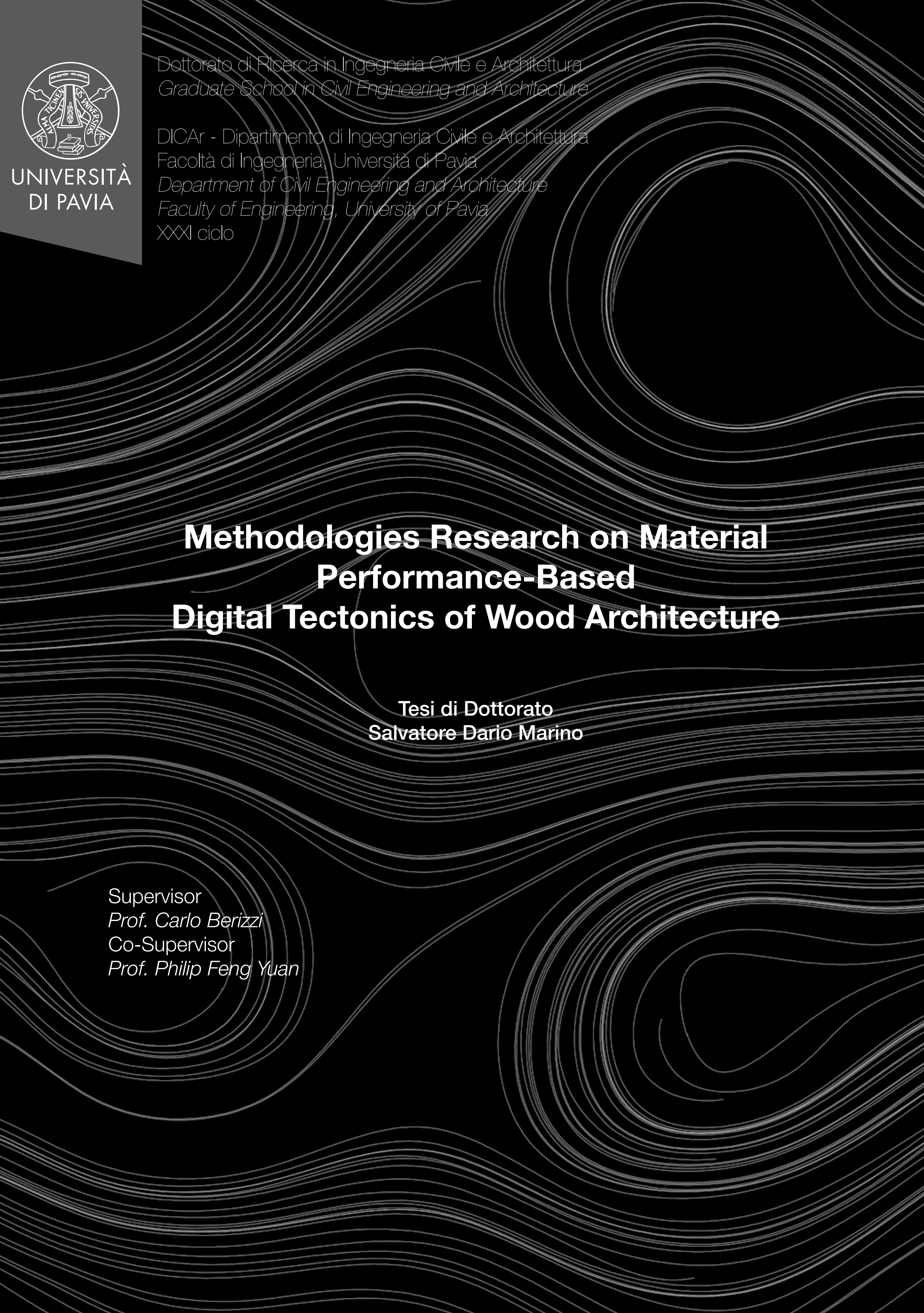


UNIVERSITÀ
DI PAVIA

Dottorato di Ricerca in Ingegneria Civile e Architettura
Graduate School in Civil Engineering and Architecture

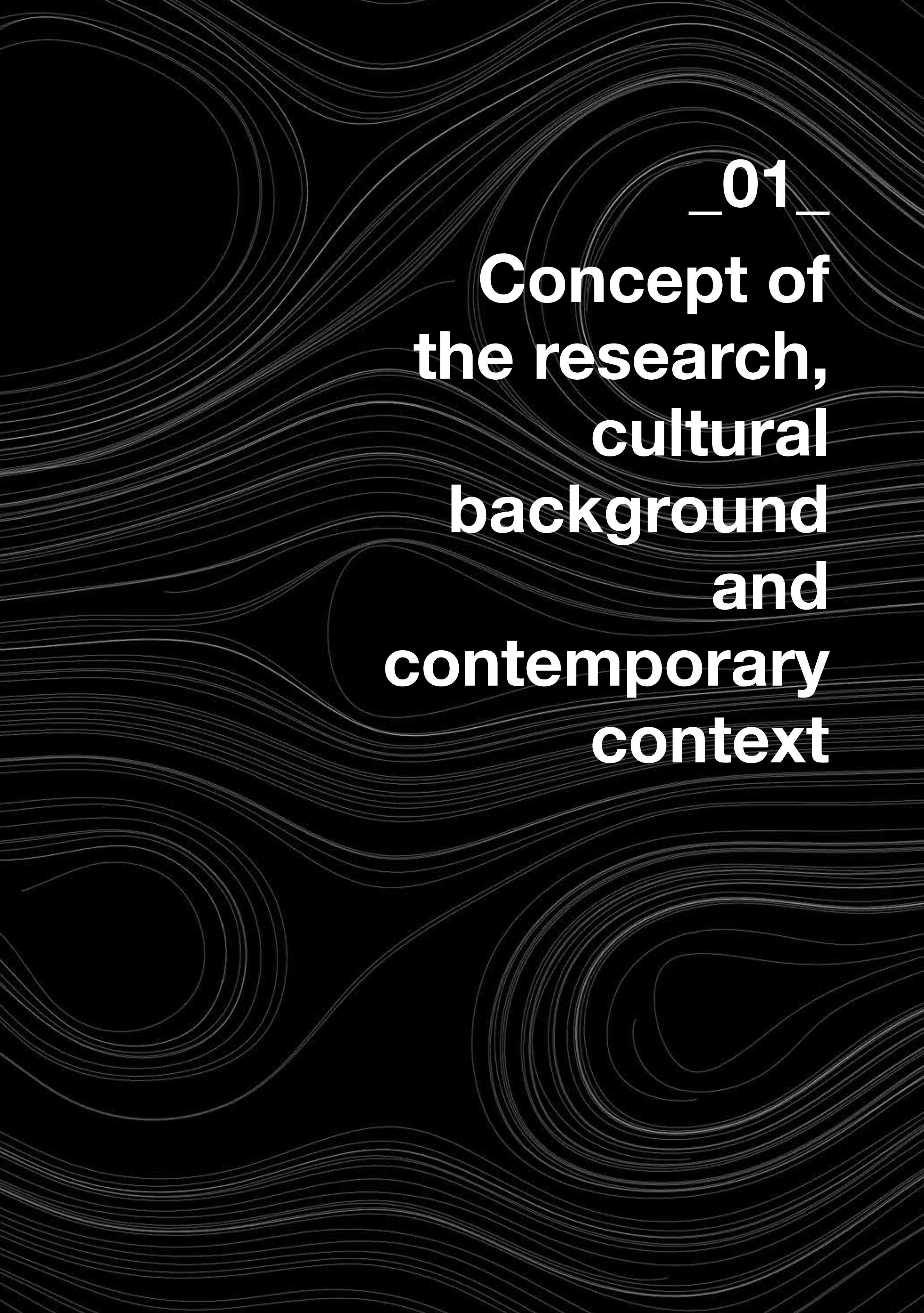
DICAr - Dipartimento di Ingegneria Civile e Architettura
Facoltà di Ingegneria, Università di Pavia
Department of Civil Engineering and Architecture
Faculty of Engineering, University of Pavia
XXXI ciclo

Methodologies Research on Material Performance-Based Digital Tectonics of Wood Architecture

Tesi di Dottorato
Salvatore Dario Marino

Supervisor
Prof. Carlo Berizzi
Co-Supervisor
Prof. Philip Feng Yuan

Contents



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Concept of the research, cultural background and contemporary context

Contents

1. Concept of the research, cultural background and contemporary context

1.1. Introduction

Concept and structure of the research

Recent technological developments, that rapidly evolved within the last two decades, are questioning the conventional design methodologies and fabrication techniques providing a wide field of exploration of digital culture in architecture. Starting from this consideration, the thesis observes and analyzes the **impact of digital design and robotic fabrication technologies in wood architecture** unfolding an innovative tectonic character of the construction brought by material performance-based design approaches. Beyond the opening to new possibilities of language and new compositional paradigms, digital design and fabrication tools are enhancing alternative methodologies that expand material properties no longer as passive component applied to a previously determined form, but as an active generative design feature thanks to integrative workflows. The focus on the emergent material culture - supported by the widespread dissemination of computation - and the related 'digital tectonics' in performance-based design is presented in this thesis through the analysis of the state-of-the-art in contemporary research and practice. The research was enriched thanks to the visits to Stuttgart's ICD (Institute for Computational Design) and Zürich ETH laboratories, considered among the most innovative research institution in this field, that through open discussions and guided tours allowed me to have an understanding of the fabrication facility set-up and of the complexity and multi-disciplinarity involved in the design phase. Moreover the periods spent in Tongji University of Shanghai under the supervision of Prof. Philip Yuan, expanded the horizons of the research through the design and construction of full scale architectural prototypes for two editions of the international workshop DigitalFUTUREs Shanghai in 2017 and 2018.

The thesis considers computation, algorithms and robots in terms of innovative tools applied in architectural research and practice. In our times it became fundamental to deeply understand the role of technology that is influencing every professional field, modifying the traditional approaches. In the last twenty years there have been many developments - a part the technological ones - from the cultural point of view in the application of digital tools within the architectural framework. A digital turn that began in the early 90's and that today reached a mature phase in the international academic research. Architects plays a crucial role in the exploration of integrative design strategies which make use computation, parametric models, algorithmic description and robotic fabrication and assembly. From here arises the need to define, understand and disseminate not only the operative tools and the methodological exploration but also the cultural and theoretical background identifying the 'ethic' of the construction and design in the information age.

The thesis starts describing the general context in which we are operating as architects and researchers, introducing the first applications of digital technologies in design, and follows talking about the evolution of digital theories in architecture. The first influences of electronic components in the early '90s that opened the mind of great thinkers and designers such as Peter Eisenman and Greg Lynn who introduced the theoretical interpretation of the fold in architecture as a constant dislocation of the relation between the object and the observer. The following years elaborated a smoother and more continuous version of the fold with the spread of 'blobs' - binary large objects - in the exploration of formal freedom allowed by computer modeling. From here have been subsequently developed the theories of a non-linear architecture dominated by free forms. Later on, digital tools, computation in particular, gained a more integrative role in the definition of new form generation methods as morphogenesis and in the exploration of emergence and complexity theories derived from the study of natural formation phenomena. These approaches, together with the experimental researches of Frei Otto brought influences from biological principles in architecture and moved the focus to a structural performance-based design. Computational morphogenesis was deeply studied at AA London in the EmTech (Emergence and Technology Group) and by the more contemporary ICD approaches that activates material properties in the design process. In this framework was introduced the criticized manifesto of 'Parametricism' as a 'style' by Patrik Schumacher, Zaha Hadid Architects, who intended to mark the paradigm shift in architecture as a revolution dominated by digital tools that enhanced dynamic free-forms, supporting the architectural philosophy of his office. Through the years the digital model became not only a representative mean but a working tool that integrates material informations and relates them to other design features. Consequently, platforms of associative algorithmic modeling (Rhino-Grasshopper environment among them) became fundamental tools to manage the whole design workflow till the fabrication and to allow iterative optimization based on selected performative criteria. These contributions formed the main technical and theoretical background for contemporary approaches which mature results are visible in the researches of the most relevant research institutions in this field such as Zürich ETH, Stuttgart ICD, Lausanne IBOIS including global-scale references as Shanghai Archi-Union. This maturity is not just linked to a mere technological progress – after all there have been about 25 years of technological and scientific development – but, above all, it is determined by a more conscious employment of the digital potential that integrates material properties and behavior with form generation, structural principles and robotic fabrication.

The correspondence between the physical materiality, technique and design concept testify a process which finds its expression in the tectonic character. This architectural theme is discussed in the third chapter, starting from the definition of the term 'tectonics' in architecture passing through the contributions of the XIX century till the contemporary debate on 'digital tectonics'. Wood is particularly inherent to the tectonic discourse since the term derives from 'carpenter' - *tektōn* (τέκτων) in ancient greek - the wood worker that craft the material to get a functional and aesthetic result based on his knowledge and cultural values. Frampton analyzed the various contributions on the topic of tectonic as 'poetic of the construction' in architecture, one of the most relevant is the interpretation of Semper who considers tectonics not only as an expression of the 'visible' technique but also of the 'invisible' cultural values. The absence of a cultural framework able to conjugate 'digital' and 'material' reduced the relevance of the tectonic topic within the architectural scene since the post-modern. Indeed, around the mid '90s, Frampton criticizes, among other causes, the advent of digital tools and their misuse in architecture. Today, it appears clear that the exploratory phase contributed in the definition of the technical and cultural background for the development of maturer theoretical position and a renewed interest in the tectonics. Even the early interpretations of 'digital tectonics' were contrasting and not always focused on a link with the studies of Frampton. This thesis try to give a contribution in the discourse of digital tectonics highlighting the cultural values of the 'digital crafting' in current state-of-the-art best practices.

From here a link of performative design with tectonics and digital tools emerges and is discussed in the fourth section. It is not about measuring the efficiency of a technical issue of a pre-determined building, performance is intended as an integrative feature, that can be pertinent to multiple domains, able to determine architectural relationships rather then just technical ones. Performance is not new in architecture, many examples in vernacular architecture based their morphological relationships and compositional patterns on environmental comfort issues, for instance, integrating the design with certain local requirements. Thanks to contemporary digital tools we can measure certain degree of material performance in terms of tension, compression or bending strength, thermal behavior, hygroscopic behavior, carbon footprint etc. Wood is considered as a material of the tradition which reveals to be highly performative under multiple aspects especially considering its natural role in the ecosystem. Wood is a material that, despite is one of the oldest material employed in architecture, still allows for remarkable innovation given its exceptional structural performance and workability.

The last two sections present the innovative potential of wood in the framework of contemporary performance-based design unfolding the design workflows. The analysis of the most relevant approaches to wood employment is classified into five methodologies:

morphogenesis and biomimetic, robotic timber construction (RTC), robotic customized timber components, folded timber plates, raw wood fabrication. Digital technologies - which comprises interconnected design, modeling and fabrication tools - question the conventional design methodologies and require to set new processes that are based on the scientific character of research. Through the analysis of selected case-studies based on research-by-design strategy the thesis unfolds the workflows and highlights the specificity of each approach in the vision of a performance-based digital tectonics. This vision is finally described through three projects designed and fabricated within the research frame of the thesis during the periods spent as visiting researcher at Shanghai Tongji University. Through these three projects the thesis proposes an additional approach to wood peformance-based digital tectonics experimenting different workflows.

Keywords and Definitions

To make clear the concepts discussed in this thesis, it is useful to provide a quick overlook on some keywords definitions and on the structure of the work. Each keyword is firstly described through a definition – from various sources – that highlight their conventionally known meaning, and then shortly analyzed to provide an interpretation in reference to the research framework.

Wood // Timber

wood[1]***:*** */wʊd/ [noun] 1. The hard fibrous material that forms the main substance of the trunk or branches of a tree or shrub, used for fuel or timber.*

Origin: old English wudu, from a Germanic word related to Welsh gwŷdd 'trees'.

timber[2]***:*** */ˈtɪmbə/ [noun] 1. Wood prepared for use in building and carpentry. 'the exploitation of forests for timber'.*

1.1 Trees grown for use in building or carpentry. 1.2 A wooden beam or board used in building a house or ship.

Origin: old English in the sense 'a building', also 'building material', of Germanic origin; related to German Zimmer 'room', from an Indo-European root meaning 'build'.

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[1] Oxford Dictionaries online en.oxforddictionaries.com

[2] Ibidem

Mankind exploits wood properties since centuries, from small objects to massive constructions to merely temporary structures it has contributed to shape the tradition of many cultures in history from all over the world. Moreover, wood is the only material used in architecture that is directly derived from nature, and thus it is a renewable resource that can be sustainably grown and cultivated with a positive carbon footprint even considering the contemporary massive industrial production methods. Differently from the other materials used in constructions (glass, steel, concrete, etc.) wood is characterized by structural anisotropy and imperfections which make it less desirable from certain points of view but, at the same time, it has remarkable load-bearing capacity given the fact that its shape and internal composition are developed and evolved to behave as a load-bearing structure.

Tectonics // Digital Tectonics

> ***tectonics*[3]*:*** *(from Latin tectonicus; from Ancient Greek τεκτονικός (tektonikos), meaning 'pertaining to building') is the process that controls the structure and properties of the Earth's crust and its evolution through time. In particular, it describes the processes of mountain building, the growth and behavior of the strong, old cores of continents […].*
>
> ***tectonics*[4]*:*** */tɛkˈtɒnɪk/ [adjective] 1. In geology, relating to the structure of the earth's crust and the large-scale processes which take place within it. 2. Relating to building or construction.*
>
> *Origin: mid 17th century (in tectonic (sense 2)): via late Latin from Greek tektonikos, from tektōn ‘carpenter, builder’.*

In the half of the 19th century the German architect Gottfried Semper introduces the concept of tectonic as poetic of the construction, as the artistic expression of the technique which results in a coherence between design, construction method and structure. Semper analyzes the vernacular architecture, going a step back in the past in the attempt to understand, interpret and give ethical meaning to his contemporary architecture during the time of the Industrial Revolution. From his analysis of the vernacular architecture emerges the value of the technique employed to work a material. There are four basic elements that composes this architecture: the roof, the heart, the enclosure and the mound. Specifically, Semper distinguishes the art of construction in two processes the “stereotomy” of the mound, and the “tectonic” of the framework. A distinction from light to heavy, but

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[3] Wikipedia, accessed November 2017

[4] Oxford Dictionaries online en.oxforddictionaries.com

both processes are influenced by culture and tradition. Therefore, to Semper, tectonics is not only a derived from visible technical solutions, but also from invisible cultural values.

The meaning of this "poetic of the construction" evolved over time together with the introduction of new production technologies and materials. As these reflections were made by Semper and others during the Industrial Revolution of the 19th century, we can identify a loss of these values during our industrialization age that came after, where the standardized production and processing of the materials interrupted the coherence that goes from the design to the manufacturing. Today we are probably facing a turn in favor of a new digital crafting of the material, the availability of digital tools makes possible to reconnect the workflow from the concept to the fabrication generating new design methods. In this last decade the digital culture evolved and reintroduced the discourse as 'digital tectonics'.

Performance-Based design // Material Performance-Based Design

> ***performance*[5]*:*** */pəˈfɔːm(ə)ns/ 1. The action or process of performing a task or function. 'the continual performance of a single task reduces a man to the level of a machine'. 1.1 A task or operation seen in terms of how successfully it is performed. 'pay increases are now being linked more closely to performance'. 1.2 The capabilities of a machine, product, or vehicle. 'the hardware is put through tests which assess the performance of the processor'*
>
> ***Performance-Based Building Design*[6]** *is an approach to the design of any complexity of building, […]. A building constructed in this way is required to meet certain measurable or predictable performance requirements, such as energy efficiency or seismic load, without a specific prescribed method by which to attain those requirements. This is in contrast to traditional prescribed building codes […].*

Latest development in digital technologies allows to produce informed models which, thanks to associative relations and generative algorithms, are able to change the design parameters according to a given feedback. This procedure can change the design based on a specific performance that we want to achieve. Branko Kolarevic defined this approach as "performance-based design" or "performative architecture". According to Kolarevic[7] this

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[5] Ibidem

[6] Wikipedia accessed November 2017

[7] Kolarevic B.: "Back to the Future: Performative Architecture", International Journal of Architectural

is not a radically new way of conceiving a design methodology, he claims that the first steps in this direction were made in the ‘70s by Tom Maver and his team at University of Strathclyde’s Department of Architecture and Building Sience (Glasgow), who aimed in finding a computer driven alternative to simulate building performance.

For some reasons, including the limitations in computation power in the ‘70s for instance, this field of research evolved only in the last years. Within the framework of contemporary performance-based design, the research will show some examples on performance driven projects and then it will concentrate on material performance-based design, with specific reference to wood. The anisotropy of the wood, its internal fibrous irregular structure, its history in construction and design, make it an interesting material to focus on, to forecast future directions of its application in architecture.

Methodology

***method*[8]:** */ˈmɛθəd/ [noun] 1. A particular procedure for accomplishing or approaching something, especially a systematic or established one. 1.1 The quality of being well organized and systematic in thought or action.*

Origin: late Middle English (in the sense ‘prescribed medical treatment for a disease’): via Latin from Greek methodos ‘pursuit of knowledge’, from meta- (expressing development) + hodos ‘way’

***methodology*[9]:** */mɛθəˈdɒlədʒi/ [noun] 1. A system of methods used in a particular area of study or activity.*

Origin: early 19th century: from modern Latin methodologia or French méthodologie

Based on a recognition of the state of art of the contemporary context in digital design, the research wants to explore the processes and solutions involved in the use of digital fabrication in wood structures, focusing on the material performance as a “generative” design factor. Current digital technologies enabled, in general, new ways of conceiving and employing the material and, consequently, there must be a change in the design processes which involves a deep understanding of material properties and related construction

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Computing, 2 (1), pp. 43-50, 2004

[8] Oxford Dictionaries online en.oxforddictionaries.com

[9] Ibidem

techniques. Going through the evolution of digital design in last twenty-five years, the thesis attempts, on one hand, to demonstrate the actual change in design processes since the early introduction of digital technologies and, on the other, tries to envision future directions of design methodology focusing on a specific material. Based on the experience acquired from the past, including conventional design methodology in architecture, the research will highlight the different current approaches to the formation processes in wood architecture opening to new scenarios in language, tectonics and structure for the future of architecture and the employment of digital fabrication tools.

1.2. The contemporary context: innovation in production and research in architecture in the digital age

> “Since the Industrial Revolution the world of design has been dominated by rigors of manufacturing and mass production. [...] We're living in a very special time in history, a rare time. A time when the confluence of four fields is giving designers access to tools we've never had access before. These fields are: computational design, allowing us to design complex forms with simple code; additive manufacturing, letting us produces parts by adding material rather than carving it out; materials engineering, which lets us design the behavior of materials at high resolution; synthetic biology, enabling us to design new biological functionality by editing DNA” [10]

Some technological innovations over the past two centuries have represented the milestones that revolutionized the industrial processes and the Western world production[11],

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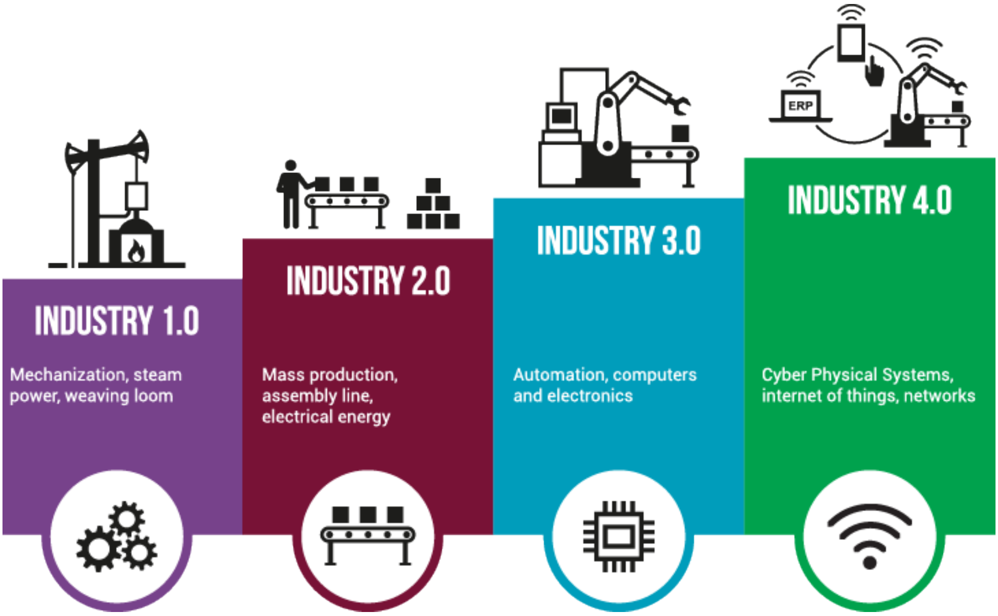
[10] Neri Oxman, Designer & Architect, TED Talk 2015 www.ted.com/talks/neri_oxman_design_at_the_intersection_of_technology_and_biology?language=en (accessed November 2016)

[11] www.economyup.it/innovazione/3713_cos-el-industria-40-e-perche-e-importante-saperla-affrontare.htm (accessed November 2016)

Fig. 1.1 Diagram that briefly presents the steps of industrial revolutions



making a significant change in society: the emergence of the **steam engine** in 1784; the beginning of mass production through the increasingly widespread use of **electricity**, the advent of the **internal combustion engine** and the increased use of oil as a new energy source in 1870; the birth of computer science, which gave impetus to the digital era aimed at increasing the levels of automation making use of **electronic systems and IT** (Information Technology) in 1970. It is known, as a result of these three historical moments, that the contemporary era is considered the stage of so-called "fourth industrial revolution." This "industry 4.0" is characterized by some major development guidelines[12]: the use of data and connectivity (big data, Internet of Things, cloud computing); strategies and methods for the analysis and the use of these large amounts of data; the man-machine interaction through more and more user-friendly interfaces; the materialization of digital to real involving 3D printing, robotics, etc. in which they fit new production methods labeled as *digital manufacturing* and *digital fabrication*.

City and architecture in the 4th Industrial Revolution

Undoubtedly, today, we are in a very special *era* from different points of view, in **an ongoing revolution** that reflects some consequences in the field of design and planning, involving two different scales: from the big scale of the city, on one hand, to the smaller scale of the architectural construction, on the other. At the **urban scale**, new management strategies and interpretation of big data and information have activated innovative planning processes for more intelligent cities, conscious and sustainable: the so called *smart cities*. In this sense, a great contribution comes from the liberalization of the **connectivity network** and the spread of systems and devices to access it, which nowadays are easily available for everyone, simplifying a series of daily actions (as an example, take the smartphones and everything that is connected to them). The connectivity has literally shortened the distances and revolutionized, somehow, our daily life. We constantly deal with actions that involve the use of the network, both in the professional context and in the social one, modifying the relationship between individuals and communities. The spread of connectivity has led to the emergence of an increasingly “digital culture”, allowing us to easily find a huge amount of free information, facts, figures and news that are updated in real time. From the economic, social and environmental context some globally identifiable trends emerge: the exponential growth of large cities, the search for urban development strategies (smart cities), the huge availability of information and knowledge accessible and shareable thanks to the Internet. On the other side there are processes, methodologies and strategies involving the **architectural scale**, intended as the scale of the building or artifact, which are the focus of this thesis. The topic of technology in architecture is very wide and can bring to various interpretations and results depending on what is being considered. From

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[12] See. Supra, 1

home automation to energy-saving strategies, the technological solutions improve our daily environment and help to control and reduce the carbon footprint. Within the architectural scale the digital developments are deeply influencing the design processes and the innovative potential is currently being explored by the contemporary research agenda. Many of the examples and approaches that will be presented in this thesis, although some of them are still at a very experimental stage, aims to change the architectural paradigm by introducing new design and fabrication solutions. It will be shown how deep scientific studies in academia support the material saving strategies and the optimization driven by several factors (structural, environmental, acoustic, etc.). These "*generative factors*" change the design processes enhancing the development of new design and construction methodologies.

Research and practice

> "The architectural research does not develop in isolated recurrence of each experiment, but it must also involve other experiments in order to create new forms of knowledge" [13]

In the contemporary context, research in architecture and urban development plays an important role, interacting effectively with professional practice and bringing innovation. In the analysis of current relationships between research, practice, and knowledge sharing, Maurizio Sabini, professor of architecture at Drury University[14], argues that *"while, on one hand, the explosion of the computing power has allowed us to process exponentially larger amounts of information, on the other hand the changes in the mass media and the invention of the network and social media, have given the opportunity – and produced the demand – for a more shared knowledge"*[15]. The combination of rapid technological development and the possibility to process and share information is determining **a cultural change**, also affecting the research field that, consequently, spreads outside the academic circles and **influences the architectural practice.** According to Sabini, architecture has to revise the paradigms of a **culture of the profession**, matured and established during the Modern, which today are challenged by this new changing turn at innovation, both in the practical field and theoretical one. In the last century, and particularly in these times, research has increasingly established itself **as instrument of acquisition of new knowledge**, on the one hand aiming to develop what is not typically possible to do in the profession and bringing ideas and concepts to the limit utopia, and, on the other, by introducing innovation

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[13] Tehrani N., "Un manifesto disaggregato: riflessioni sul mezzo architettonico e sul regno della strumentalità", editorial in The Plan 095, 2017

[14] Drury University, Springfield, Missouri - USA

[15] Sabini M. "La nuova frontiera dell'architettura ", editorial in The Plan 095, 2017

in the built architecture. Outside of academia and parallel to the architectural practice, research groups are rising in architectural offices, dividing the theoretical activity from the practical one, they aim to bring innovation in the construction field to adapt the architectural solutions to the needs of contemporary society. An emblematic case is the research group AMO (Architecture Media Organization) developed by the architect Rem Koolhaas from 1999 within OMA office. Some other similar realities are, to name a few, the research sections in international studies BIG, MVRDV, and Italian firms by Mario Cucinella and Aldo Cibic. Since the typical strategy of OMA is to engage in research before dealing with an architectural design, almost as a necessary step, AMO represents the opportunity to create a parallel collaboration between research and practice, to use the words of Rem Koolhaas "it is an entity that is able to renew and reinvent constantly"[16]. Similarly, many architectural firms have established parallel spin-offs dedicated to the research and its integration with the architectural design. The research approach has been, therefore, extended in a transversal manner in architecture, distinguishing different areas, more or less

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[16] Rem Koolhaas in conversation with Giovanna Borasi and Mirko Zardini (Canadian Center for Architecture) OMA and AMO, https://www.youtube.com/watch?v=RA2HDn-igFI

Fig. 1.2 Ivan Sutherland showing the functionalities of sketchpad.

specific, in which **multidisciplinary collaboration mechanisms** are involved. Among the different research directions developed over the past two decades in architecture, this thesis aims to deepen the theoretical framework and application of computational design approaches and digital fabrication tools, stressing how the influence of digital technologies in the design process and their applications in production, are profoundly changing the paradigm of contemporary architecture.

Introduction of digital technologies in architectural design

The introduction of digital technologies in architecture and design deeply influenced not only the way of representing and communicating a project, but also the mental landscape and thus the design methodology, opening up a wider scenario of possibilities, continuously changing. From a technical point of view, one of the earliest revolutionary inventions that introduced the digital world in the design and graphic representation was *"Sketchpad"*, the PhD project at MIT by Ivan Sutherland (Fig. 1.2), in 1963. It was a tool that allowed, for the first time, a designer to digitally represent points, curves and primitive geometries, through a hardware interface. From this moment begins the development of computer graphics and CAD (Computer-Aided Design) software. The most extensive deployment of these applications in professional offices happens around the '90s, when

Fig. 1.3 An overview of the design and modeling softwares available on the market today.

information technology starts to take roots in different areas, introducing the computer as a cutting-edge tool for the improvement of working efficiency. Early versions of CAD software did not exploit a particular computational potential, but provided the designer a digital version of the tools always used and, therefore, the mere possibility of working digitally with primitive and two-dimensional geometric shapes. We can classify the categories of software for the drawing and design, distinguishing by degrees of complexity and articulation (also corresponding to a chronological introduction in the market). The first category includes the **2D processing software**, not only technical CAD softwares but also other programs used for graphics and communication of the project, Photoshop, Illustrator etc. The second category is the **3D graphic-based software**, primarily aimed at entertainment world of films and animations, is later absorbed in architecture and used, initially, to produce renders, photorealistic images that designers find functional to communicate the project. The digital three-dimensional modeling in architecture proves to be a useful support for the designer, which is facilitated in the different phases of the project management and control of all the elements that compose it, also allowing for greater ease of modification and exploration of different solutions. The further development of these tools produced and distributed on the market several more advanced software - such as *Building Information Modeling* or **BIM** - that are no longer used only for handling graphics and but allow the organization and the development system of large amounts of data. The BIM presents characteristics that are especially useful in the management of large works and complex projects, thereby facilitating the control of the entire process, in relation to the economic aspects and construction. A further degree of complexity is represented by **parametric modeling software** (i.e.: *Grasshopper* for *Rhinoceros*) (Fig. 1.4) that enable three-dimensional modeling by acting on specific parameters set by the designer. The last category is for the **analytical software** (applied in various fields, from environment to structural) that help to create informed models and work in collaboration with algorithmic and scripting-based software. This combination allows to use the analysis's results as parameters linking the behavior or shape of architectural object to the studied performance. These last two categories, based on 3D modeling platform, enabled "performance-based" design approaches and generative processes which form a consistent field of exploration in current architectural research.

Regarding the introduction and use, now spread in all the architectural firms, computer-aided design, Shajay Bhooshan, partner of Zaha Hadid Architects and co-founder of CODE, the section that deals with research in computational design in ZHA, claims that these tools have necessarily influenced the profession introducing new paradigms and design methods. In the last fifteen years, architects have rethought their approach to the digital world of computers. In particular, we assisted to a first "exploration" phase of discovery of the possibilities offered by new tools, and a second phase of "exploitation" more aware of the potential offered[17]. The two phases differ in one fundamental point: in the first, the operational means to turn the idea into an architectural work are not entirely clear, this is why we speak of exploration; while in the second, is precisely the mastery and knowledge of these tools that gives rise to new solutions and possibilities. Today we are in a phase of consolidation in the use of these technologies in architecture, and, together with technological development, we see how research and profession often find a common field of action generating **interdisciplinary collaborations**.

1.3. The change of design methodology in the digital age

Contamination of technology and computing power gained in recent decades, immediately provided the basis for **theoretical exploration in design fields**. Since the early ‘90s the architectural debate starts to grow, albeit weakly than today, even in this direction, giving rise to new definitions and classifications of design approaches. Gero (1994), for

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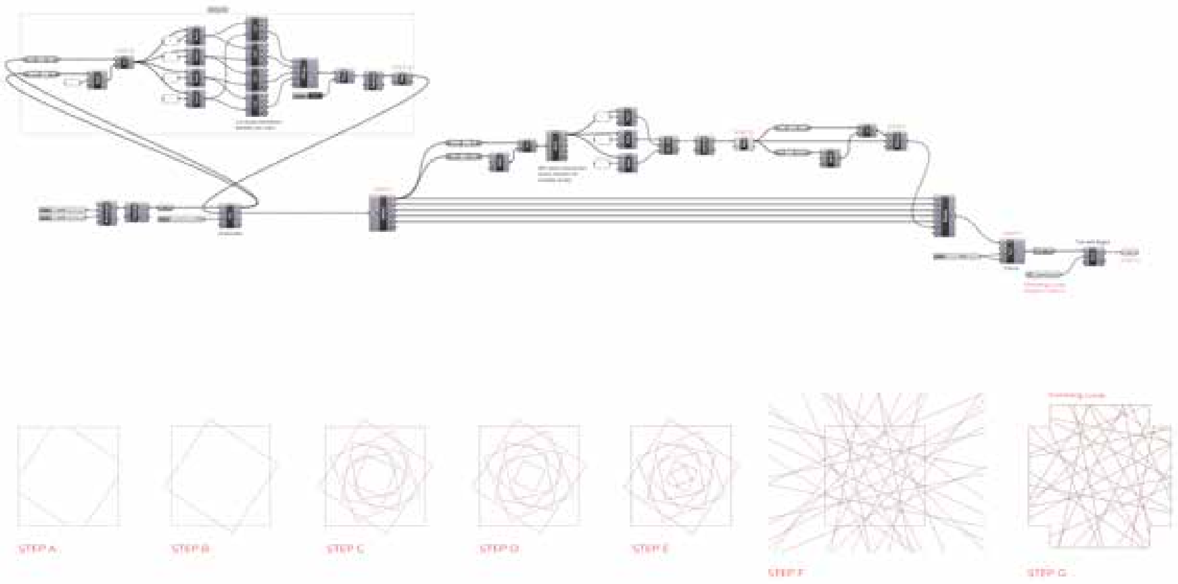
[17] See. Bhooshan S., "Upgrading Computational Design" in Architectural Design: "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" (AD2 / 2016)

Fig. 1.4 An example of algorithm generated in Grasshopper that shows part of the steps for the modeling of the Serpentine Pavilion 2002 by Toyo Ito and Cecil Balmond



example, introduces a fundamental separation in the way of conceiving “design methods” in connection with the introduction of new technologies in architecture, identifying two macro-areas of influence in *“computer aided design”*: the representation and production of the *geometry* and place of the designed objects, and the representation and use of *knowledge* to support the project[18]. The first case refers to the use of CAD software, aimed at **increasing the efficiency** in the design and in the representation: the CAD software is then simply used as a “drafting machine” in digital. In the second case it opens a theoretical treatment to **innovative approaches**, like performance-based ones or generative ones, that exploit the computational potential as a support to the design process and the search of the project idea[19].

As previously mentioned, today research in architecture can be considered as “antechamber” of innovation which, in a sense, anticipates what could possibly bring innovation in design. Moreover, in the contemporary context, research represents a theoretical and practical support to the construction industry. In this sense it is worth to mention how the first IT innovations in the early ‘90s have begun to profoundly influence the conception of the design process and the act of designing thanks to the visions introduced by research. In particular J. Gero (1996) says:

> “Designing is one of the most significant of human acts. It is one of the bases for change in our society. Designers are amongst the least recognised of society's change agents. Surprisingly, given that designing has been occurring for many millennia, our understanding of the processes of designing is remarkably limited. Part of our understanding of designing comes not only from studying human designers as they design but from postulating design methods which describe some aspect of the design process without claiming to model the processes used by human designers. The early approaches to design methods were prescriptive when applied to human designers. More recently, design methods have been formalized not as humano-centred processes but as processes capable of computer implementation. Amongst the goals of these endeavours are to develop a better understanding of the processes of designing, to develop methods which can be computerized and to aid human designers through the introduction of novel methods which have no human counterpart. This move away from modeling human design processes and from prescriptive methods for human designers has opened

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[18] See Gero J., preface, in J. & E. Gero Tyugu "Formal Design Methods for CAD." Elsevier: Amsterdam, 1994

[19] See Gürsel Dino I., "Creative design exploration by parametric generative systems in architecture", in METU Journal of Faculty of Architecture, 2012/1 207-224

> up new areas in the development of formal design methods for computer-aided design.[20]"

Already during the early phases of diffusion of information technology in architecture and design, the debate starts to rise not only in the professional field but also in the academia. As suggested by Gero, the role of technology is seen as a support to the **definition of new design methods** and implementation of the traditional ones.

Introduction to Parametric Design approaches

Parametric design is built on rules and algorithms and their potential of space exploration through the manipulation of variables and parameters. The main mechanism that is at the center of parametric and generative design is the algorithm, and it is the crucial technical aspect for the generation of the model. An **algorithm** is defined as a block of ordered instruction aimed to generate a result within a determined number of steps. One or more values are entered as input, processed by a series of computational steps and finally transformed into one or more values as output; in order to control the design process, it is necessary to know the logic of the algorithm and how it works, this is called **algorithmic thinking**. In an informal way a recipe, for example, functions like an algorithm, it guides the process through operations and steps that follow a precise order and get to the final output. The algorithm could be understood as an extension of the human mind that facilitates a series of operations. To adopt a design method that uses this system it is necessary to understand the logic, to **think algorithmically**, structuring the thought so that the idea of the project is appropriate for use of the algorithm.

Introducing these design methodologies, it is appropriate to provide an overview of the meanings of algorithm aided and parametric design. According to Neil Leach[21] **Parametric** is a term which can be find in various disciplines from mathematics to design. It means working within parameters of a defined range. The term is related to the use of software which allows to control a design process manipulating associative relations of parameters. These softwares differ from the traditional CAD based on given geometrical objects. The use of parametric software is not limited to form-making, they also provide a great control over the whole design process and team work management (BIM). On the other hand, an **algorithm** is a set of instructions programmed as an ordered sequence of operations. In the field of digital design the algorithm refers to the use of scripting techniques (programming) which allows the designer to go beyond the limitations imposed by the software user interface. An algorithm can facilitate a series of operations which would

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[20] See Gero J. and Fay Sudweeks, preface in J. Gero preface in "Advances in Formal Design Methods for CAD". Springer Science + Business Media, Dordrecht 1996

[21] Yuan P.F., Leach N., *"Scripting the Future"*, Tongji University Press, Shanghai, 2013

otherwise take a big amount of time. Therefore, it lends itself to optimization processes based on given parameters integrating the feedback from the results of specific analysis previously performed. Leach conclusion is that *"algorithmic techniques are based on the use of code. Parametric techniques are based on manipulation of form"*. We could more simply say that parametric design is quite coincident with algorithmic design, from a computational point of view, in fact, there is no difference between algorithmic and parametric design: the algorithm operates on parameters, which are the structuring part of the parametric system. The main difference is that the algorithm itself is built on generic values applicable in most cases, while the parametric design focuses on explicit parameter values to get the changes on a specific object in the design phase[22].

The use of algorithms in design moved the focus from the final object to the whole process. To this regard, when this process is informed by specific values we can also talk of a **generative design system** that tie the design process and the use of digitally controlled parameters to a generative factor derived from previous researches – it could be the analytical feedback of structure, circulation flows, acoustic, thermal, biomimetic etc. The generative factor is translated in parameters into an algorithmically defined 3D model, which gives the possibility to generate several outcomes of the project. Typically, infact, in generative design there could be more outputs after an iterative process. The number of outputs depends on the number of iteration processed. Every time that the designer adjusts the parameters he can run the entire process and obtain the new result. It is not easy to give universally valid definition of 'generative system' because, over the years, it has developed different sub-sectors that deals with specific areas of computational design and, therefore, focus on various aspects, from the structural behavior to the studies on the material performance. In general, we can state that a generative system[23] is a system that, through a series of instructions, input, rules, constraints and parameters, allows to control the **process** that will lead to the final artifact. The process is usually composed of four basic elements: the initial conditions or parameters (input), a generative mechanism (rules, algorithms, etc.), the generation of different options (output), and the best option choice. At the theoretical level this approach has references in the history of architecture, such as those analytical settings or design method focused on the process that leads to the final product. Le Corbusier, for example, in his "five points" gives the instructions to generate the basic elements of modern architecture and identifies the main parameter in the *modulor,* around which rotates its conception of architectural space. Even Peter Eisenman

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[22] Gürsel Dino I., "Creative design exploration by parametric generative systems in architecture" in METU Journal of Faculty of Architecture, 2012/1 207-224

[23] On this subject, see Gursel Dino I., "Creative design exploration by parametric generative systems in architecture", 2012

deepened the studies on the process in the design of a number of houses (House I - X). In his research Eisenman claims that *"the house is not an object in the traditional sense - which is rather the result the end of a process - but more precisely the recording of a process"*[24]. Even in the field of contemporary engineering, the feasibility of a structure can be considered as a form of beauty which is reached through an "*aesthetics of the process*", rather than through the traditional *"aesthetic object"*[25]. This **emphasis on the design process**, instead of the mere final product, and the act of conception of form connote the generative system as *"essential structural element of the architectural synthesis"*[26].

The use of a parametric method allows to get rid of certain spatial and geometric constraints, this, however, can lead to an excessive concentration on the shape and the final appearance of the artifact generating autoreferential forms which ignore the relations with the surrounding context, the technical requirements, the energy performance, the quality of the generated space or constructive feasibility. In a sense, this is visible in the early "digital" works by Frank Gehry or Zaha Hadid, for example, considered as pioneers in digital design. Heirs of the post-modern culture, in the early '90s they rediscover a formal and representational freedom, made possible by the emerging digital technologies, but that often sacrifice the coherence between the structural characteristics of the material used, the constructive method and form. The Guggenheim of Bilbao, for instance, in order to celebrate the formal freedom, is constituted by a "skin" apparently light from outside, but in reality supported by a massive and weighty steel structure that finds no tectonic correspondence with the elaborated form. This is obviously an early stage of digital design that has raised many criticisms regarding the adoption of alternative and *avant-gardist* approaches, but at that time they provided the first theoretical and practical basis for bringing coherence between formal, structural and constructive expression achieved through digital tools.

The introduction of advanced softwares in architecture can lead to mainly two different strategies of its use. The first concerns the application of such software solely in terms of **technical tool**, and workflow optimization; the second, more articulated, is **embedded in an new mindset**, is a cultural fact supported by a theoretical framework. In this latest case the technology is used since the early phases to achieve innovative architectural result; to this regard we can speak about digital design. To clarify this issue, it is useful to report two simple descriptive examples: the Kilden Performing Art Center in Kristiansand (Norway) and the Aviva Stadium in Dublin.

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[24] Eisenman, P. VI House, Progressive Architecture, 1977

[25] Lim J. "Bio-structural analogues in architecture", BIS Publishers, Amsterdam, 2011

[26] See. Gürsel Dino I., "Creative design exploration by parametric generative systems in architecture", in METU Journal of Faculty of Architecture, 2012/1 207-224

For the project of the **Kilden Performing Art Center** (Fig. 1.5), the ALA office, the computational potential of a parametric system has been used only in the final stages of the design. The project is characterized by a large curved and inclined wall that separates the theater from the foyer. The wooden corrugated wall meets with a glass facade on the main elevation and with an aluminum coating on the lateral elevations. In the planning of the construction details, in particular at the intersection of different materials, it was taken into account a number of criteria that have led to the use of a parametric model. In this case the parametric model was used to accurately define the best position of the load-bearing structural parts in relation to the overall characteristics of the project, and to study the details for the assembly, ensuring an easier construction.

The **Aviva Stadium** (Fig. 1.6), realized through a collaboration between Populous, for the architectural part, and Buro Happold, for the engineering, is an example of performance-oriented design in which the parametric approach is applied from the earliest stages of the project. From an architectural point of view, a process of form finding has been applied to meet certain spatial, aesthetic and linguistic requirements. From the engineering point of view the parametric system was used to optimize the structural and technical issues,

Fig. 1.5 Kilden Performing Art Center Kristiansand (Norway) designed by ALA office

passing through software for structural analysis. Moreover, thanks to a single parametric model, shared by the two offices, it was possible a multidisciplinary approach that helped to coordinate a complex project.

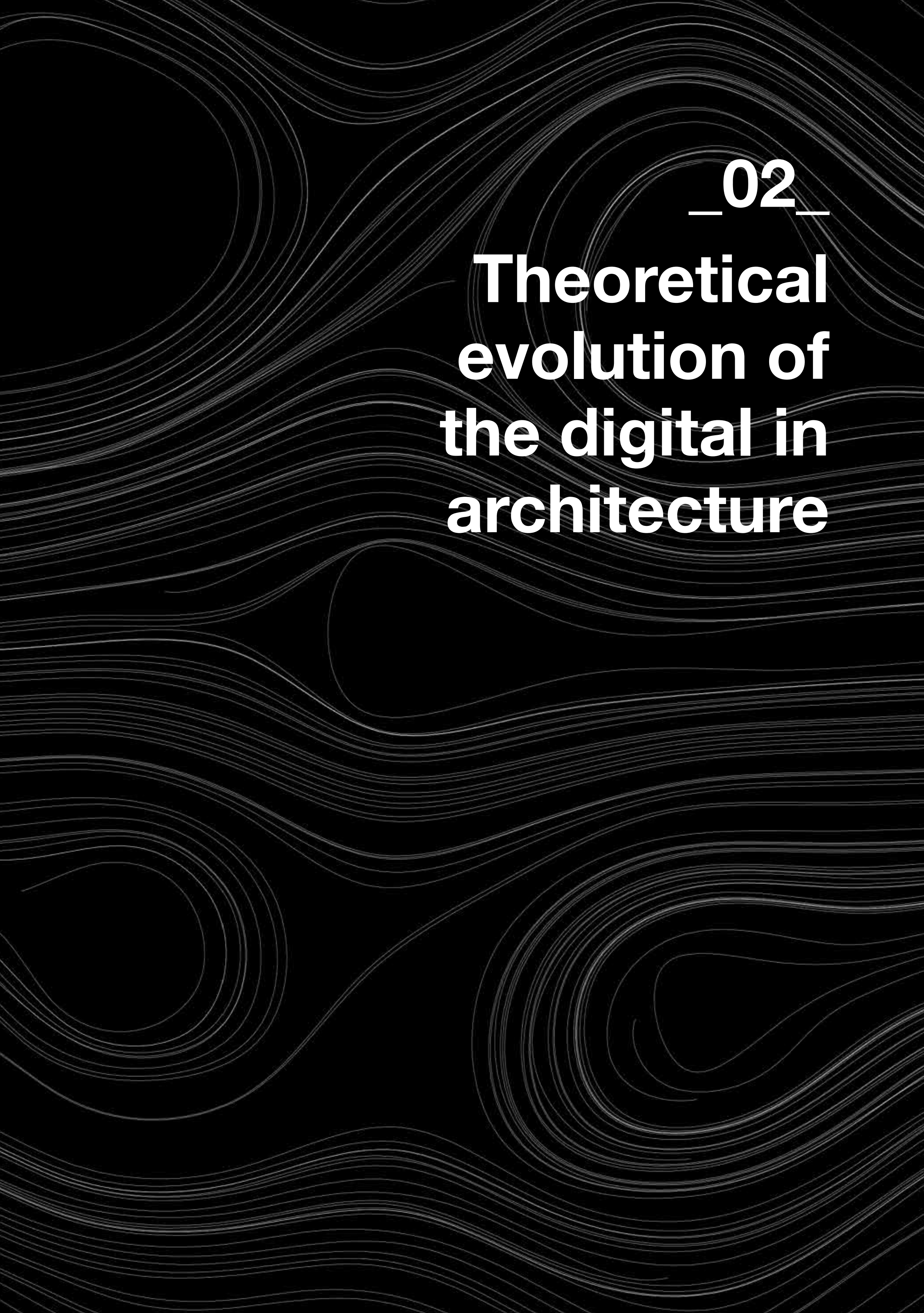
Today it is reductive to generically speak of digital architecture if referred to applied research direction taken by both institutions and professional firms because of the hyper-specialization that has emerged in recent years. There are several fields of study and approach to the subject of digital technologies in relation to their effect on the implementation and potential impact on architecture and design. As stated Bob Sheil and Achim Menges in their introductory contribution to Fabricate 2017:

> “We can no longer talk in general terms about 'digital architecture'. Such a generalization no longer seems to do justice to the multifaceted cultures of computational design and digital fabrication, their finely differentiated approaches and their different physical manifestations [...]. Equally, we are witnessing a rapidly blurring boundary between computational design and digital fabrication. The clear line that once existed between these two domains has become increasingly questioned by cyber-physical productions systems and challenged by new

Fig. 1.6 Aviva Stadium in Dublin design by Populous and Buro Happold

> forms of man-machine collaboration (designer collaborations and robots, in most cases)”

Among several active research frameworks in the field of computational design some deepen the use of DNA and the contamination of synthetic biology (such as research conducted by Neri Oxman at MIT), others focus on specific areas of robotics and human-robot interaction in the process of construction and design (at the ICD in Stuttgart or the ETH Zurich, for example), or kinetic architecture, integrating and programming sensors capable of meeting bioclimatic needs and language, others apply the use of drones and sensors for analysis on an urban scale to evaluate environmental quality (such as searches for Biayna Bogosian at the University of Southern California USC). Moreover, many international conferences held in different parts of the world have grown, in the last decade, qualitatively and quantitatively, contributing to the debate and discussion on issues that are increasingly globally shared. The various contributions presented at international conferences – ACADIA, CAADRIA, Fabricate, Rob-Arch to name a few – provide an interesting overview of the contemporary context and the ubiquitous multidisciplinarity, anticipating revolutionary applications of computational design for architectural research and practice.



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Theoretical evolution of the digital in architecture

Contents

2. Theoretical evolution of the digital in architecture

The beginning of Digital Architecture in the late XX century

The new contemporary material culture and the developing technologies have brought to an expanded relationship between the computer and the architecture, and contributed to define *"a digital continuum from design to production, from form generation to fabrication design"*. In these terms, the digital technologies are not intended merely as tools but as *"a medium that supports a continuous logic of design thinking and making"*. The digital profoundly revolutionized the theoretical though including the interrelation of several complex fields like science, technology, mathematics, in the architectural culture. There is an always stronger connection between *"the formulation of design processes and the developing technologies"* enabled by the digital in architecture[1].

What we are achieving today is not only enabled by a mere technological evolution. The pure **functionalism** in architectural design processes was already experimented decades ago, and the results demonstrated the rigidity and incapability of adaptation to the changing needs of socio-economic and cultural context – see, for instance, the residential compound projects in Italian's suburbs and the related difficulties of integration in the contemporary urban planning strategies. We can observe **direct and indirect consequences** of technological influence in architecture and design. Direct consequences of the application of technology (automation) in design process (creativity) are easily perceivable in workflow optimization, management and designer's productivity, supported by digital tools. But this way of combining technology and design, when misused and misunderstood, could bring to an **automated creativity** where your digital tool is just a medium to do faster what you were already doing before. Instead, there is an always growing awareness, fostered by academic research, that a **creative automation**, lead by the designer to expand the design space, is a meaningful direction to include digital potential in architecture. In this second interpretation the 'digitality' becomes an active feature in the design process – as an indirect consequence with a broader field of action – aiming to bring innovation in practice and give efficient answers to the issues of contemporaneity. The results of in-depth theoretical and practical application of 'the digital' are visible, for example, in the many projects of academic research institutions realized in the last decade. Many of the progresses done in this field not only brings technological evolution but also contribute to the construction of a theoretical background.

The introduction of 'digital' in architecture was not the cause for the construction of new

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[1] See: Oxman R., Oxman R. "Theories of the Digital in Architecture", Routledge, Abingdon and New York, 2014

theories, on the contrary, the 'digital' fit itself in a theoretical context that was already changing, as it always and constantly does. Architecture has always been a discipline that found its references in different fields of culture: mathematics, science, philosophy, social studies etc. All the architectural movements (styles) we've gone through are causes and consequences of cultural changes, and somehow, they necessarily reflect the condition and character of their contemporaneity.

Eisenman and 'the Fold'

A theory of the digital in architecture rises around the early '90s, by some avant-gardist philosophies and in few years generated a large amount of contributions that opened the debate on many aspects. For the aims of this thesis I tried to highlight only some of these theories, considered to be the most relevant ones that could support it. In the first place it is fundamental to understand the changing point in which technology – and 'the digital' – introduced itself within the architectural paradigm, not as a mere tool but as a catalyst of new thought.

In 1992 Peter Eisenman wrote an essay, published in Architectural Design – an architectural review which started to embrace the topic of digital design – that opened up to alternative visions of 'that' contemporaneity and started debating on the possible role of architecture in those circumstances. The thought of Eisenman, expressed in these essays, is a spontaneous continuity (an evolution) of the deconstructivist theory. In *"Visions Unfolding: Architecture in the Age of Electronic Media",* Eisenman introduces themes that will be at the center of the theoretical debate for the following decade. The beginning of this vision is expressed by the comparison of the primary means of reproduction available at the time: the **photograph** and the **fax**, which represents the paradigm shift of the '90s from the mechanical to the electronic one. The photograph is under the control of human vision, and thus the human is an interpreter, and there's a value in the original reproduction. With the fax – and by extension all the other related and similar technologies introduced at the time as copy machine and printers – there's no human interpretation, ad the concept of originality is challenged, in the transmission the original remains untouched and without alteration, but this doesn't give it a different value since the original is not sent. This is to say that the electronic paradigm introduces the *"mutual devaluation of both original and copy"* and questions the interpretative vision of the observer. For Eisenman this issue is transversal, with effects on architecture. He claims that the mechanical paradigm is the *sine qua non* of architecture; reciprocally, architecture is the monument of the mechanical paradigm. The electronic paradigm challenges this condition because *"it defines reality in terms of media and simulation; it values appearance over existence, what can be seen over what is. Not the seen as we formerly knew it, but rather a seeing that can no longer interpret. Media introduce fundamental ambiguities into how and what we see".* In architecture the **mecha-**

nism of vision is not questioned since the introduction of perspective in the 15th century; in the traditional understanding of architecture sight is superior, not questionable. *"It is precisely this traditional concept of sight that the electronic paradigm questions".* Until this moment the vision of the subject in architecture is **monocular**, all the projections of space can be resolved on a single plane surface. There have been some attempts in other disciplines to challenge this monocular and anthropocentric vision; the drawings of Piranesi, for instance, had multiple vanishing points that made difficult to correlate all the elements into a unified whole, or even Cubism proposed a non-monocular perspectival condition (or vision). For Eisenman in architecture this was attempted through Constructivism and Modernism (mentioned as the architectural normalized version of Cubism), but he claims that, except from the look, *there was no shift in the relationship between the subject and the object* and that there was never a real questioning and deflection of the subject because *architecture, unlike any other discipline, concretized vision*. Vision in architecture can be defined as a way of organizing space and elements in space, it also describes the relationship between subject and object. Vision in its traditional meaning is a way to rationalize the position of the subject in space. The idea of Eisenman is that the new electronic paradigm, as introduced before, **dislocates vision**. The mechanical reproduction is static, the electronic reproduction is **dynamic**, it belongs to files, and numbers that can continuously change. To dislocate the vision in architecture Eisenman proposes the idea of 'looking back', not intended as the object that become the subject, anthropomorphizing the object, but as a possibility of detaching the subject from rationalization of the space. He proposes a **logical process** to dislocate the traditional relationship subject-object, and introduces, for the first time in architecture, the 'strategy' of **folding**, derived from the philosophy of the differential calculus by Deleuze (and his interpretation of Leibniz).

