Performative Architecture and Wooden Structures: Overview on the Main Research Paths in Europe

Angelo Figliola and Alessandra Battisti

Abstract One of the main aspects investigated in the European research context on Performative Architecture is related to the use of digital innovations in wood structures construction of units and technological systems as well as architectural organisms at 1:1 scale. To analyze the different approaches the contribution proposes a series of case study and the results of two applied research, the 1 to 1 scale pavilions *Fusta Ròbotica* and *Digital Urban Orchard*. The case studies are selected verifying the correspondence to the following parameters: the presence of a performance-based process through which explore informed architectures; the use of low-engineered and natural wood and the engineered one; the materialization of the digital model through innovative manufacturing processes, specifically robotic fabrication. The contribution allows gathering pros and cons in the three different investigative macro areas: performance-based design, material culture, and fabrication process. This analytical investigation helps to create a clear research scenario around the topic of digital wood design as well as the definition of an innovative pathway for future researches, looking forward the assimilation of these innovative concepts in the building construction sector.

Keywords Wood design · Parametric design and fabrication strategies
Parametric timber engineering · Complex timber structures
Optimization of wood architectures

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1 Introduction: Performance-Based Process and Wood Architectures

The recent publication Parametricism 2.0 (Schumacher 2015) has highlighted the beginning of a new testing phase that targets the use of computational algorithmic tools for the resolution of environmental and social matters, returning to deal with issues that warranted the birth of digital computing itself in the 70s (Frazer 2016). The ability to process information, and then to use the data as guiding elements of the design process (Deutsch 2015), opens many and largely unexplored possibilities for environmental and technological design. The theoretical assumption defines the architectural shape as a result of a diagram of forces within a morphogenetic process (Hensel et al. 2010; Hensel and Menges 2006) and offers new investigation fields in relation to the possibility of creating performance-based (Kolarevic 2003; Kolarevic and Malkawi 2005; Grobman and Neuman 2012; Oxman 2009) or performance-oriented architectures (Hensel 2013). The performance requirements made clear by codes and regulations raise the issue of performance as a design focus at the centre of the debate. So far, the first digital era has interpreted the performance as a necessary antidote against formal arbitrariness generated by digital processes or as a representation of a new hyper-functional complexity. Today, performance-based architecture represents an absolute necessity, ethical obligation of the profession due to environmental problems[1] that afflict the earth. To operate within this scenario, the technological innovations are essential to ensure that the performances do not remain only numerical parameters but represent a source of formal exploration and process information. Hence, the objective of the generative process is the exploration of design solutions that can be optimized in relation to a space of design possibilities defined by the designers through the formulation of a meta-project (Kolarevic 2015). This design tool is based on the definition of geometric variables and constraints, genotype, and design goals to achieve through an optimization process. The generative process offers the opportunity to explore complex and informed geometries in a flexible and relatively fast way, transforming the material from a passive receiver to a design agent as driving element of creative process (De Landa 2015). The transition from passive to active receiver is based on the exploration of its mechanical, structural and behavioural properties to inform the design process (Menges 2012). The application of the methodology involves the overcoming of the typological paradigm in favour of a continuous formal variation that changes depending on system boundary conditions. The customization of the form can be linked to a responsive interpretation of local and regional variations in characteristics (Yuan 2015) thanks to the data-driven strategy and the ability to interconnect design and fabrication in a single workflow. To transfer an informed architecture from the digital to the physical world, it is necessary to integrate various skills and technologies used in other areas of architecture to implement standard processes. The birth of the first architectural

[1]The environmental problems like global warming, acid rain, air pollution, urban sprawl, waste disposal, ozone layer depletion, water pollution, climate change and many more affect every human, animal and nation on this planet.

robotic laboratory at the ETH in 2005, with the direction of Gramazio and Kolher, marked a new course for the digital fabrication in architecture by introducing innovative design paradigms that soon became cornerstones of the main researches issues (Gramazio et al. 2014). The generic industrial machine becomes a design tool able to convert virtual models in material systems through a single computational workflow that introduce the innovative concept of digital materiality (Gramazio and Kohler 2014). The potentials of this design methodology, extension of the *file-to-factory* (Sheil 2012) concepts, are investigated with respect to several lines of research that have in common the development of processes related to the definition of informed architectures through a digital path that includes innovative computation methods, material computation and digital fabrication. The digital-material relationship allows to combine the research of new formal codes with performative aspects that ensure the manufacturability of what is generated in the digital space and apply it to the scale of architecture (Gramazio and Kohler 2008). The integration of the concepts listed above opens the post-industrial era based on the customization of architectures in relation to performance exploration and optimization. Moreover, the hybrid space of interaction between designer and machine is contaminated with other disciplines in order to investigate different digital fabrication strategies but also to stimulate creativity through a fruitful collaborative process. The interdisciplinary defines a post-industrial phase in which issues related to analogue design and manufacturing methods are interrelated with disruptive digital technologies.

2 Research Lines in the Field of Performative Wood

One of the main aspects investigated in the European research context on Performative Architecture is connected to the use of innovative technologies in the field of wood structures for the production of technological systems as well as architectural organisms at 1:1 scale. Wood is one of the architectural longest-lived materials because of its physical and mechanical properties, flexibility in structural application which allow to use it indifferently to traction, compression and flexion stresses. Compared to traditional wooden applications those related to digital computation, generative design and robotic fabrication, open new horizon of research with different purposes, sharing the same investigative tools (Fig. 1). An overview on the theme is outlined by the texts Advancing Wood Architecture (Menges et al. 2016) and Advanced Timber Structures (Weynand 2016) that identify the main topics and the research centers involved to define the possible future research directions. The investigations conducted can be summarized in two distinct approaches: the first concerns the use of engineered wood's elements to attempt to exploit its physical and mechanical properties; the second approach provides the use of wood as natural and low-engineered material for structural applications that benefit from the complex relationship between computational design and digital fabrication.

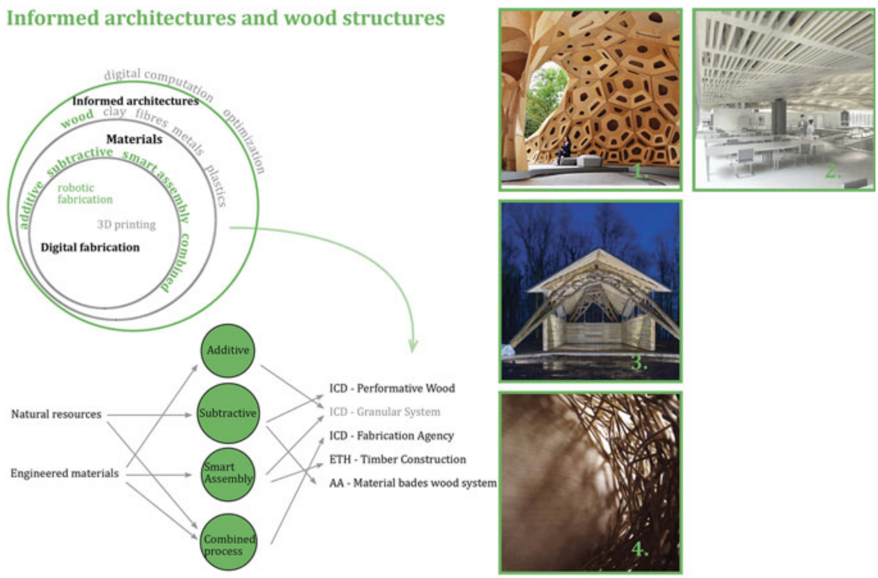

Fig. 1 Informed architectures and wood structures. Overview of the main research topics

2.1 *Wood Computation: Exploit Material Behavior as Design Agent*

Regarding the first approach, one of the focus of research consists of the exploration of mechanical properties of the material to transform them into design opportunities in the formal generation process. The computational method becomes the mean by which to discover advantages offered by wood in relation to its complex and non-linear behavior. The physical and mechanical properties of this material, especially if used in the form of thin panels handled by a rolling process, such as heterogeneity, anisotropy, hygroscopic and irregularity, can expand the range of design possibilities and stimulate the creative process. The studies on wood computation has been for some years part of the research conducted by Achim Menges at the University of Stuttgart, Institute for Computational Design, ICD, within the Performative Wood research line; by Michel Hensel at the Research Center for Architecture and Tectonics at the Oslo School of Architecture and Design. The investigations on the topic concern two performance aspects of the design that can benefit from the material qualities: the structural behavior and geometric-formal responsiveness (Persiani et al. 2015). Within this research field can be identified different lines of research, which can be summarized as follows:

– Activation of the anisotropic properties of wood, to set different structural behaviors in relation to differentiation of stiffness in the direction of the fibers;

- Use of elastic properties of wood as a factor design, through bending processes (La Magna and Schleicher 2016) to design not standard structures;
- Exploitation of irregularity, through selective processes of digital fabrication to eliminate portions of inactive and inefficient material;
- Use of hygroscopic properties of wood to actuate morphological transformation processes.

