Teaching Digital Design and Fabrication to AEC's Artisans

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Abstract This contribution describes an operative research activity within the teaching of digital design and fabrication to Architecture, Engineering and Construction (AEC) artisans. The didactic approach described arises from the lack of academic paths thought for AEC's artisans, highlighting the reason why this aspect is relevant for both the AEC and the artisanal fields. In particular, the article reports a research project carried out by two artisans who attended the C.E.S.A.R. Course, an annual university course organized by the Politecnico di Bari in collaboration with Les Compagnons du Devoir, a historic French professional association. In particular, the research project concerns the study and the digital transposition using digital design and fabrication processes and tools of the "Bridge over the Basento River" designed by Sergio Musmeci.

Keywords Digital fabrication · Digital crafting · Architectural didactics · Digital artisans · Basento Bridge

United Nations' Sustainable Development Goals 8. Promote sustained · Inclusive · And sustainable economic growth · Full and productive employment · And decent work for all · 9. Build resilient infrastructure · Promote inclusive and sustainable industrialization · And foster innovation · 12. Ensure sustainable consumption and production patterns

1 Introduction

The paper aims to describe an educational experience of designing and building a prototype using digital fabrication techniques and its consequent didactic implications. The experimentation is based on the didactic method of learning by doing and experiential learning, where knowledge is transmitted not only through lectures but also and above all through proactive and laboratory experimentation. This approach

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has already been adopted by the author, with other colleagues, and with architectural students during the design workshops in the third and fourth years. The method is particularly useful when it is necessary to acquire skills in complex and interrelated topics such as digital design and fabrication, architectural geometry, and form-finding. The case study of Musmeci's Basento Bridge was chosen because it is suitable for bringing all these aspects together and giving students an overview of such aspects. In particular, the paper refers to the teaching of digital design and fabrication to professional artisans without a specific background in AEC design topics, which is an uncommon didactic case study for architectural schools' agenda. The advanced digitalization of the craftsman operating in the AEC sector (both inside factories and building sites) is essential to reach the new 4.0 standards of the fourth industrial revolution, also when they are employed in SMEs, or they are self-employed.

