ARCHITECTURE 4.0 – INFLUENCES OF DIGITAL DESIGN IN CONTEMPORARY ARCHITECTURE: TOWARDS THE DEFINITION OF NEW LANGUAGES AND TECTONIC

1. INTRODUCTION

Nowadays, applied research in architecture plays a significant role in the relationship between innovation and professional practice. Maurizio Sabini[1] analyzes the relationship between architectural research – increasingly widespread even outside academic environments – the profession and the sharing of knowledge – a feature considered peculiar to our times. Sabini's initial observation is that "while the explosion of our computing capabilities has allowed us to process exponentially larger amounts of information, changes in mass communications and the invention of the network and the social media have determined the opportunity for – and produced the demand for – a more shared knowledge." Thus, the combination of rapid technological development and the ability to process and share information has led to a cultural change, also affecting the research sector. For Sabini architecture needs to rework the paradigms of a "culture of profession" matured and consolidated during modernity, which are now being challenged by this new "tension" to innovation both in the practical and the theoretical fields. In the last century, and especially in the last twenty years, research has become more and more consolidated as a tool for acquiring new knowledge. On one hand, research seeks to develop what cannot typically be done in the profession, bringing ideas and concepts at the limit of *utopia*, and on the other hand introduces innovation in built architecture. Also outside the academy and in parallel with the profession, research groups develop that, distinguishing the theoretical activity from the practical one, tend to bring innovation to the new constructions to adapt to the needs of contemporary society. There are a lot of architectural studies that have created a true theoretical research center that supports design practice such as OMA, through the creation of AMO, and other major international studies as BIG and MVRDV, or the smaller Italian practices as Mario Cucinella and Aldo Cibic

The changing process of the architectural paradigm is being strongly influenced by the rapid technological development that has exponentially manifested in recent decades. To understand, in general, the context in which we live, it is useful to trace a rapid historical picture of advancing technologies over the last two centuries. Within this framework, it is possible to identify the fundamental stages that have revolutionized the industrial and manufacturing

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[1] Maurizio Sabini "La nuova frontiera dell'architettura", editoriale in The Plan 095, 2017

processes of the western world by making a significant change in society[2]: in 1784 with the introduction of the steam engine; in 1870 with the beginning of mass production through the increasingly widespread use of electricity, the introduction of the internal combustion engine and the intensification in the use of oil as a new energy source; in the 1970s with the emergence of information technology, from which the “Digital Era” emerged to increase the level of automation using electronic systems and IT (Information Technology). Today we are in the midst of the "Fourth Industrial Revolution" in which it is possible to identify the main development paths that characterize it[3]: the first concerns data usage and connectivity (big data, internet of things, cloud computing), the second it is about strategies and methods for analyzing and using these large amounts of data, the third is man-machine interaction through increasingly user-friendly interfaces, and the fourth is the part that deals with the concretization of digital to real and it involves 3D printing, robotic fabrication, etc.; which introduced new production methods labeled as “digital manufacturing” and “digital fabrication”.

2. INTRODUCTION OF DIGITAL TECHNOLOGIES IN ARCHITECTURE

The introduction of digital technologies in architecture and design has profoundly influenced not only the way of project representation and communication, but above all the design approach, opening up wide scenarios possibilities which today are still deeply evolving. One of the first revolutionary inventions that introduced the digital world into design and representation was "Sketchpad" by Ivan Sutherland in 1963. It was a computer tool that, through a hardware interface, allowed for the first time A designer to digitally represent points, curves, and primitive geometries. From this moment on, the development of digital graphics and CAD-based software (Computer-Aided Design) begins. A widespread diffusion of these applications in architecture offices is perceived only from the '90s, when information technology takes foot in many areas, introducing computers as a cutting-edge tool for work efficiency. The first CAD software versions did not used a particular computational potential but provided the designer with a digital version of the tools used ever since, as the simple possibility of digitally managing primitive and two-dimensional geometric shapes. In the following years, the development of 3D graphics, mainly aimed at the entertainment world and then the production of films and animations, is absorbed in architecture and used, initially, to produce render, photorealistic images that designers find functional for a more immediate communication of the project. 3D digital modeling in architecture is a useful support for the designer, which is facilitated in managing the different phases of the project and in controlling all its components, it also allows relatively quick modification and exploration of alternative solutions. The further development of these tools has produced and diffused on the market several more advanced software – such as those now known as Building Information Modeling or BIM – that are no longer used only for graphic and aesthetic management aimed at communicating the idea, but they allow large amounts of data to be organized and set up. BIM has