2.2 Wood Computation: Smart Assembly, Natural and Low-Engineered Materials

A further aspect of research on the application of innovative technologies in wood constructions concerns the design and the prototyping of new spatial and structural configurations. This approach benefits from the digital design and robotic manufacturing with special attention to the smart assembly. The Institute of Technology in Architecture, ITA, of the Federal Polytechnic of Zurich, ETH, is one of the most active research centers on the topic of complex and optimized wood structures explored through the construction of a series of prototypes made in collaboration with construction industries. The recent research developments on the topic, focus on the possibility to extend the sensory capacity of the robot through a series of sensors and a feedback loop system between the machine and the material system. Talking about feedback loops means building relationships and designing a dynamic and non-linear systems capable of guaranteeing adaptability to the local scale. The machine becomes extension of the craftsman who perceived and analyzed physical properties of a material through his own hands. The sensing ability of robots can be considered the main innovation of the discipline. This methodological approach constitutes a design response to theory of soft system or adaptable systems and in continuous evolution whose dynamism is constantly fed by a flow of information coming from outside. The ability to act and react dynamically makes the system responsive to variations due to the interaction between the parties involved. These aspects are investigated by the Institute for Computational Design in Stuttgart in a research path defined as Fabrication Agency. Another field of investigation conducted mainly at the Architectural Association, AA School of Architecture in London and IAAC, Institute for Advanced Architecture of Catalunya, concerns the use of low-engineered and natural material present in great abundance in nature to create complex and optimized wood structures (Menges et al. 2016). The project Woodchip Barn from AA is a manifesto of this specific approach. The role of digital computing and the importance of data-driven strategy is evident: the scanning of the shrub and the consequent creation of a digital catalogues based on dimensional and morphological parameters represent the true innovation of the design process. Through the three-dimensional scanning and reconstruction of the elements it is possible to realize a complex surface starting from natural curvature and dimensional parameters of the trunks, avoiding expensive industrial bending processes. The computational process allows to integrate in the project the data related to the natural material used, the structural performances and the parameters of the construction site. The relational models obtained by the generative process define the concept of informed morphology.

3 Performative Wood: Case Studies

To analyze the different approaches the contribution proposes a series of case study and the results of two applied research, the 1 to 1 scale pavilions *Fusta Ròbotica* and *Digital Urban Orchard*. The case studies are selected verifying the correspondence to the following parameters:

- the presence of a performance-based process through which explore informed architectures;
- the use of low-engineered and natural wood and the engineered one;
- the materialization of the digital model through innovative manufacturing processes, specifically robotic fabrication.

All the projects are the results of a performance-based process through which the generative process is informed by performative parameters (e.g. structural, environmental) (Fig. 2). This methodology enables the exploration of innovative formal codes using different typology of wood as construction material. The presence of innovative digital fabrication tools such as robots implies that the Universities involved in the survey are the one equipped with robotic fabrication laboratories and who work to realize 1 to 1 scale projects (Fig. 3).

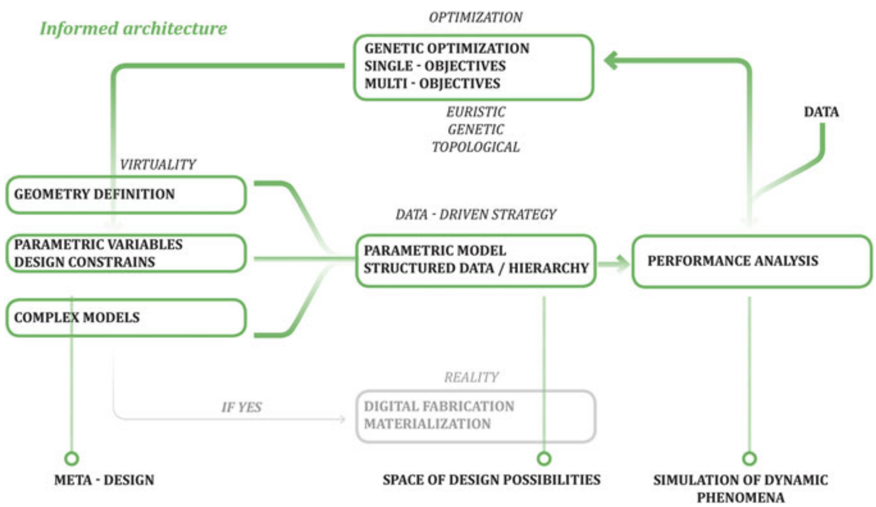

Fig. 2 Informed architecture: computational workflow between shape generation and manufacturing processes

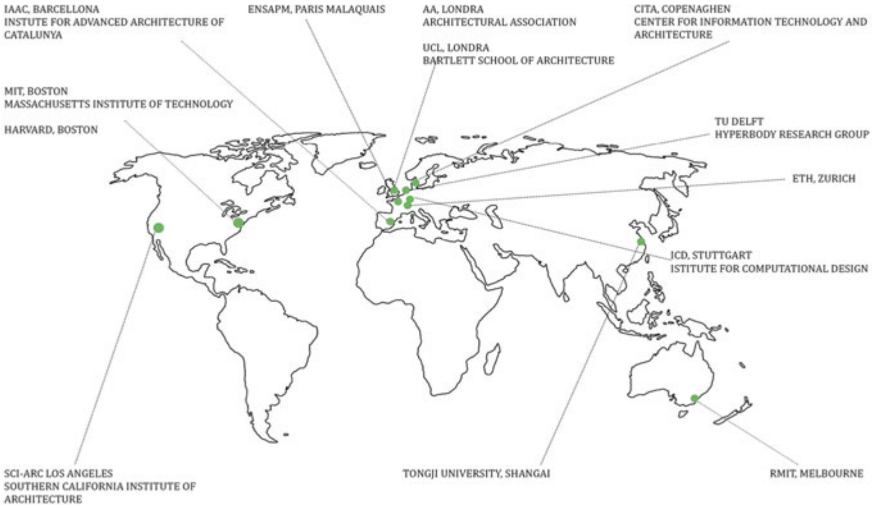

Fig. 3 Informed architecture: universities active in the research paths on informed architectures

3.1 Wood Chip Barn: Exploring the Potential of Natural Material

The case study *Wood Chip Barn*[2] (Fig. 4) represents the real transposition of a complex functional program through the use of a natural material, large wooden tree trunks, and an informed computational process. The project comes from the selection of 250 tree trunks grown in the Hooke Park forest that surrounds the homonymous Campus.[3] The tectonic and structural experimentation is informed by the 3D scan of the bifurcated wood trunks to extract the geometric characteristics and organize the elements in the three-dimensional space. From the scanning of the elements the following data are extracted: volumetry, central axes of the trunks with respect to the bifurcations present as well as points of intersection between the axes themselves. The extracted information is used to create a digital catalogue of solutions for the spatial organization of the trunks in the formation of the main beams. The spatial organization of the trunks is optimized to achieve a structural system able to increase the structural stiffness and minimize shear stresses. The optimization process relies on the use of genetic algorithms through the definition of the fitness value, target, and variable parameters, genome. The arch structure, composed of different beams connected in the central points of the bifurcations, is anchored to the ground by foundations in concrete while the beams are pre-assembled by dividing the arc into two

[2]AA Wood Chip Barn. Students: Zachary Mollica; Swetha Vegesana; Sahil Shah; Vivian Yang; Mohaimeen Islam. Tutors: Martin Self, Emmanuel Vercruysse, Jack Draper, Charley Brentnall, Toby Burgess. With: Pradeep Devadass (Robotic Developer), Arup (Engineering).

[3]Hooke Park is a research campus in Dorset for experimental wood architectures of the Architectural Association of London, AA.

Fig. 4 AA, Woodchip Barn, Architectural Association: pavilion robotically fabricated and made by natural and low-engineered wood. © AA, Architectural Association, Valerie Bennett

halves to be assembled in situ (Mollica and Self 2016). The robotic manufacturing process that involved the use of a Kuka KR 150 robot with a milling spindle made it possible to create customized male-female joints between the different elements that make up the main beams with six hours of processing in the robot cell. Thanks to the use of the subtractive milling process, it was possible to realize male-female interlocking joints as well as joints for the installation of the secondary structure on which the wooden covering was installed. The proposed case study demonstrates how with new production technologies, together with a computational process informed by real-time data, is possible to realize optimized architectonic bodies that use non-engineered materials. The prototype, is the result of a data-driven computational process able to use the material and structural performances as guiding parameters of the design, the acquisition of real-time data as feedback loop between the digital environment and the real one, and the genetic optimization to determine the best spatial configuration of structural elements. Through the 3D scanning process, the natural material, bifurcated wood logs, is digitized to acquire the dimensional and geometric parameters necessary to inform the digital model (Fig. 6). The operative methodology has allowed to realize an optimized structure able to respond to performance parameters derived from the material, from the project site as well as from the structural conformation. In conclusion, the methodology applied to the Wood Chip Barn project has allowed to obtain an informed geometry whose materialization has been possible thanks to a robotic manufacturing process (Fig. 5) through which to realize the customized connections (Fig. 7) in relation to the optimized spatial configuration. Nonengineered material and a non-industrial production setting open up new tectonic speculations and formal codes for sustainable architectures.