2 Background: Digital Design and Fabrication Within the Academic Context

Digital fabrication is intended as the manufacturing process in which the physical model is produced through machines controlled by the computer starting from a digital model. Between the 1990s and the 2000s, the widespread use of computers in architecture changed the way buildings were designed and built. In 1992 the Gehry Partners LPP studio created a fish-shaped pavilion to be placed on the Barcelona seafront. The three-dimensional IT model was obtained starting from a study maquette. The surface thus generated was then utilized to perform the structural analyses and to obtain all the building components. For the first time, the production and assembly of the components of the structure were completely directed starting from the digital model [17: 8]. Kolarevic and Male-Alemany [13] emphasized that, following Gehry's example, the architects understood that the information of the digital model could be used directly for fabrication and construction, thanks to the use of numerical control machines. Kolarevic stated that the most interesting potentiality of integrating digital fabrication in the architecture practice is to revitalize the close relationship that once existed between architecture and construction: "By integrating design, analysis, manufacture, and the assembly of buildings around digital technologies, architects, engineers, and builders have an opportunity to fundamentally redefine the relationships between conception and production. The currently separate professional realms of architecture, engineering, and construction can be integrated into a relatively seamless digital collaborative enterprise, in which architects could play a central role as information master builders, the twenty-first century version of the architects' medieval predecessors". In this direction, other authors [6] stated that the contemporary designer can be defined as a novus architetto adaucto; in other words, an "expanded designer" who possesses new (robotic) arms which allow him to cut and shape the materials according to his direct requirements (almost) without any external mediation, paradoxically like the architect-master (or master builder) of the past. Anyway, as for architects and engineers, there is no evidence to exclude artisans from this important change. In fact, like during the Middle Ages, when stonemasons directed the construction of the cathedrals, being effectively responsible for how they were built, nowadays artisans can take part in the design and construction choices of the contemporary building sites, if adequately prepared and skilled. It is a fact that digital fabrication brings a significant change in Architecture, Engineering and Construction (AEC) industry, particularly in the planning and execution phases. As a result, scholars have already highlighted that it is expected that current construction roles will evolve, and new roles will be created: the responsibilities of the construction workers will shift from unsafe and hard conditions to safer and less labour-intensive, such as monitoring and control automated processes by transferring their know-how to the robotic systems [5]. In the absence of specific academic training paths for artisans who operate in the AEC sector (that we call "AEC'S artisans"), the acquisition of digital competences is left to the resourcefulness of individual workers or to the companies where they work. The birth and diffusion of the Internet have contributed to creating a pervasive digital culture (makers culture), that has allowed us to fill formative gaps casually and informally. Lee [16], analysing the "maker mindset" and its implications for education, has defined this mindset as playful, asset-and growth-oriented, failure-positive, and collaborative. Some scholars believe that the Fab Labs could potentially challenge the structure of society in the coming years because with their diffusion, knowledge is no longer statically placed in universities, companies, or research centres, but it is increasingly moving towards the creation of a fluid and adaptive network able to informally spread knowledge and innovation [17]. Despite this view, it is undeniable that the academic context had a crucial role in the birth of the maker's movement: the first digital fabrication laboratory (Fab Lab) has been founded at MIT in 2001. Again, at MIT in 1998, Neil Gershenfeld - director of the Center for Bits and Atoms - inaugurates the course called "How to make (almost) anything". As a computer scientist, Gershenfeld conceives an interdisciplinary course, in which students can learn how to use CNC machines of industrial derivation to develop fully functional experimental prototypes [10]. Afterwards, several scholars studied the relationship between didactics and digital fabrication, especially in architecture schools. For example, a 2-year course called "File-to-Factory Digital Fabrication" has been launched at the University of Nebraska-Lincoln in the early 2010s. The course goal was for students to synthesize various disparate architectural assemblies and materials with the file-to-factory digital fabrication process to understand the making architecture [11: 22]. A mix of classes and lab periods has allowed the students a better understanding of digital design and fabrication processes and the production of physical prototypes [11: 29]. Another didactic model, called "Digital Design Build Studio" has been organized in both individual activities (first part of the studio) and group work (second part); for the final part one project has been selected and developed further, to test ideas on a 1/1 scale, to allowing "the studio to fit in the existing curriculum but also allows for an investigation and research that goes beyond the regular design studio setting" [21: 201]. In a study about engineering education, Sheppard et al. [22] proposed the categorization of laboratory instruction into three levels. As summarized by Celani [4: 476], the first level concerns novice students that must follow the instructor’s directions strictly, step by step, to reach the desired results, which will demonstrate a concept. Next step concerns intermediate students, that must do some exercises to understand the mathematical description of the theory. The last step consists of developing laboratory simulations that illustrate the same phenomenon, in which advanced students can validate the concepts learnt by testing them with different parameters and conditions. Celani states that “as digital fabrication labs become more common in architecture schools and are assimilated by design instructors, they can promote changes in architectural education, allowing students to become closer to the production process and to have a better control over building parts and materials” [4: 480]. Furthermore, Celani affirmed that digital fabrication laboratories have the potential of promoting experimental methods in architecture together with a scientific approach, which is the basis of contemporary architectural practice [4: 480]. In fact, in the last decade, several digital fabrication laboratories have transformed their pioneering explorative research into a scientific activity, with the design and fabrication of full-scale models (that we may also call “proto architectures”) that aim to demonstrate the goodness of an empirical hypothesis. Anyway, these advanced research activities are not usually accessible at the undergraduate level of education, but they are thought for master’s and Ph.D. students, generally enrolled at Institutes of Technology and Polytechnics. To overcome this limitation in the so-called “post-digital era”, Figliola [9: 35] proposes the inclusion of modules relating to computational design and digital fabrication in educational programs starting from the first university education cycle. As stated before, a similar approach was developed by the author’s research group during architectural design studios held during the 3rd year course (out of 5 years degree program) at Politecnico di Bari [7, 8], in which a “learning by designing” approach was adopted both in the realization of scaled models of building components, realized by using digital design and fabrication tools, and in the architectural design of the whole buildings, which embedded those components into the overall design. Stavric et al. [24] underline that the teaching approach for learning digital design and fabrication should be based strongly based on geometry, mathematics, programming, hardware computing and material behaviour. Again, the translation of digital models into physical ones is one of the cores of the teaching activity. Anyway, other scholars argued that the introduction of digital fabrication and design in upper primary and lower secondary schools poses several issues related to the contradiction between a curriculum-based and highly goal-oriented school setting and an experiment-based and highly explorative maker culture. The study revealed that teachers were not technologically or methodologically prepared for an educational program that did not align with the structure of conventional training, because the explorative nature of digital fabrication challenged the authority of the teachers and jeopardized their feeling of being in control [23: 46]. In any case, the education on digital design and fabrication seems nowadays essential for all kind of students, especially for those will start an academic path into STEM disciplines or for those that will work into companies related to manufacturing or engineering. Numerous architecture schools all around the world have incorporated digital design and fabrication coursed into their degree programs. Regardless of the education path of each, Gershenfeld believes that the digital revolution in manufacturing will allow people to produce objects and machines on demand, allowing the birth of new hybrid professionals, named "makers" or "digital artisans".