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[2] Cfr. http://www.economyup.it/innovazione/3713_cos-e-l-industria-40-e-perche-e-importante-saperla-affrontare.htm

[3] Cfr. *supra*, n.1

features that are particularly useful in managing large works and complex projects, facilitating control over the entire process at the various scales of representation and allowing them to modify and search for alternative solutions in a short time. In this context, digital technology has been embedded in architectural discipline: thanks to the support of computational methods developed over the last few decades, it has opened the way for new theoretical and applied research fields.

Technology influenced not only the efficiency of design workflow, but also the exploration of innovative design approaches and fabrication methods. A new paradigm of architecture emerged in the last two decades; at first it was very rough and superficial and somehow “suffered” the inheritance of post-modern architecture and the fashion of labeling architectural movements. Some claimed the existence of a new movement in architecture, the Parametricism (Schumacher, 2008), but this label mostly contributed to emarginate the community of pioneers from the architectural debate minimizing its potential impact on innovation in contemporary architecture. Nowadays, also thanks to the scientific support of contemporary academic research and despite labels and dogmatic positions, there is a new focus on parametric architecture. The term includes a variety of approaches which consider numerous aspects ranging from form-finding process and structural optimization to material properties and construction methodologies.

From a technical point of view, parametric design is built on rules and algorithms and their spatial exploration potential by modifying variables and parameters. The main mechanism that is at the center of parametric and generative design is the algorithm, and is crucial to the technical aspect of the model generation. An algorithm can be defined as a block of instructions designed to generate a result in a specified number of steps. One or more values are entered as inputs, processed by a series of computational steps and finally transformed into one or more output values. In order to control the design process, it is necessary to know the operation and the logic of the algorithm, this is defined as “algorithmic thinking”. Informally, for example, a recipe can be compared to an algorithm that starts from the ingredients as input, passes through operations and steps that follow a very precise order and arrives at the final output. The algorithm can be understood as an extension of the human mind that facilitates a series of operations and helps to reach a – sometimes unexpected – result.

Through the analysis of two international contemporary case-studies the paper shows how the digital design is influencing the architecture practice not only from a linguistic point of view but, most important, in the process of design itself and in the construction methodologies. In fact, the analysis of these two projects is mostly focused on the process followed by the authors to reach the results, rather than just on a critique about its final exterior aspect or its relationship with the context. It is also worth to mention that the following case-studies are results of academic studies, which demonstrates the importance of research in the architecture field and its innovative potential. This two pavilions approach the theme of timber construction from different points of view: the first shows an efficient workflow and introduces the potential of robotic fabrication and digital-informed system for the construction of a grid-shell in the case of a large-scale building scenario in which construction regulations and requirements need to be satisfied; the second focuses on a material oriented structure which exploits wood structural properties and, consequently, proposes an innovative joint connection for such structure.

3. CASE STUDY 1: Timber Structure Enterprise Pavilion at Horticultural Expo

Timber grid-shell

This project supervised by Prof. Philp F. Yuan, chief architect of Shanghai-based architectural firm ArchiUnion, demonstrates the potential of a digital geometry system to integrate robotic fabrication and structural performance-based design in a large-scale building scenario. Advancements in timber construction technologies, such as CLT (Cross-Laminated Timber), brought wood to be a widely-used building material with properties of large-scale adaptability, high structural performance and long durability. Among the numerous examples of timber use in architecture, during the last century wood has been frequently used to construct large grid-shell structures. Timber grid-shell is a complex system since it involves special drilling and cutting process and a sophisticated joint system. In usual timber grid-shell structure an optimized combination of a structural performative geometry with simple joints and details is difficult to achieve, because an optimized macro-scale geometry would lead, most of times, to have a variety of different beams components and, thus, to different connections. Moreover, the design and construction of timber shells is highly restricted by building regulations which requirements spans from fire resistance performance to structural stability for wind and seismic loads. These observations bring to consider different parameters for the design and construction of a timber-shell structure. The project demonstrates how it is possible to manage all these parameters together and build, in a short time, a pavilion that correlates structural performance-based design with timber grid-shell construction process, through an integrated digital platform.