Fig. 5 AA, Woodchip Barn: complex joints made by robotic milling process. © Genny Spyridonos

Fig. 6 AA, Woodchip Barn: complex joints made by milling process informed by data-driven design. © Swetha Vegesana

3.2 ICD/ITKE Research Pavilion 2011: Discover Opportunities Offered by Wood Complex Behavior

The research pavilion 2011[4] is produced by the Institute for Computational Design and Construction, ICD, Stuttgart (Fig. 8) in collaboration with the Institute of Building Structures and Structural Design, ITKE, and other industry partners. The aim of

[4]Institute for Computational Design—Prof. Achim Menges, Institute of Building Structures and Structural Design—Prof. Jan Knippers. Concept and System Development: Oliver David Krieg, Boyan Mihaylov.

Detail Design and Fabrication and Construction: Peter Brachat, Benjamin Busch, Solmaz Fahimian, Christin Gegenheimer, Nicola Haberbosch, Elias Kästle, Oliver David Krieg, Yong Sung Kwon, Boyan Mihaylov, Hongmei Zhai. Scientific Development: Markus Gabler (project management), Riccardo La Magna (structural design), Steffen Reichert (detail design), Tobias Schwinn (project management), Frédéric Waimer (structural design).

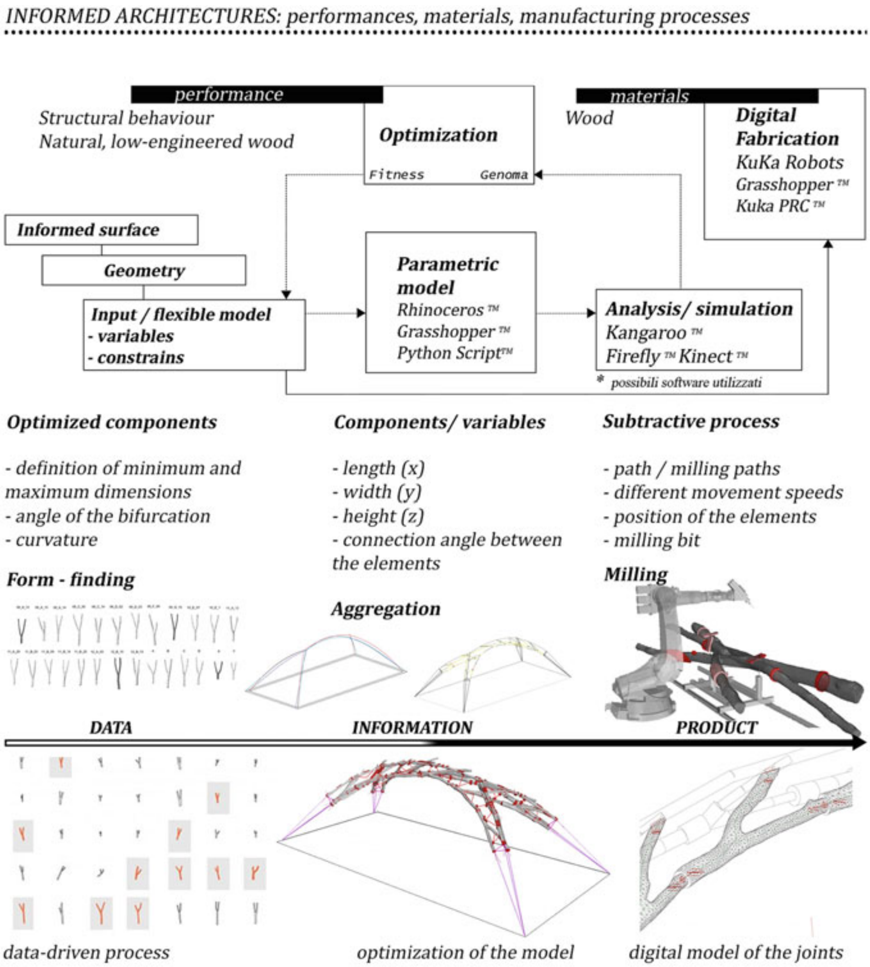

Fig. 7 AA, Woodchip Barn: performances, materials, manufacturing processes. A design methodology

the investigation is to propose a wooden structural system at 1 to 1 scale as result of a computational and manufacturing processes informed by a series of performative parameters extracted from the analysis of a specific biological organism (Jodido 2013). Specifically, the research involved the study of the structure of the skeletons of the Echinoid, sea urchin, in relation to their composition and the rules of aggregation. The biological system is analysed to extract the physical and geometrical principles to be transferred to the structural-material system through the compu-

Fig. 8 ICD, research pavilion 2011. © ICD/ITKE

tational process. The analysis carried out on the organic organism has allowed to extract the fundamental geometric principles including the modularity of the system that allows a high degree of adaptability and a performative structural system (Knippers et al. 2012). This organizational principle is transferred to an optimized surface, obtained through a form-finding process integrated with structural analysis, through the tessellation of the same with hexagonal geometric components. The hexagonal components are assembled with two different strategies: the plates that make up the single three-dimensional technological unit are connected by structural glue while the assembly of the different units takes place thanks to the realization of 100,000 geometrically different joints and subsequent nailing process. The structure turns out to be so hierarchical and heterogeneous, since the size of the hexagonal cells is informed with respect to the curvature of the surface, anisotropic, as each hexagonal unit is oriented with respect to the mechanical-structural stress determined by the distribution of loads on the surface. The construction optimized in relation to structural performance parameters, was achieved through a robotic manufacturing process and a mechanical processing of the subtractive, milling type, through which it was possible to guarantee the customization of the various connections, defined as finger joint. The proposed methodology has allowed the creation of an architectural body of considerable size using only plywood wood in panels with a thickness of 6.5 mm, creating 850 geometrically different components and 100,000 finger joint joints between the different elements. The research pavilion is the result of the trans-

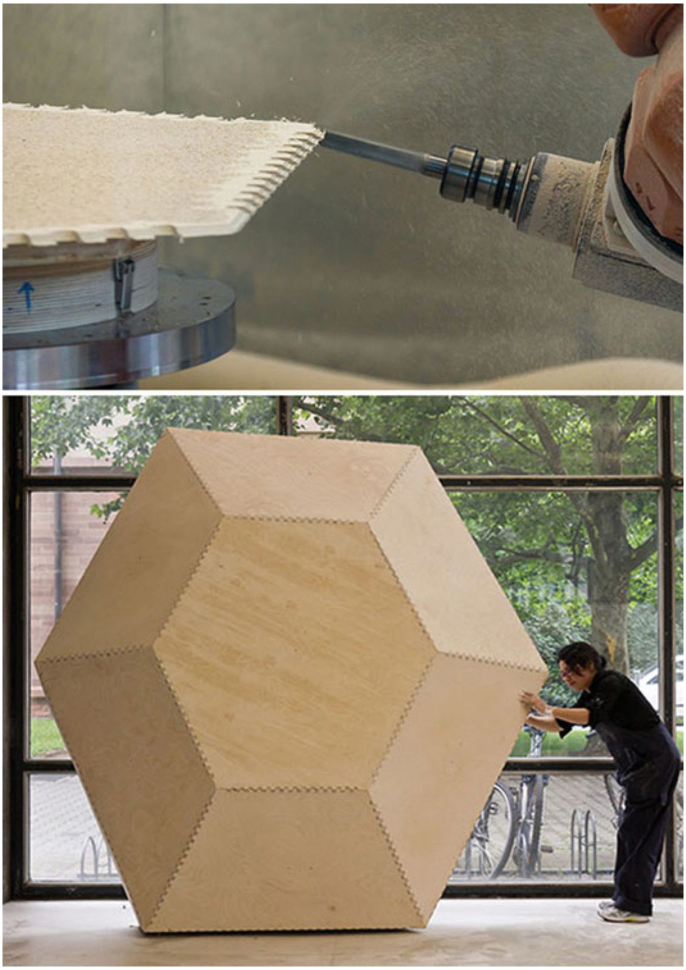

Fig. 9 ICD, research pavilion 2011: tailored finger joints and assembled hexagonal cells. © ICD/ITKE

fer of biological principles in the project through digital computation and a robotic manufacturing process (Fig. 9). The proposed methodology is based on the information of the process with respect to data obtained from the analysis of the biological organism under investigation: scientific data, such as modularity and adaptability of the natural system, are transformed into geometric rules used to discretize an optimized surface through a form-finding process (Menges 2013). The result of this process is a heterogeneous responsive morphology to realize an architectural struc-

