

Tangible Computing

Manufacturing of Intertwined Logics

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This paper explores the process of digital materialization through robotic fabrication techniques by presenting three wooden projects. The analysis of the case studies is oriented to underline the impact that computation had on architectural construction due to its methodological and instrumental innovations over the last decades. The absorption of computing and digital fabrication logics within the discipline is explored from either an architectural point of view and from the improvements related to automation of the constructive process. On the one hand the case studies are caught because of the desire to expand material complexity and, on the other hand because of the integration with other technological systems. The narrative allows gathering pros and cons in three different investigative macro areas: material culture, methodological oversights, and operative setbacks coming from digital machine and communicational constraints. This analytical investigation helps the definition of a new pathway for future researches, looking forward the assimilation of digital materiality learning in building construction.

Keywords: *computational design, file-to-factory, large-scale robotic woodworking, new production methods*

COMPUTING OF DIFFERENTIATED LOGICS

This paper explores the seamless control between design and materialization of form made available to architects by recent developments in the fields of computational design and digital manufacturing. Beside a brief theoretical background, the paper considers the impact of computation on the architect's design mindset highlighting different case studies to discuss the thesis: they are effective proving grounds considering different approaches at different scale of

the "new digital continuum" (Kolarevic, 2003) that has entered in academic research.

Over the past decades, computation has entered in the common designing approach and architects have started to develop ways of thinking divergent from the deep-rooted and demiurgic practice, by borrowing from other disciplines promising logics. Historical and epistemological roots referred to linguistics, sociology, physics, and biology laid the basis to put forward an understanding of computation

not as a marginal remedy to architectural design, but as a methodical vehicle. The teleological studies on *gestalt* (form) and *bildung* (formation) epitomise the founding factors of the theory of morphology: this discipline has a major impact on architecture inasmuch it regards the evolution of form. This pivotal but general concept that is mainly borrowed from exact sciences reveals its operational potential in architectural design when paired with cybernetics. On a theoretical standpoint, first designing episodes started to embed the theories of formation, transformation and of growth of form within the project path and resulted instrumental to promote cybernetics concepts in the architectural investigative agenda.

The word cybernetics stems from Greek *kybernetike*, meaning governance: although it is referred to conceptions that appear far apart from architecture - namely control systems, or logic modelling - the intellectual domain of cybernetics advances the research of the "goodness of fit" (Alexander, 1964) by augmenting its transdisciplinary value. Cybernetics, defined "as a field that illuminates the concepts of adaption and control by way of abstraction" (Riiber, 2011), specifies that systems are built on regulation, adjustment and purpose. The advent of computational design, thanks to its generic and flexible nature, constitutes a convenient platform in matching the growing body of available information. It steers the generation of mutual interactions among constituents while the computed agent (the object) is distinguished from the computational process (the method). Rather than implying cybernetics as the oversampled way to control an architectural system by using technology (i.e. hardware or software technology), the most effective value of computational design arises from the opportunity to arrange manifold focuses, which are decoded and conceptualized as iteration, generation and variation of geometric formation. As consequence, the attention of a common digital approach is focused on the shift from a "pre-emptive act" (Sheil, 2012) towards a procedural process that implements performances relying on shapes validating innovative spatial configuration.

The relentless digital enhancement in architectural design has progressively transformed the architect's drafting board into a software ecosystem, and has made the sequential separation between modeling, optimization, analysis and fabrication processes more evident. While strengthening further the separation between design and making already theorized centuries earlier by L. B. Alberti, the "computational fallacy" stated by S. Kwinter (2003) demands the seamless correspondence between original ideas and material fabrication as a resolving answer to a jammed computational scenario. Architects have already realized that computing is not only a convenient gizmo for formal and aesthetic investigations, but it inaugurates an operative dialogue with the digital manufacturing lattice on which the project can be based. Therefore emerging frameworks and techniques in the fields of design and construction are contributing to a disciplinary revolution due to the progressive convergence of computation and materialization.

Thus the recent achievements demonstrate the impact of IT on both the ideation and the digital manufacturing of unconventional prototypical architectures. A profound upheaval has been put in place by avant-garde academic and professional practices since the introduction of tailored CNC and robotic fabrication systems, mainly borrowed from automotive. In particular, the narrative traces different ways through which digital fabrication technologies are simultaneously developing and expanding the role of computation as interface between the digitally computed design and the physical world.

