable material is crucial. Canes like giant reed or bamboo are largely available in many regions of the world and have a rapid growing cycle, i.e. if compared to timber. Reed canes like *Arundo donax* can be found all around the Mediterranean Sea and in the Middle East. Similar species grow in other continents. The areas where bamboo is native include almost all tropical regions of Asia, Africa and Latin America, but most of the 1.600 known species can grow up to a latitude of 41° North and South [11]. Vegetable rods are commonly used as building materials. [12–18]

The present research focuses on bamboo grown in Italy, mainly *Phyllostachis viridiglaucescens*. This species can provide culms of up to 11 m of length. Its diameters appear in a range between 40 and 80 mm with a wall thickness of mature material that reaches 4 to 5 mm.

The diameters vary along the culm with a maximum at approximately 1 m from the ground and then a constant decrease towards the top. This constrains the cane's bending behaviour, which typically has larger radii in its lower part and the possibility of tighter bends in the upper part. The result is a characteristic asymmetric arch.

Bamboo strips are an alternative to round culms. To source them whole canes can be divided with a splitter, a cutting tool with 3, 4, 5 or more blades, according to the diameter and to how broad the strips shall be. The bending behaviour of strips has less constraints compared to entire canes which allows for freely designed shapes. Freshly cut, 3 cm broad, green strips of *Phyllostachis viridiglaucescens* can bend with a radius as small as 35 cm.

2.2 *Digital Design and Production Tools*

Algorithmic design [19–22] (also defined parametric) makes use of specific, so-called generative software, whose use is growing in industry 4.0. The final design conformations emerge from a set of pre-established relations and the results vary as the parameters vary in a form finding process [23–28]

Generally, the algorithmic design work is associated with CAD/CAM processes, and thus allows to carry out mechanised production processes with a numeric control [29]. Such computer numeric control machines (CNC) can process various materials, even of natural origin, but with one common feature: the format of the materials is standard.

In the case studies presented here the bamboo material is used in its natural form, in whole rods or strips, and as such the format varies in thickness, length, weight, as well as for the numerous irregularities it presents on the external surface.

The need to use bamboo in its natural form has triggered the creation of a specific construction process, capable of translating digital data into very precise manual operations, so as to combine the advantages of parametric performance control with a constructive model which is close to tradition. This allows us to incorporate consolidated solutions or to involve specific locally available skills.

2.3 The Case of Triaxial Bamboo Strip Gridshells

Gridshells are lightweight constructions made of linear elements and nodes that collaborate in order to reach an efficient structural performance [30]. Strips of split bamboo can be used as building material for such works.

This study examines methods of digital design to control shapes and performances of such gridshells (Fig. 1).

The bamboo strips are organised in three layers according to their orientation (horizontal, left and right). The three families of axes cross in a mesh of nodes, each node joins three strips, one from each layer.

The digital model contains all the needed information in terms of proportion, size and scanning of the parts. The tolerance between the digital and the physical model is in the range of a few millimetres; a tolerance that does not affect the building's performance but, on the contrary, allows for more leeway while dealing with the natural material's peculiarities.

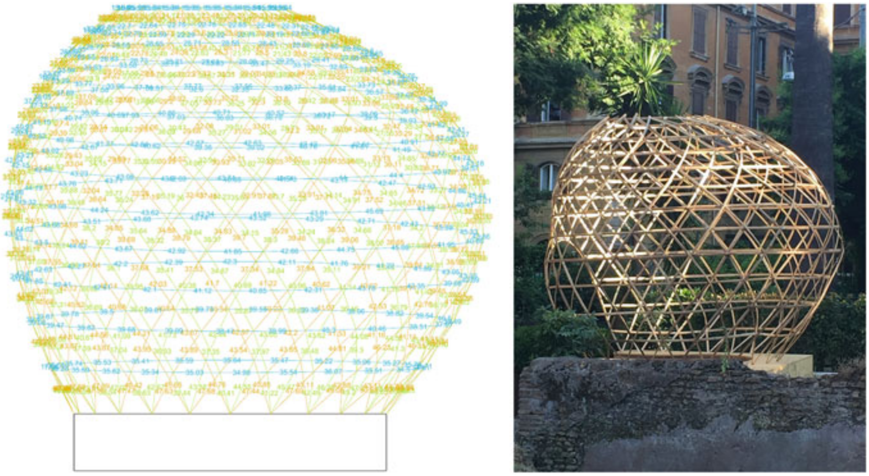

Fig. 1 *Pagurus urbanus pacificus*, a leisure pavilion in a public garden in Rome as a virtual model and in built reality

