WOOD, CAD AND AI: Digital Modelling as Place of Convergence of Natural and Artificial Intelligent to Design Timber Architecture

Fabio Bianconi and Marco Filippucci

Abstract The contemporary development and digital culture in architecture, from the idea to the realization, lead to a rewriting of the coordinates of the deep relation between model and pre-figuration, especially in the timber structure field. Artificial intelligence opened new potentialities that rewrite the project paths through the evaluation of computational design, with a model set as the place of simulation and experimentation, in order to locate solutions for more and more high requests made by architecture. Wood's natural intelligence inspires artificial intelligence's principles, and it is projected as the new frontier of the research, in its possibility of defying optimized solutions also in function of multiples objectives and parameters. Wooden architecture design correlated to a history of tradition, which is established on descriptive geometry, finds today multiple application fields for the research. In this sense, representation supports the knowledge and the innovation, able to continue and express its operative aspect full of culture and, at the same time, its tecné sense, which etymologically it is meant as art and technique. The present chapter shows different ways to apply the contemporary principle of descriptive geometry in digital wood design research, in a multidisciplinary and contaminated learning environment. In all the illustrated cases, the generative design has a central role, in an integration addressed to the need of optimization of architectural form, using Genetic algorithms in order to analyze and to understand the relationship between form, geometry, and construction.

Keywords Representation · Generative design · Artificial Intelligent

---

F. Bianconi · M. Filippucci (✉)
Department of Civil and Environmental Engineering, University of Study of Perugia, Perugia, Italy
e-mail: marco.filippucci@unipg.it

F. Bianconi
e-mail: fabio.bianconi@unipg.it

F. Bianconi and M. Filippucci (eds.), *Digital Wood Design*, Lecture Notes in Civil Engineering 24, https://doi.org/10.1007/978-3-030-03676-8_1

1 Introduction

The new paradigm of digital tectonics is developing the coincidence between geometric representations of structuring and the program to modulate them (Oxman 2006, pp. 229–266; Oxman and Oxman 2010b). In architectural representation, the model allows to analyse and simulate according to the behaviours of structures and materials with the energetic performances of the analysed buildings (Brown and Mueller 2016). For example, the innovation of Building Information Model (Eastman 2011) has to be considered firstly connected to the management of Big Data, to the possibility of replicating in virtual field the immaterial implications of the form. These conditions tell us how CAD is orienting to Computational Design for Architecture, and how now here it is changing the design process (Menges and Ahlquist 2011).

The theme of simulation (Baudrillard 1981) is the centre point of the actual development of digital representation, which is connected to the theme of augmented reality and the actual trend to replicate in a three-dimensional simulacrum the form that, until now, was expressed in the planarity of the image.

Simulation is also related to the themes of prototyping (Chen and Sass 2017; Larry Sass and Oxman 2006) manufacturing (Kolarevic 2004; Kolarevic and Klinger 2008) and fabrication (Austern et al. 2018; Corser 2010; Krieg et al. 2014; Sakamoto and Ferré 2008; Sheil 2005), with a 3D printing (Correa et al. 2015; Le Duigou et al. 2016), CAD/CAM system (Chaszar and Glymph 2010; Lawrence Sass 2012; Lawrence Sass and Botha 2006) and robotics (Eversmann et al. 2017; Gramazio and Kohler 2014; McGee and Ponce de León 2014; Menges 2012, 2013; Menges et al. 2017b), it developed according to the possibility of new tools to deconstruct the forms for the constructive process. In this sense, if "architecture continually informs and is informed by its modes of representation and construction, perhaps never more so than now, when digital media and emerging technologies are rapidly expanding what we conceived to be formally, spatially and materially possible" (Iwamoto 2009, p. 4). We are living in a cultural revolution, because "fabrication is not a modelling technique, but a revolution in the making of architecture" (Oxman and Oxman 2010a, p. 24). Digital representation is ever more characterized by an hybridization between reality and virtual, in the simulation that defines also the physical result of the architecture.

The digital representation is ever more characterized by a hybridization between reality and virtual, in the simulation that defines also the physical result of the architecture.

Anyway, it is possible to replicate aspects connected not only to the morphological aspects, or organized by the constructive workflow, it includes the form-finding approach to functions like energy consumption or structural deformations also related to the form (Adriaenssens et al. 2014; Menges 2012). The simulation firstly it opens to interaction, as a new way to involve the user in the comprehension of architectural implications in form and function (Greenough 1947).

This condition is strictly related to the revolution of parametric (Schumacher 2011). The extrapolation of logical connections in the construction of the form is based on the individuation of relations and dependences (Jabi 2013), defining ranges

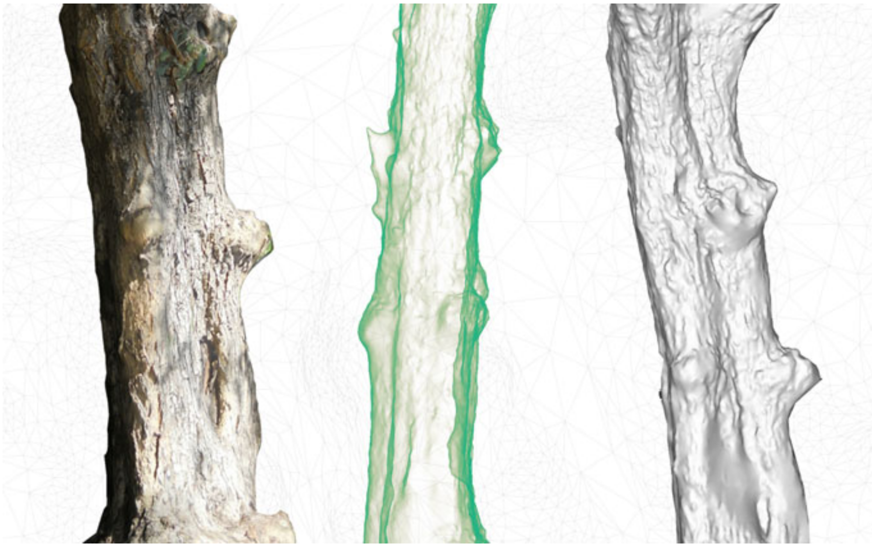

Fig. 1 Digital wood: architectural survey and modelling of natural shapes of an olive tree

of the possible input data to determinate the options. The centrality of the model as an organic system of relations, it defines the variation as a result, according to the question that "difference is not diversity. Diversity is given, but difference is that by which the given is given … Difference is not phenomenon but the noumenon closest to the phenomenon" (Deleuze 1994, p. 222). For this reason, we think is more correct to define this approach as a generative design, rather than parametric, in order to mark the capacity of this modelling of discovering new forms.

In this sense, this methodology responds perfectly to the modern request, proposed by the father of the descriptive geometry, Gaspard Monge, when he writes about its objectives: "*Le premier est de représenter avec exactitude, sur des dessins qui n'ont que deux dimensions, les objets qui en ont trois, et qui sont susceptibles de définition rigoureuse. … Le second objet de la géométrie descriptive est de déduire de la description exacte des corps tout ce qui suit nécessairement de leurs formes et de leurs positions respectives. Dans ce sens, c'est un moyen de rechercher la vérité; elle offre des examples perpétuels du passage du connu à l'inconnu*" (The first is to represent with precision in drawings that have only two dimensions objects that have three dimensions and that can be defined rigorously … The second objective of the descriptive geometry is to deduce from the exact description of the bodies, everything that is necessarily followed by their forms and their respective positions; in this sense it is a means of seeking truth, as it offers perpetual examples of the passage from what is known to what is unknown" (Monge 1789, p. 2) (Fig. 1).

The generative design, anyway is a two-dimensional drawing, defined by the connections between simpler algorithms, it defines rigorously the form as any digital path and it offers also the exact description of bodies, integrating also different information. But the real question about generative essence is this "seeking truth", not as a path of passage from ignorance to wisdom, but from "what is known to what is unknown", a condition that operatively it is possible to test stressing the parameters and their combinations.

In the construction of the system of relations and dependencies, the generative design is a "representation of a representation", a "square representation", able to amplify in an "exponential way" the passage form logic of model, linking geometry and computer syntax (Filippucci 2012a). The deconstruction of elements, fundamental also for parameterization, together with the representation of connections and structures it clarifies the mutual positions of algorithms. Digital revolution has strengthened the requests of rigorous with its own syntactic alphabet, purely mathematical, able to procure synthetic elements and morphological patterns, a network of nodes and connections that can be considered ideogrammatic morpheme of contemporary hypertext communication (Bianconi 2002, 2005). Generative modelling becomes an instrument able to reinvigorate the union of the graphical representation of space and digital space, a process that explains what a form is made of, and not what kind of form it is. In representing a logical net, the parameterization of the elements is a consequence, an opportunity of digital descriptive text to regain possession of its infinite potential and dynamic heuristic, analysis of a path, understanding singular elements of digital syntax. In this way, it is possible to have a "critical analysis of digital representation's performance", as descriptive geometry discipline required (Monge 1789).

Generative design, anyway, represents a spontaneous evolution of digital modelling, aimed to make the most of its potential, valorising the capacity of computer to simulate all the possible combination and to evaluate the solution for the best. It represents a support and a response to the contemporary architectonical criteria founded in the performances and defined by the organic system, which is oriented to its formal definition (Hensel 2013; Oxman 2009; Turrin et al. 2011). Inside the generative interpretation, here is in fact hidden an organic interpretation of the model according to the "deep principles" of Nature (Petra Gruber and Jeronimidis 2012).

Natural Intelligence (NI), which is all the systems of control and not artifacts, but rather is present in biology, is the font of inspiration for the architectonic research (Goel et al. 2014; López et al. 2017; Vattam et al. 2007). Nature offers not forms but processes to think about form (Oxman 2009) and it teaches how to create forms (Barthel 1967; Bhushan 2009) in efficient structures (Knippers and Speck 2012; Wester 2002) explaining how the roles of a design (Mattheck 1998; Mazzoleni 2013) really is adaptive and optimized (Pawlyn 2011). NI defines the paradigms that could be receipted not as "an ignorantly copy of the shapes" … but in the acknowledgement "that biomimetics teaches that shape is the most important parameter of all" (Vincent 2009, p. 81), because at all levels it builds responsive and adaptive forms to conserve material and energy resources through the use of modular components combined with least-energy structural strategies (Pearce 1979).

The biological paradigm (Thompson 1917) becomes operative in digital representation through the development of new technologies (Hensel et al. 2010). In this centrality of biomimetic (Bar-Cohen 2016; Benyus 1997; Kuhlmann 2011; Lynn

1999; Myers 2012; Pedersen Zari 2015) recent developments focus on multi-scale models and the interplay of mechanical phenomena at various hierarchical levels (Knippers et al. 2016), as it is shown in some architectural experimentation (Bechert et al. 2016; Krieg et al. 2015). Beginning with Ingo Rechenberg, the first application of the Genetic Algorithms to the aerodynamic wing design (Rechenberg 1965), the computer research began to develop algorithms inspired by natural evolution (Fogel et al. 1966) in order to generate solutions to problems that were too difficult to tackle with other analytical methods (Floreano and Mattiussi 2009, p. 1), founded in the cycle between analysis, selection, coupling, and coalescence steps that are repeated until reaching the solution (Rutten 2013). The logic of this approach is to find "*Solutions with better fitness values that are more likely to survive and to join the next generation in a genetic algorithm*" (Medaglia 2007); the application of Darwinism's two fundamental contributions, to "move in the direction of a science of multiplicities: the substitution of populations for types, and the substitution of rates or differential relations for degrees (Deleuze and Guattari 1987, p. 48). Evolutionary Algorithms, applying the biological principles of mutation, selection, and inheritance, reinterpret the parametric system that becomes the genome, the field of alternatives is the same of the population, and the architect's design goal becomes the fitness criteria. It is possible to define the genetic algorithm as a series of mathematical operations that transform individual objects of a given population into a subsequent new population, by selecting a certain percentage of objects according to fitness criteria. Anyway, genetic algorithms are instruments to solve constraint satisfaction problem, typically solved by using a form of search, pertinent to the process of building (Fig. 2).

Genetic algorithms are the expression of the use of Artificial Intelligence in digital representation; they are innovating this field by introducing a no-handed drawing, with no direct representation of the form, no direct use of the fundamental algorithms of representation, points and lines (Bianconi et al. 2017a; Filippucci 2015). The development of evolutionary strategies reinforces the horizon of a generative modelling (Renner and Ekárt 2003) by supporting the definition of unthinkable and performative solutions (Menges 2009). In this simulation, it is possible to exploit the computational capabilities of digital tools and to explore the possible combinations, not only one parameter at a time, with the goal of improving a single aspect of a building (Jones 2009a), but, more of them simultaneously.

The development of evolutionary strategies for construction issues (Kicinger et al. 2005) finds new life thanks to the support offered by AI: environment can be considered as Active Agent of the design (Hensel 2010) and in the range of solutions and in all possible combinations AI chooses and draws the solution with the best fitness. The proposed parametricism is not connected only to a variation of geometrical parameters to change the final shape, but also it can be derived from an input not directly connected to the form. In fact, it is possible to consider external environment as a font of possible input data (Hensel and Menges 2008; Woodbury 2010), by integrating also those derivable from Big Data (Couldry and Powell 2014) or from the internet of things (i.e. in domotic, a form that can derive from an external signal—temperature—which drives a form—the opening of a louvre) to support the

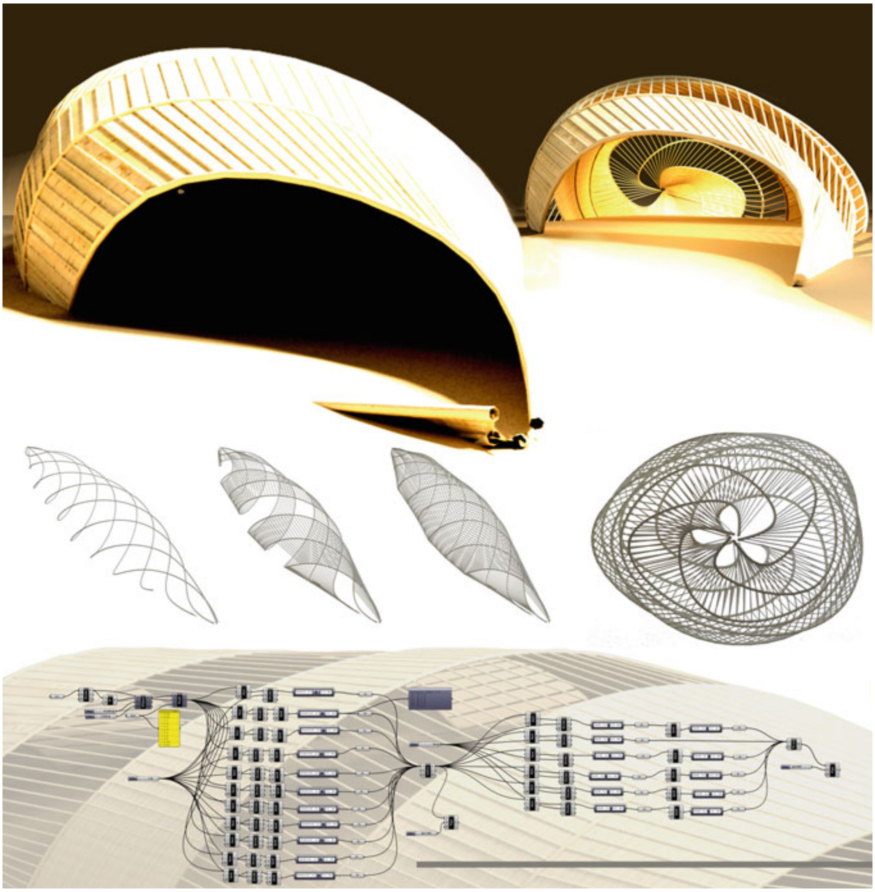

Fig. 2 Digital design: didactic generative modelling of Toyo Ito's snail shell-shaped timber structure inspired by NI

decision-making. The frontiers of the computational design see the organization of the information and the management of big data, which can become the input data to generate solutions. The volume of activity per minute on the Internet is something like 347,222 tweets written, 51,000 apps downloaded from the Apple app store, 300 h of videos posted on YouTube, 4,166,667 Facebook "Like", 110,040 calls made by Skype, 17,336,111 photos "liked" on Instagram… (Iafrate 2018, pp. 45–46). Artificial Intelligence will learn ever more quickly with the increasing amounts of data to "consume". Computer really aids design, the intelligent machine codesigns architecture, because it finds solution and draws form without a direct representation, and also because in the acquisition of external (and big) data, AI also does self-learning, remembering experiences of past actions (Fig. 3).

Fig. 3 Wood design: didactic modelling to materialize the space

As Darwin lesson about ex-aptation shows us, this process is not teleologic, so the genetic algorithm shows us how it is possible to adapt a form to a changing context (Woodbury 2010), by defining a new form of thinking design (Oxman and Oxman 2014). From another point of view, we can describe the same process by affirming that an object described by parameters can be uploaded and it can evolve, so we can say that AI redraws it (Vierlinger 2015), with results (Vierlinger 2013) that could be valued also for their "artistic" value (Bittermann 2009; Pearson 2011) and their role in space discovery, in a digital path anyway is open and flexible (Vierlinger and Bollinger 2014).

Adaptation, responsivity, flexibility, evolution, are the keyword connected to NI, that characterize the actual architectonic debate. Also, if NI opens to other horizons and conceptualizations, in this context, it is possible to link this theme to the relationship between design and construction, deepening, in particular, the wood as a paradigmatic matter. A Morpho-Ecologies approach (Hensel and Menges 2006) "commences from the unfolding of performative capacities inherent in material systems in relation to the specific environment they are embedded within, as well as an intensively empirical mode based on physical and computational form-generation and analysis methods" (Hensel and Menges 2008). This new approach is changing the paradigms and the processes of architectonic research because structure, form, and materials are not taken separated one from the other, but together in an organic project where the digital process can simultaneously design and stress their characteristics.

Artificial Intelligence appears now as the future of digital representation. The smart culture needs to "do more with less", it defines the need of a performative result, and the intrinsic capacity of computation inside the digital process, with the guaranty of achieving this goal in relation with the design (Grobman and Neuman 2013). Robots can adapt like animals (Cully et al. 2015) and through AI also drawing is becoming every day more "complex, creative and surprising" (Lehman et al. 2018). Someone is scared by this automation and the possibility of transhumanists, but even if a drawing without hands is developing, the role of the designer is still the center of modelling question; it is impossible to peerless our creativity and our capacity of innovating, by disrupting our limits and ideas, the awareness, which is the central question of the design process. At the basis, there is geometry and its capacity of describing reality, by abstracting the phenomena in a mathematical model. This because generative design changes the design thinking, by only marking the abstraction process defined by a mathematical language and by an algorithmically logic (Woodbury 2010).

In the abstraction of the virtual space, it is possible to forget the weight of materiality, the concretism of the architectural question. In digital representation is possible now to reproduce any form. In the real world, this is not useful. In the digital representation, the time dimension can be unconsidered. In the real world, this is not possible. It is really important not to fall in love with the model and the instrument. Not totally at least, because in the real and concrete world there is what is concrete and real, there is a natural intelligence.