> A possible first step in conceptualizing this other space, would be to detach what one sees from what one knows – the eye from the mind. A second step would be to inscribe space in such a way as to endow it with the possibility of looking back at the subject. All architecture can be said to be already inscribed. Windows, doors, beams and columns are a kind of inscription. These make architecture known, they reinforce vision. Since no space is uninscribed, we do not see a window without relating it to an idea of window, this kind of inscription seems not only natural but also necessary to architecture. In order to have a looking back, it is necessary to rethink the idea of inscription. [...] To dislocate vision might require an inscription which is the result of an outside text which is neither overly determined by design expression or function. But how could such an inscription of an outside text translate into space? Suppose for a moment that architecture could be conceptualized as a Moebius strip, with an unbroken continuity between interior and exterior. What would this mean for vision? Gilles Deleuze has proposed just such a possible continuity with his idea of the fold. For Deleuze, folded space articulates a new relationship between vertical and horizontal, figure and ground,

> inside and out – all structures articulated by traditional vision. Unlike the space of classical vision, the idea of folded space denies framing in favors of a temporal modulation. The fold no longer privileges planimetric projection; instead there is a variable curvature".
>
> "Folding changes the traditional space of vision".
>
> "Folding also constitutes a move from effective to affective space".
>
> "Folding is not another subject expressionism, a promiscuity, but rather unfolds in space alongside of its functioning and its meaning in space – it has what might be called an excessive condition or affect".
>
> "Folding is a type of affective space which concerns those aspects that are not associated with the affective, that are more than reason, meaning and function".
>
> "The fold presents the possibility of an alternative to the gridded space of the Cartesian order. The fold produces a dislocation of the dialectical distinction between figure and ground; in the process it animates what Gilles Deleuze calls a smooth space. Smooth space presents the possibility of overcoming or exceeding the grid. The grid remains in place and the four walls will always exist, but they are in fact overtaken by the folding of space. Here there is no longer one planimetric view which is then extruded to provide a sectional space. Instead it is no longer possible to relate a vision of space in a two-dimensional drawing to the three-dimensional reality of a folded space. […] Architecture will continue to stand up, to deal with gravity, to have 'four walls'. But these four walls no longer need to be expressive of the mechanical paradigm. Rather they could deal with the possibility of these other discourses, the other affective senses of sound, touch and of that light lying within the darkness".

Eisenman's theory initiated a totally new debate in architecture during the '90s. For the first time the French philosopher Gilles Delueze is cited in the architectural discourse, and it will remain a reference for the following decade. Was his work "The Fold: Leibniz and the Baroque"[2] which inspired, through mathematics and philosophy, new visions

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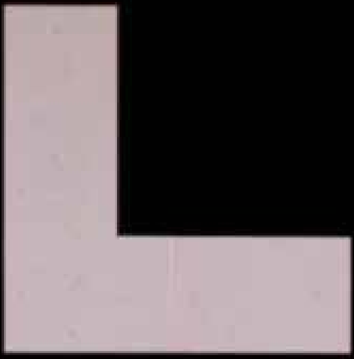
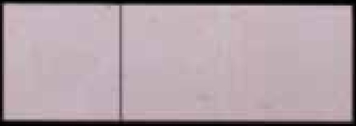
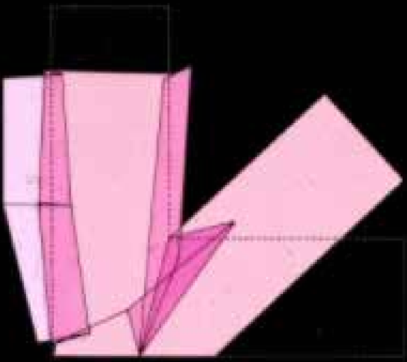
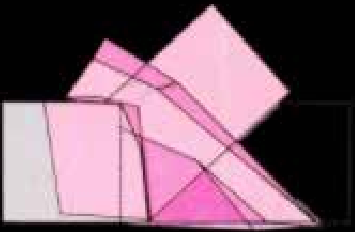
[2] Published in France in 1988; translated in English in 1993.

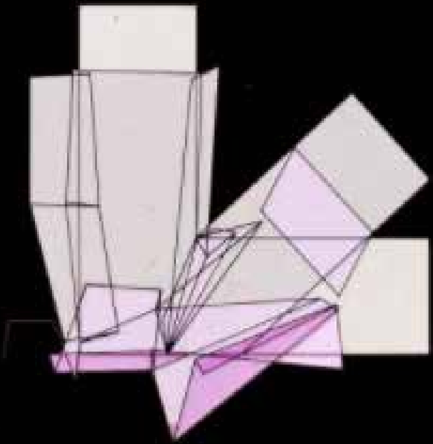
Fig. 2.1 Concept elaboration for the Alteka Office Building, Tokyo, Peter Eisenman 1991. *"This project suggests another relationship to the city. Caught between the traditional city fabric and the Jigamae, a new large avenue, our folded tower suggests that an object is no longer defined by standard of maintaining the appearance, or imposing a law, of constancy, but by a situation in which the fluctuation of the norm replaces the permanence of law, with the object taking place in a continuum. Thus, the object no longer corresponds to a spatial mold but rather to a temporal modulation that implies a continual variation as much as a perpetual development of the form. The object becomes an event, opening up, unfolding. The building evades a purely Cartesian definition by not representing an essential form. Instead, it is a form "becoming"."* Source: eisenmanarchitects.com

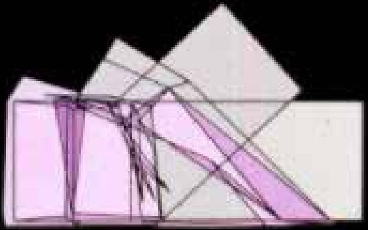


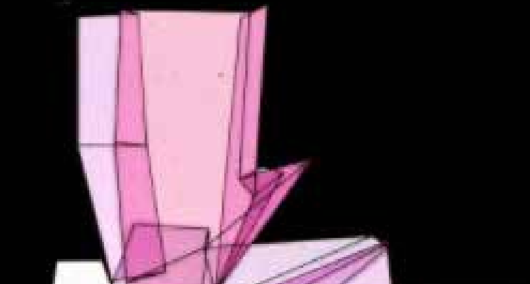


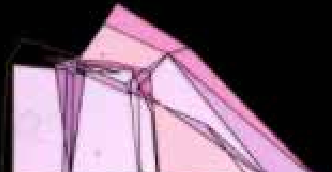












and perception of space (reading and writing of new spaces), enabling the development of new theories. In the early stages of theorization Eisenman shifts from the almost literal interpretations of Deleuzian concepts (even recalling them by the same names) to a more architectural version, including the use of diagrams as a tool to develop the project, a way of recording the process of morphing and changing. Deleuze talks about the "fold" as a unifying figure where segments and planes are joined in continuous lines and volumes[3]. Eisenman identifies, through this outset, a new category of objects, not for what they are but for the way they change ad for the laws that describes their continuous variations[4], this brought a new emphasis on the generative process of a project. Mario Carpo highlights how the folding process remains purely generative and it cannot be confused or related with the final form: *"Forms do not fold, because buildings do not move: when built, architectural forms can at best only represent, symbolize or somehow evoke the continuity of change or*

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[3] Carpo, M. "Ten Years of Folding", in Lynn G. "Folding in Architecture" AD Wiley-Academy, West Sussex, 2004

[4] An interesting analysis of folding is provided by Carpo, M. "Ten Years of Folding", in Lynn G. "Folding in Architecture" AD Wiley-Academy, West Sussex, 2004

Fig. 2.2 Section of Alteka Office Building, Tokyo, Peter Eisenman 1991

motion"[5].

After Eisenman, Greg Lynn published "Folding in Architecture", in 1993, a volume where this concept of continuity is furtherly deepened in all its possible aspects or conditions: visual, programmatic, formal, technical, environmental, socio-political and symbolic. After more than two decades, some of Lynn's developments to the folding theory didn't led nowhere, and just remained as cultural "leftovers" but they provided us the reason why certain topics were made at that time. On the other hand, many arguments remained and evolved till today opening up the discussion and contributing to the construction of the theoretical background of digital design.

One of the case studies that Lynn presents in his volume, and considers emblematic of this continuity theory, is the Odawara Gymnasium by Shoei Yoh (1991). The project by the Japanese architect, although unbuilt, shows some features derived from the concept of continuity and continuous differentiation; the key-element is essentially a big roof that

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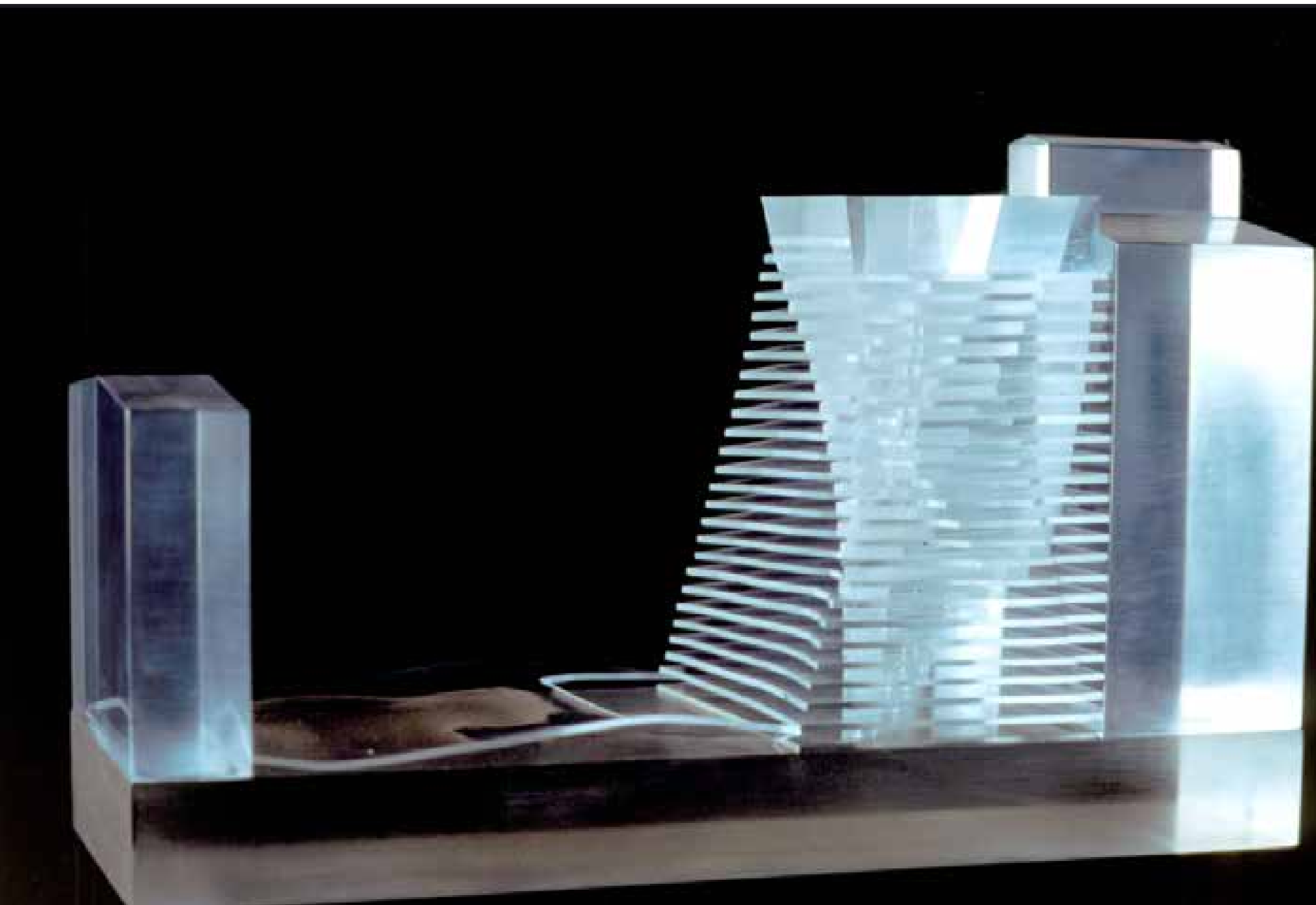
[5] Carpo, M. "Ten Years of Folding", in Lynn G. "Folding in Architecture" AD Wiley-Academy, West Sussex, 2004

Fig. 2.3 Model of Alteka Office Building, Tokyo, Peter Eisenman 1991



adapt itself on the different spaces and functions with variable heights. Under the roof all the spaces are connected and open in a continuous space. Lynn is fascinated about this project because it is perhaps one of the first approaches that exploit the continuous topological differentiation under the structural, functional, geometrical point of view – if you contextualize it in the early '90s – and it could not have been possible without the support of computation to calculate the differentiated truss beam (both in their materiality and in their structural performance). This approach opens to new tectonic visions based on material properties and structural performance as well as the formal expression of the final artefact, and it will be deepened furthermore in the next chapters of this thesis.

By the end of the '90s the approach to continuous differentiation is not only pursued by the most advanced offices in digital technologies, the case of FOA (Foreign Office Architects) highlights how this 'tendency' was even cultural and political. FOA explains its contribution as the willing of construct a new model capable of integrating differences into a coherent system. Their philosophy of the "foreign" (outsider, external) was born from the cultural context of the late '90s, where the succession of architectural movements demonstrated the willing of sabotage the authorial homogeneity of the Modernism. FOA keeps distance from the architecture as a representative mean for ideology; they want

Fig. 2.4 Yokohama International Port Terminal, Foreign Office Architects, 1995

to build spaces and find how the global can inform local differences coherently; they want to produce *"space as the articulation of global processes with local specificities [...] after Post-Modernism, after critical regionalism, after Deconstructivism, our strategy is to articulate the production of space which is coherently differentiated"*[6]. This would offer a language that is flexible, adaptable and variable that could respond to the challenges of the late-capitalist globalization. The Yokohama International Port Terminal (Fig. 2.4) by FOA is a consistently big infrastructure that alternates public spaces, facilities and a cruise passenger terminal. The main concept was derived from the idea of mediation between a garden and a harbor in order to provide a structure that could combine two different realms: the public space system of Yokohama and the infrastructural facility of the terminal. The strategy to blur the boundaries between these two systems together is a differentiated space, articulated and continuous. Given the condition of the site, a long stripe of land in the water perpendicular to the coast, there's a strong directionality in the organization of the spaces. A combination of the urban leisure facilities with the interlaced loops of the circulation avoids the "dead space" at the end of the pier articulating an active public space. There are also references to the Japanese culture of origami, the surface folds creating walls, roofs, floors in a dynamic structure.

In this chronological moment we can both observe the dynamic theories of architectural debate and the spread of computer in the '90s. According to Mario Carpo – as discussed in his analytical essay for the re-publication of Lynn's volume "Folding in Architecture" in 2004 – the introduction and development of continuity in architecture, enhanced the use of computer to deal with the complexity brought by this concept. He claims that the only the dialectical interaction between technology and society can bring the technical and societal change which in then reflected in change in architectural form. Carpo explicit the reason of a direct correspondence between digital technology and complex geometries: without computers we could have not been able to produce (conceive, measure, design) the complex forms derived from the concept of continuity; but it is a wrong generalization to think the way around: computers are responsible for the complex shapes. *"Computers per se do not impose shapes, nor do they articulate aesthetic preferences. One can use computers to design boxes or folds indifferently. [...] the theory of folding created a cultural demand for digital design [...]. Consequently, when digital tools became available, they were embraced and adopted".* Few years after the potential of computation grew and computer were performing better results. This allowed the continuity of the fold to become a smooth curvilinearity, generating what was then called blobs.

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[6] Foreign Office Architects, "Yokohama International Port Terminal", AD July–August, 1996

Curvilinearity and continuity

The technical definition of blob stands for 'binary large object', the term was introduced but Greg Lynn to express how the curvilinear structure are built through the computer, although it is often related to the "blobby" forms generated by this system - and possibly referred to the alien-monster in the American horror movie of the 1958 "The Blob" (Fig. 2.6). Beyond the literal definition, blobs characterized a second phase of the folding theory in which architects started new exploration of the computer-generated forms. Between the 1995 and the early 2000's blobs became a built reality, but – luckily – they were not the only expression of digital architecture at the time. Antoine Picon[7] claims that blobs were just a part of a broader research on the topological properties of surfaces and volumes and the relative geometrical operations on the computer. On the other hand, as for the folding, the smoothness was interpreted both in a literal and metaphorical sense. If intended in the metaphorical sense there's of course a wider set of geometry "produced", from here the

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[7] Picon A., "The Seduction of Innovative Geometries" in Picon A., "Digital Culture in Architecture", Birkhauser, Basel, 2010

Fig. 2.5 Kunsthaus Graz, Peter Cook, 1999-2003

derivation of geometries with more angular features – almost deconstructivist. Picon talks about the seduction of geometry enabled by digital design tools highlighting the fact that the computers enabled to incredibly wider the range of formal possibilities; before the 90's there were already many formal and structural explorations mostly based on mathematical geometries (Candela, Otto, Isler, etc.) but the computer not only changes the 'vocabulary' of forms but also allows to define them rigorously. The possibility of conceiving formal complexity with the computer is strongly related with the technical method to produce them. NURBS (Non-Uniform Rational B-Splines) are the basic element, introduced in those years, that allow to represent and draw on computer complex shapes, surfaces and volumes – they are still used today, Maya or Rhinoceros are NURBS based software. The next step that enabled further and way more articulated evolution and exploration in digital design was the introduction of parametric software for modelling. As the possibilities offered by the technological progress helped continuous geometrical exploration, even concept, visions an theories continued to develop, contributing to define a field of 'digital architecture'.

Fig. 2.6 A screenshot of the movie "The Blob" of 1958

Non-linear Architecture

Knowledge in **science and methodology** is constantly evolving through research and, sometimes, also through visions. The end of the XX century saw the growth of new mental landscapes enabled by the theories of complexity landed in various fields. Charles Jenks[8] embraces this topic and analyzes the relationship running between science and architecture, and their relative changings (or evolutions). To be more specific, Jenks focuses on the topic of non-linear theories as the contemporary framework of thought opposed to the mechanical and linear paradigms of modernist-based knowledge. The **nonlinear paradigm** proposes visions and approaches to the sciences that goes beyond the linear theories consolidated till the modern age – Newton, Euclid, Darwin and others. The term non-linear comes from the mathematics to describe functions where the output is not proportional to the input, where the relation between two variables cannot be diagrammed as a straight line; the term represents unpredictable or indeterminate systems, or system where the variables are not directly linked by cause-effect direct relationships. In opposition to the modern science (predictive), the nonlinear sciences assume the existence of self-organizing systems where the matter can behave following patterns that are unpredictable and never repeat themselves. Although these models of complexity were diffusing in various fields (Jenks's essay is from 1997), this doesn't mean that the scientific community totally agreed on the non-linear paradigm substituting the traditional approach, moreover this new paradigm does not correspond to a single voice and theory (organicism, complexity science, nonlinear dynamics, new genetics). Then there is a basic question: if there is a shift in philosophy and world view, why there must be a shift in architecture too? According to Jenks this change of the basic framework of though we all rely on, also affects architecture *"because, like other forms of cultural expression, it is embedded in the reigning mental paradigms"*. Today, after twenty years from Jenks's introduction of nonlinear theory, we can see many experiments in architecture very much related with science driven factors. The nonlinearity is still an alternative, a vision, an explorative possibility, but not yet a solid reality. Although we can assist to many experiments and progresses, and we can be fascinated by them, the built world around us very slowly tend to this direction. Possibly, nonlinear models will help us to define better the future of cities. Then Jenks's questions somehow remain open.

> "Are we seeing merely a parallel between science and architecture or something deeper? Is it only a question of using computers and designing curved buildings – a fashion – or a change

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[8] The following theme is deeply analyzed in Jenks C., *"Nonlinear Architecture: New Science = New Architecture",* Charles Jencks (guest-editor), New Science = New Architecture, AD Profile 129, AD 67 September–October 1997, pp 6–9. © 2012 John Wiley & Sons Ltd.

> in the mental landscape? Philip Johnson's recent conversion to the paradigm, evident in his Monsta House, suggests it is both. To be specific: how much do architects understand of fractals, emergence theory, folding, nonlinearity and self-organizing systems? How much is this a formalist trend? Can they furnish a new iconography, a new style and set of meanings? Can one design a whole city fabric in their image? The most profound question is: why does it matter? Is the new Nonlinear Architecture somehow superior, closer to nature and our understanding of the cosmos, than Old Modernism? Is it more sensuous, functional, liveable? Is it closer to aesthetic codes which are built into perception? Has it supplanted the traditions from which it has grown – Post- Modern and Deconstructivist architecture? The answer to these questions, which implicitly justify a change, might be 'yes', but it is too early to tell. There are other supporting arguments of a cultural and spiritual nature: architecture, to be true to the spirit of contemporary life and the life of forms in art, must explore new languages"[9].

In 1997 the most advanced architectural design (both conceptually and technically) taking this direction were the projects by Gehry, Eisenman, FOA, Libeskind, Miralles, Koolhaas, Ben Van Berkel. Jenks considers some of those projects as emblematic of the nonlinear architecture. They introduced a completely new conception of complexity in architecture and most of it was possible tanks to the digital tools.

Emergence and Morphogenesis

With the spread of complexity theories and nonlinearity concept, around the early 2000's architects started to embrace topics derived from science and developmental biology and often related with mathematical models. **Morphogenesis and evolutional theories,** ruled by complex relationships, became unexplored references for architectural and urban models. They started to be transposed into computer modelling using scripting techniques instead of the genetic code and representing script models into different 'material events' instead of the variations of phenotype exposed to external forces[10]. The model to which architects refer to is described by the concept of **emergence**. Derived from systems theory, emergence defines a system as a large entity composed by a complex (often self-organizing and nonlinear) aggregation and/or combination of smaller and simpler entities such that the larger entity showcases properties that the smaller ones don't. In other words, is the property of a system which cannot be simply extracted from the sum of its parts. Within the first decade of the 2000's architectural research on this field expanded at an incredible

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[9] Jenks C., *"Nonlinear Architecture: New Science = New Architecture",* Charles Jencks (guest-editor), New Science = New Architecture, AD Profile 129, AD 67 September–October 1997, pp 6–9. © 2012 John Wiley & Sons Ltd.

[10] Carpo M. introduction to "Morphogenesis and Emergence" in "The Digital Turn in Architecture 1992-2012" John Wiley & Sons Ltd, 2013

rate and produced a considerable body of knowledge and bibliography which is very hard to entirely showcase and summarize in these few paragraphs, but they can give a general understanding of this approach, which is, however, constantly updating. Since the construction of emergent models is based on sets of mathematical rules, computational designers elaborated scripting techniques that can reproduce the formation processes of such systems. The mathematical models derived are then used to generate forms and evolving structures in morphogenetic processes within computational design.

Morphogenesis, intended as the study of the evolutive structure of an organism in nature, has significant implications both in theory and research approach of form generation in digital design. Since these phenomena are reproduced through digital modeling, this field is also often referred to as 'digital morphogenesis'. Nature provides models of evolutionary development that are opening to a wide field of research in design approaches. The organization of material and forms in nature and their adaptive response to external environmental forces, are taken as references to reproduce ecological oriented systems in the current researches of performance-based design. The application of such strategies for architectural models often requires going through *form-finding* processes, this is not the first time that the designer operative gesture moves from a traditional *form-making* methodology to the innovative one of *form-finding*. During the past century there have been many experimental architects (Gaudì, Isler, Otto, Candela, etc.) that operated through analog from finding using physical models. In particular, Frei Otto experiments are still today a strong reference as design strategy since he relied on his models to study form and natural behavior of the material. His models and studies using soap film bubbles, to search for the minimal surface of a form, or the emulation of tree branching in structural design, became very famous and they, for sure, can be considered as precedent body of knowledge for contemporary form-finding methodology. Morphogenesis brought in architecture a completely new field currently in exploration, and introduced different approaches and methodologies. Moreover, digital morphogenesis, based on the reinterpretation of form and on the role of the material and its structure and organization in the form, reformulates the concept of tectonics which evolved in these latest years as *digital tectonics*, as it will be discussed in the next chapter. For similar reasons, many researches in morphogenesis consider the materials performance and their capacity to adapt and react to external forces. This focus on **material performance**, together with the already ongoing topic of environmental sustainability and resources availability in nature, is a consistent part of a research and application field, known as performance-based design, where the performance is an active generative component that concur in the formation process.

Parametricism and Tectonism

At the beginning of the 20th century, the Modern movement redefines the architectural character, and creates a strong line of stylistic and conceptual demarcation, separating itself clearly from the architecture of the past and introducing new design principles. The 20th century was marked by major technological innovations, which have led to a radical change in society. The change was also welcomed by art and, in particular, by architecture, which materializes the set of innovations that characterize modern lifestyle: rules are introduced to ensure the health and brightness of the rooms, the house is conceived as a "machine for living", the new is placed above all, the architectural language is free from any ornament. According to Patrick Schumacher, something analogous is happening today. Schumacher claims that the last two decades of innovation in digital technologies, not only are changing our lifestyle, but they are also visible and perceivable in architecture and design, in a cultural movement that uses the new available tools to introduce innovative design methodologies, strategies and ambitions, with the same cultural weight as the Modernism in the previous century.

> "Parametricism is a mature style. That the parametric paradigm is becoming pervasive in contemporary architecture and design is evident for quite some time. There has been talk about versioning, iteration and mass customization etc. for quite a while within the architectural avant-garde discourse"

Patrick Schumacher, partner of the firm Zaha Hadid Architects since 1988 and founder of AADRL - Architectural Association Design Research Lab - is one of the leaders and most prominent theorists a contemporary architectural vanguard defined by himself "Parametricism". In the wake of the various currents of thought that have occurred in the architectural and cultural debate of the previous decades - Postmodern Deconstruction, Minimalism - Schumacher identifies a new global trend and exposes its theoretical principles in a manifesto - sometimes dogmatic and formalistic, and not immune to criticism - which was presented for the first time in 2008 at the Venice Biennale of Architecture[11]and later published in *"Parametricism. A new global style for architecture and urban design"*[12] in 2009. According to Schumacher *"Parametricism"* is the architectural and urban response to the socio-economic contemporary context, in constant motion, and to the technological transformations of the "information age", that can *"organize and articulate the great complexity of post–fordian society"*. The era of Henry Ford is often quoted in the bibliography of studies and researches on parametric design. On one hand, as is the case today, it is intended as a symbol of one of the early 20th century industrial revolution that

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11 Schumacher P., Parametricism as Style - Parametricist Manifesto, London 2008. Presented and discussed at the Dark Side Club, 11th Architecture Biennale, Venice 2008

12 Schumacher P., "Parametricism. A new global style for architecture and urban design "Architectural Design (AD 2009)

has accelerated technological development processes, thus affecting society and economy, on the other hand, many people criticize the mass production character and standardization now overtaken by the increasing customization requested from contemporary society. Schumacher said that the introduction and spread of digital technology in architecture - animation techniques, simulation tools and form-finding, parametric modeling, scripting - have inspired a collective movement with radically new ambitions and values that justify the definition of a new style. *"The shared concepts, the use of computational design techniques, the formal repertoire, and the tectonic rules crystallize into a solid and new paradigm for architecture".* In the manifesto of Schumacher, it is interesting to note the definition of *"style"*, according to which, in architecture stylistic vanguards are *"to be interpreted and evaluated as new scientific paradigms that offer new conceptual frameworks and formulate new goals, methods and values".* The style is an architectural research program that is moving in a new direction. The architectural innovation occurs through the progression of styles over time, with alternating periods of "cumulative progress" (more static), and periods of transition and change from one style to another. It is this alternation that generates innovation and tracks research directions. *"Parametricism is the new big move after Modernism. Postmodernism, Minimalism and Deconstructivism were transient moments that led to this new wave of research and innovation".*

The concepts exposed by Schumacher have not been free from direct and indirect critiques within the architectural debate. Nader Tehrani[13] argues that, in this particular moment of contemporary architecture – multidisciplinary approach, variety of visions, rapid technological progress, etc. – the idea of a "manifesto" seems a limited and partial solution and the "call to arms" brings with itself an emergency condition that creates a crisis just to substantiate what is claimed. Apart from this observation, we still need a clear vision of what is happening today and of the contemporary architectural debate issues, to which Tehrani dedicates a thorough analysis. The recent spread of "hyper-specialization", the "flood of skills" from different fields, change the way in which architecture interacts with the contemporary context. On the one hand it has greatly expanded the domain in which architecture operates, on the other it has narrowed the range of action, fragmenting and categorizing the architect's involvement. The architect is in fact perceived as *"bearer of common and non-specialist skills, who can only deepen some disciplines".* The architect must once again take possession of a condition of freedom, and this is possible only through a deep understanding (appropriation) of the tools and methods related to the design pro-

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[13] Nader Tehrani, "Un manifesto disaggregato: riflessioni sul mezzo architettonico e sul regno della strumentalità", editorial in The Plan 095, 2017

Fig. 2.7 Zaha Hadid Arum Installation Venice Biennale 2012 cess, which are now evolving continuously, to return to the link between "doing" and "thinking" architecture. It is within this cultural context that the theories supported by academics and professionals contribute to build a framework for action and a theoretical background for digital design.

In recent years, professionals and researchers have payed greater attention to parametric design techniques, already known in the past and of which some applications will be examined. This is due, in part, to the spread of parametric modeling tools that employ relatively simple user interfaces and do not require special programming skills (eg: Grasshopper for Rhinoceros). As demonstrated by Schumacher, the spread of these instruments, however, has led to some extreme positions, conceiving the technological tools and new approaches they made possible as the birth of an architectural style rather than a process to monitor and articulate the design complexity. Formal and partly stylistic analogies due to freedom of generating complex forms obviously exist, but this is neither a sufficient condition, nor an exclusive feature of a language or of a style14. Moreover, a parametric approach can be applied both to formally complex projects, and to projects with a simpler character and which consists of basic geometry. Geometric complexity is not necessarily a symptom of the existence of a new architectural movement, especially when we consider that in the past several architects of the 20th century have approached the issue of complex shapes before the existence of computational techniques.

> **Parametricism as Style - Parametricist Manifesto**
>
> **Patrick Schumacher, London 2008**
>
> **Presented and discussed at the Dark Side Club, 11th Architecture Biennale, Venice 2008**
>
> We pursue the parametric design paradigm all the way, penetrating into all corners of the discipline. Systematic, adaptive variation, continuous differentiation (rather than mere variety), and dynamic, parametric figuration concerns all design tasks from urbanism to the level of tectonic detail, interior furnishings and the world of products.
>
> Architecture finds itself at the mid-point of an ongoing cycle of innovative adaptation – retooling the discipline and adapting the architectural and urban environment to the socio-economic era of post-fordism. The mass society that was characterized by a single, nearly universal consumption standard has evolved into the heterogenous society of the multitude.
>
> The key issues that avant-garde architecture and urbanism should be addressing can be summarized in the slogan: organising and articulating the increased complexity of post-fordist society. The task is to develop an architectural and urban repertoire that is geared up to create complex, polycentric urban and architectural fields which are densely layered and continuously differentiated.
>
> Contemporary avant-garde architecture is addressing the demand for an increased level of articulated complexity by means of retooling its methods on the basis of parametric design systems. The contemporary architectural style that has achieved pervasive hegemony within

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14 See. Gürsel Dino I., "Creative design exploration by parametric generative systems in architecture", 2012

the contemporary architectural avant-garde can be best understood as a research programme based upon the parametric paradigm. We propose to call this style: Parametricism.

Parametricism is the great new style after modernism. Postmodernism and Deconstructivism have been transitional episodes that ushered in this new, long wave of research and innovation.

Avant-garde styles might be interpreted and evaluated in analogy to new scientific paradigms, affording a new conceptual framework, and formulating new aims, methods and values. Thus, a new direction for concerted research work is established. My thesis is therefore: Styles are design research programmes.

Innovation in architecture proceeds via the progression of styles so understood. This implies the alternation between periods of cumulative advancement within a style and revolutionary periods of transition between styles. Styles represent cycles of innovation, gathering the design research efforts into a collective endeavor. Stable self-identity is here as much a necessary precondition of evolution as it is in the case of organic life. To hold on to the new principles in the face of difficulties is crucial for the chance of eventual success. This tenacity - abundantly evident within the contemporary avant-garde - might at times appear as dogmatic obstinacy. For instance, the obstinate insistence of solving everything with a folding single surface - project upon project, slowly wrenching the plausible from the implausible – might be compared to the Newtonian insistence to explain everything from planets to bullets to atoms in terms of the same principles.

“Newton’s theory of gravitation, Einstein’s relativity theory, quantum mechanics, Marxism, Freudianism, are all research programmes, each with a characteristic hard core stubbornly defended, … each with its elaborate problem-solving machinery. Each of them, at any stage of its development, has unsolved problems and undigested anomalies. All theories, in this sense, are born refuted and die refuted.”4 The same can be said of styles: Each style has its hard core of principles and a characteristic way of tackling design problems/tasks. Avant-garde architecture produces manifestos: paradigmatic expositions of a new style’s unique potential, not buildings that are balanced to function in all respects. There can be neither verification, nor final refutation merely on the basis of its built results.

The programme/style consists of methodological rules: some tell us what paths of research to avoid (negative heuristics), and others what paths to pursue (positive heuristics). The negative heuristics formulates strictures that prevent the relapse into old patterns that are not fully consistent with the core, and the positive heuristics offers guiding principles and preferred techniques that allow the work to fast-forward in one direction. The defining heuristics of parametricism are fully reflected in the taboos and dogmas of contemporary avant-gared design culture:

Negative heuristics: avoid familiar typologies, avoid platonic/hermetic objects, avoid clear-cut zones/territories, avoid repetition, avoid straight lines, avoid right angles, avoid corners, …, and most importantly: do not add or subtract without elaborate interarticulations.

Positive heuristics: interarticulate, hyberdize, morph, deterritorialize, deform, iterate, use splines, nurbs, generative components, script rather than model, …

Parametricism is a mature style. That the parametric paradigm is becoming pervasive in contemporary architecture and design is evident for quite some time. There has been talk about versioning, iteration and mass customization etc. for quite a while within the architectural avant-garde discourse.

The fundamental desire that has come to the fore in this tendency had already been formulated at the beginning of the 1990s with the key slogan of "continuous differentiation"6. Since then there has been both a widespread, even hegemonic dissemination of this tendency as well as a cumulative buildup of virtuosity, resolution and refinement within it. This development was facilitated by the attendant development of parametric design tools and scripts that allow the precise formulation and execution of intricate correlations between elements and subsystems. The shared concepts, computational techniques, formal repertoires, and tectonic logics that characterize this work are crystallizing into a solid new hegemonic paradigm for architecture. One of the most pervasive current techniques involves populating modulated surfaces with adaptive components. Components might be constructed from multiple elements constrained/cohered by associative relations so that the overall component might sensibly adapt to various local conditions. As they populate a differentiated surface their adaptation should accentuate and amplify this differentiation. This relationship between the base component and its various instantiations at different points of insertion in the "environment" is analogous to the way a single geno-type might produce a differentiated population of pheno-types in response to divers environmental conditions.

The current stage of advancement within parametricism relates as much to the continuous advancement of the attendant computational design technologies as it is due to the designer's realization of the unique formal and organizational opportunities that are afforded. Parametricism can only exist via sophisticated parametric techniques. Finally, computationally advanced design techniques like scripting (in Mel-script or Rhino-script) and parametric modeling (with tools like GC or DP) are becoming a pervasive reality. Today it is impossible to compete within the contemporary avant-garde scene without mastering these techniques.

Parametricism emerges from the creative exploitation of parametric design systems in view of articulating increasingly complex social processes and institutions. The parametric design tools by themselves cannot account for this drastic stylistic shift from modernism to parametricism. This is evidenced by the fact that late modernist architects are employing parametric tools in ways which result in the maintenance of a modernist aesthetics, i.e. using parametric modelling to inconspicuously absorb complexity. Our parametricist sensibility pushes in the opposite direction and aims for a maximal emphasis on conspicuous differentiation.

It is the sense of organized (law-governed) complexity that assimilates parametricist works to natural systems, where all forms are the result of lawfully interacting forces. Just like natural systems, parametricist compositions are so highly integrated that they cannot be easily decomposed into independent subsystems – a major point of difference in comparison with the modern design paradigm of clear separation of functional subsystems.

The following agendas might be proposed here to inject new aspects into the parametric paradigm and to push the development of parametricism further:

1.Inter-articulation of sub-systems:

The ambition is to move from single system differentiation – e.g. a swarm of façade components - to the scripted association of multiple subsystems – envelope, structure, internal subdivision, navigation void. The differentiation in any one systems is correlated with differentiations in the other systems.

2. Parametric Accentuation:

The ambition is to enhance the overall sense of organic integration through intricate correlations that favour deviation amplification rather than compensatory or ameliorating adaptations. For instance, when generative components populate a surface with a subtle curvature modulation the lawful component correlation should accentuate and amplify the initial differentiation. This might include the deliberate setting of accentuating thresholds or singularities. Thus, a far richer articulation can be achieved and thus more orienting visual information can be made available.

3. Parametric Figuration:

We propose that complex configurations that are latent with multiple readings can be constructed as a parametric model. The parametric model might be set up so that the variables are extremely Gestalt-sensitive. Parametric variations trigger gestalt-catastrophes, i.e. the quantitative modification of these parameters trigger qualitative shifts in the perceived order of the configuration. This notion of parametric figuration implies an expansion in the types of parameters considered within parametric design. Beyond the usual geometric object parameters, ambient parameters (variable lights) and observer parameters (variable cameras) have to considered and integrated into the parametric system.

4. Parametric Responsiveness:

We propose that urban and architectural (interior) environments can be designed with an inbuilt kinetic capacity that allows those environments to reconfigure and adapt themselves in response to the prevalent patterns of use and occupation. The real-time registration of use-patterns produces the parameters that drive the real time kinetic adaptation process. Cumulative registration of use patterns results in semi-permanent morphological transformations. The built environment acquires responsive agency at different time scales.

5. Parametric Urbanism:

The assumption is that the urban massing describes a swarm-formation of many buildings. These buildings form a continuously changing field, whereby lawful continuities cohere this manifold of buildings. Parametric urbanism implies that the systematic modulation of the buildings' morphologies produces powerful urban effects and facilitates field orientation. Parametric Urbanism might involve parametric accentuation, parametric figuration, and parametric responsiveness.

Modernism was founded on the concept of space. Parametricism differentiates fields. Fields are full, as if filled with a fluid medium. We might think of liquids in motion, structured by radiating waves, laminal flows, and spiraling eddies. Swarms have also served as paradigmatic analogues for the field-concept. We would like to think of swarms of buildings that drift across the landscape. Or we might think of large continuous interiors like open office landscapes or big exhibition halls of the kind used for trade fairs. Such interiors are visually infinitely deep and contain various swarms of furniture coalescing with the dynamic swarms of human bodies. There are no platonic, discrete figures with sharp outlines. Within fields only the global and regional field qualities matter: biases, drifts, gradients, and perhaps even conspicuous singularities like radiating centres. Deformation does no longer spell the breakdown of order but the lawful inscription of information. Orientation in a complex, lawfully differentiated field affords navigation along vectors of transformation. The contemporary condition of arriving in a metropolis for the first time, without prior hotel arrangements, without a map, might instigate this kind of field-navigation. Imagine there are no more landmarks to hold on, no axis to follow and no more boundaries to cross. Contemporary architecture aims to construct new logics – the logic of fields – that gear up to organize and articulate the new level of dynamism and complexity of contemporary society.

Furniture and product design fully participates in the parametricist agenda we are pursuing. We consider furniture not in terms of isolated objects but as a pre-eminent space-making substance. Our design efforts need to encompass the domains of interior design, furniture

> design, and even product design. We can orchestrate all those registers to advance the design of integrated, immersive worlds. Our handling of interior furnishings as dynamic swarm formations, or sometimes as a continuous surface/fluid mass, is geared towards the detailed elaboration of the continuously differentiated fields described above.

Recently[15] Schumacher has reiterated his previously expressed ideas in his manifesto, talking about a new and more conscious phase of parametric design which he called *"Parametricism 2.0"*. Following criticism received in recent years, after the release of the first edition, Schumacher remains on its position, provocative somehow, reaffirming the existence of a contemporary architectural style, reinforced by new research from professionals and academics. He also identifies several subsidiary-styles of Parametricism (Foldism, Blobism, Swarmism) and believes that the most developed today is "Tectonism", defined as *"Tectonic articulation in the context of architectural semiology"* and that *"implies the stilistic heightening of engineering and fabrication-based form-finding and optimization process. [...] Architectural/Tectonic form is multi-functional and needs to be selected in accordance with two sets of very different functional selection criteria: technical functionality, in terms of physical performance, and social functionality, in terms of communicative performance. The coincidences between these two criteria are serendipitous"[16]*. He argues that Parametricism is the only approach in line with the dynamism of the Information Age society, referring in particular to what is happening in many contemporary projects of urban infrastructure and transport as the Terminal Shenzhen Fuksas (2013), the Beijing Airport Terminal Zaha Hadid (2019) or other recent projects by Jean Nouvel.

Adaptability and regionalism in contemporary parametric architecture

Philip Feng Yuan, founder of ArchiUnion office and professor at Shanghai Tongji University, considers adaptability one of the main features of parametric design, that can be extended to material properties, tectonic rules and social dynamics, to meet specific needs and local variations (regional). This approach brings back the attention of architectural design and research to the *genius loci*, in a globalized world where it is more and more difficult to manifest specificity. Yuan's "regionalism"[17] is not only defined by local context or climatic conditions, but, above all, by the culture and use of local materials and craft techniques. In the digital age the craft contribution and its tradition acquire a deep ethical and social meaning. Yuan experimented in his projects the use of local materials – or

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[15] See. Schumacher P., in Architectural Design: "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" (AD2 / 2016)

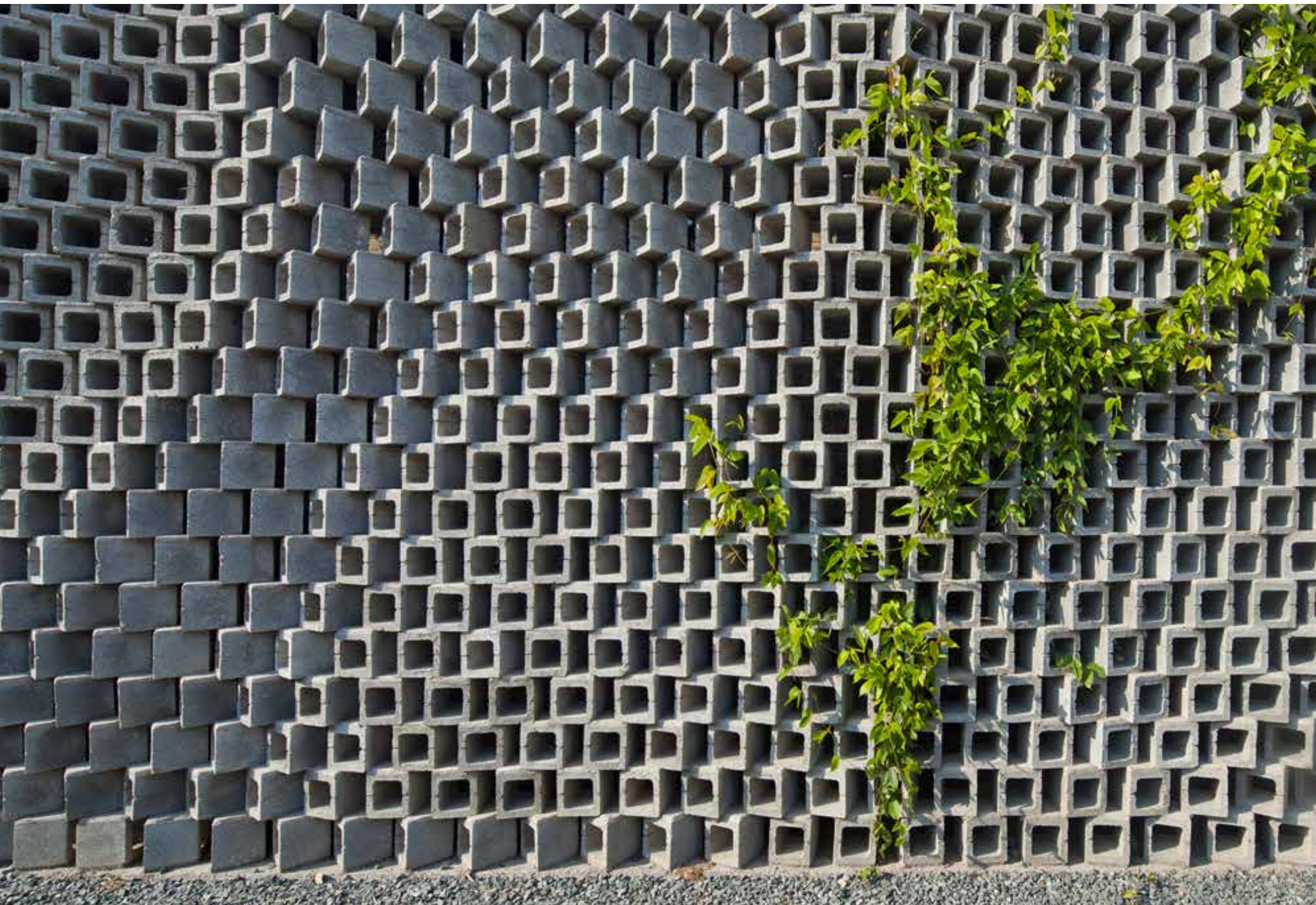
[16] Schumacher P., lecture at Digital Future Shanghai 2017 workshops

[17] On this theme see Yuan P.F., "Parametric Regionalism" in "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" AD 02/2016

materials traditionally used in China as brick, concrete, wood – through a computational approach, exploring new possibilities of language from the union of these seemingly radically different disciplines. To Yuan architecture exists within visual, physical and social context. In the information age the wide availability of "big data", not only gives us a globalized world thanks to the easy exchange and comparison of information, but it allows us to have a new key to reinterpret the environment, building materials, social organization, and the behavior of people from a local perspective. Direct communication between information coming from the Internet and social organization based on local characteristics highlights the customization and versatility of globalization. Therefore, "regionalism" in the digital age is conceived as the integration and regeneration of real physical and virtual information data through new technologies. Parametric design represents a new approach to architectural knowledge and to the organization of space and it is interesting to incorporate local knowledge.

> "Architects, in this new age, are combining advanced architectural practices with traditional Chinese culture, developing performative local building materials and adaptive forms of ar-

Fig. 2.8 Archi-Union Office facade in Shanghai designed by the fouder Philp F. Yuan



> chitecture through digital design and fabrication, and exploring the new possibilities of the integration of Parametricism and regionalism through new digital craftsmanship."[18]

For Yuan the meaning of theoretical research related to advanced technologies in architecture lies in the opportunity for a deeper understanding of the tools that can actually change the future. Computational design developed in recent years has strongly influenced the contemporary design processes. The creation of parametric models, for example, has made possible to blur the border between design and fabrication, leading to a methodology made by steps that goes from the conceptual to the operational phase, and then to revision and construction through the manipulation of geometric information. The prototype of the parameterized model directly connects the geometry, and so the morphology of the architectural structure, with the selected environmental parameters, such as: climate, local materials, structure, etc. The choice of the parameters to consider, is the key step in a parametric approach. Information can be entered directly into the parameters that control and define the elements of the geometric model. Clearly, this approach will lead to focus the attention on architectural components (i.e. bricks), opening to the possibility to build with local materials, and to simultaneously gain organizational instructions on building system. Considering that architecture is made of components and elements (doors, windows, stairs, etc.), as claimed by Koolhaas in the Venice Biennale of 2014, a great explorative potential of parametric thinking emerges in the definition of the individual architectural component in relation to its adaptability to the environment, society and materials. Yuan supports Schumacher's theory about the existence of an architectural movement referred to as "Parametricism" and, more generally, the idea that parametric design is a vanguard characterized by an elevated level of "adaptability". This adaptability enhanced by Parametricism makes possible to decline the design to the local context in which the subject operates from the architectural, cultural and social point of view. Therefore, it is possible to outline a more specific area of interest – defined as regional parametricism – which examines the morphological and linguistic aspects, contributing to the debate on the role of parametric design in contemporary architecture. This innovative methodology brings emerging tectonic to support the architect in transforming the current situation of architectural design and production, in the digital era.

Parametric Structuralism

The approach to computational design of the research team BRG - Block Research Group - ETH Zurich, directed by Prof. Philippe Block, finds references in the history of architecture: the design and construction of structural shells in aesthetic balance between form

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[18] Yuan P.F., "Parametric Regionalism" in "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" AD 02/2016

and structure. The references in question range from expressive structures of the Gothic up to the early 20th century designers such as Felix Candela, Torroja, Nervi - to name a few – whose style employed form and structural strength contributing to the architectural beauty of the object. Block believes that after the '60s the interest of architects and engineers toward this type of construction has diminished due to a variety of reasons: the difficulty of programmatic integration, the complexity in structural calculation and in architectural detail, the excessive costs of construction. From these challenges BRG finds a language that integrates cheap construction techniques with the expressiveness and elegance of the structural shell. Much of the research shown has an interest in this direction – highly experimental – in which key roles are played by shells resistant to either compression or tension stresses, formwork systems that use less material and are reusable, integration of programmatic needs with complex geometries. Today, the available softwares are able to elaborate, in a short time, form-finding processes that allow a wide spatial and geometric experimentation, researching structural strength through form. Thanks to the computational potential we can go over geometric typologies of shell elaborated by designers of the 50's or 60's, widening the range of action in this field of research while keeping in mind that *"learning from the past helps us build in the present with logic and restrain".*

Fig. 2.9 Ultra thin concrete shell for the roof prototype of the NEST-Hilo house, an experimental project by Block Research Group of Zurich ETH

> "Complexity for the sake of complexity, especially if accompanied by a disregard for material flows or financial resources, is not intrinsically interesting or stimulating. We need to be asking the question: can we do the same - or more - with less?" [19]

Philippe Block's approach is based on an engineering knowledge, but, simultaneously, considers structural form as part of the project, similar to the predecessors mentioned above. One of the most significant contributions that Block has given, both in the academic and professional context, it is the release of the free plug-in RhinoVault, a form-finding system that allows to manage and design pure compression – or tension – resistant structures. Block's contribution facilitates the sharing of knowledge and design methods and management of the structures developed by his research team. In addition, the approach conducted by BRG highlights the tectonic and the poetry of form in the digital age. The materials mainly used are concrete and bricks and, in some cases, wood. Thanks to the methodology developed in BRG experimental projects, the results show great consistency between the technique, technology, the structural properties of the material and the composition of the form; through the reading of these projects, which combine history and progress, the characteristics and intrinsic properties of the material emerge, in direct relation with the processing methods.

Material Computation

Amongst the biggest challenges faced during the last 10 years are to be mentioned the research projects of Stuttgart University ICD (Institute for Computational Design). Their contribution strongly focuses the attention of current research on what can be defined as *"Material Computation".* This definition includes some specific research orientation such as: the deep understanding of robotic fabrication possibilities, the introduction of material properties during the form finding process, the structure optimization based on biomimetic principles. This clearly opens a wide field of research and implements what already exists in the computational design theoretical and applied research agenda. The ICD is directed by prof. Achim Menges, his contribution in academic, scientific and professional field, is one of the most influential and it finally opens to a radically new approach to the design process.

> "The omnipresence of CAD and its inherently shape-oriented representational design techniques has preconditioned contemporary design thinking to such a degree that, even in design computation, materiality is still conceived as a passive property of form rather than as an

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[19] Block P., "Parametricism Structural Congeniality" in Architectural Design: "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" AD 02/2016

> active form-generator." [20]

Despite CAD software are widely used and diffused in the design practice, this represents more of a commercial success than the sign of a digital turn. This is because CAD is still deeply rooted in the conventional way of design thinking. Moreover, materiality is the very last property to be assigned to previously defined geometries, it is considered as a passive property and very rarely as a generative driver. Menges's approach allows the *"innate characteristics, behaviour and capacities of the material systems that define the very physicality of architecture to play a more active role in design computation"*[21]. Here, material characteristics are not perceived as a constraint but rather as a resource viable for guiding a design process.

Menges's approach becomes clear when looking at the experimental pavilions projects of

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[20] Menges A., "Material resourcefulness. Activating material information in computational design", AD 02/2012

[21] Menges A., "Material resourcefulness. Activating material information in computational design", AD 02/2012

Fig. 2.10 HygroScope demonstrator is a research project by Achim Menges, ICD Stuttgart, that exploits material behavior to design a responsive architecture according to environmental conditions

ICD/ITKE since 2008, they show how the research direction is strongly material-oriented (mainly based on timber construction and fiber composite such as carbon and glass fibers) and performance-oriented from the structural and constructive point of view. Each pavilion and research project at ICD calls into questions and challenges the paradigm of contemporary architecture but, at the same time, it also gives answers about the future potential of "material computation" and steadily demonstrates the tectonic behind it. Several schools are investigating on material behavior as a leading aspect of the architectural project, as a generative mean able to hold together coherently every single design choice. Moreover, material computation is enhancing interdisciplinarity in architectural institutions, laboratories and practice when it comes to deal with this field of exploration. In the age of hyper specialized professions there's a lot to learn and explore from interdisciplinary approaches, in order to achieve innovative results both in academia and in the architectural practice. *"In material-based design approaches, computation allows for higher integration on a multitude of levels, ranging from the composition of the material itself to the assembly of systems from multiple material elements to the behaviour of systems of manifold material constituents affecting each other and interacting within a field of various external influences"*[22].

Form Generation Models

Within all the approaches – results of an evolution – described so far, we can observe that 'form' is one of the key-points challenged by digital design. We assist to a conceptual and operational shift from the traditional compositional form, to the procedural and generative one. Speaking of which, Rivka Oxman identified six models of form generation in digital architecture, each of them is paired with theoretical models.

Mathematical Form Generation: use of mathematical formulae as the basis for the generative procedure (WaterCube, Beijing).

Tectonic Form Generation: related to mathematical models, it employs tectonic pattern as the basis for form generation (Serpentine Pavilion 2002, Toyo Ito and Cecil Balmond; Serpentine Pavilion 2005, Alvaro Siza and Cecil Balmond).

Material Form Generation: tectonic generation based on three-dimensional material structures. It involves procedures of folding, braiding, knitting, weaving or others traditional interlaced material systems. This model can also be referred to as textile tectonics, based upon modelling of 3D textile interlacing material structures parametrically modulated.

Natural Form Generation: is the morphogenesis that exploits natural forms, phenomenon, process, procedures and biological principles (for references see Otto, Menges, Wein-

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[22] Menges A., "Material computation. Higher integration in morphogenetic design", AD 02/2012

stock).

Fabricational Form Generation: it uses fabrication design logic to develop procedural model of design (for references see Mayer's Metropol Parasol in Seville, Gramazio and Kohler, Iwamoto)

Performative Form Generation: the ecological factors derived from the analysis of physical data of the context (wind, sun, sound, etc.) provide inputs for the design process. The parametric model can be modulated to achieve a solution which considers performance and other desired objectives.

Oxman showcases, through this classification, the relationship between form generation and digital techniques; there is a balance between theoretical positions and the technological potential. The classification proposed by Oxman[23] it is an interesting guideline that helps to identify the focus of certain form generation processes; but it is not to be limited to the exposed categories, a combination of more models is also possible. Taking the Performative form generation model, for instance, we cannot exclude that the performance of a design process could be derived from biomimetic principles, nor that the it does not showcase tectonics. Similarly, a fabrication process could be connected with the tectonics and technique, and also showcase performative features related with material properties. Although this definition by Oxman cannot be taken as an absolute classification in which we can identify strict categories, it still demonstrates the variety of approaches derived by theoretical models, it gives a general framework of contemporary possible methodologies in digital design.

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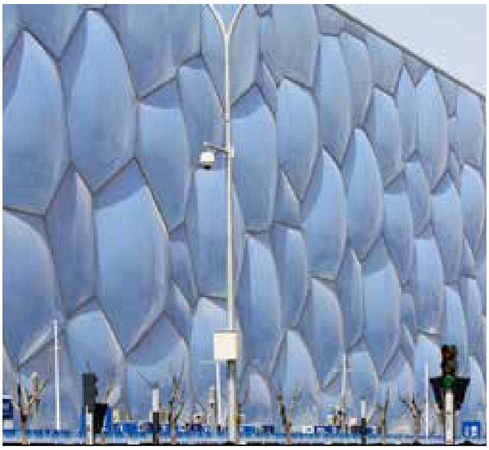
23 The classification for form-generation methods is taken from Oxman R., Oxman R. "Theories of the Digital in Architecture", Routledge, Abingdon and New York, 2014



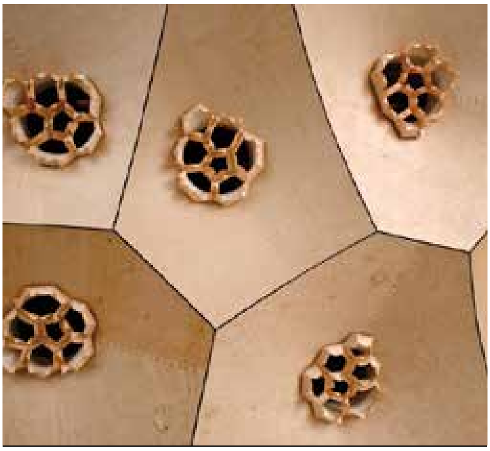
Mathematical Form Generation

Tectonic Form Generation

Material Form Generation

Natural Form Generation

Fabricational Form Generation



Performative Form Generation:

Fig. 2.11 Examples of the form generation models suggested by Oxman R. “Theories of the digital in architecture”

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The culture of digital tectonics

Contents

3. The Culture of Digital Tectonics

3.1. The concept of tectonic culture

Although it might seem a redundancy of a well-known notion for architects, it is still necessary to make the point on the definition of *tectonic*, especially if we consider the contemporary context and the digitalization of more and more aspects of this practice. For the aims of this thesis, focused on the understanding of performance-based digital tectonics in wood architecture, while it might appear contradictory the juxtaposition of "digital" and "physical", the digital tectonics is a cultural and theoretical support to the changing methodology in architectural design, therefore it is worth to go deeper analyzing the fundamental contributions on this concept.

Origins and historical debate

The development of a theory on tectonics principles in architecture is mainly acknowledged within the studies of German theoretician Gottfried Semper, who wrote in 1852 *"The four elements of architecture"* in which he identifies the essence of architecture studying the vernacular way of constructing, diffused, with some relative differences, all over the world. In his though the elements that compose the basic traditional dwelling are: the roof, the heart, the enclosure and the mound. In this classification the elements are derived from the applied arts, Semper categorized the art of construction in two essential processes: the tectonic of the framework in which light and linear wooden elements are assembled together to enclose a spatial matrix, and the stereotomy of the mound, in which the stones are cut and layered one over the other to create the foundations of the house defining its relationship with the ground. Semper, thus, distinguishes the light texture from the heavy layered foundation, and identifies their mutual relationship where one supports the other and where the traditional way of working with the material is expressed in the construction. Semper's concept of tectonic is very much related with the cultural aspects that used to be expressed by architecture; by culture here is meant the art of using the materials according to – local – craftsmanship rules. From this interpretation it is possible to assert that tectonics is not only related to the tangible characteristic of the construction but also to intangible features such as culture and craftsmanship tradition.