3 Digital and Empirical Information Management

3.1 Morphogenetic Design

The digital design is developed with *Rhinoceros* [31] combined with the plugin *Grasshopper* [31], a generative software for parametric design. The design phase, or in other words, the development of the virtual project [3] is divided into two steps: the definition of an algorithm and the application of differentiated parameters for the single case [23, 24].

The virtual project represents, like the genotype of an organism, a range of formal possibilities that determine the specific case, the phenotype (Fig. 2).

The morphogenesis of a formal composition is in relation with the most suitable parameters for the project's logic and function. Along with the freely chosen parameters that shape the design, the algorithm can be fed with information on the material's physical constraints such as bending radii, torsion data as well as structural parameters, environmental factors, functional or even cultural data.

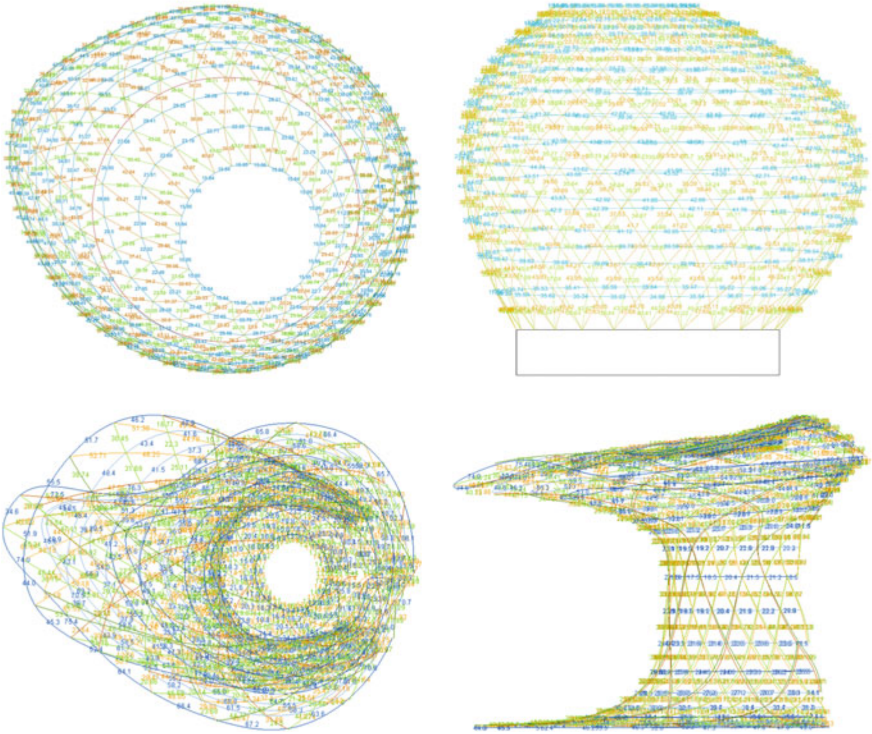

Fig. 2 Two projects (*Pagurus*, Rome 2019 on the left and *Jinen* for Tono Mirai, Venice 2021) compared. The top views highlight the origin of the two designs from a common genotype while the side views clearly show the phenotypic peculiarities

3.2 Curvature and Torsion as Parameters

The data on minimum curvature constrain the composition's formal possibilities. The local datum affects the global behaviour, determining variations on the composition.

The curvature analysis (Fig. 3) refers to the curvature of individual strips, organised by warping or to the surface that determines the overall shape of the structure. The analysis of single strips allows us to investigate possible criticalities of different variants. Once bending radii that are inappropriate for the available material are detected, the design can be modified with a reiterated feedback process until a suitable result is reached.