In this context, wood represents a particular matter perfect for the application of this approach. Wood is naturally connected to the smartness of biology (Ugolev 2014), the cause of its functional characteristic (Herzog et al. 2004), variable in quality. Priory renewable resource (Dangel 2016) with an aesthetic appeal, workability, flexible, relatively light, versatility, low thermal conductivity, wood presents also unwanted characteristic for its sizing limits and deformations, isotropism, hygroscopicity and degradation. Through its engineering aimed at homogenization of the characteristics of this material every day more, wood represents a performing solution that integrates fabrication as a generative paradigm into the design process (Gramazio et al. 2010, p. 111). For these conditions, wood represents one of the most important field of application of parametric design (Chilton and Tang 2016; Kaufmann and Nerdinger 2011; Menges et al. 2017a; Vierlinger 2015; Weinand 2016) where "non-standard timber structures can be efficiently aggregated from a multitude of single timber members to foster highly versatile timber constructions" (Willmann et al. 2017, p. 26). In hybridization and integration of digital wood design, the innovative tools involve a transformation of paradigm and form, connections and limits. Wood, CAD, and AI, all dynamic elements in evolution, those are transforming our research, because as underline Achim Menges, "rethinking wood through a computational perspective has only just begun" (Menges 2017, p. 108) (Fig. 4).

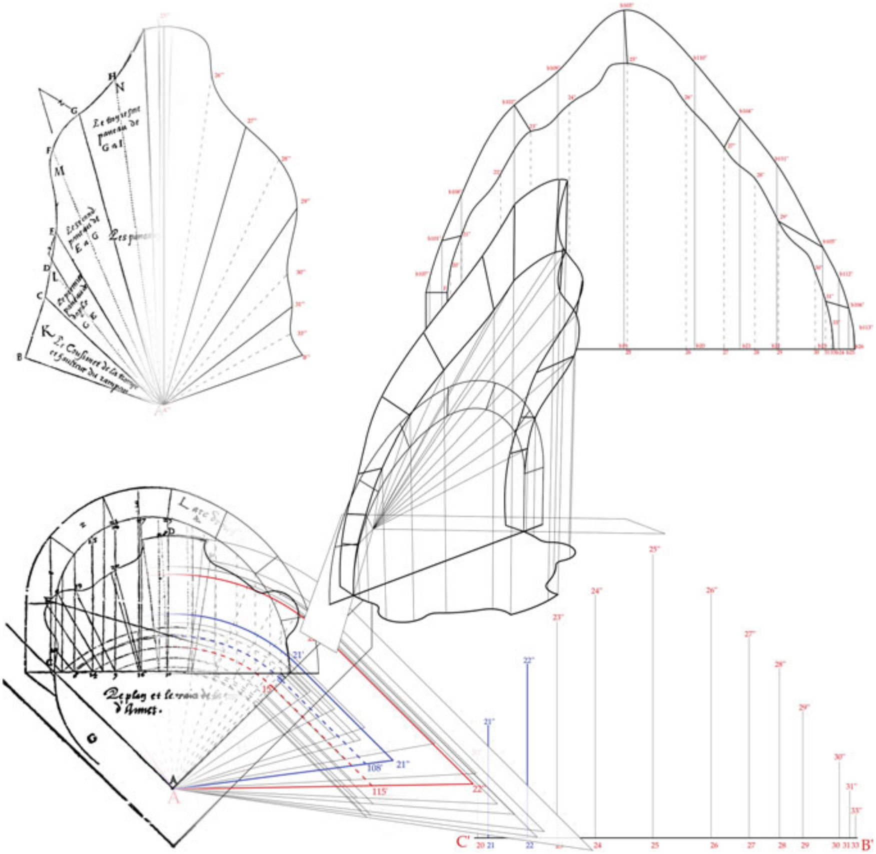

Fig. 4 Traditional parametric wood design: digital reconstruction of geometrical process for the cutting of "trompe" ashlar in Philibert Delorme's Le premiere Tome de l'Architecture" (1567)

2 Background

Defined these coordinates, it is possible to present how AI is changing our research experiences, developed inside the Department of Civil and Environmental Engineering at the University of Perugia and the International Research Laboratory on Landscape. The themes of all the research are always linked to the field of study of the science of representation, deepening the potentiality of digital instruments and the construction of models.

This approach had deepened roots in history, in the research to apply geometry to rationalize the real, and from the origin related to wood design. As implicitly reported in the Laugier's hut archetype (Laugier 1735), geometry represents a *tecné* to trace signs in order to have constructive forms; a technical process that leads to developing theoretical paths, which are defined by stereotomy traits. This science, particularly asserted in France, was born from projective geometry's principles (Evans 1995), which evolve in the gothic (Sanabria 1989) until they reach a theoretic apex in XVIII century with the definition of descriptive geometry by Gaspard Monge (Loria 1931). Father of this technique could be Philibert de L'Orme, he who in his treaty call himself as the creator of the method meant as a path "to unify the practice of geometrical traits with Euclid's theory", with the aim of "reviewing Euclid" (De L'Orme 1568, l. 3f.62). The passage from projective geometry to the Euclidean one is connected then to Girard Desargues' researches (Desarguer 1640), which are already connected to stereotomic teaching (Saint Aubin 1994), this tries to connect prospective with projective geometry (Field 1987, pp. 3–40). The value of the research, studied also by Bosse (1643a), "it is not completely new and revolutionary in principles or in mechanism: but in the drive to theory and in the abstraction from the particular problem" (Trevisan 2011).

The wood stereotomy (Paris 2009) is connected to the descriptive geometry which derived from Gaspard Monge's revision, as testified it is by the nineteenth treaty of Leroy (1857) or of Pillet (1887) or of the italian Peri (1884). Through the analysis of the peculiarity of the material, the first researches were involved in supporting carpenters in the cuts and in the realization of nodes and joints. Using the exact instrument of the design, as rules and compass, in general the stereotomy is a procedural strategy correlated to the constructive phases, following a space discretization process, a simulation of the realization of the form in a geometry of the cut representation, the integration of the static analysis in the centrality of representation together with the graphics analysis and the mechanic of rigid bodies. The growing complexity imposes a structural strictness that leads to the transformation of stereotomy's statute, which moves from "art to science of the cut", where intersection curves are treated between section planes and geometric corps, and the projection of those curves on the different planes (Fallacara 2007, p. 57): it is a historical evolution that finds a decoding of already present notions, because Desargues (Bosse 1643b), La Hire (1596) and Frézier (1737a, 1760) "didn't know they knew descriptive geometry" (Trevisan 2011) but they had implicitly assimilated its prodromes (Salvatore 2012).

Maybe also the contemporary digital world design is not completely aware about its knowledge on the rules of descriptive geometry, which is applied with the same aim of setting in relation the design with the many performance exigencies of the constructions, according to *ante litteram* mass customization logics (Andia and Spiegelhalter 2017; Paoletti 2018). Digital wood design is based on procedures that are so similar to those used in the past, so much that there are many different reinterpretations (Block et al. 2017; De Azambuja Varela and Sousa 2016; Fallacara 2006; Fernando et al. 2015; Rippmann and Block 2011) surely influenced by the possibilities offered by smart fabrication (Davis et al. 2012; Eastman et al. 2009; Li et al. 2008; Popov et al. 2010).

In this cultural root, it is possible to find the reasons that describe the centrality of design as a model and its transdisciplinary language. It is not a whole design, but those are parametric procedures in an implicit way, able to respond to many different solutions. Representative logic expressed, the same one that is the foundation of our thought, it is revealed in its description capacity, to let know the project process.

In this relation, actually contemporary principles of the topological approach of the generative design are present as prodromes, as the logic of similar elements with "modifiers" that lead to the deformation of a "figure" (therefore to the creation of the form) through the "repetition" of the creative act (Fallacara 2007).

This approach of representation is connected to the creation of models for the interpretation of reality, a path applied "from the spun to the city": drawing is always the instrument to understand the complexity of the reality, to analyse and project it and on these coordinates it is insert the writing action, which in the last years it lead to analyse multiple and heterogeneous fields (Bianconi 2005; Bianconi et al. 2006, 2016a, b, 2017a, b, c, d, e, 2018a, b, c, d; Bianconi and Filippucci 2015, 2016a, b; Filippucci 2010, b; Filippucci et al. 2016a, b, 2018, 2017). In the vastness of the application it is possible to find out the centrality of representative research as an instrument to know and innovate, able to continue and to express its operative aspect and at the same time full of culture, the sense of its tecné, etimologically meant as art and technique.

3 Methods and Materials

In our research we are testing different ways to apply the contemporary principle of descriptive geometry to digital wood design research, almost contaminated in a multidisciplinary learning environment. Moreover, the research reported shows also the connection with local small enterprises and Administrations, a knowledge transfer that is the strategy to survey the research. It is important also to mark how in Italy the architectonic culture of wood building is really reborn after the predominance of industrialized construction, even if in the last years these solutions have been finding a vaster market.

In all these cases, generative design has a central role. Moreover, in this process, here are always integrated different tools and software for multidisciplinary analysis. This integration is address to the need of optimization of architectural form, using Genetic algorithms to analyse and to understand the relation between form, geometry and construction.

All the researches start redrawing themes. The transcription through the new medium of generative design changes the messages, verifying the condition and using more performing tools to explore the boundary condition.

In this chapter we describe our works proposing a path of five integrated step in the valorisation of NI in wood design and the opposite engineering of the material, the results of generative transcription, the horizon of form-finding and multi-optimization in the use of AI, the realization of a pavilion.

4 Experimentations

4.1 Responsive Architecture: Study, Characterization and Realization of "Unplywood" Panels for Passive Ventilation Systems

This research is founded on the idea of indulging the natural characterises of the wood, in a path that starts from phenomenal observation and it arrives to define a digital model (Fig. 5). The research aim tries to answer to the needs of a reduced energy consumption building, that has recently led to the development of expensive and technological smart materials (Addington and Schodek 2005; Loonen et al. 2013). The exploitation of certain properties of natural materials can reduce the economical and the environmental impact, which define the new technologies. Inside the different characteristics, the study analyses the hygroscopic behaviour of wood, always considered as a negative property of the material for its end-use, with the aim of transforming this in a positive feature in the realization of a double-layered composites which passively react to the variations in relative humidity (Holstov et al. 2015; Reichert et al. 2015). The bending reaction of "unplywood" is investigated and applied to a passive ventilation system in indoor environments, where relative humidity rapidly changes, and is used to parametrize the architectonical shapes (Figs. 6 and 7).

The research finds its inspiration in the previous works developed by the Institute for Computational Design at the University of Stuttgart (Krieg et al. 2015; Menges and Reichert 2012; Reichert et al. 2015; Wood et al. 2016, 2018), by Newcastle University (Holstov et al. 2015, 2017) and by the ETH of Zurich (Rüggeberg and Burgert 2015). The research is developed by a group from Department of Civil and Environmental Engineering in University of Perugia, which includes the authors and Giulia Pelliccia in the architectonic and representative theme, together with the group of Giorgio Baldinelli and Antonella Rotili from CIRIAF center of the same university to support the energy theme, and the group with Marco Fioravanti, Marco Togni and Giacomo Goli from GESAAF center in Florence University to support the wood research from. The research, started with a master thesis, is developing in a knowledge transfer to the SMe ABITARE+ which is involved in timber construction process.

The integration of different skills is linked to the increasing of building energy efficiency, one of the most important goals to achieve both in existing and new buildings, thus, passive design strategies are becoming a strategic part of the contemporary architecture projects. Wood is a perfect example of a natural smart material: its hygroscopic behaviour makes it responsive to relative humidity variations and the shape-memory effect (Ugolev 2014), it allows its return to the initial configuration

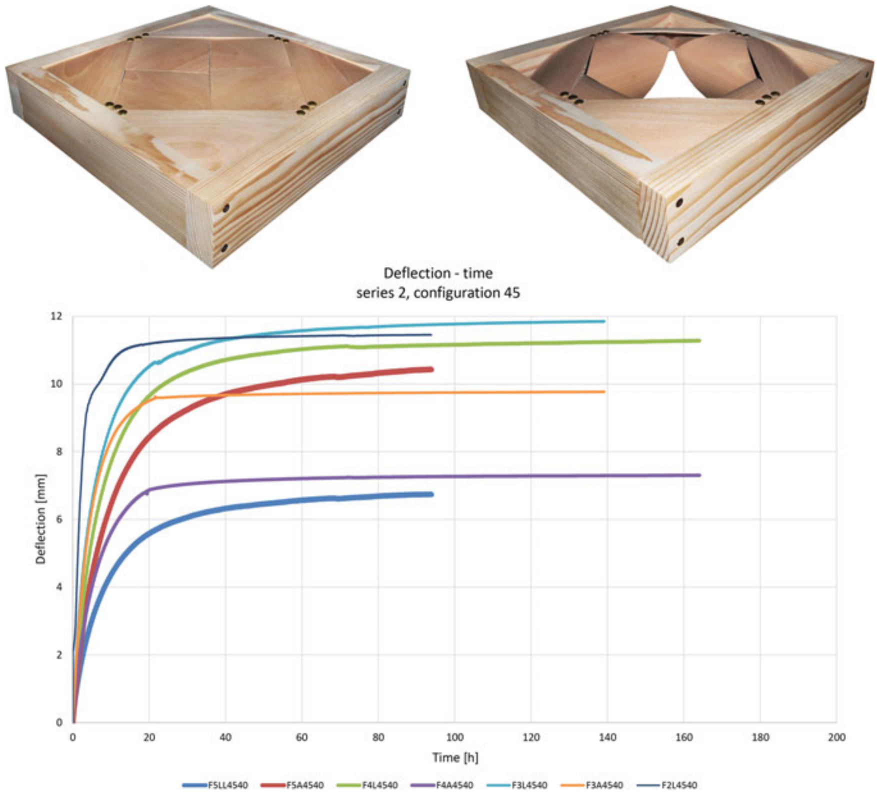

Fig. 5 "Unplywood" panels: empirical researches about the hygroscopic behaviour in displacement of different panels in function of the time

that it had before humidity changes. The absorption of water results in the swelling of wood; if, instead, the relative humidity decreases, wood will loss water and shrink (Fig. 8).

The wood subjected to a variation in moisture content will change its dimensions causing, as a result, aesthetic as well as functional problems. To take advantage of natural hygroscopic properties of wood could be a better solution rather than prevent them with expensive equipment, when the aim is that of designing responsive panels to be used in building air conditioning.

Based on the example of the structure of the pine cones (Burgert and Fratzl 2009; Dawson et al. 1997; Reyssat and Mahadevan 2009; Song et al. 2015), whose double-layered scales bend in reaction to humidity variations, an entirely wood-made panel, called "unplywood", is realized in this research. The two layers of the panel, active and passive, must be cross-grained and the tangential direction of the active

Fig. 6 Modelling as result of observation of phenomena: curvature in function of the humidity in climatic chamber tests

layer corresponds to the longitudinal one of the passive layers, which is almost non-reactive to humidity (Rüggeberg and Burgert 2015; Vailati et al. 2018) in order to have a bending of the "unplywood".

The research stars from the study through experimental tests of some materials and configurations, to evaluate the potential applicability of wood bilayers to the indoor thermo-hygrometric comfort control in conference or meeting rooms, or indoor vanes, where relative humidity rapidly increases and a humidity control system is not present. Wood is used for the active layer beech (Fagus sylvatica L.), while for the passive layer is used spruce (Picea abies Karst.) in some specimens and European larch (Larix decidua Mill.) in others. A one component polyurethane adhesive is used to glue the layers. Both active and passive layers are quarter cut veneers oriented according to the wood anatomical directions. The specimens are 10 cm long, 10 cm wide and with a variable thickness, some of them have the grain direction parallel to the edge (called "90 configuration") and some others are parallel

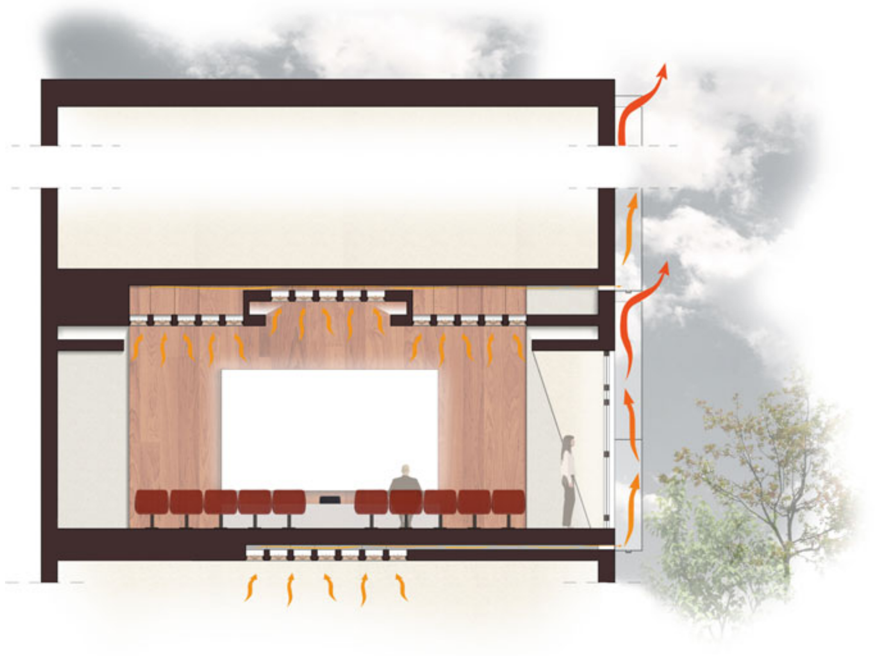

Fig. 7 Wood NI for building energy efficiency: the exploitation of hygroscopic wood transformations for a natural indoor thermo-hygrometric comfort control

to the diagonal of the specimen (called "45 configuration").

The experimental tests and the statistical analysis results lead to the construction of the prototype of a modular panel for a false ceiling, simulated in a meeting room and in a conference room. The humid air inside the room makes the false ceiling open, as a reaction to the relative humidity difference between its faces. Then, air flows in an interspace of 10 cm directly connected with the outside. The air is then introduced in a space, wide not more than 50 cm, between the external wall and a glass wall; for the greenhouse effect, the air inside that space is heated and it moves upwards, until it reaches the opening to the outside at the upper floor level. The application of this ventilation system requires a building of at least one floor above, which must be dehumidified, in order to activate the stack effect. The external wall where the glass is fixed can be totally opaque or transparent, or equipped with some openable windows inwards (in this case, the indoor relative humidity control will be lost).

The parametrization of the architectonical shapes allows to reproduce any plane tessellation to be applicable on every dimension surface: whole surfaces can be covered with different types of tiles. The "unplywood" panels can be used to realize a modulus for a false ceiling for the dehumidification of indoor environments. Through

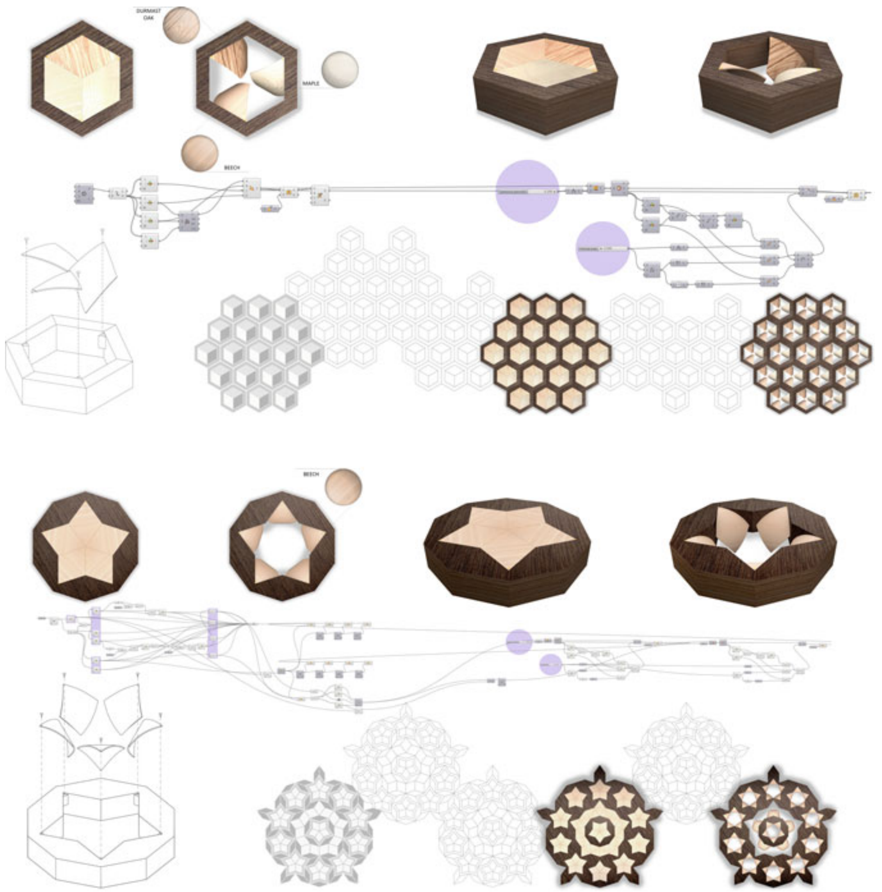

Fig. 8 Digital panel design: parametric variation of the modular configurations for plane tessellation

Grasshopper for Rhinoceros, these three typologies of plane tessellation are reproduced, realizing every tile with “unplywood” panels, whose movement, depending on the maximum deflections reached in reaction to humidity variations, is parametrized in some algorithms base.