COMPUTATIONAL AND MATERIAL COALESCENCE

The digital turn has definitely triggered a considerable symbolic and systemic revaluation in architectural design; by the same token the digital manufacturing of material space has been introduced as one of the computational parameters. Once the mindset about forms that "are no longer designed but calculated" (Cache and Speaks, 1995) has been en-

Figure 1
Overall view of the
Landesgartenschau
Exhibition Hall. ©
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compassed, the focus of the research shifts from the computable abstraction to the tangible computing of its manufacturing process. The same transdisciplinary key concepts - such as automation, adaptation, emergence, convergence, communication, efficiency, efficacy, and connectivity -, that have been the foundational thoughts for the transfer of cybernetics' logics within the architectural designing flow, are now becoming paradigms addressed towards fabrication. Thus, the project conceptualized as a computational system transfers its rule-based design in criteria involving both digital machineries and materials. The spread of digital fabrication facilities in architecture activates the "new digital continuum" (Kolarevic, 2003) inasmuch capabilities like standardization or automation don't represent simply practical solutions, but they become design parameters in assuring architectural qualities.

Three wooden structures are shown as representative of full-scale implications; they outline part of the evolving array of interoperable tools and processes that allow the design-to-production chain of non-standard outcomes. As matter of fact architects have developed pioneering and innovative material fabrication setups, which purposefully allow the transfer in actual-size constructions of essentials from manifold branches of knowledge as well as from different craft expertise. Material, manufacturing constraints and assembly logics become designing pa-

rameters proving that file-to-factory is not a process as linear and reductive as some detractor may claim (Sheil & Glynn, 2011). As M. Burry suggests, the digital fabrication advent has taken the credit of blurring the model and prototype boundaries (Sheil, 2012), focusing on a discipline that intertwines design and production.

CASE STUDIES

Amidst the broad array of digital fabrication applications, the dissertation chooses wooden structure as case studies in order to investigate theoretical statements. Architects are honing robotic and CNC fabrication techniques for manufacturing purposes reconsidering wood and its derivatives as suitable building materials for the experimental design researches at an actual scale and no longer as an out-of-date material. Recent years have seen unprecedented innovation of new technologies for "advancing wood architecture" (Menges et al., 2016).

The selected case studies - the Landesgartenschau Exhibition Hall (University of Stuttgart, 2014), the Woodchip Barn (Architectural Association, Design&Make, 2015), and the Digital Urban Orchard (Institute for Advanced Architecture of Catalonia, OTF, 2016) - bring forward different achievements and perspectives on digital fabrication in architecture to illustrate the interplay between the virtual design and the virtue of material.



Figure 2
Left: robot milling
from the public
information panels.
Right: internal view
of the plate outlines
that visually reflect
the changing of
Gaussian curvature.
© Miro Bannwart

As a prime example, the Landesgartenschau Exhibition Hall (LaGa from here on) largely demonstrates the efficiency of the “machinic morphospace” (Menges, 2012) first applied at a building size. The applied morphogenetic process explores the multifarious advantages arising from the reciprocal influence between the rationalization of biological rules, the material fabrication requirements and from the multiple performative applications. The entire constructive principle of this exhibition hall is based on the large-scale application of the robotically fabricated finger joint system, developed in the previous biomimetic research of the Research Pavilion 2011 by ICD and ITKE.

The LaGa’s final morphology results in a permanent, fully enclosed, insulated and waterproof building (Figure 1), which uses beech plywood plates as the primary load bearing elements. The resulting three layers’ sandwich dome-shaped shell considers solutions to the programmatic requests (two functional zones were required: a reception and an exhibition area) while applying a form-finding strategy oriented to generate a lightweight structure. In fact the implemented Agent-Based Modelling (ABM) algorithm allows the discretization of the doubly curved surface through planar subdivision accordingly to the Tangent Plane Intersection (TPI) strategy. Each individual and unique polygonal plate interacts with its neighbours ensuring the structural stability through the distribution of in-plane shear forces

along the plate edges. The computed plate outlines visually reflect the changing of Gaussian curvature between the two computed synclastic main areas. Besides the programmatic, geometric and structural focusing, the plate-structure and the relative three-dimensional finger joints have been generated following also other parameters. For example the robotic workspace, the angle variety achievable by the robot-arm equipped with the spindle and paired with the turntable, and even assembly-related functionalities or material conditions, such as the stock material size (Figure 2).

This comprehensive computational approach, in making every detail adaptable to local and global geometric parameters, represent a valuable proof of concept of the integration of innovative constructive process and technological system - e.g. load-bearing structure and insulated sealed shell - within a computational protocol. However the resource-efficient lightweight structure and its corresponding fabrication procedures reveal minor cons. They directly arise from the high level of specialization in the study, limiting the conception stage of the design process and consequently the spatial configuration of the final shape.