The analysis of the surface curvature is represented by a graph with a colour gradient which, in our example, goes from red (maximum) to yellow (minimum) and defines the degree of curvature of the surface in relation to the minimum and maximum of the specific template (Fig. 4). It is a less precise tool compared to the previous one, because it does not provide absolute but only relative data. It is not

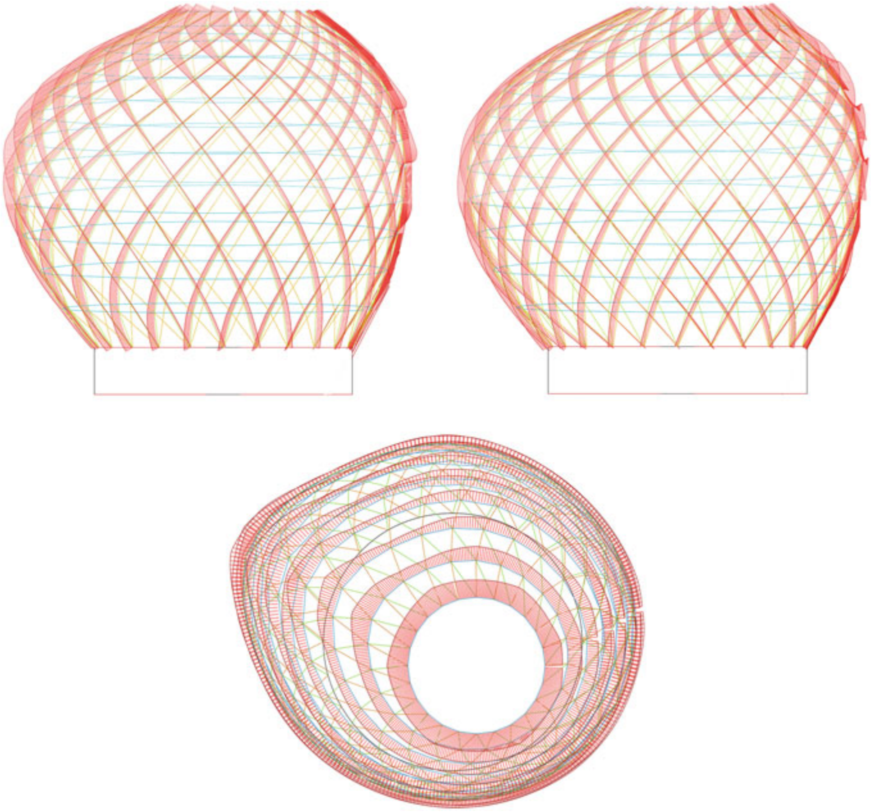

Fig. 3 Analysis of bending curvatures within a gridshell configuration

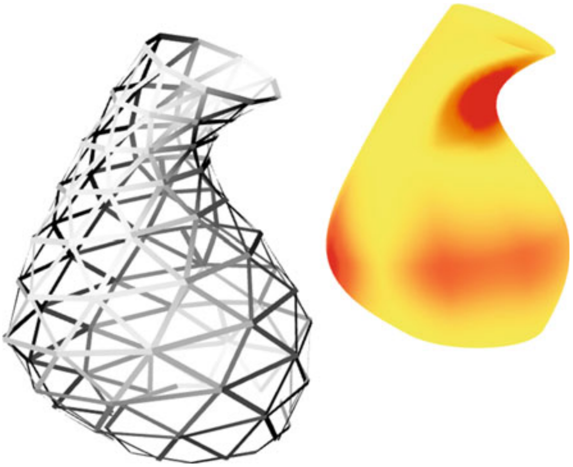

Fig. 4 Surface curvature analysis. Red highlights areas with excessive bending stresses

fruitful to use it in the definition phase of the project, because it does not determine the points that exceed a certain degree of curvature, but it is very effective in the phase of detail design.

The singular (non-standard) nature of bamboo makes it possible to distinguish the strips in relation to the variations in performance that come along with their dimensional features. Having a simplified scheme that identifies the points that require a greater bending effort, allows to better distribute the material with respect to flexibility and extend the optimization process throughout the whole construction phase.