3 A Didactic Approach for AEC's Artisans Within the Academic Context

In [3] Richard Barbrook and Pit Schultz coined the term "digital artisan" in their Manifesto for describing who works within hypermedia, computing, and associated professions. Even if the definition is not specifically related to who commonly can be defined as "artisan", their Manifesto does not preclude the inclusion of them, because the authors intended to celebrate the Promethean power of the digital artisans' labour and imagination to shape the virtual world. They imagine that digital artisans will build the wired future through their own efforts and inventiveness by hacking, coding, designing, and mixing. Thus, the introduction of such topics into traditional teaching programs poses different challenges but it could also be an important opportunity for developing a holistic approach and developing critical thinking skills. Anyway, the use of the Internet to share knowledge openly and fluidly within the makers' context is one of the reasons which is not easy to establish proper academic paths to transfer knowledge from universities to qualified workers who need to update (or create) their digital skills. In other words, it is easier for them to search informal didactic resources (articles, blogs, tutorials, etc.) rather than start an academic formative path. There are two reasons for it: the first lies in the lack of academic coursed dedicated to AEC'S artisans; the second lies in the fact that often a professional diploma is not a sufficient requirement for being accepted in a traditional academic course. These challenges can be overcome by establishing innovative formative partnerships between professional associations and academic institutions, joining their efforts to support workers and companies in the so-called "lifelong learning". Regarding the relationship between the AEC industry and the artisanal field, there is a need to formulate a didactic approach adequate to train artisans (who may be employed both by manufacturing and construction companies) in a way that they can be part of a holistic framework where design, fabrication, and construction aspects are seamlessly linked together. The recent development of the Industry 4.0 imposed the development of the homologous "Architecture 4.0" in which designers (architects and engineers), artisans, workers contractors, suppliers and construction companies share the same language and the same processes [2]. Lanzara [14] states that the involvement of the academic world plays an important role in the process for the improvement of collective awareness towards a multidisciplinary collaborative ecosystem, by sharing advanced activities to support training and entrepreneurial activity of students or artisans, and for developing a digital conscience.

4 The Theoretical Models Adopted for Teaching Digital Design and Fabrication to Artisans

The operative research described in this paper is representative of the experience that the author has accumulated over the years at the C.E.S.A.R. Course (Cours de Enseignement Supérieur en Architecture et Restauration), held annually since 2015 at the Politecnico di Bari. The uniqueness and the novelty of the course stand in the fact its goal is to create and train a professional profile who can create a closer connection between the restoration site manager (architect or engineer) and the various specialists involved in the study, protection, restoration, management, and enhancement of the architectural heritage, also adopting contemporary tools, such as parametric and digital modelling software or digital fabrication techniques. Inside the overall didactic scheme of the C.E.S.A.R. Course, the classes held by the author about digital design and fabrication are essential for training the new generations of "digital artisans". The digital design classes concern the understanding of the different levels of interaction between the designer and the digital environment, also explaining the differences that exist among the various 3D modelling techniques (Table 1). Digital fabrication classes followed a similar structure that those regarding digital design themes. They are summarized in Table 2. They are concerned essentially with the relationship between the design outputs allowed by using different digital fabrication tools and techniques. In other words, the intention was to transfer the design thinking underlying the different projects who take advantage of digital fabrication processes.

The course is incardinated on the use of the NURBS-based modelling software Rhinoceros. This software has been adopted not only for its user-friendliness but also for its versatility which allows transforming the software into a powerful platform, capable of easily embedding different 3D modelling techniques (NURBS, mesh and subd modelling) thanks to both its native features, above all, using specific plug-ins (for example Grasshopper for parametric modelling, VisualARQ for Bim, etc.).