In his book on tectonic, Kenneth Frampton[1] gives a definition of tectonic starting from the interpretation of architecture based on the historical meanings of space generation and structure generation – and their mutual relationship – which were deeply theorized

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[1] Frampton K., "Tettonica e architettura. Poetica della forma architettonica nel XIX e XX secolo", Skira, Milano, 2007

by the architects between the 19th and 20th century. After the crisis induced by the post modernism, there is a need to identify the "ethic" of a construction, passing through the spatial and structural character of architecture. Frampton tries to enrich the spatial character of architecture by re-considering the construction and the structural methods through which it must pass in order to be accomplished. The aim is not to glorify the "technique" but to reveal its expressive potential. Tectonics is the poetic of construction and it delivers an artistic meaning, which is not just figurative or abstract. Frampton wants to communicate the nature of a construction process both from its physical materiality and its visual characteristic without leaving aside its spatial value. For him, the construction is the convergence of three elements: "topos, typos and tectonic", which are the typology of the occupation in the context – in the site –, the typology of the construction and the typology of the structure, meaning by "type" the ideal and original model. Thus, Frampton's concept of tectonics is related to site-specific architecture, he stresses the importance of the local context and the relation with the ground.

Speaking of tectonics, it is necessary to introduce its etymology. The term comes from the greek "tekton" and it means "carpenter" or "builder" and it is referred to those craftsmen who work with hard materials – such as wood and stone – but not metals (since they need to be fused to be worked). Consequently, as we all know, from here derives the "architekton" which is the "master carpenter". The meaning of the term "tectonic" was later interpreted, with a deeper understanding, to define an aestethic category rather than just a technological one. Speaking of this, Kenneth Frampton cites Adolf Heinrich Borbein (1982) who affirmed that: *"Tectonic becomes the art of connection. Art here is intended as "tekne" (technique) of the enclosing and, consequently, it refers to tectonic as an assembly not only of building components but of objects too, in particular of craftsmanship objects. Differently from the ancient definition of the word, tectonic aims to the construction or fabrication of an artistic or craftsmanship product [...] It depends more from the correct or incorrect applications of craftsmanship rules [...] Only if meant in this terms tectonic can include a judgment on the artistic production."* [2]

Another contribution on this topic is given by Karl Botticher who distinguishes the "kern-

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[2] "La tettonica diventa l'arte della connessione. 'Arte' deve qui essere intesa come tekne del racchiudere e, di conseguenza, indica la tettonica come assemblaggio non soltanto di parti edilizie, ma anche di oggetti di artigianato in senso più stretto. Rispetto all'antica accezione della parola, la tettonica tende verso la costruzione o fabbricazione di un prodotto artigianale o artistico [...] Dipende molto più dalle applicazioni più o meno corrette o scorrette delle regole artigianali o dal grado in cui è stata raggiunta la sua utilità. Soltanto con questa ampiezza la tettonica comprende anche un giudizio sulla produzione artistica." Translated in English by the author from: Adolf Heinrich Borberin quoted in Frampton K., "Tettonica e architettura. Poetica della forma architettonica nel XIX e XX secolo", Skira, Milano, 2007 (p. 22)

form" and the "kunstform", which are the core-form and the art-form. The connection between the timber beams of an ancient greek temple's roof and their "artistic" representation of the same elements, made by stone, on the frieze. The temple is understood as one object and the tectonic connects all its parts. This distinction between *ontology* (what has a purpose in the architecture) and *representation* (what doesn't have a technical function) is one of the most recognized contributions of Botticher on the topic of tectonic in architecture. In his thought the combination of these two aspects, science and technology on one hand and art on the other, is needed to reach the final architectural construction. Moreover, for Botticher the art-form – the representation – was intended to *"symbolize the concept of structure and space which, in its purely structural state, could not be perceived"*, mentioned here to recall the always present character of architecture as generator of space.

Contemporary 'crisis'

Frampton deeply describes the tectonic character of architecture through an analysis and critics of the last two centuries, but in the conclusions of his essay he complains the absence of such principles in contemporary architecture, and he warns about the condition of contemporary practice. Frampton declares himself skeptic about the growing presence of technology in architecture. At first, he criticizes the lack of an appropriate method in contemporary architectural school and institutions, which, consequently, "produces" students less bounded to the tradition or the cultural aspects that characterize or "leads" some choices in architecture. Then he affirms that the technology is transforming architecture in an empty container without contents, the excessive concentration on the environmental control let the design being led by the facilities and technical aspects. The focus of the design is moved from the plasticity of the materials and articulation of the form, based on the semperian categories, to something where the cultural value of tectonics is completely underestimated. *"Simulation, rather than presentation and representation, constitutes the principal way of expression"*[3]. As also R. Gregory Turner claims: *"the project nowadays is conceived as the work of an architect who designs an envelope and a nucleus that will have to hide the work of engineers and technicians specialized in different areas: structural, mechanical, electrical"* [4]. An exhaustive example of this anti-tectonics direction is understandable by

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[3] "…la simulazione, piuttosto che la presentazione e rappresentazione, viene a costituire la modalità principale di espressione." translated in english by the author from: Frampton K., "Tettonica e architettura. Poetica della forma architettonica nel XIX e XX secolo", Skira, Milano, 2007 (p. 415)

[4] "Il progetto consiste attualmente nell'opera di un architetto, il quale concepisce un involucro e un riempimento che nasconderanno il lavoro di una serie di ingegneri e tecnici caratterizzati da una dicersa specializzazione: quella strutturale, quella meccanica, quella elettrica e impiantistica" translated in english by the author from: Turner R. G., "Construction economics and buildig design: a historical approach", quoted in Frampton

looking, for instance, at the Gehry's Guggenheim in Bilbao, where the artistic expression of the architect through the free-form facade is, in reality, bear by a massive steel structure which does not 'participate' to this desire of expressive lightness (Fig. 3.1). It is the opposite of what happens in the Center Pompidou Metz by Shigeru Ban, where the large double-curved roof is supported by a timber structure which both absolves the structural function (ontology) and the related architectural expression (representation) (Fig. 3.2 and Fig. 3.3). There is an interesting interpretation of the contemporary crisis exposed by Frampton in which he asserts that nowadays the architect is experiencing the same moment of crisis that Gottfried Semper experienced in 1851, when he saw the failing of the current cultural values initiated by the introduction of new machines and new material in architecture. Moreover, in his opinion, in the last 150 years this cultural devaluation just grew up becoming more focused on the economic aspects. Marketing is leading the main

Fig. 3.1 The massive steel structure supporting the external facade of the Guggenheim in Bilbao is an example of anti-tectonics since the correspondence between the language of the cladding and the truss system is limited to functional and merely structural issues.

K., "Tettonica e architettura. Poetica della forma architettonica nel XIX e XX secolo", Skira, Milano, 2007 (p. 414) direction for construction choices. One of the biggest responsible, for Frampton, is also the blind administration and thus the political issues that, unfortunately, today influences the architectural practice. The private sector is pervading more and more the institutional heritage, leading the topic on specific economic interests. For Frampton the architectural practice must be able to face this situation, or it will be dragged by the continuous transformations of technological development. This is not an easy task especially if we still look at the architect as the only figure able to organize all the issues involved in the design and construction. In this sense it is comprehensible – and essential – the introduction of multi-disciplinary approaches. The complexity and hyper-specialization of current tools and technology make the multi-disciplinary approach a necessary condition, in the contemporary age, in order to be able to deliver coherent architectural contents. *"Architects will have to guide the sector of industry, by designing the relative components supporting a predominant tectonic paradigm, and, subsequently, they will have to refine the results of this combination taking part to an accurate process of coordination"*[5]. Considering that the text of

Fig. 3.2 The double-curved roof of the Center Pompidou Metz is an example of contemporary tectonic

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[5] "…agli architetti toccherà sempre più il compito di indirizzare i differenti settori dell'industria, nel senso

Fig. 3.3 Detail of the timber double-layered structure of the Center Pompidou Metz which has been processed by robots to achieve a curvature of each element in two directions

Frampton is from almost 20 years ago[6], and considering the rapid change and diffusion of technological development, it is in within the aims of this thesis to discuss how nowadays the architect is updating his skills and knowledge and is able to operate as leading figure when coordinating a multidisciplinary group. Although most of the approaches taken in exam in this thesis are often - but not always - more pertinent to an academic field rather than the one of "built architecture", we can still say that architecture is taking control of the potential that technology has to offer. Of course, the academia is a more favored field of action since it concedes to concentrate the intellectual energies and resources on selected topics and to be - partially - independent from the economic and political pressure. So, in a way, the problem exposed by Frampton is not at all solved yet – if it will ever have a solution – but today there's a different, and more mature, awareness of the great potential that the technology could manifest in the built environment and, most important, the topic of digital tectonics is globally rising among the academic and professional contribution. Contemporary approaches, that embrace the technological tools, the computer and algorithm aided design and manufacturing, are contributing in the construction of a theoretical background, going beyond the simple exploitation and exploration of these tools, by rebuilding a link with the history of architecture, in some cases, or with the culture and tradition – using local materials and reinterpreting the traditional techniques – in some other cases, or by re-establishing the principles of design in empowered network of scientific studies. Patrick Schumacher claims the existence of a style, nevertheless styles have historically always been embraced, somehow, by the society because they were representing the culture or the avant-garde of that specific historical moment and they were actually expressed in different disciplines. Probably, before rushing into the definition of a style, there need to be a certain chronological distance from those facts, which can provide a better interpretation of that specific context and a better analytical understanding. Clearly, after the modern movement and the tabula rasa in culture, architecture, art and design, it might sound nostalgic and pretentious to affirm that there is something substantial involving the society and culture at all levels which can be summarized in a "style" or labeled as a "movement", but, nevertheless, it needs to be recognized that this call hails from somewhere and it aims for unify a variety of yet slightly disaggregated approaches. In a way the call of Patrick Schumacher makes sense if we think that something is actually happening in architecture and manufacturing, and it also involves fabrication and design processes, but perhaps the big heterogeneous society is not yet completely embedded in

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di progettare le rispettive componenti a supporto di un paradigma tettonico dominante e, successivamente, di rifinire il risultato di queste combinazioni ricorrendo a un processo di coordinamento attento e accurato." translated in english by the author from: Frampton K., "Tettonica e architettura. Poetica della forma architettonica nel XIX e XX secolo", Skira, Milano, 2007 (p. 421)

[6] The book's first publication is from 1995

it and, additionally, it is not used any longer to the feeling of unification under the same "flag", while it rather pursues a radical customization. A pursue for a mass-customization demonstrated by the innovation in production enabled by the new technological tools (3D printers and programmable robotic arms for instance).

3.2. Digital Tectonics

Academic researches from all over the world are contributing in the definition of innovative approaches that explores the potential of technology and are re-directing the interest of architecture toward a coherence of the construction, the use of material, the reinterpretation of tradition, through the employment of developed digital tools. In many of these researches there is often a correspondence between the material performance and the tectonic character of the construction. In a way this recalls the concepts introduced by Karl Botticher of ontology and representation. In particular, as it will be shown in some of the analyzed case-studies, the boundary between the ontological, the essence of the structure, and the representational aspect almost disappears. This strengthen the coherence of the construction and, thus, its tectonic character, because, perhaps, in these contemporary approaches the "representation" is more directly symbolized by the technical feasibility (the *tekne*), that is to say by the construction method, similarly to what Semper theorized. What is generating this awareness in digital architecture, is both an advanced knowledge of new and existing materials and the innovative developed techniques in material fabrication and assembly. Industrial and technological revolutions are trigged by new philosophies of thought and, thus, by new cultural contexts which impose a reinterpretation of current knowledge – both technical and theoretical. We can recognize this patterns in the great revolutions of the last two centuries. In the XVIII century Enlightenment introduced the rational and scientific thinking over the traditional thinking, creating a vibrant cultural context in which the first industrial revolution took place. As for architecture, new material and construction techniques were introduced, radically changing the conventional way of thinking and making architectural structure and space. Thanks to innovative technology the structures are freed from the old constrains, enhancing a diversity of approaches and experiments. A great part of this was expressed, for example, in the cultural and architectural 'event' of Paxton's Crystal Palace for the 1st Universal Expo in 1851, when Gottfried Semper, seeing the innovations brought by the revolution, felt the need to re-establish the essential principles of architecture to prevent a misuse of this new knowledge. The year after Semper published his book on tectonics in architecture, in which he strongly highlights the cultural value of local craftsmanship reflected on the architectural construction.

Analogously, we can read a paradigm shift, within the architectural domain, during the early '900 with the Modernism. Mies or Le Corbusier, for example, completely re-established a new tectonic and articulation of the space, they reformulated the rules of architecture and construction. The new logic was contextually driven by the new industrial production of steel, reinforced concrete, glass and their potential of expression. Therefore, as Rivka and Robert Oxman suggest, *"if we can accept the equation of tectonic change with technological development, then the impact of digital media on architectural practice within the last decade would appear to be a motivating factor in a paradigm shift in tectonic theory of no less consequence than the emergence of modernist tectonics".* [7]. Digital tectonics could provide a cultural continuity with the paradigm of modernist tectonics, and introduce a new interpretation. According to Oxman digital tectonics is a transition from the modernist poetic of the construction in which the relationship space/structure was the subject, to a new poetics where the subject is moved to material/structure or material/tectonics.

Digital tectonics is a concept that started to be debated within the architectural discourse since about fifteen years. It is thus a quite recent topic in contemporary theory, and its body of knowledge is still a bit vague and is evolving together with the emerging theories of the digital in architecture. Digital tectonics is highly determined by the study of material complexity, its behavior and its structure. The study of material in contemporary digital architecture opens the discussion to new and wide fields of research and theory: there are different strategies to approach this topic which lead to distinct, equally interesting, outcomes. From the analysis of wood fibers behavior to 3D printed plastics, these studies attempt to introduce material performance in the formation process. This combination brings a cultural innovation that allows us to exploit the technological development with awareness through new design methodology.

Today, material systems can be parametrically generated as non-linear structures – and enclosures – this possibility have consequences both on the operative and theoretical point of view. On the operative point of view, we should need to understand how to manipulate and manage these systems, generated through parametrically controlled algorithms, and explore what we can do with them. On the theoretical point of view, we should avoid that this manipulation of the digital remains within a pure formalism which does not bear a significant meaning. To this regard, the discourse of digital tectonics was embraced in 2004 by Neil Leach[8] who particularly focuses on the potential of digital technologies to generate non-linear structures merged in the formation process of architecture. Leach introduces the definition of 'swarm tectonics'[9], based on the emergent characteristics of

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[7] Oxman R., Oxman R. "Theories of the Digital in Architecture", Routledge, Abingdon and New York, 2014

[8] Leach N., Turnbull D., William C., "Digital Tectonics", Wiley Academy, 2004

[9] Leach N., "Swarm Tectonics" in Leach N., Turnbull D., William C., "Digital Tectonics", Wiley Academy,

complex systems (non-linear). The interest in this direction was primarily influenced by the introduction of non-linear scientific thinking and complex systems theories – as discussed in the previous chapter of this thesis – spread at the beginning of 2000's and which find its most relevant scientific foundations in the academic community of the Santa Fe Institute[10], New Mexico. This experimental field of science, which introduced new visions in the scientific academy, transversally influenced research and therefore even the experimental side of architecture. It proposed ways to understand the structures and principles of self-organizing systems and emergence phenomenon (intended as the property of complex systems which cannot be derived from the simple sum of its parts). In nature, swarms present this characteristic, if we think, for instance, to an ant colony, the complex structure that they create and manage is way more articulated than the simple sum of that number of ants. Neil Leach tried to propose one of the first theoretical framework to illustrate what can be interpreted as digital tectonics and what could be the contemporary references. He distinguishes two outlooks in the history of architecture: one is principally aesthetic and tend to impose form on building material, according to some pre-determined rules; the other is principally structural and tends to allow forms to emerge based on specific requirements. The first approach, according to Leach, is called Romanesque and is observable in Classical styles, Roman, Greek and their derivations and all the approaches that focus on the appearance over the performance. While the second approach is the Gothic, not as a style but as a method, since it privileges process over appearance. Leach elaborates these concepts from the philosophical essays of Deleuze and Guattari[11] who analyze

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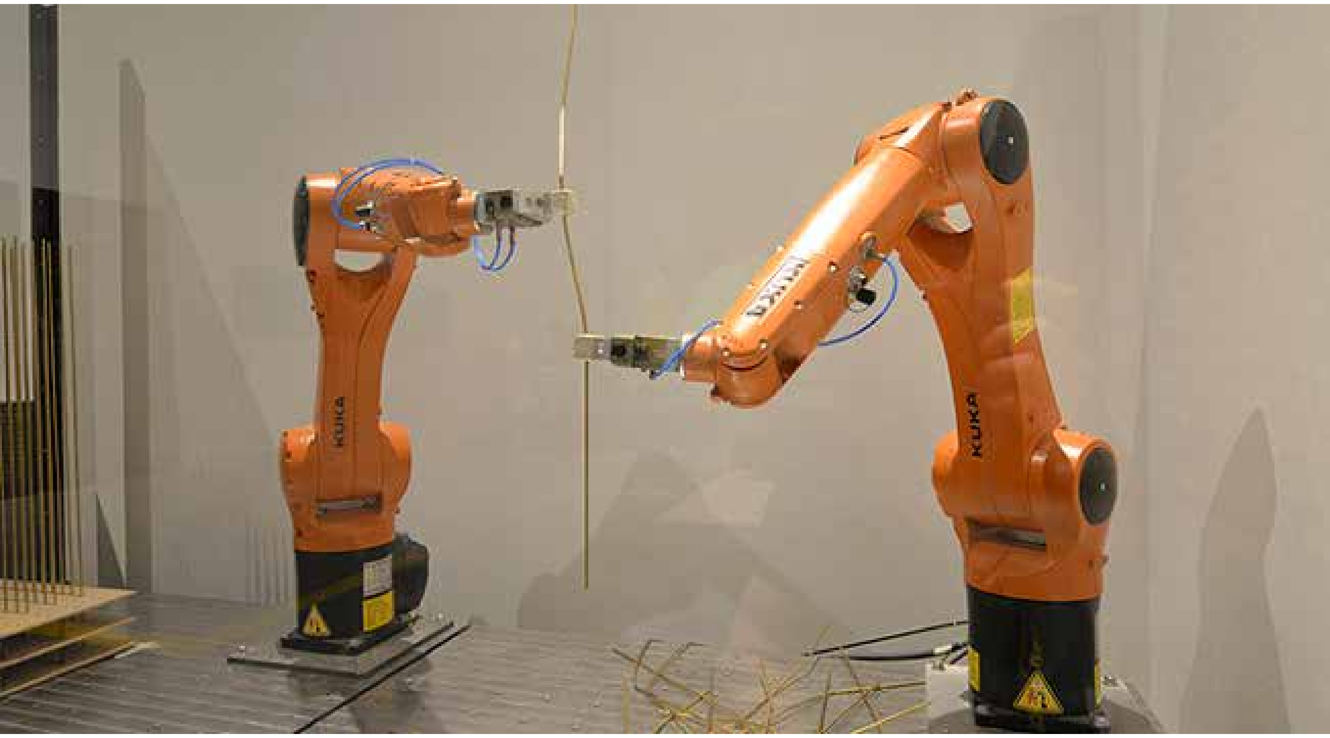
2004

[10] *"The Santa Fe Institute is a nonprofit, independent research center that leads global research in complexity science. SFI scientists seek the shared patterns and regularities across physical, biological, social, and technological systems that give rise to complexity—in any system in which its collective, system-wide behaviors cannot be understood merely by studying its parts or individuals in isolation. Insights from complexity science are increasingly useful in understanding questions far beyond the boundaries of traditional academic disciplines—urban sustainability, disease networks, and financial risk, to name a few."*

[11] *"A Thousand Plateaus: Capitalism and Schizophrenia"* (French: Mille plateaux) is a 1980 philosophy book by the French philosopher Gilles Deleuze and the French psycholanalyst Félix Guattari. The authors draw upon and discuss the work of a number of authors, including Sigmund Freud, Carl Jung, and Wilhelm Reich. A Thousand Plateaus is written in a non-linear fashion, and the reader is invited to move among plateaux in any order. It is the second volume of Capitalism and Schizophrenia, and the successor to Anti-Oedipus (1972). Before the full English translation by social theorist Brian Massumi appeared in 1987, the twelfth

Fig. 3.4 Brass Swarm is an experimental prototype developed through self-organisational algorithmic design processes and robotic fabrication. The project explores spatial self-organisation, emergent tectonics and the relationship between robotic and algorithmic behavior. Source: kokkugia.com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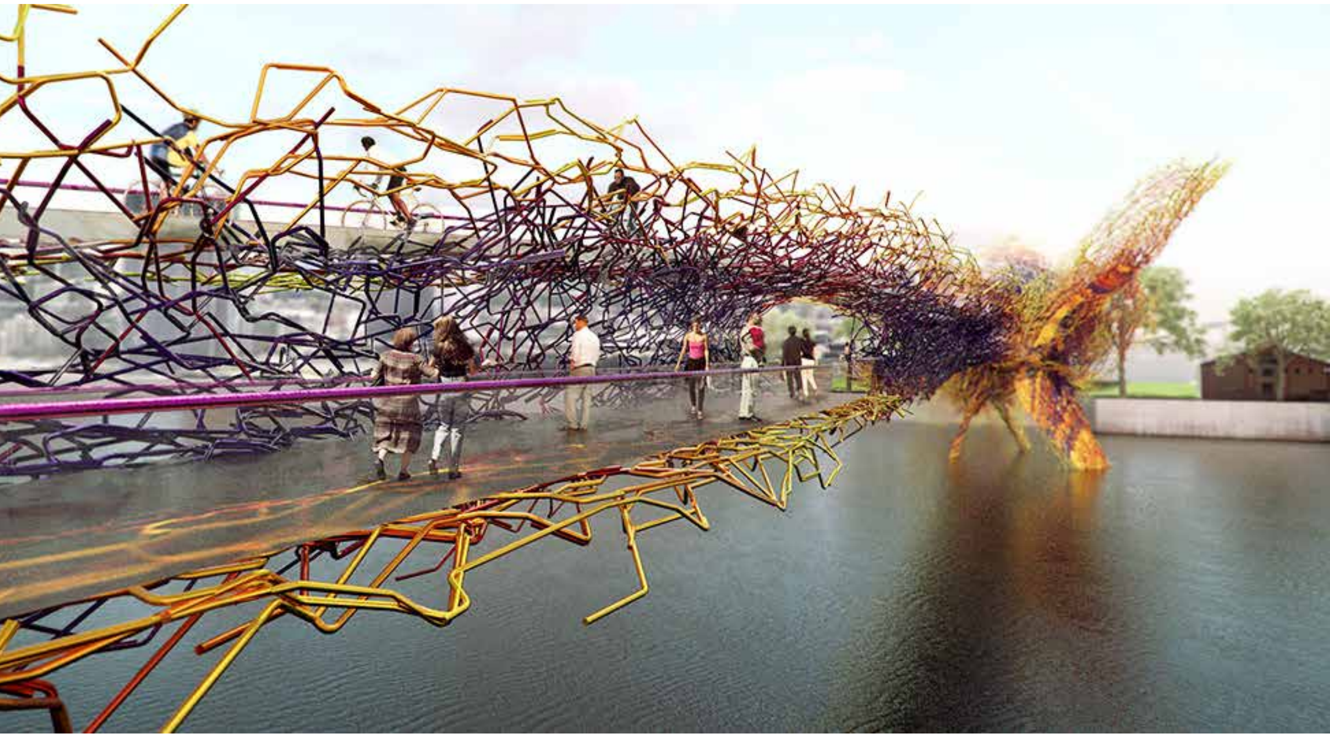

the distinction between Romanesque and Gothic from a qualitative perspective: a static model vs a dynamic model of understanding architecture. This dynamic model would be more coherent with the emergent digital tectonics since digital technologies allow to determine the behavior – and thus the performance – of an artifact, regardless its form or aesthetic. The aesthetic value comes from the expression of resultant behavior, achieving a performance-based relationship of form-structure-material and technique, as emergent tectonics experimented in the structures of Roland Snooks and kokkugia research group (Fig. 3.4 and Fig. 3.5). The Gothic outlook, in fact, highlights an attention for structure which Leach reinterpret and recognize in the works of Gaudì and Frei Otto, to name some of the pioneers, who manifested the intention of going beyond conventionally-conceived structures and forms and experiment a reversed and more direct relationship between form and structure. According to Leach (2004), this outlook could also be found in the works of FOA, UN Studio, Reiser+Umemoto, Mark Burry, Lars Spuybroek, which shares an interest in structural engineering and consider the structural concerns as a component integrated in the design process. Leach concludes:

> “The computer is being used not as a tool of representation, but as a generative instrument that is part of the design process itself. In other words, at most radical level, the computer has redefined the role of the architect. No longer is the architect the demiurgic form-maker of the past. The architect has been recast as the controller of processes, who oversees the ‘formation’ of architecture. With the development of new computational techniques, we find ourselves on the threshold of a new paradigm for architecture – a paradigm in which ‘swarm tectonics’ plays a crucial role”.

Technology dramatically changed and evolved in these fifteen years, therefore more innovative and articulated approaches are available, and the digital tectonics is experiencing new results built on a contemporary digital technique with its own tradition. By these regards, we could extend the definition provided by Leach to even more contemporary approaches, especially in academia, that includes Achim Menges (Fig. 3.6), Gramazio and Kohler, Philippe Block, Philip Yuan who also share an interest in structure and perfor-

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"plateau" was published separately as Nomadology: The War Machine (New York: Semiotext(e), 1986). Though influential, and considered a major statement of post-structuralism and postmodernism, the book has been criticized on many grounds. (Wikipedia, accessed January 2018)

Fig. 3.5 The Brass Swarm structure prototype serves as abstract experimental inspiration which has been embedded in the design of a pedestrian and cycling bridge over the Thames in London. The bridge blends between the typologies of arch, truss and cable, creating an innovative structural model that opens up new possibilities for architectural expression. The bridge’s hybrid structure does not apply specific elements to structural roles (such as cable, mast, arch etc), instead these various structural roles operate through a cloud of components – a fuzzy hybrid. This blurred condition masks the structural logic and instead focuses attention on the experience of this immersive space. Source: rolandsnooks.com

mance in their experimental design and researches. We are talking about a new tradition that is included in the design process. Frampton based his interpretation on the ancient classic culture of architecture, reinforced by the romanticism of 19th century's German intellectuals, and he finally expresses the value of the construction in its cultural roots, in the poetic of the construction, in the artistic value of the technique, in the materiality of the object, in the expressive potential of form and structure. Today we can understand the excitement of the late nineties for the promising technological evolution, and we are therefore able to interpret the cultural positions emerged in architecture during those years. The direction of studies introduced by theorists about digital tectonics was, and still is, not strictly defined and it is constantly changing on one hand because it is based on fairly new concepts, on the other because there has not yet been the time to sediment and consolidate this new knowledge. This makes more complex both the dissemination of the concept and its application in construction, which is, at the end, the necessary condition for tectonics. Thus, the current theoretical framework of a digital tectonics is still finding its way in the architectural debate, the bibliography about it is growing and it is perhaps preparing to 'wrap up' the concepts as Frampton did in the nineties after centuries of architectural debates and styles. For these reasons it is not immediate to find a common definition of the concept shared by a community of researchers and practitioners in architecture but what has been discussed and presented so far tries to give a contribution in this direction. After all Frampton too presents the conceptual shades of tectonics finding a path through history and modernist paradigm.

Material-Based Design and Informed Tectonics

Undoubtedly, the contemporary changing definition of tectonics is based on current evolution of digital design. We are assisting to an increasing coherent interrelationship between technology and design. As we already discussed, this integrative direction of research and practice is mainly enhanced by the computational processes that are enabling a digital control over the design phases and, most importantly, are favoring a continuity from the conception to the materialization and production. Computational design processes allow the integration of structure, material and form within the fabrication logic. Then the core of the conceptual design is no more the mere final formal result, but more complex actors are involved in the design phases. Architecture finds its definition through materiality, and computation is widely expanding the possibilities of achieving this materiality. Material-Based Design is a spreading approach in the experimental realm of academia – and in some cases in the professional one too – as a computational informing process where

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Fig. 3.6 ICD ITECH Master, Pavilion 2016-2017 features a morphogenetic biomimetic approach that explores the potential of fibrous tectonics (or textile tectonics) where the arrangement of carbon and glass fibers are computationally elaborated and robotically fabricated the integration of material information completely changes the design methodology and involves cultural and theoretical effects. Therefore, academia and research-related fields of architecture are providing definitions of design methodologies based on seamless processes from design to fabrication where the material behavior and characteristics play a crucial role in the definition of form, structure, and construction logic. We can recognize two types of practice models: the traditional 'horizontal' model and the new 'vertical' model[12]. The first one is the well-known traditional model of design approach, while the second is a transversal approach which emphasizes the role of new techniques and technologies and the experimental design. Material-based design is a vertical model which is becoming the emerging design strategy that integrates digital design, materiality and fabrication. Within this theoretical and operative framework Rivka Oxman introduces the term *'Informed Tectonics'* as key component of this vertical model, and highlights that the shift towards this new interest in material design necessarily questions the current definition of tectonics[13]. Oxman frames the concept of digital tectonics as follows:

> "Theories and technologies of digital design have contributed new meaning to the term 'tectonics'. The digital has become an informing media in its ability to integrate, mediate and differentiate tectonic content […]. As a result of the enhanced tectonic capabilities deriving from digital media and computational technologies, various different approaches and definitions of the term 'digital tectonics' have been proposed over the last decade. The term 'digital tectonics' was first introduced by William Mitchell[14]. He proposed the term 'virtual materiality' to describe a virtual computational space that accommodates the representation of materiality. This was seen as a counterposition to that of Frampton. In defining the possibility ad potential of a digital tectonics, Mitchell also superseded the 'earthwork' that Gottfried Semper identified as one of the four elements of architecture. Today the concept of digital tectonics is expanding the function of materiality in design and contributing to a new perspective of computational methods of tectonics"[15].

Moreover, Oxman identifies the differentiation of digital tectonics related to the variety of approaches enhanced by computation. Beyond the conceptualization of tectonics as

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[12] Kennedy S., *"Responsive Materials"* in Schröpfer T. (ed.) *"Material Design. Informing Architecture through Materiality"* Birkhauser Basel, 2011

[13] Oxman R., *"Informed Tectonics in Material-Based Design"* in Oxman R., Oxman R. *"Theories of the Digital in Architecture"*, Routledge, Abingdon and New York, 2014

[14] Mitchell W., *"Antitectonics: the poetics of virtuality"* in Beckman J. (ed.) *"The Virtual Dimension"* Princeton Architectural Press, New York, 1998

[15] Oxman R., *"Informed Tectonics in Material-Based Design"* in Oxman Rivka and Oxman Robert, *"Theories of the Digital in Architecture"*, Routledge, Abingdon and New York, 2014

virtual materiality expressed by Mitchell – where the object remains prevalently a digital and virtual entity – the topic of digital tectonics can be described as[16]:

Physical Materiality: where digital tectonics is the characterization of the influence of digital media and technologies in experimental and explorative design that modifies the conventional concept of tectonics. Here the focus is on dynamic factors of motion, information, generation and fabrication. This interpretation is thus related to the exploration of construction technologies in adaptive-responsive systems (such as responsive facades for instance), able to provide four-dimensional – time based – dynamic properties.

Fabricated Materiality: where the innovative fabrication logic goes together with the conceptualization of the design, increasing the importance of the link that there is from digital design technique to fabrication technique (Fig. 3.7).

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[16] Classification by Oxman R., in Oxman R., *"Informed Tectonics in Material-Based Design"* in Oxman Rivka and Oxman Robert, *"Theories of the Digital in Architecture"*, Routledge, Abingdon and New York, 2014

Fig. 3.7 The theater designed by the IBOIS reseach center of EPFL, Losanne, is an example of 'fabricated materiality' that links together the structural principle and the fabrication method.

Structured Materiality: this interpretation includes the theories expressed by Leach, Turnbull and Williams[17] which propose digital tectonics as a paradigm shift characterized by a structural turn. As previously described, this approach values the new synthesis between architecture and structural engineering and it highlights the possibilities offered by the digital platforms to generate and manage form, structure and material.

Digital Form-Finding and Morphogenetic processes: where the form generation is achieved through materiality in digital form-finding and natural systems. These approaches derive the formation process from biomimetic principles enhanced by digital form-finding methodology.

Adaptive Materiality: this field is related to the use of innovative smart materials able to change their behavior and replace the mechanical principles. Smart materials could introduce empowered characteristics in responsive-adaptive architectural systems.

The classification proposed by Rivka Oxman is convenient to recognize the variety of interpretations of digital tectonics but is not to be limited, as discussed before, to a strict taxonomy. What links all these interpretative visions and approaches is materiality, which is achieved through different means or strategies and supported by computational techniques and digital technologies. As materiality is the concrete expression of architecture, it is necessary to understand the current changing paradigm of the digital culture that finds its formative features in the exploration and exploitation of material properties and behavior in relationship with form-generation and tectonics.

> “Design by the digital and the material is becoming a system in which the synthesis of architects, engineer and fabricator again controls the responsibility for the total process of conceptualization and materialization. This change provides a reconciliation of digital tectonics with arguments of Frampton and Semper. The changing definition of tectonic relationship may be considered one of the formative effects of the emergence of digital tectonics”[18].

By this regard the concept of ‘informed tectonics’ plays a key role in the development of a new design methodology which contemplates a strong multidisciplinarity since the early phases of the process. It defines the multi-faced cultural background and operative framework of the digital in architecture. Since about 2000 (when BIM was introduced in the market) the use of 3D model in architecture acquired a different role, from a mere representational tool to a work-tool embedded with information. This information inclusion

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[17] Leach N., Turnbull D., William C., “Digital Tectonics”, Wiley Academy, 2004

[18] Oxman R., *“Informed Tectonics in Material-Based Design”* in Oxman Rivka and Oxman Robert, *“Theories of the Digital in Architecture”*, Routledge, Abingdon and New York, 2014

made the difference by enhancing future development in the use of 3D models. In fact, the use of this information and the manipulation possibility granted by algorithm-aided design, opened the study-field to a deeper understanding of the results of such implementation for architectural design. Moreover, the possibility of being independent from standard industrial production techniques, thanks to the diffusion of multi-axis robots, CNCs and 3D printers in many experimental laboratories of academic and professional field, gave a considerable degree of freedom in the fabrication and management of all the tailored customized components of the project. The information management and the possibility to control it within the fabrication logic, defines a new fundamental dimension of tectonics and strengthen the insoluble link between architecture and materiality, and, thus, between architecture and structure. Such innovation gave a cause for reflection on the expression of the technological development in the design process, introducing a methodology which re-establishes the operative and theoretical framework, especially in the experimental academic research field. Informed Tectonics is the outcome of the 'design engineering', an approach that has developed new models for the design of geometrically complex structures. There is no longer *a posteriori* involvement of the structural engineering, but it becomes a generative component of the design. Projects as the Sidney Opera House were pioneers in the definition of architectural form through structural behavior and material coherence. With the years this branch of architecture, which looks for an extreme correspondence between form and structure, produced a series of remarkable design where the structure defines the tectonics of the building. Today's advanced computational techniques reinforced this direction of formal research, material practice and tectonics, in a call for a new structuralism[19] where the digital is an active generative tool embedded in the process. In this framework, the tectonic articulation of form-structure-material-fabrication is the synthesis of a contemporary design methodology identified as Material-Based Design.

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[19] Oxman Rivka, Oxman Robert, "The New Structuralism: Design, Engineering and Architectural Technologies" Introduction of "New Structuralism" AD 04/2014

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Material performance in wood architecture

Contents

4. Material Performance in Wood Architecture

4.1. Methodology and Performance in Architecture

The Paradigm Shift in Design Methodology

The realm of digital tectonics is a cultural reflection within the theoretical discourse of contemporary design approaches enabled by computation. In particular, as it has been discussed in the previous chapter, we are witnessing to a more and more strengthened connection between materiality of tectonics and the digital computational potential, as Leach declares:

> "The seemingly paradoxical use of the immaterial domain of the computer to understand the material properties of architecture has spawned a new term in architecture: 'digital tectonics'. In other words, the old opposition between the highly material world of the tectonic and the immaterial world of the digital has broken down. What we have instead is a new tectonics of the digital or 'digital tectonics'".[1]

A significant paradigm shift, represented by the rise of these new cultural landscapes, moves the focus of architecture from a primarily 'aesthetic' domain to matters once considered secondary of structure, construction, economic and environmental issues. It is the overcome of the "Gothic" over the "Romanesque", to say it in a symbolic way, or, to be clearer, it is **a shift from an object-oriented design to a process-oriented one**. In terms of architectural culture this can be analyzed as an attempt to move the debate away from the decorative scenography of Post-modern paradigm, which privileged the appearance of aesthetics, towards a global conception of performance. Contemporary research in architecture is, in fact, focusing on a more 'objective' and scientific framework where the efficient use of resources (materials) acquires a primary importance over the traditional approach. This does not represent the end of the creative process in favor of an aseptic and distant one, the architect changes his role of director from a 'form-maker' to a controller of a more complex generative process where his creativity is not the only agent concurring to the 'final outcome'.

There is a fundamental difference between these methods discussed so far: the first one, the 'traditional' methodology, can be defined as a top-down process of form-making while the latter delivers **a reviewed logic of form-finding which brings to establish a different methodology**. The process of conception (design thinking) and its materialization in the final result, determine a new logic where the form is generated by certain conditions, es-

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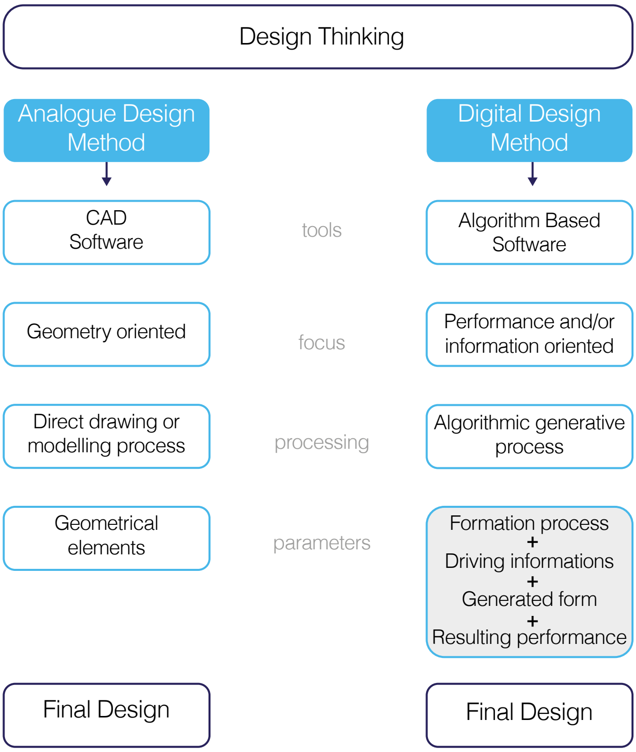
[1] Leach N. "Digital Morphogenesis" AD Volume 79, 01/2009

tablished by the architect, in relation with material or environmental performance.

If we look at, for example, the designs produced during the very early phase of digitalization in architecture, such as the projects of Frank Gehry or the early Zaha Hadid, we might misinterpret them as linguistically ‘similar’ to some more contemporary and mature designs, as the Sequential Roof by Gramazio&Koheler, because of the formal ‘freedom’ that characterizes both. Gehry operates within the ‘traditional’ methodology and a post-modern approach, he follows a top-down process where the architect is an expressive master and structural engineering is solved a posteriori. On the other hand, the Sequential Roof, as well as many other contemporary projects which make use of computation, is designed through a bottom-up form-finding process where the structural performance of form and material is considered since the conception phase. This is possible thanks to the control that architects and structural engineers can share on the process with the aid of digital computation. Achim Menges, director of the ICD at University of Stuttgart, defines this changing as **a shift from computerized design to computational design**[2],

Fig. 4.1 Fundamental differences in the analogue and digital design methodology, the design thinking remains a common base while the rest pf the process brings to totally different results



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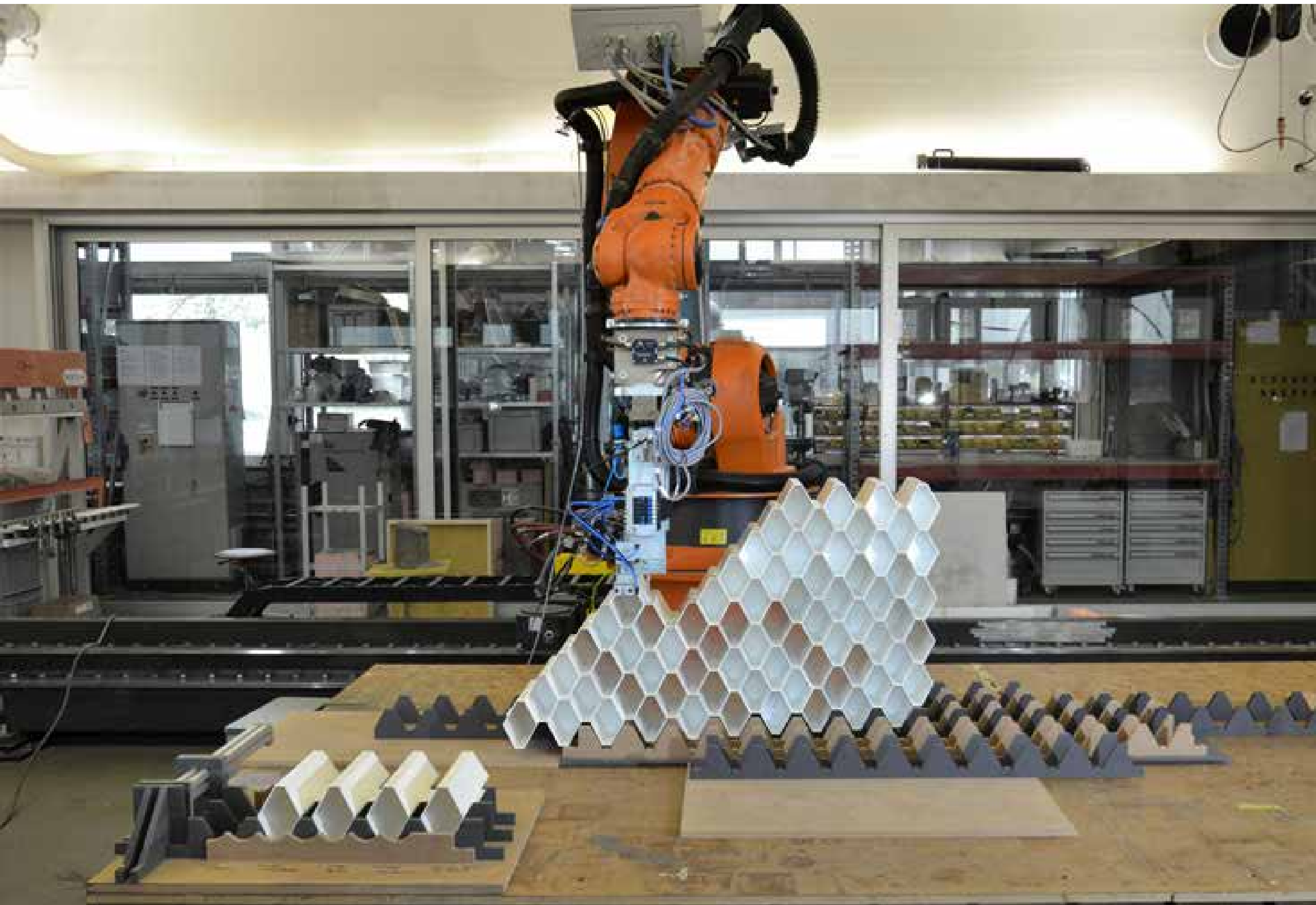
[2] Menges A. *“The new cyber-physical making in architecture. Computational construction”* in AD 05/2015

which is then extendable to a shift from computerized making to computational making. Computerization is a digital version of well established processes, while the computational approach proposes the algorithmic exploration of undetermined processes. In fact, in the most diffused use of CAD software, architects work with a defined set of drawings or models which constitutes a rigid transfer from the virtual to the physical world. On the other hand, today's computational digital models are a result of generative and associative algorithms which allow to integrate information and easily manipulate the design.

Computational designs are realized through non-standard fabrication techniques, often based on programmable CNC machines, 3D printers, robotic arms with customized toolheads. In a first phase of development and application of such making strategies issues of 'rigidity of the system' emerged. In fact, in this making process any deviation from the virtual model to the physical one is understood as inaccuracy. For example, in the fabrication of a complex form through robotic assembly the robot might find a difference of some millimeters in placing a component in a predefined location because (Fig. 4.2), perhaps, the entire system has moved a little bit due to a structural setting. In this system, if the robot is not able to perceive this physiological movement of the structure, problems

Fig. 4.2 Acoustic wall, research project by Gramazio&Kohler research group. The robot moves each brick in its targed position based on a digital blueprint.



of assembly can emerge. What the technological development attempted so far is the reduction of this range of inaccuracy to smaller gaps. But today the most advanced available technology in robotic construction allows to inform the process even in the fabrication phase, therefore the machine gains, somehow, the ability to sense and react. In a way, the machine is 'aware' of the possible divergences – through sensors for instance – and it is able to compensate them. The employment of this technology allows a behavior-based making process which reflects a change in the design methodology, other than a 'mere' revolution in fabrication processes.

> "In behavior-based making, data is continuously gathered and fed back to the system, which means that new information is gained on the run and new insights can be had; or in other words, design can evolve in the process of making. Gone is the idea of dump machines that simply execute static and predetermined tasks, replaced with that of production environments that allow the processes of fabrication, assembly and construction to have a say in the forms we create. Materialization thus becomes an active driver of design, not only through the an-

Fig. 4.3 ICD research Pavilion 2012. Morphogenesis is a form-generation process based on computational modelling. The model generates shapes according to the principles and boundary conditions set *a priori* by the designer. In cases like this, as affirmed by Carpo, the researchers essentially create a virtual database of cases under specified conditions and then they pick the fittest one according to the required performative parameters.

> ticipation of its affordances and constraints in the domain of virtual design computation, but also by extending this towards the physical computing of form, structure and space during ongoing material unfolding. Predictive modelling, both as geometric notation and numerical simulation, may eventually even be replaced by real-time physical sensing and computational analysis, material monitoring, machine learning and continual (re)construction"[3].

Through technological innovation, computation is thus blurring the line between design and construction, a fusion of these two processes challenges the established design thinking and design techniques. To this regard, an intellectual shift is necessary for a coherent exploitation of such innovation. For the exploration of the computational potential in design and making, Menges finds a great inspiration in biological – rather than technological – models which denote peculiar features in material distribution and form generation in a performance-based approach. The theme of form and, before, of formation process, becomes one of the main focuses in the field of computational design and is a key-point in the definition of a performance-based methodology.

By this regard, Mario Carpo stresses the **intellectual shift from the traditional thought** by claiming the end of modern science[4]. As previously discussed, the introduction of complexity theories and the study of non-linear emergent systems transversally influenced many disciplines, among which the approach to design and form generation processes. Carpo gives an additional interesting interpretation explaining that thanks to today's possibility of collecting huge amount of data and sort them with extreme facility, we might not need anymore the traditional scientific notation and, therefore methodology. Modern experimental science is based on the assumption that certain events that happens under certain conditions may be predicted analyzing their 'behavior' in experiments. Thus a scientific notation is provided to express a short schematic version of the relevant and recurrent results – mathematical formulas and structural engineering force distribution schemes for instance – allowing to predict a future analogue experiment or happening. But, this is often contextualized in a condition where it is almost impossible to precisely evaluate all the possible events of that type that happened throughout all history: the amount of data would be enormously big to consider, sort and manage. Therefore the experimental science gives the possibility to deduce this event based on the previous limited experience. For example consider a wood beam that brakes in a point after excessive loading, the experimental science predicts how, if and why a beam would brake, in the future, under certain load conditions. Since it is impossible to collect all the previous events of the same type we can process a limited amount of data, saving the most relevant

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[3] Menges A., "The new cyber-physical making in architecture. Computational construction" AD 05/2015

[4] Carpo M., "The Second Digital Turn. Design beyond Intelligence" The MIT Press, Cambridge Massachusetts, London England 2017

findings and discarding the irrelevant ones. Thus, 'modern' experimental science is based on extrapolation, generalization, induction of patterns and on the transmission of records through compressed expressions and theories. Carpo interpret the modern science as a retrieval, not a prediction, as an old science of small data which retrieved events recorded in an abbreviated, condensed form because of the limits of old technology of data recording and transmission. Therefore, the point of Carpo is that today's computational capacity of processing Big Data has removed many of those limits. The new science of Big Data could retrieve the precedent events almost in their entirety, allowing to integrate a higher degree of complexity and completeness to the prediction. Moreover, in computational processes used to analyze the data, the precedent we are looking for does not necessarily need to be a real one because, through simulation tools, is possible to create virtual data sets to examine. For instance, in the morphogenetics approaches such as the Stuttgart ICD's pavilions (Fig. 4.3), the study starts with a geometrical and material layout derived from biology, then the structural behavior is simulated using finite element analysis (FEA), the result of the simulation allows to understand what needs to be improved in the global geometry and/or component's layout, these aspects of the design are 'fixed' by changing some parameters and the process is then repeated on the new model. These steps are reiterated many times until the results are acceptable. In this process – which will be deeply discussed in the further paragraphs – lies the power of test and simulation tools since in few hours a huge digital database of possible combinations is created. The results of these projects are first of their kinds but, through computation, they create the necessary 'historical archive' where to look for the best solution. It is a transversal outlook provided by Carpo where he affirms that *"by simulations and iterations, they (the researchers of ICD) generated a vast and partly random corpus of very similar structures that all failed under certain conditions; and they chose and ultimately replicated one that did not"*[5]. The discourse in which Carpo introduce this topic is a wide and comprehensive outlook of the contemporary trends in scientific research enabled by computation. On the basis of these studies, new branches and paths for academic research are being developed and explored.

Performance-based Design in Architecture

In contemporary research we can identify approaches that use "performance" as a generative design principle. This branch of architectural design is defined as "performance-based design" or "performative architecture". In general, the performance referred to, may be linked to various aspects, from economic, spatial, social and cultural, to the more technical of structure, environment, acoustic etc. From a computational point of view the topic is not completely new in relation to architecture, as it has already been introduced around

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[5] Carpo M., "The Second Digital Turn. Design beyond Intelligence" The MIT Press, Cambridge Massachusetts, London England 2017

the '70s by Prof. Thomas Maver at ABACUS (Architecture and Building Aids Computer Unit, Strathclyde) a research group of Strathclyde University, who proposed that building design could be driven by a range of integrated performance appraisal aids running on computer. The tool proposed by Maver was called PACE (Package for Architectural Computer Evaluation) and it was developed as a "computer-aided appraisal facility for use at strategic stages in architectural design". PACE was intended to be an integrative system able to work with sets of appraisal measures instead of optimizing a single parameter. The program measured costs, spatial, environmental and activity performance. The 'spatial performance' component measured the site utilization, plan and mass compactness (this feature's aim could be the optimization of buildings space occupation, given, perhaps, certain economical interest involved in construction industry). The 'environmental performance' was measured in relation to plant size which was necessary to give satisfying environmental condition considering heat gain and loss. After evaluation the program would give a feedback and translate it into suggestions for the designer on how to operate on geometrical information. The designer would change the information and then, if necessary, re-iterate the procedure. Doing so the solution would have been better over the subsequent steps reaching, at the end, an optimized solution. Possibly, due to low diffusion of computers back in the 70's and 80's and considering that the digital turn in architecture still had to come, the visionary proposal of ABACUS did not experience the hoped success. Nevertheless, if we look at the process employed by PACE we can see that it worked as a base for contemporary digital morphogenesis based on computational models where parameters are set at the beginning and the model is ran in loop on every form generated.

Performance-driven architectural design through computational elaboration did not showcase significant developments until recent years, in which we are witnessing a renewed interest. This interest in performance is strictly related to the current shift in design methodologies, enabled by the dissemination of computational strategies in design. As previously stated within this thesis, the current leading research field in architecture is very much science-based and such strong characterization involves multidisciplinarity to approach complex problems resulting in integrative and innovative solutions. The **complexity** considered here is multifaceted: it is **theoretical** because it moves the focus to innovative arguments and, therefore, it seeks for a new cultural interpretation of current transformation in design practice; it is **procedural** and methodological because not only the cultural vision needs to be reset but even the workflow needs to be re-established given the inclusion of advanced tools of evaluation, analysis, modeling, simulation; it is **scientific** because it brings architectural design to operate within science-based paradigms.

From an overview of current approaches in research-by-design and from the analysis of

Carpo, introduced in the previous paragraphs, who exposes how the information age is affecting data collection and manipulation for design, emerges the **tendency to explore, exploit and evaluate 'performance' as a core element of the design process**. This direction suggests science-based approaches for precise performance evaluations. The involvement of science and technology-based knowledge in a creative process requires to face the crossover between the 'expressionism' of the architect, typically based on a form-making approach, and a more objective paradigm driven by data and information leading to new design methodologies to control the form-generation processes guided by these variables. The scientific contents can be developed within a creative process 'optimizing' the result on a functional level, the optimized character is, then expressed through tectonics. Architectural design has a physical condition determined by the equilibrium of features that belong to different domains – structural layout, environmental stresses, material characteristics, etc. By embracing the deep understanding and full description of such domains – together or separately – one could optimize such physical condition by accurately working on these features looking for the best possible combinations of equilibrium (there could be more than one). Optimization is the improvement of a certain performance which responds to conditions established by the designer. To embrace this design direction new

Fig. 4.4 Interior view of the Multihalle that shows the quadrangular grid layout and the double layer.

methodologies are necessary to value the project performance over its mere appearance, these innovative procedures are described as 'performance-based design' or 'performative design'. Optimization in performance-based design involves a set of seminal concepts: **simulation**, achieved through digital or physical analysis in an informed model; **performance definition**, which depends on a range of selected factors and relates to the single project; **evaluative criteria**, which express the boundaries of the search of performance. These three 'steps' describe the general procedure of optimization in current design approaches, but each architectural project needs to be studied in depth and its specific features needs to be unfolded since constructions are always 'one of a kind' – differently from product design for instance – and thus customized solutions are always needed. Different strategies are used to approach performance-based design and they relate to different degree of complexity and domain of performance involved in the process.

Form-finding processes are among the strategies employable to achieve performance as they disregard a top-down approach of form-making while they rather pursue a bottom-up design procedure where certain characteristics of the projects emerge from its appearance. Form-finding is a performance-based procedure, usually oriented to structural

Fig. 4.5 Hanging chain models are often used as form-finding methods. The structure of many projects by Frei Otto are based on this approach and they find their scientific reference in the Hooke's Law.

optimization, it offers solutions for structural layouts according to relationships between form, material and force distribution analysis. The great precursors of form-finding, such as Otto and Isler, introduced integrative systems able to solve complex interrelations of factors in a structural-oriented design.

The **Multihalle of Mannheim** (Fig. 4.6), Germany, designed for the garden show of 1975, is one of the most emblematic construction of wood performance-based design available in recent history of architecture: a large-scale wood lattice arranged according to a form-found layout derived by Otto physical experiments. The garden exhibition *'Bundesgartenschau'*, horticultural German biennial show, was located in *Herzogenried Park,* represented for the history of Mannheim an important moment of growth and reconstruction after the heavy damages caused by World War II. Local architects and landscape architects were asked to submit proposals for the exhibitions, among these, the proposal of Carlfried Mutschler and Winfried Langner was considered the most interesting not only for the design concept but also because it proposed a low budget construction. Their concept was focused on a lightweight construction as a sort of hill harmonizing with the surrounding

Fig. 4.6 Mannheim Multihalle, roof engineered by Frei Otto in collaboration with Ted Happold and Ian Liddle (Ove Arup).

park and giving to the exhibition an identity associated with lightness of nature. They wanted to create this lightweight hill with an organic shape and they presented different solutions to achieve their aim, among these they proposed to suspend large umbrellas with helium balloons or stretched membranes, but it was rejected by the planning authorities. In the phase of research for a structural efficient solution, Frei Otto was introduced in the design team to manage the layout articulation of the big roof, imagined by Mutschler and Langner, and collaborated with engineers Ted Happold (founder of Buro Happold) and Ian Liddle of Ove Arup. Otto proposed a wood grid shell construction (Fig. 4.4) achieved using the hanging chain method as form finding procedure (Fig. 4.5) which, starting from a flat layout, allow to form a double curved layout. This structural strategy is addressed to as **'strained gridshell'** as the initial elements are flat and become strained during the erection because of the bending action of wood. The other strategy, more commonly used is the **'unstrained gridshell'** where the timber components are already curved before construction, therefore there no post-stress applied to the final structure. Strained gridshells offer the advantage to start from a flat grid layout, which makes the material production

Fig. 4.7 Wealt and Downland wood gridshell by Buro Happold and Edward Cullian Architects. The structural resistance relies on the post-tensioned timber grid, similar to the principles employed in the Multihalle

significantly cheaper, and to employ the post tension as structural reaction, therefore optimizing the material use and allowing wide spans compared to cross section thickness, but, on the other hand, they are not easy to erect and requires several scaffoldings. For the Mannheim Multihalle the overall structure occupies a space of 85x60 meters, the maximum span is 60x60m with a height of 20m and a final weight of 16kg/m. Hanging chain models were previously explored by the same Otto in other design experiments and even before by Gaudì, who based the design of Sagrada Familia on this procedure. The principle derives from Hooke's law of XVII century according to which a hanging chain which forms a catenary arch in tension can became an ideal arch in compression when inverted. Otto employed the same principle on a set of chains linked together that finally form a double curved surface. The grid model is initially flat, and its components are tied together through hinges which allows rotation so that once the grid will change configuration from flat to double curved it will allow the lattice distortion. The peculiar system of Mannheim Multihalle roof is a grid shell made up of four layers, consisting of a doubled basic orthogonal grid, because a simpler two layer structure layout would have not been stiff enough and, on the other hand, a thicker layer would have been heavier and too stiff to bend in the second phase. Therefore it was decided for a double grid of overlapping laths with a section of 5x5 cm, resulting in a total thickness of 20 cm. Another factor to consider was the construction process: after the grid is built on the flat, temporary scaffold towers are needed to lift the structure from below in its final position, the less stiff is the grid shell the more supports it will need in this phase, therefore this consideration was essential to provide local stiffening through tension cables. The four layers distribute the load to the outside perimeter beam of the shell and they work together with the cable system employed to improve the stiffness of the structure. The perimeter is complex and differentiated but it is mostly composed by a wooden board where the laths are bolted, and then connected to a concrete beam as main support. The attention for **connection details** (both in the internal joints and perimeter connections), the **structural performance** analyzed trough physical tests and the **elements layout** (four layered grid shell made with laths) compose the **material system as an integrative model** able to express a strong tectonic character. This project can be defined as **material-based design approach**, which coherently highlights structural system, alternative design methodology, material properties and architectural space definition. Similarly to this case-study, in the recent history of architecture we can find other examples of timber grid shells that explores analogous systems of strained gridshells (Fig. 4.7). In contemporary practice, enhanced by powerful digital tools for design and especially simulation, material-based design is being further explored in academic environment and tested through research by design approaches.