Actually, this research represents just a first concretization of the potentialities that “unplywood” shows in the bioclimatic architecture, with the possibility to be applied to every indoor environment, thanks to the adaptability of their shapes and dimensions (Fig. 9).

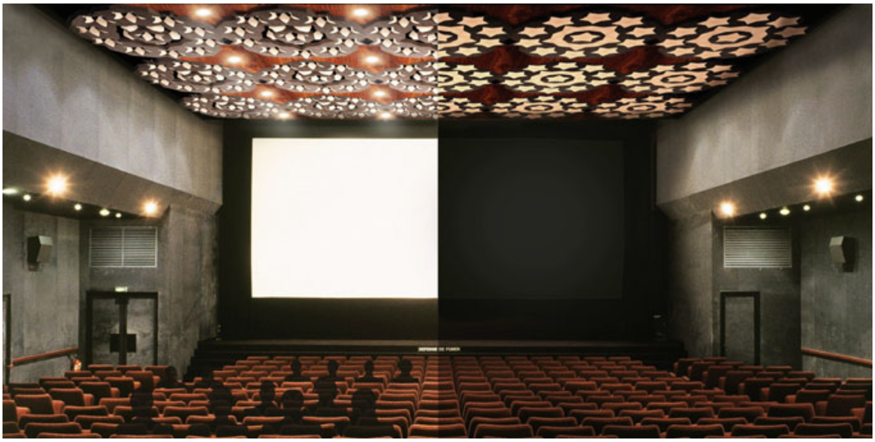

Fig. 9 Digital simulation: open and close configuration of the panelling in an hypothetic ceiling of a meeting room

4.2 *Innovations and Experimentations for Double-Curved Timber Surfaces: Design and Characterization of a Flexible and Engineered Solid Wood Panel*

In contemporary architecture, the language used to draw forms is connected to the possibility of expressing freely any shape. Geometrically, this condition is guaranteed by the double-curvature surfaces and for this is fundamental the material, which is transformed by innovative technologies to overcome the formal constraints for the realization or by a discretization of the surface curvature through a tessellation process. The topic of the research is the study of the double-curved timber surfaces, in the limitation of the wood characteristic for its organic, heterogeneity, anisotropy and personality. The real challenge is to make wood flexible in double-curvature and to obtain a spatial bending, overcoming the limits imposed by nature of the material itself (Fig. 10).

The research is developed by a group from Department of Civil and Environmental Engineering in the University of Perugia that includes the authors and Simone Moroni and Daniela Ripa for the architectonic and representative theme, and the support for wood research from the group with Manuela Romagnoli from DIBAF of University of Tuscia.

The study begins with the impossibility of creating a double curvature surface using wooden planking, due to the not developability of this class of surface. The path starts from the maps of the world and the necessity to cut double curvature surface to develop it in a plane and little approximation, a technique applied in wood design through an oriented cut (Grima et al. 2016).

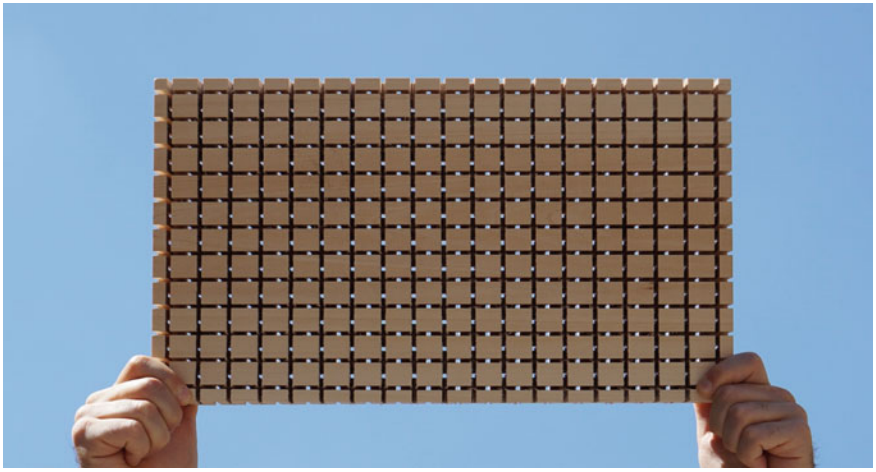

Fig. 10 Flexible solid wooden planking: the discretization through the cut for the double curvature of the panels

Also, if this kerfing technique is noted in the scientific literature (Menges 2011, pp. 77–78; Zarrinmehr et al. 2017), the central question is the definition of engineered solid wood panel as able, flexible and resistant to deform itself in a double-curvature shape. For this reason, in a generalized vision of panelling (Eigensatz et al. 2010; Konaković et al. 2016; Ohshima et al. 2013; Son et al. 2017), the research can be considered as a modelling reverse of the design of a pattern of geodesics on a freeform surface (Pottmann et al. 2010) to obtain a flexible developable surface (Solomon et al. 2012).

The study analyses the factors influencing the laser cutting of the wood (Barnekov et al. 1986) and the proprieties of different wood species; it has developed more than 400 mechanical samples tests by using different wood species (beech, poplar, spruce, lime), with the aim of characterizing their maximum bendability, their bending resistance, and their load resistance. Furthermore, the trend of the stresses internal to the samples is defined by the determination of the critical area of breakage. This provides the ideal cutting frame dimensions which allow to reduce the internal stresses in the weaker zones and to maintain the same bendability capacity, in order to achieve a tenfold increase in curvature for carved panels with a quadrupled cross-section (Figs. 11 and 12).

Through the parametric algorithm, it is possible to simulate the form and the behaviours of these elements, and to modify, according to the performance requested for the panel to have. The panel thickness, the cutting depth, and width, as well as frame dimensions can be changed. For the analysis of the double-curved wooden shapes, the surface cutting is first studied, then some wood folding techniques have been analysed, through cuts, in order to make the material flexible. This condition

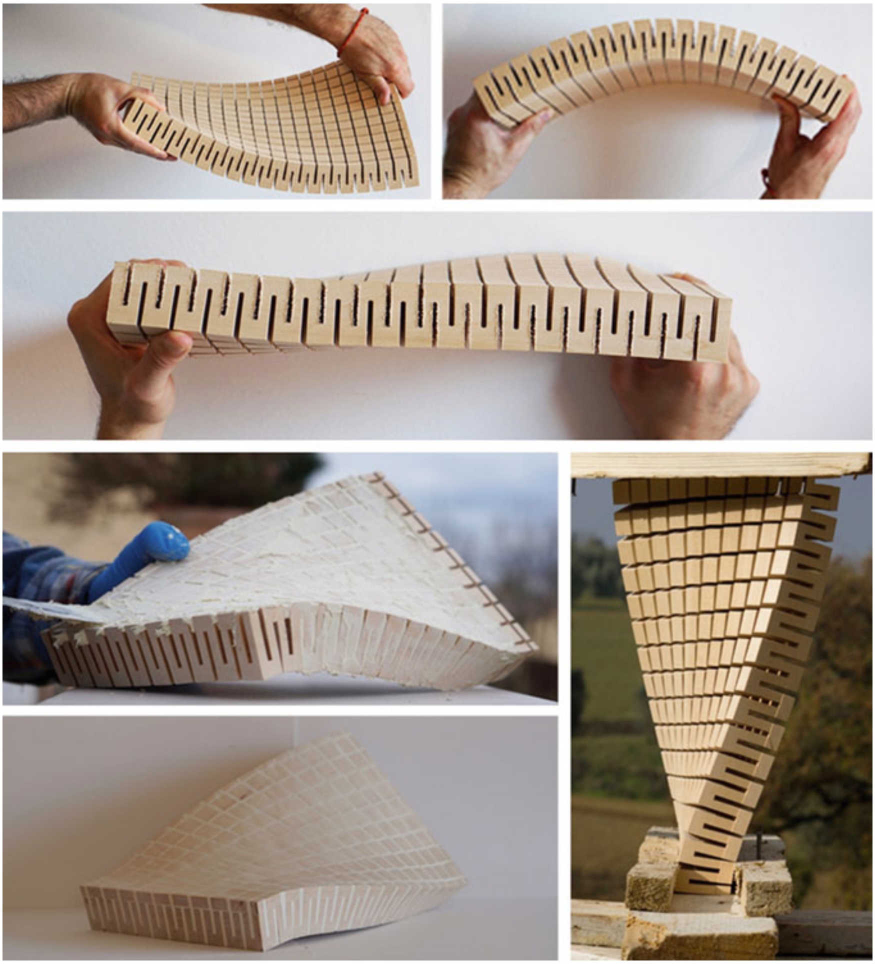

Fig. 11 Kerfing and resin: the construction of a developable panel and the transformation in a structural element

represents just a first phase of the study, that test also the mechanical characteristics of the panel adding different resins, considering the cut like a fist phase, to obtain free form, that through this filling material arrives, in a second phase, to guarantee a structural resistance (Fig. 13).

Empirical research is translated in the digital environment to define, in a different way, the characteristic of the wood redrawn by the digital design. The experimentation on the flexible panel allows to consider the application in design and to bring the deformation capacity of the material to the limit.

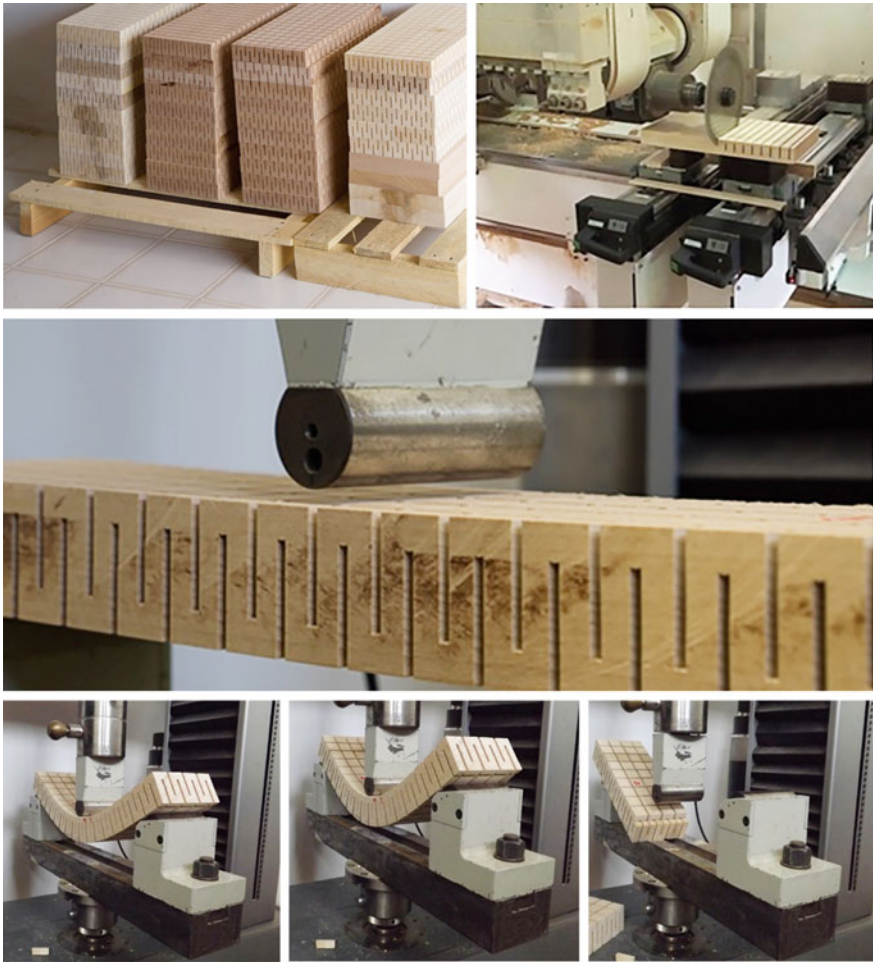

Fig. 12 Mechanical tests: the definition of the cutting frame in 400 specimens in function of the different wood species for the characterizing of maximum bendability, bending resistance, and load resistance

In parallel to the empirical tests, the panels have been digitally reproduced and simulated in digital environment to analyse them under a set of applied loads through the software SAP. The behaviour of the panel has been simulated entering the Young's modulus values obtained from the real bending tests, in order to analyse the internal stresses distribution both in the longitudinal and in the transversal direction to the fibers and to more carefully evaluate the most solicited zones. The research shows as the possible application of the flexible panel as structural element and for this reason are tested different resins, to arrive at breaking strength of 1100 N.

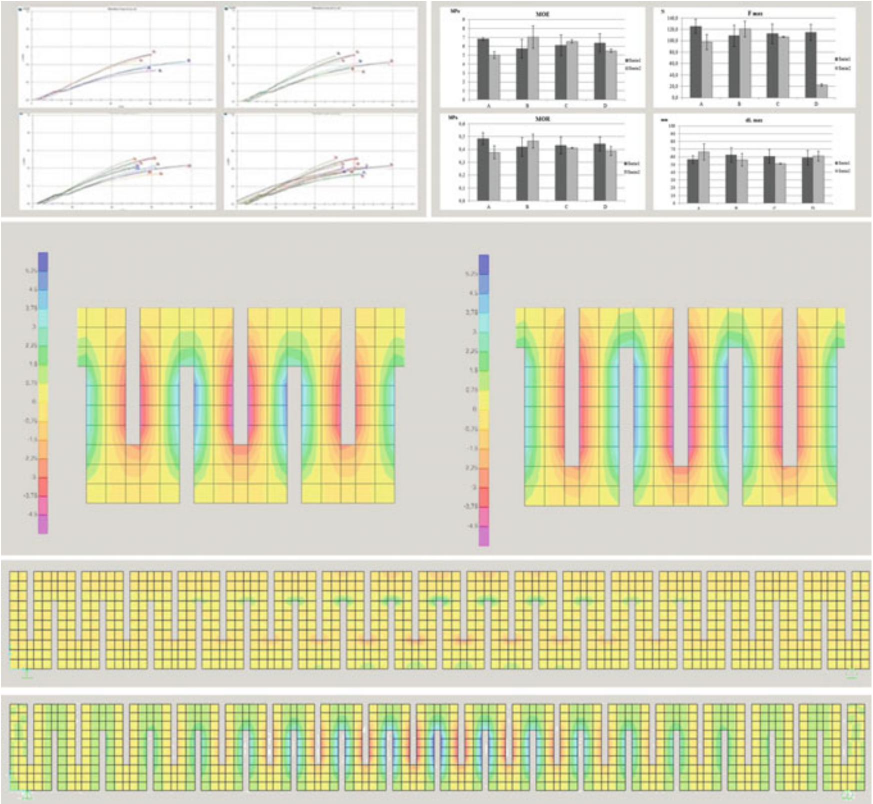

Fig. 13 Digital analysis and design: internal stresses distribution in the structural simulation

4.3 Redrawing Descriptive and Projective Geometry: Generative Design of Stereotomy and Japanese Joints for CAD/CAM Application

Stereotomy means to cut solids, from Greek "stereós" and "témno", geometrization and generalization of architectural elements, and vice versa the application of pure geometry to the architecture of "stereotomy policy". This approach results extremely congenial to the parametric tools today applied to many architectural projects, according to a rule based on a design that today is evermore stronger in generative design.

The research, developed by the authors together with Filippo Bruno Palazzari, starts from the transcription in generative environmental of the drawing published in the eighteenth century Frézier publication (Frézier 1737b), where it is given special importance to the quadric surfaces, by studying firstly the resulting curves from reciprocal spatial relation, the intersection of two quadric surfaces (planar curves or spatial curves). Rewriting these classes of surface in parametric language (Burry 2014) and linking them with the process of smart fabrication (Bidgoli and Cardoso-Llach 2015; Duro-Royo and Oxman 2015; Rippmann and Block 2011; Svilans et al.

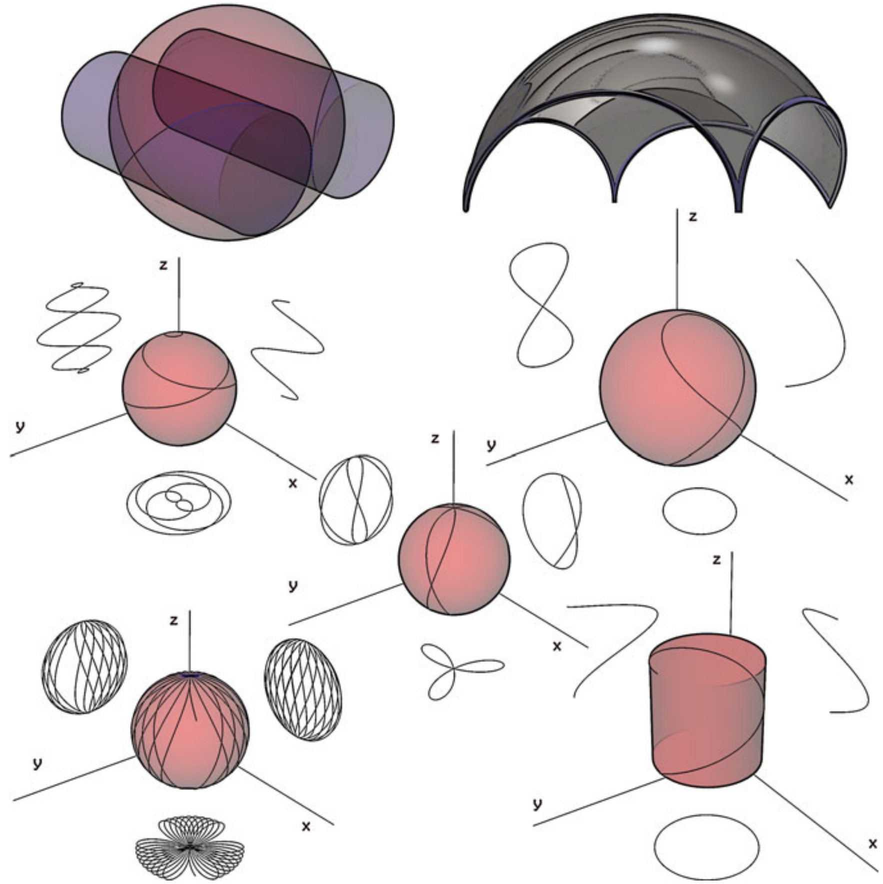

Fig. 14 Parametrizing gemetrical forms: three-dimensional development and parallel projections of hump spirals

2018), it is possible to have parametrized solutions, but also "unknown" forms, also interconnecting, contemning and transforming the classical path (Fig. 14).