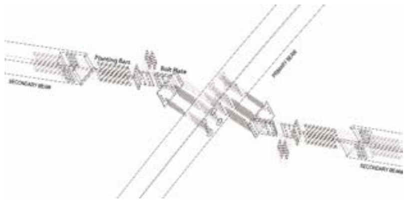
As a demonstration of the innovative impact of academic research on architectural practice, the project fabrication method and design approach was firstly introduced, discussed and tested during a research workshop supervised by Prof. Yuan at Tongji University of Shanghai. The design mainly focuses on two aspects: design and construction process of non-uniform timber shell structure and “large-scale” architecture practice – which needs to deal with local construction regulations. Moreover, the project aims to test and spread applications of parametric design approaches and robotic construction methodologies on built architecture.

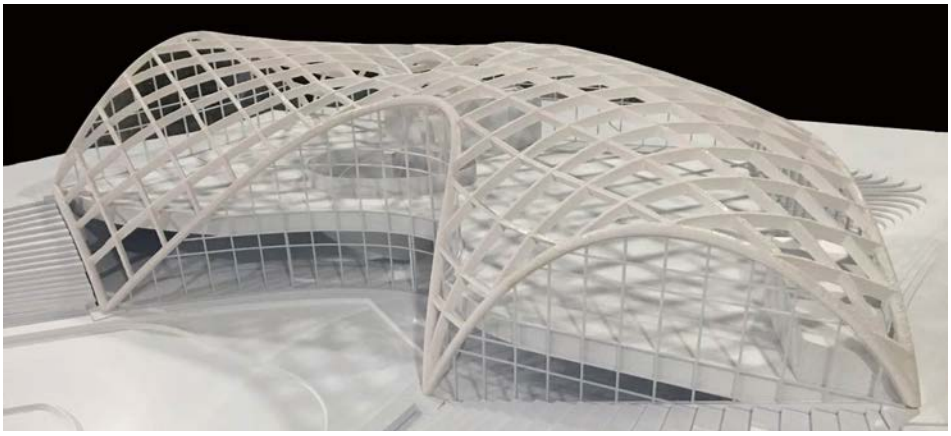
In a first phase a form finding process through structural simulations of a gravity-based shell was performed. Then the grid was set up on the resulting shell, and a series of basic prototypes have been developed for the study of joint connections. The form finding process, performed with RhinoVault (a Rhinoceros® plug-in developed by Block Reaserch Group at ETH Zurich) takes in consideration few constraints such as the site boundaries, the entrance, and a central pillar as element of complexity. The form finding process is limited to calculate static equilibrium of stress distribution based on gravity, for this reason a number of structural simulation tests were conducted to optimize the structure behavior also for lateral loads (wind and seismic). These tests helped to define the beams cross section which continuously varies from 65 cm x 25 cm to 35 cm x 25 cm.

The second part focused on a detailed development of the joints and fabrication of optimized components, which were studied according to local curvature and stresses. In particular, the primary beams and the steel joints were fabricated using traditional CNC industrial processes, while the secondary beams cutting and drilling were implemented by robot. The robotic fabrication helped milling the holes for the steel plates, since they are not perpendicular and would have been difficult to realize by traditional techniques.

The third part regarded the gap between virtual design and physical realization. All the information and parameter that affected the final geometry (including structural and fire regulation) were inserted in a virtual model which was later used to export the codes for the CNC machines, to perform the structural analysis and simulation for optimization.