Otto and the other forerunners of structural form-finding were extremely innovative at their time, they explored unknown boundaries of structural design without the strong computational potential that we have today. The debate of architectural and urban design kept these pioneers as isolated expressionists who were pursuing something alternative to the post-modern mainstream diffused since the 70's. Nonetheless, their contribution is highly recognized, especially in contemporary research, and, somehow, they initiated a tradition of an alternative and explorative design methodology which today is being recalled gaining a new interest in research institutions. The re-introduction of alternative design methodologies with a focus on performance as design driving factor is also partly due to the emergence of sustainability in our contemporary context. In fact, the performance of a construction can be described through multiple domains, from financial, cultural, spatial, to the technical aspects of structure, thermal comfort, acoustic etc related with sustainability. The performative features can be simultaneously embraced through multidisciplinarity forming a networked design environment. The inclusion of such issues in the early design stages represent a dynamic integrative approach to design which does not address the problems to merely functional solutions but it aims to solve them through the

Fig. 4.8 Windcatchers are typical persians towers integrated in a construction to help the air flow circulation and favor a fresh environment during the hot summer. They are similar to many other structures used in arab vernacular architecture. These structures base their functioning on the architecture of the buiding itslf and their opening and orientation in related with local environmental most frequent conditions. They provide a model to solve a performative issue (refresh inner rooms) based on an integrative design solution.

architecture. To highlight these concepts Kolarevic affirms:

> “It is important to note that performance-based design should not be seen as simply a way of devising a set of practical solutions to set of largely practical problems, i.e. it should not be reduced to some kind of neo-functionalist approach to architecture. The emphasis shifts to the processes of form generation based on performative strategies of design that are grounded, at one end, in intangibilities such as cultural performance and, at the other, in quantifiable and qualifiable performative aspects of building design, such as structure, acoustic or environmental design. Determining the different performative aspects in a particular project and reconciling often conflicting performance goals in a creative and effective way are some of the key challenges in performance-based design.”[6]

We could identify a set of ‘cultural’ steps to describe the development and inclusion of performance in architecture considering on one hand the computational introduction of the topic by Maver in 1970 and, on the other, the methodological shift on form generation processes proposed by Otto around the same period. The technology-based approach remained somehow undeveloped within the architectural field because, possibly, computational design was not ready enough to embrace it, while the technical-procedural one manifested its interesting results through the years also thanks to well-known design firms,

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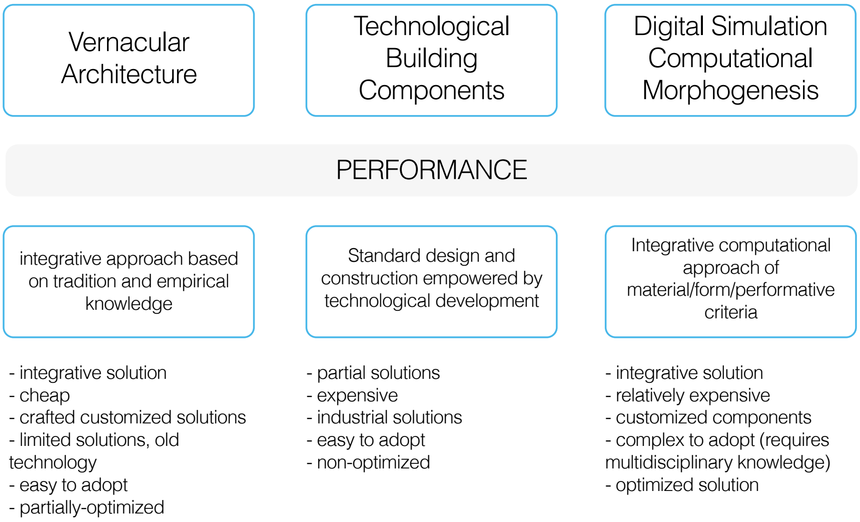
[6] Kolarevic B., *“Computing the performative”,* in Kolarevic B., and Malkawi A. M., “Performative Architectures: beyond instrumentality”, Spon press, New York and London, 2005

Performance in architectural development



and it sedimented a knowledge to be explored in the years to come. Subsequently, after the computerization was introduced in architecture, the decade approximately between 1995 and 2005 explored the digital simulation/evaluation of technical building performance reviving the computer-aided appraisal. Many projects developed during this period embraced the digital quantitative and qualitative definition of performance enhanced by the spread of advanced analytical techniques such as FEA (Finite Elements Analysis) and CFD (Computational Fluid Dynamics) which work on defined mesh-based geometries and therefore rely on a more user-friendly graphical output for evaluation. Today, the topic of performance matured after decades of explorations – which are still going on – and a balanced integration of both technological and procedural development are concurring in the definition of innovative design methodologies. The dissemination of digital fabrication tools, learning-machine procedures, introduction of new materials and improved knowledge of the existing materials, converge in the paradigm shift of architectural design and find their synthesis in a performance which is both technological and procedural. The recent research-by-design approaches of international research institutions showcase stunning developments in the combination of that technology-driven design firstly introduced by Maver in the 70's and the procedural revolution of alternative form-finding techniques which finds in Frei Otto one of its greatest precursors. The focus of these contemporary design methodologies is moved to the process, more specifically to a performance-driven process able to support material-based design solutions.

Vernacular architecture already faced performance-related design and making issues since the first human settlements in history. Much of the architectural knowledge on building performance is also derived from traditional construction (Fig. 4.8) coming from diverse cultures which developed in areas with specific environmental and cultural characteristics. Vernacular architecture gives contemporary architects empirical and successful models which can support a performance-oriented design. Nowadays many materials of the tradition and construction techniques are rarely used being substituted by industrial serial production of economic solution easy to find and build. Nonetheless within the framework of sustainability computational-aided design could find great inspiration in vernacular architecture as starting point, employing similar principles and improving the performance thanks to previous simulation. Moreover, the dissemination of robotic fabrication and assembly facilitates the use of non-standardized construction techniques giving the opportunity to explore and upgrade traditional details, assembly logics and spatial articulations for example. As Yuan affirmed[7], the regionalism, the cultural and traditional local values, can experience a renewed interest by integrating parametric-based design ad

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[7] Yuan P.F., "Parametric Regionalism" in "Parametricism 2.0: Rethinking architecture's agenda for the twenty-first century" AD issue 02/2016

digital fabrication techniques.

Performance in architecture is not a new concept introduced in the latest years, many factors determined its role in design throughout the decades, think about industrial production of building components, political interests in construction field, or emergence of sustainability issues and favorable technological development. Due to these factors the general approaches to the topic have experienced ups and downs and adapted to partial and localized solutions losing the vision of an integrative coherent system as reported by vernacular architecture. Based on what have been described so far, we could do some observations by retracing a general cultural evolution of the performance 'niche' in architectural design through a rapid historical overlook. At first vernacular architecture produced, for long time, prototypes of integrative performance-based empirical solutions which became part of a tradition. The tradition developed over the centuries losing its performance-oriented nature and keeping the technical feasibility and construction speed. Eventually this transformation moved the focus to economical profit because of the rapid urbanization processes. Then the emergence of sustainability brought back the discourse of building performance, based on environmental and comfort issues, which have been mostly achieved through partial high-tech expensive solutions. Today, the general trend is slowly changing, and both scientific research and an on-going cultural shift are setting the bases for the future of performance-oriented integrative design approaches. Therefore, we could recognize three peak phases where the theme of performance is present in the design approach: the **vernacular architecture**; a **technology-aided architecture** developed from about the '90s till today with the improvements of technological building components; the **computational architecture** introduced about ten years ago and still under development, based on powerful digital tools for analysis and simulation. The thesis will focus on the third phase showcasing the contribution of current research approaches in performance-oriented architecture with a particular focus on material-oriented solutions of wood experimental architecture.

4.2. Material Information in Performance-Based Design of Wood Architecture

Material and environment behavior as performative feature

> "Material constraints do not have to be understood as limitations to the design, but rather as a set of rules complementary to the geometric constraints defined by architectural intention. Form and material work hand in hand to process various load conditions; deformation of form and the distribution of material are reciprocal methods of design that help to 'digest' the flow of forces imposed upon the architecture. Freedom of design arises from the balancing of these two principles."[8]

Materials are defined by their specific physical and chemical properties described by their internal microstructural composition, the relationship with the environment, their behavior under certain conditions. Some materials present relatively constant properties some others may change because of their interaction with independent variables. Steel, for instance, experiences dimensional variations in relationship with thermal variations of the environment. Other materials, like wood, change their behavior in different hygroscopic conditions. On the other hand, materials can absorb or reflect thermal energy or moisture, thus even the environment can be affected by the reaction of certain materials creating, for instance, micro-climatic conditions which could be advantageous factors in some cases. This explicit knowledge of materials' diverse behavior under specific conditions and of their innate properties can be an interesting input for more detailed studies that could help to exploit such characteristics as performative issues. An understanding and awareness of material properties is not enough, it is necessary to actively employ their potential in order to enable performative capacities. Performance aims to efficiency and, as previously described, the efficiency seeked could belong to different domains (structural, environmental, thermal, acoustic etc.) and materials can affect the reaching of such efficiency. It is then necessary an active exploration of the full potential of material properties to reach performative criteria; architectural research, in this sense, supported by interdisciplinarity, prospects answers for future developments even through experimental – most of times temporary – designs.

The variable properties of materials offer new explorative path for performance-based design, or material-based design to be more specific, but, on the other hand they find relevant obstacles in current construction practice. The standardization of industrial production and the construction codes, within the various countries, are not ready yet to embrace this direction. There are tight tolerances to respect in building industry and, in general, a de-

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[8] Kotnik T., Weinstock M., "Material, form and force" in AD 02/2012

clared variable material behavior is considered as a negative characteristic. Architects tend to avoid the employment of such materials properties or to neutralize their effects, also because the tests for the analysis of divergences due to material behavior are often expensive, therefore this realm remain framed in research institutions. Michael Hensel[9] illustrates the potential of material behavior through an interesting overview which consolidates the position of contemporary research in this field of architecture. Hensel focuses on wood[10] as one of the few organic materials employed in architectural construction, and as such it showcases a series of variable characteristics. There is a new growing interest in the employment of wood today in architecture but **some of the essential characteristic of wood are often considered undesirable**, its material differentiation conflicts with the standardization of current production logic, therefore it is processed in such a way – lamination for instance – that the imperfections become irrelevant. Hensel proposes an alternative approach to look at this material, starting to observe the reasons why wood comes to be this way. Scientific researches[11] give evidences that the structural arrangement of wood is related with the environmental conditions in which the plant has grown, other than the essence intrinsic properties obviously. **Environmental conditions could bring to two major considerations**: first, they have an impact on the material structure differentiation during the growth phase; and second, after the harvest when the wood is employed in a construction, there is a two-way exchange between the wood and the environment it is placed in. Based on these observations, Hensel assumes that the variables that concur to material differentiation in wood could be, by some extend, designed or programed, and in doing so even the behavior can be way more predictable; this would completely change the current supply and demand chain. At Oslo School of Architecture and Design, "Holistic and Integrated Wood Research" was proposed as a research frame of a possible *scenario* of future wood production for a performance-oriented approach in architecture.

> "This involves the detailed mapping of related existing research and of the sustainability aspects involved across the supply and demand chain. As industrial forestry is under increasing pressure to emphasise biodiversity instead of monoculture and architects seek a much broader range of available wood species and products, a promising match of interests emerges. However, the question arises as to how to reposition the intermediary parts of the wood industry

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[9] German architect and researcher, he is currently professor of Architecture at the AHO, Oslo School of Architecture and Design. Hensel is founder of the EmTech (Emergent Technologies and Design Program) at the AA London together with Achim Menges and Michael Weinstock.

[10] Hensel M., *"Performance-Oriented Architecture. Rethinking Architectural Design and the Built Environment"*, John Wiley & Sons, 2013

[11] As cited by Hensel. Schweingruber F.H., *"Wood Structure and Environment"*, Springer, Berlin; Heidelberg; New York, 2007;

> such as wood sorting, treatment and machining. Likewise, policy makers will need to rethink the role and extent of existing and future standards and tolerances in material behaviour. This can only be accomplished in a concerted effort that involves all stakeholders. Moreover, such efforts need to engage knowledge and skills of traditional wood craftsmanship, scientific knowledge of wood properties and behaviour and a related detailed logic of wood sorting, storage, tooling and fabrication. Any change in the way wood properties and behaviour may be used will involve the consideration of different timelines. Clearly the change of the forestry industry from an emphasis on monocultures of spruce and pine to one focused on biodiversity will require decades, even centuries. Changes in tooling and machining will take a number of years. The enhancement of awareness through research-by-design experimentation can, however, commence with immediate effect and may need to focus on two aspects: firstly, the development of reliable data; and secondly, the production of intellectual tools and sensibilities in education to provide architects and craftsmen with the required knowledge and skills."[12]

Although utopian and perhaps excessively optimistic, the vision proposed can still have repercussion in the current practice since it contributes to culturally enlarge the operative landscape of material performance-based design. This approach is gaining interest in research and, in few isolated cases also in practice. Several factors still make difficult the dissemination in construction industry, among which the uncertainty encountered by possible investors in the employment of such strategies, and, above all, codes and regulations which tend to be reluctant in the adoption of alternative progressive solutions.

Evolution of wood processing technologies and tools

Wood is a deep-rooted material in the architectural culture, as for centuries – till the XVIII century – it was the most employed material for buildings, therefore humans learned throughout history the use and exploitation of its potential. Wood is the only natural material still employed in building construction – other natural materials, such as stones and marbles, are used for different aims and, most important, they are not renewable – and **during the preindustrial time the heterogeneity of its structure was accepted and utilized** as such through hand craft working techniques. These fabrication techniques allowed to cut and bend the tree trunks coherently with grain direction, therefore the manual crafting of wood was in close relationship with the material anisotropic characteristics. Industrialization then changed a lot of this paradigm by introducing new artificial – man-processed – materials as steel, glass, concrete and making more uniform and homogeneous the structure of wood. Today the dissemination of digital technologies

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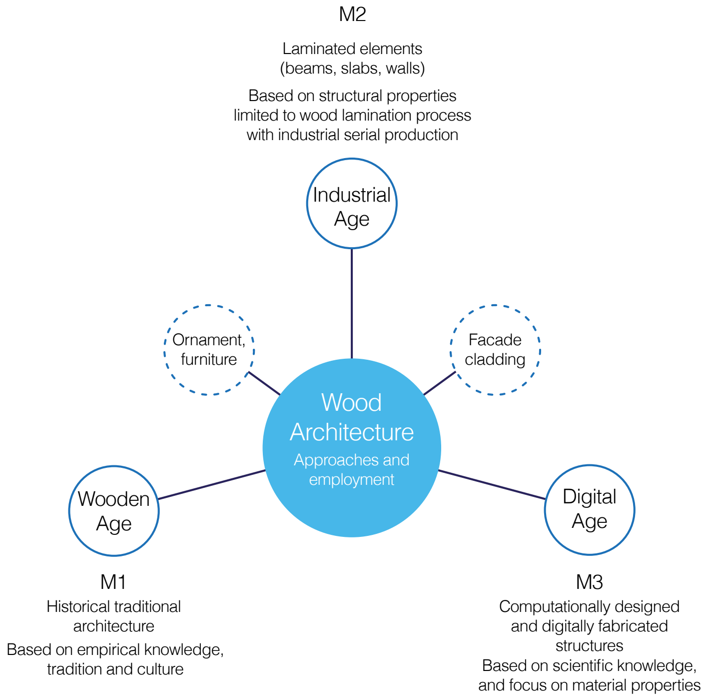
[12] Hensel M., *"Performance-Oriented Architecture. Rethinking Architectural Design and the Built Environment"*, John Wiley & Sons, 2013

opened new possibilities for a material-based design that were lost in the last centuries of industrial serial production. These technological aids substantially generated **two main approaches to wood elaboration for architecture**: one works with the specific intrinsic properties and anatomy of the plant as form-defining element exploiting directionality, anisotropy and heterogeneity and reflecting this in the construction logic and tectonic articulation; the other approach focus on the homogenization of the material, to have a more predictable behavior, faster or industrialized joining solutions, transforming the wood in a more generic material but still maintaining some of its advantages. Interesting to note that the industrial processes of reorganization and reassembly of wood brought an evident transition from the production of **'linear elements'** such as beams and columns to **'planar elements'** such as fiber-boards, cross-laminated timber, plywood. These planar elements expanded the strategical construction possibilities beyond grid structures toward plate and surface structure offering multiple choices for architectural construction. On the other hand, the digital innovation is bringing an updated revival of the craft techniques. Current industrial processing of wood is already employing advanced tools, such as tomography, to analyze the trunk structure and algorithmically derive the best way to

Evolution of wood methodology processing in architecture



cut it for maximum profit[13]. Based on this kind of information, designers and architects can choose wood-design strategies offered both by computational approaches, that aims to employ wood properties as a generative factor, or the industrial fabrication of timber elements. Both directions are interesting, and not mutually exclusive, as can be seen from the case-studies presented in the further sections. Yet on the employment of wood as a high-tech and sustainable material for the future architecture Menges affirms:

> "Why should one relate an innovative computational design approach to what initially appears as a fairly archaic building material? In the light of the environmental challenges the building sector is facing, wood is no longer disregarded as outmoded, somewhat nostalgic and rooted in the past, but increasingly understood as one of the most promising building materials for the future. Indeed, there are hardly any other materials that can rival wood's environmental virtues. Wood grows as the biological tissue of trees. This process is mainly powered by solar energy during photosynthesis, which also transforms carbon dioxide into oxygen. Thus, wood holds a very low level of embodied energy together with a positive carbon footprint [...] For example, the production of a panel of a given compressive strength in wood requires 500 times less energy than in steel. Thus wood is one of the very few highly energy-effi cient, naturally renewable and fully recyclable building materials we currently have at our disposal." [14]

Since this research focus on technological evolution and its relative impact on design method, and fabrication of wood architecture, it is useful to retrace a chronological evolution of processing technology and tools. Innovations are introduced in architectural design through technological revolutions, happened in particular historical context, and expands the design possibilities. In architectural terms the transposition of the technique in the art of making is defined as 'tectonics'; the term is particularly referred to wood since the origin of the word become from ancient greek *tektòn*, which means master builder or carpenter. It is possible to **relate technological developments to fundamental moments of changing in wood construction**. Buri and Weinand[15] identify two important moments of radical transition in the evolution of technological tools employed in wood architecture. The first is the transition **from hand-tool technology to machine-tool technology.** The second

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[13] Menges A., Schwinn T., Krieg O. D., *"Advancing wood architecture: an introduction"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

[14] Menges A., "Material resourcefulness. Activating material information in computational design", AD 02/2012

[15] Buri H. U., Weinand Y., *"The tectonics of timber architecture in the digital age"* in Kaufmann H., Nerdinger W., (editors) *"Building with Timber Paths into the Future"* (ISBN: 978-3-7913-5181-0), p. 56-63 Munich, Germany: Prestel Verlag, 2011

is the transformation of the **subjects involved in the fabrication processes**: due to the increasing specialization the traditional carpenter is superseded by interdisciplinary highly-specialized teams to accomplish a more complex and optimized design. Together with the technological improvements even the design methodology changed, from the plan and elevation as descriptive geometry language, to parametric informed 3D model that no longer simply defined the geometry but contains a number of invisible data that can be recalled at any time needed. Therefore, these transitions separate three technological phases[16] in wood construction that reflects different technical approaches, design strategies and, thus, tectonic character. The wooden age (hand-tool technology), the industrial age (machine-tool technology), and the digital age (information-tool technology).

In what is identified as **wooden age**, tectonic character was very evident, there were some established empirical rules on building construction, based on proportion more than absolute units and general layout to follow. The details (joints for instance) were different expressions of local tradition, moreover there was not the culture of descriptive drawings and the builder directly draw the plan on site in scale 1:1. The **industrial age** was strongly characterized by production rationalization. The primary task was a serial production of large quantities, consequently this required standardization, a shift away from individual adapted components. Standardization in wood processing also required homogenization of irregular internal structure of the material, hence the tools helped the manipulation of the material, as lamination for instance, introducing planar plywood opening new possibilities of employment. The carpenter become mostly a mere executor and technical planning is directed by engineers and architects, therefore the group of involved subjects is expanded and there is a higher specialization both on design and construction stages. Tectonics in this phase is less present, the constructive systems start to be uniformed to modular components. The planar elements were at first employed as planking or for bracing of linear frame structure; later, when the production of such elements became easier and with less restriction in dimensions, they started to be used as primary structure while the linear element used for bracing. Therefore, planar elements gain more interest in building industry and are developed accurately providing various possibilities. Moreover, the tectonics is no more determined by the art of connection of linear elements and new tectonic principles are explored through the employment of planar elements. The third stage of this tool-development process is represented by the contemporary **digital age**

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[16] The following taxonomy and comment is based on Buri H. U., Weinand Y., *"The tectonics of timber architecture in the digital age"* in Kaufmann H., Nerdinger W., (editors) *"Building with Timber Paths into the Future"* (ISBN: 978-3-7913-5181-0), p. 56-63 Munich, Germany: Prestel Verlag, 2011

which is bearing significant innovations for further future strategies in wood constructions unfolding the full potentiality of this natural material. The digital age experiences some opposite trends compared to the industrial age, in fact there is a growing **call for customization** fostered by two principal factors: the possibility to electronically control the wood processing tools (robots and CNCs) and the employment of parametric design tools that allow to manage complex interrelations of multiple factors and improve the workflow. The machines become more complete, equipped with multi axis arms able to freely move in space, like a human arm but with electronically controlled precision, and the possibility of changing tool-head on the same machine within the same workspace (not necessarily a chain). This required further specialization and multidisciplinarity in wood processing industry as well as in design and fabrication. At the same time wood, an old traditional material, gains the properties of a high-tech material upgraded by scientific innovation. If in the wooden age the design and crafting skills were mostly absolved by the craftsman as single subject, today, in the digital age, the same skills are divided among different specialist (designer, technical support, structural engineer, informatic and electronic engineer, material experts etc.) making necessary an accurate planning and coordination of the involved subjects at the different stages. Furthermore, planning today can be rationalized by informing the process (a digital one) with data and information about the material and inserting them into a parameter-based model which works as a powerful interface and seemingly links design and fabrication phases. This become one of the **primary characteristics of the digital age:** the inclusion of fabrication, production, design, analysis, assembly as a continuous workflow.

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Design methodologies in material performance-based wood architecture

Contents

5. Design Methodologies in Material Performance-Based Wood Architecture

Differently from other materials, timber represent a particular case in which robotics and computation fostered a radical technological reorientation, started around 1980s, improving the industrial production and expanding design possibilities. Together with the development of high-quality timber elements for construction industry, the transformation towards the digital technologies brought a considerable increase in flexibility and manufacturing productivity. Research, beyond the industrial logic of profit, started around the 90s' to contribute in the construction of a scientific, technological, and cultural background as a reference for the exploration of digital tools and technologies which employ timber as building material. Many Universities set up robotic research facilities and started a path of **research-by-design** or empirical research for non-standard timber construction and expanded the design and fabrication possibilities offered by this material. In the framework of this thesis the main strategies which explores the advancements of research in wood architecture have been identified with a specific focus on material performance:

- **methodology of morphogenetic design and biomimetic approach**, showcases performative features from biological models both on the formation process and on form itself other than deeply integrating material system in the complex design workflow;

- **methodology of robotic timber construction**, develops integrative automated construction process through the assembly of simple timber components guided by an informed and informing digital blueprint;

- **methodology of custom robotic timber fabrication**, shortens the gap between research and practice, employing alternative material fabrication techniques for full scale construction;

- **methodology of timber folded plates**, experiments the structural potential of timber plates creating active surfaces without any additional fastening than interlocking joints;

- **methodology of robotic raw wood**, proposes the use of timber components employing their natural forms as they are.

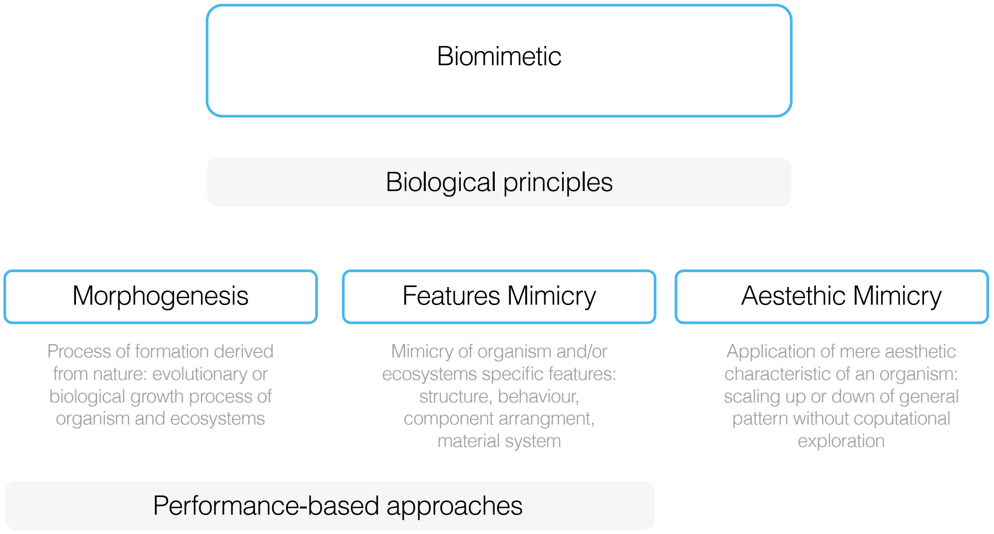
All the exposed methodologies have a focus on specific aspects of material performance: from fibers arrangement, to the working flexibility of wood till its applications as a non-processed material. The identified approaches are presented through the analysis of case-studies which have been realized within the last ten years.

5.1. Methodology of morphogenetic design

Performance through Biomimetic

Nature can provide references and inspirations for the design of performative structures and for the employment of innovative form generation strategies in architecture. Biomimetic – the study of natural structures, and of the properties, characteristics and behaviors of natural organisms or ecosystems that could be transferred and inspire other fields of science and research – has emerged in the latest years as a research direction in architectural design. It is a strategy of performance-based design, as it seeks inspiration in nature not for a mere aesthetic result but for a specific performance, it is articulated in different directions in its application on design disciplines. Based on the information gained on this topic through bibliographic research, the thesis proposes a macro classification of the approaches that showcase natural references, as a general subdivision of the possible research and design directions to clarify the term 'biomimetic' (Fig. 5.1). Biomimetic can be considered as a strategy inspired by nature which is reflected in design through: mimicry of the processes or morphogenesis, mimicry of organism or ecosystem features, mimicry of aesthetic and merely formal aspects. While this last category is the least interesting for the aims of this thesis, the other two share the seek of performance in design in

Fig. 5.1 Application of biomimetic approach in architectural design and research. The morphogenesis and the mimicry of organism features can be applied in an integrative way or can be separated. While the third identified mimicry of the aesthetic is not functional to the aims of performance-based design



two different but interconnected ways. Morphogenesis reproduces the form generation process of architectural structures by transferring principles of evolution and biological growth of organisms. Morphogenesis does not necessarily include the mimicry of some specific features of an organism – such as bones structure, articulations, behavior under certain environmental conditions, components' shape, material composition, etc. – of a natural organism – animal or plant indifferently. These two directions can be distinct or can be taken together by applying both growth or evolutionary principles and organism performative features. The choice of a reference organism, the mimicry of its performative features, could be a further – optional – step in the morphogenetic process, or it could be a separated approach.

It is useful to understand the biological principles that generally lead a biomimetic approach and to provide the basis for reading the performative features of an organism, other than giving some definitions and classifications. **Biomimetic**, from a biological perspective, can be structured in three distinct levels[1] according to the following taxonomy[2]: **organism, behavior and ecosystem**. The 'organism' refers to a specific animal or plant, the mimicry can regard a part or a whole of the such organism. The 'behavior' level refers to how an organism interacts with its context. The 'ecosystem' level aims to transfer on design the properties of ecosystems where a set of general principles enable them to function successfully. The analogy of such levels can be respectively translated in meanings, properties and **rules in a computational model**. Moreover, these levels are a sort of ascending scales of the studied entity: from the cellular growth principles, to the anatomical properties and structural behavior till the micro and macro-environmental characteristics of the context in which the organism develops. These levels can be employed in architecture not necessarily at the corresponding scale: they can find **applications from the microstructure of a material or its assembly principles, to urban planning strategies**.

The ecosystem is considered the highest level, it showcases a global complexity which affects behavioral and organism levels, therefore it is worth to illustrate a set of characteristics that have been extracted from multidisciplinary analysis, according to which ecosystems:[3]

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[1] On this argument see El Ahmar S., Fioravanti A., Hanafi M., *"A Methodology for Computational Architectural Design based on Biological Principles"* Computation and Performance - Proceedings of the 31st eCAADe Conference, Volume 1, Edited by Rudi Stouffs and Sevil Sariyildiz. eCAADe: Conferences. Delft, The Netherlands: Delft University of Technology, 2013.

[2] Zari M.P., *"Biomimetic Approaches to Architectural Design for Increased Sustainability"* in Sustainable Building Conference, Auckland, 2007.

[3] Zari M.P. and Storey J.B. *"An ecosystem-based biomimetic theory for a regenerative built environment"* in Sustainable Building Conference 07, Lisbon, 2007.

- are real-time dependent on sunlight;
- optimize the system rather than its components;
- are attuned to and dependent on local conditions and situations;
- are diverse in components, relationships and information;
- create conditions favorable to sustained life;
- adapt and evolve at different levels and at different rates.

This generalization and abstraction of ecosystems principles represents a possible set of tools for the designer willing to adopt a biomimetic-based design methodology, aimed to focus on performative features which requires a deeper study of one or more specific properties of the ecosystem (structural, thermal, acoustic etc.). A combination of all these principles in a single architectural project can be complex to achieve, but experimental projects by international research institutes demonstrate the possibility to efficiently employ some of them in architectural design, applicable, for instance, in the study of lightweight self-supporting structures. The ICD of Stuttgart, one of the most emblematic institution in computational design in this moment, it is strongly focused on such kind of explorative approach together with biologists teams, working with highly multidisciplinary teams.

The classification of the above mentioned biological principles have been further unfolded[4] as: adaptation, material system, evolution and growth, form and behavior, emergence.

Adaptation. It is a basic characteristic for organisms and ecological system to survive and sustain life. Adaptation is essential both in evolutionary process (long time span) and in the biological growth process. Organisms adapt and respond to environmental changes and conditions. Adaptation in design could be a static feature, achieved during the design phase as a durable condition (openings according to sun exposure or wind for instance), or a dynamic one achieved through responsive components (movable devices electronically and/or environmentally controlled).

Material System. Ecosystems and organisms optimize material distribution, form and energy employment acting globally in the entire system rather than in the individual component. Material system synthetizes this capacity of natural organism to optimize the material organization in a global system affected by external and internal forces distribution,

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[4] El Ahmar S., Fioravanti A., Hanafi M., "A Methodology for Computational Architectural Design based on Biological Principles" Computation and Performance - Proceedings of the 31st eCAADe Conference, Volume 1, Edited by Rudi Stouffs and Sevil Sariyildiz. eCAADe: Conferences. Delft, The Netherlands: Delft University of Technology, 2013.

required resources, functions, form etc. In architecture it is reflected in the description of the complex interrelation between material, form, structure and space.

Evolution and growth. Evolutionary processes are the principal tool of adaptation of organisms and ecosystems in nature. Through evolution the performative features of an organism emerge in relation with the environment in which it develops. Simulating the genetic code and transferring its rules and process in design, architects could generate forms that 'evolve' in relation to the desired criteria.

Form and behavior. Forms in nature are related to function and behavior. The form of an organism affects his behavior in the environment, different environmental conditions which requires different behaviors can reflect different form. In architecture the relation form-function is a cultural position, here the function is intended as the performative feature which is supposed to describe or 'inform' a certain morphology, therefore is more appropriate to use the term 'behavior'.

Emergence. Emergence is the complex behavior of natural structure which cannot be described through linear relations. It is the characteristic of a system which cannot be derived by looking at its single components. The performance of a natural organism emerges from the complex interrelation of form material and structure and its properties cannot be derived by the properties of any of them alone.

Morphogenesis: evolutionary and growth design strategies

Morphogenesis as an experimental field of study in architectural design exploits the potential to innovate the form generation process and to give a stronger meaning and coherence of technology employment in design. The difference with the traditional approach lies in **the emphasis of form-finding over form-making**. Once again, Gothic vs Romanesque. Many pioneers in the expressionist period of the '70s and '80s already set an explorative path of this technique, Frei Otto, for instance, established an innovative design methodology through the analysis of analog models. Many studies conducted by Otto tested the behavior of structures generated following material properties and geometrical principles. Otto also introduced the relevance of natural structures for architectural design, his soap films experiments gave a glimpse of the natural morphogenetic process based on saving resources and improving of structural efficiency of the employed material. A deeper implication of such progressive approaches proposed by Otto – and others like Heinz Isler or Gaudì etc. – is the essential integration of the design process from conception to materialization. This manifests a reverse trend after centuries of consolidation of a different mindset and methodology; since the Renaissance, in fact, we witnessed an increasing separation between process of design and making[5], and it is what most of the designers and architects still do. In morphogenesis the process is not just one way to achieve the result, but it is an active part of the design, the process needs to be designed and deeply understood to deliver a set of successful outputs.

In the contemporary context, influenced by the continuous exchange of digital data and information and by the need of being efficient in every aspect, we could frame the focus on **'formation processes'** as a concept strongly linked with two other essential definitions: **'information'** and **'performance'**, both enhanced by powerful available computational tools. The information introduced in the process is determined by performative principles derived from previous analysis and/or considerations set by the designer and actively concur in the definition of a project. In other words, *'form' must be 'informed' by considerations of 'performative' principles to subscribe to a logic of material 'formation*[6]. The logic of morphogenesis could also be related to ethical themes such as material and resources saving. If we can design forms that are optimized according to structural principles or that are efficient in energy consumption, then we can use less material and reduce the amount of used resources. In a global scale this vision can have a significant impact on material and resource savings, on the other hand this employment of technology in architectural design is still highly expensive, very experimental and it is not suitable for the traditional (old), but still very much diffused, industrial logic of serial production. To this regard, the ongoing revolution of 'Industry 4.0' is contributing in the generation of an innovative framework for design and construction.

It is fundamental, for the aims of this research, to understand morphogenesis in design, as it is a scientific concept of 'formation process' and supports the performance-based design strategy through inspiration by natural organism and ecosystems. Achim Menges, Michael Hensel and Michael Weinstock[7] wrote – together and separately – several articles on the topic of morphogenesis in architecture, therefore these publications offer an essential bibliography, which has been taken as reference, to discuss the topic in the framework of this thesis. **Morphogenesis unfolds morphological complexity and performative capacity without separating materialization and formation process.** It is an integral process of the complex interrelation between form, material and structure. This should not be mis-

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[5] Menges A. *"Material Systems, Computational Morphogenesis and Performative Capacity"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

[6] Leach N. *"Digital Morphogenesis"* AD Volume 79, 01/2009

[7] Achim Menges, Michael Hensel and Michael Weinstock are founder of the EmTech master at AA London and founder members of the Emergent Technologies and Design Group.

understood with material simulation, as many software allow to understand the structural behavior of a certain form based on explicit material characteristic expressed by numerical variables. Therefore, it is useful to make a distinction between material simulation and the design-oriented research which characterizes computational morphogenesis. Material simulation requires to set all the variables at the beginning of the process, the morphology and the material are established *a priori* and independently – or not necessarily interrelated – and then perform the analysis and simulation of the behavior; on the other hand, the computational morphogenesis allows for integral exploration and bring to unexpected results but at the same time it respects the material-structure-morphology interrelation. Computational morphogenesis methodology is consistently influenced by the material system. **Material system** does not refer here to the material components of a construction, but it describes, in a system-theoretical sense, the complex **reciprocity between materiality, form, structure and space**, the related production and assembly process, the performative effects that emerge from the interaction with the environment in terms of forces, temperatures, etc.[8] Such system is very complex to elaborate but when carefully managed it delivers revolutionary and progressive outcomes. By this regard computational potential is essential in the resolution of all the variables and reciprocity involved. The computational process consist of an algorithm were all the information are fed and it allows to evaluate and explore the system's performative capacity within the limits of material properties. The formation process is continually informed through an iterative feedback loop with the data derived from material system interaction with statics, thermodynamics, lightning etc. The designer does not merely define the shape, but rather he works on the behavior of the entire system, therefore **a tectonic coherence emerges since all the components are designed and fabricated according to an integral logic**.

Morphogenesis means, in general, 'formation process' or 'form generation' but specifically it finds great inspiration in natural processes of form generation, given nature's peculiar performative capacity of arranging material and structure in coherence with its environment. Regarding the growing interest in natural organism which is recently spreading in architecture and engineering Weinstock says:

> "The current widespread fascination with nature is a reflection of the availability of new modes of imaging the interior structures of plants and animals, of electron-microscopy of the intricate and very small, together with the mathematics of biological processes. New working methods of architectural design and production are rapidly spreading through architectural

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[8] Menges A. *"Material Systems, Computational Morphogenesis and Performative Capacity"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

> and engineering practices, as they have already devised the world of manufacturing and construction. The material practices of contemporary architecture cannot be separated from this paradigm shift in the context within which architecture is conceived and made. The study of natural systems suggests the means of conceiving and producing architecture that is more strongly correlated to material organizations and systems in the natural world.
>
> Computational form-generation processes are based on 'genetic engines' that are derived from the mathematical equivalent of the Darwinian model of evolution, and from the biological science of evolutionary development that combines processes of embryological growth and evolutionary development of the species. Evolutionary computation offers the potential for relating pattern and process, form and behavior, with spatial and cultural parameters. Evolutionary computational strategies for morphogenesis have the potential to be combined with advanced structural and material simulations of behavior under stresses and gravity load. This approach is part of the contemporary reconfiguration of the understanding of 'nature', a change from metaphor to model, from 'nature, as a source of shapes to be copied to 'nature' as a series of interrelated dynamic processes that can be simulated and adapted for the design and production of architecture" [9]

Concepts of **evolutionary science** are then unfolded and taken as reference models for architectural form generation. A strategy is to build a computational model and inform it with variables derived from environmental conditions and design needs to achieve the required performative capacity. A loop of generations is created where every individual is re-iterated in the system with the same (or adjusted) variables. The computational system randomly acts within a range of parameters – often even in contrast among each other – the 'fittest' individuals – individuals that best fit the performative criteria – are reiterated in the process to achieve the best possible performative configuration. To adopt these developmental strategies derived by nature in architectural design it is necessary to understand the basics of two processes distinct but strictly linked. As Weinstock affirm *"every living form emerges from two strongly coupled processes, operating over maximally different time spans: the rapid process of embryological development from a single cell to an adult form, and the long slow process of the evolution of diverse species of forms over multiple generations. Fossil evidence suggests that the history of biological evolution is a sequence from simple cell organism to the higher complexity of plants and animals"*[10]. The derivation of biological evolutive and developmental principles of nature is a complex subject with more than a century of explorations – from Darwin to all his successors – but, for the aims of this thesis, it is sufficient to have a

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[9] Weinstock M. *"Evolution and computation"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

[10] Weinstock M. *"Evolution and computation"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

general awareness of the topic and understand the mechanism of evolutionary and growth principles in computational design. **Evolutionary algorithms are iterative processes** that follows simplified and abstracted logic derived from biology and history of evolution, and they have been frequently used in various disciplines to solve non-linear problems. The process can be roughly summarized as follows:

- the initial phase is the construction of the information or **'genome'** of the form which includes the mechanisms of selection, reproduction and mutation;

- then a random population of forms initiate the process;

- among them the 'fittest' individuals, the individuals that best match the design criteria, are re-introduced in the process an produce a 'fitter' form then the previous, and so on.

Evolutionary process allows the exploration of design space and the related development of system's performative capacity. Evolutionary computation, similarly to algorithmic growth simulation, **implements the generative process** exploiting the evolutionary mechanisms of combination, reproduction and mutation through a genetic algorithm and related selection criteria. The continuous differentiation of the system and its elements is driven by a random search of form – as nature does – in combination with fitness evaluation – on the phenotypes – after each generation. The selection and description of fitness criteria, variables and environmental conditions is not only reached through computational means, but also through tests on physical models, which are often determining in the system's definition.

According to Weinstock, the use of evolutionary algorithms in architectural design has been quite limited, and, moreover, algorithms that combines both principles of biological growth and evolution over multiple generations of forms, have not yet been successfully reproduced. Hence, concepts derived from developmental biology of 'genotype' and 'phenotype' are taken as scientific reference to manage the complex and articulated system. The **'genotype'** constitutes the invariable **genetic information**, while the **'phenotype'** is the **individual form emerged** from the interaction of the genotype with the environment in which the development happens. From a genotype several phenotypic variations can come out, as to say from a genetic code several forms can emerge, characterized by some differences but recognizable in their global aspects; this differentiation of various forms derived from a genetic determination is referred to as **'phenotypic plasticity'**. With other words this plasticity is also referred to as 'morphospace', which is a tridimensional description of the possible shapes that can emerge. The application of these concepts in architecture makes possible a computationally driven form generation which leads to unexpected results and where the designer establishes variables and boundary conditions.

There are basically two employable computational strategies based on evolution and growth to achieve these results: **ontogenetic growth** process of individual systems[11] and **evolutionary development** of system's populations through several generations, both are considered in the computational morphogenesis. Such evolutionary or growth process are algorithmically simulated, taking inspiration from existing natural processes, and their technical implementation can vary depending on system type and design strategy. A common aspect, in both strategies, is the proliferation of elements across several growth steps where each element is regenerated. In the iterative cycle each element or component morphologically adapt by calibrating its local performance in relation to the overall system.

Characterizing of morphogenesis is the **integrative differentiation**[12] of elements and components of a system. Many times, we see **'patterns'** where their components are different one from the other, but they are integrated in the global system: in the framework of this research field, the differentiation is aimed to satisfy performative requirements, therefore **the components are informed about the local conditions of the system** and their dependencies with the surrounding components. To be more precise we could say that in computational morphogenesis the definition of a genotype is manifested in **a performative phenotypic material system which is achieved through integrative differentiation** of its elements driven by multiple performative requirements. This **performative phenotypic components** are driven by feedbacks obtained through simulation and analysis tools. In the definition of components even their relations need to be set in the model. Often, in computational design, the relation of components is expressed through topological exactitude rather than metric precision. In other words, the material system's dependencies of component assembly are expressed through the topological relations[13] of

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[11] "*Ontogeny (also ontogenesis or morphogenesis) is the origination and development of an organism, usually from the time of fertilization of the egg to the organism's mature form—although the term can be used to refer to the study of the entirety of an organism's lifespan. Ontogeny is the developmental history of an organism within its own lifetime, as distinct from phylogeny, which refers to the evolutionary history of a species. In practice, writers on evolution often speak of species as "developing" traits or characteristics. This can be misleading. While developmental (i.e., ontogenetic) processes can influence subsequent evolutionary (e.g., phylogenetic) processes (see evolutionary developmental biology), individual organisms develop (ontogeny), while species evolve (phylogeny)".* Wikipedia accessed April 2018

[12] On this argument see Menges A. *"Material Systems, Computational Morphogenesis and Performative Capacity"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

[13] "*Topology is concerned with the properties of space that are preserved under continuous deformations, such as stretching, crumpling and bending, but not tearing or gluing. This can be studied by considering a collection of subsets, called open sets, that satisfy certain properties, turning the given set into what is known as a topological*

proximity and contiguity of its elements rather than the Euclidean metric definitions of length, area and angle. In fact, in Euclidean geometry the relation between elements is expressed through fixed length, distance etc., that defines how far are the elements one from the other. While in topological space the distance expressed in length cannot define the dependencies or proximities because the length does not remain fixed. These relationships among components and their integrative differentiation is achieved through advanced behavior simulations.

It is worth to mention that within a morphogenetic design environment the analytical tools and strategies change based on the specific need of the project, among them a powerful tool is multi-physics computer fluid dynamics (CFD) for the investigation of thermodynamic relations, light and acoustic analysis. Although CFD is a very advanced tool it can only provide a general and partial insight since thermodynamic is far more complex due to several environmental interactions of fluids, extremely difficult to fully reproduce and simulate in the computer. Here lies another key-point in the application of this approach in architectural design, as the prediction of precise data derived from the exploitation of such powerful tools is not the primary task, while it is more interesting to **determine and recognize the behavioral tendencies and patterns formation**.

Methodology of Morphogenetic Design and Biomimetic Approach

Through a case-study analysis the methodology of morphogenesis and biomimetic is here unfolded and described. Although the focus of the thesis is on wood-based design and all of the analyzed case-studies follows this selective criteria, the first analyzed example is based on steel and membrane. The main reason is that this project is particularly well documented and it can therefore makes up for the lack of bibliographic availability with such precise description in wood-based designs. As stated before, material system is a fundamental component of this process and it is true that the behavior of the system and the variables considered change from one case to another, but it is also true that the global approach remain quite similar and can be to some extend generalized.

The example that is here shortly described for a first unfolding of a morphogenetic pro-

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space. Important topological properties include connectedness and compactness." Wikipedia accessed April 2018. Topological objects can be deformed, stretched or scaled but cannot undergoes operation of 'cut and paste': a sphere and a cube are topologically equivalent objects (homeomorphs or topologically isomorphs) because you could transform one in the other through stretching and deformations without tearing and gluing operations, while a sphere and a torus are not topologically equivalent since the sphere cannot be transformed to a torus, because the characteristic hole of the torus cannot be reproduced simply through deformations.

cess is the AA Component Membrane[14] 1:1 prototype. Although this project is quite old (2008) and employs different materials it is still significant for showcasing the morphogenetic approach since it is among the first workflows set by AA London in this field. The project was developed within the EmTech master program in 2007 under the supervision of the Emergent Technologies and Design Group with the collaboration of Buro Happold for the structural engineering. The **design brief** required to build a sun and rain shelter on the terrace of AA building, but which should present a high degree of porosity to not obstacle the view of the surroundings and to not oppose resistance to the horizontal wind force to avoid excessive stresses on the few support points available. In fact, three existing columns, which could withstand minimal bending moment, were the only possible points to support the canopy. Therefore, the design intended to **integrate the tectonic site conditions, the environmental influences, construction limitations, functional requirements in one system** through the definition of a performance profile and related **fitness criteria** which constrained what is called the 'design space', in other words limiting the range of possible design proposals by excluding or including sets of options according to

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[14] The following description is based on Menges A. *"Material Systems, Computational Morphogenesis and Performative Capacity"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

the variables and restrictions. Even the material system and assembly procedure had to be extremely simple in order to be built by unskilled labor and to accommodate the budget limitations. After the design brief analysis, the next steps for the development and differentiation of the system were to **embed the parameters, hierarchies, dependencies, variable ranges through the definition of the genotype.** To do so, it was necessary to establish the basic and the variable system component. Based on the previously exposed constraints the basic component includes: a framework of compression elements (galvanized steel tubes), a framework of tension elements on the perimeter (steel wires), an internal tension system (membrane assembly). The membrane patches significantly contribute to the load-bearing structure capacity as they work as principal tension element and, simultaneously, work as system skin. Then the **material system setup** (not as standardized building system) is built through an integral computational model. First, the **geometric description** of the model is established, not as a static shape but rather as a parametric model which includes variables and allows multiple possible formations once the algorithm is executed. After the general geometric layout is set up, the **material system** needs to be completed with the introduction of the variable parameters, in particular, the range of variability is determined according to the affordances and constraints of each individual elements.

In other words, the project is **based on a pattern** – of tensile membrane and compressive metal frame – where each component can vary the dimension, rotation, position according to a range of established maximum and minimum values. These values are determined through physical tests that explores system's constraints and its performative capacity. In this case, the **two main systems** to understand are the membranes behavior and the tube frame. About the **membranes**, it needs to be defined their forming behavior[15] in relation to the anchor points position of each component. Their geometry is parametrized and the variation of the parameters leads to different equilibrium states which relates acting forces with membrane shape. Consequently, the parametric description of the **tubular steel frame** is dependent from the membrane system, but it also has its own rules independent from the membrane, as the maximum deviation of joint angles, maximum length to prevent local buckling according to the compression force applied and the diameter constraints due to manufacturing and global weight limitations.

This kind of design approach frequently employs **patterns**, which are defined by components. As in this case, the **definition of a component** is not only an essential base to

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[15] The forming behavior is the tendency of the material to change its form when it is under specific forces and/or environmental conditions (temperature, humidity, etc.). In fact, depending on the relative position of the anchor points, the pre-tensioned membrane settles into different individual shapes. Within a certain parameter range all the membranes tend to share some characteristics: they all fit to a hyperbolic-paraboloid geometry with negative gaussian curvature.

control the limits of fabrication, self-forming tendencies and material constrains, but it also gives the possibility to build a larger system. Once the component is defined, the topological relations and dependencies between components needs to be established. Finally, all the factors set up and derived from multiple values, physical and digital tests, and interrelations, define a first genotype of the system's basic constituent. The **genotype** therefore describes material properties, self-forming capacity, geometric characteristic, manufacturing constrains and assembly logic as reciprocal interdependencies within specific variable margins. Changing the values within the defined range in the associative model produces the differentiated components all related one another and responding to the needed performance. This procedure demonstrates the complex interrelations – which can be even greater or smaller – of an integral system that enables local variations according to pre-defined performative criteria.

Case-study: AA Wave Component

This project follows analogous procedural guidelines than the previous one based on membrane component. For the Wave Canopy[16], 2009, the **design brief** asked to reproduce on the AA building terrace a lightweight protection from sun and rain using the three existing steel columns as support points and reducing as much as possible the lateral loads to avoid bending moment. In this case the material system was based on wood veneer assembled to form a stiff, lightweight partial shelter. The principle is to **explore evolutionary process** and inform it through feedbacks by physical experiments developing a geometry related to material behavior. The first exploration of the design initiated with tests on physical models by experimenting different types of waved layers overlapping, deriving the parameters for the iterative process based on a computational model.

The structure is based essentially on **two interconnected systems** developed together in parallel: the waved thin wood veneer that composes the general pattern, and the wood fins which works as main supports and connections to the steel columns providing local stiffening of the canopy. The **physical models** provided a general understanding of the behavior which was then refined in the computational model by introducing more precise parameters. Even the spatial arrangement and environmental condition were transformed into data for the model which, after 20 iterations, gave back the initial surface which minimized lateral load exposure, and directed the water to drainage points. Further iterations used CFD to evaluate the possible geometrical variation under different environmental conditions, and progressively helped to reduce the turbulence flow under the canopy, increase the laminar airflow, increase the porosity to avoid sail-effect and improve the structural capacity. The physical models were used also to generate the information about

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[16] Weinstock M., "The Em-Tech Wave Canopy 2009" in AD 2009

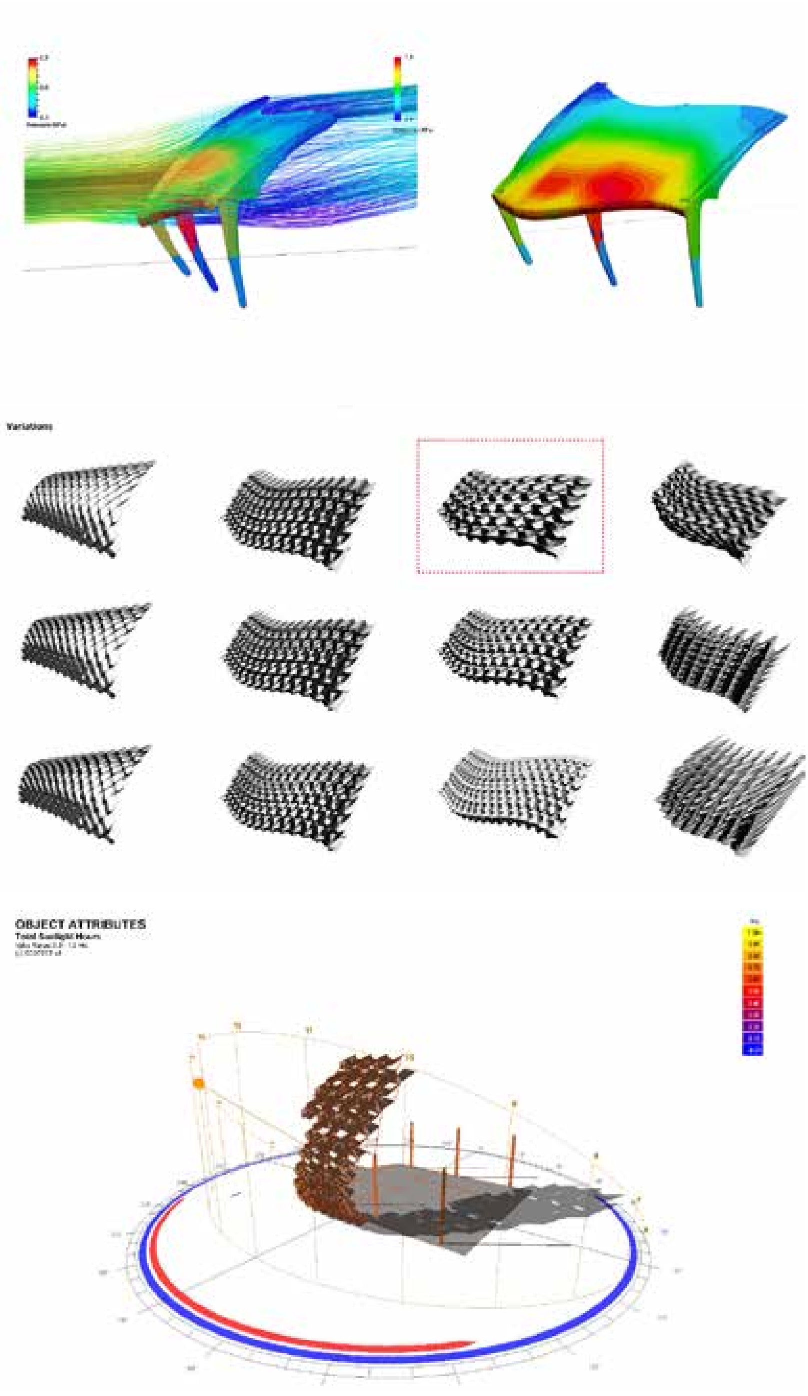

Fig. 5.2 From top to bottom: a) CFD analysis for surface behaviour evaluation of wind effects; b) morphogenetic iterations and selection of the final geometry; c) evaluation of shading conditions

the specific curvature radii that could be achieved by bending the wood veneer. At the end, because of the insufficient resistance of a single wood foil, the solution was to glue two layers of veneer adding an intermediate glass-fiber layer and a final exterior resin coating to improve stiffness. For the fabrication process the stripes were cut with a CNC machine and then a jig was built to correctly bend each stripe matching the curvature of the digital model. The final structure assembled on site was 5 meters long and composed by 1.5 mm thick waved wood layers; the fins were composed by three thick layers, two outer layers made of 12 mm plywood and a central layer of 18mm. The project employs a morphogenetic approach through an informed evolutionary processes based on a material system focused on wood elasticity as a generative design factor.

Fig. 5.3 Final prototype realized on the roof terrace of the AA building in London

Case-study: AA Patagonia Shelter

Another case from the same set of studies conducted by AA is the Patagonia Shelter, also designed by the EmTech Master students in 2007 and built in the Quitralco fjord in Patagonia, Chile[17]. The shelter needed to be a protection for visitors and is located on a panoramic terrace watching over the landscape. This small project is worth to be shown here because it can demonstrate the **feasibility of small constructions with low budget by employing the morphogenetic methodology**.

The shelter had to be built by using only one kind of simple wood planks available on site and by employing local knowledge in timber construction. This constrains influenced the general geometrical properties by **limiting the shape catalogue to simple ruled surfaces,** which makes the structure easier to build since ruled surfaces can be achieved by using only straight elements. Another constrain was the **resistance to earthquakes and wind**

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[17] based on Menges A. *"Material Systems, Computational Morphogenesis and Performative Capacity"* in Hensel M., Menges A., Weinstock M. *"Emergent Technology and Design. Towards a Biological Paradigm for architecture"*, Routledge, 2010

Fig. 5.4 Interior view of the final shelter

which represent considerable stresses for the structure. Therefore, the material system was defined as a ruled surface made of timber planks with a considerable resistance to horizontal stresses and bending moment. By this regard the intrinsic properties of wood have been exploited and used as generative factor guiding the design flow. Wood shows very different elastic behavior according to the direction of the stress in relation with the fiber direction: the modulus of elasticity parallel to the main fiber direction is approximately fifteen times higher then the perpendicular one. This means that the boards can slightly bend along their longitudinal direction depending on the overlap and joint points enabling the construction of a ruled surface where the planks are not coplanar. This degree of deviation from coplanar planks enables a specific curvature – by measuring how much a single plank bends – that is fed as a function in the joint of each plank. Therefore, the **design exploration** was based on the variation of the guide curve which generates the ruled surface, the length of the planks and the maximum angle between planks. Additional requirements defining the evolutionary process were the need of an enclosed volume in relation to the envelope surface, a minimum ceiling height for allowing people to stand in the shelter, and s principal direction given by the landscape view, wind and rain protection. These conditions of constrains and requirements were set in the computational design process

Fig. 5.5 Exterior view of the shelter and the platform

where a **series of ruled surfaces configuration were generated and evaluated to inform the next cycle of subsequent generation**. The final selected form is composed by the two symmetric ruled surfaces 'convergent' in a central axis creating a roof-alike structure and supported by a A-shaped timber frame made by grouping eight planks together. From the information available in the bibliography the structure resisted to several earthquakes till the fifth degree of the Richter scale. The morphogenetic approach helped to find an optimized and functional solution by employing very simple fabrication method and material system through an integral computational model considering performative requirements and constrains. Moreover, this case-study is a further demonstration that every computational model follows a specific process based on the characteristics of the project, and it is different every time because the material system, the constrains and the performative capacities taken into account are different.

Case-study: ICD Pavilion 2015-2016. Sewn Timber Components

The research project conducted at the Institute of Computational Design of Stuttgart, is an experimental pavilion which explores material-oriented design and innovative joint in a light-weight timber shell[18]. Thanks to the advancements in timber constructions technologies such as the introduction of cross-laminated timber (CLT), nowadays we are able to use wood structural properties in an extremely adaptive and flexible way. But still, the typical use of CLT structures is characterized by massive cross section of the elements and thick metal joints. The research of ICD explores a light-weight and structurally efficient construction by using very thin timber components and reconsidering the new typology for joints connection. On the other hand, **morphogenetic form-finding principle**s allows a deep understanding of structural behavior for free-form shells construction. Moreover, even in this case, component differentiation allows to exploit performative capacity of wood employing the least material possible.