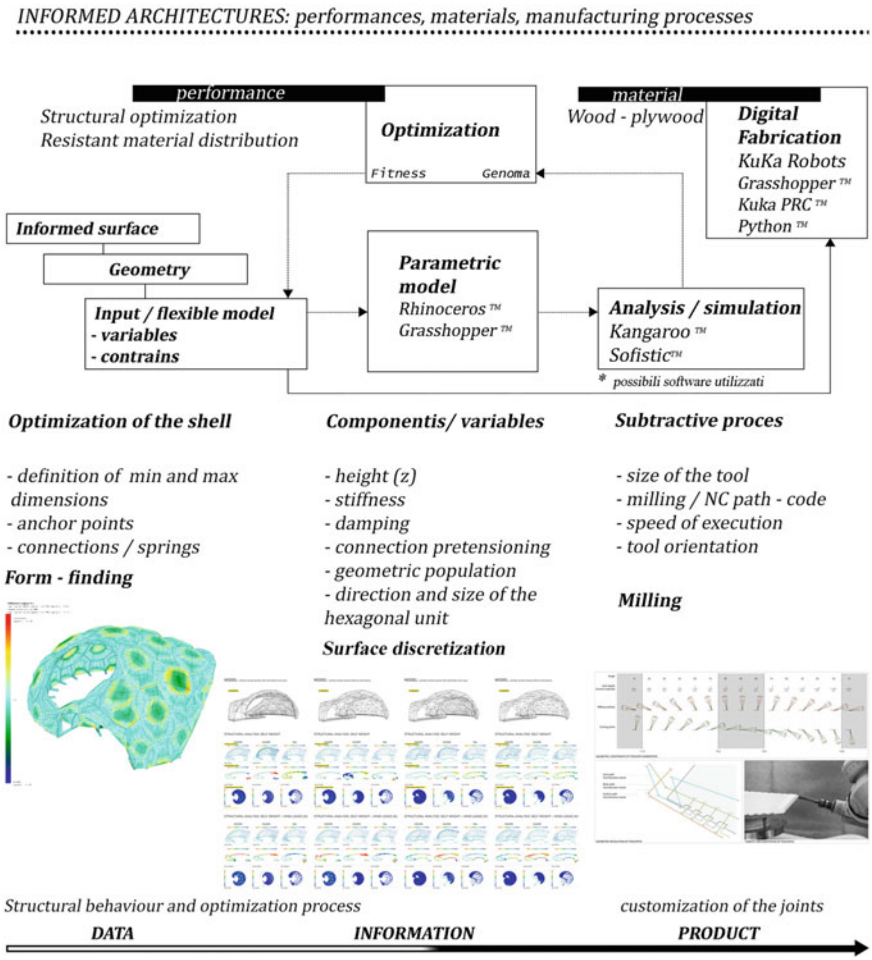

Fig. 10 ICD, research pavilion 2011: performances, materials, manufacturing processes. A design methodology

ture in which the performance characteristics respond to variable external inputs. The possibility of realizing this structure through the assembly of different units made of extremely light wood panels, confirms the excellent structural performance that the architectural body can guarantee even if it requires a ground anchor to withstand the horizontal wind load. The major problems derive from the complex system of joints, the result of the heterogeneity and anisotropy of the material system, which makes the management of the production process complex compared to the generation of the manufacturing code and the speed of the production process (Fig. 10). One of the possible implementations may derive from the simplification of the tessellation geometry and the connection system as well as the use of the entire volume of the hexagonal units.

3.3 ETH, the Sequential Roof: Robotic Manufacturing and Smart Assembly

The proposed case study[5] presents a responsive technological system (Fig. 11) for structural applications in 1:1 scale to be applied to free-form surfaces realized by the *Gramazio and Kohler Research Group* as part of the research on *Additive Robotic Fabrication of Complex Building Structures* (Gramazio and Kohler 2014). The 168 reticular beams, composed of 23 layers assembled for a total thickness of 1,145 m with three types of sections, 50 mm × 115.140, 180 mm, and two support points, were used to create a coverage area of 2,308 m^2 whose morphology was determined thanks to a process of structural, energetic and constructional optimization. The structural analysis allowed to optimize the morphology compared to the multiple load conditions while the density of the structural elements was determined after a series of tests on the permeability of natural light. The studies and analyses were conducted through digital models informed through evaluations on scaled physical models used to perform load analysis and, through an artificial sky dome, natural lighting. This methodology has allowed to inform the morphology with respect to the data obtained both in digital and physical environments and the resulting customization requires an innovative and efficient constructive approach (Krammer 2016). The construction process definition required a series of tests with a multi-functional end-effector able to position the structural elements in wood and automatically apply the polyurethane glue to then evaluate the tolerance of joints after operations of fixing. Thanks to a 1:2 scale model it was possible to determine the criticality and potentiality of the process in relation to structural stability before scaling the whole process on an industrial level. The proposed technological system explores the application of an informed design strategy with respect to structural and environmental data for the realization of a non-standard reticular structure. The checks carried out following the construction of the prototype have allowed us to test the actual veracity of the simulation and of the structural and environmental optimization conducted in the digital and physical environment, defining the process ready for possible applications to the architectural

[5]Collaborators: Aleksandra Anna Apolinarska (project lead construction), Michael Knauss (project lead building project), Jaime de Miguel (project lead preliminary project), Selen Ercan, Olga Linardou.

Selected experts: Dr. Lüchinger + Meyer Bauingenieure AG, SJB. Kempter Fitze AG, Prof. Dr. Josef Schwartz (Chair of Structural Design, ETH Zurich), Prof. Dr. Andrea Frangi (Institute of Structural Engineering, ETH Zurich), Estia SA (EPF Lausanne), ROB Technologies AG. Selected contractors: Arch-Tec-Lab AG, ERNE AG Holzbau.

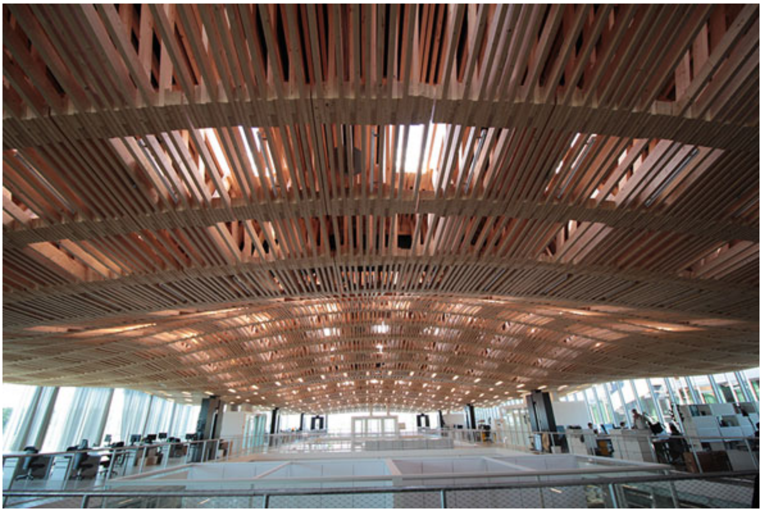

Fig. 11 ETH Zurich, Sequential roof, Arch_Tec_Lab of the Institute of Technology in Architecture (ITA). © Angelo Figliola

scale in the structural field, as well as for multi-layer architectural wrappers in wood. The proposed methodology (Fig. 12) and the resulting responsive structural model will be applied for the realization of the coverage of the *Arch_Tec_Lab* of the Institute of Technology in Architecture (ITA), ETH Zurich; the management of the robotic manufacturing process for the realization of the roof was managed by ERNE AG Holzbau through Gantry Robot and an industrial endowment of this type:

– 7 axes (2 parallel);
– dimensions: 48 m length, 5.60 m width and 1.40 m height;
– 3 zones, each zone is 14 m long;
– maximum speed of 120 m/min (7 km/h);
– maximum load capacity of the gripper 250 kg;
– tools: circular saw, milling, closing, lifting;
– machine for wood, metal and other materials;
– ability to determine the assembly sequence independently.

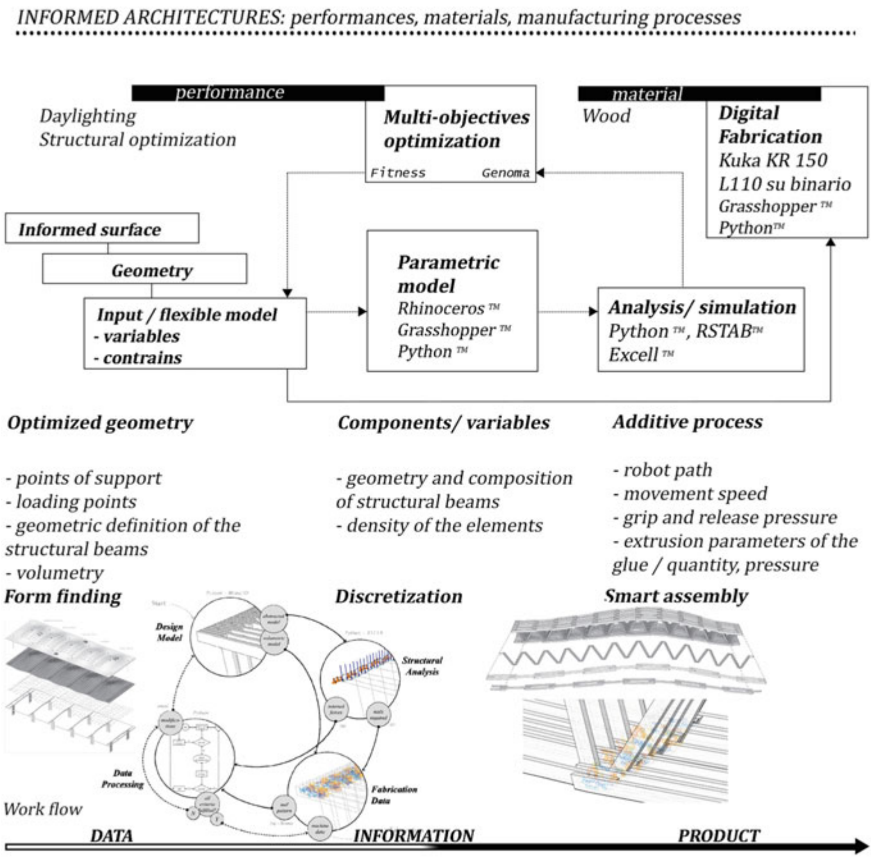

Fig. 12 ETH, Sequential roof: performances, materials, manufacturing processes. A design methodology