Table 1 Digital modelling strategies topics of the course

Modelling strategy	Modelling typology
Direct modelling	Solid
	Parametric solid (semi direct)
	Polygonal
	NURBS
	Sub-d
	VR modelling
	Digital sculpturing
Non-direct modelling	Procedural
	Parametric-associative
	Computational
	BIM

Table 2 Digital fabrication strategies topics of the course

Fabrication strategy	Fabrication typology
Subtractive fabrication	Cutting of flat elements
	Cutting of volumetric elements
	Carving of volumetric elements
Bending	Bending of rigid elements
	Bending of flexible elements
	Bending of flat elements using a cutting pattern
Formative fabrication	Digital weaving
	Stretching of elastic material
	Thermoforming
Additive fabrication	Material extrusion of monolithic objects
	Material extrusion of discrete assemblies
	Binder jetting of monolithic objects
	Binder jetting of discrete assemblies
	Additive formworks

Furthermore, Rhinoceros allow the investigation of the three levels of interactions aforementioned: direct modelling, parametric-associative modelling, and computational modelling. Direct modelling refers to the use of modelling software through a consequential but static process. In other words, the digital model is manipulated directly by the user, but any additional modification makes it impossible to go back. In this type of modelling, it is therefore important to preserve the fundamental steps of the modelling process, to be able to return to an earlier phase of the process. It is a typical design process in which we start from the global geometry up to the definition of all the details. A change in the initial global geometry determines the need to restart the modelling process from the beginning. Parametric-associative modelling refers to the use of a parametric modelling software or application for defining the digital model. In this case, the designer concentrates on defining the logical consequentiality of the various steps, which can proceed from the overall geometry to the detail or vice versa. Thus, the designer does not directly generate the digital model, as in the previous case, but generates a parametric "code", i.e., an algorithm governed by some fundamental parameters that define the geometry. For computational modelling, we mean the use of a programming language (embedded or not in a parametric or modelling software) for the definition of an interactive model, in which the designer can simulate various types of phenomena characterized by high conceptual or geometric complexity. Also, in this case, we can proceed from the global geometry up to the detail or vice versa.

The course goal is not only to transfer the artisans some 3D modelling skills but to provide critical thinking to understand the theoretical differences between the different levels of interactions and their use to achieve different fabrication results.

This is because the modelling strategy to be undertaken cannot follow predetermined paths but will be influenced by the need of the specific case. Summarizing these differences, direct modelling is indicated in all cases in which is possible to generate the 3D model easily and at the same time it is not yet possible to define the project parametrically, due to the uncertainty on the road to be taken. This is particularly useful in the initial study phases of the forms. Parametric-associative modelling can be useful when the project is still in an exploratory phase, but it is already possible to define some parts of it from an algorithmic point of view (for example, the tessellation of a vaulted system that is not too complex). In this way, different solutions for a specific design aspect can be examined more easily. This type of modelling can be useful even when the complexity of the project is not so high that it must necessarily use more sophisticated computational tools. The increasingly widespread dissemination of parametric-computational strategies in the design field has made it possible to apply new operative models of computer origin also in the fields of architecture and engineering.

In general, it is possible to state that the computational and parametric design can follow two models: top-down and bottom-up. Both models have been theorized in the field of computer science and are used as strategies for writing parts of program codes. In top-down models, the starting point of the design process is represented by the formulation of a general systemic idea, from which all the sub-problems that compose it follow. The model provides the progressive finishing of all parts as they are designed, and new elements are added to the system. In bottom-up models, the starting point of the design process is represented by the detailed definition of individual elements of the system, which are subsequently connected and interrelated to each other, up to the definition of the overall system.

5 Operative Research: The Digital Design and Fabrication Transposition of the "Bridge Over the Basento River" by Sergio Musmeci

In this section, top-down operative research (final exam) carried out by two student-artisans is described. This project is described as an example of the application of the didactic approach described before, concerning the study and the digital transposition using digital design and fabrication techniques of the shape of the "Viadotto dell'Industria" (Industry Viaduct), commonly known as "Ponte sul Fiume Basento" ("Bridge over the Basento River"), designed by Italian engineer Sergio Musmeci and built between 1971 and 1975. Musmeci's Bridge has been chosen for different reasons: firstly, the project is a unique engineering (and architecture) masterpiece, and it is also a clear example of what is possible to achieve when the architectural shape is completely linked to structural behaviour aspects. Plus, the project has been originated by generating different physical models, as described afterwards, and it is generally considered one of the precursors of contemporary digital form-finding techniques. Lastly, the bridge presents a non-Euclidean, complex shape, suitable to be used as a case study to train the students in advanced and parametric modelling, digital fabrication, and architectural geometry.