As wood structural behavior is highly influenced by its **fibers direction**, current construction technologies tend to use the more processed materials as plywood or fiberboards for their homogeneous behavior. The research reconsiders the **textile properties of wood** and anisotropy, applying techniques such as sewing, patterning and lacing for optimizing the structural behavior. Using very thin rotary sliced veneer (1mm) the material become extremely flexible and it behaves is like a textile. Therefore, **sewing technique for connection** results an interesting approach, as for the textile, since it allows a good distribution of

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[18] Schwinn T., Krieg O. D., Menges A., "Robotic Sewing. A textile approach towards the computational Design and fabrication of lightweight timber shells". Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA 2016), University of Michigan Taubman, College of Architecture and Urban Planning, Ann Arbor

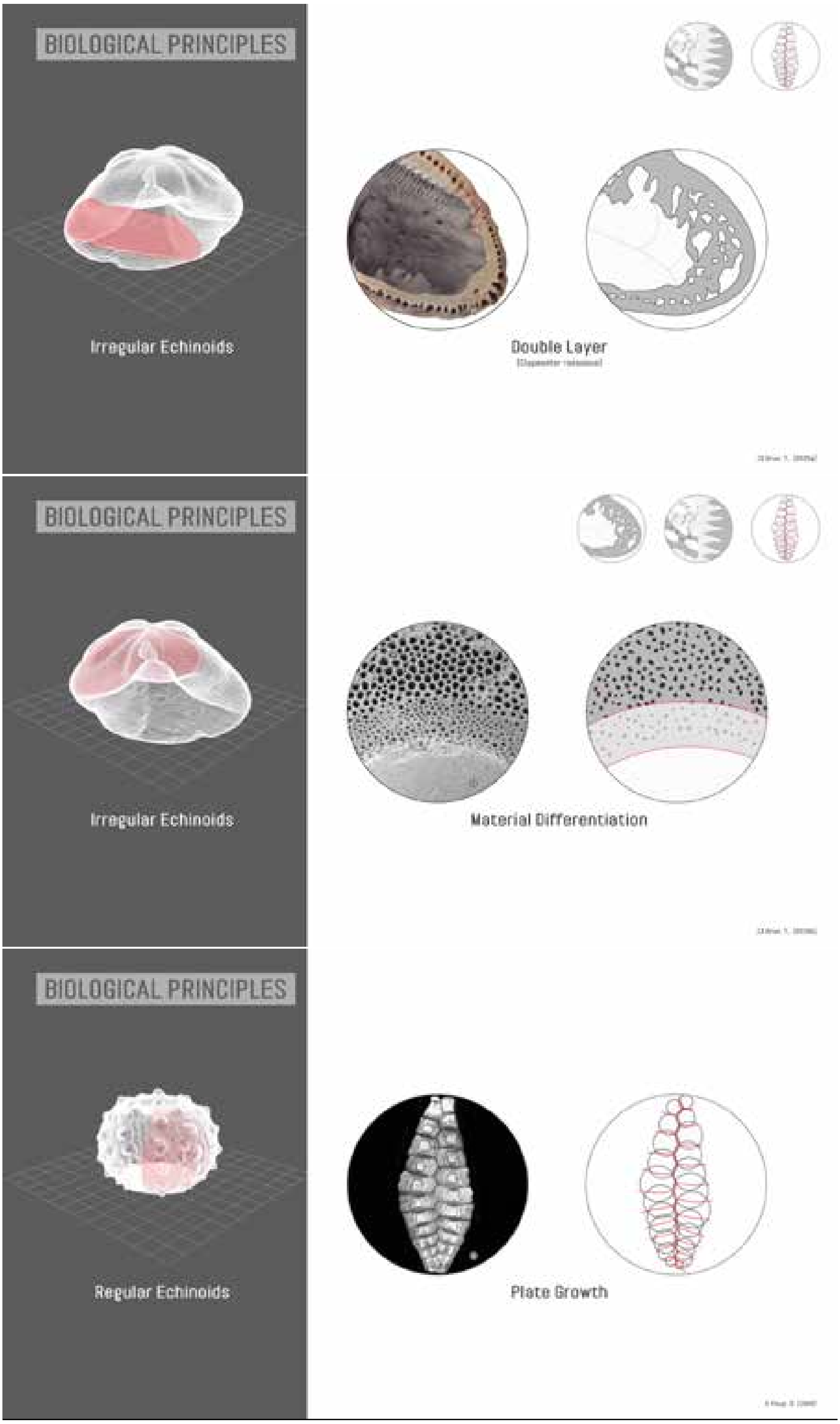


Fig. 5.6 Extraction of biological principles from seashells urchins

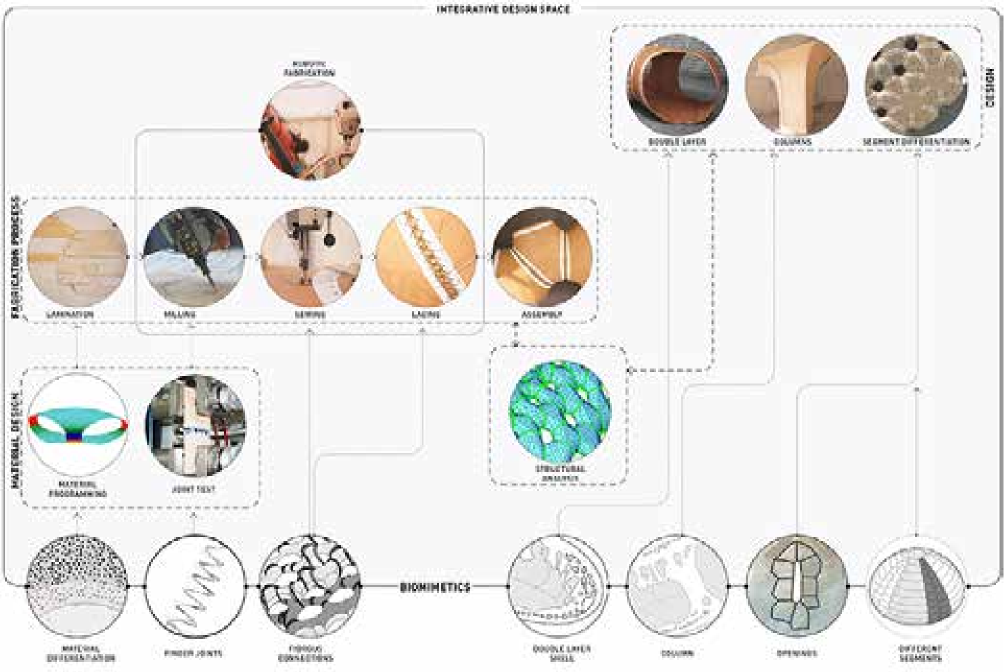


Fig. 5.8 Diagrammatic set-up of the computational workflow

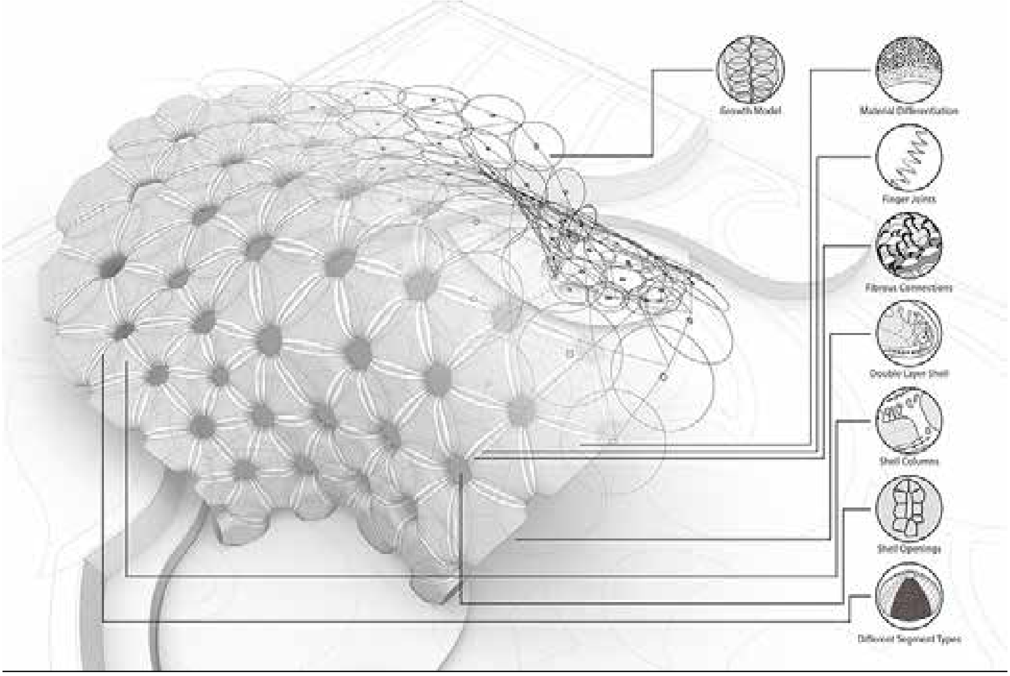


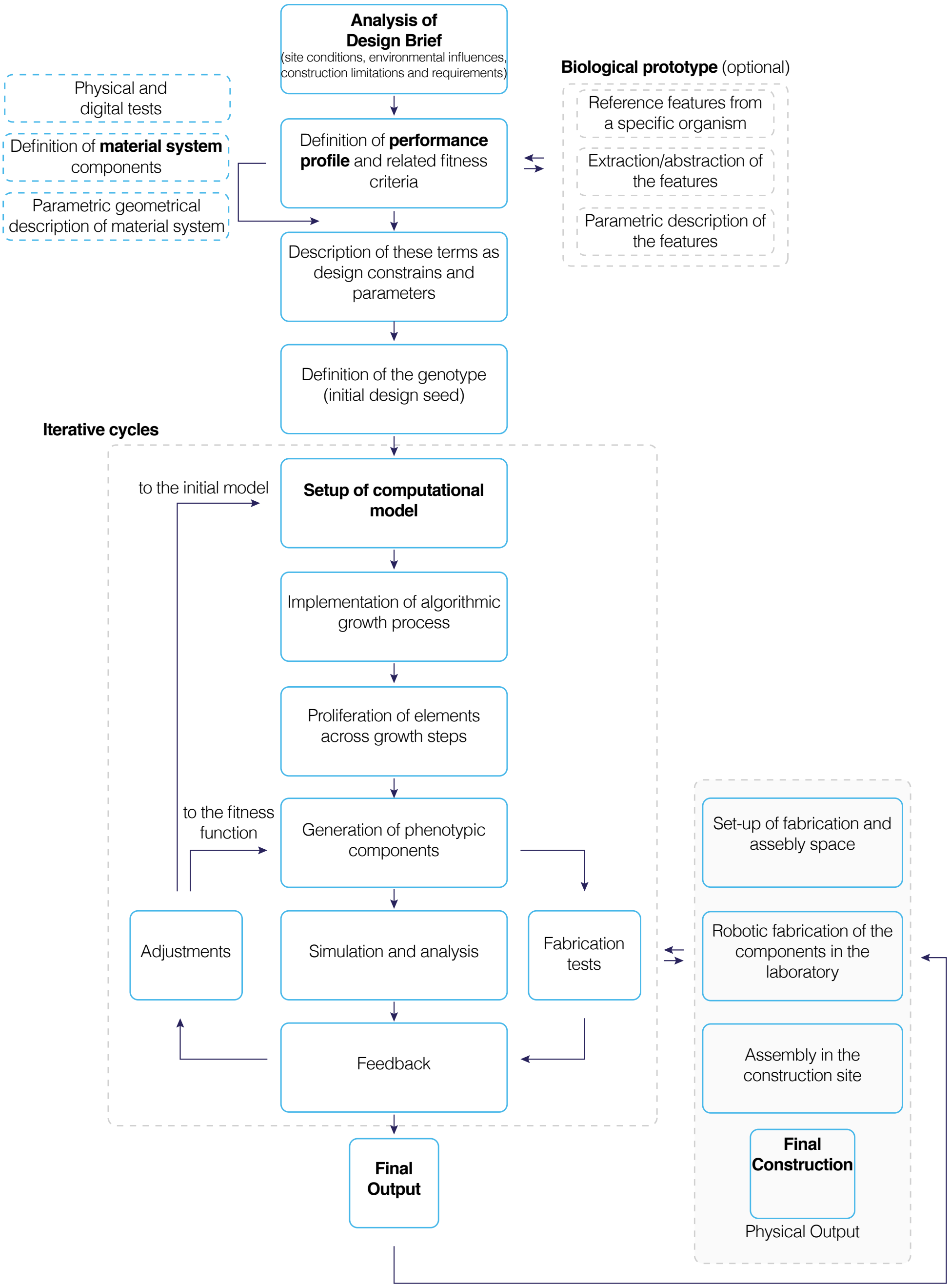
Fig. 5.7 General features of the final pavilion

the stresses in the joints. Although in the sewing technique human labor is still required because of textile complex behavior and simulation complexities, the use of robotic arms opens to wide possibilities in the case of 3D sewing without a constrained working plane.

The morphogenetic approach provides the tools for extracting properties and behavior from natural organisms and systems, for the generation of a self-supporting and structurally efficient shell. In this case the characteristics of **Echinoids seashells** (Fig. 5.6) were taken as biological prototype: the growth rules of the shell plates, fiber and finger joint connections between components, the shell double layer and the material differentiation. The shell has been parametrically generated through a computational morphogenetic model and represented using NURBS, to get spatial and geometrical characteristics of the pavilion and perform the structural analysis. The domain of the structure has been defined as a particle system, originating in the support points and generated through a **growth algorithm** that follows the plate growth principles of *Echinoidea*. Each particle is the center point of a "segment" – the basic cell of the pavilion – represented initially as a circle with a growing radius over the time of the population process. The result is an evenly spaced arrangement of input points which are centers of tangent circles with an increasing radius related to the distance from the seeding origin (the further is the circle from the origin point, the greater is the radius). In a subsequent phase a triangulation of the points has been done, and the edges of the resulting triangular mesh form the basis for the generation of the differentiated components. The computational model built for the morphogenetic process, **integrates the design intent, material properties of bending custom-laminated plywood and fabrication constrains**.

Since the wood is here treated as a textile, the relation between bending stiffness and direction of the grain has been studied and tested. The areas with high curvature requires thin material layer and the direction of the **fibers is almost perpendicular to the bending direction**. On the contrary, the areas with low curvature has thicker material layer (almost double) and the **fibers direction is parallel to the bending direction**. The physical and digital test performed guided the formation of the material system and, consequently, the description of each differentiated component in relation to the stresses that it must bear. The single "segment" of the pavilion is composed by three stripes, each stripe is divided into 100 mm wide areas (with variable length) in order to differentiate the grain direction according to the variable curvature previously analyzed. A robotic prefabrication is used to bend together the stripes which are then glued together forming the segment. Then an industrial sewing machine is used for **sewing and reinforce the connection** of the three stripes. Along the three edges of each component an additional membrane is sewed with a similar process, such membrane will allow the connection with neighbor segments through lacing. After the 151 segments have been completed, they were assembled on site by human labor using lacing technique. The final structure has a weight of almost 800 kg, covers an area of 85 square meters and span for 9 meters. In this case the biological principles were directly derived from a specific organism, the methodology of algorithmic growth inspired by the plates structure of the *Echinoidea* has been used as principal formation process. Moreover, it is interesting to note the abstraction, crossover and coherent combination of the organism properties on one side – which not only influenced the formation process but also structural pattern, differentiation, behavior, assembly logic – and wood properties on the other side, which, apparently, do not have any contact point.

Diagram for morphogenetic design methodology



Diagrammatic process proposal for the Morphogenetic methodology. This diagram is a modified version of the one proposed by Ahmar, Fioravanti, Hanafi *"A Methodology for Computational Architectural Design based on Biological Principles"* Proceedings of the 31st eCAADe. Based on this procedural logic the diagrams of other methodologies have been elaborated.

5.2. Methodology of robotic timber construction

The development of novel methodologies in wood performance-based design is manifested in different directions of contemporary research in architecture. While on one side the biomimetic approach to architecture has a strong science-based focus on the application of biological concepts in design, on the other there are industrial-oriented approaches referred to advanced assembly systems aimed at improving productivity and construction quality unfolding the potential of robotic-based assembly and digital strategies. We can identify mainly **two different approaches of robotic timber construction** (RTC): one, developed earlier, features an additive **layered process** employing simple elements positioned one over the other by a robotic arm (this included different materials, from bricks to non-standard timber slats); the other is the assembly of **spatial structure** made of non-standard timber components, it goes beyond the layer logic, here the robot is able to freely position the elements in space. The research group Gramazio-Kohler at Zurich ETH started to investigate these novel approaches since 2008, with the principal task of applying such technology and methodological approach in building industry in order to better employ human resources, save time, expand the design space. The first prototypes where oriented on layered construction, the very early experiments used standard components as bricks – see for instance the Gantenbein Vineyard – and then evolved to non-standard timber components where both a novel aesthetic and a functional potential is liberated through the introduction of customized individual components[19] (i.e. timber slats with different lengths or cut angles). These components are both **robotically cut and assembled** joining the flexibility of customized building parts with the advantages of additive mass production since they can be fabricated without the need of a chain (there are no repetitive actions), at a low cost and with a constant and controllable quality[20]. According to Gramazio and Kohler RTC brings to a minimal material waste and improve material savings since there is no need to construct external scaffolding or temporary support. Moreover, the creation of a **continuous workflow** controlled by scripting, from the computational modelling of geometries and information to the digital fabrication tools which concretize this information, enforces the link and the control between design and make. This process increases building components' information level, which are made of a number of geometrical single elements that compose the joint, and digital information about functional data and material. About this relation between design and construction Gramazio and Kohler affirm:

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[19] Gramazio F., Kohler M., *"Digital materiality in Architecture"* Lars Muller Publisher, Baden, 2008

[20] Willmann J., Gramazio F., Kohler M., *"New paradigms of the automatic"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

> “The question arises of how to deal with this on the one hand powerful, but on the other hand critical, direct relation of design and construction. If the programming of detail systems is within the control of the architect, new potential for the design is possible. The architect’s design data does not need to be converted to construction instructions by a number of different parties involved in the building process but can be used for fabrication as is. A mere rationalization of workflow might discard the creative potential that could emerge from the interdependence of design and fabrication. Only through the configuration of detail systems that encapsulate the increasing amount of material and fabrication parameters within simple and manageable methods can a new design space evolve. This allows designing with the specific characteristics of a building process and at the same time shaping the process itself. In this case, one should be aware that a major difference exists between the precise numeric design and the physical world – geometric and fabrication data do not contain information about physical conditions such as gravity or material properties per se. Conversely, this means anticipating physical requirements at the outset of the parametric design process and using material conditions as well as assembly logics as the basis for coding. […]
>
> Achieving a sophisticated building component with a simple material and connection through a high level of knowledge of construction techniques can be compared to methods used by manufacturers from pre-industrialized ages. […] With computer-aided manufacturing (CAM), the tool is controlled through explicit routing data, which leaves no room for interpretation and adaptation. This change of workflow redefines the interface between architect and manufacturer. The manufacturer becomes a specialist in operating CNC machines and the architect designs control data for these machines. To derive solutions that effectively negotiate between beauty and construction without resorting to unmanageable complexity, the architect and the manufacturer must collaborate. The architect needs to be knowledgeable about the production conditions and able to integrate the implicit knowledge of the trades he or she is working with into the design of explicit machining code. These changes in production conditions and working processes lead to the assumption that new forms of architectonic expressions will emerge. They require appreciation for the elegance of construction that is less based on demonstrating the perfected functionality of each singular building element, but should negotiate differing functional requirements of architectural components to form a coherent synthesis of material and design system.” [21]

The questions that research is called to answer to are not limited to methodological issues – which remains fundamental at this stage – but they also address theoretical issues, fostering a cultural approach to the topic rather then a mere technology-driven one. Research-by-design is being taken as major strategy in the exploration of the design space by many international institutions, supported in parallel by scientific contributions of the

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[21] Gramazio F., Kohler M., Oesterle S., “Encoding material” AD 04/2010

various fields involved in a project (mechanics, automation, material science, etc.).

Case-Study: West Fest Pavilion and Sequential Walls

The first exploration phase of RTC conducted at Zurich ETH was based on layered arrangement of timber slats; this approach allows to manage a relatively simple component arrangement – the positioning is limited to a plane – and understand how to interface the robot with design and construction issues. On the other hand, it is a strategy that can offer limited geometrical configurations other than relying on material redundancy for the structural resistance.

The West Fest Pavilion[22] made in 2008 (Fig. 5.9), explores in a first phase the relationship between the technology-based criteria of digital fabrication tools and the related effects on the architectural outcome. The project is based on a system of stacked standard timber slats that compose a set of columns working both as vertical support and roof. The columns have a changing 'cross-section' which is gradually twisted and enlarged from the

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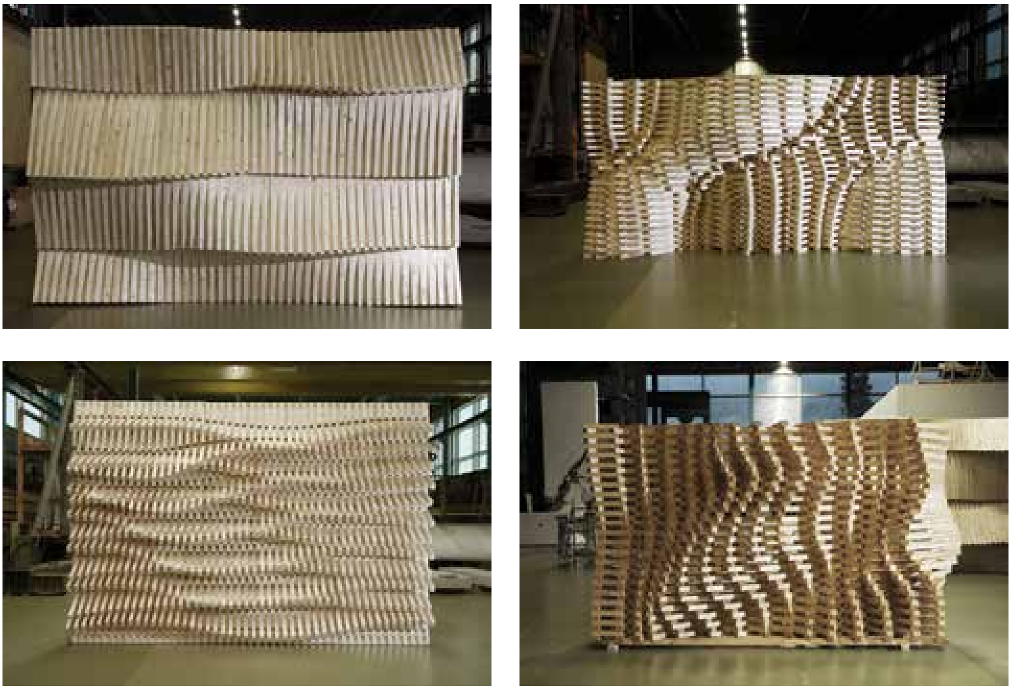
[22] Gramazio F., Kohler M., Oesterle S., "Encoding material" AD 04/2010

Fig. 5.9 West-Fest Pavilion 2008, Gramazio&Kohler research group

bottom to the top in such a way that the edges of adjacent columns are connected on the top composing a sort of roof. The variable cross-section is achieved by using timber slats of different lengths assembled by the robot. The **general process** is divided as follow: the robot grips the batten from a stack of material, moves it on a working table in the correct position for the cut according to information about length derived from the digital model, a worker cuts it by actioning the circular saw, then the robot moves again the batten from the working table to its final position adding another layer to the column in construction, here another worker screws it together with the previous layer. The columns compose both the spatial and structural layout of the pavilion. The structural principle is based on minimal joining surface between the layers that can transfer the vertical loads, doing so the columns is dissolved toward the top reducing the weight by using the least possible amount of material for this kind of structural layout based on layering. This brings some advantages: the lower part of the structure is subjected to a minor load; the cantilever of the top part of the column can be larger than it would be with a 'full-layer' structure; and the architectural result is more interesting since in allows light to pass through the columns accentuating the tectonic character of the structure.

The strategy employed in the RTC of the West Fest pavilion has been employed as a base for the development of a set of projects addressed to as "Sequential". The Sequential walls

Fig. 5.10 Sequentials projects of walls based on RTC



were taught at ETH Zurich in 2008 (Fig. 5.10), the principle is the same of the presented pavilion but here more functional requirements were added to explore alternative solution of a different structure (walls instead of columns). The wood battens are stacked to form a load-bearing shelter for a hypothetic building including the performance requirements related to weather protection and thermal insulation. Physical experiments were done to explore alternative arrangements and variations of the wood battens, some of them were based, for instance, on water tests, trying to understand possible ranges of overlap and length of the battens to efficiently flow the water away.

Case-Study: The Sequential Roof

After a first experimental stage in RTC, Zurich ETH started the exploration of a full-scale structural roof component for the new building of the Arch_Tec_Lab research facility, located at the Hönggerberg campus in Zurich. This structure is among the first – perhaps the first – **robotic assembled permanent construction** opened to host public working there, therefore, differently from temporary demonstrative pavilions, it had to pass several steps for checking structural resistance and technical issues within the standard required by swiss building regulations. In fact, it has been defined has "*real-scale demonstrator showcasing innovative approaches to architecture and construction in terms of parametric design, digital fabrication, sustainability, HVAC (heating, ventilation, air conditioning), MEP (Mechanical, electrical and plumbing) and structural systems*" [23]. The design was developed by Gramazio and Kohler research group who is investigating in the field of robotic construction since many years, among which the prototypes presented above.

The roof covers a total are of 2.300 m², it consists of nearly 50.000 different timber elements design with a parametric model based on customized algorithms and then cut and assembled by a robot. The building is a rather simple structure 28mx80m with a central double-height area, the primary structure is a steel frame supported by twelve columns, while the robotic assembled roof-trusses work as secondary beam structure with a regular span of 14.7m and 1.15m wide, each truss is made of 23 layers 50mm thick. The **layering logic** is based on a **basic truss form** and consists of continuous top and bottom cords with diagonal webs: between every three chord elements there is a layer of web elements. Top and bottom chords to be continuous need in fact to be composed by three alternat-

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[23] Citation and further description is from Apolinarska A.A., Knauss M., Gramazio F., Kohler M., *"The Sequential Roof"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

ed layers while the webs lie in the one layer. One of the advantages of this **layout** is that it allows a great flexibility in the **curvature variation of the truss profile**, which is the basic architectural principle of the project. Moreover, the distribution of nodes and diagonal webs can be locally modified to improve structural performance or to adapt to the interface with other building components. The structural approach and the truss layout generates a sort of redundancy of material thanks to which some individual elements may occasionally be left out if needed. The roof package, as discussed, is composed by a primary steel structure, the timber structure and integrated with artificial lightning, windows for natural lightning, waterproof and insulation layer, sprinklers according to fire regulation, smoke exhaust. The integration of the timber structure with many functional parts demonstrate another level of success of this project, even the technical components are designed and arranged in the space following the architecture of the building, they are not treated as subsequent additional layers.

The timber chosen for this structure is a **solid wood** with strength class C24[24] 50mm thick, which is a low-engineered – therefore less processed and more sustainable – timber product since it is made of double layer glued solid wood. The trusses have been differentiated and structurally optimized according to local needs, therefore three different cross section heights are employed: 115mm, 140mm, 180mm. For the construction process the material was organized in untreated slats 10m long, joined through finger joints. Possible dimensional changes due to natural shrinking or swelling that could be accumulated through the 23 layers, have been considered, by adding a 15mm gap between the trusses.

The **connection system** also had to be **fully-automated** therefore the hypothetical solutions and tests were performed on systems that could be easily integrated in the robotic construction process. At first a fast-curing glue connection was considered, but the glue typically needs a considerable pressure to work efficiently and this could cause problems on a skewed stack of timber slats. Therefore, another fast technique was a mechanical connection using nails. Nails are ductile and have the advantage to compensate the brittle behavior of wood under structural failing, offering a smoother stresses re-distribution instead of a sudden collapse. On the other hand, nails can cause fiber splitting in wood if not carefully positioned. Swiss norms provide some **distance parameters** to respect for the **nailing** of wooden structure in relation with the diameter of the nail, which describes

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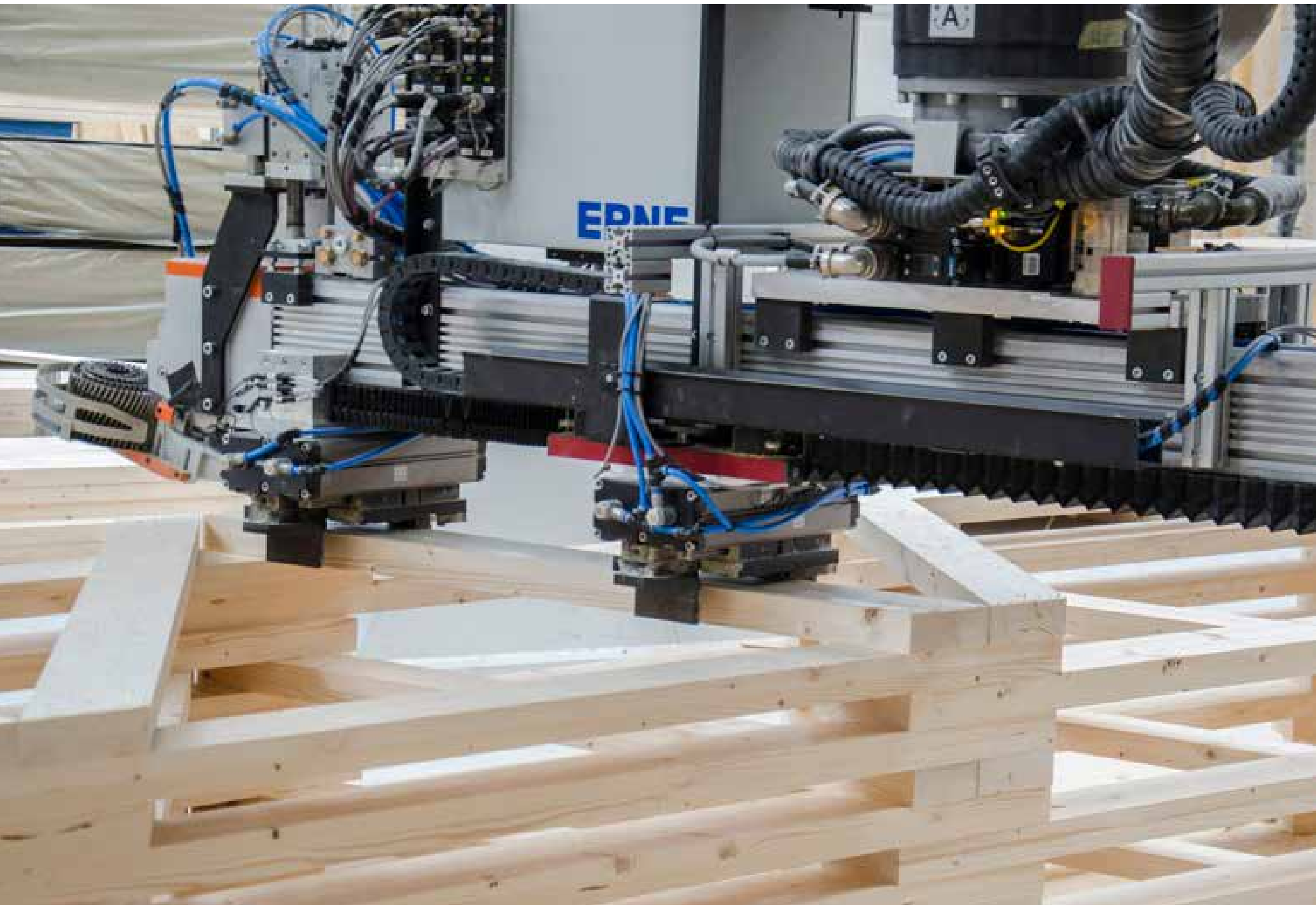
[24] According to European regulations EN 14080:2013 and EN 338:2016 the solid conifer soft-wood identified with a strength class C24 has a resistance to bending moment of 24 N/mm^2.

Fig. 5.11 Opposite page: closeup of the Sequential Roof from the inerior of the building

an elliptical area. In this case the distance necessary for the used nails was 34mm in the grain direction and 17mm in the direction perpendicular to the grain. Every nail connects two layers, thus it must be considered not only the position of the other nails in the layer below but also the ellipse orientation according to the grain distribution of both layers. Finally, the joints are structurally analyzed to determine the number of nails needed which, throughout the whole structure, range from a minimum of 4 to a maximum of 20 nails per joint.

The methodology employed in RTC goes beyond the established design phases **developing concurrently concept, structural layout and behavior, and construction details**. Therefore, the traditional process needs to be reconsidered including different types of information within one integrative workflow. Parametric design and computational tools are helpful in the generation of informed models. Often, when facing this kind of approaches, the commercial available software are not sufficient in the resolution of such specific problems, both because of the "one-of-a-kind" nature of a building and the experimental nature of this design strategies. Therefore, through scripting, the development of bespoke software components is necessary. In this project the team developed an **algorithm-based**

Fig. 5.12 Closeup of the robot grip while placing a timber slat during the construction of a beam.



model to generate the **volumetric representation** and an **abstracted data model for the structural analysis and fabrication simulation**. An **additional algorithm** was written to automate the **setup of the structural calculation** based on the previous model, in a way that changing the first model the new structural calculation is obtained. The results of the structural analysis were processed by the fabrication simulation algorithm which also generated the nailing pattern. The initial model of the roof, with all slats of the same size (cross-section 50x100 mm), demonstrated, through the structural analysis to not be resistant enough, therefore local changes of individual element was necessary. In an **iterative cycle**, the **changes to the geometrical model**, based on parameters, inform the structural analysis model which gives back the new results. The changes, at this stage, were based on the **structural behavior** of the timber members and of the joints. To equilibrate the internal forces the cross-section of some members was increased, while to guarantee the required number of nails in a joint the overlapping areas were increased by extending the slats ends or increasing their cross-section. The changes were performed through several iterations till reaching the final structure which correctly responded to the structural anal-

Fig. 5.13 Interior view of the final construction for the ITA section at Zurich ETH.

ysis. Once the geometrical model passed the structural analysis tests no further post-production was necessary thus this information was directly used for the fabrication process.

The final design was digitally checked, through the structural analysis algorithm after all the necessary iterations, and further validated through physical experiments. In a initial phase of the physical test a series of specimens of single node consisting of three timber slats were checked with different configurations – assembled at different angles between them: 0°, 45°, 90° – and with different nail patterns. The data received from the physical tests were re-introduced in the model to refine the calculations adjusting the geometry where needed. Before the construction the design was further checked by testing 15 full-scale trusses. At the same time the fabrication of these trusses was useful for testing the robotic assembly process.

The robotic fabrication of such structure required a **special layout** (Fig. 5.14) with a considerable workspace (48x6.1x1.9m) and a six-axis overhead gantry robot which was set up at ERNE AG Holzbau[25]. The six-axis gantry robot features also a mechanical wrist

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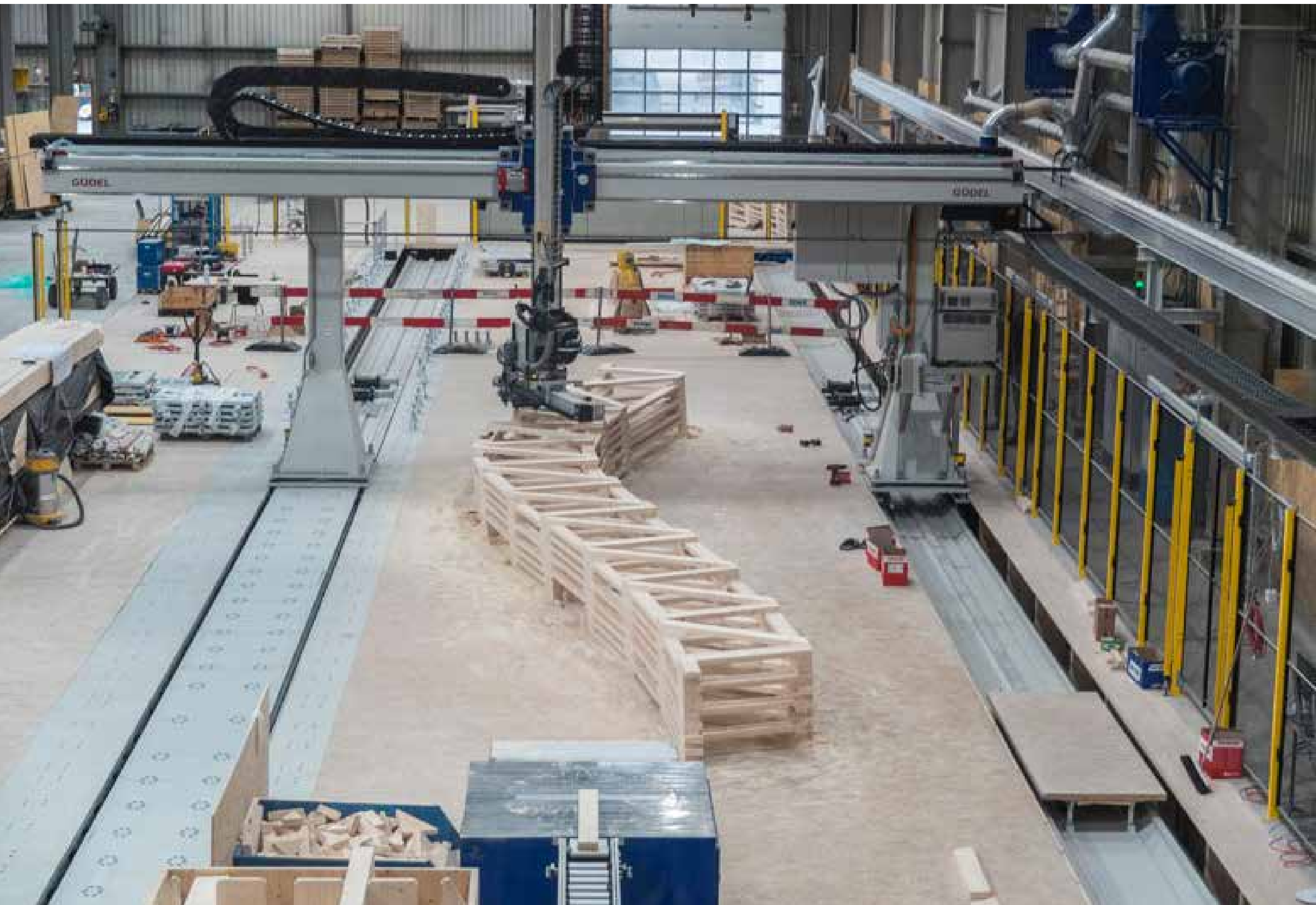
[25] Swiss timber construction company which took part to the experimental project.

Fig. 5.14 Set-up of the laboratory with the 6 axis gantry robot working on one of the beams.



with exchangeable end-effectors, a sawing table, a tool changing rack and a repository of 10m long timber slats of three different sizes. The 168 trusses were fabricated **layer by layer**: the robot pick the timber slat and cut it automatically with a circular saw at the required length and angle derived by the digital model; the piece is then moved to the target position on the workspace and fixed preliminarily with one nail at each end to keep the position; in some cases, when additional trimming is necessary, the end-effector is changed with a circular saw and adjust the laced timber slat, this is also due to the fact that the layers are slightly skewed to form a double curved surface in the final assembly; before starting with the next layer a camera on the robot checks for deviations or errors. This project brings, for the first time, an experimental **fully automated assembly system** at the full scale of a permanent building; it represents a fundamental model in the change of industrial production of building components. The approach experimented here liberates from the constrains of traditional industrial logic based on standardization and repetition, but it also finds a way to re-organize the production of timber components for customized solutions with a general set up which, once established, can be employed in further projects. This approach additionally allows the fabrication and assembly of the components to take place almost simultaneously, reducing the logistics issues and the need of labeling each component and re-assembly them in the construction site. Moreover, in a **tectonic vision**, the layering logic represents the fabrication process and the structural layout in a coherent architectural continuum which was developed as an integral system.

Spatial-assembly systems in RTC

A layer-layout system of robotic timber construction proved to be structurally reliable in a full-scale construction and allows a relatively simple assembly logic by limiting the main spatial reference to a plane and thus simplifying the related issues (joints above all). On the other hand, this layout presents some **limitations in geometrical configurations** and employs a significant **amount of material**, since it is not optimized on this direction but rather on the automation of an integrative process. Therefore, further experiments brought to consider a **spatial-layout system of robotic timber construction** referred to spatial timber frames. Zurich ETH together with Bern University of Applied Science are developing robotic spatial-assembly systems along three principal and complementary research directions: assembly-driven design processes; material and constructive systems; integrated robotic fabrication[26]. These directions have first been studied separately in depth through full-scale architectural demonstrators in a logic of complementary integration and they have been later joined on an integrative design able to express the complex aspects involved in structure, details, automation and resulting tectonic. A **multi-layered**

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[26] Willmann J., Knauss M., Bonwetsch T., Apolinarska A.A., Gramazio F., Kohler M., *"Robotic timber construction – Expanding additive fabrication to new dimensions"* in Automation in Construction 61, 2016

truss system has been developed as a prototype to test the complementary research direction, the subsequent project related with this topic, which is an ongoing design and will be presented by autumn 2018 at ETH DFAB HOUSE, features a full-scale complex timber frame robotically assembled for a two floors house. First it will be described the content of the **three integrative research directions**, then the multi-layered truss system will be analyzed as case study, finally the house prototype project "Spatial Timber Assemblies" will be shortly described (being still in production).

The **first research direction** intends to establish the **computational framework** for a novel methodology of design where the fabrication logic is integrated in the process. The introduction of material information and fabrication logic in design requires the development of new computational processes which have been tested and iteratively optimized through full-scale prototypes. In the workflow every timber element is defined as a logic entity which includes the specific information about its relation to the neighboring members, the end-cut angle and the spatial sequencing of its robotic assembly[27]. A customized

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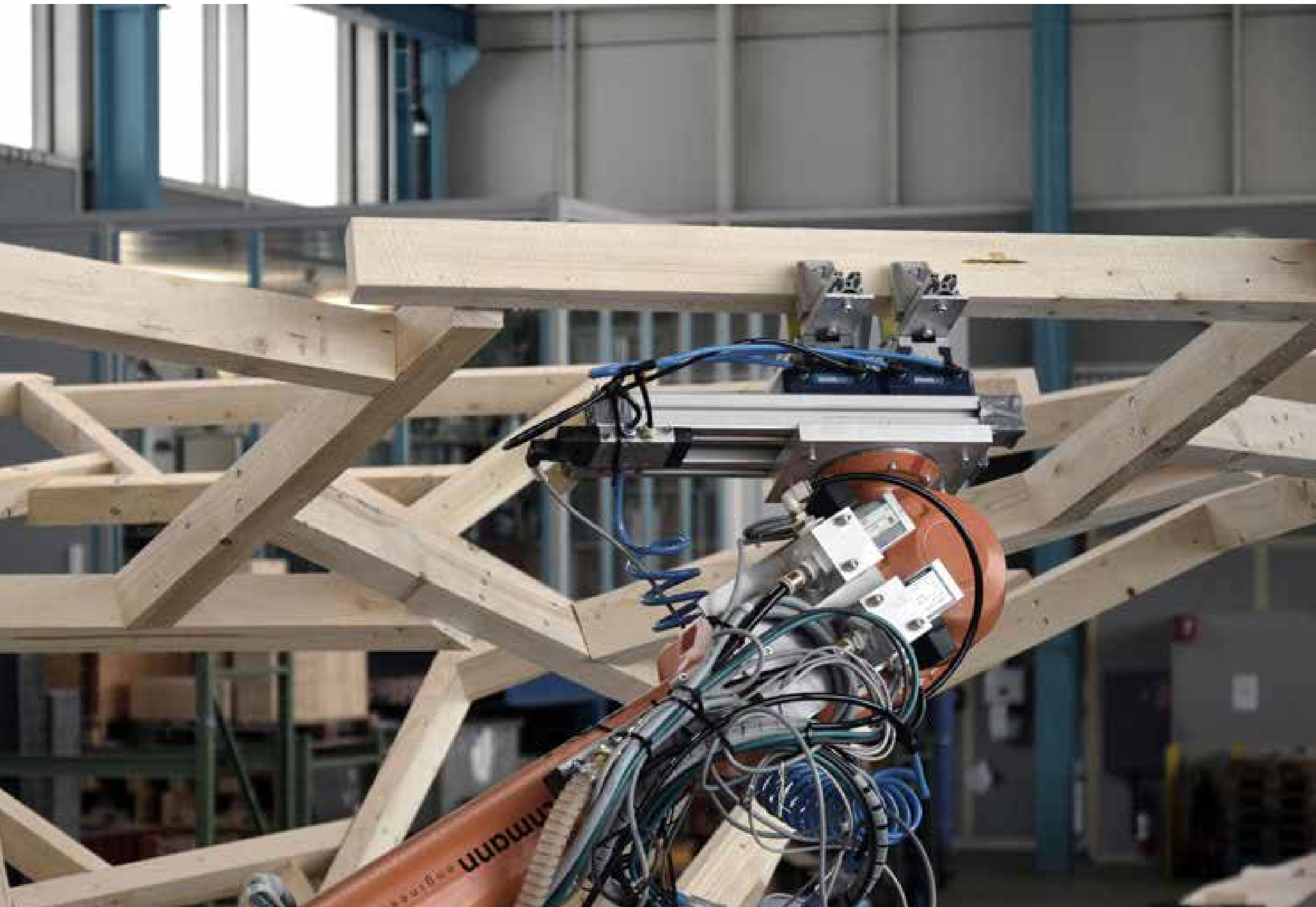
[27] Willmann J., Gramazio F., Kohler M., *"New paradigms of the automatic"* in Menges A., Schwinn T., Krieg

Fig. 5.15 Robotic assembly of an experimental spatial structure



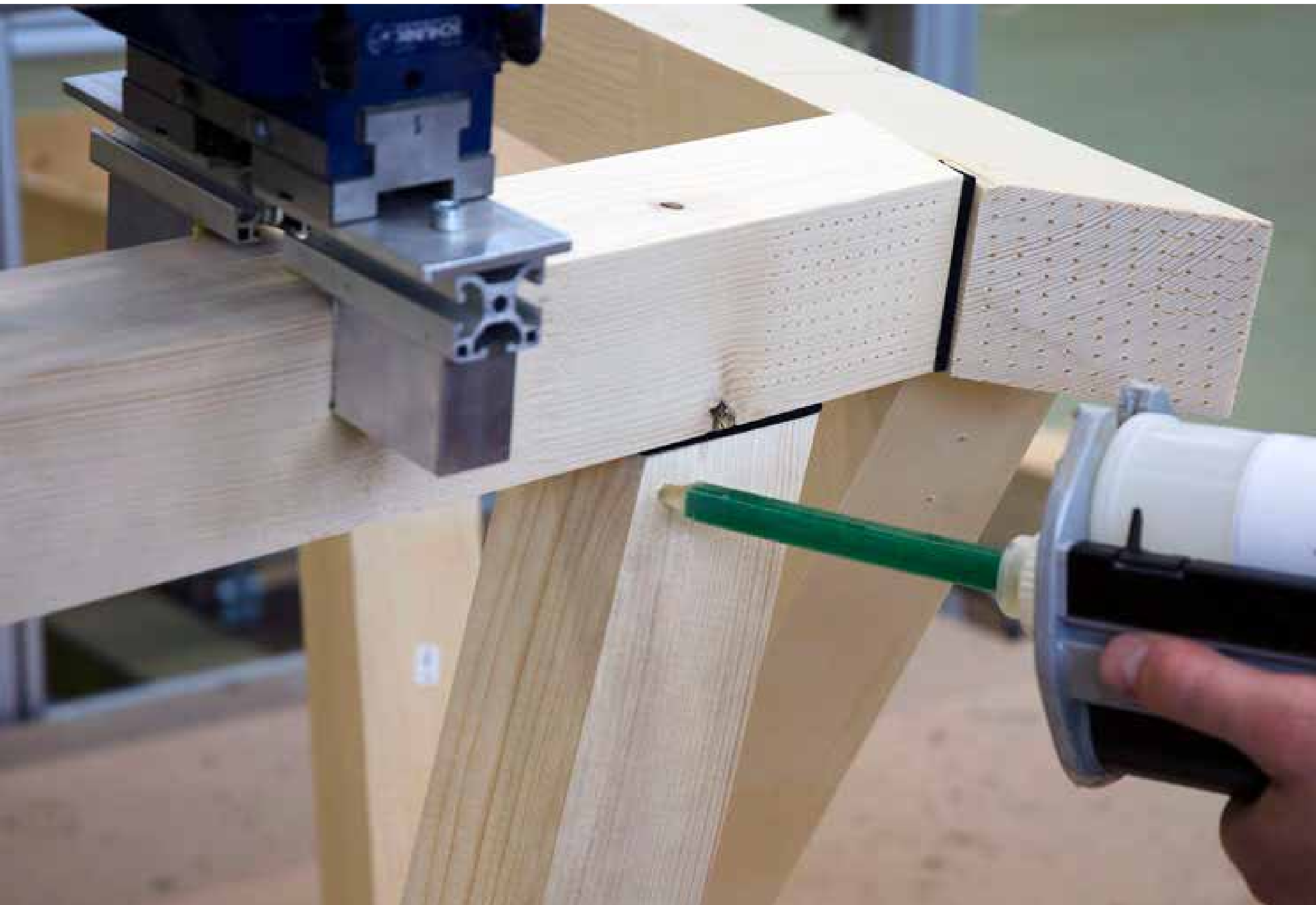
digital design workflow has been developed through scripting in Python language while design and fabrication are embedded in the CAD platform (Rhinoceros) and provided an interface to the structural analysis software for performance evaluation. This workflow allows to analyze and manage the form as a group of ideal number of components considering the assembly sequence of the robot. Moreover, even the information regarding the end-cut geometry and the pre-drilled holes for the joints were integrated in the model. *"The ultimate goal of such new (computational) design ontology is an architecture that is not defined primarily as a final geometric form, but as a complex and refined generative process of digital materialization"*[28].

The **second direction** focuses on the definition of a **material and constructive system**

O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

[28] Willmann J., Knauss M., Bonwetsch T., Apolinarska A.A., Gramazio F., Kohler M., *"Robotic timber construction – Expanding additive fabrication to new dimensions"* in Automation in Construction 61, 2016

Fig. 5.16 Glued connection in a robotic assembled spatial truss; the fast-curing glue is manually injected in a hole that reaches the interface between two components, after few seconds the robot grip leaves the timber slat and moves to the next operation



understanding how these individual components are connected to each other. New typologies of joints have been developed by keeping in consideration the automated process and the sequencing and positioning of each timber slat. A first useful reference for the development of the joints was found in the **reciprocal frames**, these structures are based on the interdependency of relatively short and simple timber slats which reciprocally distribute and optimize the internal force flow of the structure. Reciprocal frames have a peculiar connection typology which has three essential advantages for a digital fabrication framework: first, the joint is an **expanded node** that separates the connection from three members in one single point to three eccentric points (a triangle) in which every point connects two members, once at time, this becomes fundamental in the sequence of a robotic assembly; second, **every member can be customized** by an angle cut at both ends, the simplicity of this kind of adaptation is such that it can be integrated in the robotic assembly process; third, the **triangular arrangement of the node** provides a simple mean to control the stiffness of the structure by varying the eccentricity of the triangle, this offers the possibility to locally adapt the structural stiffness. Another fundamental path of this research on the material system is the connection technique, a possibility explored here is the employment of gluing technique developed in addition to conventional nail technique. The idea is to use a fast-curing glue which presents the advantage to speed up the robotic assembly process; in fact, the robot keeps the member in the target position, the glue is injected and after few seconds it can pass to the next operation (Fig. 5.16). Within this exploration have been tested several connection typologies for glue-based joints to understand which one could offer a structurally stable solution.

The **third part** of this complementary research is the integration of robotic fabrication with all the **different machining processes** in the design. The single timber member gets gripped, cut at ends, drilled (Fig. 5.17), and moved into final target position and fixed within one single process. The integration of these steps in the overall design is fundamental to prevent problems in the sequence – the form and its fabrication is studied in a way that the robot can place the next component without difficulties – and to simplify logistic issues avoiding intermediate material storage. Other issues related to the robotic fabrication are precision and material tolerances. **Tolerances** emerges because of possible divergences given by the anisotropy of the wood or even by the robot, their accumulation throughout the structure can cause problems during the automated assembly, therefore a sensor is necessary to adjust the digital blueprint and consequently update the robot motion path in the physical reality. These adjustments are made in real-time during the fabrication, and for this reason a technological evolution and its understanding represents a fundamental direction in the exploration of adaptive building processes. The results of such implementation are very much influenced by the advancement in sensors capabilities in order to reach a smooth real-time adaptation of the construction process. In general, the assembly performance is, comprehensibly, deeply influenced by the infrastructural setup and material logistic of the workspace.

Case-study: Multi-layered truss system

An interesting example that encloses the described research directions endorsed by Gramazio and Kohler group of ETH and Bern University of Applied Science is the full-scale **prototype of a multi-layered truss system**[29] (Fig. 5.18). The constructive system is, in fact, based on the expanded node as fundamental element that reduces the complexity of multiple elements in a single node and allows sequential joining process. This kind of node guarantees a high bending moment and shear resistance distributing the internal forces reciprocally through the components. Usual single-layer reciprocal structures – based on two-dimensional nodes – determines the rigidity by increasing the cross-section

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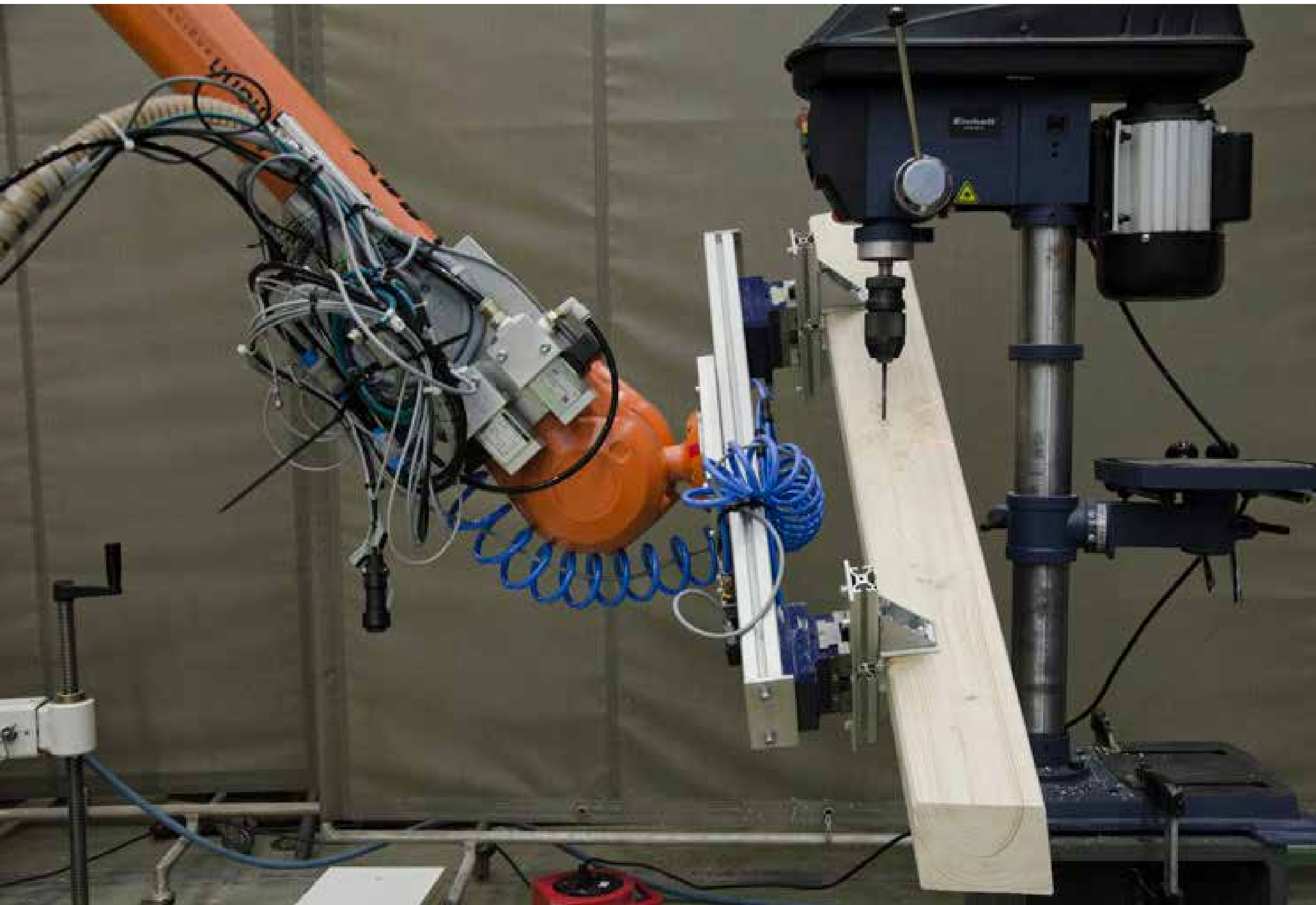
[29] Helm V., Knauss M., Kohlhammer T., Gramazio F., Kohler M., "*Additive robotic fabrication of complex timber structure"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

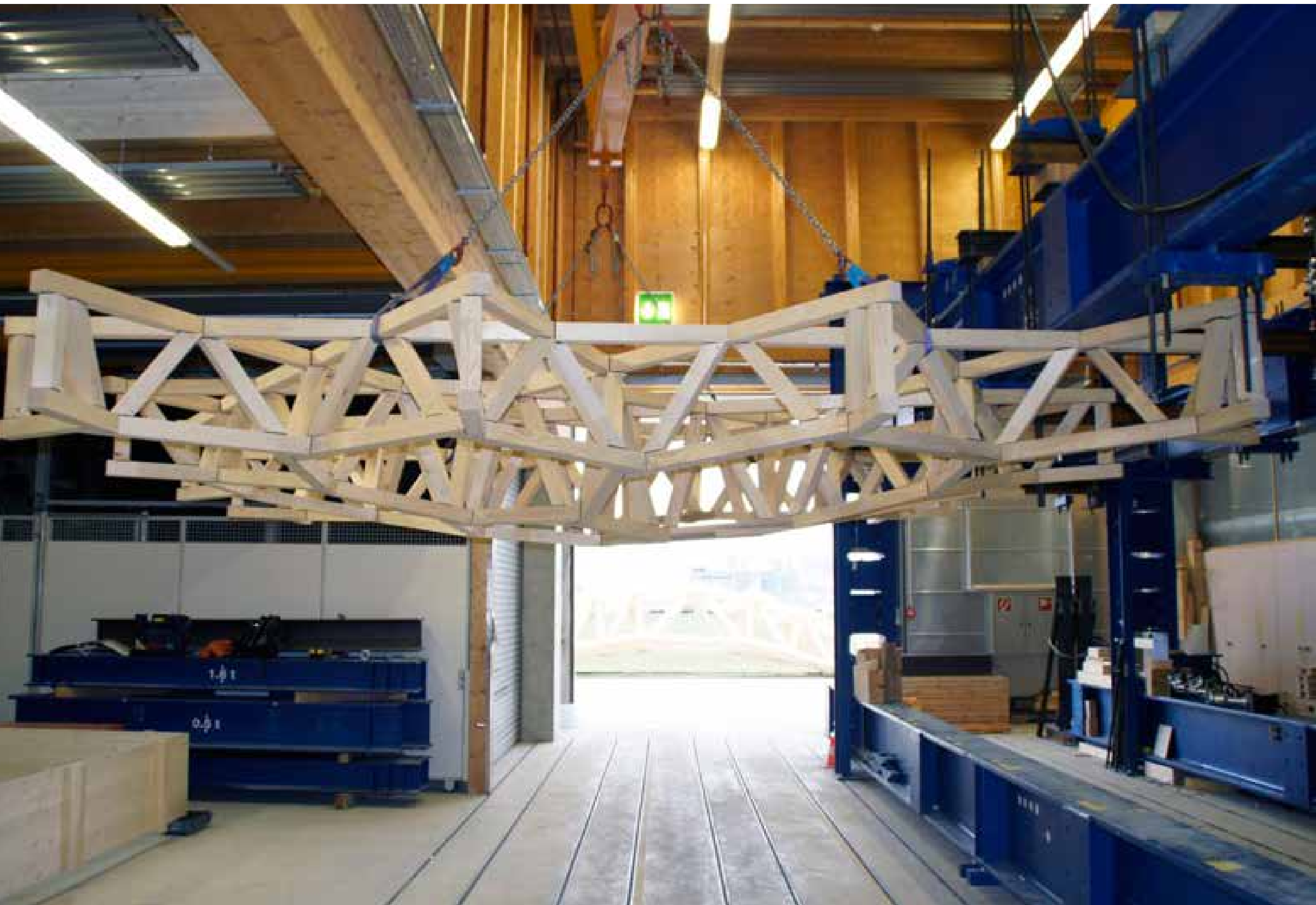
Fig. 5.17 All the operations are of gripping, moving, placing, cutting, drilling etc. are integrated in the operative construction workflow. In this image is shown the drilling of a timber slats within the workflow.



of the components, on the other hand this research consider a **three-dimensional node** that offers a wider range of application thanks to higher bending resistance. It is a combination of the truss system and the expanded reciprocal node system which generates a structural solution organized in three layers: upper, intermediate, lower. Upper and lower layers define surfaces with reciprocal node structure and they are under bending stresses when loaded vertically, while the intermediate one consists of diagonal bars that links the two outer layers and are subject to normal stresses. The **main geometrical parameters** considered for the structural performance were the **node expansion**, which affects the upper layer structural performance, and the **span-height ratio** which is determined by the intermediate layer (as in normal truss-systems). The structural analysis showed that the performance is primarily dependent on the span-height ratio and secondarily on the node expansion. Nevertheless, the node expansion directly affects the node stiffness, therefore it is still a parameter to consider in case of joints with low bearing capacity.

