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Post-industrial robotics: the new tendency of digital fabrication for exploring responsive forms and materials through performance

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Abstract

The contribution proposes the experimental results of research on robotics manufacturing issues for the realization of informed architectural organisms on a 1:1 scale. The pavilions Fusta Robotics and Digital Urban Orchard and the technological system In.Flux represent the results of tests in which material, environmental and structural performance inform the computational process and the consequent materialization. The two pavilions, both wooden, constitute the physical implementation of different functional programs realised through a collaboration with industrial partners. Fusta Robotics is the result of a collaboration between industry and universities for the tectonic experimentation derived from the use of local 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 for a new concept of socialization space and food production within the agenda at the self-sufficiency in Barcelona. Finally, through the In.Flux prototype, we investigated the relationship among formal generation, structural analysis and robotic manufacturing for the realization of concrete free-form structures. The analysis of the prototypes opens the debate on the role of IT in the post-digital era when the design process manifest through the control and management of the flow of information affecting the digital computation and fabrication and the material behaviour. The resulting theoretical assumption considers the architectural form as the result of a diagram of forces where the achievement of the performance is the driving parameter for the formal geometric exploration. The continuous variation resulting therefrom is informed by performance parameters that define a new aesthetic which represents together the manifestation of objectively measurable performance parameters and the power of the tool through which the form is generated.

Keywords

Performance-based architecture; flexible models; optimization; data-driven strategies; robotic fabrication.

Note

The paper is a critical synthesis of parts previously published at conferences and seminars. The project Fusta Robòtica was presented to the International Conference REDS 2 ALPS as paper and poster while the project Digital Urban Orchard was presented as poster to AAG Conference at ETH in Zurich. Both projects have been subject of study in further paper to the conference Colloquiate 2016 in Matera, Italy.

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New paradigms for responsive architectures between computation and digital fabrication

The proposed contribution investigates the sector of product and process innovation which ranks as a priority to identify and define an applied methodology that combines digital computing, optimization and innovative production methods in order to determine the potential and critical issues related to a possible introduction of such strategy in the construction process or for what concerns the definition of a new concept of responsiveness. The recent publication "Parametricism 2.0" (Schumacher, 2016) has highlighted the beginning of a new testing phase that targets the use of computational-algorithmic tools, in their theoretical and practical aspects, for the resolution of specific environmental and social issues returning to deal with issues which warranted the birth of digital computing itself in the 70's (Frazer, 2016).

The ability to process information and then to use the data as guiding elements of the design process and not as add-on to use later on (Deutsch 2016) opens many, and largely unexplored, possibilities for environmental and technological design in all project scales. The theoretical assumption defines the architectural shape as a result of a diagram of forces (Thompson, 1992) and opens new investigation fields in relation to the possibility of creating and implement performative architectures, performance - based (Hensel, 2010). Hence, the geometrical and formal generation and exploration has the achievement of tectonic, structural, material and environmental performance as a driving parameter. It can be optimized in relation to a "space of possibilities" (De Landa, 2011) defined by the designer himself through a project goal (Kolarevic, 2016). The generative process offers the opportunity to explore complex and informed geometries in a flexible and fast way, to investigate natural phenomena, transforming the material from a passive recipient of shape to a design agent, such as driving element of the creative process, through the exploration of its mechanical, structural and behavioural features (Menges, 2012).

Based on this new paradigm the term performance takes on a new meaning. Talking about performance means to relate various aspects affecting the project by watching and learning from the natural and biological world: starting from the material, structural and spatial organization up to the environment and energy, the performance can inform the architecture and make it similar to a biological organism (Hensel, Menges & Weinstock, 2010). To transfer a performance - oriented architecture from the digital to the physical world, we must establish a new relationship between architecture and manufacturing among modern era paradigms. This need arises from the impossibility to use mass produced identical building elements as a solution to be applied in any context, even though it is subjected to input and dynamic variables of various kind. Through this methodological approach, we may have complex and responsive geometries in relation to external variable inputs, a digital customized process able to convert these morphologies in simple geometric elements and a highly performing and competitive manufacturing process (Gramazio, Kohler, 2014). This way the manufacture process will be informed by the performance defining a new concept of responsive architecture where the focus is placed on the generative and computational process, based on data rather than electronic and kinetic devices to be applied later on. To transfer a responsive Architecture from the digital to the physical world, we have to interconnect various skills and transfer to the field of architecture technologies used in other areas.