The operative research method was based on the learning-by-doing approach. Thus, a sequence of tasks has been assigned to the students to allow the acquisition of knowledge on the chosen topic proactively and progressively:

1. Historical investigation of the case study and understanding of its cultural value for architecture and engineering.
2. Investigation of design and form-finding strategies to obtain the overall shape of the bridge.
3. Critical evaluation of the design and form-finding outputs and the model-making feasibility.
4. Definition of the final digital design and fabrication process.
5. Critical evaluation and description of the design issues and improvements.

6 Historical and Cultural Research

Basento Bridge is one of the best examples of a shell structure built during the XX Century in which physical models have been used to determine its optimal shape. Even if physical models have always been used in architecture for different reasons, like representing the project, studying its proportions, its structural behaviour, etc., the models used for searching the optimal shape of a given structure are of more recent introduction. It is important to underline that not all scale models can be used for structural purposes. The phenomena or structural behaviours that can be scaled linearly, concern the linear dimension of a structure, the funicular form of a vault, of a dome or a shell, and the stability of a masonry structure subject to compression only [1]. In the Sixties Sergio Musmeci used a form-finding technique originally developed by Otto and Rasch [18], to determine the initial form of the structure of the Basento Bridge. The technique consists of the immersion of metal profiles of the desired shape in soapy water, and it has been used to research the shape and to start the initial calculation processes [15]. Musmeci continued the research by building a neoprene model that allowed the study of the tensions in the two perpendicular directions. Subsequently, a methacrylate model of two spans of the bridge was then built on a scale of 1:100 to verify the correspondence of the form to the design program and was subjected to elastic tests that allowed a first partial control of the calculation forecasts. Finally, before the construction of the bridge, the Superior Council of Public Works requested the construction of a scaled-down (1:10) model made of micro-concrete for loading tests [19: 17–24], a technique already used by Eduardo Torroja in 1933 for the project of the colossal dome of the Algeciras market in Spain. Later, different analogue form-finding techniques have been translated into the digital environment, especially in the last decades.

7 Investigation of Design and Form-Finding Strategies

Among the various digital form-finding techniques developed, like Dynamic Relaxation, Force Density Method, and Thrust Network Analysis, students investigated the use of the Particle-spring system for the investigation of the bridge's shape. As the name suggests, the Particle-spring system is composed of a set of particles connected by a system of springs: the particles represent the points where the mass is concentrated, and the springs are schematized as elastic lines connecting two points. Applications of this form-finding system within computational design have been developed by Kilian and Ochsendorf [12] conceiving CADenary, and Daniel Piker who developed Kangaroo Physics, a particle-spring tool available inside Grasshopper, the visual programming language of Rhinoceros [20]. Considering this background, a particle-spring form-finding technique has been used during the course to train students to understand the relationship between architectural geometry and structural optimization and behaviour. Kangaroo 2 has been initially used for trying to recreate in the digital environment the form-finding process utilized by Sergio Musmeci. The simulation consists of creating a basic flat mesh placed on the XY plane, which represents the membrane on which to apply the form-finding process. On the base mesh, the designer defines the anchor points that will remain fixed while the other points (particles) are free to move according to the resistance of the elastic lines (springs) that connects the various particles. However, in this case, the process provides that some anchor points will no longer be on the XY plane, but they are moved on the Z axis to give the bridge the actual arcuate shape (Fig. 1). Students were asked to replicate the form-finding process described to evaluate the feasibility of physical model fabrication, considering also different materials and production methods.