The bamboo strips, in addition to curvature, are subjected to twisting. As for the bending behaviour, the study phase can highlight critical points of torsion and thus warn the designer. In some cases the torsional effect can enhance the material's natural resistance within the gridshell. Most criticalities can be faced with empirical adjustments. As an example, longer screws can be used for those nodes where the torsion is expected to be higher. The loser spacing between the three layers of strips allows for a reduction in torsion. Manual dexterity and some experience in handling the material can empirically solve such situations.

3.3 Shape Optimization

Generative software allows for shape optimization in relation to endogenous and exogenous parameters.

Endogenous parameters include the limit figures for curvature and torsion. While in the process of analysing such data, as described above, is a matter of verification, the same information packages can drive the optimization approach in a process of morphogenesis. The implied numerical values can make a solution emerge that can be considered as optimal with respect to the examined data set.

When gravitational forces and exogenous weight forces are combined with the material's features, structural morphogenesis is possible.

Other plug-ins, *Kangaroo* [32] and *Karamba* [33], are added to the Rhinoceros + Grasshopper [31] software system, which simulate the physical behaviour of structures. The structure's final shape emerges from the forces it is subjected to. In bamboo gridshells, this structural optimization work allows for experimentation with complex yet stable compositions.

Climatic factors such as sun or wind patterns can determine a morphogenesis for the optimization of environmental comfort. In this case the bamboo gridshell becomes the supporting structure of shading systems or corridors for cross ventilation.

3.4 Quantity Design

Working with parametric software allows us to keep a large amount of numerical data related to the project under control in real time. This can include material quantities.

For example the software can help in defining the total length of the bamboo strips, from which the number of whole rods is easy to obtain. Further data include the actual number of strips with its specific length. These data are also organised in groups according to the shell's wrap. Knowing the length of each strip allows for a resource optimisation while choosing the material to use. It also helps in defining the additional amount of overlap material to consider for those strips that can't be built from one single piece. The number of nodes, another information that can be assessed in real time, corresponds to the number of connectors needed.

Keeping the quantities under control while designing also allows to adjust the outcome according to changes in material availability or budget.

Designing with real time quantity control speeds up the construction process, ensures greater precision and helps to reduce waste.

3.5 Digital Models for Triaxial Bamboo Strips Gridshells

The digital model of the bamboo gridshell is generated by a surface, which follows the logic of morphogenesis and formal optimization and is then divided into a triaxial pattern that discretizes the surface in triangles and vertices. In the physical translation, the pattern's edges correspond to bamboo strips with a width between 25 and 30 mm and a thickness of approximately 5 mm, while each vertex represents a node or connection.

As the morphogenetic process includes specific parametric data on the material's behaviour, specific constraints come as a result. With respect to the described bamboo strips, the distance between two distance points varies in a range between 10 and 50 cm. A smaller distance would make the assembling process difficult while meshes with more than the said maximum distance could lead to buckling effects and affect the object's overall stability.

Even in the various compositions, the three axes have a similar organisation: the first axis is composed of arches or closed circles, the other two cross along the first with an opposite inclination.

The model is represented in a simplified way through the segments between the nodes in which each strip is discretized. The overall form is already readable, however in order to have a graphic representation which is more consistent with the final result, strip thickness or colour information can be added.

3.6 The Translation from Digital to Manual

In order to translate the virtual model into built reality some additional passages are needed, especially with respect to how the flux of information from the software to the building site is managed. The steps of this process are: definition of the virtual model, prefabrication, assembly. The prefabrication process consists in pre-perforating each strip with its connection holes in the exact position.

The virtual model already contains the indication on where to drill, a geometric entity that corresponds to the distance between two specific nodes. It is actually possible to visualise this information as a cloud of figures; a suggestive but not easy to read representation. The need for readability comes along with the fact that the natural material requires to be processed by humans. An assembly map with a specific level of abstraction solves this gap (Fig. 5).