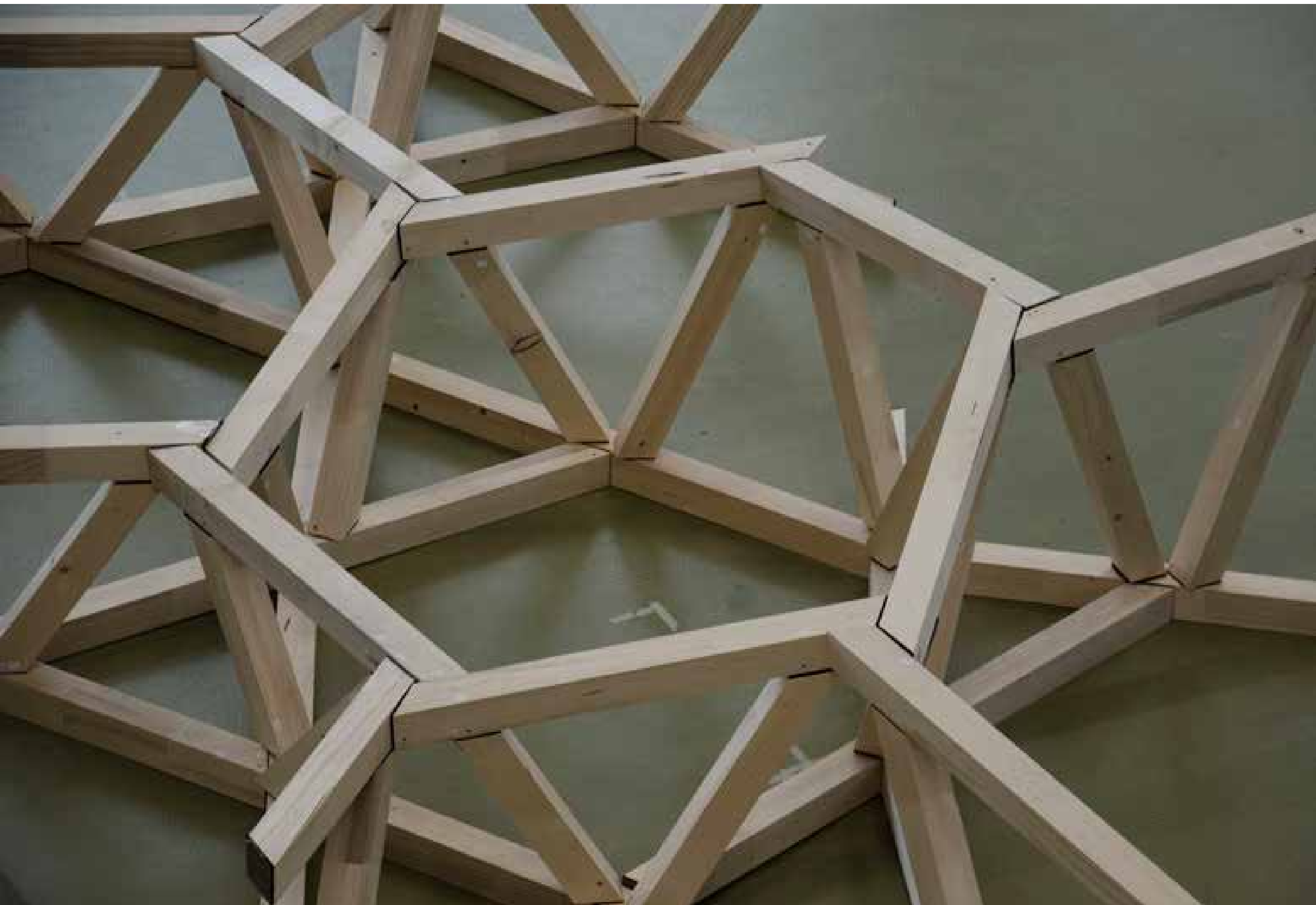
The connection technology chosen for joining the timber member is a special fast-curing glue. Although it is a non-structural glue it proved to be sufficient for the aim of this proj-

Fig. 5.18 Robotic assembled timber spatial truss system developed by Gramazio & Kohler research group of ETH Zurich and Bern University of Applied Science



ect; it was tested by trying some possible configurations based on glue-only connection or rod-shaped/flat elements glued connection. The tests were done on a longitudinal joint connecting end-grain since it is usually the most critical connection. Finally, glue-only connection was the solution suitable enough for the project. Within the aims of the project there is the creation of a seamless flow of robotic fabrication which stars from the geometrical information and data of a digital model. The 3D model has been coherently studied looking at the fabrication method and the structural principle of trusses Furthermore, thanks to parametric tools, which are essential in all these researches, the model contains the information for been processes by robots. It is exported as xml file which contains identification, length, cutting angles and target position of each timber member and the overall order of the assembly sequence. In the sequence, as in the previous project, the robot grasps the wood batten, place it on a working table where a circular saw cut it at both ends with the needed angle and place it straight away in its target position. Through a rubber seal, a small interface of 0.5mm is left between the two members to allow manual glue filling, which is then compressed to 3.5mm. In this first experimental phase the gluing is still manual, but it has been declared that further prototypes would integrate this

Fig. 5.19 Closeup of the timber spatial truss system



step in the automated process. Because this interface can cause **dimensional deviances** that can be problematic when accumulated, a digital feedback was introduced to adjust the digital blueprint according to the physical reality, the new information is then passed to the robot. A **custom scanning process** was established to calculate the position of timber elements just before their placement, reducing positioning errors to the required range of tolerances. The final assembled prototype has ad dimension of 5x5m and a variable height from 0.5m to 0.7m to test a differentiated structure. The calculated load bearing capacity at design level was 5.7 kN in addition to the dead loads. An interesting aspect is that since the structural behavior relies on redundancy, even if one component brakes the structure is still able to partially bear load avoiding a sudden collapse. The physical tests in which the structure was vertically loaded with sand proved to resist to 20 kN, a positive result possibly influenced by the quality of the wood and the redundancy of the structure which offers much better performance then the expected. A second test was performed on the same structure with hydraulic cylinders, but this time the supported load reached 8.5 kN, possibly because the first test weakened some connections.

The RTC methodology of truss-system is currently being employed by ETH Zurich in

Fig. 5.20 Robotic assembly with two gantry robots collaborating in the construction of a full-scale house timber frame to be completed at the DFAB unit by autumn 2018

another **full-scale prototype of a house**, to be completed by autumn 2018, at the DFAB house project, where every research laboratory of the ITA (Institute for Technology in Architecture) is building architectural demonstrators pertinent with their research directions in architecture, from 3D print to free-form metal mesh for concrete casting, till the robotic timber construction. The project **Spatial Timber Assemblies** (Fig. 5.20), currently going on, is a robotic collaboration in timber construction, it features a relatively complex customized timber frame for a two floors house and the methodology employed tests the collaboration human-robot in the construction, being as much realistic as possible, trying to be closer to the construction market. The robot, as in the previously described processes, grab the beam, cut it at both ends and, furthermore, the robot changes tool-head to pre-drill the holes and even to mill the joints at both ends. Then the robot moves the timber component in the target position and hold it for the worker who manually fixes the components with screws; at some points, two robots are used simultaneously to hold two members against a third (previously fixed) or two members against each other and the worker screws them together. The robot holds the timber components freely positioned in space, and this represents one of the great advantages for the construction of complex

Fig. 5.21 Render of the final construction for the Spatial Timber Assembly project of a house at the DFAB unit

timber frames. Furthermore, to prevent collisions while the two robots are moving, researchers had to elaborate an algorithm able to recalculate the motion path of both robots in relation with the current state of the construction. Since the project is still on-going there is not yet available any scientific publication, but, based on the previous analyzed cases and on some information from the press-release, the description provided is reliable for the understanding of this process.

The methodology experimented in both projects expands the boundaries of knowledge in design and fabrication for complex spatial truss-systems since, before these attempts, the digital tools have been employed to manage complex parametric geometries and fabricate components based on manual assembly. This empirical tests, together with the previous experiences of the Sequential projects, create solid bases for the exploration of future direction of RTC and, most important, it opens a **cultural ad operative debate** in the context of an architecture which is no more isolated in academic environments but is getting closer to be part of the current construction sector. Much of the dissemination of the research advancements in RTC is due to academic institution, but another important part is

Fig. 5.22 Robotic assembly of timber plates with integral mechanical attachment of through-tenon joints, developed by IBOIS laboratory at EPF Lausanne and ETH Zuich

played by to the **partnership and proactive collaborations with construction firms** that operates in this field and look out for future development of industrial wood production.

Further research contributions on automated robotic assembly are provided by a collaboration between IBOIS of EPF Lausanne and ETH Zurich, which investigates **robotic integral attachments of timber plates** shells[30] (Fig. 5.22). The joints between plates employed in this research has been declared to be equivalent or even better than current traditional connection with screws and nails. The research relates the mechanical behavior with precise fit of the joints: the absence of any gap between the components ensures a tight connection and therefore a better employ of robotic arm since manual assembly of this kind of tight connections can be very difficult. The aim here is to **revolutionize the concept of joints** by avoiding any glue or nail and rely all the connections on through-tenon joints in a folded plate construction. Folded plates, as will be discussed in the further case-study analysis, proved to be structurally satisfying, starting from early experiments related with origami techniques. The machining of folded plates is longer and more complex then the wood beams which just need to be cut at their ends. In this case the workflow optimization is focused on finding the right balance between the force needed by the robot for the automatic assembly and the size of the wedges, to provide a smooth assembly process and an adequate resistance after the assembly without using glue or nails.

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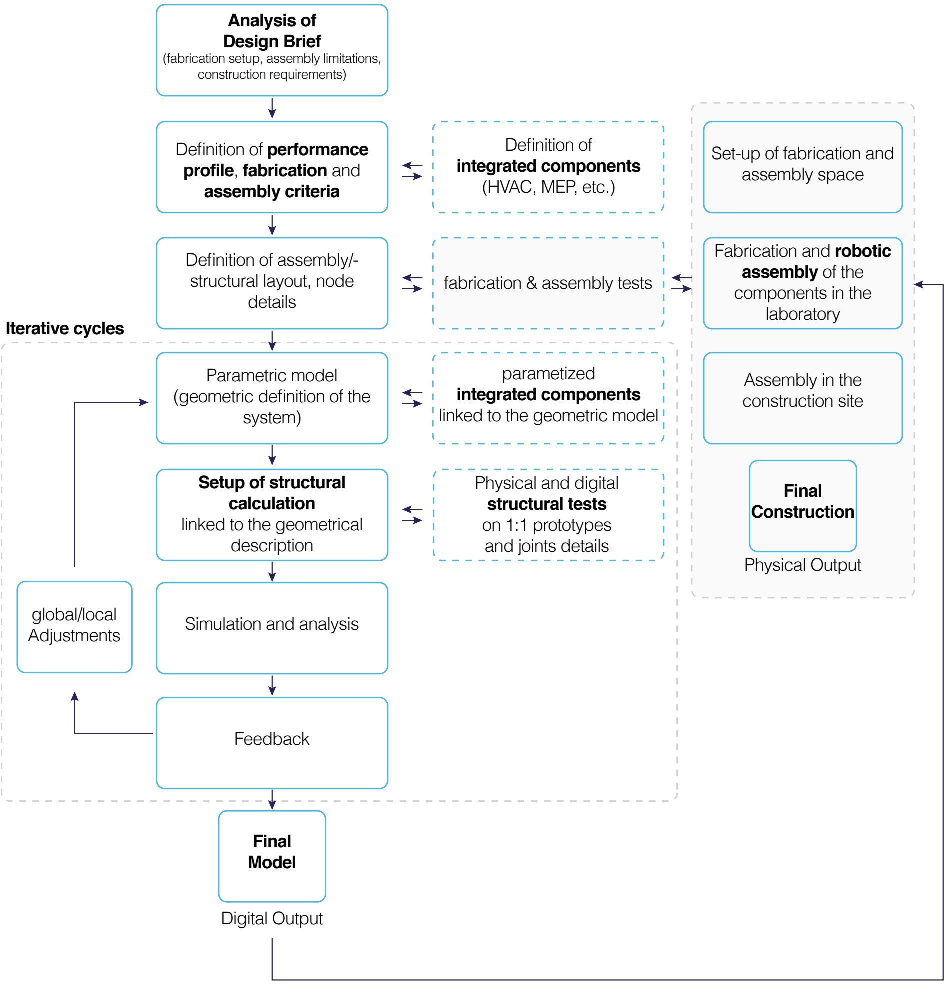
[30] Robeller C., Weinand Y., Helm V., Thoma A., Gramazio F., Kohler M., "Robotic integral attachment" in Menges A., Sheil B., Glynn R., Skavara M., "Fabricate 2017. Rethinking design and construction" UCL Press, London, 2017

Diagram for RTC design methodology



5.3. Methodology of custom robotic timber fabrication

This section analyzes an approach with a focus on digital fabrication tools – digital milling and cutting of wood through robots and CNCs – as part of the construction process in full-scale permanent buildings. This methodology develops a step further in a well-established industrial processing of wood in the building construction industry, fostering the applicability of such processes to full-scale architectural construction. In previous examples we have seen how through digital tools – from the parametric models to the analytical instruments till the interfaces for information transfer to and from the robots – architects have the possibility to manage both the design and the fabrication of non-standard advanced timber structures. Essentially, based on this principle, it is possible to identify two directions fostered by these tools in wood construction. On one side, these tools function as catalysts of novel generative processes of the architectural form, changing the traditional conception of design and production and bringing a scientific multidisciplinarity as one of the primary conditions of the process. In this case the performative potential of the material system and of the assembly process is explored. On the other side, the digital design and fabrication tools introduced a methodology which is yet innovative, based on a more traditional design thinking, upgrading the process to another level of formal freedom and tectonic correspondence between form, structure and material. In this case the use of advanced technology supports design choices as **non-standard fabrication tools** rather than as generative process of the form. This difference become evident when comparing the case studies presented in this section with the Morphogenetic or Robotic Timber Construction approaches. The projects presented in this section – the Centre Pompidou Metz, Timber Pavilion in Suzhou Horticultural Expo – feature a more conventional **top-down design thinking**, although some gravity-based form-finding techniques are used, the overall process is yet closer to a traditional one rather than to an experimental one. Such methodology supports the fabrication phases introducing robots and milling machines in the industrial process of component fabrication to satisfy the **customization requirements** of the project, based on a performative logic. These projects are lead and influenced by the rules of full-scale building constructions, since they must be open to the public they have to respect certain requirements. This methodology plays a key role in the **transfer of knowledge** from research to the building construction industry, favoring the application of non-standard design and fabrication strategies. Furthermore, within the workflow, this approach proposes an easier management of the building regulation-related issues (fire-poof and structural requirements or joints certifications for instance) and of the spatial layout, being based on parametric models.

Case-study: Centre Pompidou Metz

The Centre Pompidou Metz (Fig. 5.24) by Shigeru Ban and Jean de Gastines is a building which functions as cultural infrastructure with a considerable impact on the city of Metz, France, comparable to the Pompidou of Paris designed in 1977 by Renzo Piano. It is a space of more than 10.000 m² which hosts cultural activities and exhibitions and function as catalyst for this part of the city. The main concept is based on three large rectangular galleries – 80 meters long and almost 20 meters tall – covered by a double curved timber grid shell. The reference for the roof structure took inspiration from the straw texture of Chinese hats; translated in a building scale the straw strands are timber beams with a cross-section of 14x44cm. The structure is composed by hexagonal cells built through the braiding of six timber beams organized in four layers to solve the joint connections. The beams – which run for a total length of 18 km – pass through a parametric model which allows the management of the complex geometry and two fabrication processes; in the first fabrication phase the beam are produced in factory through lamination and bent along their primary curvature, while in the second phase the **robotic wire-cutting** implemented the geometry of each beam. One of the main constraints in the fabrication process was

Fig. 5.23 Detail of the double curved timber beams employed in the Centre Pompidou Metz

to keep the fibers continuity of the wood by limiting the cuts relative to fiber direction to less than five degrees. The structural engineering was curated by Ove Arup London while the specialist firm 'designtoproduction' worked as main technical consultant in the management of the complex 3D model[31] contributing to optimize the logistic and construction of the roof, not only for this project but also for another design by Shigeru Ban, Nine Bridges Golf Resort, in South Korea, which features an analogous structure. This highlights how new technical professions are emerging from the introduction of novel fabrication methodology in contemporary design, by this regard, Fabian Scheurer, founder of 'designtoproduction', affirms:

> "The recent evolution of parametric CAD systems and digital fabrication technologies has

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[31] As stated by its founder, Fabian Scheurer in "Materialising Complexity" in AD 04/2010 "New Structuralism" ed. Oxman Rivka., Oxman Robert, Designtoproduction, firm based in Germany and Switzerland, is building a profession out of the management for the construction of complex structures spreading in contemporary architectural approaches.

Fig. 5.24 Interior view of the Centre Pompidou Metz

> made its mark on contemporary architecture. It creates new prospects, but at the same time generates new challenges, mainly due to the immensely increased amount of information that needs to be handled in the planning phase. The integration of knowledge about structure, materials, fabrication and construction into the design is key to the creation of efficient planning and production processes, but let us be honest – this is nothing completely new, it should have always been the lodestar for every good design. Perhaps what has changed is the fact that all this knowledge has to be incorporated into continuously digital production chains that connect design, fabrication and building and ensure the efficient and frictionless flow of all the information, including all necessary translations between different data formats"[32].

Therefore, it is true, following the words of Scheurer, that every good design includes a coherent strategy of production with respect to the material properties, structural performance and functional requirements, but it is also true that the hyper-specialization typical of our times could cause a fragmented design process with the risk of losing the global picture. The Pompidou Metz is one of the **largest constructions** considered as case-study in the framework of this thesis, as such it is of interest to note how complexity and innovation in the production structural timber components can be interfaced with all the regulations and safety requirements that must be satisfied according to legal standards. The design process itself is closer to a traditional top-down approach, where the designer establishes the boundary conditions and thus operates through form-making approach. On the other hand, the fabrication and construction phases involved in this project, unfold the **innovative possibilities of mass customization** and fabrication performance techniques to produce double-curved structural timber components. However, the adoption of such strategies is still a bit more expensive compared to typical serial industrial-based fabrication processes. This is mostly due to the need of set-up a customized fabrication infrastructure, which is already expensive by itself, and to the difficulty in finding an adequate know-how able to manage the whole workflow. To this regard, this project represents one of the first attempts – since it was built in 2010 – to transfer the technological knowledge gained in research to the construction industry. Moreover, this direction pro-actively influences new visions for the architectural practice fostering alternative fabrication techniques and providing the technical and theoretical knowledge necessary to establish a smoother production process of double-curved structural timber components.

Case-study: Timber gridshell pavilion at Suzhou Horticultural Expo

The project for the temporary pavilion at Horticultural Expo in Suzhou, China, was supervised by Prof. Philp F. Yuan, founder of Shanghai-based architectural firm ArchiUnion,

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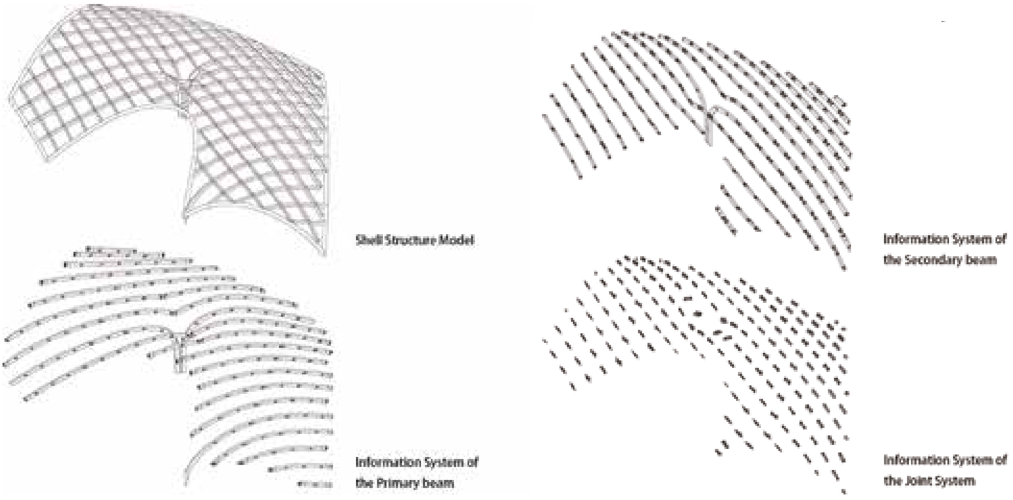
[32] Scheurer F. "Materialising Complexity" in AD 04/2010 "New Structuralism" ed. Oxman Rivka., Oxman Robert.

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

Fig. 5.25 Geometry system of the Pavilion at Horticultural Expo in Suzhou by Archi-Union



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

In a first phase a **form-finding process through structural simulations of a gravity-based shell** was performed. Then the grid was set up on the resulting shell, and a series of basic prototypes have been developed for the study of joint connections. The form-finding process, performed with RhinoVault (a Rhinoceros plug-in developed by Block Research Group at ETH Zurich) takes in consideration few constraints such as the site boundaries, the entrance, and a pillar as central supporting element that makes more complex the overall form. The form-finding process is limited to the calculation of static equilibrium of stress distribution based on gravity, for this reason a number of **structural simulation tests** were conducted to optimize the structure behavior also for lateral loads

Fig. 5.26 Timber gridshell at Horticulural Expo Suzhou during construction

(wind and seismic). These tests helped to define the **beams cross section which continuously varies** from 65 cm x 25 cm to 35 cm x 25 cm. The second part focused on a detailed development of the joints and fabrication of optimized components, which were studied according to local curvature and stresses. In particular, the primary beams and the steel joints were fabricated using traditional CNC industrial processes, while the secondary beams **cutting and drilling were implemented by robot**. The robotic fabrication was also used to mill the holes for the steel plates, since they are not perpendicular and they would have been difficult to realize by conventional techniques. The third part regarded the gap between virtual design and physical realization. All the information and parameter that affected the final geometry (including structural and fire regulation) were inserted in a virtual model which was later used to export the codes for the CNC machines, to perform the structural analysis and simulation for optimization. The final structure of this project, a 2000 m^2 space with a maximum span of about 40 m, demonstrates the potential of parametric design approaches through the workflow optimization, on one hand, and the customization possibilities of components thanks to robotic fabrication technique. It represents a hybrid of multiple fabrication methods, and one of the first application of such techniques in large scale building scenario in China.

Fig. 5.27 Robotic drilling of a beam for the gridshell pavilion of Suzhou Horticultural Expo

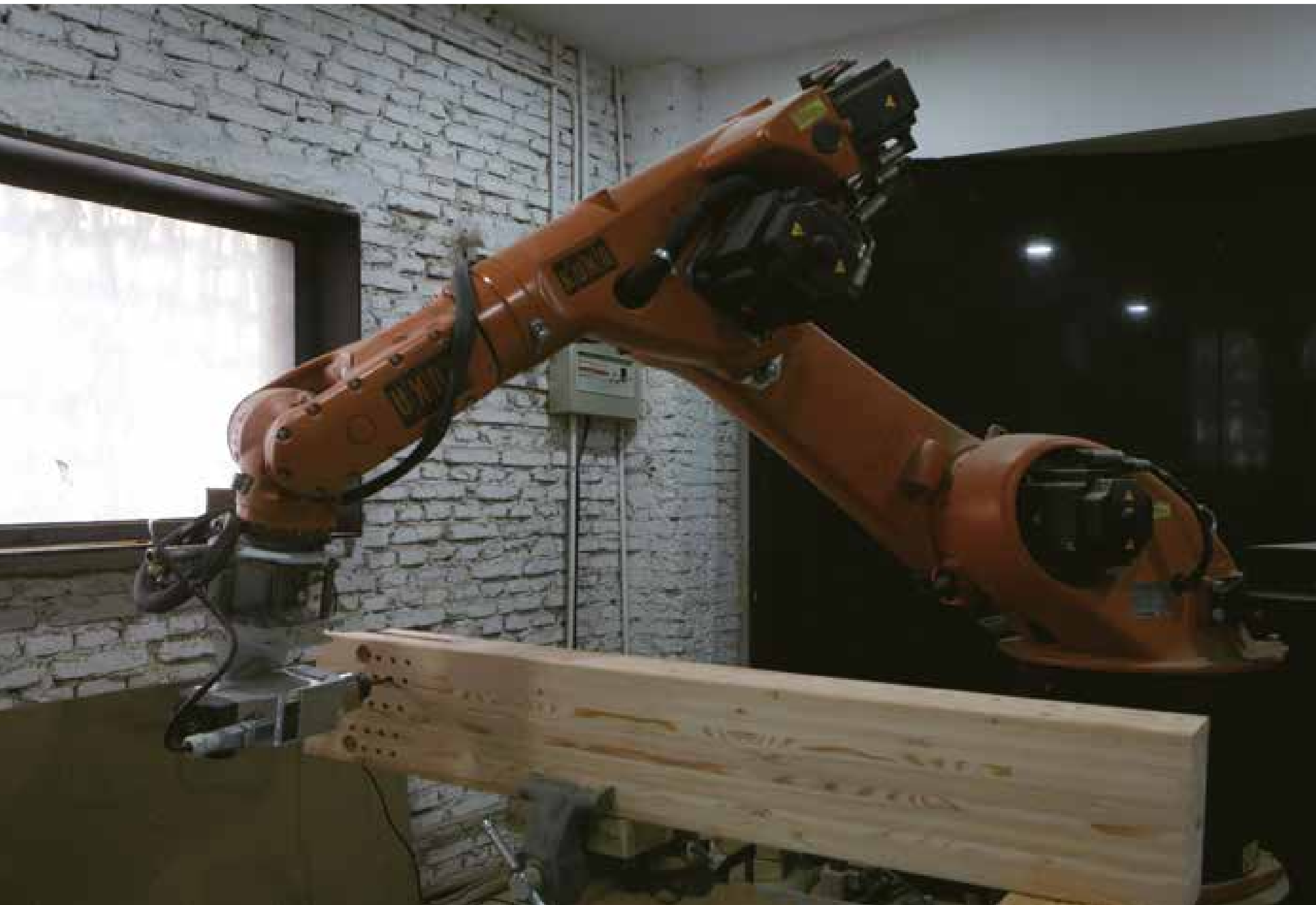
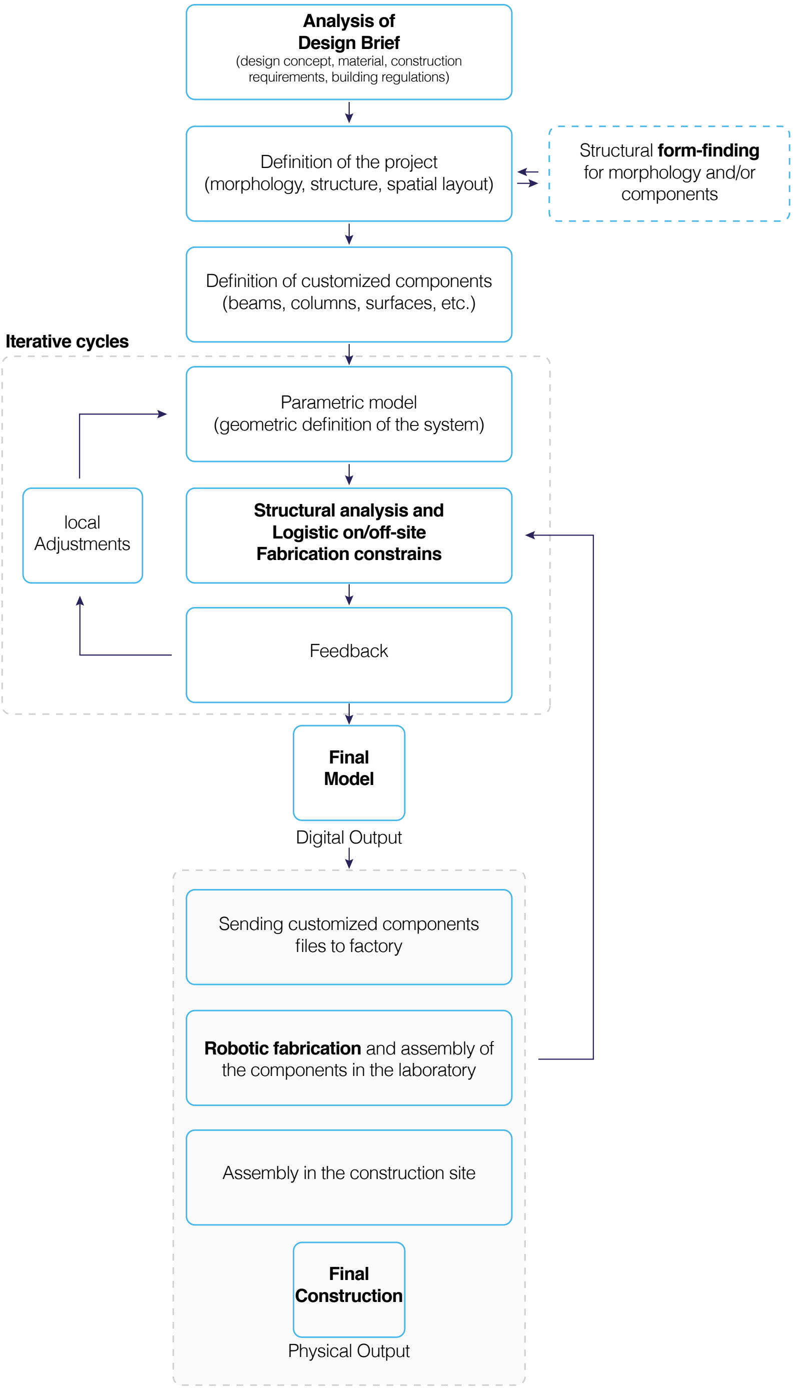


Diagram for custom robotic timber fabrication design methodology



5.4. Methodology of timber folded plates

Among the research project conducted by IBOIS laboratory at EPF Lausanne one of the most promising direction regards the construction of shells using folded timber plates. The laboratory presented many researches on this topic also assembling the plates to form hollow quadrangular differentiated sections. Some of these more articulated structures are still under development therefore it will be illustrated here the approach with simple folded plates. This so-called **surface-active structures** are **self-supporting and column-free shells configured as folded plates** that can have large spans with relatively thin plates. Robeller and Weinand[33] since 2006 investigate in this direction applying the flexible and sustainable characteristic of wood to an old structural layout used as surface-active structures in the construction of coal bunkers around the '20s. The first versions that employed folded plate layout in the coal bunkers were made of reinforced cast concrete and they also featured additional steel bracing on the diagonal of the plates faces that were gradually reduced and later removed because unnecessary for the structural performance. These structures did showcase a relevant structural resistance given by the rigidity of the fold between two faces. The construction of these in-situ cast concrete plates was labor intensive and in the years later several method were developed for construction with other materials among which fiber-reinforced plastic. A notable example that inspired the folded plates of IBOIS was the research presented by the by Z.S. Makowski at University of Surrey in United Kingdom. In 1965 he proposed an alternative **geometry of bidirectionally folded cylindrical vault** that allowed for the construction of **large shell from small components easy to handle**[34]. Later on the structural efficiency of these so-called antiprismatic shells was demonstrated by Pieter Huybers.

These contributions provided the scientific background to experiment timber folded

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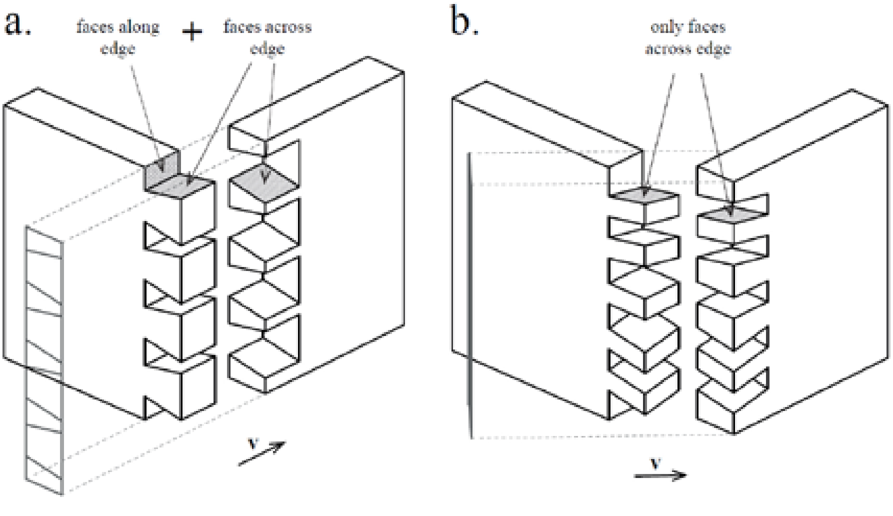
[33] The main references on this research are provided by: Robeller C., Weinand Y. *"Integral joints for timber folded plate structures"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

[34] Based on the researches by C. Robeller for his PhD thesis *"Integral Mechanical Attachment for Timber Folded Plate Structures"* EPFL, Lausanne, 2015, he states: *"[...] the prototypes designed and built by Zygmunt Makowski's Research Group and Pieter Huybers took particular advantage of the lightweight property of fiber-reinforced plastics.[...] The Folded-Plate Topologies of these designs were different from those of the concrete Folded Plates. Due to the relatively small faces, a corrugation in two directions was necessary, as well as a certain curvature of the entire assembly. These requirements were accommodated through hybrid Curved-Shell / Folded-Plates designs, which Zygmunt Makowski refers to as Folded Plate Barrel Vaults. The production of the individual parts and modules for these structures was carried out manually using molds. The designs were therefore typically assemblies of geometrically identical components, which could all be produced on a single-mold."*

plates at IBOIS using plywood panels given their favorable weight-to-strenght ratio, their availability in relatively large sheets and the ease of manufacturing of wood. The early experiments of IBOIS were based on a bidirectionally folded plate structure which also finds reference in the traditional Japanese origami paper folding technique. In the first prototype the components were connected through miter-joints with screws. The load stress tests demonstrated that a more rigid connection could improve the overall performance of the structure since, in this structure layout of folded plates, the fold is the most solicited part that acts as structural frame. Therefore, to provide a stiffer connection were employed **integral timber joints**. As discussed in the previous chapters, wood crafting techniques were reflected in the tectonic of the construction. In the pre-industrial age the manual labor, based on hand tools, allowed to fabricate customized joints for timber structures which were also related to the local cultural background and knowledge. Subsequently the industrialization replaced them with simpler connection, such as screws, rivets, nails, which were not necessarily structurally more performative but easy to produce in series. Today numerically controlled fabrication methods are able to **overcome the limits of serial identical production** allowing for the efficient production of variation between parts when required. An interesting consideration to this regard is that, starting from the 1980s, automatic joinery machines were capable of fabricating customized integral joints

Fig. 5.28 Comparison of two types of dovetail connections, in the European (a) one the insertion direction is perpendicular to a one plate and lies on the direction of the other, therefore it does not fit to a multi-directional and simultaneous assembly with other plates. While the Japanese dovetail joint (b) is geometrically formed to have an insertion direction more variable in relation with the angle of the plates and it does not necessarily lies in the direction of the plates. In a simultaneous assembly of multiple plates for a doubly folded timber shell this represented a suitable solution. Source: Robeller C., Weinand Y. *"Integral joints for timber folded plate structures"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017



similar to the hand crafted ones of the preindustrial age. A series of factors, among which the increasing demand for prefabrication, the replacement of manual labor with fabrication technology, and the improvement of computer, softwares and processing machines brought the automatic production of integral joints for timber frames to be a common state in the art of the last 20 years of wood manufacturing.

While there is a deep knowledge for timber frames that employ linear elements it is different for timber plates structures based on planar elements. The introduction of timber planar elements in the construction industry provided an enclosure in timber frame structures and worked as bracing at the same time. In these cases joints were not required between plates but only between the panels and the linear timber component (beam or column). With the introduction of new building products such as cross-laminated timber or laminated veneer lumber the structural layout can be fully based on the assembly of these structural plates. While the orthogonal connections of simple box-like timber building components can be easily designed and produced, the connections in surface-active plates structures are way more complex.

Fig. 5.29 Surface-active shell built at IBOIS as demonstrator for the structural resistance of timber forlded plates and the related integral attachments in wood. The shell geometry is based on a slighlty double curved arch and the connections are based on japanese dovetail finger joints.

This research by IBOIS unfolds the design and making issues and relate them with structural analysis and assembly criteria. The main studies are focused on alternative dovetail interlocking joints, often used in furniture design. A first consideration is that spruce plywoods provide a tighter connection than hard woods. Moreover, there are more advantages in using processed wood (plywood) instead of solid wood boards: in the first case the cuttings and connections can be made in any side of the panel because the crossing fibers direction compensate the material behavior, while in the second case the joints can be crafted only on the end-grain edges perpendicular to the wood fibers.

Dovetail connections are based on interlocking prisms which can be assembled only along one translational direction that determines the insertion vector. The geometry of the prisms can block all the movement leaving only one degree of freedom along the insertion vector and can therefore transfer shear stresses, traction and bending moments that occurs in folded plates structures. The research studied two types of dovetail connections (Fig. 5.28) derived primarily from furniture crafting: the European model and the Japanese one. In the European dovetail joint the assembly vector is perpendicular to the edge and lies on the face of one of the two plates. This is not an ideal solution for non-parallel edges of folded plates structure because it wound result in at least three different insertion direction which can never be assembled simultaneously. On the other hand the Japanese joint allows for an insertion vector that does not lie on either direction of the two plate. Thus it was studied in depth to understand the degree of flexibility in terms of maximum and minimum angle and it was tested on a **cylindrical vault** prototype bidirectionally folded. The vault was composed of trapezoidal panels and the sequence for assembly was studied in advance. The system, that did not used any additional connection other than the integral attachment of wood, proved to be very resistant: under a load equal to its self-weight only a deflection on 1/750 of the span was measured. The next prototype was based on a **double-curved vault** (Fig. 5.29), to deal with more complex geometrical conditions, where the second curvature was obtained from the incremental changes in geometry of the plates. Even this second arch proved the stability of folded plates structures with dovetail integral timber joints.

Research in timber folded plates structures and their relative connections is still going on at IBOIS and brought to develop other systems. A fundamental change is the employment of **mortise and tenon connection** between timber plates which, eventually, guarantee a stiffer and more stable structure. The research outcomes could be divided into two different paths. On one side the study is on the combination of timber plates to form hollow quadrangular profiles, very resistant to bending moment stresses, which allow to form double curved shells with a significant span. On the other side the exploration is still based on folded plates inspired by origami technique. Both researches employ mortise and tenon connection to join the timber panels. Moreover, a further implementation on this integral attachments is the robotic assembly[35] of such stiff connection, this approach has been quickly introduced in the previous section as it might be considered as more pertinent to the RTC methodology.

This research direction provides an essential method for the **stress transfer in surface-active structures** as the timber folded plates, and it fosters an alternative and efficient use of planar products available in the construction industry since a single system works both as enclosure and structure. The study on the integral timber joints opens the way to many explorations and unveils the tectonic character of such assembly and structural system in the definition of dynamic spaces. From a compositional point of view this layout recalls the projects of FOA, such as the Yokohama ferry terminal or the retail complex in Istanbul, of the early 2000s where the fold expresses the architectural dynamism of spaces. The folded plates layout finds connections with the recent theoretical history of digital architecture and, in addition, it carries a structural meaning that enhances the tectonic correspondence between architectural space, crafting technique, material performance. This method, by employing certified cross-laminated timber panels used in construction market, found less difficulties than other alternative wood processing strategies in the application of full scale buildings. Although labeled as 'temporary pavilions' the projects realized under the supervision of Prof. Yves Weinand, director of the IBOIS laboratory, contributed to get closer the research in digital technologies for architecture and the construction industry.

Considering the constrains and regulations, still very strict for timber constructions, the results achieved by the two small projects, a temporary chapel for the Deaconesses of St-Loup and the Vidy Theatre pavilion of Lausanne, demonstrated the applicability of such system on full-scale buildings open to the public. In the **transition from research to practice** there are many challenges to face such as the integration of impermeable membranes, vapor barriers, protection from rain, foundations, solve the interaction with architectural elements as windows and doors, integrate the electric systems and lights etc. Therefore, considering the experimental character of the structural layout made with wood, it is not trivial to apply research advancements in architectural practice. In this framework the temporary buildings are more flexible as they reduce some of the main legislative and practical constrains, and, at the same time, they are a useful mean to understand advantages and limitations of the method in a relatively small scale.

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[35] Robeller C., Weinand Y., Helm V., Thoma A., Gramazio F., Kohler M., *"Robotic integral attachment"* in Menges A., Sheil B., Glynn R., Skavara M., "Fabricate 2017. Rethinking design and construction" UCL Press, London, 2017

Case-studies: Temporary Chapel in St-Loup and Vidy Theatre Pavilion

The first of the two projects is the **temporary chapel** for the Deaconesses community of St-Loup. In 2007 the studio Localarchitecture and architect Danilo Mondada were requested to renovate the historical building of the mother house of the Deaconesses St-Loup community and, since the intervention would have lasted several months, they proposed to build a temporary chapel (which is actually still standing) where to accommodate religious worship during the renovation works. Instead of employing standard solutions they collaborated with IBOIS to design an innovative structure that showcased the current advancements on timber folded plates structures. The shape of the small chapel was generated using a digital geometrical construction method proposed by IBOIS[36] based on two input curves, the cross section and the plan profile which takes inspiration from the origami technique (Fig. 5.30). In this form-making process are incorporated the infor-

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[36] Buri H.U., Weinand, Y. *"The tectonics of timber architecture in the digital age"* in Kaufmann H., Nerdinger W., "Building with Timber Paths into the Future" p. 56-63 Munich, Germany: Prestel Verlag, 2011

Fig. 5.30 Exterior view of the final construction for the temporary chapel in St. Loup (canton of Vaud) designed by Localarchitecture, Danilo Mondada in collaboration with IBOIS laboratory of EPFL Lausanne

mations for structural evaluation and material fabrication through CNC machine. The structural principle relies on the stiffness provided by the folds; for a span of 9m the panels were 40mm thick for the walls and 60mm thick for the roof, organized in two layers, and connected by folded metal plates with screws. The steel plate connection was sufficient from the structural point of view and also faster and cheaper because the machining and design of integral joints is time consuming. From a structural and manufacturing point of view the folds increase the stiffness of the thin plates and allows to build a free space out of a structural solution which at the same time defines the interior space and function as an envelope separating the outside from the inside. The shell integrates support structure, insulation, lightning into one homogeneous form. The trapezoidal cross-section defines the simple structural principle with two plates as walls and one for the roof for each fold. This solution, compared to the experiment made in the laboratory, significantly reduced the number of component and cutting time, resulting in a faster and economical approach that is based on the same principle. From an architectural point of view the chapel recalls the shape of single nave church which, moreover, compresses the space toward the altar, and vertically pushes up the folds. This transition from horizontal to vertical gives a clear

Fig. 5.31 Interior view of the temporary chapel of St. Loup (canton of Vaud)

Fig. 5.32 Top: construction process of the theater pavilion on site. Bottom: interior view of the roof after the assembly of the strucutral elements; the through-tenon connections remain visible in the final construction

direction to the chapel and articulates the space with the rhythm of the folds as if they were columns of traditional church. This small project demonstrated how the integration of structural, architectural and engineering requirements into one design and make process is made possible only through a parametric workflow that, moreover, can bring to innovative results and evocate te tectonic character of timber construction.

The second project based on timber folded plates structure is the **pavilion for the Vidy theater in Lausanne**[37]. Even in this case the pavilion is a temporary construction built in the campus of the Vidy theatre where is also located the principal building of the 1964 and two other permanent buildings. The pavilion, built in 2017, substitutes a temporary heated tent creating both a better place for people and an opportunity for a technological transfer from research to practice. The theatre has a flexible layout with retractile seats that can be closed when a larger space is needed. The scene is not elevated so that it makes easier to adapt the space to multiple functions such as exhibitions or performance.

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[37] Source: https://ibois.epfl.ch/page-139247-en.html (accessed May 2018)

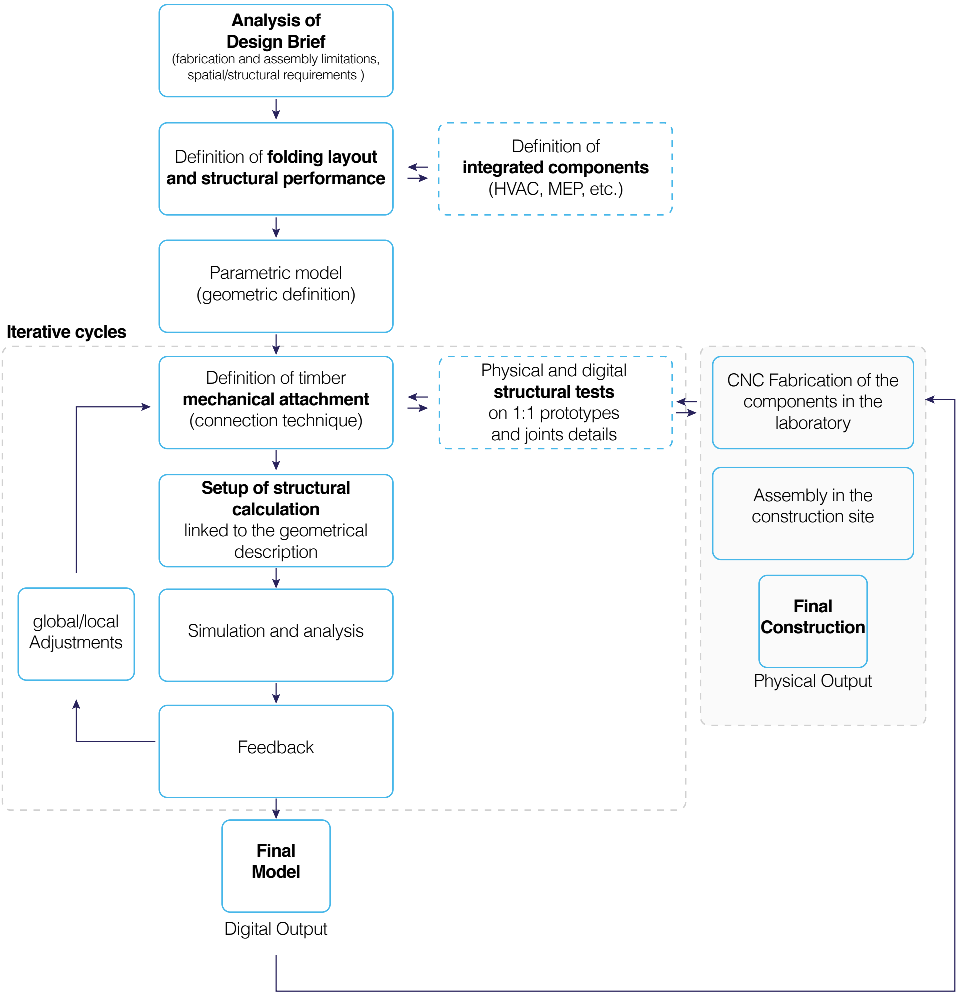
Fig. 5.33 Interior view of the theater finished with all the equipements of a full functioning building

The connection technique employed in this pavilion, representing the current research advancements at the IBOIS, is based on **timber mortise and tenon joints** without additional fasteners. The assembly of double layered folded plates becomes, once again, together structure and enclosure and, moreover, it defines the tectonic of the building, further highlighted from the connections visible from the inside. The previous experience of the chapel and the advancements in the research, contributed to a more aware design that better testifies the academic results and their transfer in architectural practice.

The theatre is assembled from prefabricated customized timber panels 45mm thick which were cut with a CNC machine. The **assembly system is based on a double layer** with a distance of 300mm that improves the stability of the roof/beam forming a stiff arch-like shape that concentrates most of the bending stresses along the folds (Fig. 5.32). The stress distribution was controlled on the digital model and the shape was adjusted to have an homogeneous situation through the whole structure. The span of the arches goes from 20m to 16m without any additional support. The space between the two layers is also used to solve functional issues integrating sound and heat insulation. The project coherently responds to the sustainability issues using old recycled paper and wood leftovers for the insulation, moreover the use of local wood and the CO2 absorption during its growth ensures a **low carbon footprint** of the whole construction.

Both projects presented here showed an integrative transfer of methodological and technological knowledge in the architectural practice. The development of a workflow that considers the final full-scale construction is a relevant contribution of this approach to timber construction proposed by IBOIS. In particular, here, the connection detail of integral joints (be it dovetail or through-tenon joint) represents the tectonic expression in the final structure. Not only the detail is visible in the final construction but its aesthetic reflects the *tekné* - aided by digital tools - and its relative structural purpose, defining, in this way, the tectonics of the construction. Such direct relation appears clear in the theatre pavilion, although many architectural issues remains unsolved, given its character of temporary construction, the system aesthetic reflects the essence of the construction principle.

Diagram for timber folded plates design methodology



5.5. Methodology of robotic raw wood fabrication

Wood intrinsic properties, deriving from fibers alignment, remain often unexplored and unexploited in architectural design since the development of engineered wood products introduced a more stable material with predictable behavior. Although outstanding results can be achieved in timber construction thanks to modern regularized wood products, on the other hand an alternative research direction aims to employ **wood in its natural form** to obtain the best of its performance. Wood in its natural form keeps intact the chains of fibers that are **naturally optimized to transmit forces**, while the interruption of fibers continuity with cutting and re-assembling compromises the original performance. There are many other advantages derived from processed wood but a fact is that in the process wood is homogenized as any other material. This generalizes the employment of wood as a mean to achieve a shape rather then a material whose complex characteristics can be exploited to obtain a better performance. Moreover, aside from the differences in the performative aspects, wood is produced almost anywhere but its processing requires a centralized infrastructure, as for steel for instance. This means that the wood environ-

Fig. 5.34 Workshop building by Frei Otto at the Hooke Park during construction. The wood structural elments are formed by bent raw wood harvested from the surrounding forest.

mental qualities - CO_2 absorption during the growth process - are compromised by the energy used for transportation and heavy material processing. Current economy, based on industrialized serial production, favors the constant production amount of raw material causing, in the case of wood, intensive mono-cultures. This trend, from an environmental point of view, goes against the need of forest diversity aimed to increase plant robustness and reduce climate change[38]. An alternative model is the distribution of a localized wood production for architecture would be more sustainable since it would require less energy input. In order to promote such model new fabrication and construction tools and techniques, together with the innovative information exchange and ease of communication, needs to be exploited and further developed.

This approach has been embraced by Architectural Association of London through the "Design&Make" program settled in Hooke Park, a 150-hectare woodland in the west of England. Before that AA inherited the woodland, in 2002, it was already an experimental campus to test novel approaches to timber construction managed by the Parnham School of Woodland Industries and in which Frei Otto designed and built two significant structures that summarize the research ethic of this direction. These two buildings are the Prototype House - today the refectory - and a Workshop building that make use of roundwood without excessive additional processing. In the Prototype House Otto exploits the tension strength of wood through a structure layout based on spruce elements in tension on the roof. While in the Workshop (Fig. 5.34) thin roundwoods are elastically bent to form catenary compression arches that supports the roof, the load transfer in this way is aligned with the plant grains direction ensuring the maximum structural performance. Since AA took over the Hooke Park continued the research on natural form wood employed in architectural construction. The research at Hooke Park is conducted through the teaching master program "Design&Make" which offers students and tutors the chance to **study and explore the characteristics of raw wood and directly employ them in the fabrication of a full scale construction**. The first of a series of constructions, that follow this research-by-design approach of the school, is the 'Big Shed' (Fig. 5.35) constructed from roundwood larch and that became the main building for fabrication activities. The building structure is based on **customized truss beams made of raw wood** - from the woodland of Hooke Park - where the components are linear and simple and the steel joints are engineered to fit the different connections. The wood skeleton is covered by a folded surface of corrugated steel cladding for the roof, and red cedar planks from the surrounding forest for the walls. The space today hosts the robotic fabrication lab and is an opens

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[38] Self M. *"Hooke Park. Applications for timber in its natural form"* in Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach"*, Routledge, Abingdon and New York, 2017

space for prototypes construction and timber framing activities. Together with this, other constructions have been added to the campus in the latest years, from student facilities and dorms to experimental structures, all of which are based on an analogous methodology and use of local material.

The use of raw wood to exploit its natural form and get the best of its **structural performance** avoiding the interruption of fibers continuity, is further implemented at Hooke Park through the application of digital scanning technologies. The project for the Biomass Boiler House of the campus is made using natural curved tree trunks stack one on the other, like log cabin construction, to form a curved wall. The 3D scanning helped to create a database with information about the geometry such as the principal curvature of the centerline, and then use it in a form finding process. In this framework a new research direction is leading the upgraded philosophy of the school and it takes reference from the use of curved wood branches in English and French warship building during the 17th century. In ship constructions the geometry of different components were matched with naturally grown tree forms. The principle is that in natural branching the grain structure

Fig. 5.35 The 'Big Shed' is a large space built using straight round-wood assembled to create customized truss beams. The space is used by students, tutors and workers of the Design&Make program for the robotic fabrication phases of the various projects.

evolves to produce maximum resistance to the forces it is subjected to, therefore the trees were mapped and surveyed to maximize the availability of curved timber shapes. Using 3D scanning and digital form finding AA studied workflow to configure wood branching components in an optimized topology.

Case-study: Woodchip Barn

Digital technologies in architecture unfolded the potential of non-standard components fabrication leading to new tectonic visions in the architectural debate, especially in the case of wood as construction material. These technologies are able to open up the exploration of raw, unprocessed, natural wood components to organize them in **optimized topologies**. This research project by AA master students of the "Design&Make" program aims to exploit natural branchings of wood in a **spatial truss arch**. The branches of trees have natural joints that are able to carry significant cantilevers optimizing the material use. In that point the complex distribution of the fibers maintain their continuity, providing a better material behavior than an artificial joint. In line with this principle, the Woodchip

Fig. 5.36 View of the wood-chip barn designed and built at AA Hooke Park using local raw wood. The structural principle is based on the use of tree bifurcations which have been computationally assembled based on thei geometric and structural characteristics.