It is possible to show this principle in the ideation of a staircase defined by stereometric rules, reinterpreting the Vis de Saint Gilles (Pérouse de Montclos 1985; Sanjurjo Alvarez 2010; Tamborero 2006). Beginning with the generative design of the helicoids, the algorithm, which is created in Grasshopper for Rhinoceros, defines a unique step in the application of classical rules, with variable solutions for its parametric nature in the possibilities of acting on decided upstream parameters, as the diameter of the stairwell, height difference to be overcome, number of windings of the helix and others. As it was in the past, the questions involved regard serialization, minimization of work waste, dry installation. Moreover, the characteristic of the material is another boundary condition, as it was also for the stone cutting in the past. To construct the stairwell by using wood, one of the most important aims is the management of acute angles and maximize contact surfaces. To realize this

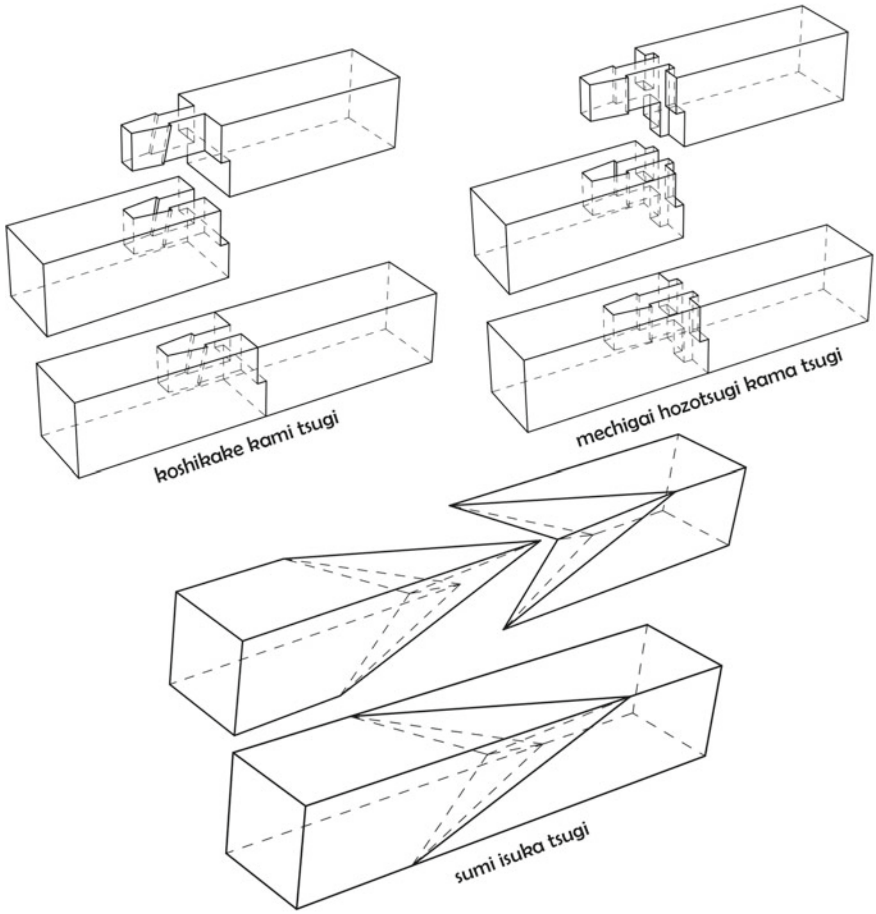

Fig. 15 Digital fabrication as contemporary carpentery: parametric transcription of the art of traditional Japanese wood Joinery

objective, it is necessary to design the form by using solids, which are characterized by perpendicular surfaces, defining for every riser the normal surfaces to the planar helicoid. In the experimentation developed, the helical staircases are digitally defined by five principal surfaces, one planar helicoid, and four spatial helicoids, these define the intrados and extrados of the staircase and its lateral surfaces. In the end, to design the treads of the stairs, with Boolean operations, the extrados helicoid has to be cut by parallel plans to Cartesian plane "xy" (Figs. 15 and 16).

The creation of optimized contact surfaces between the *voussoirs* of a vault (whether it is a staircase or a "classic" vault), so important for wood stereotomy, is realized by joints between the elements of a structure. To design the joint between the steps, the open path guaranteed by the generative design is contaminated with a really different culture of the Japanese carpentry (Brown 2014; Kuroishi 2015;

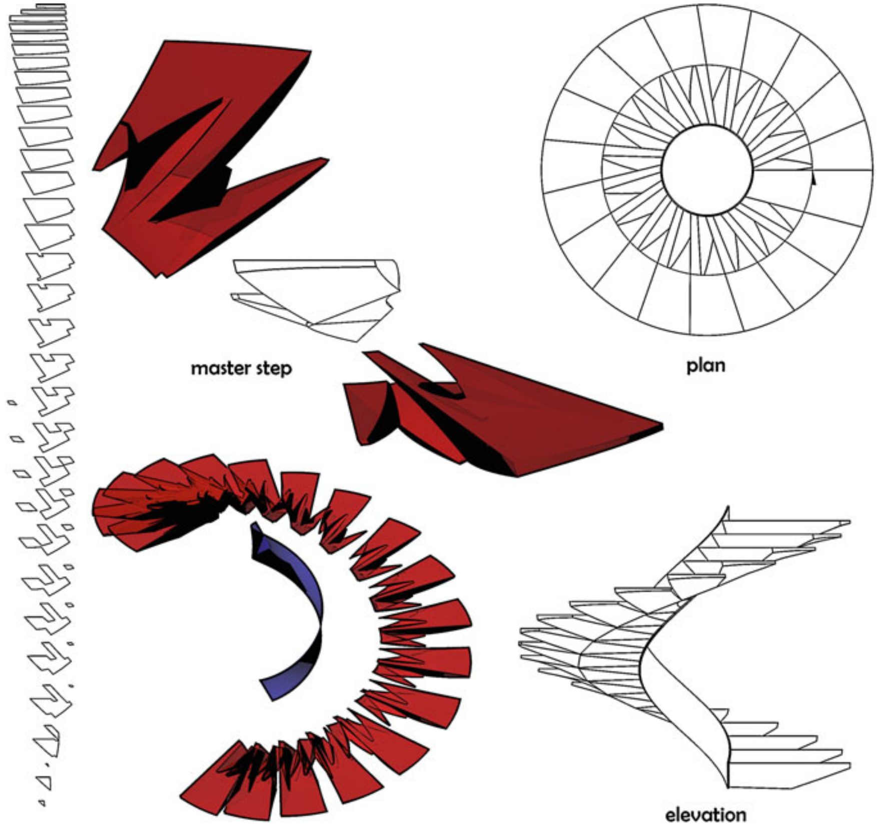

Fig. 16 Digital commingling in generative stereotomy: parametric design for the generalization of helicoidal stairs and the standardization in the serial fabrication through the definition of an unique step incastred by "Sumi Isuka Tsugi" oblique scarf join

Nakahara et al. 1995; Seike 1986; Zwerger 1997). Some joints are rewritten by generative design, in order to transform parametrically any solid. Inside the different joints, it is proposed the application of *Sumi Isuka Tsugi*, which can redraw the serial element. In digital design, by applying a morphing process, it is possible to create stair characterized by the same form for all the steps (excluding the first and the last).

The digital model developed is useful for the structural analysis (applied with Abaqus software) in order to define deformations and internal tensions, and also to simulate the different behaviours, by using integrative structural support. The same model is also useful for 3dprinting, tested by using the additive material, but also useful for laser cutting. By using CAD-CAM technologies, it is then possible to skip the last step, in fact, the designer himself can easily obtain the "Panneaux 2.0" or rather he can obtain numeric codes to be supplied to CNC machines, that can easily construct all of what the designer wants.

In this contamination of disciplines ad solutions, the purpose was reached by letting the possibility of creating one reference step, provided of carpentry joints, into

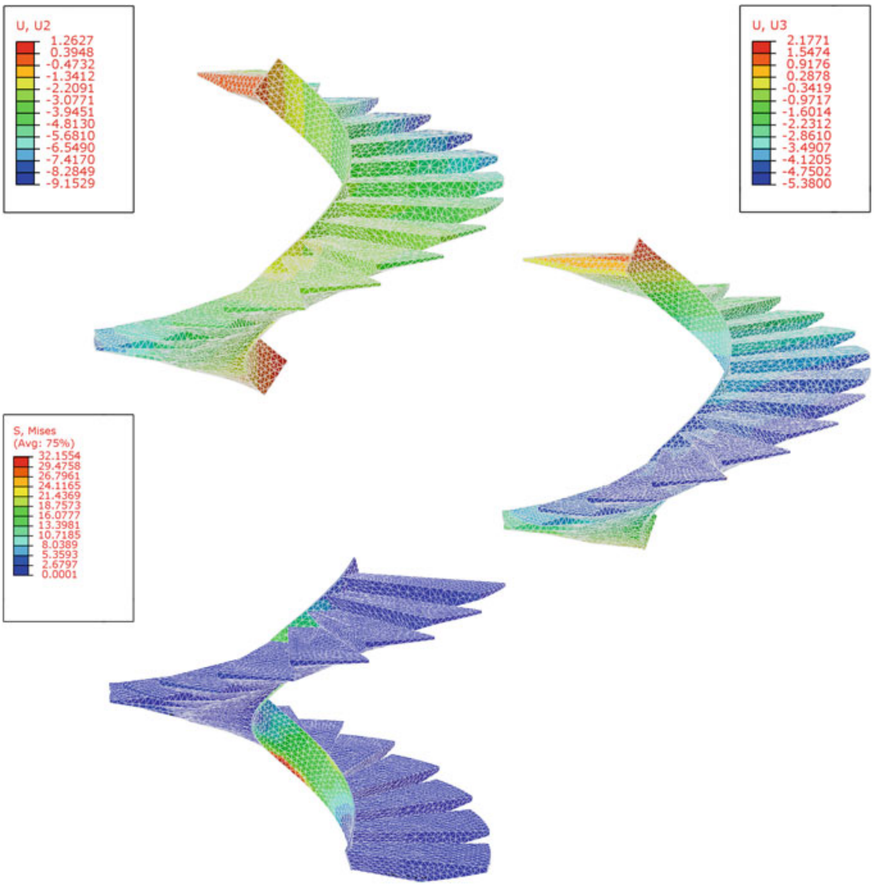

Fig. 17 Generative path for the optimization of the results: computational design for the individuation of the best combinations to minimze deformations and internal tensions

a simple parallelepiped volume, then with (simplistic) the use of topological criteria (namely, geometric transformation without cutting, overlays or gluing) the reference geometry has been morphing into the five basic surfaces of the helical staircase. The research represents one of the new horizons opened by digital representation and parametric tools in the renew of descriptive geometry. Rewriting through these instruments, based on parametrization, the logic of a process, aimed to support the seriality of applications, to guarantee a correspondence of intents from past scopes to the present ones.

The integration of instruments and paths becomes an intercultural instrument able to connect different cultures and different historical results in a contemporary language, which useful to answer to the request of optimization. The historical lesson shows its value and role for the construction of our future (Figs. 17 and 18).

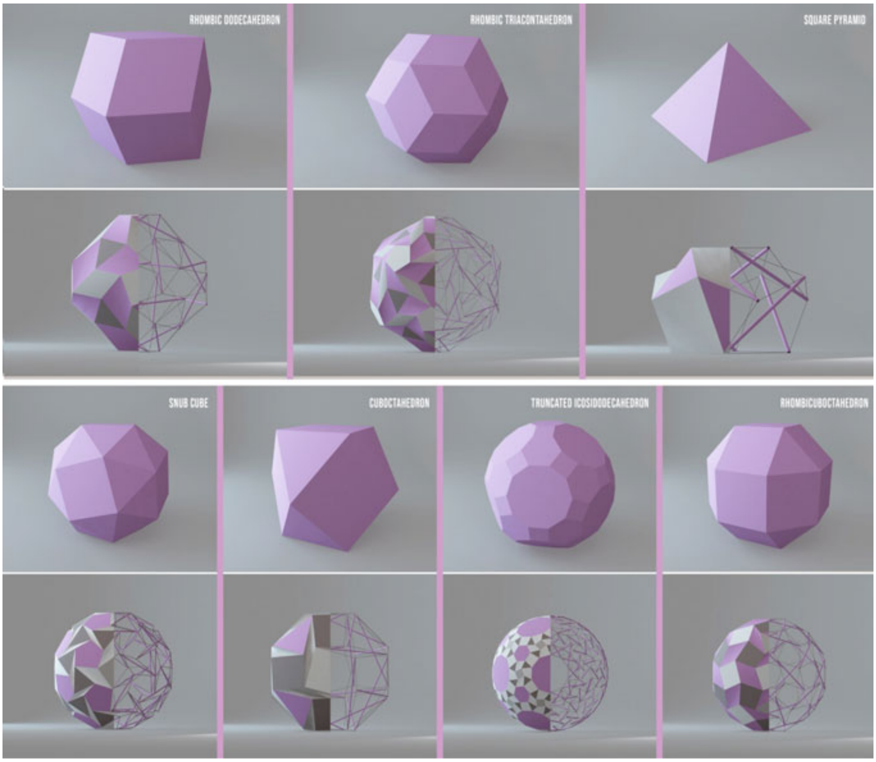

Fig. 18 Generative trascritions: geometrical trasfromation of polyedra for the definition of tensegrity structures

4.4 Wooden Tensegrity Structures and Morphological Evolutions of Transpolyhedra

The construction of innovative structural solutions arises also from the graphic evolution of simple forms. Digital representation, in the transcription of forms, helps to understand the centrality of the medium to understand the form. It is the case of tensegral structures, a study developed by the authors together with Margherita Stramaccia and Matteo Margutti (Bianconi et al. 2017g, 2018), where the geometrical solution is originated by the movement of poles on polyhedric geometries, developed by generative paths. Without graphic support, it's hard to understand what a tensegrity is; it is definable as "a system in a state of stable self–balance including a series of compressed components inside a continuum of tensed components" (Motro 2003, p. 19). Analysing this statement, it is possible to identify the "compressed components" as the poles present inside the system, while the "tensed components" are made up of a net of tie–rods that connect each element and create this continuum (Lonardo 2011, p. 5).

The term "*Tensegrity*" was created in the early Fifties by Richard Buckminster Fuller, as a contraction of the two words "*Tensional*" and "*Integrity*". The main original studies of these structures (Lalvani 1996) was firstly developed through different approaches by Ioganson, the protagonist of the artistic research in Russian Constructivism (Gough 1998), by Emmerich, who was interested in plane and spatial tessellations (Emmerich 1988, 1996), by Snelson, who started from the polyhedral artistic reinterpretation (Snelson 1996, 2012), and Fuller, the most famous (Fuller 1963; Marks and Buckminster Fuller 1973; McHale 1964), who realized some buildings using this class of structures (Buckminster Fuller 1961; Calladine 1978; Krausse and Lichtenstein 2017; Marks and Buckminster Fuller 1973; Sadao 1996) considering the structure as physical manifestation of his theories on synergetics (Buckminster Fuller 1975). Tensegrity is linked to polyhedron (Pugh 1976a), and it can be inserted in the theory of reciprocal structure (Baverel and Larsen 2011; Olivier Baverel and Pugnale 2014; Gherardini and Leali 2017; Kohlhammer and Kotnik 2011; Popovic Larsen 2003, 2008; Thönnissen 2014; Thönnissen and Werenfels 2011), which is just known in history as Leonardo projects show (Di Carlo 2008; Pedretti 1988) but their codification is recent, as testified by the sort of war in patent between the protagonists of last century (Buckminster Fuller, US3203144A 1961; Emmerich Patent 1377290, 1964; Snelson Patent US3169611A, 1960).

Tensegrity structures are analysed by several researches (Burkhardt 2008; René Motro 2003; René Motro and Raducanu 2003; Pugh 1976b; Skelton et al. 2002), those have shown how these structures present interesting peculiarities: for example the extreme lightness accompanied by a surprising structural rigidity, a condition that makes them ideal for the challenge of the research of the minimum mass design (maximum resistance with minimum mass), therefore ideal for the achievement of a more aware eco-friendliness, which is not just focused on mere energetic saving. Other peculiarities that characterize these structures are the capacity of redistribution of the loads on almost the totality of the structure, or once again, the recovery of its own balance independently from the direction of the disturbances that solicit it, all properties that are not possible to find in the actual structural configuration, which is characterized by a superimposition of compression. Every stable three-dimensional structure, composed by p-planks, with a polygon of p sides connected through cables on the top and a polygon of p-sides, when connected through elements solicited by traction as a base, it fits the definition of tensegrity prism (Skelton and de Oliveira 2009, p. 19). For these reasons, tensegrity is subject of theoretical research (Cefalo and Mirats Tur 2010; Chandana et al. 2005; Connelly and Back 1998; Connelly and Whiteley 1992; Fagerström 2009; Hanaor 1992; Masic et al. 2005, 2006; Mirats Tur and Juan 2009; Murakami 2001; Oppenheim and Williams 1997; Tibert 2008; Tran 2002; Vassart and Motro 1999; Zhang et al. 2006) but it is also applied in different field and applications (Abdelmohsen et al. 2016; Adriaenssens and Barnes 2001;

Bouzanjani et al. 2013; Bruce et al. 2014; Chandana et al. 2005; d'Estrée Sterk 2003; Dogra et al. 2015; Lenyra et al. 2006; Liapi 2004; Nestorovic 1987; Paronesso and Passera 2004; Peña et al. 2010; Riether and Wit 2016; Schlaich 2004; Stephan and Klimke 2004; Tachi 2012; Van Telgen et al. 2013; Tibert and Pellegrino 2011; Wang 2004).

Our construction of this systems is based on the same geometric process used for every type of polyhedron, whether it's regular, semi-regular or Catalan. The generative path is structured by a set of rotations and translations, to which it follows the connection between cables and poles, in order to provide the proper redistribution of the tensions. The morphological evolution of the polyhedra passes through the intermediate polyhedric configurations, called "transpolyhedra". The tensegral structure, according to the geometric process previously described, is totally inscribable inside these solids and therefore, between them there are various geometric relations: decomposing the polyhedron in regular figures is therefore possible to recognize the number of poles of the tensegral structure, the number of cables, the geometries to the knot and to have a map of the connections between the same. The creation of the algorithm for the tensegrity structures can become from both the polyhedra and the plane tessellations. In particular, the algorithm for the polyhedra realizes translations and rotations of the corners of the examined polyhedron. It's easy to grasp that the number of corners and faces modifies the dimension of the algorithm generated. The algorithm, due to how it was developed, allows us to vary in many cases the tensegrity structure from both the dimensional point of view and the configuration one; by doing so it will be possible to adapt the polyhedron with the respective tensegral transpolyhedra to every planning necessity, whether it's about a small object or about architecture (Fig. 19).

According to the geometrical correlation between tensegral structures and transpolyhedra, it is possible to consider the generative design of the polyhedron as a vehicle of representation of spatial definition. The same representation, in addition to supporting the idealization process, becomes substantial for the analysis of the form. It's possible to know the number of poles, the number of cables, the dimensions of the same and their spatial disposition, identifiable (though only partially), through the inner corner in the plane figures of the relative transpolyhedra. This abstracted research, founded in geometry and representation, needs to a have another important step in order to be concretized, in the definition of a digital handcraft process. For the characteristics of the material, wood represents in the history a particular field of application for the design, and now it is possible to underline a new development of digital woodcraft (Tamke and Thomsen 2009).