The architects go back to deal with problems related to the construction process, "the design of the process", and not only with the creative and compositional stage bringing back the division between mental and manual labour that has existed since the Renaissance with the models proposed by Leon Battista Alberti and Brunelleschi. The Dome of "Santa Maria del Fiore" in Florence made by Filippo Brunelleschi in 1436 is an example of a process-oriented design in which the architect has been involved in the whole process. From the concept and creative stage to the design of technological details of a custom machine realized in order to be able to materialize an architecture that responds to spatial and structural performances, not possible with standard procedures and technologies.
Learning from the Brunelleschi's dome, the fabrication process becomes a design input that informs the design process defining a new concept of responsive architecture that exceeds the logic of the assembly to achieve certain performances that may not be the same for each project and each application context. If the production processes derived from the industrial revolution are performative about costs and times of production, at the same time they are not suitable to manage the customisation and complexity of the components. Hence, the necessity to investigate and experiment manufacturing and design innovative processes able to subvert the concept of mass production of industrial origin. By doing so, it is possible to expand the range of materials used and discover new applications for traditional materials in order to give life to informed and sustainable processes. That enable a shift from serial mass produced components to a design that can take into account the performance of the materials, the application context and the characteristics of variables that inform the design process for which it is not possible to resort to standard prefabrication (Gramazio, Kohler, 2014).

Figure 1.

Robotic fabrication process: pick, cut and place. b. Final prototype. Source: Andrea Quartaraa.

Figure 2.

a. Robotic fabrication process. b. Wood structure assembled on IaaC rooftop Source: Andrea Quartara

Figure 3.

a. Robotic Milling process b. Final prototype at AA Hooke Park Campus. Source : Elif Erdine

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Digital manufacturing, now a well-known process in the architecture and industrial design sector, allows achieving a high degree of variation and complexity through the direct connection between geometry, virtual model and physical reality. The evolution of 3D Printing, from printing small items to printing architecture prototypes in 1-to-1 scale and the additive and subtractive techniques that characterize the world of digital fabrication (Naboni, Paoletti, 2013), are the demonstration of this theory. The connection between the generative process and the manufacturing process does not follow a formal evolution without logic and compositional relationships but rather uses the machine as a medium that allows producing complex geometries informed by optimization processes. One of the latest experiments in the digital manufacturing field linked to the world of construction is the introduction of industrial-robots. In 2015, the research conducted on these issues by Professors Fabio Gramazio and Mathias Kholer at the ETH Zurich has reached its 10th anniversary and has achieved such a high testing level to induce the Swiss government to invest huge resources in the NCCR project, 2015-2018, that will have the full-scale application of digital manufacturing robotics as output. The industrial machines, anthropomorphic robots, used in the automotive field since the 80's (Gramazio, Kohler, 2014) to perform specific tasks are reprogrammed and used to transfer digital models in the real world through this direct link.
Thanks to the abilities of the machines, it is possible to build and materialize complex and informed geometries.

Responsive architecture: methodology applied for the realization of experimental structures.

The proposed methodology was tested by carrying out a series of experimental architecture at 1: 1 scale through which it was possible to define the potential and critical issues coming from the application of the theoretical assumptions. The construction of the prototypes, Fusta Robotica (Figure1), Digital Urban Orchard (Figure 2) and In.Flux (Figure 3) represents the practice of a new design paradigm based on the information of the process that sees environmental, structural, tectonic and space performances as a factor driving the entire design process. The performance criteria derived from the material, the structural and environmental behaviour have informed the computational process, subsequently materialized using a generic machine, anthropomorphic robot, able to transpose responsive digital models with different functional programs in reality, through a non-industrial setting and using simple, irregular and low-engineered elements. The prototypes built as explication of the theoretical assumptions are the result of an

16. A single processor working 1000 GIPS can only perform 10^{18} operations in a year. So, if 10^{400} computers will work in parallel (because the problem is not sequential), they will be finished in a year; or 10^{800} computers in half a year. In other words, 10^{7K} is indeed an impossible number for us but not necessarily so for a network of computers.