Barn project tries to make full use of this capability of natural wood thanks to 3D scanning, digital evolutionary solvers and robotic sawing and milling. Beyond experimenting a novel method for design and fabrication of natural wood based structural layout, this workflow also avoids the energy-consuming industrial processing of wood using directly the geometries that the surrounding forest can provide. The Woodchip Barn is based on a structurally determined arch that functions as a Vierendeel truss made with **wood forks** selected from the local woodland of Hooke Park. Once stated the concept's principles and defined the boundary conditions, the first operative step was a photographic survey and the relative creation of a **database** to decide which trees needed to be cut. The initial survey brought about 200 beech trees and provided an approximated idea of the encountered topologies. Among these a second selection was made based on two-dimensional representation[39] for a geometrical evaluation, resulting in about 40 suitable trees which

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[39] Given the height of the branches from the ground, around 5-6m, it have been very time and energy consuming to physically measure the diameter for all of them. A 23-segments polyline, that simplified and made measurable the photographic data collected, was used to trace the perimeter of the fork branches visible in the

Fig. 5.37 Wood-chip barn during the construction phase after the completion of the raw-wood truss arch and of the lower walls.

fit the criteria of the pre-engineered truss arch. At the end of this second selection process 25 trees were harvested. All the forks were detailed 3D scanned with photogrammetric method; once the **mesh** was created from the points-cloud the centerline of each fork was extracted. Given the irregular shape of a tree trunk another simplification was needed to overcome the geometrical complexity. A set of planes intervalled at regular distance was used to obtain the cross sections along the geometry and determine their relative centroid through wich the centerline would pass. This extraction method for the **centerline** proved to be sufficiently precise for the end points of the forks while larger deviations were registered in the node but that was disregarded since no fabrication operations had to be done in that point. The next step was to organize the forks on the truss catenary arch. The **truss is based on two inclined catenary arches in a Vierendeel configuration** that exploits the moment resistance of the forks nodes[40]. Together with engineers from Arup

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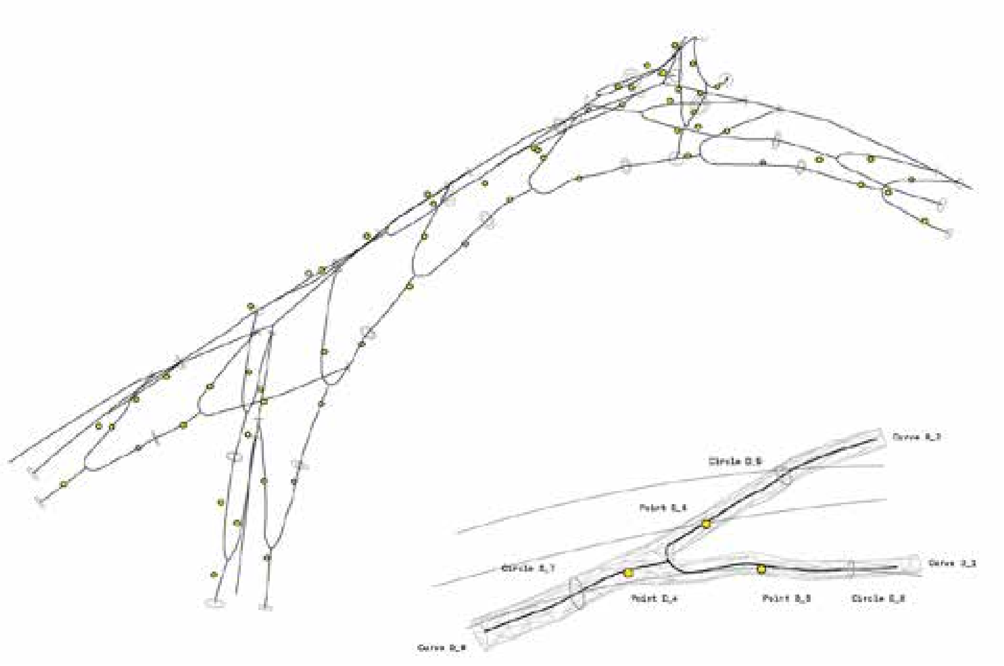
picture and delivering an approximated diameter size.

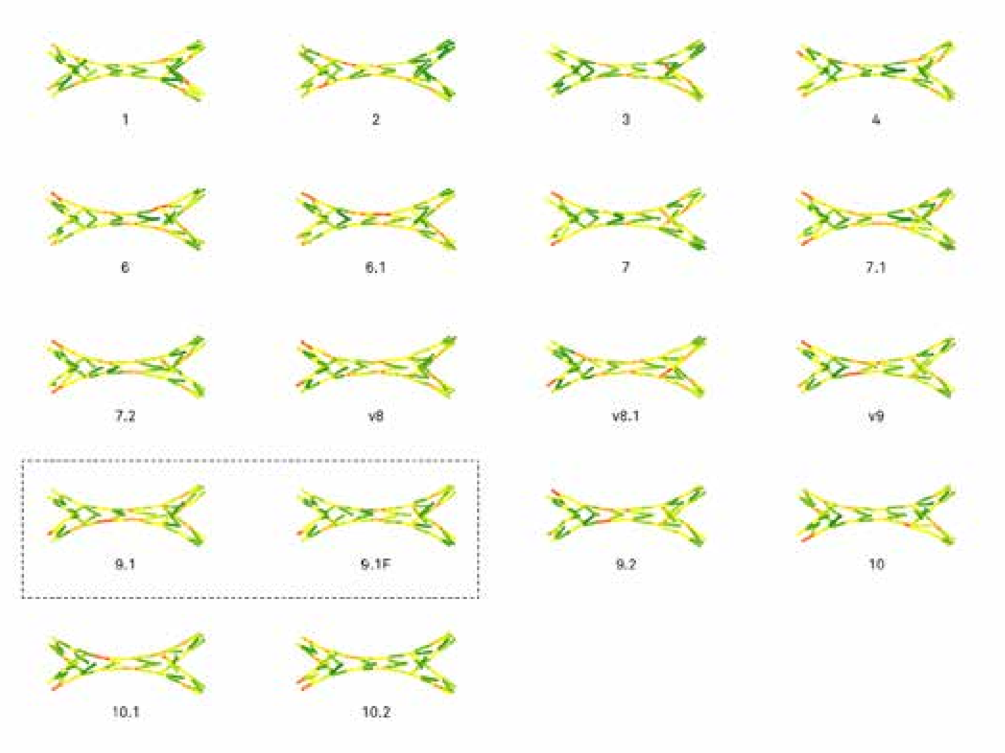
[40] Self M., Vercruysse E., *"Infinite variations, radical strategies"* in Menges A., Sheil B., Glynn R., Skavara M., *"Fabricate 2017. Rethinking design and construction"* UCL Press, London, 2017

Fig. 5.38 Diagrammatic view of the fork's centerlines in the final configuration. The grey circles indicate the start/end points of the forks, while the yellow dots (three for each fork) are the points that function as reference system for the correct orientation of the fork in the space.



it was decided to use an equilateral triangular cross section for the truss arch, to better fit the forks, with a side of 90cm. The two inclined arches formed the sides of the triangular section while straight transversal components (that act as lower chords) formed the base. The final truss-arch is supported by four ‘inverted tripods’, where, in each of support, the three vertexes of the triangular cross-section converge into one point. One of the challenges of this project was achieve an adequate construction precision since the original material exhibited complex irregularities. To avoid as much human crafting as possible (which however remained an important contribution in this workflow) and to leave to the robots the milling of connections among the forks, a **reference system** based on three points was set up. The system functioned as physical and digital reference and helped to determine the components position in every phase of the project, from the harvest to the location in the final construction. The three points were physically drilled on the three forks, one on each branch, and defined a local origin point, orientation axis and plane. The holes were also surveyed through the 3D scanning and they were included in the digital model and finally they were transferred back to the physical world and used as support points for the

Fig. 5.39 Resulting configurations from the evolutionary solver and selection of the fittest individuals.



robotic fabrication process[41].

Based on this setup an **evolutionary solver** helped to determine the best **position of the forks** on the target curves of the arches. In the Rhino-Grasshopper environment an organizational algorithm was based on a sequence of three transformations. The first was to move the principal branch of fork on the lower curve, then a 3D rotation was needed to match the same curve with a point on a secondary branch, finally another rotation found the intersection of the third branch with the upper target curve. The final step was the **evaluation of deviations** between the placed geometry and the target curves. The minimization of this deviation would contextually minimize the non-compressive force distribution. This pattern was used for all the components in each iteration of the evolutionary process, and it became more articulated by adding further fabrication infor-

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[41] Mollica Z., Self M., *"Tree fork truss. Geometric strategies for exploiting inherent material form"* Adriaenssens, S., Gramazio, F., Kohler, M., Menges, A. and Pauly, M. (eds.), Advances in Architectural Geometry 2016, Zurich, p.138-153.

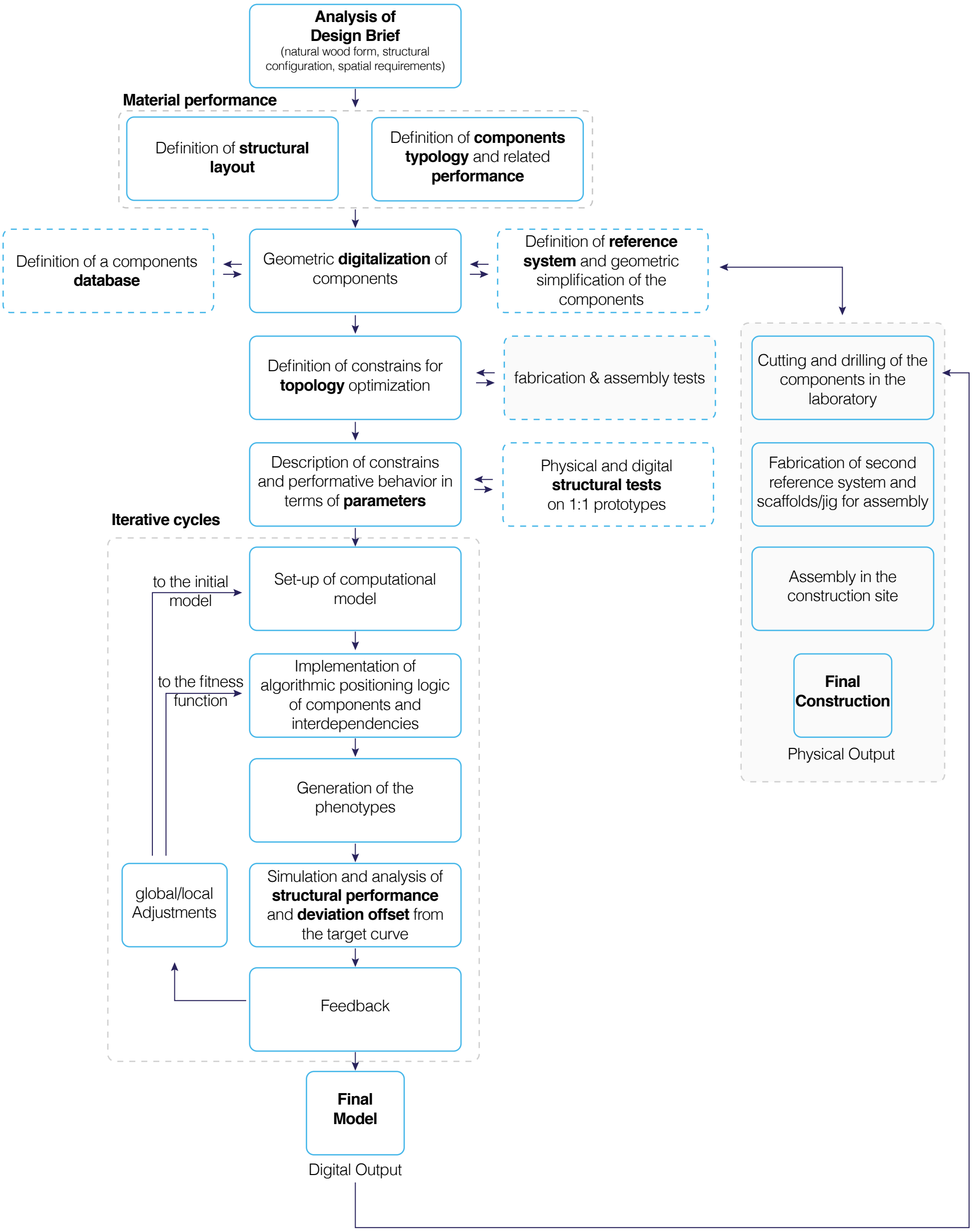
Fig. 5.40 View of the roof truss arch for the Woodchip Barn project in Hooke Park

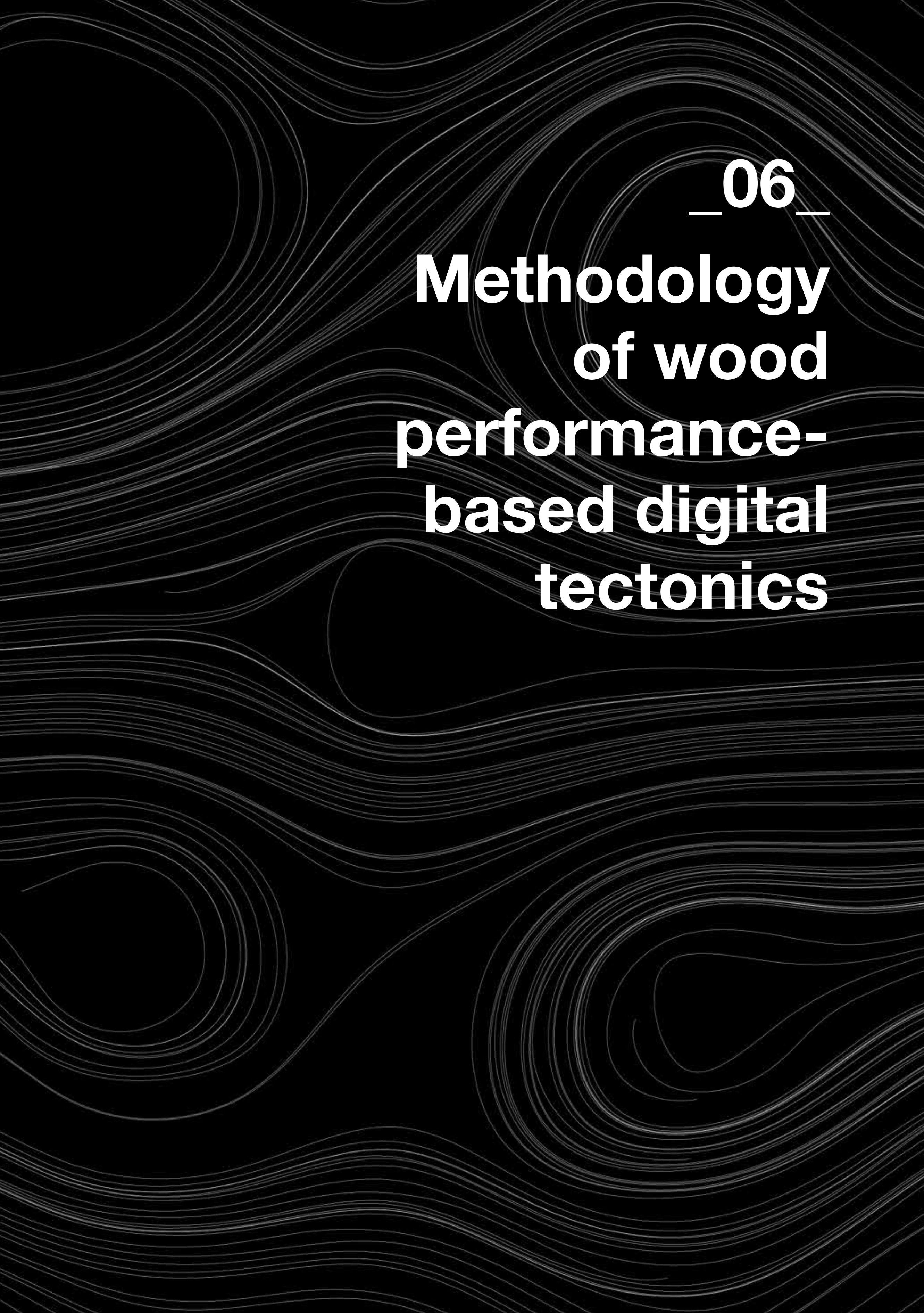
mations and constrains. In the iterative process the forks were allowed to move globally (change their position in other points of the target arches) and locally (adjusting their position in that point of the target arches) aimed to minimize the deviation from the target curves. From the iterative procedure, which was the core computational challenge of the project, a series of possible truss were output and structurally analyzed to select the best configuration based on structural performance. The complex computational procedure led to the final structure, and its the 3D model was used to determine the informations for robotic milling and sawing. The **fabrication** was based on determining the subtractive volume to mill and to program the robot toolpath to achieve that geometry. The reference system with the three drilled points was fundamental in this phase to correctly locate the component from the digital to the physical robotic environment. Moreover the tolerances for this robotic fabrication approach for non-standard wood components were augmented from the usual ±2mm to ±10mm, since it was not possible to exactly locate the surface geometry of the component the subtractive volume used was larger than the tree itself. In the assembly process the strategy for the connection was to maximize the transfer of compressive stresses, giving continuity to the catenary arch, and use steel bolts to prevent shear and tension stresses where needed. **Three types of connections** were fabricated in relation with the different meeting points within the structure. The first was the connection along the truss-chord, joining the planar faces at the endpoints of each fork, and holding them together with a couple of steel bolts. The second connection type was between the end of the branch and the upper chord, achieved though an oblique through-bolted mortise and tenon joint. The last type was used to connect the smaller reinforcements truss to various points of the forks; the mortise and tenon connection was based on different primitive geometries to be milled from the forks.

After the fabrication was finished an assembly jig was prepared to join together the complex building components. The arch was pre-assembled in two smaller parts of about 8m by 6m. The two parts were made of 10 forks each which needed to be carefully and precisely assembled in order to build the whole arch and then connect every joint. To achieve this precision a **second reference system** was made from three new squared holes that where milled by the robot during the fabrication in such a way that they would be vertically oriented when the component is in its final position. Therefore the **scaffolds** were built using CNC milled OSB panels which vertically stand and fitted the square holes of the forks lifted into place by a crane. The two arches were first assembled and then joined through the bracing components. In the final stage the worker checked all the joints and adjusted them according to the Rhino model to get as close as possible to the intended position.

This project opens up an important exploration on multiple levels. It brings a new methodology for the design and construction of structures based on raw wood components. One of the most important contribution is the unfolding of the computational process, through an evolutionary solver, that needs to be set up to manage the automated positioning of non-standard components which the computer is able to optimize. Moreover this method also experimented a robotic fabrication approach to the complexity of these non-standard components, which is one of the most critical parts when passing from the digital model to the physical reality. Ultimately, the **tectonics of the construction** assumes a relevant and radically new role in this architecture as it relies on an innovative use of raw wood, upgraded by the **digital crafting**, but showcasing structural performance of unprocessed wood. One last consideration is that this design process employed computational morphogenesis using predefined components (the forks) to be assembled in the best possible configuration. Although the role of the **morphogenesis** resulted essential for a successful result of the project, the principal feature of the design and fabrication approach is the use of wood in its natural form for architectural construction. Therefore it is still functional to distinguish this methodology from the others, being strongly characterized by more evident features than the morphogenetic process, remembering that the presented subdivision are not strict and aims to propose a clearer interpretation of the current state of the art in research.

Diagram for robotic raw wood design methodology





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Methodology of wood performance-based digital tectonics

Contents

6. Methodology of wood performance-based digital tectonics

The following section will describe the workflow of **three research projects** which investigate the performative capacity of wood and test the application of robotic fabrication, according to a proposed methodology. The projects have been successfully realized during an academic exchange at Tongji University of Shanghai under the supervision of Prof. Philip Yuan, on-site, and Prof. Carlo Berizzi of University of Pavia, off-site. For all of them the available amount of time was very limited, since they have been developed in the framework of international workshops, therefore they left open many possibilities and sparks for future developments. In spite of this, considering the research context, the tools and knowledge available, the results were promising and represent a step forward in the exploration of wood digital tectonics in the contemporary research agenda. The **first** project for the exploration of the methodology is the design and fabrication of a wood structurally optimized chair inspired by natural organisms. It is not a morphogenetic approach, while it rather takes inspiration from some features present in natural structures. The choice to use a chair as initial model offers the opportunity to have a first approach on a simple prototype to test and unfold procedural, structural and aesthetic issues. The **second** project is a strained gridshell pavilion for the DigitalFUTUREs Shanghai 2017 annual workshop. It tests a new process to generate a strained grid on a complex double-curved surface. Strained gridshells use to have limitations in their geometrical complexity because the of the problems that can arise during the erection, this research proposes an alternative workflow to generate the curves network and reduce their curvature to extend the application on more complex surfaces. The **third** project was the tectonic tower pavilion for the DigitalFUTUREs Shanghai 2018 workshop. Based on Chinese traditional tectonics determined by the joining principles, the project proposes a reinterpretation of it into digital tectonics of wood structure through robotic fabrication techniques. In particular, it tests interlocking nail-free and glue-free joints for timber linear components. As the current research agenda proposes many examples of interlocking timber plates using planar components, this research expands the exploration of interlocking joints to linear elements.

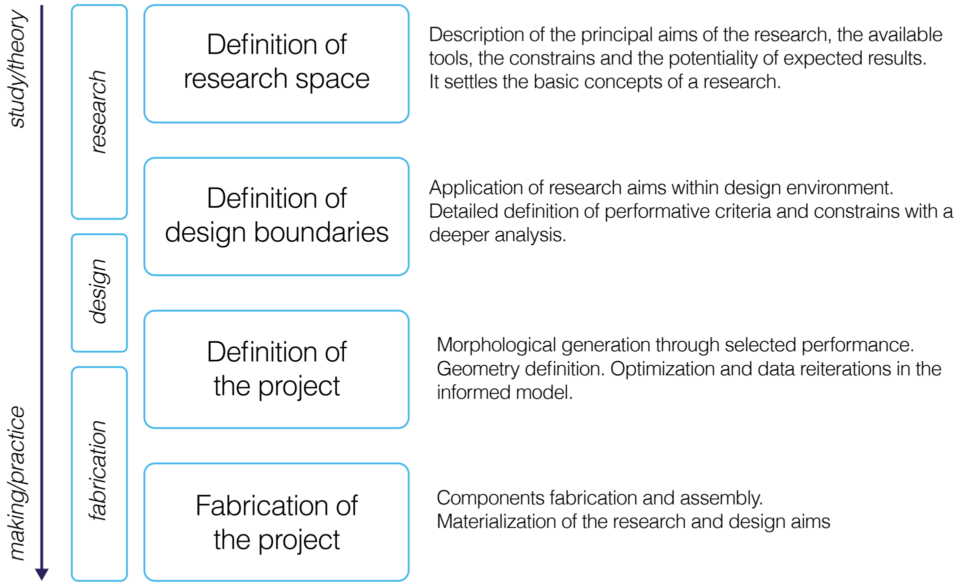
Although different among each other, because they are representative of different stages of this research matured over the last two years, the presented contributions supported the definition of a further design methodology to approach wood digital tectonics in a performance-based design strategy. The methodology elaborated through this research-by-design experience have been derived unfolding the design workflows of the three projects and embed them in an integrative approach for the exploration of wood performative behavior. This methodology intends to offer an additional interpretation of the performative wood architecture focusing on the **tectonic correspondence between structural**

response, material use, spatial definition and digital crafting. A distinction needs to be made between the concept of methodology and workflow as employed in this thesis. On one side, a 'methodology' have been identified as the set of interrelated concepts that describe the global design approach and supports the definition of a strategy. On the other side, a 'workflow' represents the unfolded process specifically linked to the different operative steps taken on during design and fabrication phases. Therefore the methodology is here intended as the general/global strategy applied through a specific/local workflow.

The methodology have been divided in four phases which describe the research strategy from the initial theoretical phases to the operative digital crafting and assembly, considering them as interrelated stages to achieve an integrative design. Therefore the steps are organized in a transition from 'studying' to 'making'.

The first phase is the **definition of the research space** which is related to the research agenda; it includes the description of the principal aims of the research, the available tools, the constrains and the potentiality of expected results. This is a brainstorming phase where no lines are drawn but instead it settles the basic concepts of a research.

Fig. 6.1 Proposed structure for an architectural design methodology of wood performance-based digital tectonics



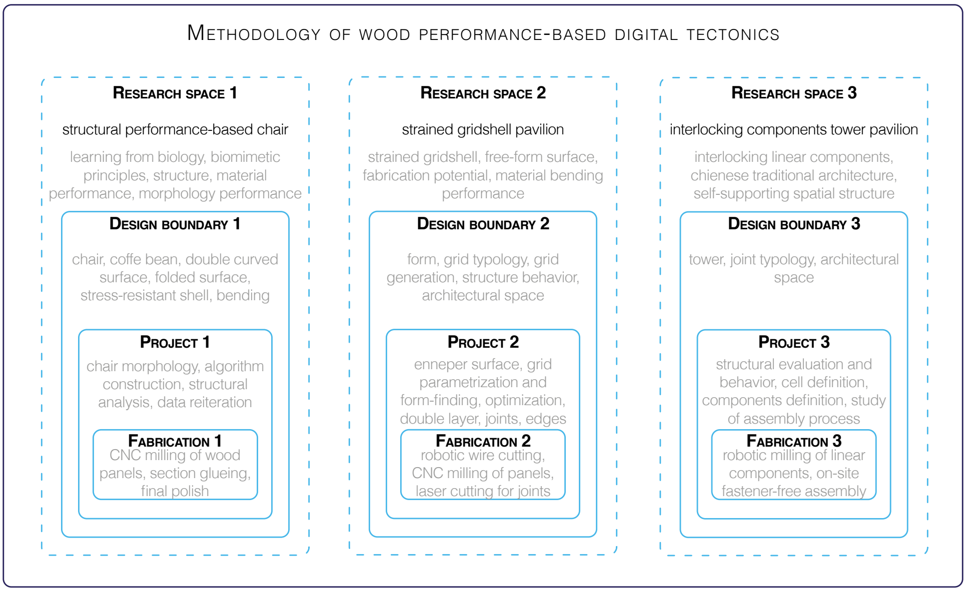
The next step is the **definition of design boundary conditions** and is related to the “design brief”; it brings together research aims and design features, it is a more detailed phase than the previous with a deeper analysis, the criteria and constrains are more selective and explicit.

The third identified step is the **project definition**; it introduces the morphological generation and the performative features as generative factors, it includes reiterations of structural simulation for the optimization, it is a phase in-between design and fabrication since it considers construction issues as well.

The last phase is the **project fabrication**; it is a mainly operative phase were the fabrication and construction physically take place, it materializes the research and design aims.

All the phases are interrelated and inform one each other in an integrative workflow: for instance the fabrication constrains determine the construction details and therefore influences the global component assembly; or the material properties inform the fabrication process and the structural behavior.

Fig. 6.2 Organization of the projects within the frame of the proposed methodology



6.1. Design and fabrication of a performance-based wood chair

[Phase 1: definition of the research space]

The first research project that is here presented, supervised by Prof. Philip F. Yuan (Tongji University of Shanghai), aims to showcase an approach of "learning from biology" applied to the design of a chair, employing a performance-based design strategy derived from the analysis of natural organisms. The object 'chair' is taken as a prototype model which offers incredible variations within a wide design space; it is one of the most explored objects in history of design. Since, in this case, the aim is to explore a alternative design methodology, the **chair represents an ideal model for testing an experimental approaches** because it is an object with simple and commonly defined properties: it requires a specific load-bearing capacity easy to manage and calculate (the average weight of a person), it has a clear and simple function and it is open to infinite aesthetic possibilities. Therefore, working on a small-scale element reduces the complexity of many issues – involved in a

Fig. 6.3 Final prototype of the chair

building for instance – and allows a better control over the fundamental aspects of a design process – from concept to fabrication – suitable for the exploration of structural performance and optimization "learning from biology".

This research approach of experimental testing **through chair-design** has been widely employed in computational design during last years to asses both innovative digital design methodologies and digital fabrication techniques (from 3D printing to CNC wood-milling machines). To mention some examples, at last ACADIA conference 2016 were presented some experimental design approaches focused on structural optimization and fabrication. The "Durotaxis Chair" (Fig. 6.4) explores *"a material-based design process by responding to a challenge of designing a 3D print rather than 3D print a design"*[1]. In this concept, the material and the process of fabrication determine the generative design and the process to follow for its realization. The chair, fabricated as a half-scale prototype, features a three-dimensionally defined wired mesh which varies in density, color and rigidity and it is inspired both from the biological process of cell-migration, *durotaxis*[2], and from the variable density structure of the bones. Another example presented at the ACADIA conference 2016 is the work of Gilles Retsin and Manuel Jimenez Garcia of Bartlett School of Architecture/UCL, which explores the potential of toolpath design for a spatial 3D printed method (Fig. 6.5). The research tries to solve the problem of continuous space printing for large-scale structure. In continuous systems, the problems that can be encountered are infinite and all different, moreover each problem requires a specific solution. It would be very time consuming and it would need a huge amount of algorithmic work and use of memory, to solve and predict every time a different problem that could be encountered during the printing. To avoid this condition the research team focused on a method to limit and serialize the problems which can share the same solutions. The strategy is to use a discrete fabrication method through a voxel[3]-based approach. A continuous path

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[1] Huang A., *"From bones to bricks. Designing 3D printed Durotaxis chair and La Burbuja lamp"* in POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines: Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)

[2] Durotaxis is a form of cell migration in which cells are guided by rigidity gradients, which arise from differential structural properties of the extracellular matrix (ECM). Most normal cells migrate up rigidity gradients (in the direction of greater stiffness) – Wikipedia accessed in May 2017.

[3] A voxel represents a value on a regular grid in three-dimensional space. As with pixels in a bitmap, voxels themselves do not typically have their position (their coordinates) explicitly encoded along with their values. Instead, the position of a voxel is inferred based upon its position relative to other voxels (i.e., its position in the data structure that makes up a single volumetric image). In contrast to pixels and voxels, points and polygons are often explicitly represented by the coordinates of their vertices. A direct consequence of this difference is that polygons are able to efficiently represent simple 3D structures with lots of empty or homogeneously

is generated combining curved toolpath segments with a voxel-based data structure. A combinatorics algorithm is used to link together all the voxel-based segments, in this way, the number of problems is limited to amount of connection between the segments. The method has been applied to the model of the Panton Chair which for its complex and continuous geometry is suitable for the aim of the research. The model is voxelized and then, according to the structural analysis and stress distribution, the density of the pattern is modified using four different scale of voxel segments, the smallest are for the most dense and stressed parts and the largest are for the less stressed parts and create a less dense pattern.

Learning from biology: analysis of the coffee bean

[Phase 2: definition of the design space]

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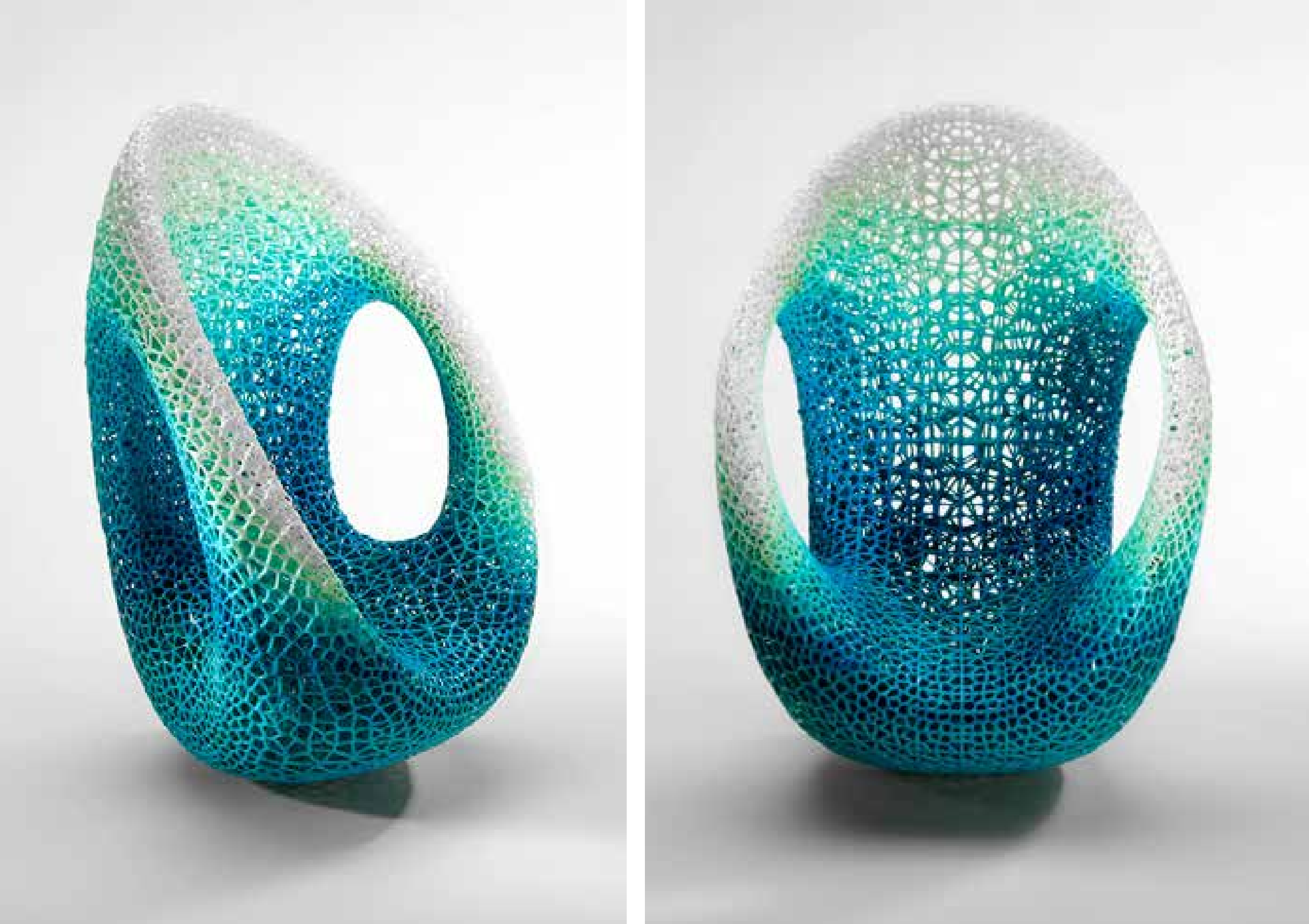
filled space, while voxels are good at representing regularly sampled spaces that are non-homogeneously filled. – Wikipedia accessed in May 2017.

Fig. 6.4 Prototype of Durotaxis chair by Alvin Huang, USC



The project here presented aimed to develop a structurally performative design based on the analysis of a natural element and its structural-geometrical properties. The chosen element to be analyzed is the **coffee bean**, which, for its geometrical construction, is strongly characterized by a visible seam that makes it different from any other bean. An analysis of the coffee plant and bean has been conducted, both at micro and macroscopic point of view, looking for the very peculiar characteristics regarding geometrical and structural properties. At the **macroscopic level** the plant presents a pentagonal flower and it often grows creating small and dense groups of flowers that will later give the cherries. The coffee tree develops according to a common triangular shape while it grows in height. The microscopic scale has also been taken in consideration, looking for patterns or structures that could determine the formation principles. Analyzed through the microscope the coffee bean presents the typical cell structure of a vegetable. The coffee microscopic structure resembles a Voronoi[4] tessellation, this is not one of its most evident and characterizing

Fig. 6.5 Study prototype for a 3D printed chair by Gilles Retsin and Manuel Jimenz Garcia at UCL Bartlett

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[4] In mathematics, a Voronoi diagram is a partitioning of a plane into regions based on distance to points in

properties, since such structure is very common in vegetables.

On the other hand, the study focused on the understanding of the most typical feature, that makes the coffee bean unique, is its **peculiar central “seam”** resulting from the **growth process.** Looking at the cross section of a green coffee cherry it is possible to note that it contains, typically, two symmetric beans, each of them grows starting from the center occupying the space of half cherry (Fig. 6.6). From a merely geometrical point of view the two beans develop as double curved surfaces folded on itself which starts and finishes in the center of each bean. In this point the characteristic “seam” is formed as a consequence of the start and end of the growth process. Moreover, this **rolled surface**, creates a **compact shell** which, at this small scale, functions as “structure”, or stress-resistant feature of the bean, that protects the internal soft tissue.

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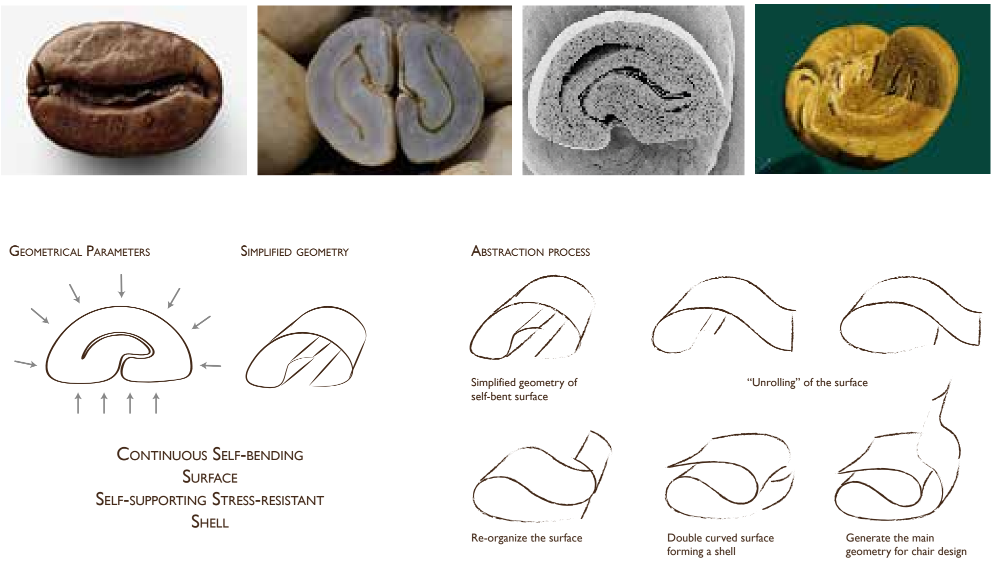
a specific subset of the plane. That set of points (called seeds, sites, or generators) is specified beforehand, and for each seed there is a corresponding region consisting of all points closer to that seed than to any other. These regions are called Voronoi cells. The Voronoi diagram of a set of points is dual to its Delaunay triangulation. – Wikipedia accessed in May 2017.

Fig. 6.6 Analysis of coffee bean morphological features and conceptual formation process for the chair



Based on this, the bean has been three-dimensionally reconstructed in Rhinoceros to better understand its geometrical qualities and exploit them in the design process. The first step was to redraw the main cross-section and longitudinal section of the bean. Looking at several microscope pictures and X-ray images[5] from scientific papers that studied biological aspects of the coffee bean, it was possible to see how this bending shape is developed. To rebuild the shape, a series of cross-section curves has been drawn along the main direction of the bean, based on the sections made in different points, and then a "loft" command has been performed in Rhinoceros. Afterwards a general and simplified geometry has been built and used in the early phases of the design in order to develop a coherent process of transformation from the biological element (the bean) to the chair.

Structural optimization and performance

[Phase 3: project definition]

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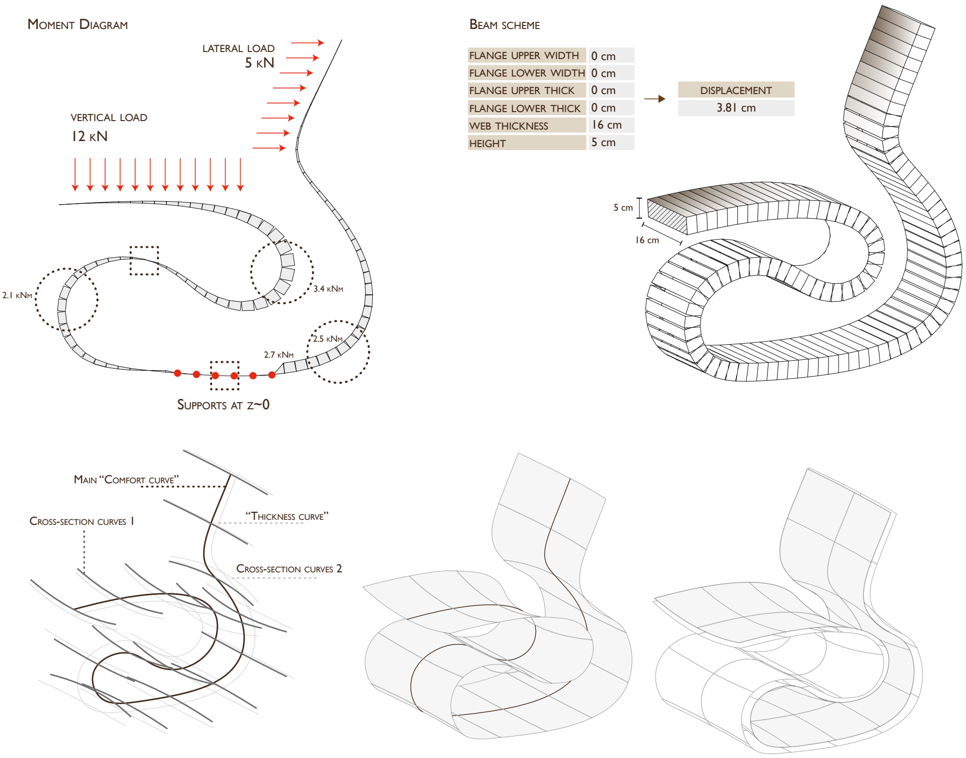
[5] Pitta P., et al., *"Evaluation of Microstructural Properties of Coffee Beans by Synchrotron X-Ray Microtomography: A Methodological Approach" – Journal of Food Science, Vol. 76, Nr. 2, 2011*

Fig. 6.7 Top: structural analysis of the chair with determination of displacement. Bottom: formation strategy employed in the parametric model



FLANGE UPPER WIDTH	0 cm
FLANGE LOWER WIDTH	0 cm
FLANGE UPPER THICK	0 cm
FLANGE LOWER THICK	0 cm
WEB THICKNESS	16 cm
HEIGHT	5 cm

DISPLACEMENT
3.81 cm

According to the principles that characterize the coffee bean and determines its structural performance, a process of abstraction and adaptation of the topology guided the formation of different possible shapes suitable for a chair. The process conceptually treats the bean as a **folded-up double-curved surface** which, in the first phase, has been "unrolled" and then folded again to a new shape. A series of alternative shapes, generated with the same principle, were taken in consideration and then a comparison with other famous chair designs helped to determine the correct proportions and dimensions for the comfort requirements.

The first study model in scale 1:5, realized with a laser-cutting machine on 3mm wood panels, highlighted some critical points which have been reconsidered during the structural optimization process. Due to the bending and continuous shape of the chair, the draft model showed that some parts could touch each other once the load is applied (once a person is seating on the chair). To avoid this situation, which would not only give an uncomfortable feeling when seating on the chair but also represents a weak structural solution, the structural optimization process focused on the displacement of the cantilevering part.

In the **FEA structural analysis** the structure of the chair was considered as a **beam**; although a first hypothesis was based on a shell surface, the beam radically simplified the structural analysis and therefore offers an easier understanding of the results. The beam profile used to test the structure represents the central cross-section of the chair. After constructing the central beam – assuming that most of the load will be evenly distributed in the center of the chair - an optimization process has been conducted through Karamba, a plug-in for Grasshopper. A load of 120 Kg (1.2 kN) was applied to the seat and 50 Kg (0.5 kN) to the seatback, to test the worst possible condition. The aim of the analysis is to use the moment diagram, which corresponds to the "deformed beam", to understand where more material, and thus more thickness for the beam, is actually needed according to local stresses. From the diagram, three main points have been identified as subject to highest bending moment, and they correspond with the three main curves of the cross-section. Then the definition of the beam has been assumed as a "I" beam in Karamba with no flanges and only web thickness and height, in order to study a full rectangular section instead of a hollow rectangular section. The analysis has been focused on finding the best relation between the beam height-width and the consequences on the displacement of the cantilevering parts. According to Karamba results, if the central section is considered as 5 cm thick and 16 cm wide, the **maximum displacement would be 3.81 cm**, which was considered satisfying since the distance between the seat and the underlying part of the chair is about 13 cm. Thus, it was decided to thicken the cross section in the three most solicited parts derived from the analysis, all the rest of the section is gradually reduced to a minimum thickness of about 1.5 cm, limited by fabrication constrains.

Once the design boundaries have been established, a **parametric 3D model** was built as main platform for design and fabrication. Since in this case there were no numerical data derived from the analytical phase, the main parameters consisted of geometrical constrains and rules expressed through the algorithm. The geometrical inputs in Rhinoceros are the two curves that describe the main section of the chair, all the rest is parametrically related to these curves. This set-up belongs from the coffee bean geometrical reconstruction which has been simplified as a double-curved surface constructed through one main curve defining the folding direction and a series of secondary cross section curves which follow it. In the same way, the process was applied to shape the chair. Once defined the main profile, two principal curves have been generated, one as a **"comfort curve"** and a second as a **"thickness curve"**. The "comfort curve" is used to specify in the algorithm all the necessary geometrical parameters that will form the parts in contact with the body: the seat and seatback. The "thickness curve" determines the thickness of the central section based on the results derived from the structural analysis performed in Karamba: 5 cm in the critical points, where the bending moment is higher, and then gradually thinner till a minimum of about 1.5 cm in the other parts less subjected to stress. On each of this two

Fig. 6.8 Fabrication of the section on 18mm plywood panels with a 5 axis CNC machine of the DDRC (Digital Design Reserch Center) of Tongji University Shanghai

principal curves have been parametrically constructed, through Grasshopper definition, the cross-section arches which will form the two surfaces. The surfaces' edges have then been connected through bi-arches to smoothly construct the chair edges. The same operation has been made for the corners. In this way, all the parts of the model are parametrically linked and defined by an algorithm, and every time a change is made on the principal curve, all the geometry is already adapted to the new condition. Using this digital set-up, the final geometry has been defined, after trying some different cross-sections, and it was then connected to a second algorithm for the fabrication. The model was cut into slices with a **maximum thickness of 18mm**, in relation with the available commercial wood panels.

Programming of CNC and fabrication

[Phase 4: project fabrication]

The fabrication algorithm verified the maximum thickness of the slices, and then distribute them on five wood panels 1.20x2.40m, six sections in each panel for a total of thirty

Fig. 6.9 Final prototype of the chair in scale 1:1

unique sections. The fabrication phase and the programming of the 5 axis CNC milling machine path was curated by the technical team of the DDRC at Tongji University Shanghai. After cutting some sections, when groups of three or four of them were ready, they were meanwhile polished, glued and assembled by hand.

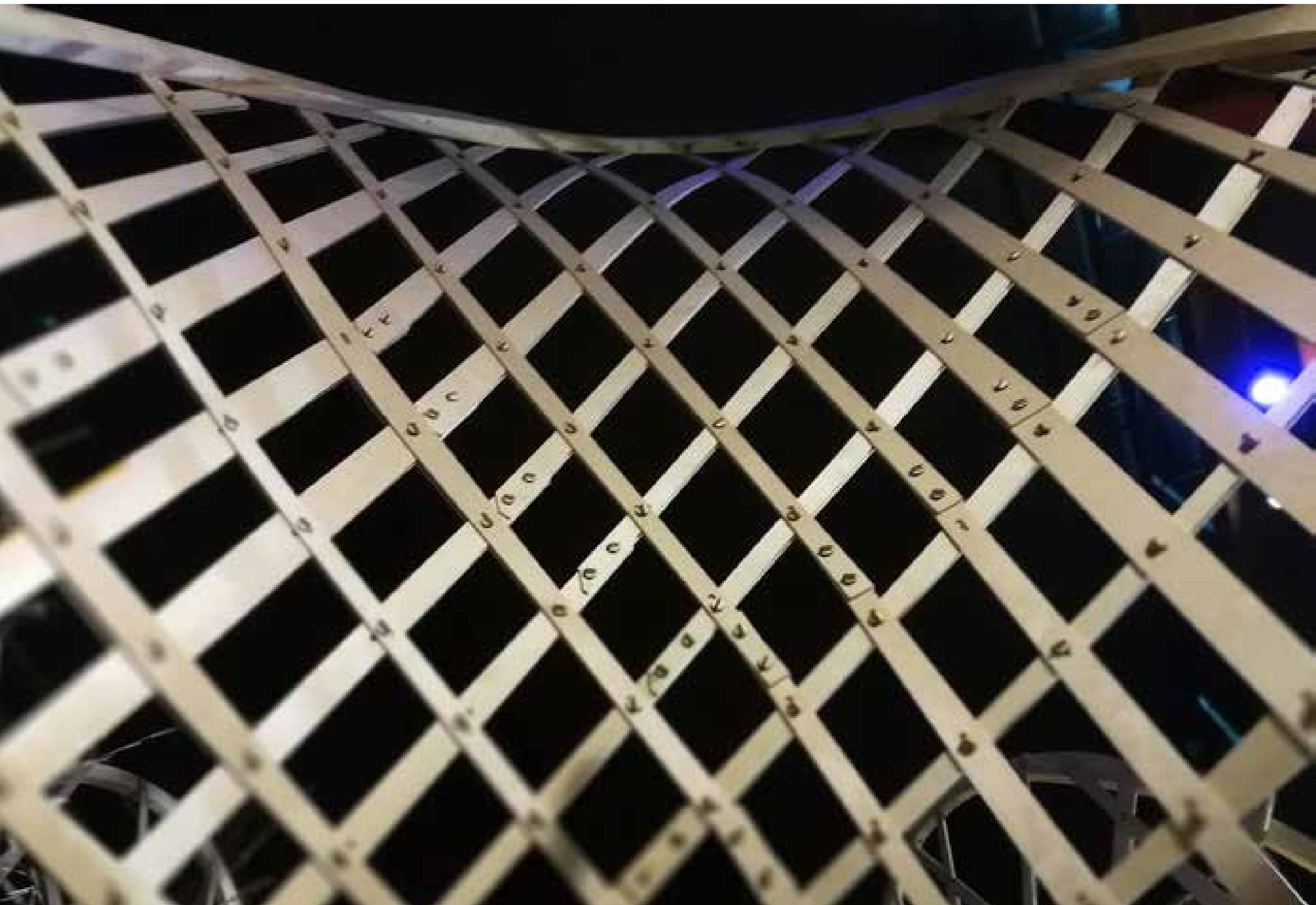
The final prototype in scale 1:1 proved to be comfortable and resistant with a very small displacement on the seat edge. The geometrical continuity of the final surface resembles the coffee bean geometry, and this become particularly evident when comparing the cross-sections of the two objects. Moreover, the material continuity of wood contributes to the structural performance evenly distributing the load along the structure. The material used is a cross-laminated fir panel where the fibers are rotated of 90° at each layer, this lamination process reduces the anisotropic behavior of the wood and homogenize its reaction to external forces. Therefore, once all the thirty sections are glued together (no nails or any other connection is used) the wood behaves basically as a homogeneous material although the fibers main direction is still co-planar with the sections guarantees a higher resistance and stiffness. From this point of view, a further investigation for this research could be to work with customized material fiber distribution focusing on the employment of the minimum material possible. The challenges for these future studies would be to manage the material and fibers continuity in the three more critical points which have a minimal curvature radius and alternated directions, and to employ a different fabrication strategy based on custom lamination process. In this way the model could be further optimized exploiting the bending moment resistance of wood and therefore reducing the amount of material and the weight of the final structure.

6.2. Optimized strained wood grid-shell. Pavilion for the "DigitalFUTUREs Shanghai 2017" workshop

[Phase 1: definition of research space]

The design and construction of **strained grid-shells** did not find frequent applications in the recent history of architecture given their limitations mainly due to complexity in design method and structural evaluation, on one hand, and on assembly and construction issues, on the other. The principal advantage of strained grid-shells is that they are erected from **initially flat elements** which, indeed, become strained when the structure is built and therefore gain their strength and stiffness from the bending stress induced by the double curved final shape. Differently, the unstrained grid-shells are built from pre-bent structural elements (see the Centre Pompidou Metz or Horticultural Expo Pavilion in Suzhou presented before, as well as many other grid-shells design) which make the construction process simpler, but the material employment might be more expensive or time-consuming in terms of fabrication.

Fig. 6.10 Detail of the final pavilion presented at the 7th edition of the international workshop Digital FUTUREs Shanghai 2017



Nevertheless, strained grid-shells are rarely used as the design method is the most crucial part, and, moreover, they still have a limited range of forms they can be applied to. Therefore, in the framework of the summer school “Digital Future Shanghai 2017” held every year since 2011 at Shanghai’s Tongji University and curated by Philip Yuan and Neil Leach, we proposed the exploration of design methodology for a strained grid-shell applied to a double curved surface[6]. The focus of the project, presented here, was to employ simple planar elements to achieve a double curved articulated surface which would describe an architectural space, the methodology was demonstrated through the construction of a full-scale prototype.

[phase 2: definition of design space]

For the design requirements and given the explorative aims of the research, we decided to work on a model of a mathematical minimal surface. A minimal surface is a surface that connects given edges locally minimizing its area, with mean curvature equal to zero. Nature often and easily organizes its structures according to this principle. Since the last two centuries this topic interested mathematicians who tried to scientifically define this kind of forms through the use of parametric equations. Some examples of minimal surfaces could be obtained dipping a shaped frame into a solution of water and soap, a soap film will be formed, and it will represent the minimal surface which connects the given frame edges. These experiments were widely studied by Frei Otto who was a pioneer in the development of advanced lightweight structures inspired by the performative logic of nature. Among the examples of minimal surfaces derived from mathematical models, we found interesting, for our structural and aesthetics requirements and for the research purposes, the **Enneper surface**, introduced by Alfred Enneper in 1864 in relation to the minimal surface theories. Starting from this surface a design process was set up for the construction of an **experimental pavilion** as a case study for testing wood structural performance through a computational design approach and testing different fabrication tools.

Grid form-finding and optimization

[phase 3: project definition]

The definition of the **grid-shell pattern** is the key issue of this experimental pavilion. The obtainable forms starting from a flat grid are strictly limited in conventional design processes, therefore, instead of using a flat grid in the first place, the approach here was

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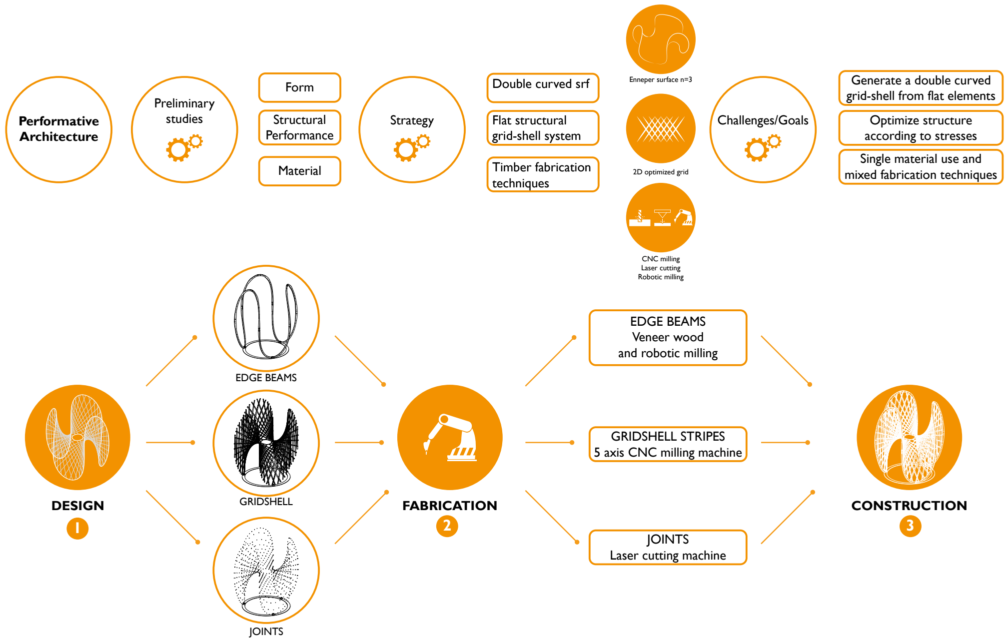
[6] Yuan P. F., Hua C., Jinxi J., “Digital form-finding and fabrication of strained gridshells with complex geometries” in T. Fukuda, W. Huang, P. Janssen, K. Crolla, S. Alhadidi (eds.), Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference - Volume 1, Tsinghua University, Beijing, China, 17-19 May 2018, pp. 267-276

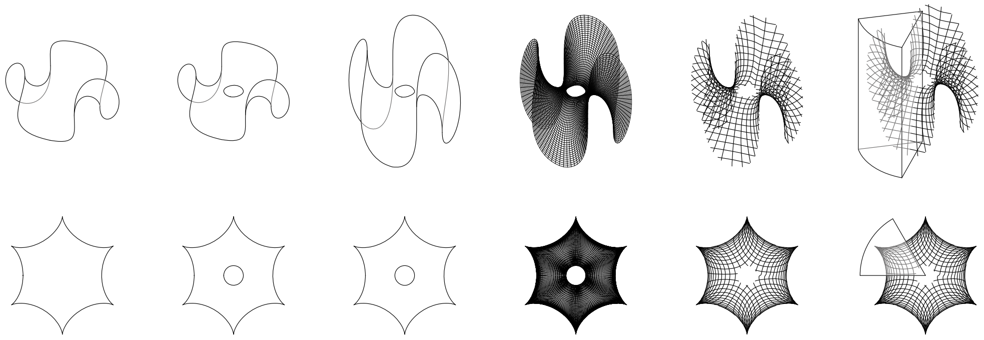
to **optimize the grid pattern working directly on the surface**, reducing as much as possible the laths curvature and, thus, the stresses, but still employing planar wood laths. Previous studies show the different methods available for the generation of a grid on a double-curved surface, extracting the isocurves, principal curvature lines, asymptotic lines, geodesic lines, principal stress lines. The **fittest grid generation method depends from the surface type** and is therefore related to the geometry configuration. Extracting the **isocurves** is a very common approach suitable for many surfaces but, in the case of an **Enneper surface of third degree**, selected as initial prototype for this project, it was an ideal strategy for creating the grid pattern because of the two set of curves U and V, one is made of closed curves, the other intersect several times in the central point, both of them cause evident problems in the management of strained grid-shell. Therefore, the further option was to use **principal curvature lines**. Before doing so the surface was adapted to site proportions, it was scaled along the vertical axis and, to avoid central intersections in the subsequent grid generation, the radial domain was redefined leaving a central opening. The model was set up in Rhinoceros and all the modelling and analytical operations were done through Grasshopper algorithms. The principal curvature lines were generated using Millipede, plug-in for Grasshopper, through a **"surface reparameterization"** tool that allows to extract the curves and control their density, resulting in a relatively uniform orthogonal grid. The generated curves might still have **excessive curvature** and they

Fig. 6.11 Design workflow and fabrication strategy of the Strained Gridshell Timber Pavilion for the 7th edition of the Digital FUTUREs Shanghai 2017

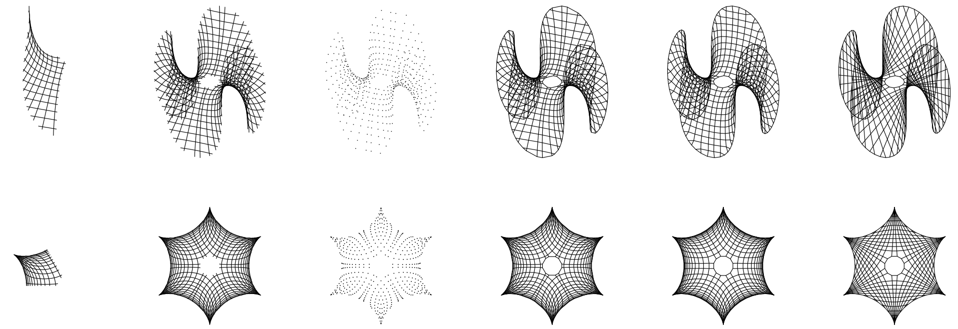


could cause bending problems when applied to the wood laths. Therefore, an optimization process was employed to reduce the curvature through the live physics engine Kangaroo by applying bending stresses to the generated principal curvature network lines. Each continuous curve was considered as one timber lath where the bending force was applied, through a digital simulation process in Kangaroo. Among the constrains input in the Kangaroo solver was specified that the curves could move only along the surface during the simulation. Once the **simulation** was started the curvature of each element tended to decrease in relation to the increase of the applied bending force. This process caused the simultaneous shifting of the whole grid which resulted into a new **optimized network** of curves (Fig. 6.12). As **optimization criteria** was set that the curvature of each element should have been smaller than the **maximum curvature admissible** for the employed material, considering its application on a full-scale architectural prototype. Therefore, the supported curvature was empirically measured by manually bending a sample of laths 5mm thick, 100mm wide and 1000mm long. The ratio between the height of the arch and the initial length was used to quantify the material's bending resistance, which result-

Fig. 6.12 Gridshell optimization and form-finding process



1. Initial Enneper Surface
2. Redefining the radial domain for a central opening
3. Scaling according to site
4. Mesh generation Radial UV grid
5. Grid reparametrization in MIllipede
8. Symmetrized grid

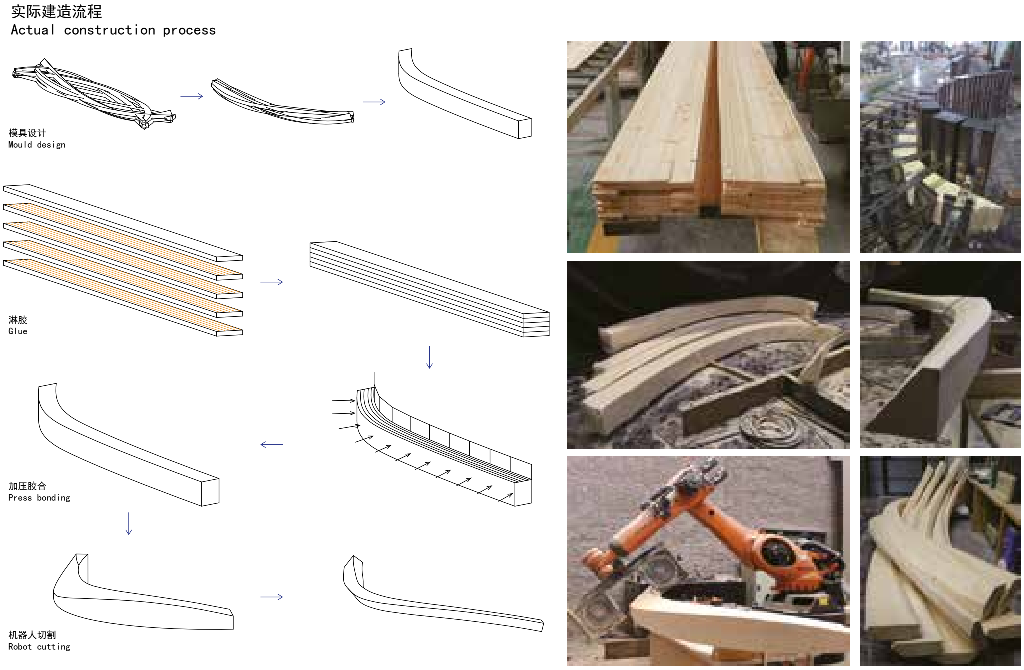


7. Segment to mirror for symmetrization
8. Symmetrized grid
9. Extraction of intersection points for polyline grid reconstruction
10. Polyline grid reconstruction
11. Segment lenght optimization with Kangaroo
12. Final grid optimization with bending stress in Kangaroo

ed in 0.34. The initial network of curves presented a ratio of 0.416 which, after the optimization, was reduced to 0.151. **The optimization process considerably reduced the initial curvature**, helping to find an alternative grid starting from the principal curvature and making possible the construction of the strained grid-shell. For simplicity, the process was run to optimize curves instead of surfaces, as the actual timber laths are. On the other hand, such simplification brought some advantages since the stiffness of the whole grid increased because of the effect of the torsion adding more pre-stress to the structure.