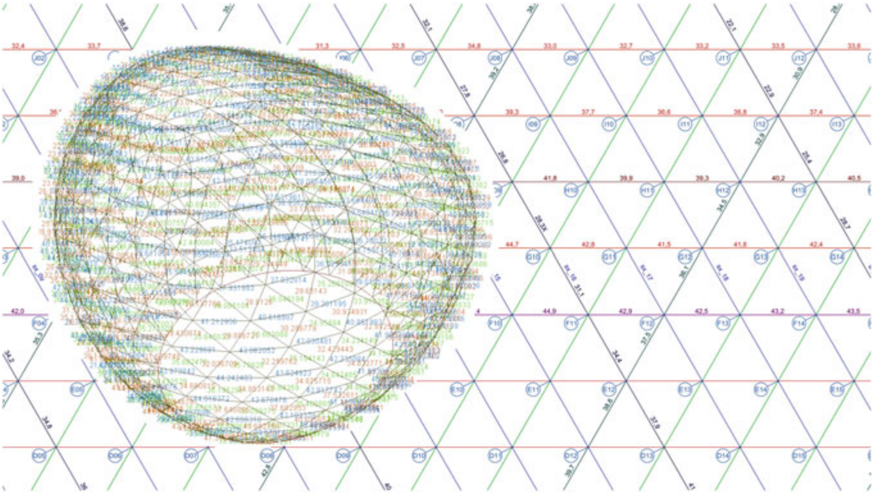

Fig. 5 Numeric assembly map. The number cloud (left) represents the actual shape while the abstract plane representation makes the manufacturing possible

A special script allows to project each distance-figure onto a grid of equilateral triangles just for the sake of graphic order. For every strip to be used in the final work, this simplified representation makes it easy to deduce the following information:

- _total length,
- _alphanumeric code attributed to the strip,
- _distance between each node,
- _alphanumeric code attributed to every node.

This last information is crucial for the passage from prefabrication to final assembly where nodes with the same name have to be joined with a connector element as shown in Fig. 7.

3.7 Nodes and Joints as Control Entity

Bamboo strips can mainly be connected in two different ways. If interwoven in patterns that are tight enough, it is possible to generate stiff curved shapes that can stand only through friction. Such weaving patterns can be bi-axial (warp and woof) or tri-axial with a pattern of hexagons and triangles (Fig. 6).

As an alternative, bolts or other punctual connections can be used to join different layers of strips. According to the design's overall character, iron bolts or timber pins can serve as connectors to hold a grid pattern in place (Fig. 7).

In both cases it is important to consider the right bolt or pin diameter which has to cope with the strip's width in order to balance connection strength with the fact that the strip shall not be injured too much. The connector's length varies according to the degree of curvature and torsion in the various positions of the shell surface.

The described nodes are reversible which allows disassembling and reassembling the structure several times, an additional benefit in terms of circularity.

Fig. 6 Woven shells with bi-axial (left) and tri-axial (right) patterns

Fig. 7 Iron bolts (left) or timber pins with hemp rope (right) as node-connectors

Triangular patterns are the most used due to their intrinsic stability. At the same time triangular meshes are also easy to control with algorithms. In the virtual model the physical node is nothing else than the intersection of three axes.

In the built reality, the three orientation axis lay on three overlapping layers which requires an offset adjustment of the virtual model that takes the strip thickness into account.

3.8 Construction

The gridshells are assembled manually with simple tools: saws, drills, screwdrivers and similar carpentry tools. The precise execution of the indications contained in the assembly map shown in Fig. 5 makes the designed shape appear progressively.

At the end of a correct execution the final design exactly corresponds to the morphogenetically designed virtual model (Fig. 8).

4 Conclusions

The use of locally sourced natural material in architecture is getting of crucial importance if we want to shape appropriate spaces for a growing world population. Facing the increasing complexity that comes with global interconnection and always more rapid new scientific notions, calls for control tools in all design stages.

Methods that can make the non-standard, natural peculiarities cope with algorithmic (or parametric) design tools have to be found. *Digitalbamboo* is a first attempt to make these two realms come closer to one another in a perspective of defining a new architecture that is natural and digital at the same time.

Fig. 8 *Jinen* for Tono Mirai (design: Tono Mirai; technical implementation: Salvatore, A., Siani, R., Pollak, S. - Venice 2021) and *Pagurus urbanus pacificus* (Rome 2019) built

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