The large-spanning and unprecedented Vierendeel-style truss built by the Design&Make team (Figure 3), while been focused on the evolutionary metaheuristic optimization placement technique, considers the substantial material parameter

Figure 3
Overall view of the
Wood Chip Barn
with perimeter
walls and roof on
top of the truss. ©
Andrea Quartara



in robotic fabrication as strength of the applied research. The Woodchip Barn project is entirely built with non-engineered wood and thoroughly relies on a data-driven process coming from the survey of the tree forks' digital catalogue.

An ambition of the project is achieving a structural diversity not only thanks to the differentiated robotic processing, but also directly from the natural conformation of the 25 selected forks (Figure 4). Each one of them is wholly unique by nature and the shape is optimized by itself: the capacity of carrying "significant cantilevers with minimal material" (Self and Vercruysse, 2017) is exploited by a customized robotic fabrication setup that augments its inherent structural and geometric qualities. A 6-axis robot arm equipped with a routing spindle has machined each tenon-mortise connections; they were defined between each root and branch of the forks as volumetric subtraction of geometric primitives - e.g. cuboid, cylinder, truncated cone - correctly aligned. The tolerances management was a key point in the whole computational process, highlighting the consistent system of geometric references developed to ultimately achieve the maximum construction precision with irregular natural round-wood. The connection strategy designated the use of "steel bolts and split rings to provide tension and shear capacity" (Mollica and Self, 2016) to the compression transfer through timber-to-timber joints.

Besides the uniqueness and the noteworthy of the truss, the final result totally relies on the algorithmic process of metaheuristic repositioning of the forks selected from the photographic campaign done in the forest of Hooke Park. Whenever this process would be applied in another place, the structure will be limited to the configuration and size of natural material available on that specific site.

Figure 4
A tree fork before
been machined. ©
Andrea Quartara



The Digital Urban Orchard research project (DUO) involves the construction of a functional prototype to be implemented in urban public spaces within the self-sufficiency programme of the city of Barcelona. The OTF pavilion stems from the relation among form, function and application context for a new concept of socialization space and food production (Figure 5). As subsidiary section of the study, the built prototype hosts a hydroponic farming system and a opening silicone skin able to ensure the indoor comfort conditions for plants by natural ventilation. The simultaneous concerns on designing a stable yet iterative structure and on the solar gain have required

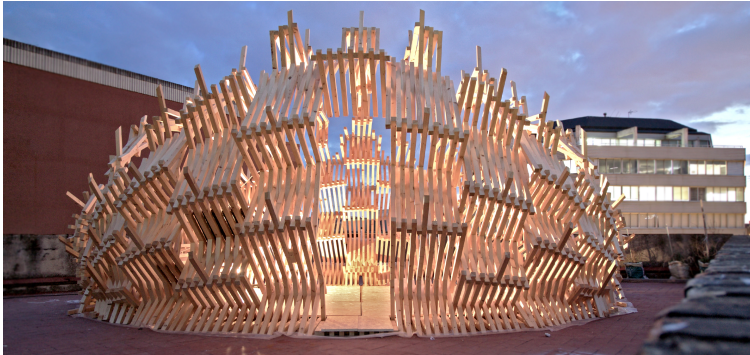


Figure 5
DUO: overall of the
wooden structure,
without the silicone
skin. © Andrea
Quartara

multiple design expedients in complying each one of the functional, structural and environmental performance criteria. In order to inform the genetic optimization of the shape (i.e. genotype), a data-driven strategy was set: the multiple phenotypes, among which the designer has found the final form, were generated through the progressive modification of environmental, geometric and manufacturing parameters.

The adopted hyper static structural system is generated from a pantograph-like pattern: the repetition of diagonals elements at differentiated angles ensures the structural rigidity. Despite the fact that at first sight the structure is an undifferentiated set of stick nailed to each other, each Redwood stick of Flanders, according to its position performs diversified tasks. Through the adaptable pattern of angled end-cuts, the stick-assembly alternately offers flat supporting areas for the hydroponic pipes, or it constitutes space-functional furniture or either some extended sticks are designed as holder of the silicone skin. The density of the structural pattern also responds to optimization logics for solar gain and considers almost total transparency at the top of the pavilion. The final shape has been discretized according to robotic fabrication constraints and manual assembly logics in 6 types of sections, for 12 components in total.