The structural and constructive system of the pavilion consist of **three parts**: rigid edge beams, continuous laths and rotatable joints. The rigid **double-curved edge beam** was necessarily realized through glue-lamination process, while **the laths composing the grid** take reference from the double layer system developed by Frei Otto and are fabricated from flat planar panels. **The joints** were developed analyzing some Chinese traditional joining systems which provided resourceful models for proposing an innovative connection. Based on a mortise and tenon system the proposed joints were fast to assemble, highly resistant and easy to disassemble which was suitable for the requirements of the experimental pavilion that was later moved to another exhibition. The joints also allowed

Fig. 6.13 Fabrication process of the edge beams



some tolerance displacement, due to the settle of the structure, and, most importantly, they were easily made out of wood which **significantly reduced the weight** on the final structure, given their amount.

The further step in this workflow was to adjust the material amount in relation with the needed local resistance. This operation was performed on the final geometrical model, used as model for the FEA, and therefore it was not a generative iteration while rather an action to globally reduce or increase the material where necessary varying the cross section. The **FEA** performed in Karamba was based on the digital model and material of the components as input. Initially a structural simulation was run under different loads and boundary conditions and the outputs of the simulation, in terms of material utilization efficiency, were used as data to re-calibrate the cross-section of the structural elements of both the laths and edge beam. The bending action was considered as a pretension stress applied to the grid beforehand, since it was hard to simulate it in Karamba. Finally, the cross-sections were varied in relation to the **material utilization indexes** derived from the simulation. The edge beam cross-section, which originally was set to 80x100mm, varied between 60x90mm and 90x120mm, while the laths cross-section, originally set to 70mm, varied in width between 40mm and 90mm maintaining the constant thickness of 5mm. Thanks to this process the direct connection between form and inner forces became visible in the final construction.

Fabrication and assembly

[Phase 4: project fabrication]

This experimental design allowed to test interrelated research objectives; the principal aim was to design a strained grid-shell on a double-curved surface, in parallel to this, another spark was the use of a **single material** – wood – **for all the components** and process it with **different techniques**. In particular, the three principal elements that compose the system – the edge beams, the laths grid and the joints – defined the different fabrication technology to employ based on their intrinsic properties. The simplest and fastest technique was the laser cutting of the wood joints, a small tolerance was added to the cut to allow an easy assembly avoiding too tight connections. The laths were straightened on a plane and subdivided in segments to fit the machine working area. They were CNC milled from 5mm thick plywood panels of 1220x2440mm, in total the 38 panels were completed in 2 days. A different approach was necessary for the edge beams, since they are curved in multiple directions in space a special customized system was required for their fabrication, moreover, as they are edges of a strained grid-shell, they need to be stiff elements and therefore pre-bent and ready for the assembly. In case of planar curved beams these could be relatively easily fabricated in factory through special molds that allow curved glue lamination of the wood boards. On the other hand, the spatial curved timber beams require are more complex to process and require further steps. Robotic wire-cutting was employed to achieve the spatial curved shape of the beams form the prefabricated planar ones, by mounting a modified **bandsaw** on a Kuka R2700 robot. This process also includes the preparation of the material and make it suitable for the factory production phase. To avoid slowing down of the lamination the continuous edge was divided into twelve segments, according to the machine span, and they were fit in a geometry that could be the same for all the beams. Each spatial-curved segment was cut from the planar one through six cuts with the robotic bandsaw, the entire cutting process took about 10 days in total.

Thanks to an efficient labeling system and using the Rhino model as blueprint the prototype was quickly assembled in about 20 hours. For safety reasons a steel plate foundation was designed and fabricated through water jet cutting. The steel plate foundation was cut from 12 plates of 1100x500mm and 6mm thick, the total weight was roughly calculated to be **almost the same as the pavilion** – around 200 Kg – so that it would be able to contrast potential displacements during construction. At first the foundation was posi-

Fig. 6.14 Construction phase of the pavilion on site (hall of building C, in CAUP, Tongji University Shanghai)

tioned, the steel segments were welded on site, then the edge beams were assembled and connected using in total 12 bolts, necessary to guarantee a structural continuity to the rigid edge. After the edge was set up, the laths were assembled with each other and then fixed to the edge. The final structure, with a height of 6m and a diameter of about 4m, was built in a hall of CAUP building at Tongji University Shanghai in occasion of the annual workshop Digital Futures Shanghai 2017, and it was then disassembled and reassembled at the SUSAS space for the exhibition "This-Connection" curated by Stefano Boeri and held during the autumn 2017.

Fig. 6.15 Final Strained Timber Gridshell Pavilion

6.3. Wood Tectonic Tower. Pavilion for the "DigitalFUTUREs Shanghai 2018" workshop

[Phase 1: definition of research space]

Interlocking joints have been a diffused connection technique in many cultures since when wood was crafted with hand-tools. Nevertheless, throughout time, much of the knowledge behind these methods was put aside for new materials and for the serial production logic. After a heavy industrial phase, that aimed to simplify every detail, current design culture is now experiencing, through research, a rewed interest **in highly customized interlocking joints**. Through "digital crafting" they can be easily robotically fabricated on the wave of the mass-customization approach that is characterizing our contemporary socio-economic context. This connection methods bring some advantages in wood constructions, first of all the consistent use reduction of other materials or elements as nails or glue – completely missing in some cases – to join the components with each other, and, secondly, the possibility to explore alternative structural layouts defining an innovative digital tectonic of wood. While in the first place these joining systems can be

Fig. 6.16 Construction process of the tower on site (hall of the building C at CAUP, Tongji University Shanghai)

primarily considered as **technical solutions** which simplifies the assembly process, on the other hand they also express an **architectural value** through the articulation of the timber components that define the space, moreover they offer efficient **structural approaches**. In other words, interlocking joints are crafting and construction techniques proper of wood material culture, from which emerges the meaning of tectonic articulation. After all, it is not a coincidence that Semper recognized in wood material culture the most evident **tectonic expression**. Among the researches that represent the current state of the art of the research in wood interlocking joints, many are based on the use of **planar components** and they exploit in very different ways the potential of this connections. To mention some of the most relevant approaches on one side the finger joints researches by ICD of Stuttgart focus on the elimination of the bending moment stresses between the plates optimizing the structure based on shear stresses; on the other side the IBOIS laboratory of Lausanne explores the potentiality of the timber folded plates resulting in a stiff and stable structural system.

While the research on interlocking joints – such as finger joints, mortise and tenon, through-tenon joints – are quite diffused for **timber planar elements**, there has been less attention on this kind of connection method for **timber linear elements**, which also open to the relative reinterpretation of their structural meaning, going beyond the conventional beam-column structural layout. In this framework, the research here presented wants to address the challenges of **interlocking wood connections between linear components, without any nails or glue**, to the design and fabrication of a full-scale architectural prototype.

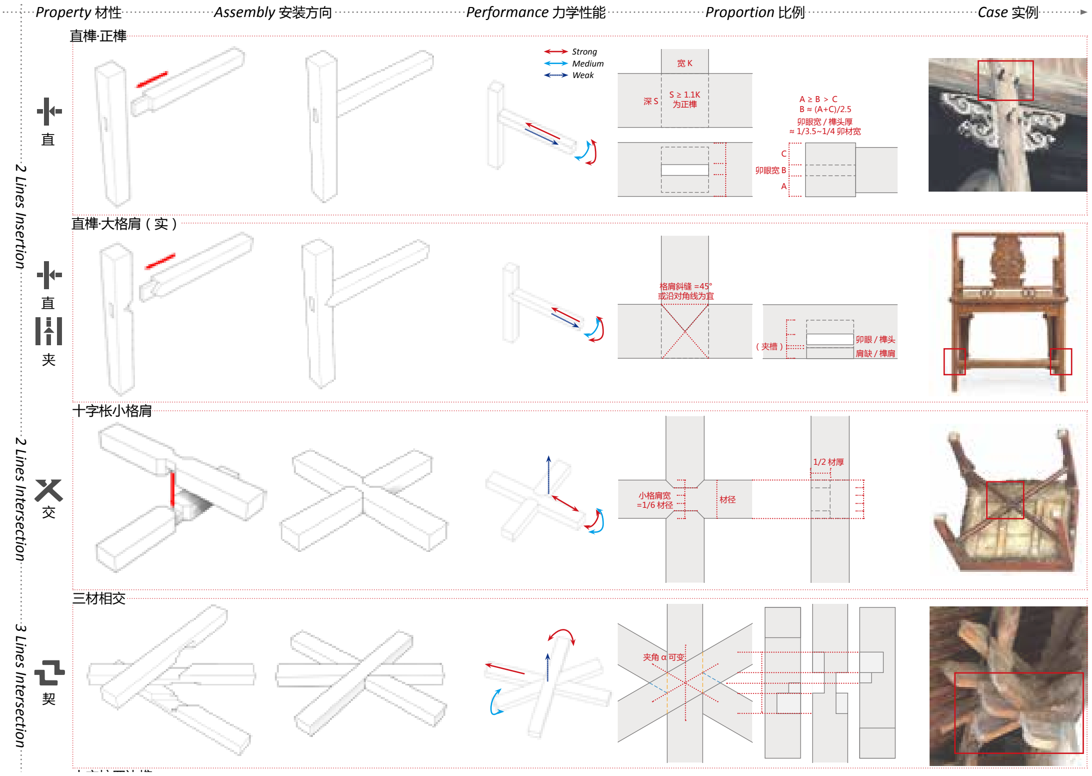
The methodology that explores wood digital tectonics was applied through a workflow divided in four parts: the initial phase focused on the analytical study of Chinese traditional carpentry that offered the cultural and technical background to operate in the exploration of nail-free and glue-free wood joints; a second step was to define the design boundary conditions that exploits the interlocking joints as generative principle; then several spatial configurations have been developed according to cell aggregation principles; the last phase regarded the robotic milling of the components and the assembly on site.

Learning from tradition: analysis of Chinese ancient carpentry

[Phase 2: definition of design space]

The main reference for the development of this system came from **Chinese traditional construction methodologies**. China has a strong culture in **wood crafting techniques** as it has been the primary construction material, together with bricks, until not long ago. From temples to simple houses till the interior furniture there is an incredible variety of connections and each of them fits the corresponding structural, functional and aesthetic criteria. Throughout the research **several connection typologies** have been analyzed regardless from the scale of their application: from the beam-column structural layout (Chan-dou, Tai-liang, Dou-gong) that support the roof, to the connection details of furniture. The analyzed joints have been reproduced as samples by laser-cutting plywood panels, obtaining study models to get more intuitively the interlockings and force distribution principles. From this analysis emerges not only the extraordinary hierarchy of detailed geometries and the crafting ability to achieve such complexity, but above all the spatial articulation of structural timber components that these systems enable especially at the architectural construction scale. The roof corner details of Chinese traditional architecture, for instance, are full expression of a tectonic culture strongly characterized by regional – local – features. They describe the assembly process, the system structural logic and the crafting technique which are proper of that specific culture, open to related local variations. Based on the **tectonic character of wood interlocking joints**, the **detail** was therefore considered as a guiding factor of the architectural design and construction and it was taken as an inspiration for the exploration of robotic fabrication in linear elements-based structures.

Fig. 6.17 Study of traditional joinery in Chinese furniture crafting and architectural elements



Through the study of traditional joinery, the architectural meaning of wood construction has been reinterpreted in a transition from traditional tectonics to digital tectonics, moreover the exploration of nail-free and glue-free joining methods have been implemented with robotic carpentry. Robotic fabrication consents to work the material with a very high precision; it can accommodate local small variations which by hand are difficult to achieve, and therefore it allows a higher degree of flexibility both in design and production. Previous researches already demonstrated the value of traditional references for advanced studies in current computational methodologies. Among them the IBOIS laboratory of EPFL Lausanne, takes inspiration from lightweight structures based on the origami technique derived from the Japanese tradition and creates tridimensional layouts "folding" planar elements. Analogously, the research presented here proposes a tridimensional structural layout of interlocking linear elements and overcomes the conventional structures reinterpreting the beam-column relationship.

As the principal objective of the research was to explore and test **robotic carpentry** based on traditional connection techniques and given the limited time available, a large part of the efforts was concentrated in the definition of the components relationships. Hence, a computational form-finding approach, which at this stage of the research played a secondary role, was put aside for future and further explorations and implementations of the topic. Instead, **a rationalized formation process was derived from the ancient method** of roof construction which follows specific rules based on the geometrical interrelation of the components. Moreover, the research presented is one of the first studies on robotic carpentry for interlocking joints in timber linear components, for this reason the lack of previous records of this kind required a deeper understanding of the technical principles in the **transition from traditional tectonics to digital tectonics**.

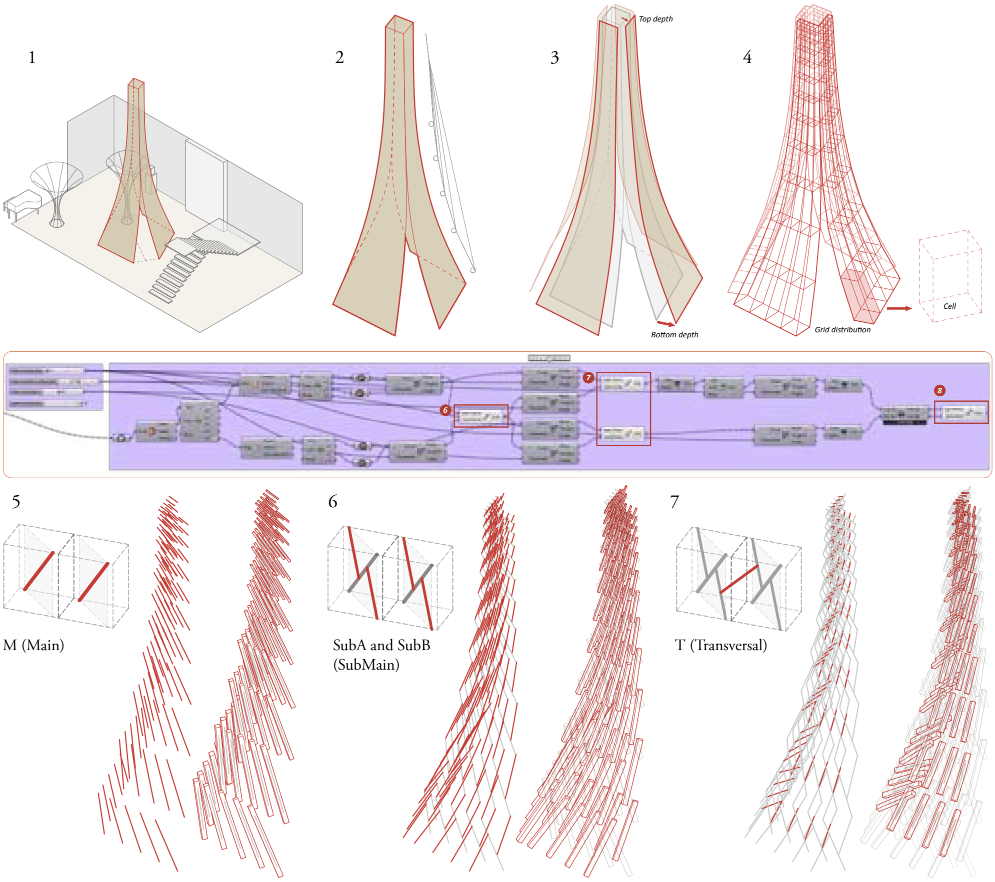
The design boundary conditions have been established according to few basic elements: the construction site, the use of timber linear components within a limited dimensional range, the interlocking joints as connection technique, the robotic fabrication for the milling of the wood. The **construction site** selected for the project was the hall of a building in the College of Architecture and Urban Planning at Tongji University Shanghai, here the spatial characteristics of the context suggested to develop a vertical shape which resembles a tower and it is inspired by traditional roofs. Then the l**ength of the timber linear components** was take into account based on logistics, robot span and assembly phase considering that they would have been handled by regular workers, hence the maximum length was limited to about 2m. The interlocking wood joints technique inspired a structural layout based on **material redundancy**, as it can be seen from the corner detail of traditional construction's roof. In particular, among the analyzed joints, the **two lines intersection was selected as main connection** given its high resistance to bending moment stresses in a vertical configuration. In some special points three lines connection were also taken in consideration to solve particular intersections. These aspects guided the process and helped to define the design environment within which was developed the final structure.

Spatial grid system and optimization

[Phase 3: project definition]

Once the boundary conditions of the design space were defined, the model was built in the usual Rhino-Grasshopper environment as two developable surfaces mirrored to compose a symmetric four-sided tower. Based on this setup some different shapes have been tried. The strategy was to **work with a parametrized spatial grid** (Fig. 6.18) so that the system could be applied to almost any set of vertical surfaces with very limited adjustments to do. For simplicity, in this case, the surface had a single curvature in the vertical direction with

Fig. 6.18 Formation process starting from site conditions (1) which suggested the development of a vertical structure (2). The next phases show the generation of the parametrized spatial grid (3-4). The cells system was used to test different configurations among which the final one (5-7).



straight top and bottom edges. This geometrical constrains, in this case, recall the Chinese traditional roof, but, more in general, they simplify the management of the tridimensional cells system. The algorithm was developed in Grasshopper based on the **two input surfaces**. The **cell system was set as a spatial orthogonal grid** obtained starting from a surface offset with a gradually decreasing distance from bottom to top. This double layer determined the inner and outer faces of the cells. Afterwards the UV lines of both surfaces were extracted and connected from corner to corner forming the actual set of cells. The grid, initially with a regular subdivision, was parametrized so that it was possible to optimize the layout differentiating the cells height according to local requirements. In this case **the cells size decreased along the height of the tower**, since there was no load to bear other than the dead load, the components were set to become smaller and lighter on top of the geometry. Finally, within this model, some **different types of periodical cells have been tried based on combination of linear timber elements**. The first attempts intended to work with a high number of small and light components, therefore the initial amount of total wood members was **more than 4000** (Fig. 6.19). Although this redundant system would have been interesting to study, it would have also required a lot of time for fabrication and assembly. Therefore, varying the internal arrangement of the wood members in the cell and trying to improve the vertical load transmission, a **final number of 840 members** was reached and considered satisfying. This iteration took some time to reach the final cell configuration. Afterwards, even the corner cells and other special points were adjusted through an algorithm so that all the geometrical description was parametrized. **Four type of members** have been identified in the cell definition: the **main member** (M) is the diagonal of the cell; on the same vertical plane lie the **sub-main members** (sub-A and sub-B) which cross the main diagonal relatively at the first and the last third (so that the main diagonal results divided into three segments); the last member it a **transversal element** (T) which creates the connection between the cells and it goes from the center of the sub-B of one cell to the center of the sub-A of the adjacent cell. This organization of the members guarantees the horizontal continuity of the connection through the T components, while the vertical one is solved by the main (M) with the sub-main A (for the upper layer link) and with the sub-main B (for the lower layer link).

On the final geometry, build according to these rules, a **structural analysis was performed to understand the behavior of the structure**. Moreover, to guarantee a better material performance, the members **sections were differentiated layer by layer**. In this case, since the structure was symmetric and there was no other load involved other than self-weight, the differentiation happened from bottom to top of the structure. In particular, a gradient of diminishing sections was defined starting from 120x120mm section for the first two layers till a 30x30mm section for the last three layers. Within cells on the same layer all the members have the **same section size**, while the different sections

■ *Variant* 变体

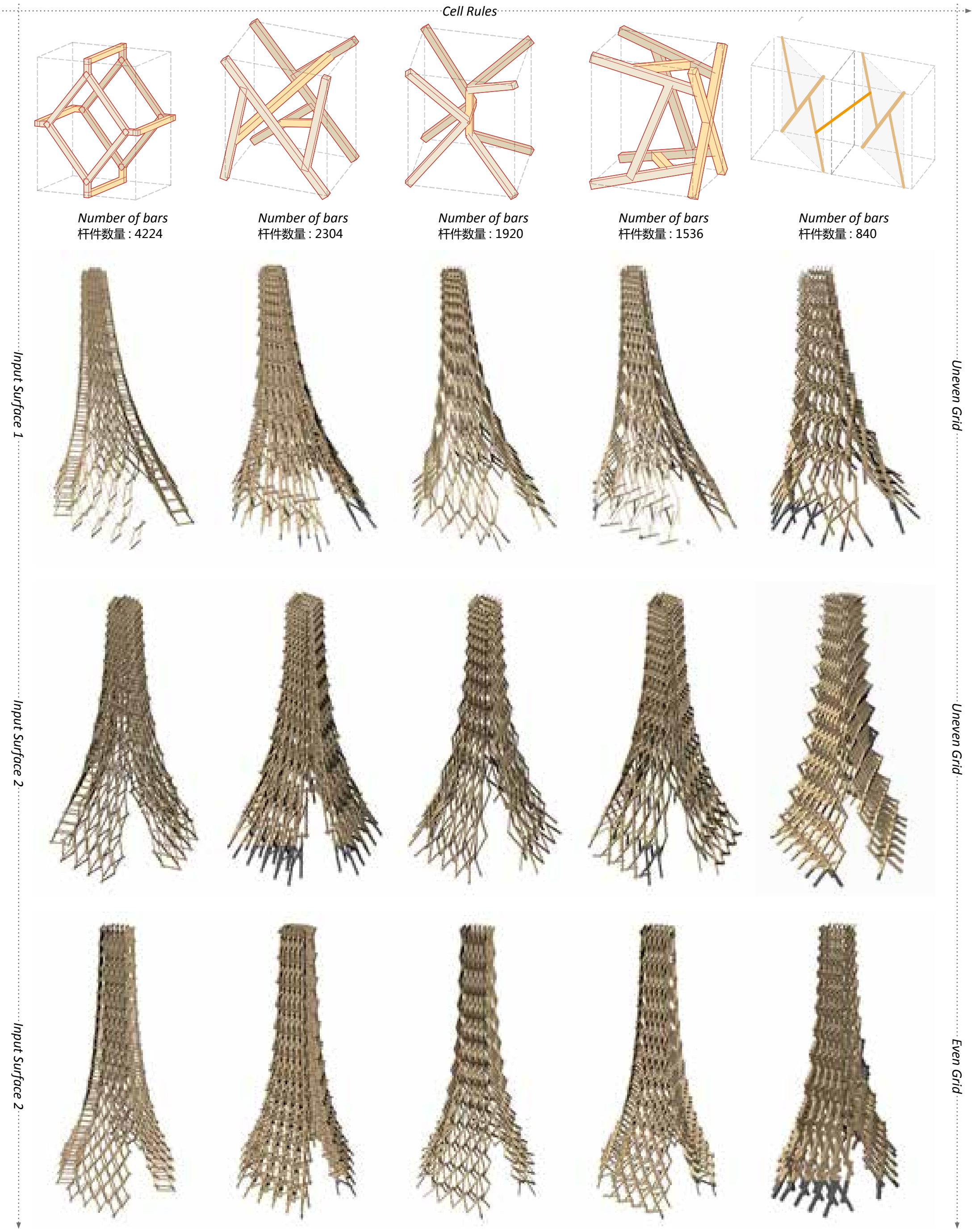


Fig. 6.19 Different cell configurations tried with variable cell distribution and surface variations. Top righ is the selected cell configurations and bottom right is applied on the final surface.

between the layers can be easily accommodated through the interlocking joints. The final structure is composed by 12 layers which height varies from 1.8m to 0.4m. Every joint always connects two members, except for the special cells at the corners, so the intersection is easy to solve and fabricate as well as more resistant. Every component should intersect with two to four other components, moreover the slot orientation of every component should always be designed according to the installation order.

Fabrication and assembly

[Phase 4: project fabrication]

The implementation of interlocking joints was tested in this project through the **robotic milling of all the cuts**. In traditional structures the joints are characterized by regular angles easy to measure. On the other hand, when the member crossings are differentiated on the whole geometry to accommodate structural optimization, the variations between the angles of the interlocking cuts can be very small and extremely time consuming if crafted by hand. Still, an industrialized production method, which might satisfy the re-

Fig. 6.20 Robotic milling process in the laboratory of the DDRC (Digital Design Researh Center) Tongji University Shanghai

quired precision, does not fit well a production were all components to be milled are different. Therefore, robotic milling was a suitable fabrication technique able to address all the difficulties, giving the opportunity to exploit the advantages of nail free connections. The laboratory was set up with two robots a Kuka KR60 and a Kuka KR120 on a rail. A support platform for each robot was prepared and calibrated to fit the timber members of different lengths leaving one movable support. The same setup was created in the digital environment. Here **every beam was correctly placed, the cuts were programmed, and the simulation of the fabrication was run to check the accuracy**. The robots mounted milling tools with a diameter of 50mm which have been used for all the timber members except the smallest ones with a section of 30mm where the tool was changed to a 30mm diameter. In the physical environment every timber element was placed by hand on the platform and clamped to the support. Another laboratory setup was organized for the special components, all at the corners of the tower, with a 5 axis CNC machine which programmed the multi-faced cuts more easily and rapidly. The programming and milling of all the 840 bars containing in total 2592 cuts was completed in two weeks.

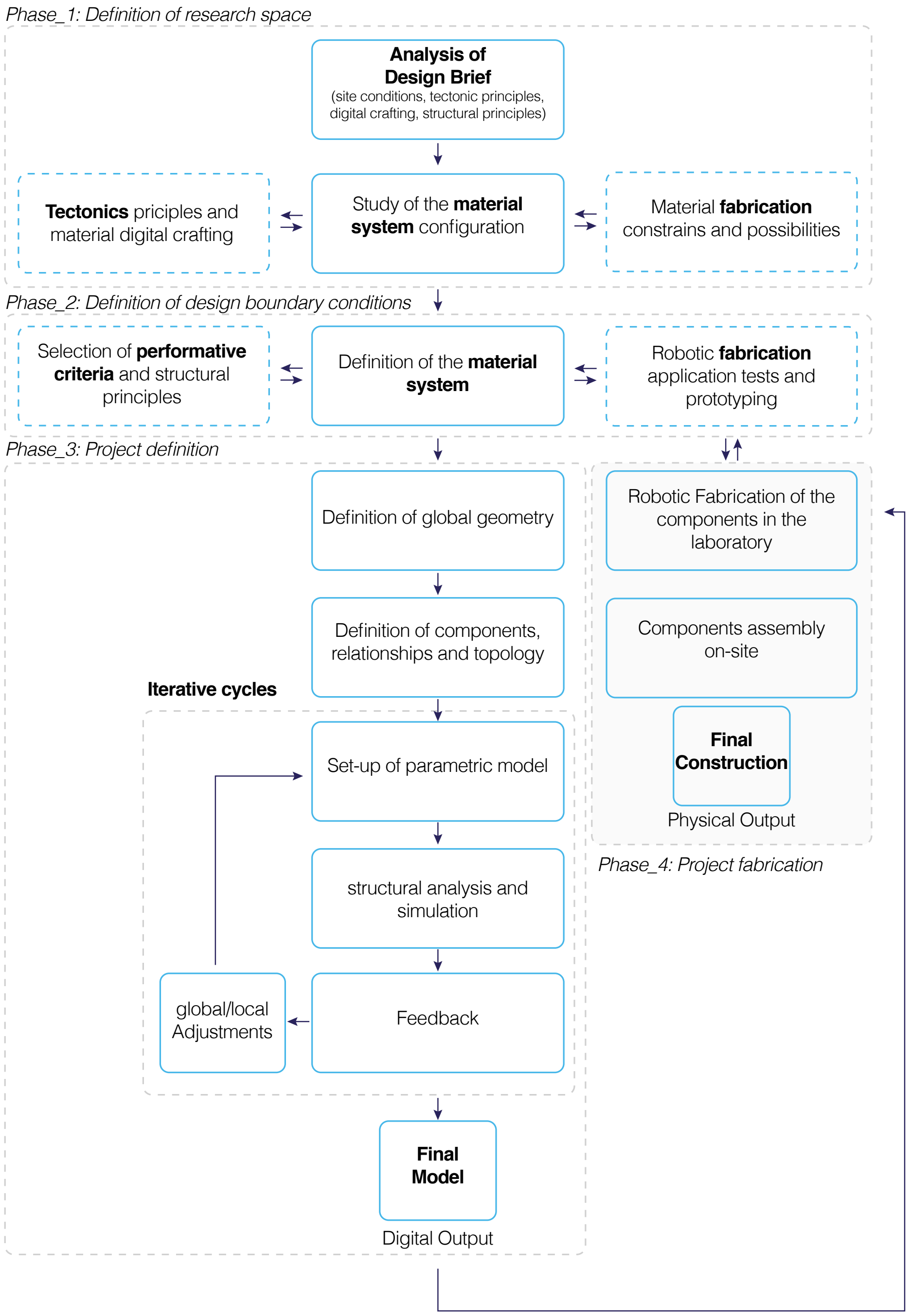
The final structure, with a total height of 9m, was **directly assembled on site**. The construction took place in the hall of a CAUP building at Tongji University Shanghai during the workshop "DigitalFUTUREs Shanghai 2018". A **steel plate foundation** 6mm thick, fabricated through laser cutting, was first assembled to allow a balanced weight distribution on the wooden floor of the building hall. The ring of the foundation also had steel plates ears, welded on the base, that firmly constrained all the **36 support points** on the ground preventing any displacement which might have caused problems. The construction process was carried on by four regular workers and one designer, through manual assembly and hammering on the interlocking joints. Once the first layer on the ground was completed, the scaffoldings were added along the external perimeter of the tower; for the subsequent layers they were built gradually following the construction. Given the weight of upper the layers and the small tolerances of the joints left for the assembly, the structure started to settle during construction because of the lack of expedients. This caused **small deviations** that, by accumulation, made stiffer the assembly of the last joints in the upper part. The construction was completed in about three days without using any nail, screw or glue, and it proved to be safe and resistant.

The purpose of this research was to **re-interpret traditional wood tectonics** with digital technology without losing their advantages and open up new possibilities for wood design and manufacture. The project demonstrates how innovative structure is allowed through

Fig. 6.21 Final Tower Pavilion in the exhibition site (hall of building C, CAUP, Tongji University Shanghai)

the **synthesis of traditional culture and cutting-edge technology.** Because of time limits for this project, several parts of the research still need further research. In addition to fabricating tests on different joints, structural testing is also required to associated different joints with their performance, which could together become a driving factor in design generation process. The robot programming process could also be optimized to improve efficiency and reduce errors.

Diagram for wood performance-based digital tectonics methodology



6.4. Possible future research developments

The research projects realized in the framework of this thesis brought to remarkable results in the exploration of wood tectonics, especially considering the strict time an resources limitations. Nevertheless they also offered some sparks for reflection of possible improvements that might be studied in future researches. Some main considerations can be done to guide possible future implementations of the research and they could be divided in relation with the three projects.

Chair: in the design workflow the formation process could be implemented introducing a morphogenetic growth algorithm based on the same rules and constrains of the coffee bean. Defining the boundary of growth, the maximum number of curves, the maximum and minimum curvature and so on, the expected result would be a series of double curved surfaces (as phenotypes) which might be very different from the current chair shape. On the other hand, the fabrication processes could also be improved testing double curved lamination process from very thin veneers and consistently reducing the leftovers. This fabrication process would also improve the structural performance using material elasticity and bending resistance and therefore reducing the global thickness of the surface in relation with the applied loads.

Strained gridshell: the pavilion introduced another workflow to produce strained gridshells. Starting from planar elements this workflow could be tested on other geometries, which might possibly follow form-finding principles to better predict or even set the kind of stresses that the gridshell should bear. Another future task could be to enlarge the scale of this structure and direct the design of the next gridshell to an actual building-scale trying to fit the building code requirements and therefore reduce the gap between research and practice.

Digital tectonic tower: One of the most time-consuming aspect of this project regarded the milling of the almost 2500 interlocking cuts on all of the 840 timber components. Further investigation would help to set the fabrication process in a way that both the path programming and the positioning and milling of so many components are drastically reduced. A possible solution could be to lie down the timber components 10 or 15 at once and provide a different input method for the path programming of the robot in grasshopper. Moreover, the adoption of different interlocking joints would be suggested for improving the structural behavior. Further studies on the form and an adequate structural simulation might also provide an optimized and lighter layout. The new results could be tested on a full-scale architectural demonstrator aimed to applications in the construction industry, for instance self-supporting wood facades or single-story construction.

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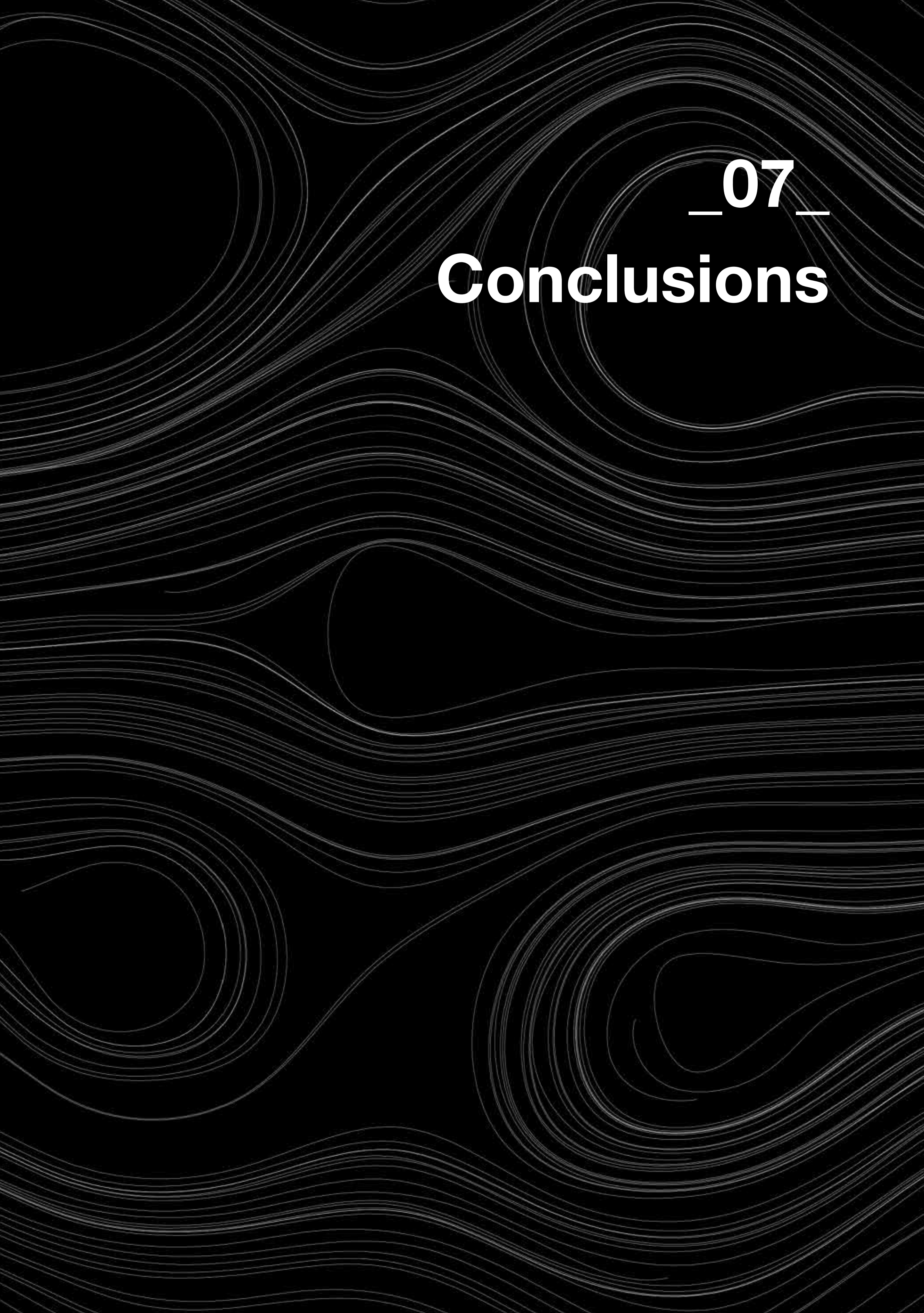
Conclusions



Contents

7. Conclusions

Paradigm shift in contemporary architectural design

This thesis aimed to demonstrate the potential of current advanced technologies applied to the design and construction of wood performative structures. The focus has been oriented on those **methodologies that enhances performance** – intended as efficiency of a selected aspect – **as a generative design feature unfolding the tectonic character of wood structures.** The research was initially inspired by a reflection on our complex contemporary context characterized by changings on multiple levels, questioning how the technological developments might change the architectural scenario in the years to come and what is already happening in current practice. The answer that this work tried to give is not merely functional, on the contrary, it faced **cultural, technical and procedural issues** embedded in the context of computational and digital architecture. An aspect highlighted by this thesis is the **different role that research has today** in the architectural discourse. For many years research in architecture remained shared among closed environments: the debate substantially persisted on a critical and theoretical level, analyzing the cultural meaning of what was happening or already happened but with a weak involvement of technology in the operative tools. An approach, this, that kept the research in architecture separated from its more pragmatical aspects. On the other hand, the technical advancements remained isolated, explored by specialist construction firms through their research&development departments limiting their discoveries to merely technical local improvements of the construction, without any particular integration in the design process. Therefore, these two versions of research, a cultural and a technological one, remained on two separated realities. A visible manifestation of the separation between technology and architecture is highlighted in some contents of Koolhaas Venice Biennale “Fundamentals”: such as the access to the exhibition section called “ceilings” that shows the contradiction of hiding the structure of the cupola to solve a functional issue (Fig. 7.1).

Today emerges a strong link between scientific research, contemporary practice and theoretical debate and it finds its roots in the early ‘90s right after the crisis of post-modernism. Eisenman was one of the first to elaborate theories inspired by the novel technologies. The contrast between the photograph and the telefax trigged a reflection not related to the image, the final product, but to the **process of making** it, to the different nature of mechanical and digital reproducibility. Mechanical copies once produced are fixed, stable, while digital copies are derived from files, number-based notations that can constantly change. Starting from this assumption, Eisenman questioned centuries of anthropocentric vision of architecture, based on monocular and perspectival tradition, suggesting a **‘dislocated’ vision** that constantly changes and brakes the Cartesian grid. It is one of the first moments of introduction of the digital discourse in architecture that highlighted *"the continuity between deconstructivism and the first age of digital design"*[1]. This introduced debates on the constantly changing architectural form, on the meaning of folding surfaces to redirect the vision of the observer, on the way to represent these complex geometries thanks to computer graphics. They became evident in many of Eisenman's works. From here many theories have been developed and, in parallel, the technological potential grew up continuously fostering alternative applications of 'the digital' in architecture. Another fundamental contribution by Eisenman was the focus on the process instead that the mere final product, as demonstrated by his experimental projects "House I-X" (Fig. 7.2). This unfolding of the process activated alternative design-thinking which, few years later, became a reference for algorithm-aided design, a design approach strongly based on the process. Thus, research in architecture started to be based on scientific contributions exploiting technology within the design workflow. The influence of scien-

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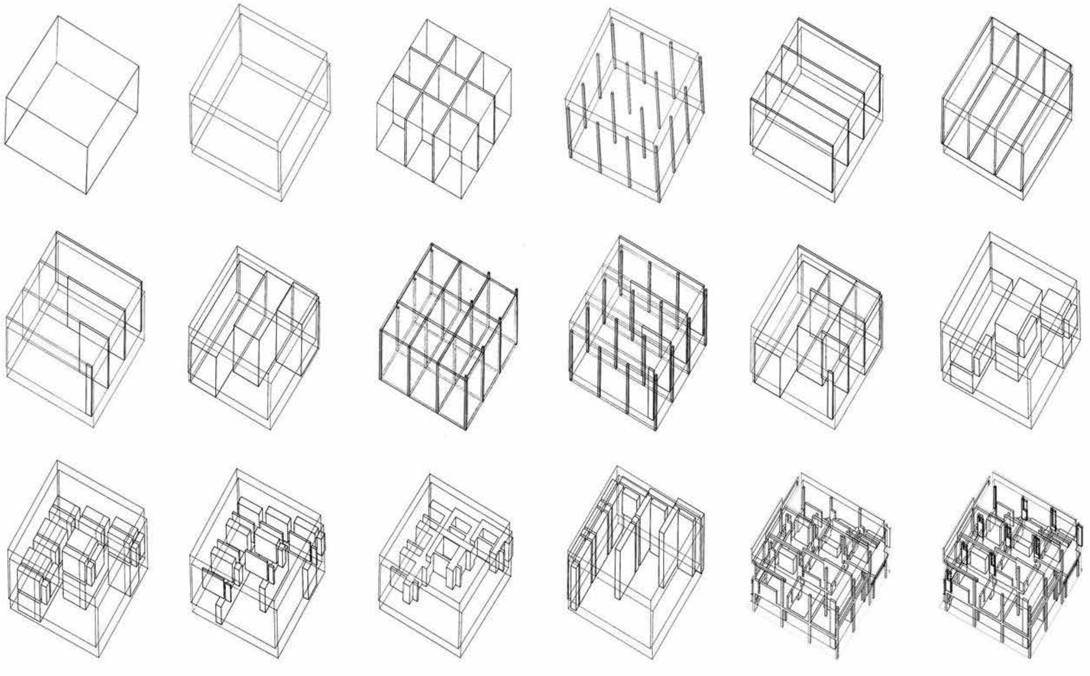
[1] Carpo M. introduction to "Visions Unfolding: Architecture in the age of electronic media" in "The Digital Turn in Architecture 1992-2012" John Wiley & Sons Ltd, 2013

Fig. 7.1 Access of the "ceilings" exhibition section at the 14th Architectural Venice Biennale curated by Rem Koolhaas in 2014

tific topics in architectural research introduced a **paradigm shift in architecture:** the conventional design methodologies are questioned in favor of a more aware exploration of the digital resources. Approaches of unfolding of the form generation processes have been introduced revolutionizing both the use of technology for architecture, which is no more a passive tool, and the workflow to achieve the form, one of the essential topics of the architectural discourse. The **digital paradigm** influenced the research in architecture bringing both highly scientific contributions, focused on an integrative development of innovative technological applications, and a revitalized architectural debate coherent with these contemporary themes. Both sides find interrelation with each other. Moreover, and here is another key-topic of the thesis, what emerges from such interrelation is **the tectonic character of the architecture** designed within this theoretical and technical revitalized environment: a cultural value that arise from the **digital crafting of the material**. The 'digital tectonics' has been explored in the framework of the thesis, at first to provide the cultural tools to read and understand it and then to include and reinterpret it in the proposed design methodology. This integrative development of technology, oriented to architectural application, matured in the last 20 years and expanded the boundaries of professional

Fig. 7.2 Peter Eisenman House II generative process



practice providing experimental prototypes through a research-by-design approach based on multi-disciplinary collaborations. To this regard the thesis aimed to describe the state of the art of contemporary research, focusing on case-studies that actively employ wood analyzing their workflows and the methodology that defines their approach. In particular, five methodologies for the design of performative wood architecture have been identified and described: biomimetic and morphogenetic-based approach, robotic construction-based design, robotic fabrication-based design, folded plates approach and robotic raw material fabrication. Thereafter the research gathered the cultural and technical knowledge and tried to propose a further methodology to describe a tectonic material-based design approach. A fundamental constituent of the 'research-by-design' strategy and, more in general, of the contemporary scientific research in architecture, is the multidisciplinarity. In the age of hyper-specialization is inevitable to involve different disciplines in a shared common ground to reach outstanding and integrative results. All the analyzed case-studies feature highly interdisciplinary design methods that involves different subjects, from the programmer to the structural engineer, from the biologist to the material expert etc. Due to time and resources limitations the work of investigation conducted in the frame of this thesis, and the related results, have been affected by the lack of interdisciplinarity leaving some questions open for future research directions.

Wood as innovative material for architecture

Wood is an ancient construction material largely used in architecture till the pre-industrial age as it was very easy to find, craft and regenerate and it has exceptional structural properties as well. The industrial revolutions then brought new and more homogeneous artificial materials – steel, glass, concrete – more structurally reliable than wood because of their isotropic predictable and standardized behavior. Therefore, for decades wood was put aside in the construction industry until the renaissance phase[2] of the 80's when, through the introduction of CNC machinery, the industrial processing methods brought in the market new products, such as the laminated timber, that made the material more homogeneous and structurally reliable. Today **wood is experiencing a renovated interest,** not only in its industrially processed stage, which moreover introduced the production of planar element beyond the linear ones, but also in the exploration of its intrinsic properties that the standardization is trying to homogenize. Both directions are of interest for contemporary research, as it emerges from the results analyzed in the case-studies: from the timber folded plates structures experimented at IBOIS of Lausanne – that employ an industrial-based planar component as plywood – to the custom lamination of lightweight structural components of ICD's research pavilion 2015 – that explore highly performative

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[2] Menges A., Schwinn T., Krieg O. D. (edited by), *"Advancing Wood Architecture: a computational approach", Routledge, Abingdon and New York, 2017*

bending resistance of wood according to fiber directions. The analysis of case-studies from the most influent research academies demonstrated that although wood is an old material, very related with tradition, its features, physical and mechanical properties, unfolded by digital technologies, still offer a wilde field of exploration. The biggest challenge, in many of these research projects, is their applicability to the actual **construction industry**: few of the presented cases have in fact been applied to full scale buildings, one of the most outstanding is the Sequential Roof by Zurich ETH. The analyzed case-studies unveil a **highly performative capacity and a strong tectonic character**, highlighting the cultural value of the digital technique under the label of **digital tectonics**, but most of times they are not ready yet for the full-scale application to real buildings. A fundamental reason is that current building regulations are not very flexible already with regular timber structures in general, and, in addition, the complexity involved here by the experimental character and the absence of certifications to satisfy different requirements, make difficult the adoption of such kind of strategies in practice. Moreover, in some of the presented cases, the research aims did not orient the project to a direct application of the results. As demonstrated by many projects of Stuttgart ICD, this freedom from applicative-related constrains allows to **push the boundaries of material behavior exploration**, computational design resources, robotic fabrication, all in one project. Research needs to be free from the building regulation constrains in an initial phase. It needs to go ten steps further from now, so that in the next three or five years we could see applied to our everyday life even a small part of that path.

The focus on wood as construction material to study and experiment innovative applications, was suggested principally by three aspects:

- the global trend of academic research;
- the need to test further design and fabrication strategies based on wood characteristics (structural behavior, ease of manufacturing, sustainability) and refine/consolidate the existing methodologies;
- the theoretical and empirical exploration of digital tectonics enabled by use of wood in architectural construction.

These three interrelated aspects contributed to the structuring of the research path. The first provided the fundamental database to study and describe the 'state of the art' which is essential to be aware of contemporary research directions and to learn from what has already been done. The second fostered the application and experimentation of alternative design and fabrication strategies to explore the potential of a resourceful material through a research-by-design approach. Wood has exceptional structural properties and it is on of the few truly renewable material for architecture, this revitalized research direction might bring considerable advantages in the sustainability challenge. For example, the absorption of CO_2 and conversion in oxygen during the growth phase of a tree plantation aimed for harvest and material processing, produces a carbon footprint still positive even considering today's heavy industrial processing methods. The third aspect is strictly linked with wood, as the origin of 'tectonics' come from the *'tektòn'* (carpenter); the study highlighted the cultural and architectural value that wood performance-based methodologies are enabling translated into digital tectonics character. Through these guidelines the research presented the digital tectonics of wood architecture achieved through digital design and fabrication tools based on material performance.

An integrative approach to wood architecture: methodology of wood performance-based digital tectonics

In conclusion, the thesis intends to propose an additional approach through a research-by-design strategy. Based on the studies conducted and on the experience as visiting researcher at Tongji University of Shanghai, the thesis encloses the knowledge gained in the last two years under an integrative design methodology of material-based digital tectonics of wood architecture. A **methodology** is here intended as a framework that goes beyond the functional unfolding of a process, it identifies a **global approach** to a selected topic, which can be described through different but correlated concepts. Hence the methodology is considered as a **general/global strategy** which is then applied through **specific/ local workflow**. The workflow is slightly different from one project to the other because it must address specific issues, nevertheless different workflows are identified in the same methodology as global approach. Research-by-design has been employed as primary investigation strategy, as many research institutions do to test their methodologies. Based on theoretical debate and scientific knowledge, that define the cultural and the technical environment within which architecture evolves, this strategy of design and construction of full-scale architectural demonstrators – from details prototyping to pavilions – represents a helpful medium to understand the technological advancements and to manage their potentiality in a conscious vision of the future.

The analyzed methodologies have been classified in categories in this thesis to highlight their primary **character and research focus** and group them according to these principles. The proposed classification is based on the most evident characteristics and it does not mean to be a rigid one; traces of interrelation can be found among each other. The folded plates strategy explored by IBOIS, for instance, could be further implemented based on biological prototype or could be robotic assembled or both things. Or, another example, the robotic raw wood strategy makes a consistent use of computational morphogenesis but, since the focus is the employment of natural wood form in architectural construction, it is still makes sense to label it another category. Therefore, the proposed classification is one of the possible ways of reading the contemporary research approaches according to specific selection criteria. Moreover it is worth to highlight that in all the presented cases the identified methodology defines the approach of the research institution. It is interesting to note that, when framing the study field on performative wood architecture, four of the most relevant research institutions in Europe represents four different promising research directions that describe the potential of material-based design. A further observation can be highlighted in these conclusions: all the presented institutions base their research advancements in architecture on a multidisciplinary approach. The joined efforts of different disciplines within the same school/institution demonstrate, in the first place, the efficiency of an integrative research program that makes a combined used of resources (both scientific and financial) and, in the second place, that the outstanding results obtained brings scientific advancements for the different disciplines involved not only for the architectural one.

As a first approach to the understanding of innovative technologies applied to wood architecture, this research tried to evaluate the different factors involved in such complex field of study which evolved rapidly in the last 20 years. From the awareness of digital potential and its corresponding materialization through robotic fabrication to the debate on the tectonic expression that these approaches enables, the research aimed to deliver a bodywork of the current state of the art in this field analyzing their workflows. To this regards the visits to the laboratories of Stuttgart's ICD and Zürich ETH have been of significant importance for a conscious vision. Moreover the direct experience in the field made at Tongji University of Shanghai under the supervision of Prof. Philip F. Yuan, was fundamental for an understanding 'from the inside' unfolding the design and fabrication processes.

The **methodology of performance-based wood digital tectonics** presented recalls the main steps unfolded in the other analyzed methodologies and tries to provide a further approach to wood performance-based design. In other words, the research aimed to deliver an interpretation of the existing context and, in addition, derive and unfold a methodological process through four interrelated phases. The first step is identified in the definition of the research space where the fundamental questions are put in place describing aims, potentiality, material exploration, available tools, in relation to the contemporary research agenda. The second step defined the design boundaries and constrains, introduces detailed project requirements, selective criteria and deeper analysis. The third step defines the project itself, through the unfolding of previous concepts, criteria, constrains and performative capacity it defines the form generation process. Different morphologies are produced and analyzed in relation to performance criteria and fabrication constrains. The last step is the materialization of the design through fabrication and assembly which is not detached but, on the contrary, it always informs the previous phases integrating digital and physical realities.

The use of technological potential has to be understood as a set of digital and physical tools that enhance integrative processes in architectural design. The interest in an integrative workflow rises from the need to coherently combine these tools in current architectural practice with the contemporary themes of material scarcity, environmental sustainability, aware resources use, avoiding unnecessary formalisms. The resulting tectonic expression stands for the validity of the adoption of these approaches in design thinking. The architect, for the nature of his profession, is constantly learning and always finds resourceful inspirations in other disciplines. A reckless technological employment, that disregards the architectural principles, would bring to meaningless results without any cultural value. For these reasons the architects need to put their hands and mind on digital technologies and direct an interdisciplinary realm towards an integrative vision.

The developments in digital technologies are reflected in a field of current economic trends addressed to as 'Industry 4.0'. The research results analyzed in the framework of this thesis testify that this trends are building the conditions that support a material culture where the customization is no longer expensive. Until not long ago it was almost impossible to think of a mass-customization system because it was inadequate to the conventional production model based on an economy of scale. Today for a programmed robot it makes no difference to make 500 pieces all equals or all different, it is not anymore an issue related to production. On the other hand digital tools allows us to make those variations in the design phases at a relatively reduced cost. The reintroduction of a material culture in architecture contextually brings a renovated tectonic vision where the digital crafting plays a relevant role. The designer can link the material behavior to global design requirements in a generative way, instead of using it as passive mean forced into a predetermined form. Digital crafting allows consequently for a greater attention in the design and make of details, liberating the project from many constrains of the mass production system. Industry 4.0 might be principally linked to the new industrial production methods, nevertheless it is certainly a manifestation of a changing culture that is pervading not only the economy but also the social context. As stated in the first chapter, the introduction of new tools influenced different professional fields, architecture felt this influence by adopting those tools in its practice. This expanded the horizons and opened the exploration of the potential of technologies in design and construction. Today we assist to the mature phase of a digital age in architecture which had access to more developed technologies, a generation that is already after the first turn of 'digital architects' *"not the founders, the folders and blobmeisters in the early 1990s but those who came to the digital scene in the early years of the new millennium, when the technical and cultural tenets of parametricism had already been established"* [3]. In fact it seems we already entered the post-digital age, which is not

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[3] Carpo M. "Post-Digital "Quitters": Why the Shift Toward Collage Is Worrying" March 2018. www.metro-

intended as the exhaustion of the digital age as “non-digital” or “anti-digital” in the way the postmodernism was for the modernism. On the contrary to what some seems to interpret which label retro-looking collage and water-colors representation of architecture (although yet ‘photoshopped’) which confuse the hyper-realistic representations as the only outcome of digital influence in architecture[4]. It is true that, as stated by Sam Jacob, the drawing is a fundamental architectural act, but this is not the point of digital turn. This vision is based on the premise that the digital age is over. Following the though of Carpo, the digital turn is farm from over and the post-digital is going to be an even more digital phase based on the technical and theoretical knowledge sedimented during the last 20 years. Artificial Intelligence, seen as the main engine of this second turn together with the related big data management, are already changing the way we interface with technological tools and interact in society. AI started in the 70s as a possibility that machines one day could emulate the human brain. This project failed long ago and the intelligence referred to in this future development is the ability of computer to deal with an enormous amount of data and solve problems within that context in a very limited time which for humans would take forever[5]. The future developments are promising to a point that there is already the belief that in many profession the computers will do the boring repetitive work while the human will have more time to focus on the creative and cultural mansions. Innovation only occurs when technical supply matches cultural demand, and when new technology and new social practices are congruent within the same techno-social feedback loop[6]. We might finally conclude that if architects will embrace this digital turn, as they did with the previous one, and will bring together culture and technology, then we could have innovation in architecture that is performative under multiple aspects and synthesized in its tectonic character.

> “If we don’t care about technology today, it is not because there is no technology out there, but because there is too much of it; it’s not because we are bored, it’s because we are quitters. And, as always, if architects stop caring about technology, someone else will in their stead.” [7]

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polismag.com/architecture/post-digital-collage/ (accessed August 2018)

[4] Jacob S. “Architecture enter the age of post-digital drawing.” www.metropolismag.com/architecture/architecture-enters-age-post-digital-drawing/ (accessed August 2018)

[5] Carpo M. “The post-digital will be even more digital. The cycle in digital architecture is far from over” www.metropolismag.com/ideas/post-digital-will-be-more-digital/ (accessed August 2018)

[6] Leroi-Gourhan A., “Milieu et techniques” Albin Michel, Paris, 1992 as quoted by Mario Carpo in the postface of its book “The second digital turn. Design beyond intelligence” MIT Press Cambridge/London, 2016

[7] Carpo M. “Post-Digital “Quitters”: Why the Shift Toward Collage Is Worrying” March 2018. www.metropolismag.com/architecture/post-digital-collage/ (accessed August 2018)

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