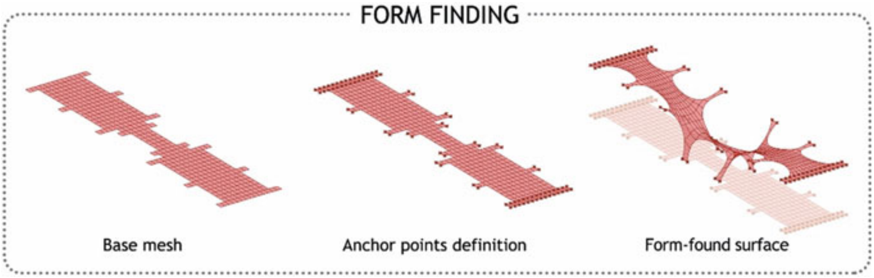

Fig. 1 Particle-spring form-finding workflow

8 Critical Evaluation of the Design and Form-Finding Outputs

Although the output model was fine in its pedagogical value, it was not for its geometrical properties. The form-found model was quite different from the actual shape of the bridge. This difference is because the actual Musmeci's bridge is not a funicular compressed-only shape but, instead, it can be approximated by a tensile minimal structure. For this reason, it has been decided to realize a more accurate 3D model analysing the laser-scanned survey carried out for the restoration study of Musmeci's Bridge. In this case, a mix of basic and advanced modelling has been used to achieve the result. The multiple modelling approach has been encouraged by the author because in this way students had the chance to be aware of the different possibilities that can choose to accomplish the fixed goal. It is important to note that the research goal was not to recreate a surface perfectly identical to the original. Instead, the main interest was to use digital processes and tools to study how to evocate the bridge's shape by taking advantage of the bending properties of a typical material available in a FabLab, like thin plywood, dividing the whole shape into small pieces. This implies the development of a comprehensive computational strategy (although simplified due to the didactic nature of the experiment), from design to fabrication.

9 Definition of the Final Digital Design and Fabrication Process

The author guided students during the development of the whole process, which is formed by several steps (Fig. 2):

- Recreation of the bridge's shape by extracting the fundamental curves from the survey, using them for creating the base NURBS polysurface of the bridge.
- Conversion of the discontinuous NURBS polysurface into a mesh model by creating an ultra-simplified network of quad meshes (coarse mesh).
- Subdivision of the previous mesh using the Catmull-Clark algorithm by simultaneously pulling the obtained mesh onto the base polysurface.
- Extraction of transverse and longitudinal mesh edges (u and v directions).
- Creation of the continuous NURBS surface by a network of curves using the ordered lists of mesh edges of the previous step.
- Study and test the tessellation pattern shape, the material type, and its physical properties (like bending).
- Population of the continuous NURBS surface according to the chosen pattern.
- Testing on a smaller part of the whole prototype the chosen pattern and material behaviour.
- After validation, production of the final model (all the pieces need to be numbered and oriented).