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informed process among performance yardsticks and a new digital production method able to guarantee quality, flexibility and efficiency (Scheurer, Schindler & Braach 2005).

Fusta Robòtica: material - informed design through design information and robotic fabrication

The Fusta Robòtica[1] prototype is the first wooden structure built using robotic manufacturing in Spain. It was born from a collaboration between the IaaC, Institute of Advanced Architecture of Catalunya, and an industry of the sector as a material and tectonic testing to be exposed at the Setmana de la fusta 2015, with the intent to show the potential derived from the application of robotics manufacturing in the construction of wooden structures.

Objectives of the research were represented by the promotion and enhancement of the Catalan wood, sustainable and of high quality, by the exchange of knowledge between industries and research centres for the innovation in the production and distribution of the model in order to test new formal codes using local material. The material used to experience a new tectonic expression, consisted of simple wooden rods, irregular and low-engineered by the size of 38 mm x 38 mm x 2000 mm. The pavilion, formed by about 1000 wooden rods of variable length, 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. The entire design process was informed by characteristics and properties extracted from the material through a series of experiments, analogical and digital, aimed at the understanding of the behaviour of the material and the structural system. The use of this sustainable material, non-engineered for the use in the construction industry, has allowed us to analyse the potential and critical issues coming from the application in Architecture as well as to inform the design process.

Through the experiments conducted on the material in accordance with the manufacturing method and the available tools within a non-industrial setting, in the specific case wood provider, circular saw and drill, it was possible to define some critical issues.

For example, the variation of the curvature following the drying process of the wooden rods and the need to maximize the resistant section of the components to increase the structural rigidity and the load carrying capacity due to the scarce structural quality of the material. In relation to this, the design process has been informed using a redundant, hyper static structure composed by a multitude of small elements in

[1] Fusta Robotics was developed within dell'OTF, Open ThesisFabrication, professional program post - graduate disbursed by IAAC, Institute of Advanced Architecture of Catalonia