3.4 Robotic Softness: Behavioural Fabrication Process of a Woven Space

Robotic Softness (Fig. 13) develops a system of relationships, feedback loop, which regulates the formal generation with respect to performance parameters identified thanks to a customized and highly specialized production process (Brugnaro et al. 2016). The process starts from the study of the natural phenomenon of nesting, typical intertwined structures used as nests from birds, to analyze and understand the logic that regulate the formation of such complex systems. Compared to the other proposed cases, *Robotic Softness*, introduces a new concept that refers to soft systems

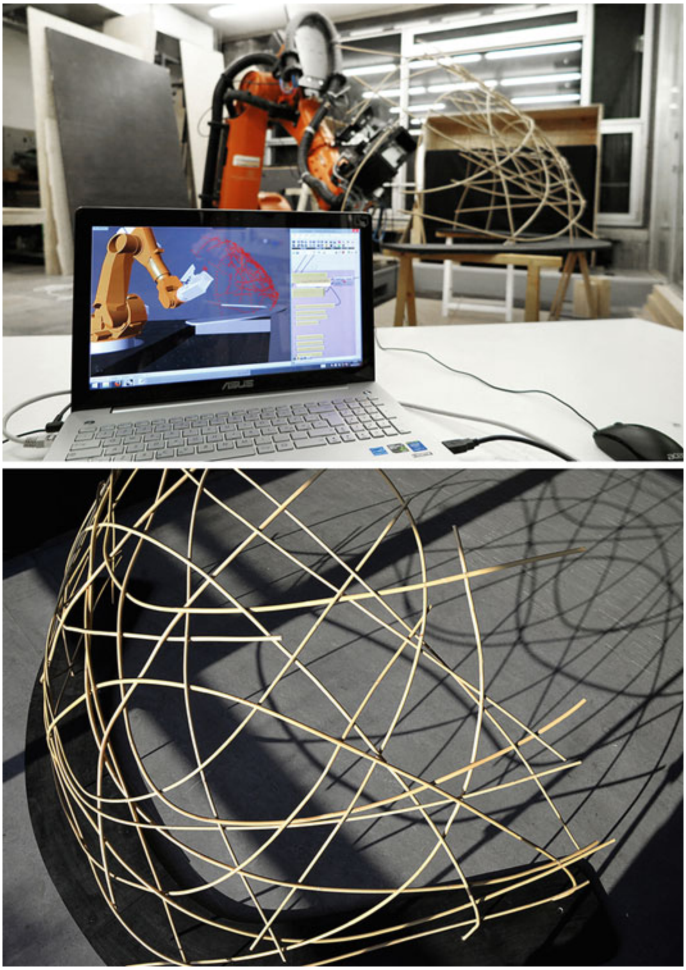

Fig. 13 ICD, robotic softness. © Giulio Brugnaro

characterized by a non-linear relationship based on continuous feedback both at the global and local scale. Just as in the volatile world the formation of the interweaving that constitutes the nest is guided by environmental and structural performances, the digital and production process that led to the prototype is informed on the global scale by evaluation parameters such as light permeability, density and thickness of the filaments, while at the local scale are the geometric parameters to inform the process with kinect sensor able to return in real time the data coming from the physical environment. Thanks to the interaction between digital and physical world, the industrial robot can be considered as an *agent* able to mediate with respect to the global scale and geometric parameters at the local scale in a process that defines only the boundary conditions and the rules general without defining the final

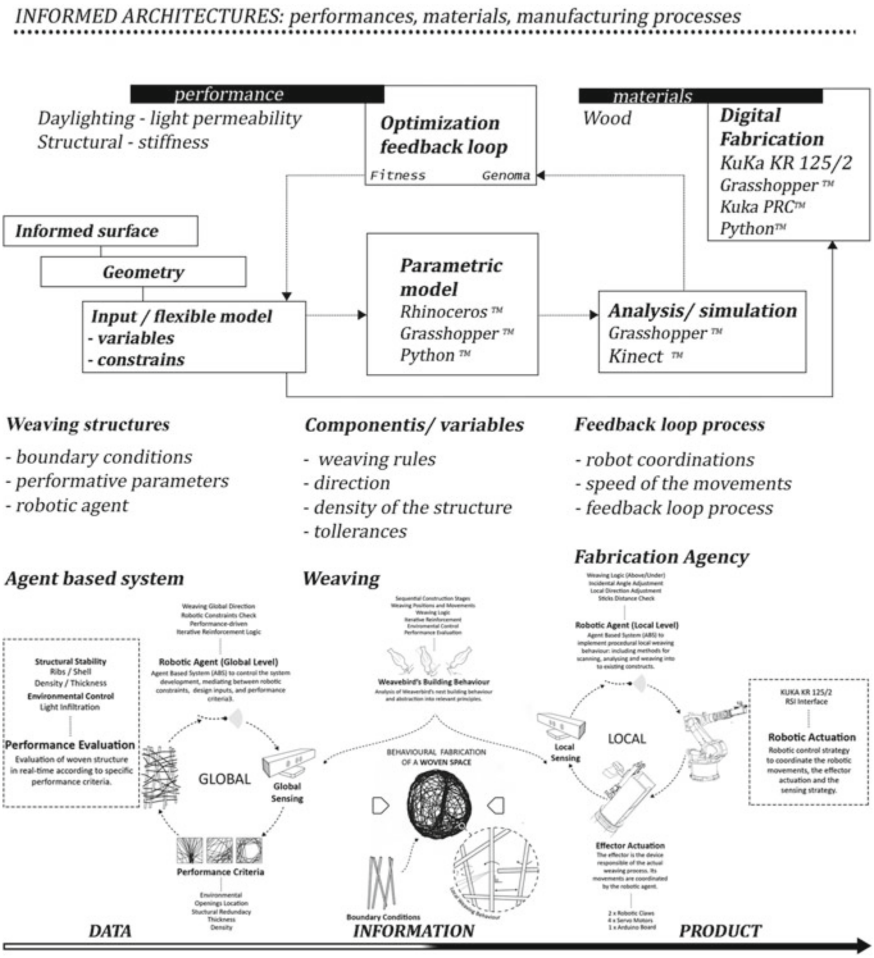

Fig. 14 ICD, Robotic softness: performances, materials, manufacturing processes. A design methodology

morphology. To develop the prototype the generic industrial machine is equipped with a highly specialized end-effector able to mediate the action with respect to the conditions of the local system in formation and the material used. The robotic system *Agent Based System* (ABS) allows to adapt, set global parameters of boundary conditions and general rules of the system, the virtual model to the materialization of the same in relation to data obtained in real time. The case study introduces an operational methodology in which the subject is in continuous transformation and its responsive behavior is regulated by real-time feedback with the physical environment. The environmental and structural performances constitute the essential parameters of the data-driven strategy in such a way as to dispose the material, and consequently increase the density of the nesting, where strictly necessary. This methodology allows to reinterpret an ancient method of processing materials, such as weaving, and an ancient material such as wood, through the fusion between digital model and physical environment just as happens in the formation of natural systems (Fig. 14). The proposed methodology and the geometry obtained presents a high degree of responsiveness with respect to external inputs, determined by the designer during the definition of the meta project, with the optimization of the model in relation to the desired performances. The realization of a customized end-effector and the presence of a kinect sensor introduces the concept of cyber-physical making in which the machine is not merely a performer of repetitive actions but interacts with the physical environment in a state of feedback loop between digital environment and physical. A responsive system of this type may be suitable for the realization of multi-layer casing elements capable of modulating natural light and solar radiation while guaranteeing energy savings and optimized use of the material. Among the critical issues we can mention the scalability of the system that needs further testing and experimentation as well as the difficulty of managing the generative computational process and the robotic manufacturing process.

4 Applied Research: Fusta Robotica and Digital Urban Orchard

The prototypes, made in collaboration with industrial partners, represent the results of transdisciplinary experiments in which environmental, structural and material performances inform the computational process and the robotics manufacturing.[6] *Fusta Robotica*, is the outcome of a tectonic exploration deriving from non-engineered material, *Digital Urban Orchard* is the formal expression of a complex functional program arising from the relationship amongst form (shape), function and context. The practice of a new design paradigm based on the information of the process that sees environmental, structural and material performances as a factor driving the entire design process. The performance criteria inform the computational process, subsequently materialized using an anthropomorphic robot that is able to transpose informed digital models into physical reality, through nonindustrial settings and using irregular and low-engineered elements (Figliola 2016).