Three manufacturing strategies have been defined depending on the size of the sections. They in-

volve the robotic processing of the entire section or of two halves or of three parts of the final arc section with 30 assembled parts in total. 2,524 shank nails were used in order to maximize the joints resistance. The collaborative fabrication process between robotic manufacturing and manual finishing was implemented starting from the achievements of the previous Fusta Robòtica Pavilion (exposed at the Setmana de la Fusta, Barcelona, 2015). Implementations concerned all stages in order to reduce material consumption and expand the range of achievable geometry within a non-industrial working setup. Furthermore the customization concerns also the hacking of standard woodworking tools placed on the rotary table, such as the miter saw which allows 3-dimensional angled cuts, or the pneumatic gripper fixed on the robot flange used as end effector, and also the sticks supplier which provides wooden profiles in three different lengths in order to reduce waste material (Figure 6). Realized with 1682 sticks, the pavilion is the result of a fast process of a design-to-production chain; 52 hours of production in the robotic room and 36 hours of unskilled manual assembly have ensured the custom digital design workflow completed in a rapid and automated production process, with only 2% of scraps from the material supply. While the OTF project involves different implications then the ones of the previous renowned design experiences, such as the environmental optimization of shape and the mass-customization advantages, its

Figure 6
 Left: robotic
 fabrication process.
 Right: DUO's inner
 view. © Andrea
 Quartara



working setup opens up the debate around the fabrication's tolerance: the integration between technical/technological systems and low-engineered setup produces variances between the virtual design and the material actual size pavilion, due to high tolerance.

In different ways the three structures demonstrate the computational path, previously theoretically introduced, actuating the digital chain and materializing it through a collaborative robotic-human production process, customized from time to time. Within this design cycle forcefully emerges the need of taking in account of the material features, not as a final add-on of the architectural process, rather as part of the required informative loop. For the final implementation of complex design programs, the development of digital fabrication facilities constitutes the essential requirement allowing the production of individually differentiated geometries. In improving one single full-scale design-to-production workflow, critical points and advantages of the bi-directional digital and physical design process arise.

DELINEATING HORIZONS

The analytical interpretation of these case studies introduces different macro areas of intertwining limitations and potentialities arising directly from an experienced computational mindset and also facets linked to fabrication facilities, or to material properties involved in the digital fabrication. Indeed the

material culture brings a projective capacity within the computational workflow, breaking the conceptual separation between the processes of design and the physical making of a built architecture. In stark contrast to precursors linear and mechanistic modes of digital making, the digital manufacturing implemented in the case studies assists the computational work progress, giving rise to an explorative "cyber-physical" (Menges, 2015) process. The material- and fabrication-aware design are reawaken not in the sense of the tenet "truth to materials" of modernist attempts, but rather as truly new design paradigms for vernacular materials by intertwining material computation, digital fabrication facilities, cybernetics and optimization. As counterpart the prediction of material behaviour, especially for natural materials and low-engineered components, is an entire field of research to be investigated in order to overturn material hurdles in material facilitations.

When architectural implementations are decidedly oriented to digital machineries they express a contrived mechanical commitment, which leads to "a lack of architectural taste", as G. Scott states in his work *The Architecture of Humanism: A Study in the History of Taste* (1914). This definition, borrowed from a context far apart from the digital fabrication's background, properly describes the risks that may occur when designers emphasize a proactive approach while embracing industrial technologies.

However, the actual change comes from adoption and adaptation of advanced production tools, complying choices for architectural space. In regards to architects, one of the most valuable features established is the management of the whole process from design-to-production, relying on a data-driven process that embed different kind of parameters and customised fabrication tools since the early design stages. Although the “new digital continuum” (Kolarevic, 2003) could be carried out within a single virtual environment, the high level of interoperability required between different programming languages can produce communicational constraints between different machine’s protocols. Given the fact that the high specificity of the case studies activates remarkable accomplishments, it means also that bespoke tools and fabrication equipment are not aimed to work for any other project and remain exclusive to only a particular design. In this sense, wider applications “related to the precise working of CNC-controlled machines [...] led to irreparable production errors” (Kloft, 2009). However some of these limitations become marginal in a trial-and-error approach; conversely their spread use in the building industry would amplify their relevance.

Another category of limitations and potentialities woven together can be described as a combination of methodological oversights and benefits. In fact, besides technical difficulties, which are inevitable during applied researches, this last group of failures is centered less on the characteristics of the machinery and more on the nature of the design process. Multifarious research projects demonstrate the sought changes in the fields of software, hardware, and mindset above all. However it is useful re-instate the difference between computerizing a design process and computing material spaces. Sometimes they can be defined as mistaken perspectives arising from emphasized fascination for computational and Computer Numerically Controlled capabilities exceeding architectural design interests. One of the most insidious attitudinal fallacies occurs when authors attribute more value to the enticing and

streamlined virtual flow, rather than to the underlying opportunities of novel tangible formations to be transferred to the building industry by means of “digital materiality” (Gramazio et al., 2008).

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