The final structure of this projects, a 2000 m² space with a maximum span of about 40 m, demonstrates the potential of parametric design approaches through the workflow optimization, on one hand, and the customization possibilities of components thanks to robotic fabrication technique. It represents a hybrid of multiple fabrication methods, and one of the first application of such techniques in large scale building scenario.





4. CASE STUDY 2

Robotic Sewing

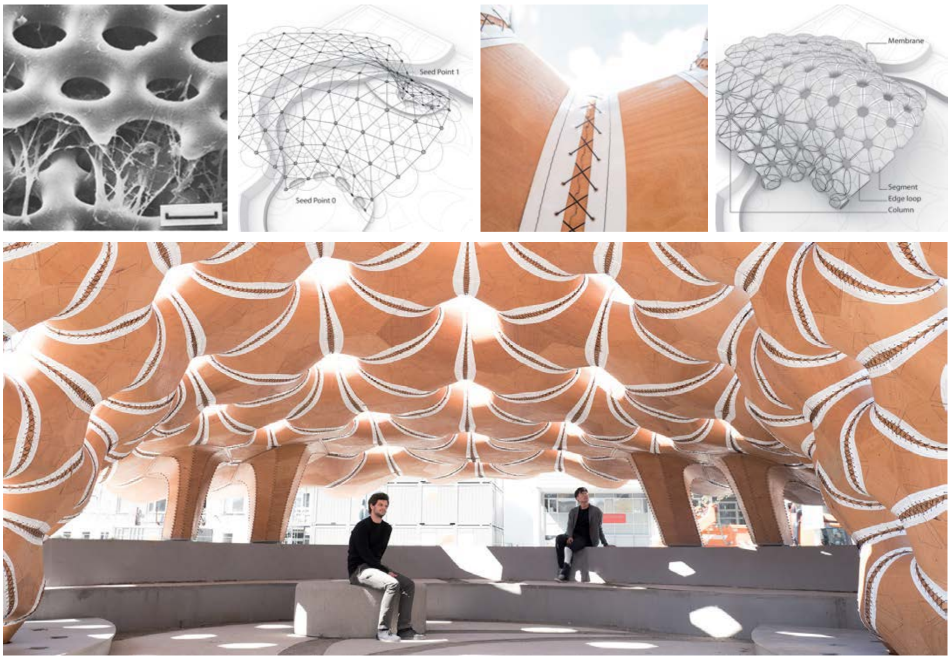
The research project conducted by Prof. Achim Menges at the Institute of Computational Design of Stuttgart, is an experimental pavilion which explores material-oriented design and innovative joint in a light-weight timber shell. Thanks to the advancements in timber constructions technologies such as the introduction of cross-laminated timber, nowadays we are able to use wood structural properties in an extremely adaptive and flexible way. But still, the typical use of CLT structures is characterized by massive cross section of the elements and thick metal joints. The research aims to demonstrate how, with the support of computational design and digital fabrication techniques, it is possible to obtain light-weight and structurally efficient construction by using very thin timber components and reconsidering the new typology for joints connection. On the other hand, recently developed form-finding principles allows a deep understanding of structural behavior for free form shells construction. Moreover, from computational design approaches we can assume that geometry variability can lead to high performance, similar to what happen in nature.

As timber structural behavior is highly influenced by its fibers direction, current construction technologies tend to use the more developed materials as plywood or fiberboards for their homogeneous behavior. The research reconsider the textile properties of wood, applying techniques such as sewing, patterning and lacing for optimizing the structural behavior. Using very thin rotary sliced veneer (1mm) the material become extremely flexible and it behaves is like a textile, and sewing technique for connection results an interesting approach, as for the textile, since it allows a good distribution of the stresses in the joints. Although in the sewing technique human labor is still required because of textile complex behavior and simulation complexities, the use of robotic arms opens to wide possibilities in the case of 3D sewing without a constrained working plane.