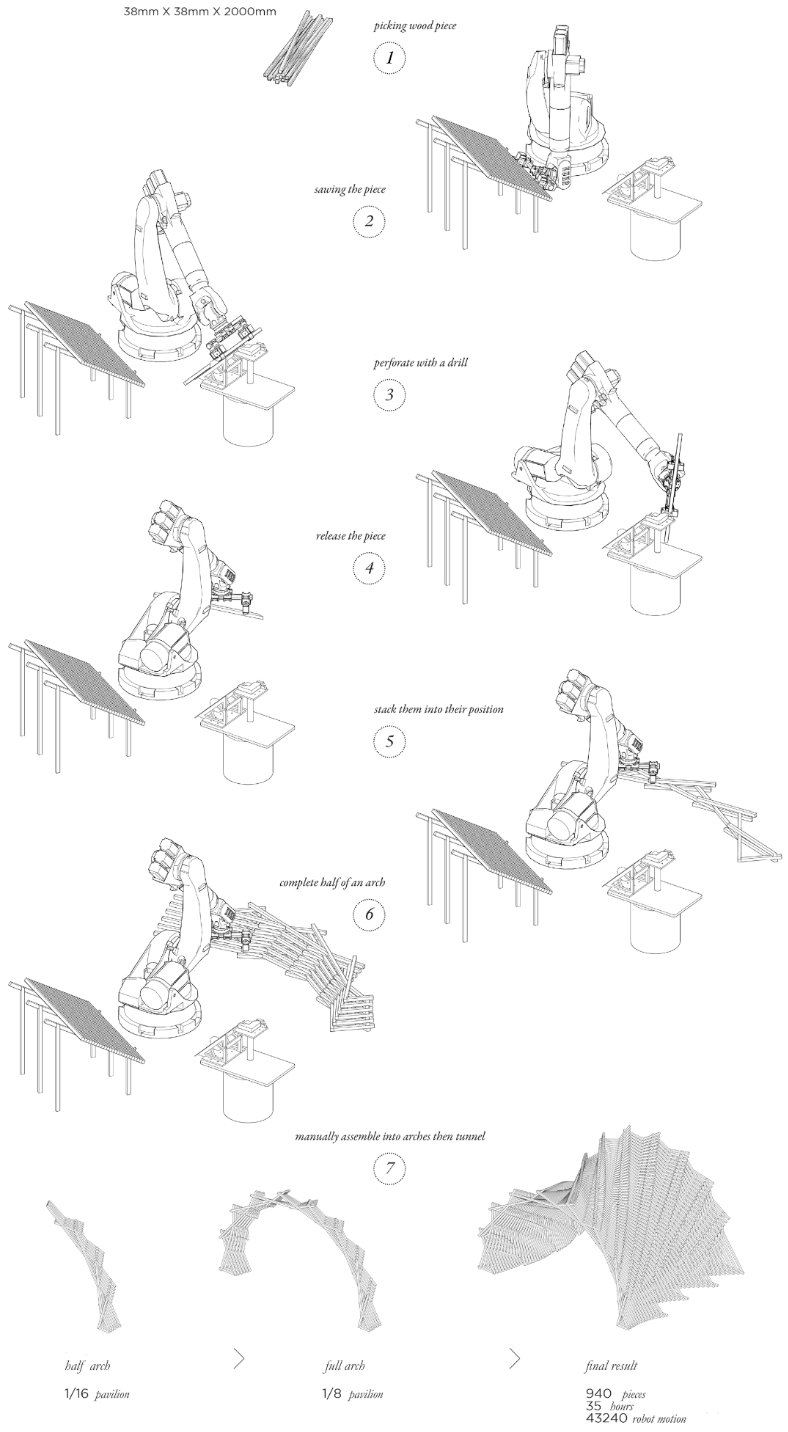

Figure 4.
Fabrication loop process. Stick picking, 2-side cut, drilling and stick placing.

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order to avoid structural problems due to excessive bending of the wooden profiles. To maximize the resistant section of the components in correspondence of the structural nodes we used nailed joints while the discretization of the shape in eight sections with a constant thickness has allowed optimizing the working space of the robot room avoiding collision problems. The design is informed and optimized within the characteristics of the production method used, the available tools, the working area, the characteristics of the material used and the structural behaviour. In parallel to the development of an analogical test, an algorithm was developed to transpose the 3D solids of the digital model into simple geometric elements such as lines and planes useful for the definition of the various processing stages.

Through the direct connection between the parametric model and the manufacturing tool, Robot KuKa KR-150, the various stages of the manufacturing process have been determined such as "picking", "cutting", "drilling" and "stacking" (Figure 4). At the end of the production process, we assembled 940 wooden rods of variable size in 8 arches divided into 16 parts with 35 hours of production. The construction of the robotic Fusta Robòtica prototype expressed the potential of digital fabrication with a non-industrial setting able to materialize the formal generation through the assembly of simple, irregular and low-engineered wooden rods.

[1] Fusta Robotics was developed within dell'OTF, Open ThesisFabrication, professional program post - graduate disbursed by IAAC, Institute of Advanced Architecture of Catalonia.

Digital Urban Orchard: form follows data flow.

The Digital Urban Orchard[2] prototype is the result of an applied research program whose goal is the design and the realization of a functional prototype at full scale to be implemented in urban public spaces. The criteria relating to material, functional, structural and environmental performance have been taken to inform the generative computational process later materialized through robotic assisted manufacturing and manual assembly process. Made from 1,681 wooden rods and 52 hours of production through a robotic manufacturing process and manual assembly, the pavilion hosts a hydroponic cultivation system and an adaptive silicone skin (currently under construction) able to ensure the indoor comfort conditions that are essential for the plants growth. The commingling amongst form, location and function has required a manifold responsiveness able to ensure proper compliance with the performance required by each of the individual parameters listed above in relation to the urban environment where it was subsequently assembled and placed. The formal generation, as well as the production process, is informed by a series of data coming from environmental analyses able to provide a