In this connection between geometry, representation, structures and form, it is possible to develop a series of practical applications, also connected to digital wood design. In particular, in this case, we tested the value of this structure in design object. A little table, lamps and more objects in wood were created through the support of this tools. Differently, from the usual condition of tensioning the cables, through wood design, we created sleeves that allow the object to be tensioned, and then to be realized through CNC technique. Also, in this case, the transcription of forms by generative

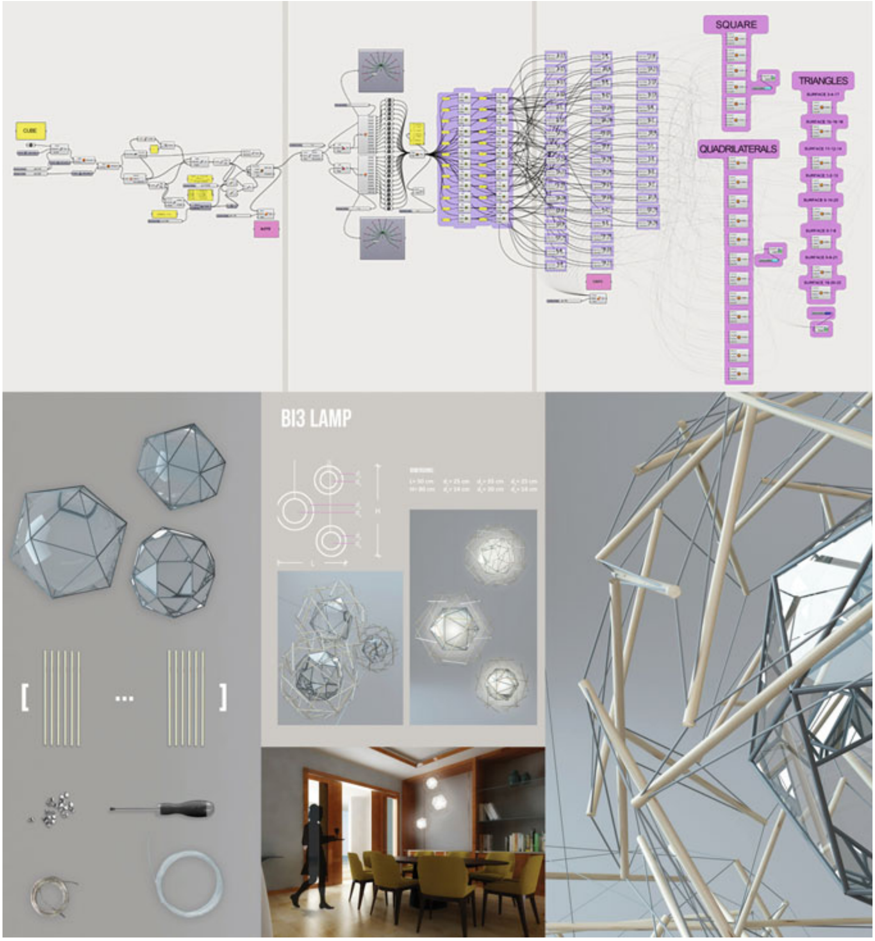

Fig. 19 Heuristic of the digital drawing: medium and message for the ideation and the design

modelling has created a series of solutions and applications, exploding the operative concept of artisan 4.0 as a result of comprehension of a geometrical path: reconnect with materiality and craftsmanship, at the same time, through standardization and simulation, they take away the properties of unpredictability and emergence that were inherent in processes that were harnessing materiality (Fig. 20).

Fig. 20 Design of wood furniture: from the idea to the realization of sleeves elements to obtain the necessary tension of the tensegral structure

4.5 AI for Mass-Customized Housing. Multi-objective Optimization as a Decision Support System

In the ideation process inside the architectural design, the performances required are increasingly becoming a structural requirement of contemporary culture. Likewise, the freedom in the formal expression, the flexibility requests and the multiple needs

Fig. 21 Variation and evolution: the genetic population for the analysis of different combinations

connected to the relation with the context are posed as favourable conditions for the development of a generative approach as a process for a responsive design. The research developed by the authors together with Alessandro Buffi, it aims to define a series of mass-customized housing models, which can be adapted to different context and conditions, providing different solutions as an interaction with the surrounding environment. Through the use of optimization tools developed in the field of AI, namely Genetic Algorithms (GA), the study deepens the possibility of using generative models and evolutionary principles in order to inform the customization process and to promote efficient use of energy and materials in the early stage of design, with the aim to building up a web-based user interface that allows customers to explore the generative potential of a model (Fig. 21).

Result of a research agreement with the Italian start-up Abitare+ involved in timber construction, the research proposes an integrated design and a production process for CLT constructions, which is based on mass-customization experiences (Benros and Duarte 2009; Bergin and Steinfeld 2012; Duarte 2005), multi-objective optimization strategies (Aish and Woodbury 2005; Kolarevic and Malkawi 2005), and data-driven design (Brown and Mueller 2017). In this process, natural inspired form-finding strategies (Bergmann and Hildebrand 2015) are used to select optimal solutions from a structural and environmental point of view, allowing the designer to visualize and evaluate thousands of design options and variations (Self and Vercruysse 2017) of the same product (Bianconi et al. 2017f) through the materialization of architecture's complexity question (Scheurer 2010).

The generative path is connected to the emerging context of Industry 4.0 (Paoletti 2018), in its contamination between design and digital fabrication (Corser 2010; Richard 2005; Larry Sass 2006), aimed to promote timber houses (Turan 2009) by redefining in a parametric way the traditional typology of the Italian single-family house. The application of wood in architecture is a technique forgotten in the Italian contemporary landscape, also because of the reconstructions needs due to the recent earthquake, evolving from the concept of prefab to the theme of mass customization (Anderson 2002; Dellaert and Stremersch 2005; Duray et al. 2000; Knaack et al.

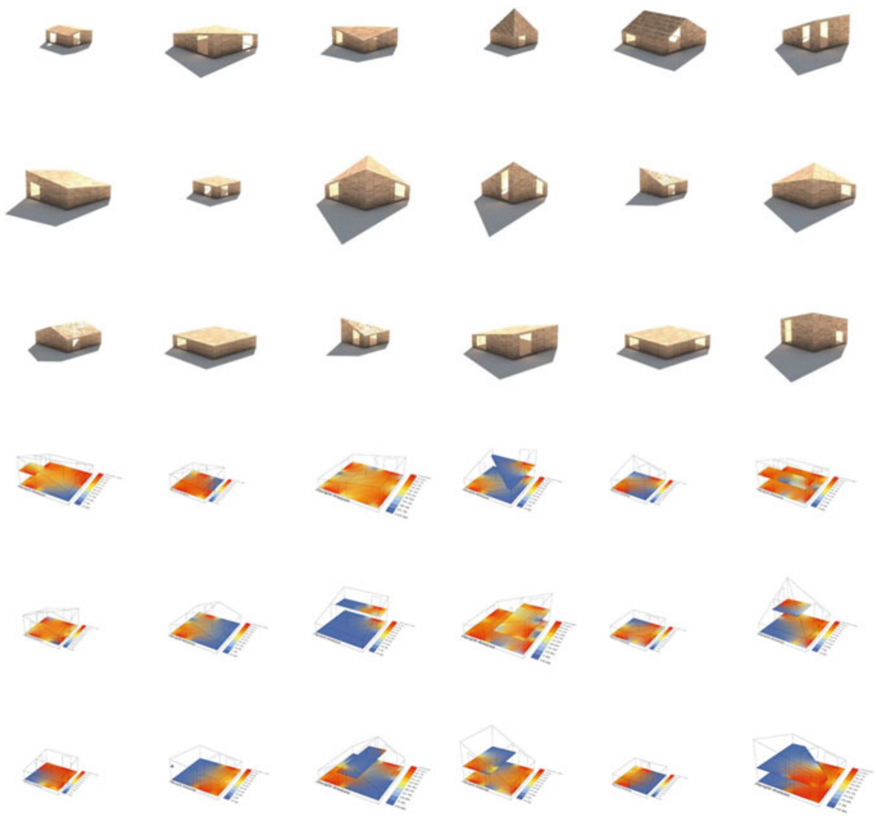

Fig. 22 Housing and mass costumization: the generative path for the optimization of results

2012; Nahmens and Bindroo 2011; Page and Norman 2014; Pine and Slessor 1999; Salvador et al. 2009; Willis and Woodward 2010; Zipkin 2001).

This model generates a wide variety of architectural solution, and each of them differs from the others mainly for their orientation, size, type of ceiling, roof slope and shape of the glazing elements. In this case, the definition of rule-based design emerges from a study of local codes and CLT construction systems; indeed, while defining the geometrical rules of the model, the researcher encoded constraints in such a manner that each solution meets codes dimensioning and affordable fabrications methods. As a result, each house in the series is unique in shape and size, even if it shares with the others the same building system characterized by CLT panels and a fixed number of manufacturing operations, in both the factory and the building side (Fig. 22).

The integrated process proposed in this research is created entirely with the Rhinoceros's plug-in Grasshopper, introducing in each phase of the project different add-ons for analysis, representation, and interoperability. The Grasshopper's add-ons Honeybee and Ladybug (Roudsari and Pak 2013) were used to inform the process

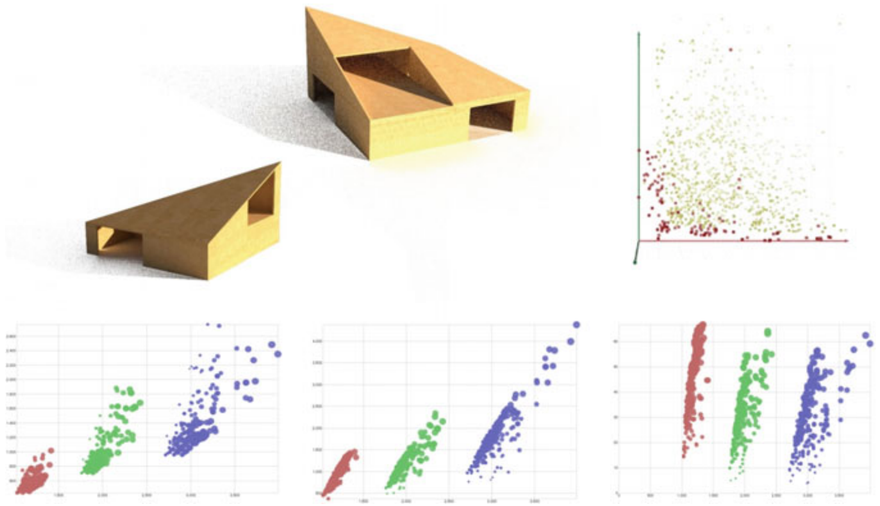

Fig. 23 Big data analysis for Data Driven Design: Pareto front (top right) and comparison between energy consumption and heating loads (bottom left), cooling loads (bottom center) and lighting loads (bottom right)

with climate data and advanced energy analysis, Octopus to perform multi-objective optimization, TT Toolbox to record the optimization process, and Geometry Gym to create IFC models for BIM interoperability. These tools along with the open-source analysis software EnergyPlus, Open Studio, Radiance, and Daysim constitute the toolset used to create the material contained in the web-based catalog. In a second moment, web implementation and data visualization were realized with java scripting starting from the open source project Design Explorer.

In this process, while some architectural characteristics are defined directly by the researcher, other qualities are supposed to emerge from an optimization process which encompasses environmental data and analysis. In this sense, Genetic Algorithms (GA) are used as virtual prototyping tools to navigate the design space of a generative model and optimize the architectural organism. In this research, the optimization process is based on Grasshopper's add-on Octopus (Bader and Zitzler 2011; Vierlinger and Zimmel 2015; Zitzler et al. 2001) that performs multi-objective optimization and allows to combine more performances criteria, namely fitness, to obtain multifunctional structures. The definition of the performance criteria started with the study of a construction model through the definition of detailed solutions and sizing of structural elements. In this phase, the construction cost was computed with the company through the definition of a series of parametric costs for the elements constituting the structural system and the envelope, while, energy performances were evaluated through advanced energy analysis by estimating building energy consumption, comfort, and daylighting (Fig. 23).

Building energy performance assessments are complex multi-criteria problems (Asl et al. 2014) that can be effectively solved by genetic algorithms (Clune and Lipson 2011; Jones 2009b). The goal of an environmental optimization is to ensure a satisfactory comfort with the minimum use of energy, through the adaptation of the architectural organism to its context and its inhabitants. Natural lighting then becomes one of the major driving forces in this design process, which aims to reinforce circadian rhythms and to reduce the use of electric lighting by introducing daylight into space, and it results an effective reduction of energy consumption and comfortable spaces. Acting with passive strategies since the initial stage of design, it is usually the most effective solution characterized by the highest rate of return on investment. Data-driven design can effectively support the designer in this process of problem-solving, by comparing the performance of different design solutions. In particular, in this research, the goal is to inform the design process in order to optimize solar gain and maximize the effectiveness of natural lighting and ventilation.

In this context, the combination of data visualization became an effective way to enhance the decision-making process (Tsigkari et al. 2013) while design space catalogs, which present a collection of different options for selection by a human designer, have become a commonplace in architecture in the perspective of the design democratisation (Kolarevic 2015). The aim is to create an open source design (Rajanen and Iivari 2015; Ratti and Claudel 2015; Weber 2005) as meta-project for adaptable and mass customized housing (Lawrence 2003). The user interface developed in this research (https://www.algoritmi.abitarepiu.com) is based on Design Explorer, an open source project realized by CORE Studio Thornton Tomasetti, that allows to intuitively visualize and effectively navigate the design space of parametric models developed in Grasshopper, Dynamo, and Catia. These tools can support the designer in the complex problem-solving processes, through the combination of the designer's preferences with the great amount of information owned by modern construction companies, thus filling the gap between technological advances and design practice. Furthermore, their usability and effectiveness will grow along with advances in Building Information Modeling (BIM), performance simulations and parametric design and hopefully, in the next future, a similar data-driven approach will help the designer to deal with increasingly complex projects and achieve both performance and aesthetic expression.

The approach developed in this research is a work in progress that is finding more declination, as it shows, for example, the green pavilion project for Perugia Municipality (Bianconi et al. 2018f), a customized and responsive architecture (Hofman et al. 2006; Huang 2008), unique design able to generate variable social pavilions for more than 100 parks presented in the territory (Fig. 24).

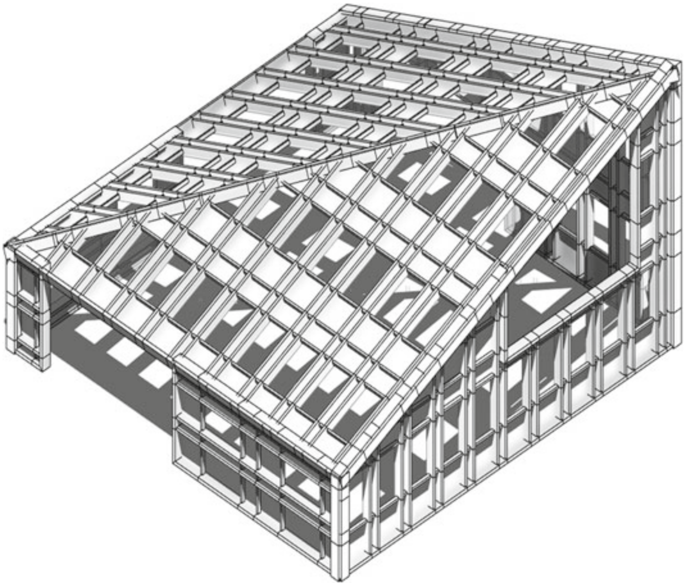

Fig. 24 From AI to the digital fabrication: details of the BIM model for the timber structures cutting

4.6 The Ames Room Pavilion. The Reinterpretation of the Classical by Generative Design

As a collateral result of the previous research path, our group has designed the Ames room pavilion, a paradigmatic architectural example that shows the flexibility of generative. The project, coordinated by the authors with the support of all the group of research (Alessandro Buffi, Giulia Pelliccia, Marco Seccaroni, Elisa Bettollini, Michela Meschini, Maria Pia Calabrò, Gianmaria Angelini, Lorenzo Ciculi), is a spatial deformation that creates an illusory image, constructed starting from the equivalence of perspective projections between homologous spaces, application of "perception seen as transactions between the observer and the world… The physical world is left as mysterious 'forms', serving as catalysts to evoke perceptions from rich 'assumptive' common sense derived from past experience, which is the seeming reality of our perceptions" (Gregory 1987, p. 277) (Fig. 25).

The study is attributed to the American psychologist and ophthalmologist of the last century Adelbert Ames Jr., that describes these forms, variable in function of monocular and binocular view (Ames and Ittelson 1952), as "… a whole "family" of distorted rooms of vastly different shapes could be built, yet all of them, if our reasoning is correct, should be seen as "normal" instead of some other way because our past experience has made it a "better bet" to perceive level floors, upright walls, rectangular windows, etc." (Ittelson and Kilpatrick 1952, p. 48). As Ernst Gombrich explains to us, "the illusion consists … in the conviction that there is only one way

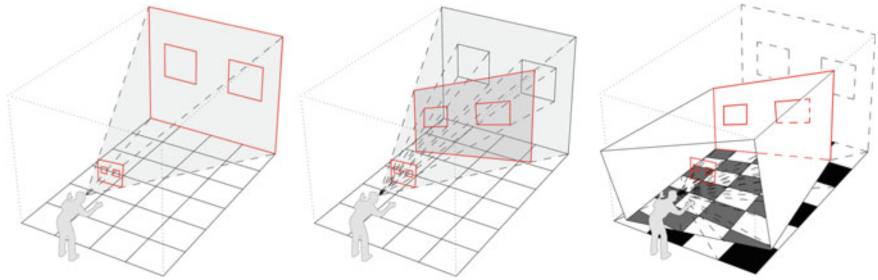

Fig. 25 Ames room: the generation of a whole "family" of distorted shapes in function of the correspondence of the image constraining the point of view

of interpreting the visual pattern in front of us. We are blind to other possible configurations because we literally 'cannot imagine' these unlikely objects" (Gombrich 1960, pp. 210–211).

The morphological transformation starts from the visual pyramid that is created in the vision of a canonically stereometric room: constraining the point of view and starting from the same image, it is possible to find a family of deformed spaces by varying the base of the pyramid. This creates a solid perspective defined by divergent and inclined the horizontal and vertical surfaces, that deceives the observer in the evaluation of spatiality, not included in its real form but as a function of the a priori critical thought with which the image is correlated to space. The deformed space, that appears regular, confuses the references and the evaluations on measures, making it appear deformed in the judgment of the dimension of what is inside it, especially in the extreme parts of the structure corresponding to the edges where objects and people are positioned in the two extremes of the room they seem to be both bigger and smaller at the same time. Besides, expanding the functioning of the process of interpretation of the form related to vision and images, this expedient is also used in cinema, for example, in Harry Potter or the Lord of the Rings, to contextually shoot characters of really different height (Fig. 26).

Ames' room is a classic experiment of visual perception (Ramachandran 1990), developed in this context with the aim to analyse perception questions. In fact, as demonstrated by Cornish, Ames' room works well because "we instinctively regard an object as extended in the plane at right angles to the line joining the object to the eye" (Cornish 1935, p. 61). In this way, Ames' room shows the invariance hypothesis: "if two objects make images of the same size, the more distant object must be larger, this is known as Size-distance invariance, therefore loses its status as a powerful explanatory concept and becomes rather a description of results obtained under conditions which have yet completely to be specified" (Kilpatrick and Ittelson 1953, p. 223). This experiment was so useful to analyse the effects of perspective alterations on apparent size and distance scales (Vogel and Teghtsoonian 1972), on distance and size judgments (Blessing et al. 1967; Epstein et al. 1961; Holway and Boring 1941; McDonald and O'Hara 1964; Teghtsoonian 1965) and the importance

Fig. 26 The illusion in the Ames room: the great professor Franco Purini with the professor Roberto de Rubertis

of object recognition in size constancy (Bolles and Bailey 1956, p. 222), all themes that show how ambiguity in itself can never be perceived (Gombrich 1960) but that illusions are more effective when they can count on certain inveterate expectations and assumptions on the part of the observer (Gombrich 1960). In this way, the camera becomes the topic of confrontation between the interpretation of perception as unconscious inference (Gregory 1970) and the theory of Direct perception (de Wit et al. 2015; Gehringer and Engel 1986; Gibson 1979; Runeson 1988) (Fig. 27).