The method used for the design and construction of the presented pavilion, starts with the application of biomimetic principles for the generation of a self-supporting and structurally efficient shell. A deep previous research provided the principles for extracting the structural pattern of an *Echinoidea* shell. The shell has been parametrically modelled using NURBS, to get structural, spatial and geometrical characteristics of the pavilion. In the subsequent phase the domain of the structure has been defined as a particle system, originating in the support points, which represents the “segment” (the basic cell of the pavilion) center points and implement the growing radius of the segments over the time. The result is an evenly spaced arrangement of input points with tangent circles indicating the increasing radius of separation between segments away from the seeding origin. In the third place a triangulation of the points has been done, and the edges of the resulting triangular mesh form the basis for the generation of the segment loop in the cell.

A parametrically designed model has been built to manage together the design intent, material properties of bending custom-laminated plywood and fabrication constrains. Each design phase has been structurally analyzed and informed, in this way the model contains also all the fabrication data. Since the wood is here treated as a textile, the relation between bending stiffness and direction of the grain has been studied and tested. The areas with high curvature requires thin material layer and the direction of the fibers is almost perpendicular to the bending direction. On the contrary, the areas with low curvature has thicker material layer (almost double) and the fiber direction is parallel to the bending direction.

The single "segment" of the pavilion is composed by three stripes, each stripe is divided into 100 mm wide areas (with variable length) so that it is possible to differentiate the grain direction according to the variable curvature. A robotic prefabrication is then used to bend together the strips which are then glued together to compose the segment.



Then an industrial sewing machine is used and the robot guides the segment through the sewing process. Along the loops an additional membrane is sewed with similar process, which will allow the connection with neighbor segments through lacing. After the 151 segments have been completed, they were assembled on site in 12 days using lacing technique. The final structure has a weight of almost 800 kg, covers an area of 85 square meters and span for 9 meters.

5. CONCLUSIONS

Thanks to the advancements in new digital technologies and fabrication techniques, in the latest two decades the research in architectural field gained a renewed interest. Not only research in becoming a fundamental step for experimentation in architecture field, but it also supports the application of scientific advancements in the architectural practice – the "large scale architecture" which is what goes beyond the experimental pavilions – bringing innovation in the use of material and exploiting recent technologies and construction methodologies. In a first phase, when digital tools were introduced in the architectural discipline in the nineties, a number of experiments and complex shaping research was performed, in order to explore and understand the potential of this tools. Some of these approaches can be summarized in the early projects of Frank Gehry or Zaha Hadid, which shows, in this initial phase, a mere formalism that lacks a solid theoretical background. Nowadays the best globally known research institutes and universities are focusing their efforts and resources on these topics, creating the theoretical and practical background needed to embrace and being able to coherently control the new technologies. As a consequence of this global direction of academic researches and experiments, a renewed interest in tectonic rules emerged, converging on the study of structural properties and performances of construction material – such as brick, stone, concrete, wood, but also plastic and carbon or glass fibers. Within this context and framework, digital fabrication and parametric design approaches – or digital design approaches – are able to introduce new patterns and a new architectural language which evidences the coherence and the relationship between form-structure-material, redefining the paradigm of known traditional tectonic as "digital tectonic".

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SUMMARY. During the last two decades, the advancements in digital technologies strongly influenced our life and spread through various professional fields. The impact of this so-called "4th Industrial Revolution" is visible both in the efficiency of the workflow and, above all, in the introduction of approaches and methodologies that allows to achieve revolutionary results. In the field of architectural design this change is bringing to new languages and tectonic rules, based on innovative design approaches, through the exploitation of digital technologies and digital fabrication methods. A basic key point of the discourse on digital architecture is the development of research, both in academy and professional offices, which deeply explores technical and conceptual approaches, bringing innovation to the architectural practice. During the last ten years, theories and debates emerged around the definition of "parametric architecture"– which is an almost old fashioned way to generally identify weird-shaped architecture – but beyond the theoretical positions, it is clear that digital design is having a relevant influence on the development of innovative approaches, enabling new fabrication methods which open to unprecedent construction possibilities. Through the analysis of two contemporary international case-studies, the article aims to show this innovation in architectural field, in particular in timber construction, led by the new digital technologies and robotic fabrication methods.