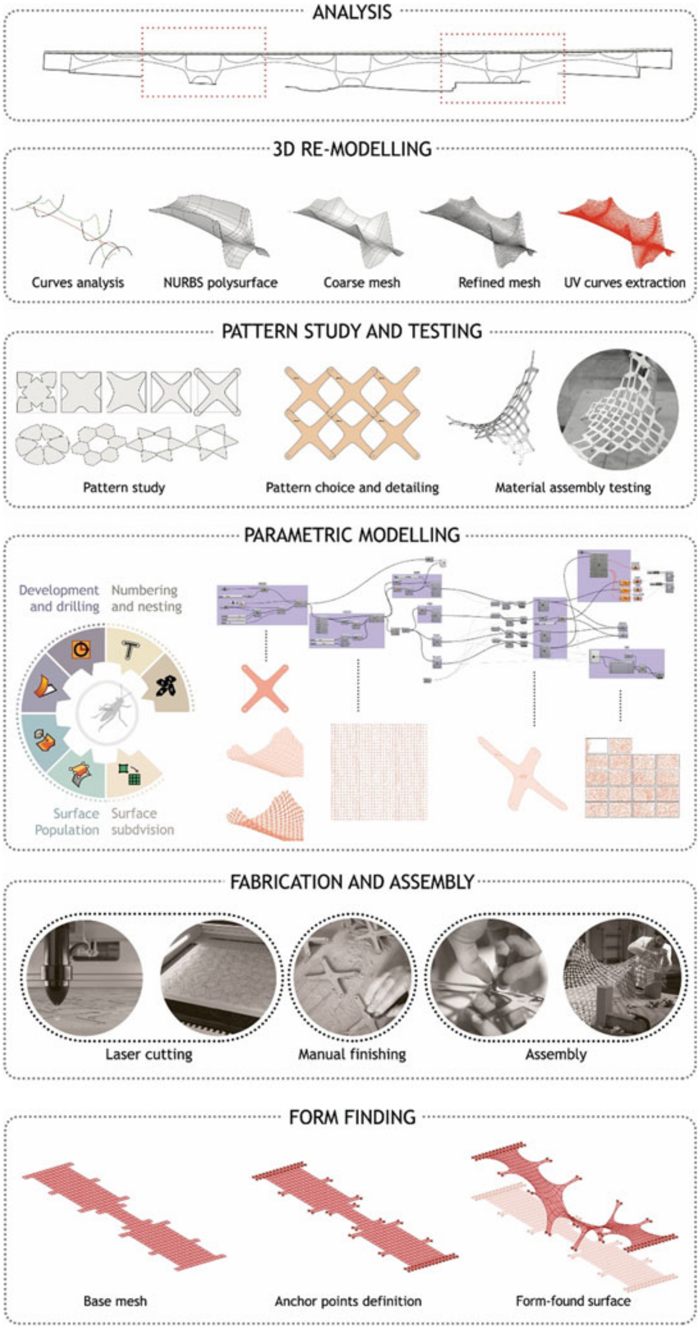

Fig. 2 Project workflow

- Nesting of all the pieces into the defined sheets of material.
- Fabrication through laser cutting tools.
- Final assembly.

10 Critical Evaluation and Description of the Design Issues and Improvements

Some considerations on the consequences of the didactic value of the learning-by-doing approach need to be highlighted. The first assumption of the research was to build a complex surface using only small flat elements. At the start, students intuitively came up with the idea of triangular modules because they are always flat. Anyway, students experimented several challenges testing triangular tessellation, as for example, the problem of the junctions between each element that converges in a point. They tried to solve this issue by adding a soft leather part to each end, but the solution was expensive, difficult to realize and inelegant. After abandoning triangular tessellations, they started to experiment with quadrangular patterns, especially studying the relationship between material bending properties and the pieces' shape. Soon they discovered that using quad pieces allowed a much cleaner and more efficient division of the surface, a better data order into Grasshopper, and a great bendable of the modules if constituted by 4 branches (Fig. 3).

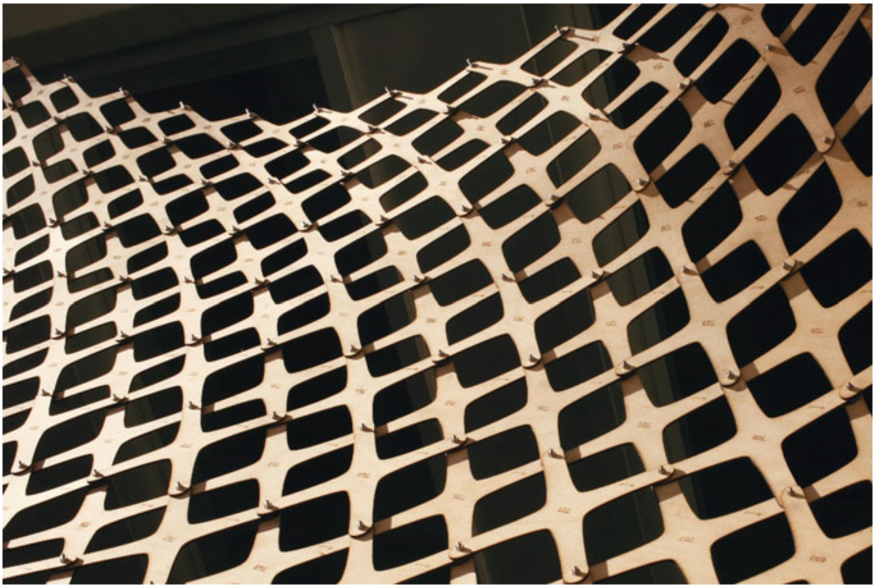

Fig. 3 Details of the assemble plywood elements

Finally, the used pattern was chosen for its aesthetics, but also and above all for its shape: the four branches that make it up are narrow, which has improved the flexibility of the modules. In this way digital and physical models have been conceived together, one influencing the other and vice versa. In fact, after the design phase, students needed to make the first prototype to assess the reaction of the material to the double curvature. The goal was to push the limits of the material as much as possible. For that, they modelled a surface like the bridge one but with a stronger curvature. After having cut all the plywood pieces, they assembled the structure by starting flat. They soon noticed that as they added more pieces, the overall shape began to form due to the tension established by the bent pieces of wood. Indeed, the fact of forcing the parts to be aligned with respect to the screw holes forced the structure to find its final shape (Fig. 4).

In the end, the final model was formed by 980 unique pieces of plywood, fabricated by means of a laser cutter. Each piece has been overlapped and fastened by bolts with to the adjacent one. The model is held on itself, using nylon threads that keep it under tension across its width. The final model has been suspended in the air at the atrium of the Architecture Department of the Politecnico di Bari: the "Flying Musmeci" prototype is ready to intrigue the next generations of students (Fig. 5).