The architectonic device developed was really firstly (Gregory 1994) guessed by Hermann Helmholtz (Cz 1896), the principal reference for the Ames' school (Pastore 1971), and it is connected to the artistic representation of the distorted room (Van De Geer, De Natris) designed by artists to simulate three-dimensional spaces, as the case of Samuel Van Hoogstraten (Brusati 1995) and of his amazing peepshow (i.e. van Hoogstraten 1655–60), but also Brunelleschi perspective machines (Arnheim 1978, 1986), the tools to realize perspective (Moscati 2012) and its poetic (Elkins 1994): in the correspondence between medium as message, Ames' room concretizes in the spatial the Leon Battista Alberti conceptualization of perspective as intersection of the visual pyramid (Leon Battista Alberti, *De pictura incipit*, cod. II.IV,38, f.119v),

Fig. 27 The illusion in the Ames room: the great professor Roberto de Rubertis with the professor Franco Purini

a geometric transcription of the optical concept of a visual cone (de Rubertis 2012), the expression of its artificiality (Gioseffi 1957), "lo inganno de gl'occhi", the eyes deception (Accolti 1625). In this way, the Ames' room is linked also to all the architectures' illusion, as the works of Andrea del Pozzo shows (Migliari 2000) or Agostino Tassi (Negro 1996) with which they share the instrument (but not the objectives): "on one hand Pozzo takes advantage of the eye's rotation, pivoting in the projection centre and resorting to other expedients, mitigating the effects of a displacement of the observer; on the other hand Tassi disregards the code in order to nullify the effects of the displacement. The perspectives painted by Tassi, thus, behave like the Ames' room, because it appeals to the viewer's experience and to his mental models, in order to hide the derogations imposed to the perspective rules and the true shape of the space that these perspectives describe, if interpreted literally" (Migliari and Romor 2015, p. 66). Reinterpreting the value of this approach for the contemporary, Ames' "perspective machine", by using projections, is based on a rigorous geometric path to create a wrong drawing (Koenderink et al. 2016), the same theme of digital virtuality founded in a distort simulation (render-to-texture).

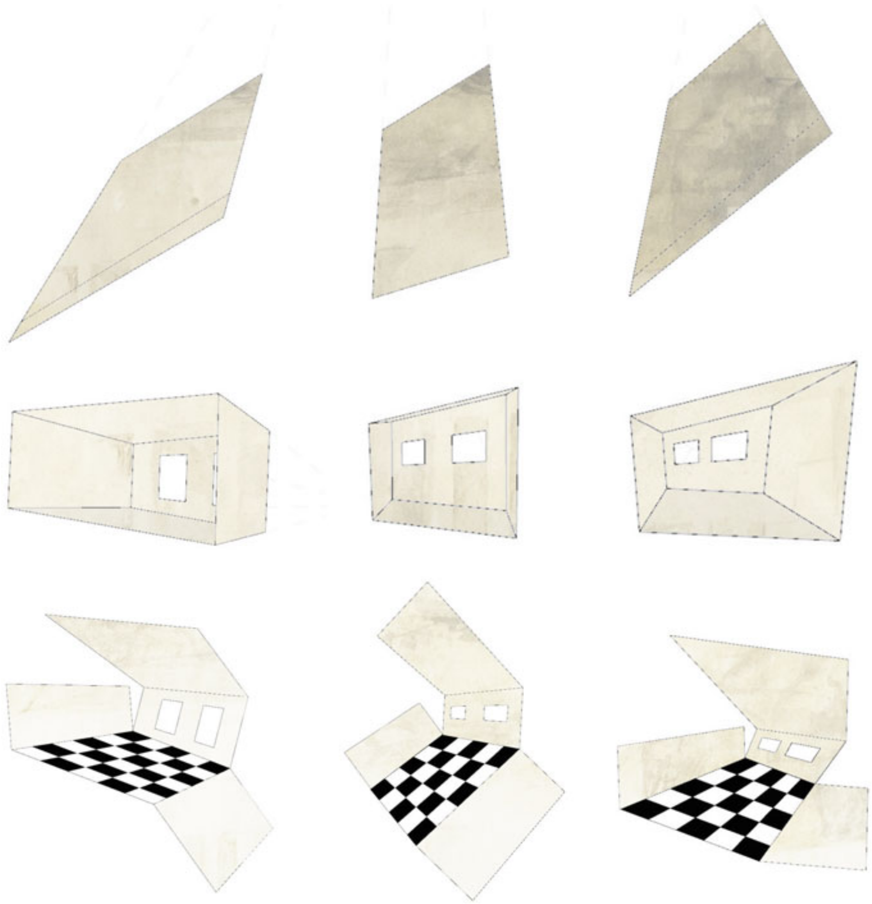

Fig. 28 Generative model: variation in the whole family of distorted rooms

A mechanical production of vision, Ames' room for its genesis it is not an artwork, but our proposal aims to demonstrate that it could become a design work. Created by ABITARE+ and designed by the research group of the Department of Civil and Environmental Engineering of the University of Perugia, coordinated by the author, the research is an expression of the path of optimization of wooden houses just described. Conceived for an exposition event, where many companies were participating, Ames' room is born inside an iconoclast strategy, that in our imagination was (Latour and Weibel 2002) important also for the building market. The unusual installation wants to respond to the homo game aesthetic (Pecchinenda 2010) and to its role in representative projection in social synthetic universes (Castronova 2007): the objective is to produce references to move around the net and to talk to the company, a result that appears reached as it is testified from Google trend data (surely reductive), which show that in the last year the name of the company was searched

Fig. 29 Digital simulation: the analysis of the results and the study of the formal details

a lot after the event in which the house was installed. The success obtained with this first manifestation leas to install the pavilion in front of the prestigious faculty of Valle Giulia of Rome University "La Sapienza" and by Engineer pole of the University of Perugia; both were events that represent only a portion of the installation series thought for the development program, a condition that granted the production of thousands of images (Figs. 28 and 29).

The "vibration of appearances that is the genesis of things" (Merleau-Ponty 1962) makes this space signed by divergent walls, dynamically conformed to the contemporary aesthetic, its form attracts people, simulacrum that transfigures the real by killing its three-dimensionality, but at the same time it creates life in the image (Debray 1994). The pavilion has its function in the substantial interactivity connected to interpretation, which is intended as an opening need to a process of deconstruction and reconstruction (Neisser 1967) of what it is perceived. The design is then reinforced, as an instrument to verify and to project, founded on geometry, that finds in generative logics a new strength.

If conceptually Ames' room summarizes a wealth of approaches inherent the representation that ranges from descriptive geometry to projective through the value of images and perception, its realization has been developed by exploiting the innova-

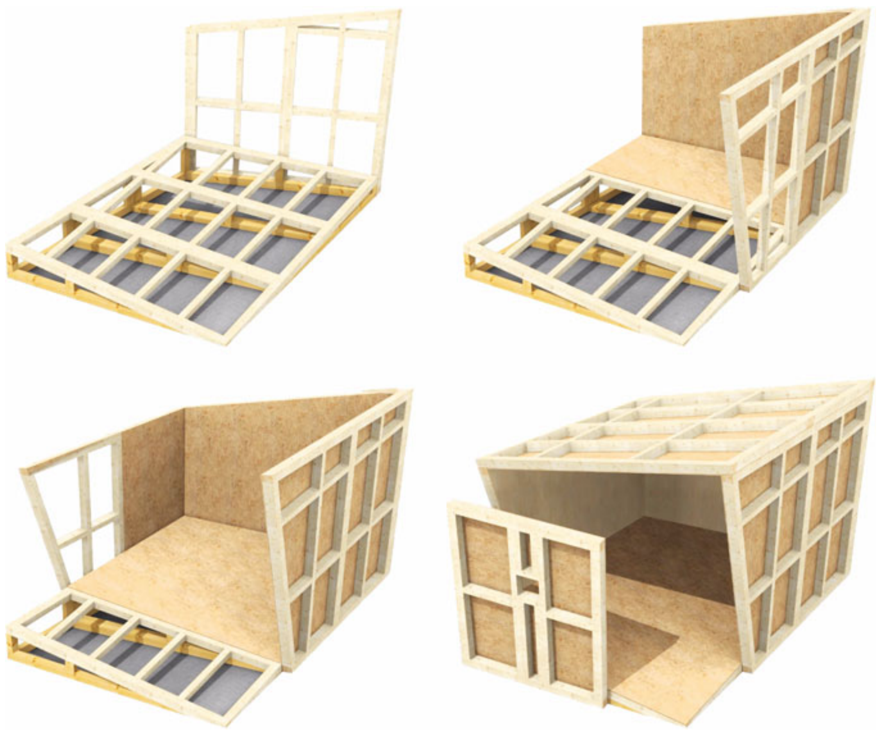

Fig. 30 BIM model: the digital fabrication of the parts and the simulation of the construction phases

tive logics of three-dimensional modelling and BIM approach. The paradigm of the approach used for the design of optimized buildings, in the room is developed in our first research as the value of generative modelling (Filippucci 2010c, 2012b), useful to represent different families of spaces and to find the best solution to respond to spatial limitations imposed by the space where it is set up. The generative process dialogues and comes into contact with the logic of BIM, in the definition of details of the constructive elements of the room, which however translates the techniques used for contemporary constructions in wood. The process thus demonstrates the value of research for industry 4.0 and the realization of the concepts of mass customization that are exemplified here (Fig. 30).

For its realization, it was designed a timber platform frame, inscribed in a three-dimensional space of 4 × 5 × 3.5 m, a solid wood structure with plywood sheathing in Pinepanels Oriented Strand Board (OSB) and interior leaning in medium-density fibreboard (MDF) panel and external leaning in black printed canvas. Our choice was to create a box in the panel positioned in correspondence to the point of view constrained, with the aim of discovering the deception only through the smartphone screen. The effect is really understood when two people in the corners of the room change their mutual position. The realization shows as restricted sight is not an

Fig. 31 The installation of the Ames' room: the timber structure and the final realization

exact point, but an area, admitting an ample displacement of the observation point (Migliari and Romor 2015), a condition that leads to an accommodation of perception that becomes accustomed to this conformation (Mitchison and Westheimer 1984), despite the clearest clues of stereoscopic vision (Pilewski and Martin 1991). To insert deformed writings and logos in the deformed back wall in function of the different events, our room doesn't have deformed windows, but using quiconce drawn on the ground, the camera pushes the people to assume that the images arise from objects of the same size (Gogel 1969), also because under reduced conditions it is demonstrated how objects are perceived at a default distance (specific distance tendency) (Gogel 1976), related to the resting state of vergence (Gogel and Tietz 1977).

Ames' room becomes an interesting paradigm of our culture of the image and of our mistrusted in them. As Karl Popper asserts, "if we are uncritical we shall always find what we want: we shall look for, and find, confirmations, and we shall look away from, and not see, whatever might be dangerous to our pet theories. In this way, it is only too easy to obtain what appears to be overwhelming evidence in favour of a theory which, if approached critically, would have been refuted" (Popper 1957, p. 124) (Fig. 31).

5 Conclusions

"*Centuries ago there lived–"A king!" my little readers will say immediately. No, children, you are mistaken. Once upon a time there was a piece of wood. It was not an expensive piece of wood. Far from it. Just a common block of firewood, one of those thick, solid logs that are put on the fire in winter to make cold rooms cozy and warm. I do not know how this really happened, yet the fact remains that one fine day this piece of wood found itself in the shop of an old carpenter*" (Carlo Collodi, Pinocchio, 1883).

As in the children novel, also "a piece of wood", a "common block of firewood", if animated by the creativity of an "old" but every innovative drawing, leads to the discovery of something vital, that is inside the material itself. Wood, by meeting human labour, is able to generate poetry. Geppetto is not just a simple character of a fable, but is the touching symbol and metaphor of those who work with matter and form, and from what appears inanimate he gives birth to something that projects and redefines its own identity.

The (digital) technical capacities, material potentialities, vitality of the creativity, all together characterize the experiences reported, they represent just a selection of a series of research developed and in developing. In all these studies it is possible to mark the centrality of form, finding the approach and the connection optimization processes in the support offered by AI in representation tool, without forgetting wood's natural intelligence. The focus, for the designer, moves on the laws that rule the organization of materials, architectures and environmental relationships.

The digital environment, the rewriting of descriptive geometry law, through the rules and the logic of the generative design, supports the construction of the performative architectural solutions. Digital representation does not appear to be a limit, but the instrument to the Mongian "passage from what is known to what is unknown". AI aids designer in the morphogenesis process, also if is it represented by stereometrics forms. All researches mark how the real question is the construction of the model, founded in the value of interdisciplinarity, an open process aimed to understand the weaving of themes included in the morphological results. The simulation offered by digital processes is the means to define the ideated image, the real soul of construction and of architecture.

References

Abdelmohsen S, Massoud P, Elshafei A (2016) Using tensegrity and folding to generate soft responsive architectural skins. In: Proceedings of the 34th eCAADe conference of complexity & simplicity. Oulu, pp 529–536

Accolti P (1625) Lo inganno de gl'occhi, prospettiva pratica de Pietro Accolti. Pietro Cecconcelli, Florence

Addington M, Schodek DL (2005) Smart materials and new technologies: for the architecture and design professions. Architectural, Oxford

Adriaenssens S, Barnes M (2001) Tensegrity spline beam and grid shell structures. Eng Struct 23(1):29–36. https://doi.org/10.1016/S0141-0296(00)00019-5

Adriaenssens S, Block P, Veenendaal D, Williams C (2014) Shell structures for architecture: form finding and optimization. Routledge, New York

Aish R, Woodbury R (2005) Multi-level interaction in parametric design. In: Smart graphics. Springer, Berlin, Heidelberg, pp 151–162. https://doi.org/10.1007/11536482_13

Ames A, Ittelson WH (1952) The Ames demonstrations in perception. Hafner Publishing, New York

Anderson DM (2002) Build-to-order and mass customization: the ultimate supply chain management and lean manufacturing strategy for low-cost on-demand production without forecasts or inventory. CIM Press, Cambria

Andia A, Spiegelhalter T (eds) (2017) Post-parametric automation in design and construction. Artech House, Boston

Arnheim R (1978) Brunelleschi's Peepshow. Zeitschrift Für Kunstgeschichte 41(1): 57. https://doi.org/10.2307/1481995

Arnheim R (1986) New essays on the psychology of art. University of California Press, Berkeley

Asl MR, Bergin M, Menter A, Yan W (2014) BIM-based parametric building energy performance multi-objective optimization. In: Fusion—proceedings of the 32nd eCAADe conference. eCAADe, Newcastle, pp 455–464

Austern G, Capeluto IG, Grobman YJ (2018) Rationalization methods in computer aided fabrication: a critical review. Automation in Construction 90:281–293. https://doi.org/10.1016/J.AUTCON.2017.12.027

Bader J, Zitzler E (2011) HypE: an algorithm for fast hypervolume-based many-objective optimization. Evol Comput 19(1):45–76. https://doi.org/10.1162/EVCO_a_00009

Bar-Cohen Y (ed) (2016) Biomimetics nature-based innovation. CRC Press, Boca Raton

Barnekov VG, McMillin CW, Huber HA (1986) Factors influencing laser cutting of wood. For Prod J 1(36):55–58

Barthel R (1967) Natural forms-architectural forms. In: Nerdinger W (ed) Frei Otto complete works. Birkhäuser, Basel-Boston-Berlin, Architecture, pp 16–32

Baudrillard J (1981) Simulacres et simulation. Galilée, Paris

Baverel O, Larsen OP (2011) A review of woven structures with focus on reciprocal systems—Nexorades. Int J Space Struct 26(4):281–288. https://doi.org/10.1260/0266-3511.26.4.281

Baverel O, Pugnale A (2014) Reciprocal systems based on planar elements: morphology and design explorations. Nexus Netw J 1(16):179–189

Bechert S, Knippers J, Krieg OD, Menges A, Schwinn T, Sonntag D (2016) Textile fabrication techniques for timber shells elastic bending of custom-laminated veneer for segmented shell construction systems. In: Adriaenssens S, Gramazio F, Kohler M, Menges A, Pauly M (eds) Advances in architectural geometry 2016. Vdf Hochschulverlag AG an der ETH Zürich, Zürich, pp 154–170

Benros D, Duarte JP (2009) An integrated system for providing mass customized housing. Autom Constr 18(3):310–320. https://doi.org/10.1016/J.AUTCON.2008.09.006

Benyus JM (1997) Biomimicry: innovation inspired by nature. Harper Perennial, New York

Bergin M, Steinfeld K (2012) Housing agency system (HAS): multi-criteria satisfying and mass-customization of homes. In: ACSA fall conference. OFFSITE, Philadelphia, pp 93–97

Bergmann E, Hildebrand S (2015) Form-finding, form-shaping, designing architecture. Mendrisio Academy Press, Mendrisio

Bhushan B (2009) Biomimetics: lessons from nature–an overview. Philos Trans: Series A, Mathematical, Physical, and Engineering Sciences 367(1893):1445–1486. https://doi.org/10.1098/rsta.2009.0011

Bianconi F (2002) Tetraktis. Strumenti, luoghi, materia, rilievo. Digital Point, Perugia

Bianconi F (2005) Segni digitali. Morlacchi, Perugia

Bianconi F, Filippucci M (2015) The dams of Rio Grande's basin (Amelia TR). In: Gambardella C (ed) XIII Forum Internazionale Le Vie dei Mercanti. Heritage and technology mind knowledge experience, vol 1. La scuola di Pitagora, Napoli, pp 1864–1875

Bianconi F, Filippucci M (2016a) Generative education: thinking by modeling/modeling by thinking. In: EGA. Congreso: XVI Congreso Internacional de Expresión Gráfica Arquitectónica "El arquitecto, de la tradición al siglo XXI", vol 1. Grupo Enlace Gráfico, pp 747–754

Bianconi F, Filippucci M (2016b) The parameterization of complex surfaces for engineering solutions. In: Le ragioni del Disegno/the reasons of drawing, vol 1. Gangemi, pp 125–130

Bianconi F, Verducci P, Filippucci M (2006) Architetture dal Giappone: disegno, progetto e tecnica, vol 1. Gangemi, Roma

Bianconi F, Filippucci M, Andreani S (2016a) Computational design and built environments. In: 3D printing: breakthroughs in research and practice, vol 1. IGI Global, Hershey (Pennsylvania, USA), pp. 361–395

Bianconi F, Filippucci M, Verdecchia C (2016b) Body movement based architecture. In: Visual computing and emerging geometrical design tools, vol 2. IGI Global, Hershey (Pennsylvania, USA), pp 744–770. https://doi.org/10.4018/978-1-5225-0029-2.ch030

Bianconi F, Catalucci S, Filippucci M, Marsili R, Moretti M, Rossi G, Speranzini E (2017a) Comparison between two non-contact techniques for art digitalization. J Phys Conf Ser 882. https://doi.org/10.1088/1742-6596/882/1/012005

Bianconi F, Filippucci M, Catalucci S (2017b) Line and Points. Critical analysis of evolution of archaeological survey in forty years of experiences in Umbria. DISEGNARECON 10(19): 4–1–E4.20

Bianconi F, Filippucci M, Catalucci S (2017c) The identity landscape in the cataloging of scattered assets in the area of Amelia. In: Putting tradition into practice: heritage, place and design. Proceedings of 5th INTBAU international annual event. Springer, pp 984–993

Bianconi F, Filippucci M, Buffi A, Calabro' MP (2017d) The value of image. The design of and data streams from the perception by design. In: Proceedings 2017. International and interdisciplinary conference IMMAGINI? Image and imagination between representation, communication, education and psychology. MDPI. https://doi.org/10.3390/proceedings1090933