[6]The protorypes, Fusta Ròbotica and Digital Urban Orchard, was developed during the Open Thesis Fabrication 2015/2016 program at Institute for Advanced Architecture of Catalunya, IAAC. OTF team 2015–2016: Areti Markopoulou, Alexandre Dubor, Silvia Brandi, Djordje Stanojevic, Maria Kuptsova//Andrea Quartara, Angelo Figliola, Monish Siripurapu, Ji Won Jun, Josep Alcover Llubia, Yanna Haddad, Mohamad Mahdi Najafi, Fathimah Sujna Shakir, Nada Shalaby.

4.1 Fusta Robòtica: Material—Informed Design

The *Fusta Robòtica*[7] pavilion (Fig. 15) is the first low environmental impact wooden structure built using robotic manufacturing in Spain. It was born from a collaboration between the IAAC, Institute of Advanced Architecture of Catalunya and *Serradora Boix Srl* as a tectonic testing to be exposed at the "Semana de la fusta 2015",[8] with the intent to show the potential derived from the application of digital computation and robotics manufacturing in the construction of wooden structures. The objectives of the research were represented by the promotion and enhancement of the Catalan wood, Mediterranean pine timber, by an exchange of knowledge between industries and research centres for the innovation of the production of the model in order to test new formal codes for a sustainable design. The material used, highly deformable and non-engineered to be used in construction, consists of small simple and irregular wooden profiles and is employed for the production of industrial or biomass pallets. The square section profiles the industry has made available for the project have the following dimensions: 38 mm × 38 mm × 2,000 mm. Another aspect to be integrated in the design process is the method of production and the production area with their tools. The pavilion was built with anon-industrial setting, represented by a Kuka KR-150 industrial robot equipped with pneumatic gripper, a device for the storage

Fig. 15 IAAC, Fusta Ròbotica, Setmana de la fusta 2015, Barcelona. © Ji Won Jun

[7]Fusta Robòtica Pavilion is a project of IAAC, developed with the generous sponsor of Serradora Boix; in collaboration with Gremi de Fusters, Tallfusta, Incafust, Mecakim, Decustik.

[8]Setmana de la Fusta is an annual event aimed to promote the use of wood Catalan that takes place in Barcelona.

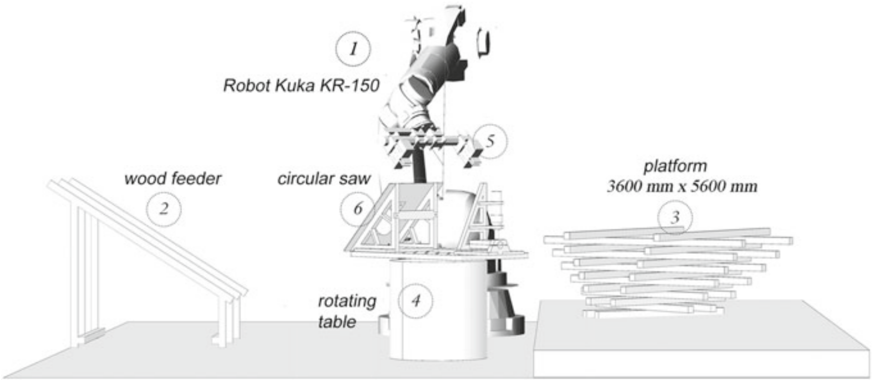

Fig. 16 IAAC, Fusta Ròbotica: set-up of the robot cell and organization of the working space. © Angelo Figliola

of the wooden profiles and a circular saw arranged on a rotary table (Fig. 16), within the university digital fabrication laboratory. The entire design process was informed by the mechanical properties of the material that were extracted through a series of analog tests necessary to the understanding of the material and structural system behaviour. Among these, we can mention the excessive bending of the wooden profiles, due to the variation of the curvature following the drying process, and the lack of structural rigidity of the profiles due to the mechanical characteristics of the material. The manufacturing method adopted also contributes to inform the design process, with the minimum and maximum workable dimensions of profiles and components that can be aggregated depending on the work area, the characteristics of the robot and their handling. In relation to this, the design process was informed using the material performances as a design input. It is possible to avoid structural problems due to excessive bending of the wooden profiles using a redundant, hyper static structure. Nailed joints allowed to maximize the resistant section of the components, in correspondence of the structural nodes. The discretization of the shape in eight sections with a constant thickness optimized the working space and weight of the robot cell, avoiding collision problems and facilitating assembly. The pavilion, formed by about 1,000 square section wooden profiles, is the result of the elaboration of a complex geometry, hyperboloid, in which the rotation of geometric continuous elements has allowed to obtain a dynamic spatial configuration, a manifesto of the potentials resulting from the use of material in the production of complex structures (Fig. 17). At the same time with the analog test development on the material system, the algorithm was developed to transpose the 3D solids of the digital model in simple geometric elements, such as lines and planes, necessary for the definition of the various processing stages. Thanks to the direct connection between the parametric model and tool manufacturing, the various stages of the production process have been defined. They can be summarized as follows:

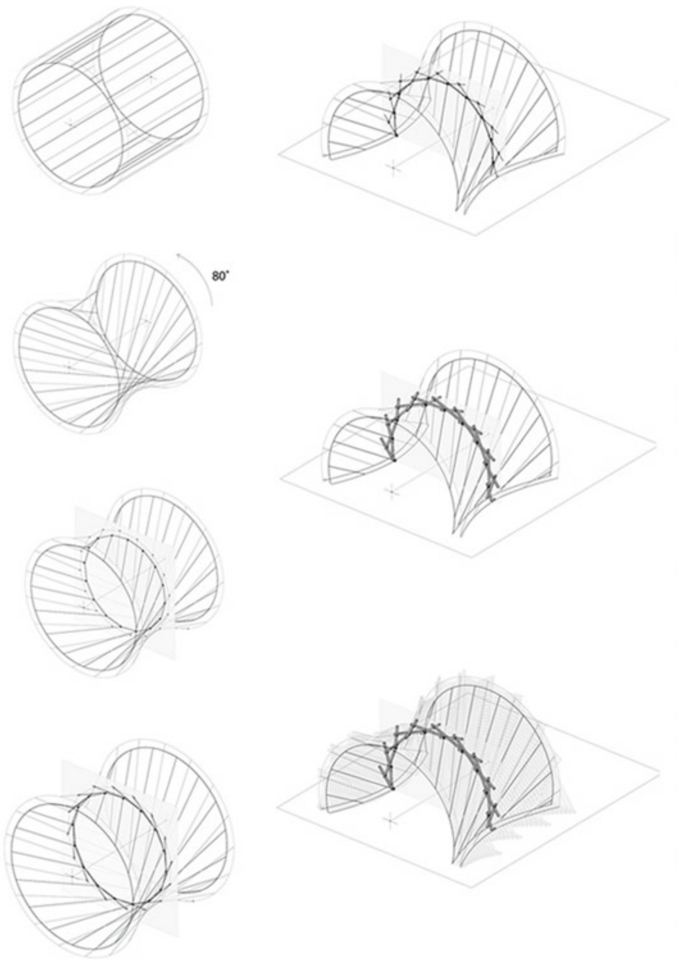

Fig. 17 IAAC, Fusta Ròbotica: computational design process. © Open Thesis Fabrication

– Taking of the wooden profiles from the storage device;
– Cutting of profiles to the corresponding size of the digital model;
– Profile deposit on the assembly platform.

Each stage of production included the manufacture of a half-arch to facilitate the operations of manual assembly and the transport to the installation site. At the end of the production process 940 pieces of wood in 8 arches, divided into 16 parts were processed and assembled in 35 h of production. The eight sections that make up the roof were assembled at the university laboratory and aggregated on the site of the installation.

4.2 Digital Urban Orchard: Form Follows Data Flow

The *Digital Urban Orchard* research project[9] (Fig. 18) involves the construction of a functional prototype to be implemented in urban public spaces within the self-sufficiency programme of the city of Barcelona, which stems from the relation among form, function and application context for a new concept of space of socialization and food production. As second part of the project, the pavilion hosts a hydroponic cultivation system and an adaptive silicone skin able to ensure the indoor comfort conditions that are essential for the plants growth. The need to design a stable yet lightweight structure and to ensure maximum solar gain for a proper growth of crops, at the same time, required multiple responsiveness able to get the proper compliance with the performance required by each of the single parameters listed above. To integrate the functional, structural and environmental-energy performance criteria, and inform the design process, the data-driven strategy was necessary to correctly set the genetic optimization by defining the genotype, the geometrical characteristics of the shape and the phenotype or quantitative parameters by which the genotype can be modified. The flexibility of the parametric model allowed to structure the meta project through the clarification of invariable parameters and genotype variable geometric

Fig. 18 IAAC, Digital Urban Orchard 2016. © Andrea Quartara

[9]Digital Urban Orchard is a project of IAAC, developed with the generous sponsor of of Merefsa, supplying the silicone and with Windmill, in particular thanks to Josep Ramon Sole and Álvaro Romera for the structural consultancy.