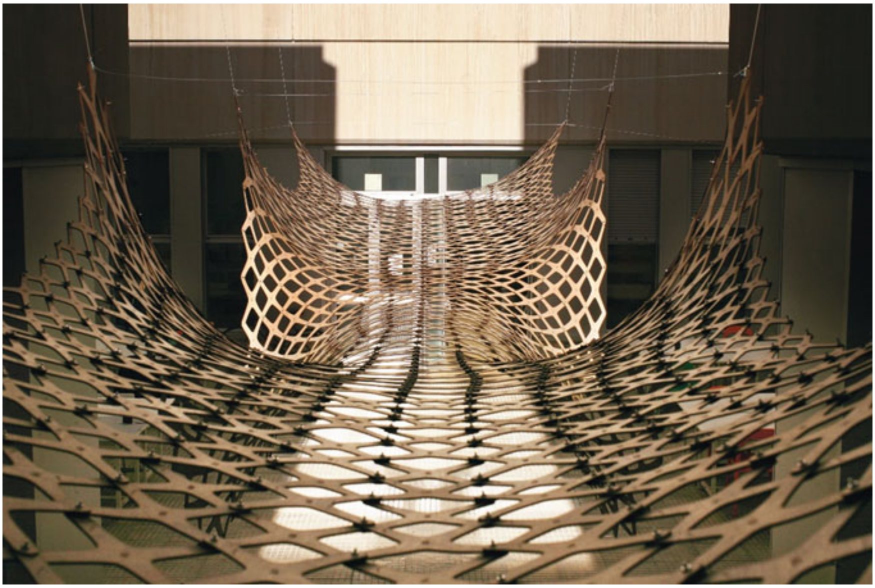

Fig. 4 View of the finished model recalling the shape of the Basento Bridge

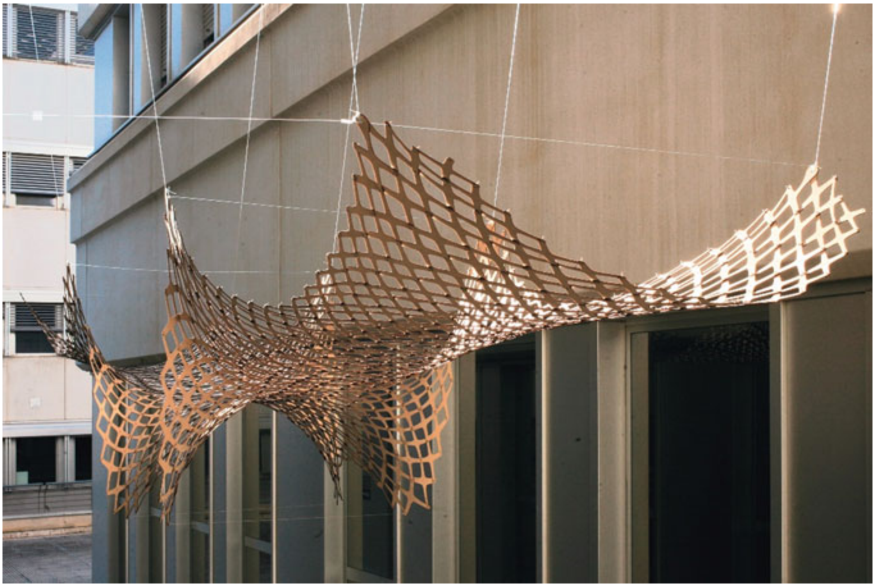

Fig. 5 Picture of the suspended model inside the atrium of the Politecnico di Bari's Architecture Department

11 Conclusions

Through the operative research presented, the proposed didactic approach shows a possible learning path for the education of professional artisans. The framework used for guiding the didactic experience of the students suggests that establishing academic paths on the critical use of digital design and fabrication tools could be a feasible way for enhancing the digital awareness and skills of artisans employed in the AEC industry, with benefits for the entire chain. It can be considered also a reference for new lifelong learning didactics for reskilling operations for experienced artisans who need to gain new abilities required by the labour market. Lastly, it's possible to state that the same approach may experiment also for the undergraduate student's curriculum (i.e., bachelor's degree) because they have similar general knowledge of AEC verticals compared to artisans, especially in the first year of studies.

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