Bianconi F, Filippucci M, Ciarapica A (2017e) Landscape, territory, knowledge. From Umbria region's atlas of objectives to the "Landscape Contracts" of Trasimeno Lake. In Crisis landscapes: opportunities and weaknesses for a sustainable development. FrancoAngeli, Roma, pp 87–110

Bianconi F, Filippucci M, Clemente M, Salvati L (2017f) Green infrastructures and biodiverse urban gardens for regenerating urban spaces. In: Gospodini A (ed) Book of abstracts of the international conference on changing cities III spatial, design, landscape; socio-economic dimensions: 26–30 June 2017, Syros, Delos, Mykonos Islands, Greece. Grafima Publications, Thessaloniki, pp 42–42

Bianconi F, Filippucci M, Margutti M, Stramaccia M (2017g) Evoluzioni morfologiche di transpoliedri. Eloquenza delle immagini per generare strutture tensegrali Morphological evolutions of transpolyhedra. Eloquence of the images to generate tensegrity structures XY(3):4–15

Bianconi F, Filippucci M, Margutti M, Stramaccia M (2018) Drawing Tensegrity, discover transpolyhedra. In: D'Uva D (ed) Analyzing form and morphogenesis in modern architectural contexts. New York: IGI Global, pp 41–68 https://doi.org/10.4018/978-1-5225-3993-3.ch003

Bianconi F, Clemente M, Filippucci M, Salvati L (2018a) Re-sewing the urban periphery. A green strategy for Fontivegge District in Perugia. TEMA 11: 107–118

Bianconi F, Filippucci M, Ciculi L (2018b) The form of music: experiments between cymatics and engineering. In Nexus 2018 architecture and mathematics conference book. Kim Williams Book, pp 233–244

Bianconi F, Filippucci M, Clemente M, Salvati L (2018c) Regenerating urban spaces under place-specific social contexts: a brief commentary on green infrastructures for landscape conservation. Int J Soc Sci 2:18–32. https://doi.org/10.20472/SS.2017.6.2.002

Bianconi F, Filippucci M, Margutti M, Stramaccia M (2018d) Drawing tensegrity, discover trans-polyhedra. In D'Uva D (ed) Analyzing form and morphogenesis in modern architectural contexts. IGI Global, New York, pp 41–68. https://doi.org/10.4018/978-1-5225-3993-3.ch003

Bianconi F, Filippucci M, Seccaroni M (2018e) Drawing architectonic choices. Representation and optimization in design pathway. In: De-sign environment landscape city. Genova University Press, Genova, p 47

Bianconi F, Filippucci M, Seccaroni M (2018f) Rappresentazione e variazione della forma architettonica per l'ottimizzazione emergetica ed energetica. In: 18th CIRIAF national congress sustainable development, human health and environmental protection. Perugia, p Cod_018

Bidgoli A, Cardoso-Llach D (2015) Towards a motion grammar for robotic stereotomy. In: Ikeda Y, Herr CM, Holzer D, Kaijima S, Kim MJ (eds) Emerging experience in past, present and future of digital architecture. The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, pp 723–732

Bittermann MS (2009) Intelligent design objects (IDO): a cognitive approach for performance-based design. www.boekenbent.com

Blessing WW, Landauer AA, Coltheart M (1967) The effect of false perspective cues on distance- and size-judgments: an examination of the invariance hypothesis. Am J Psychol 80(2):250. https://doi.org/10.2307/1420984

Block P, Rippmann M, Van Mele T, Escobedo D (2017) The Armadillo Vault: balancing computation and traditional craft. In: Menges A, Sheil B, Glinn T, Skavara M (eds) Fabricate 2017: rethinking design and construction. UCL Press, London, pp 286–293

Bolles RC, Bailey DE (1956) Importance of object recognition in size constancy. J Exp Psychol 51(3):222–225. https://doi.org/10.1037/h0048080

Bosse A (1643a) La pratique du trait à preuves, de Mr Desargues Lyonnois, pour la coupe des pierres en l'architecture. Impr. Des-Hayes

Bosse A (1643b) La pratique du trait à preuves de Mr Desargues,… pour la coupe des pierres … Impr. Des-Hayes

Bouzanjani BF, Leach N, Huang A, Fox M, Pomona CP (2013) Alloplastic architecture: the design of an interactive tensegrity structure. In: Beesley P, Khan O, Stacey M (eds) Adaptive architecture: ACADIA 2013. Riverside Architectural Press, Toronto, pp 129–136

Brown A (2014) The genius of Japanese carpentry: the secrets of a craft. Tuttle Publishing, Clarendon

Brown NC, Mueller CT (2016) Design for structural and energy performance of long span buildings using geometric multi-objective optimization. Energy Build 127:748–761. https://doi.org/10.1016/J.ENBUILD.2016.05.090

Brown N, Mueller C (2017) Designing with data: moving beyond the design space catalog. Acadia 2017 Discipline + Distruption. MIT Press, Cambridge, pp 154–163

Bruce J, Caluwaerts K, Iscen A, Sabelhaus AP, SunSpiral V (2014) Design and evolution of a modular tensegrity robot platform. In: 2014 IEEE international conference on robotics and automation (ICRA). IEEE, pp 3483–3489. https://doi.org/10.1109/ICRA.2014.6907361

Brusati C (1995) Artifice and illusion: the art and writing of Samuel van Hoogstraten. University of Chicago Press, Chicago

Buckminster Fuller R (1961) Tensegrity. Portfolio Artnews Ann 4:112–127

Buckminster Fuller R (1975) Synergetics: explorations in the geometry of thinking. Macmillan Publishing, Basingstoke

Burgert I, Fratzl P (2009) Actuation systems in plants as prototypes for bioinspired devices. Philos Trans. Series A, Mathematical, Physical, and Engineering Sciences 367(1893):1541–1557. https://doi.org/10.1098/rsta.2009.0003

Burkhardt RW (2008) A practical guide to tensegrity design. Cambridge

Burry M (2014) From descriptive geometry to smartgeometry: first steps towards digital architecture. In: Peters B, Peters T (eds) Inside smartgeometry. Wiley, Chichester, West Sussex, United Kingdom, pp 154–165. https://doi.org/10.1002/9781118653074.ch13

Calladine CR (1978) Buckminster Fuller's "Tensegrity" structures and Clerk Maxwell's rules for the construction of stiff frames. Int J Solids Struct 14(2):161–172. https://doi.org/10.1016/0020-7683(78)90052-5

Castronova E (2007) Universi sintetici: come le comunità online stanno cambiando la società e l'economia. Mondadori, Milan

Cefalo M, Mirats Tur JM (2010) Real-time self-collision detection algorithms for tensegrity systems. Int J Solids Struct 47(13):1711–1722. https://doi.org/10.1016/J.IJSOLSTR.2010.03.010

Chandana P, Lipson H, Cuevas FJV (2005) Evolutionary form-finding of tensegrity structures. In Proceedings of the 2005 conference on genetic and evolutionary computation—GECCO'05. ACM Press, New York, New York, USA, p 3. https://doi.org/10.1145/1068009.1068011

Chaszar A, Glymph J (2010) CAD/CAM in the business of architecture, engineering and construction. In: Corser R (ed) Fabricating architecture: selected readings in digital design and manufacturing. Princeton Architectural Press, Princeton, pp 86–93

Chen L, Sass L (2017) Generative computer-aided design: multi-modality large-scale direct physical production. Comput Aided Des Appl 14(1):83–94. https://doi.org/10.1080/16864360.2016.1199758

Chilton JC, Tang G (2016) Timber gridshells: architecture, structure and craft. Routledge, London

Clune J, Lipson H (2011) Evolving three-dimensional objects with a generative encoding inspired by developmental biology motivation and previous work. Eur Conf Artif Life. MIT Press, Cambridge, pp 144–148

Connelly R, Back A (1998) Mathematics and tensegrity. Am Sci 86:142–151. https://doi.org/10.2307/27856980

Connelly R, Whiteley W (1992) The stability of tensegrity frameworks. Int J Space Struct 7(2):153–163. https://doi.org/10.1177/026635119200700208

Cornish V (1935) Scenery and the sense of sight. University Press, Cambridge

Correa D, Papadopoulou A, Guberan C, Jhaveri N, Reichert S, Menges A, Tibbits S (2015) 3D-printed wood: programming hygroscopic material transformations. 3D Printing Addit Manuf 2(3):106–116. https://doi.org/10.1089/3dp.2015.0022

Corser R (2010) Fabricating architecture: selected readings in digital design and manufacturing. Princeton Architectural Press, Princeton

Couldry N, Powell A (2014) Big data from the bottom up. Big Data Soc 1(2). https://doi.org/10.1177/2053951714539277

Cully A, Clune J, Tarapore D, Mouret J-B (2015) Robots that can adapt like animals. Nature 521:503–507. https://doi.org/10.1038/nature14422

Cz P (1896) Handbuch der physiologischen Optik. Monatshefte Für Mathematik Und Physik. https://doi.org/10.1007/BF01708548

d'Estrée Sterk T (2003) Using actuated tensegrity structures to produce a responsive architecture. In: Klinger KR (ed) Crossroads of digital discourse. Ball State University, pp 85–93

Dangel U (2016) Turning point in timber construction: a new economy. Birkhäuser, Basilea

Davis J, Edgar T, Porter J, Bernaden J, Sarli M (2012) Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Comput Chem Eng 47:145–156. https://doi.org/10.1016/J.COMPCHEMENG.2012.06.037

Dawson C, Vincent JFV, Rocca A-M (1997) How pine cones open. Nature 390(6661):668. https://doi.org/10.1038/37745

De Azambuja Varela P, Sousa JP (2016) Revising stereotomy through digital technology. In: Herneoja A, Österlund T, Markkanen P (eds) Complexity & simplicity—proceedings of the 34th eCAADe conference. University of Oulu, Oulu, pp 427–434

De L'Orme P (1568) Le premier tome de l'architecture. Fédéric Morel, Paris

De La Hire P (1596) Traité de la coupe des pierres. Bibliothèque de l'Institut de France, Paris de Rubertis R (2012) Piramide visiva. Retrieved 28 Aug 2018 from http://www.wikitecnica.com/piramide-visiva/

de Wit MM, van der Kamp J, Withagen R (2015) Visual illusions and direct perception: elaborating on Gibson's insights. New Ideas Psychol 36:1–9. https://doi.org/10.1016/J.NEWIDEAPSYCH.2014.07.001

Debray R (1994) Vie et mort de l'image une histoire du regard en Occident. Gallimard, Paris

Deleuze, G. (1994). *Difference and repetition*. Columbia University Press

Deleuze G, Guattari F (1987) A thousand plateaus: capitalism and schizophrenia. University of Minnesota Press

Dellaert BGC, Stremersch S (2005) Marketing mass-customized products: striking a balance between utility and complexity. J Mark Res 42(2):219–227. https://doi.org/10.1509/jmkr.42.2.219.62293

Desarguer G (1640) Brouillon project d'exemples d'une manière universelle du sieur G.D.L., touchant la pratique du trait à preuve pour la coupe des pierres en architecture …. Melchor Tavernier, Paris

Di Carlo B (2008) The wooden roofs of leonardo and new structural research. Nexus Netw J 10(1):27–38. https://doi.org/10.1007/s00004-007-0054-x

Dogra JK, Kaur B, Parsarokh A (2015) tensegri[city]. ELISAVA, Barcellona

Duarte JP (2005) A discursive grammar for customizing mass housing: the case of Siza's houses at Malagueira. Autom Constr 14(2):265–275. https://doi.org/10.1016/J.AUTCON.2004.07.013

Duray R, Ward PT, Milligan GW, Berry WL (2000) Approaches to mass customization: configurations and empirical validation. J Oper Manag 18(6):605–625. https://doi.org/10.1016/S0272-6963(00)00043-7

Duro-Royo J, Oxman N (2015) Towards fabrication information modeling (FIM): four case models to derive designs informed by multi-scale trans-disciplinary data. MRS Proceedings, 1800. https://doi.org/10.1557/opl.2015.647

Eastman CM (2011) BIM handbook: a guide to building information modeling for owners, managers, designers, engineers and contractors. Wiley, Hoboken. Retrieved from https://books.google.it/books?id=aCi7Ozwkoj0C&dq=Eastman,+C.+(2011+BIM+handbook:+a+guide+to+building+information+modeling+for+owners,+managers,+designers,+engineers,+and+contractors&hl=it&source=gbs_navlinks_s

Eastman C, Lee J, Jeong Y, Lee J (2009) Automatic rule-based checking of building designs. Autom Constr 18(8):1011–1033. https://doi.org/10.1016/J.AUTCON.2009.07.002

Elkins J (1994) The poetics of perspective. Cornell University Press, London

Emmerich DG (1988) Structures tendues et autotendantes Monographies de géometrie constructive. Editions de la La Villette, Paris

Emmerich DG (1996) Emmerich on self-tensioning structures. Int J Space Struct 11(1–2):29–36. https://doi.org/10.1177/026635119601-205

Epstein W, Park J, Casey A (1961) The current status of the size-distance hypotheses. Psychol Bull 58(6):491–514. https://doi.org/10.1037/h0042260

Evans R (1995) The projective cast: architecture and its three geometries. MIT Press, Cambridge

Eversmann P, Gramazio F, Kohler M (2017) Robotic prefabrication of timber structures: towards automated large-scale spatial assembly. Constr Rob 1(1–4):49–60. https://doi.org/10.1007/s41693-017-0006-2

Eigensatz M, Kilian M, Schiftner A, Mitra NJ, Pottmann H, Pauly M, et al. (2010) Paneling architectural freeform surfaces. In: ACM transactions on graphics. Proceedings of ACM SIGGRAPH, vol 29. ACM Press, New York, p 1. https://doi.org/10.1145/1833349.1778782

Fagerström G (2009) Dynamic relaxation of tensegrity structures. In: Proceedings of the 14th international conference on computer aided architectural design research in Asia/Yunlin (Taiwan) 22–25 Apr 2009. CAADRIA, Taiwan, pp 553–562 (pp 553–562)

Fallacara G (2006) Digital stereotomy and topological transformations: reasoning about shape building. In: Proceedings of second international congress construction history. Queen's College Cambridge, Cambridge, pp 1075–1092

Fallacara G (2007) Verso una progettazione stereotomica: nozioni di stereotomia, stereotomia digitale e trasformazioni topologiche : ragionamenti intorno alla costruzione della forma. Aracne, Roma

Fernando S, Saunders R, Weir S (2015). Surveying stereotomy: investigations in arches, vaults and digital stone masonry. In: Architectural Research Centers Consortium (ed) ARCC 2015 conference—the future of architectural research. Perkins + Will, pp 82–89

Field JV (1987) Linear perspective and the projective geometry of Girard Desargues. Nuncius 2(2):3–40. https://doi.org/10.1163/182539187X00015

Filippucci M (2010a) Nuvole di pixel. La fotomodellazione con software liberi per il rilievo d'architettura. DISEGNARE CON…, 3:50–63. https://doi.org/10.6092/issn.1828-5961/2081

Filippucci M (2010b) Virtual in virtual, discretization in discretization. Shape and perception in parametric modelling for renewing descriptive geometry. In: Proceedings of ICGG 2010 14TH international conference on geometry and graphics. Naomi Ando et al, pp 129–130

Filippucci M (2010c) Virtual in virtual, discretization in discretization. Shape and perception in parametric modelling for renewing descriptive geometry. In: Ando N et al (ed) Proceedings of ICGG 2010 14TH international conference on geometry and graphics. Kyoto, pp 129–130

Filippucci M (2012a) Dalla forma urbana all'immagine della città. Percezione e figurazione all'origine dello spazio costruito. Sapienza Università di Roma

Filippucci M (2012b) Rappresentazione al quadrato. Il disegno generativo per il rinnovamento della geometria descrittiva. In: Carlevalis L, De Carlo L, Migliari R (eds) Attualità della Geometria Descrittiva Seminario nazionale sul rinnovamento della Geometria descrittiva, Roma dicembre 2009, marzo 2010. Gangemi, Rome

Filippucci M (2015) Primitive Urbane. Analisi interpretativa dei processi figurativi dell'immagine della città. In: Novello G, Marotta A (eds). Gangemi edizioni, Torino, p 1219

Filippucci M, Bianconi F, Andreani S (2016a) Computational design and built environments: the quest for an alternative role of the digital in architecture. 3D printing: breakthroughs in research and practice. https://doi.org/10.4018/978-1-5225-1677-4.ch019

Filippucci M, Rinchi G, Brunori A, Nasini L, Regni L, Proietti P (2016b) Architectural modelling of an olive tree. Generative tools for the scientific visualization of morphology and radiation relationships. Ecol Inf 36. https://doi.org/10.1016/j.ecoinf.2016.09.004

Filippucci M, Bianconi F, Bettollini E, Meschini M, Seccaroni M (2017) Survey and representation for rural landscape. New tools for new strategies: the example of Campello Sul Clitunno. In: Proceedings 2017. International and interdisciplinary conference IMMAGINI? Image and imagination between representation, communication, education and psychology, vol 1. MDPI, Bressanone, p 934. https://doi.org/10.3390/proceedings1090934

Filippucci M, Bianconi F, Bettollini E, Meschini M (2018) Visual perception analysis for landscape evaluation. an experimental case, Campello Sul Clitunno. De_Sign Environment Landscape City, vol p. Genova University Press, Genova, p 113

Floreano D, Mattiussi C (2009) Bio-inspired artificial intelligence: theories, methods, and technologies. Scalable Comput Pract Exp 10(4). https://doi.org/10.12694/scpe.v10i4.623

Fogel LJ, Owens AJ, Walsh MJ (1966) Artificial intelligence through simulated evolution. Wiley, Oxford

Frézier AF (1737a) La théorie et la pratique de la coupe des pierres et des bois pour la construction des voûtes et autres parties des bâtiments civils, militaires, ou Traité de stéréotomie, à l'usage de l'architecture. Tome 3 /, par M. Frézier,… Paris: L.H. Guerin

Frézier AF (1737b) La théorie et la pratique de la coupe des pierres et des bois pour la construction des voûtes et autres parties des bâtiments civils; militaires, ou Traité de stéréotomie, à l'usage de l'architecture. Tome 3 /, par M. Frézier,… Paris: L.H. Guerin

Frézier AF (1760) Élémens de stéréotomie, à l'usage de l'architecture, pour la coupe des pierres. Jombert, Paris

Fuller RB (1963) Ideas and integrities. Macmillan, New York

Gehringer WL, Engel E (1986) Effect of ecological viewing conditions on the Ames' distorted room illusion. J Exp Psychol Hum Percept Perform 12(2):181–185