[2] Digital Urban Orchard was developed within dell'OTF, Open ThesisFabrication, professional program post - graduate disbursed by IAAC, Institute of Advanced Architecture of Catalonia

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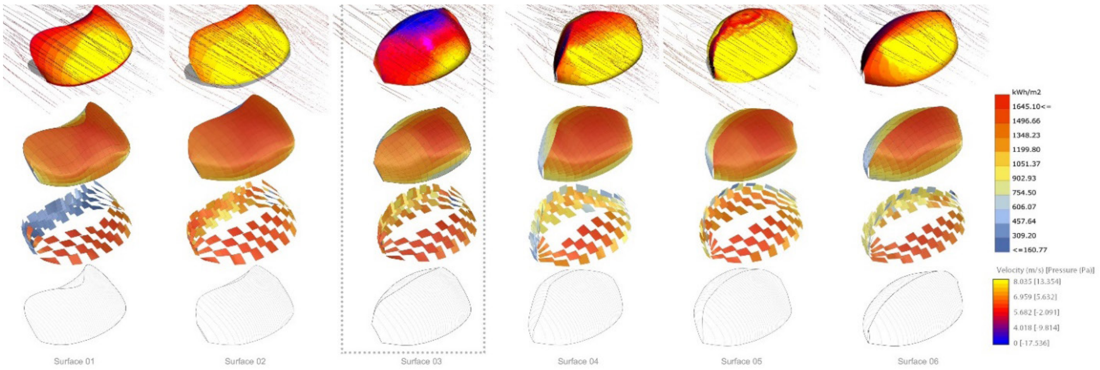

Figure 5.
Digital Urban Orchard. Shape catalogue: six different configurations resulting from the optimization. Surface 03 results as the final design choice because of the aerodynamic shape, of its global shape's solar access and of plots best orientation according to radiation values.

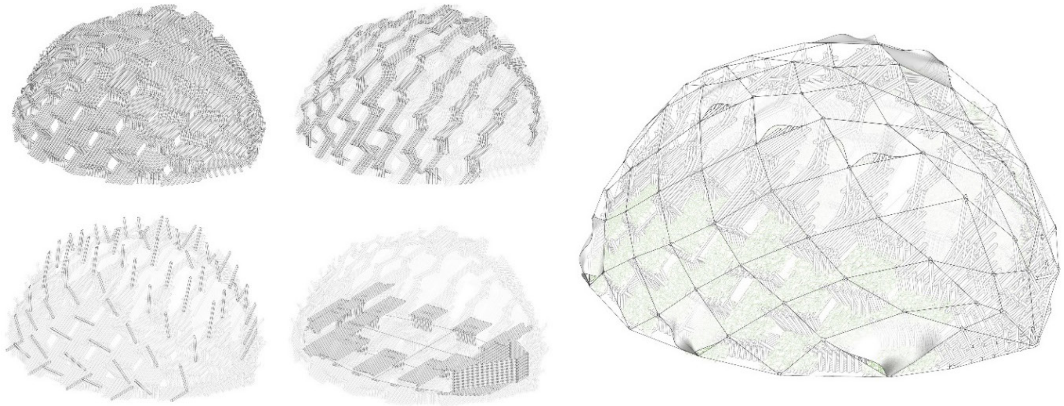

Figure 6.
Digital Urban Orchard. Structure Components: main trusses, skin holders, furniture elements and the final configuration.