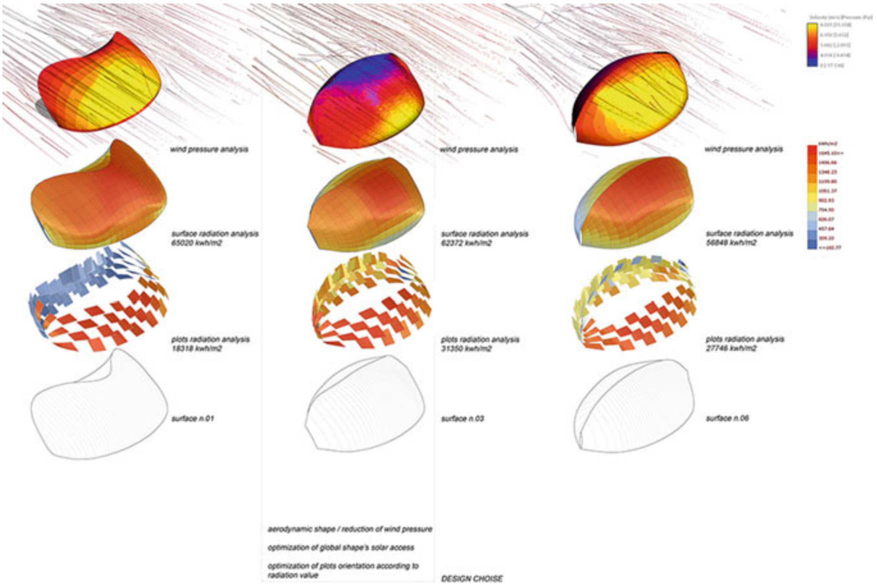

Fig. 19 IAAC, Digital Urban Orchard: digital catalogue of informed architectures. © Angelo Figliola

data, which may vary within a range aptly defined by the designer in relation to the values of the phenotype or rather quantitative parameters of performance analysis. The final shape has been selected from a catalogue of design solutions (Fig. 19), the result of genetic optimization and creative process which included the integration of different parameters:

– solar radiation on the surface of the orchard;
– solar radiation on the inclined surfaces where the plants are placed;
– wind pressure on the outer surface;
– minimum and maximum size of wood profiles that can be made with respect to the setting used;
– mechanical and physical properties of materials.

The process of genetic optimization was handled varying the geometric curves, two base ones on the x, y plane and a higher one, from which a surface is generated by the creation of a Loft and the inclination of planes that host the hydroponic system. The analysis of solar radiation on an annual basis, and the subsequent optimization, have made it possible to determine the overall shape and inclination of wooden shafts that host the hydroponic system. In parallel to the process described and thanks to a form searching process, the CFD analysis allowed minimizing the wind pressure on the outer surface of the pavilion in order to ensure the structural balance. The adopted structural principles are the same as those used in the *Fusta Robòtica* pavilion: the hyper static structural pattern, generated by the alternation of diagonals and

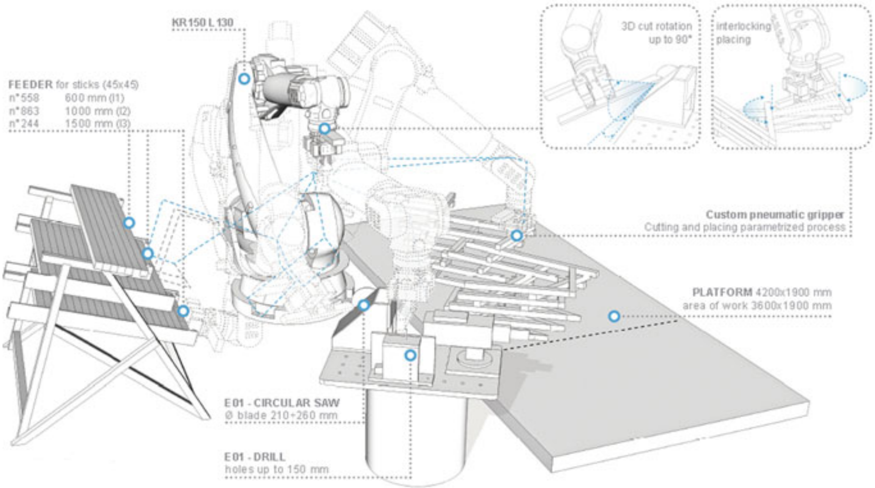

Fig. 20 IAAC, Digital Urban Orchard: set-up of the robot cell and organization of the working space. © Open Thesis Fabrication

elements able to ensure structural rigidity, is a complex system that performs the structural function. It is designed as a support plan for the hydroponic system, as support for the silicone skin and as space-functional furniture. The density of the structural pattern responds to optimization logics for solar access into interior spaces and considers almost total transparency at the top of the pavilion. The final shape has been discretized through 6 types of sections, for 12 components total. Three manufacturing strategies have been defined depending on the size of the sections and the work platform. They involve the construction of the entire section or the assembly of two/three parts of the final section with a total of 30 assembled parts. To maximize the resistant section, we used 2,524 nails in nailed joints with a collaborative process between manufacturing robotic and manual finishing. The structural analysis, conducted in cooperation with the engineering firm *Windmill*-project partner on a typical section under various load conditions, has allowed validating the structural choice made despite showing a high displacement due to the horizontal pressure of the wind in extreme conditions as set forth by the legislation. In the *Fusta Robòtica* pavilion the production process was implemented at all stages in order to reduce material consumption and expand the range of achievable geometry. Implementations concerned the customization of end effector, pneumatic gripper and tools used for the production such as the circular saw and the device for the storage of wooden profiles (Fig. 20). The customization of the circular saw has allowed to create spatial cuttings (Fig. 21) in three dimensions. Thanks to a new wood provider, the length of the profiles was diversified in order to reduce waste material. Realized with 1,681 profiles, the pavilion is the result of 52 h of robotic and 24 h of manual assembly coming from the information of the process and the optimization of the performance completed in a production process that can control the complexity and transform it

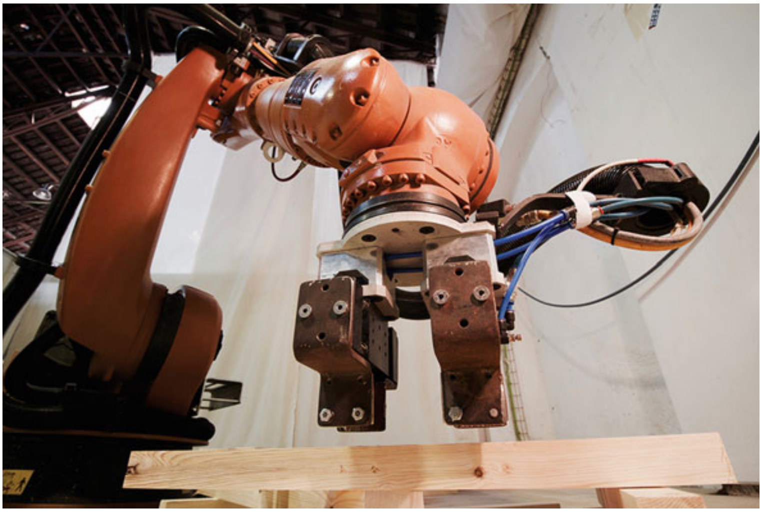

Fig. 21 IAAC, Digital Urban Orchard: complex assembly thanks to the spatial cutting process. © Andrea Quartara

into design opportunities while ensuring rapid execution, automation and only 2% of material waste. Finally, during construction, the silicone wrap production benefited from the collaboration with the silicone industry *Merefsa S.R.L.* that provided the necessary material and laser cutting tools for the proper production of components.

5 Applicability of Systems to Architectural Practice

The analysis of the case studies and applied researches, leads to a critical reflection on the possibility of introducing the technological systems proposed in the architectural practice, explaining the level of applicability and identifying the main critical aspects of the processes. The analysis represents a fundamental step for delineating innovative pathway for future researches on the topic. In fact, if it is possible to state that technology is the answer to the problems of design processes, citing the words of Price in 1966,[10] it is essential to define clearly the question, to ensure that the contribution is not nullified within a generalist thought that sees the use of emerging technologies as a solution to all critical design issues. One of the questions underlying the research concerns the concrete possibility of making a technological transfer from the academy to the actors involved in the design and construction process. Among the technological systems studied, which of them can be introduced in the architectural-executive practice? What are the critical issues that prevent a concrete application outside the experimental field of academic research? The first consideration to make,

[10]*Technology is the answer but what was the question? Cedric Price, 1966.*

for a correct reading of the application context, concerns the continuous interference and contamination between the technical elements that define the building systems. In this regard, some of the systems analysed present technological solutions that go beyond the definition of the common classes of technological units and technical elements that characterize the architectural practice. It is necessary to carry out a work of synthesis to clearly outline their field of application and, consequently, to be able to analyse their level of applicability with reference to the common technological classes. The reference categories have been defined as follows:

- Technological unit, as an element that identifies itself with a grouping of functions necessary for obtaining environmental performances;
- Technological system, as a structured set of technological units;
- Architectural organism, as a unitary and structured set of technological systems.

The following application fields correspond to the reference macro-categories:

- Bearing structures/structural systems;
- Vertical and horizontal enclosures;
- Internal partitions;
- External partitions.

For what concerns the use of wood as primary material, potential applications concern structural technological systems able to exploit the potential offered by the use of complex computational processes and digital manufacturing techniques.