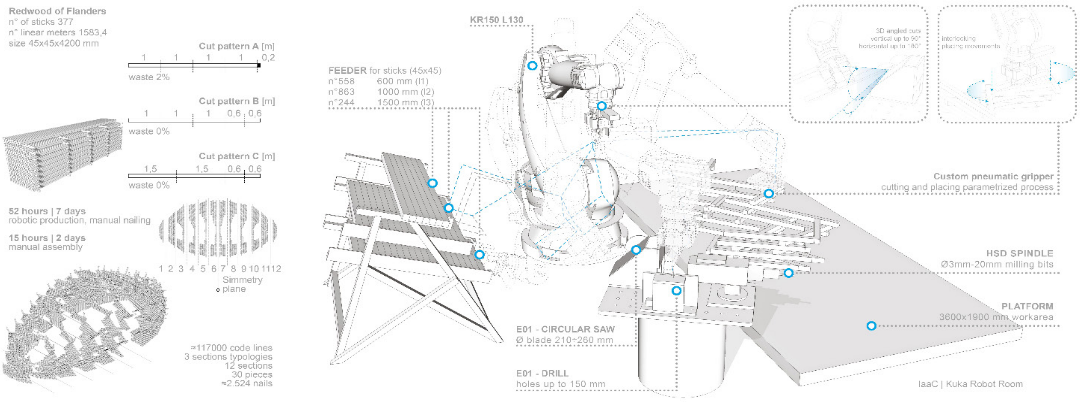

Figure 7.
Digital Urban Orchard. Statistics and Robot Room setup.

proper climate reading of the context, from the material used and the structural system.

Thanks to the computational process, the meta-design is developed through the definition and analysis of a catalogue of solutions, a possibility space that made it possible to optimize the shape among different performance criteria in order to define a responsive architecture that is the result of a mediation between the creative process and the performance-based optimization. The final form was selected from a catalogue of solutions. The solutions are the result of a process informed by the maximum size of the wooden rods in relation to the adopted production methodology and the available tools, by a range of possible angles used to cut the ends of the rods and by a series of conducted environmental analysis, more specifically CFD analysis and solar radiation. The CFD analysis allowed minimizing the wind pressure on the outer surface of the pavilion in order to ensure the structural balance while the analysis of the solar radiation has allowed determining the inclination of the wooden rods hosting the hydroponic system.

The final responsive shape has been discretized through a series of sections: 6 types for a total of 12 sections. In relation to the size of the sections and the working platform, we defined three manufacturing strategies that provide for the construction of the entire section or for the assembling of two or three parts of the final section, for a total of 30 parts assembled. The adopted structural principles are the same used in the pavilion Fusta Robòtica. The structural hyperstatic pattern based on the optimization of the material generated by the alternation between diagonals and elements able to ensure structural rigidity has been developed with a support system for the hydroponic plant, for the silicone skin and with furnishing objects that are functional to the space. 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 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 the extreme conditions as set forth by the legislation.

The implementations have been possible thanks to the end effector customization used for the production, the industrial gripper, and some tools used for the production such as the circular saw and the wooden rods dispenser. By analysing the experience previously carried out with the pavilion Fusta

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Robòtica, the production process has been implemented in all its phases of picking, cutting and stacking in order to reduce the material consumption (reducing the material waste to only 2%) and create an additional value to the production process. The formal outcome, the result of 52 hours of production with Kuka KR-150 robot and 24 hours of manual assembly coming from the information of the process and the optimization of the performance, has been completed in a production process that can control the complexity and transform it into design opportunities while ensuring rapid execution and automation. The creation of a customized digital process, rather than a product, allows making the prototype an open source through the spread of the digital model that can be customized with the information coming from the specific application context. Hence, the output will be a responsive process able to vary the morphology compared to the specific relationship among shape, context and function.

In.Flux: structural optimization and new material system for responsive architecture

The scale 1: 1 prototype In.Flux[3] represents the physical transposition of an informed design methodology in which data relating to material, structure and manufacture have determine the final morphology through a form-finding process. Through the construction of the prototype by the size of 4 meters in length and 2.2 meters in height, made of 0.75 cubic meters of high-strength concrete and 8 blocks of EPS in 1080 hours of processing, an operational methodology has combined digital computing, material testing and robotic manufacturing. The proposed operating methodology has provided the definition of a meta-design in which the start-up geometric parameters, as well as the material and the production method chosen for the realization of the prototype were made explicit. Thanks to digital computing and the construction of a flexible model (Davis 2011), the structural analysis conducted was used not only to verify of the performance among codes or regulatory aspects, but rather as a generative factor that can inform and expand the possibilities offered by the meta-design. The choice of the material and the manufacturing method, as well as the structural performance, turns out to be data project, input, and not predetermined or superimposed factors as it happens for a top-down approach to the project. The structural analysis and the optimization of the geometric parameters have defined the space of possibilities and the designer is required to make his choices in relation to the project goals. The computational tool allows taking a design strategy informed by data relating to the performance (in the specific case structural data) thanks to the possibility to process

[3] The In.Flux prototype was developed as part of AA SummerDLab 2015 workshop held at the Architectural Association in London and Hooke Park in Dorset

and using a large amount of information, transforming them into design input and elements generating shapes. In the specific case the structural iterative analysis realized by the Karamba® plug-in for Grasshopper® has allowed to define the minimum thickness of the surface in relation to the range of the displacements and identify and generate the openings so as not to interfere with the distribution of loads and unloading of the same in the foundation in relation to the stress line identified in the digital environment. In the realization of the prototype, the role of digital computing has had a dual purpose: the optimization of the structural performance and the simulation of a natural system, agent behaviour, in a digital environment.

The agent-based simulation created by Processing® software was generated starting from the curves division of the openings edge and regulated by defining parameters and values of cohesion, separation and alignment in order to determine the system behaviour. The forces acting in a perpendicular direction with respect to the previously optimized mesh, moving to the Z direction as far as the base, generate a deformation of the mesh that increases the resistant section, particularly near the openings and the base of the system in such a way that it ensures continuity in the vertical distribution of the loads. From the geometric coordinates of the vertices, the mesh necessary to define the morphology of the formwork and generate the files containing the processing paths to be transferred to the robot has been rebuilt.

Thanks to the plug-in Grasshopper © it was possible to reconstruct the mesh starting from a set of geometric information and then subsequently generate the file for the formwork as negatives of the two main surfaces of the wall that have the geometric pattern. The robotic manufacturing process was carried out by using a Kuka KR-150 industrial robot equipped with milling spindle, while the files were transferred to the machine thanks to RobotCam software through which all the parameters related to the subtractive process have been checked. When defining such an approach, the task to respond and adapt to inputs coming from the outside is transferred to the architecture through the definition of geometrical parameters. Responding to inputs via a data - driven process by using them as parameters of the project introduces a new concept of responsiveness and sustainability because each element of the system is only placed where needed. Contrary to the traditional design process, also the production method becomes a design input the designer must take into account to verify the effective constructability.

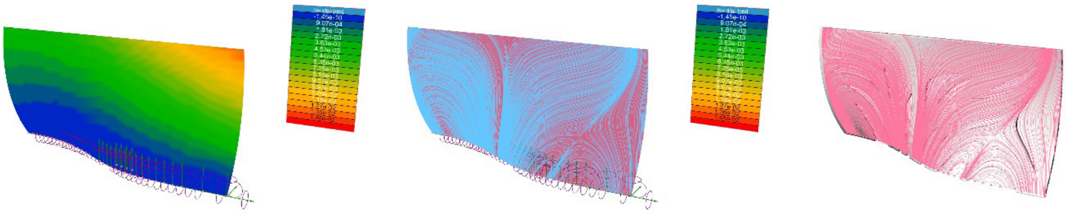

Figure 8.
Shell structure optimization with high-strength concrete (C90/105).