5.1 Wood Structural Systems

The survey conducted on the implementation of informed structural systems has demonstrated the possibility of concrete applications in architectural practice. The experiments that present a greater level of applicability are those that involve wood as a construction material in relation to:

- a computational processes of structural optimization;
- experimentation on complex spatial configurations derived from the implementation of innovative digital manufacturing methods.

The research paths on informed wooden structures benefit from a consolidated know-how for what concerns the properties of the material and the related construction technologies by all the actors involved in the design process. The collaboration between academia and construction industries lead to introduce innovative technologies like digital computation and robotic manufacturing to fully explore new formal codes related to environmental sustainability able to positively act on performative criteria such as the carbon footprint and the embedded energy of the processes. The experiments examined employed engineered material such as laminated and profiled panels and low-engineered materials while digital exploration concerned computational processes of structural and multi-objective optimization as well as the study of principles of biomimesis to be abstracted and transferred in the design of complex and organic structures. The digital manufacturing processes involved in the construction of wooden structural systems are different and can be summarized as follows:

- Subtractive processes, for the realization of differentiated joints derived from complex, optimized spatial configurations;
- Additive processes,[11] for the assembly of components by means of complex and informed spatial sequences;
- Combined, subtractive and additive processes, in which the construction sequence involves machining the components before their assembly.

6 Performative Wood and Structural Systems: Towards an Application in Architecture

Some of the wood structural systems analysed experimented the integration between different technological systems such as main structure, secondary structure, insulation, finishing and technological systems. The capability to integrate complex technological systems through a digital workflow demonstrates the applicability of the methodology and validates the processes in relation to the management of tolerances derived from the use of innovative tools in the production. Projects such as *Sequential Roof*, ETH Zurich, roof structure of the *Arch_Tec_Lab* of the Institute of Technology in Architecture (ITA), as well as the entire production of the research path on additive processes for the construction of complex wooden structures of the Swiss university, *Woodchip Burn* of the AA, Architectural Association of London, and the 2011 Research Pavilion of the ICD, basis for the construction of the *Landesgartenschau Exhibition Hall* of 2014, have demonstrated the efficiency of the computational process in the exploration of different design solutions and the concrete applicability of technological systems in relation to complex systems that characterize an architectural organism. The described experiences can be considered as proof of concept for what concerns:

- The scalability of processes and the integration of main and secondary technological systems;
- The potentiality of the morphogenetic process and digital computation in the transfer of biological principles in the virtual space, and subsequently physical;
- The advantages derived from genetic and heuristic optimization processes in the design of performance structural systems;
- The potentiality of the customization of structural joints for the construction of optimized structures;
- The management of tolerances resulting from the digital manufacturing processes used.

[11] The assembly of the components can be assimilated to other additive processes.

A further check was carried out through the construction of two research pavilions, *Digital Urban Orchard* and *Fusta Robòtica*, made at the IaaC in Barcelona. The design of the two pavilions has highlighted a further aspect regarding the applicability of structural wooden systems in architectural practice: the control of formal generation through the parametric process and the possibility of customization offered by the robotic fabrication, allows to overcome, or better expand the concept of structure to that of an integrated system that manages to aggregate primary and secondary structure, systems and furnishings through specific morphological configurations. The research on the topic presents a high level of applicability also for the direct involvement of the industries in the sector stimulated by the sharing of know-how and the possibilities offered by the combination of a traditional material such as wood and digital processes of performance simulation and digital manufacturing. Compared to the projects mentioned above, other design experiences have a more experimental vocation, in some cases mere speculations, which corresponds to a low level of applicability in architectural practice, mainly in relation to the scalability of processes. Nevertheless, starting from the analysis of the projects, it is possible to extract theoretical concepts and future applications that can be transferred to the design processes: one of these is the investigation of the soft systems, which contrasts with the hard systems discussed above, based on the adaptive relationship of feedback loop between performance parameters and formal generation. The studies that combined responsive morphologies with the robots' introduction directly on the construction site showed clearly the potentiality of their possible application to realization of structural technological systems, or vertical, performance closures at the architecture scale.

6.1 Performative Wood and Structural Systems: Bring Complexity in the Design Process

As highlighted in the analysis of the case studies, the critical points of the methodology proposed is represented by the complexity of the computational process, the intrigued material system and the managing of the manufacturing process. In relation to the computational process, the first problem concerns the designers and their background on the topic. To manage such a complex process, the designer need to possess integrated and advanced skills (Figliola 2018) that allow managing the entire design process from design to construction. In fact, the data-driven strategy envisages the integration of the formal generation and digital manufacturing process within the same workflow and this implies a greater management complexity compared to the common design processes. A further critical aspect is the complexity deriving from multi-objective optimization paths and the consequent discretization of the parametric model necessary to limit the calculation times and to guarantee the readability and usability of the obtained data that allow to choose an optimal solution in a digital catalogue. The optimization of morphology based on the information of the computational workflow brings to complex manufacturing processes that need a customization of tools and tasks and involves the design of complex communication protocols between digital model and machine as well as the engineering of custom-made end-effector. The management of the process defined as cyber physical making requires the possession of specialized skills on the border between mechatronics, electronic engineering and computer science not easily available among the sector's operators. The paradigm shift in progress leads to a further reflection on the materials used in the production processes in relation to the physical characteristics and suitable mechanical properties. The analysis of the state of the art related to the issue shows that one of the major problems concerns the technological-constructive process related to the implementation of the components: the management of tolerances, the result of non-engineered manufacturing processes that involves customized tools necessities the design of communication protocols based on the feedback loop relationship through which to adapt the production process to the digital model and vice versa. Tolerance becomes an important design theme on a par with the scalability of the processes and the study of the structural connections between the technological units and the integration with the other constructive elements that constitute an architectural organism. The definitive introduction of the design methodology and the proposed technological systems in the architectural practice passes for the resolution of technical problems and for the rethinking of the design and construction process in its complexity. The first step concerns the centrality of the production process that becomes an integral part of the design process helping to define the limits of the formal generation process and ensuring the feasibility of the components. To apply this methodology, it is necessary to have a structured knowledge regards the technical specifications of the instruments, the organization of the working area (defined as robot cell) and the characteristics of the tools used to perform a specific and unique task. The second aspect concerns the development of a new material sensitivity aimed at overcoming the consolidated relationship between material and production process that characterizes industrial processes. The material acquires a high specific weight in the preliminary phase of the design and its correct management depends on the success of the operation. The digital process is informed about the physical and mechanical properties of the materials and the constraints derived from the manufacturing method used, which consequently expands the range of design possibilities and introduces a new performative layer. The conjugation of the two terms apparently opposed as digital, representation of the virtual environment, and material, as something tangible and concrete, finds complete expression thanks to the computational-algorithmic approach. The customization of the production process and the renewed materiality imply a redefinition of the constructive logics as a combination of the performance of the material, expression of its technical characteristics and of its mechanical properties, and of innovative manufacturing methods.

7 Conclusion and Outlook

Through case studies and experimental outputs was verified the application of computational workflow for performative architecture (Figliola 2016). The integration of single and multi-objective optimization processes and innovative production technologies allow to use the material according to the performative parameters used to guide the design process. In this regard, the additive processes represent the most productive method that is suitable to optimize the material resources: the possibility to compose generic elements, considering all degrees of freedom of movement that the instrument provides, promotes the exploration of complex aggregative systems for high-performance building components, managed by algorithms. A further implementation is represented by the reintroduction of vernacular materials in designing, such as wood, and by low-engineered approaches that facilitate the development of new formal codes for the sustainable design that can extend the concept of performance to the materials used. Going from materials to the organization of the production process, the results showed the potential of digital fabrication in the development of the design complexity, using non-industrial setting in university laboratories. The efficiency of production processes is guaranteed by the power of the instrument used that allows to reduce time and production costs as well as optimize the use of human resources in the entire production chain. The use of robotic manufacturing supports the development of a technological thought based on the prefabrication of building systems to be realized dry and completely reversible through the use of eco-friendly and especially recyclable materials. The greatest potential, for what concerns the production process, is represented by the realization of units and technological systems whose minimum and maximum size is linked to the characteristics of the instrument used, to be aggregated on the project site through dry processes, minimizing the notoriously high expenditure of resources for this stage of the architectural design. This aspect could be further implemented with the introduction of operating instruments directly on the project site which, in fact, would even terminate the consumption of resources associated with the transport of components. That would encourage the testing of innovative aggregation systems that enhance the performative architecture parameters and, at the same time, stimulate design creativity to overcome the open industrial prefabrication featuring contemporary design processes. The flexibility of parametric models allows to examine and manage the complexity resulting from the aggregation of components. Aspects related to material and digital manufacturing technologies, together with the notion of informed architecture, are the main innovations of the proposed methodology as they reintroduce aspects of the project that the first digital era had identified as consequential and non-integrated processes. The informed architecture leads to the integration of the parameters concerning geometry, material and manufacturing from the early stage phase of the project giving two direct consequences: the reduction of the space of design possibilities relating to the power of digital computation and the introduction of the manufacturability limit that binds the digital model to the physical space. Further developments concern the quantitative analysis of the benefits arising from the adoption of the project methodology in the context of environmental certification protocols in the entire design process, with a focus on the performance of materials and the construction phase, as well as the quantification of the impact on grey or hidden energy of processes.

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