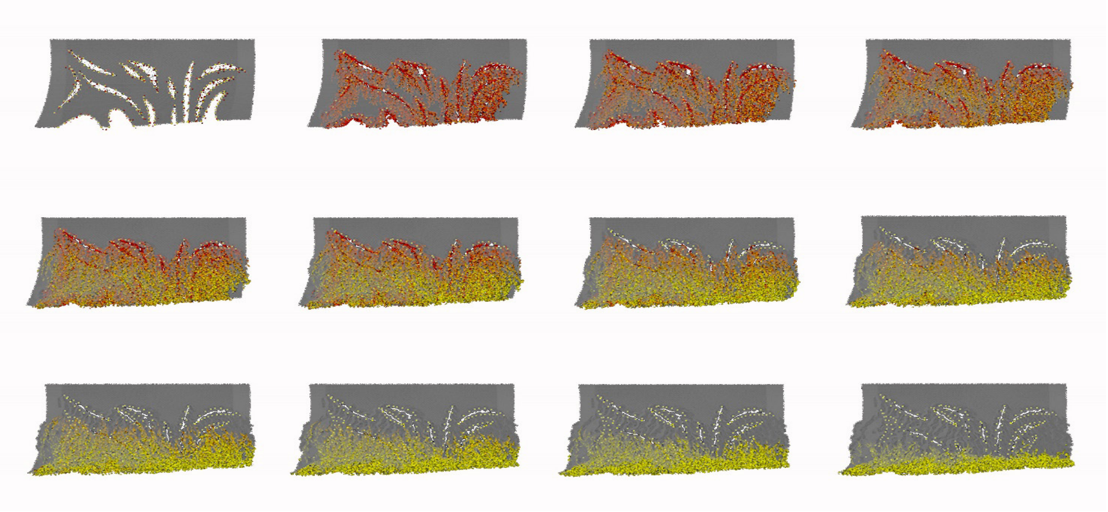

Figure 9.
Agent-based simulation starting from the optimized mesh.

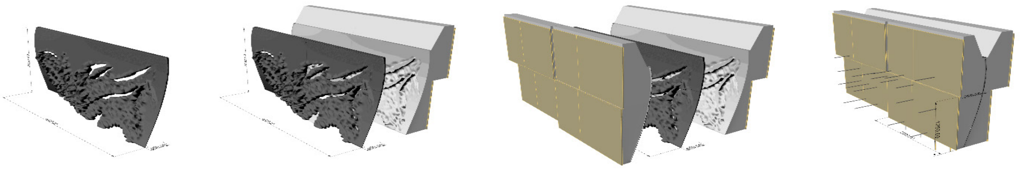

Figure 10.
Simulation of the fabrication process.

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Parameters such as the size of the workspace, the machine type, the type of end effector used and the relationship between the manufacturing method and the material become design variables expanding the space of possibilities. The result of a design methodology that provides the definition of a project goal and the space of possibilities is a responsive architecture that focuses on the process rather than on the tectonics and the final morphology.

Conclusion: define a new concept of responsiveness through data-informed design and complex fabrication techniques

The realization of prototypes has shown the possibility to materialize informed morphologies regarding performative parameters through the direct connection amongst data, flexible digital models (Davis, 2013) and robotic manufacturing. More, it has proved how to build a customized digital process able to convert complex geometries into simple geometric elements and develop an efficient manufacturing process. The raw material for Fusta Robotics as well as the complex relationship form-context-function of the Digital Urban Orchard pavilion and the structural performance of InFlux represent design inputs that generate informed architectures whose morphology is the result of the optimization of performance parameters that are objectively measurable. Architectures that can be materialized through new digital manufacturing technologies able to ensure freedom and complexity of execution with no industrial settings and not using engineered materials that are locally available. The proposed methodology reverses the mass production paradigm by introducing a new digital aesthetic where the customization of the form is interrelated with performative parameters and a material intelligence that emerges from the computational process. The continuous flow of information between design and manufacturing becomes relevant in the management of digital forms in order to start the following process of materialization. The concept of file-to-factory is enriched with new meanings beyond the dichotomy between digital file and production industrial process.

This is possible thanks to the democratization of the machines, the result of the third industrial revolution, and the possibility of decentralizing the production. With the post-industrial process, what changes is the direct relationship with digital manufacturing tools able to share and occupy the same space of the designer and to become an extension of it (Kohler 2014) in the workspace. The designer acquires a new material sensitivity and takes care of the entire design process from the concept to the construction, from an object-oriented approach to a process-oriented material approach called critical making (Ratto 2011). Starting from this scenario, future developments include the introduction of a further performative layer able to give the machine decision-making skills through the development of a system for real-time relationships between the virtual space of the digital and physical model. The design of adaptive models, able to vary in relation to the production process, allows reducing all problems related to tolerances and makes the robotics manufacturing even more efficient. The direct connection between digital and real space, guaranteed by the use of robots, eliminates process abstraction and create a new digital culture developing an aesthetic and material sense together with a social and cultural dimension. In summary, there's a post-digital era based on the performative customization of architecture and a new material sensitivity through the new computing and digital fabrication technologies.

Aknowdledgement

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