Gherardini F, Leali F (2017) Reciprocal frames in temporary structures: an aesthetical and parametric investigation. Nexus Netw J 19(3):741–762. https://doi.org/10.1007/s00004-017-0352-x
Gibson JJ (1979) The ecological approach to visual perception. Houghton Mifflin, Boston
Gioseffi D (1957) Perspectiva artificialis: Per la storia della prospettiva; spigolature e appunti. Università Degli Studi di Trieste, Facoltà di Lettere e Filosofia, Trieste
Goel AK, McAdams DA, Stone RB (2014) Biologically inspired design. Springer, London. https://doi.org/10.1007/978-1-4471-5248-4
Gogel WC (1969) The sensing of retinal size. Vision Res 9(9):1079–1094. https://doi.org/10.1016/0042-6989(69)90049-2
Gogel WC (1976) An indirect method of measuring perceived distance from familiar size. Percept Psychophys 20(6):419–429. https://doi.org/10.3758/BF03208276
Gogel WC, Tietz JD (1977) Eye fixation and attention as modifiers of perceived distance. Percept Mot Skills 45(2):343–362. https://doi.org/10.2466/pms.1977.45.2.343
Gombrich EH (1960) Art and Illusion: a study in the psychology of pictorial representation. Phaïdon Press, London
Gough M (1998) In the laboratory of constructivism: Karl Ioganson's cold structures. October, 84, 90. https://doi.org/10.2307/779210
Gramazio F, Kohler M (2014) Made by robots: challenging architecture at the large scale AD. Wiley, London
Gramazio F, Kohler N, Oesterle S (2010) Encoding material. In: Oxman R, Oxman R (eds) The new structuralism: design, engineering and architectural technologies. Wiley, pp 108–115. Retrieved from https://books.google.it/books?id=035HAQAAIAAJ&q=The+new+Structuralism:+Design,+Engineering+and+Architectural+Technologies+AD&dq=The+new+Structuralism:+Design,+Engineering+and+Architectural+Technologies+AD&hl=it&sa=X&ved=0ahUKEwjirozclondAhVMkiwKHQFfBbEQ6A
Greenough H (1947) Form and function: remarks on art, design, and architecture. University of California Press, Berkeley
Gregory RL (1970) The intelligent eye. McGraw-Hill Book Company, New York
Gregory RL (1987) Analogue transactions with Adelbert Ames. Perception 16(3):277–282. https://doi.org/10.1068/p160277
Gregory RL (1994) Even odder perceptions. Routledge, London
Grima JN, Mizzi L, Azzopardi KM, Gatt R (2016) Auxetic perforated mechanical metamaterials with randomly oriented Cuts. Adv Mater 28(2):385–389. https://doi.org/10.1002/adma.201503653
Grobman YJ, Neuman E (eds) (2013) Performalism: form and performance in digital architecture. Routledge, New York
Gruber P, Jeronimidis G (2012) Has biomimetics arrived in architecture? Bioinspiration Biomimetics 7(1):010201. https://doi.org/10.1088/1748-3182/7/1/010201
Hanaor A (1992) Aspects of design of double-layer tensegrity domes. Int J Space Struct 7(2):101–113. https://doi.org/10.1177/026635119200700204
Hensel M (2010) Performance-oriented architecture: towards a biological paradigm for architectural design and the built environment. FORMakademisk 3(1):36–56. https://doi.org/10.7577/formakademisk.138
Hensel M (2013) Performance-oriented architecture: rethinking architectural design and the built environment. Wiley, Chichester
Hensel M, Menges A (2006) Morpho-ecologies. Architectural Association, London
Hensel M, Menges A (2008) Inclusive performance: efficiency versus effectiveness towards a morpho-ecological approach for design. Architectural Design 78(2):54–63. https://doi.org/10.1002/ad.642
Hensel M, Menges A, Weinstock M (2010) Emergent technologies and design. Routledge, New York
Herzog T, Natterer J, Schweitzer R, Volz M, Winter W (2004) Timber construction manual. DETAIL - Birkhäuser, Basel

Hofman E, Halman JIM, Ion RA (2006) Variation in housing design: identifying customer preferences. Housing Stud 21(6):929–943. https://doi.org/10.1080/02673030600917842
Holstov A, Bridgens B, Farmer G (2015) Hygromorphic materials for sustainable responsive architecture. Constr Build Mater 98:570–582. https://doi.org/10.1016/J.CONBUILDMAT.2015.08.136
Holstov A, Farmer G, Bridgens B (2017) Sustainable materialisation of responsive architecture. Sustainability 9(3):435. https://doi.org/10.3390/su9030435
Holway AH, Boring EG (1941) Determinants of apparent visual size with distance variant. Am J Psychol 54(1):21. https://doi.org/10.2307/1417790
Huang JC (2008) Participatory design for prefab house: using internet and query approach of customizing prefabricated houses. VDM Verlag Dr. Müller, Saarbrücken
Iafrate F (2018) Artificial intelligence and big data: the birth of a new intelligence. Wiley, London
Ittelson WH, Kilpatrick FP (1952) Equivalent configurations and the monocular and binocular distorted rooms. Human nature from the transactional point of view. Institute for Associated Research, New York, pp 41–55
Iwamoto L (2009) Digital fabrications: architectural and material techniques. Princeton Architectural Press, Princeton
Jabi W (2013) Parametric design for architecture. Laurence King, London
Jones NL (2009a) Architecture as a complex adaptive system. Faculty of the Graduate School of Cornell University
Jones NL (2009b) Architecture as a complex adaptive system. Faculty of the Graduate School of Cornell University
Kaufmann H, Nerdinger W (eds) (2011) Building with timber: paths into the future. Prestel Verlag, Munich
Kicinger R, Arciszewski T, Jong K De (2005) Evolutionary computation and structural design: a survey of the state-of-the-art. Comput Struct 83(23–24):1943–1978. https://doi.org/10.1016/J.COMPSTRUC.2005.03.002
Kilpatrick FP, Ittelson WH (1953) The size-distance invariance hypothesis. Psychol Rev 60(4):223–231. https://doi.org/10.1037/h0060882
Knaack U, Chung-Klatte S, Hasselbach R (2012) Prefabricated systems: principles of construction. Birkhäuser, Basel
Knippers J, Speck T (2012) Design and construction principles in nature and architecture. Bioinspiration Biomimetics 7(1). https://doi.org/10.1088/1748-3182/7/1/015002
Knippers J, Nickel KG, Speck T (2016) Biomimetic research for architecture and building construction: biological design and integrative structures. Springer, Cham
Koenderink J, van Doorn A, Pepperell R, Pinna B (2016) On right and wrong drawings. Art Percept 4(1–2):1–38. https://doi.org/10.1163/22134913-00002043
Kohlhammer T, Kotnik T (2011) Systemic behaviour of plane reciprocal frame structures. Struct Eng Int 21(1):80–86. https://doi.org/10.2749/101686611X12910257102596
Kolarevic B (2004) Architecture in the digital age: design and manufacturing. Taylor & Francis, New York
Kolarevic B (2015) From mass customisation to design 'democratisation'. Architectural Des 85(6):48–53. https://doi.org/10.1002/ad.1976
Kolarevic B, Klinger K (2008) Manufacturing material effects: rethinking design and making in architecture. Routledge, New York
Kolarevic B, Malkawi A (2005) Peformative architecture. Routledge, London
Konaković M, Crane K, Deng B, Bouaziz S, Piker D, Pauly M (2016) Beyond developable. ACM Trans Graph 35(4):1–11. https://doi.org/10.1145/2897824.2925944
Krausse J, Lichtenstein C (2017) Your private sky R. Buckminster Fuller: the art of design science. Lars Müller, Zurich
Krieg O, Christian Z, Correa D, Menges A, Reichert S, Rinderspacher K, Schwinn T (2014) HygroSkin: meteorosensitive pavilion. In: Gramazio F, Kohler M, Langenberg S (eds) FABRICATE: negotiating design and making. UCL Press, Zürich, pp 272–279

Krieg OD, Schwinn T, Menges A, Li J-M, Knippers J, Schmitt A, Schwieger V (2015) Biomimetic lightweight timber plate shells: computational integration of robotic fabrication, architectural geometry and structural design. In Block P, Knippers J, Mitra NJ, Wang W (eds) Advances in architectural geometry 2014. Springer International Publishing, Cham, pp 109–125. https://doi.org/10.1007/978-3-319-11418-7_8

Kuhlmann D (2011) In: Gruber P, Bruckner D, Hellmich C, Schmiedmayer HB, Stachelberger H, Gebeshuber IC (eds) Biomorphism in architecture: speculations on growth and form. Springer, Berlin, pp 149–178. https://doi.org/10.1007/978-3-642-11934-7_8

Kuroishi I (2015) Mathematics of carpentry in historic Japanese architecture. Architecture and mathematics from antiquity to the future. Springer International Publishing, Cham, pp 333–347. https://doi.org/10.1007/978-3-319-00137-1_23

Lalvani H (1996) Origins of tensegrity: views of Emmerich, Fuller and Snelson. Int J Space Struct 11(1–2):27–55. https://doi.org/10.1177/026635119601-204

Latour B, Weibel P (2002) Iconoclash: beyond the image wars in science, religion, and art. Center for Art and Media, Karlsruhe

Laugier M-A (1735) Essai sur l'architecture. chez Duchesne, Paris

Lawrence TT (2003) Chassis+Infill: a consumer-driven, open source building approach for adaptable, mass customized housing. Institute of Technology, Massachusetts

Le Duigou A, Castro M, Bevan R, Martin N (2016) 3D printing of wood fibre biocomposites: from mechanical to actuation functionality. Mater Des 96:106–114. https://doi.org/10.1016/J.MATDES.2016.02.018

Lehman J, Clune J, Misevic D, Adami C, Altenberg L, Beaulieu J, Yosinski J (2018) The surprising creativity of digital evolution: a collection of anecdotes from the evolutionary computation and artificial life research communities. Neural and Evolutionary Computing

Lenyra S, Campos Titotto M, Egmar T, Deifeld C, Marcelo De Oliveira Pauletti R (2006) The monument to the Futile FormIi: conception, simulation and realization of a tensegrity membrane sculpture. La Tensored Rlte

Leroy C-F-A (1857) Traité de stéréotomie, comprenant les applications de la géométrie descriptive à la théorie des ombres, la perspective linéaire, la gnomonique, la coupe des pierres et la charpente, avec un atlas… par C.-F.-A. Leroy,… 2e édition… par M. E. Martelet, (Gauthiers-), Paris. Retrieved from http://catalogue.bnf.fr/ark:/12148/cb30799169v

Li H, Huang T, Kong CW, Guo HL, Baldwin A, Chan N, Wong J (2008) Integrating design and construction through virtual prototyping. Autom Constr 17(8):915–922. https://doi.org/10.1016/J.AUTCON.2008.02.016

Liapi K (2004) A computer based system for the design and fabrication of tensegrity structures. In: Beesley P, Cheng NY-W, Williamson RS (eds) Fabrication examining the digital practice of architecture: proceedings of the 2004 AIA/ACADIA fabrication conference. ACADIA, Cambridge

Lonardo E (2011) Strutture Tensegrali. Retrieved from https://issuu.com/emiliolonardo/docs/strutture_tensegrali_pubb

Loonen RCGM, Trčka M, Cóstola D, Hensen JLM (2013) Climate adaptive building shells: state-of-the-art and future challenges. Renew Sustain Energy Rev 25:483–493. https://doi.org/10.1016/J.RSER.2013.04.016

López M, Rubio R, Martín S, Croxford Ben (2017) How plants inspire façades. From plants to architecture: biomimetic principles for the development of adaptive architectural envelopes. Renew Sustain Energy Rev 67:692–703. https://doi.org/10.1016/J.RSER.2016.09.018

Loria G (1931) Il passato e il presente delle principali teorie geometriche. Cedam, Padova

Lynn G (1999) Animate form. Princeton Architectural Press, New York

Marks RW, Buckminster Fuller R (1973) *The Dymaxion world of Buckminster Fuller*. Anchor Books, New York

Masic M, Skelton RE, Gill PE (2005) Algebraic tensegrity form-finding. Int J Solids Struct 42(16–17):4833–4858. https://doi.org/10.1016/J.IJSOLSTR.2005.01.014

Masic M, Skelton RE, Gill PE (2006) Optimization of tensegrity structures. Int J Solids Struct 43(16):4687–4703. https://doi.org/10.1016/J.IJSOLSTR.2005.07.046

Mattheck C (1998) Design in nature: learning from trees. Springer, Berlin, Heidelberg
Mazzoleni I (2013) Architecture follows nature: biomimetic principles for innovative design. CRC Press, New York
McDonald RP, O'Hara PT (1964) Size-distance invariance and perceptual constancy. Am J Psychol 77(2):276. https://doi.org/10.2307/1420135
McGee W, Ponce de León M (eds) (2014) Robotic fabrication in architecture, art and design 2014. Springer Science & Business Media, Cham
McHale J (1964) R. Buckminster Fuller. Il Saggiatore, Milano
Medaglia AL (2007) An object-oriented framework for rapid genetic algorithm development. In: Rennard J (ed) Handbook of research on nature-inspired computing for economics and management. IGI Global, Hershey, pp 608–624. https://doi.org/10.4018/978-1-59140-984-7.ch040
Menges A (2009) Performative wood: integral computational design for timber constructions. In: d'Estrée Sterk T, Loveridge R, Pancoast D (eds) Building a better tomorrow—proceedings of the 29th annual conference of the association for computer aided design in architecture. Association for Computer-Aided Design in Architecture, Chicago, pp 66–74
Menges A (2011) Integrative design computation: integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions. In: ACADIA 11: integration through computation. Association for Computer Aided Design in Architecture, Banff, p 413
Menges A (2012) Material computation: higher integration in morphogenetic design. Architectural Des 82(2):14–21. https://doi.org/10.1002/ad.1374
Menges A (2013) Morphospaces of robotic fabrication. In: Brell-Çokcan S, Braumann J (eds) Rob | Arch 2012. Springer, Vienna, pp 28–47. https://doi.org/10.1007/978-3-7091-1465-0_3
Menges A (2017) Integrative design computation for advancing wood architecture. In: Menges A, Schwinn T, Krieg OD (eds) advancing wood architecture. Routledge, London, pp 97–110
Menges A, Ahlquist S (2011) Computational design thinking. Wiley, London
Menges A, Reichert S (2012) material capacity: embedded responsiveness. Architectural Des 82(2):52–59. https://doi.org/10.1002/ad.1379
Menges A, Schwinn T, Krieg OD (eds) (2017a) Advancing wood architecture. Routledge, London
Menges A, Sheil B, Glynn R, Skavara M (2017b) Fabricate: rethinking design and construction. UCL Press, London
Merleau-Ponty M (1962) Senso e non senso (1948). Il Saggiatore, Milan
Migliari R (2000) La rappresentazione e il controllo dello spazio: morte e trasfigurazione della Geometria Descrittiva. Isegnare: Idee, Immagini XI(20–21):9–18
Migliari R, Romor J (2015) Perspective: theories and experiments on the veduta vincolata (restricted sight). J Geom Graph 19(1):57–77
Mirats Tur JM, Juan SH (2009) Tensegrity frameworks: dynamic analysis review and open problems. Mech Mach Theory 44(1):1–18. https://doi.org/10.1016/J.MECHMACHTHEORY.2008.06.008
Mitchison GJ, Westheimer G (1984) The perception of depth in simple figures. Vision Res 24(9):1063–1073. https://doi.org/10.1016/0042-6989(84)90084-1
Monge G (1789) Géométrie descriptive. Boudouin, Paris
Moscati A (2012) La prospettiva pratica. Gli strumenti per costruire la prospettiva. In: De Carlo L, Migliari R, Carlevaris L (eds) Attualità della geometria descrittiva : seminario nazionale sul rinnovamento della geometria descrittiva, Roma, dicembre 2009-marzo 2010 (Gangemi). Gangemi, Rome. Retrieved from https://books.google.it/books?id=EskELgEACAAJ&dq=attualitàdellageometriaescrittiva&hl=it&source=gbs_book_other_versions
Motro R (2003) Tensegrity: structural systems for the future. Kogan Page Science, London
Motro R, Raducanu V (2003) Tensegrity systems. Int J Space Struct 18(2):77–84. https://doi.org/10.1260/026635103769518198
Murakami H (2001) Static and dynamic analyses of tensegrity structures. Part 1. Nonlinear equations of motion. Int J Solids Struct 38(20):3599–3613. https://doi.org/10.1016/S0020-7683(00)00232-8

Myers W (2012) Beyond Biomimicry. In: Myers W (ed) Bio design: nature, science, creativity. Museum of Modern Art, London, p 288
Nahmens I, Bindroo V (2011) Is customization fruitful in industrialized homebuilding industry? J Constr Eng Manag 137(12):1027–1035. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000396
Nakahara Y, Sato H, Nii KP (1995) The complete Japanese joinery. Hartley & Marks, Vancouver
Negro A (1996) Il giardino dipinto del Cardinal Borghese: Paolo Bril e Guido Reni nel Palazzo Rospigliosi Pallavicini a Roma. Àrgos, Rome
Neisser U (1967) Cognitive psychology. Appleton Century Crofts, New York
Nestorovic M (1987) Metallic integrally tensioned (Tensegrity) Cupola. In: Topping HV (ed) Proceedings of international conference on the design and construction of non-conventional structures. Civil-Comp Ltd., Edinburgh
Ohshima T, Igarashi T, Mitani J, Tanaka H (2013) Digital fabrication-volume 1-computation and performance-eCAADe 31|. In: Proceedings of eCAADe 2013 education and research in computer aided architectural design in Europe. eCAADe, Delft, pp 693–702
Oppenheim IJ, Williams WO (1997) Mechanics of tensegrity prisms. In: Proceedings of the 14th international symposium on automation & robotics in construction. Pittsburgh
Oxman R (2006) Theory and design in the first digital age. Des Stud 27(3):229–265. https://doi.org/10.1016/J.DESTUD.2005.11.002
Oxman R (2009) Performative design: a performance-based model of digital architectural design. Environ Plan 36(6):1026–1037. https://doi.org/10.1068/b34149
Oxman R, Oxman R (2010a) Introduction. In: Oxman R, Oxman R (eds) The new structuralism: design, engineering and architectural technologies. Wiley, pp 14–24
Oxman R, Oxman R (2010b) The new structuralism: design, engineering and architectural technologies. Wiley, New York
Oxman R, Oxman R (eds) (2014) Theories of the digital in architecture. Routledge, London
Page IC, Norman D (2014) Prefabrication and standardisation potential in buildings (SR 312). Branz, Wellington
Paoletti I (2018) Informed architecture: computational strategies in architectural design. In: Hemmerling M, Cocchiarella L (eds) Informed architecture: computational strategies in architectural design. Springer, pp 77–88
Paris L (2009) Stereotomia del legno. In: Migliari R (ed) Geometria Descrittiva. CittàStudi, Torino, pp 562–588
Paronesso A, Passera R (2004) The cloud of Yverdon. In: Motro R (ed) IASS symposium 2004. IASS Secretariat, Madrid, pp 184–185
Pastore N (1971) Selective history of theories of visual perception 1650-1950. Oxford University Press, Toronto
Pawlyn M (2011) Biomimicry in architecture. RIBA Publishing, London
Pearce P (1979) Structure in nature is a strategy for design. MIT Press, Cambridge
Pearson M (2011) Generative art: a practical guide using processing. Manning, Greenwich
Pecchinenda G (2010) Videogiochi e cultura della simulazione. La nascita dell' «homo game». Laterza, Roma - Bari
Pedersen Zari M (2015) Ecosystem processes for biomimetic architectural and urban design. Architectural Sci Rev 58(2):106–119. https://doi.org/10.1080/00038628.2014.968086
Pedretti C (1988) Leonardo architetto. Electa, Milano
Peña DM, Llorens I, Sastre R (2010) Application of the tensegrity principles on tensile textile constructions. Int J Space Struct 25(1):57–67. https://doi.org/10.1260/0266-3511.25.1.57
Peri G (1884) Applicazioni della geometria descrittiva alle ombre, alla prospettiva lineare e aerea, al taglio delle pietre e del legname (G. Belotti, ed.). Firenze
Pérouse de Montclos JM (1985) La vis de Saint-Gilles et l'escalier suspendu dans l'architecture française du XVI siècle in L'escalier dans l'architecture de la Renaissance (Répertoire d'Art et d'Archéologie, Ed.). Picard
Pilewski JL, Martin BA (1991) Effects of monocular versus binocular viewing in the ames distorted-room illusion. Percept Mot Skills 72(1):306. https://doi.org/10.2466/pms.1991.72.1.306

Pillet J (1887) Traité de stéréotomie (C. Delagra). Paris
Pine BJ, Slessor C (1999) Mass customization: the new frontier in business competition. Harvard Business School, Boston
Popov V, Juocevicius V, Migilinskas D, Ustinovichius L, Mikalauskas S (2010) The use of a virtual building design and construction model for developing an effective project concept in 5D environment. Autom Constr 19(3):357–367. https://doi.org/10.1016/J.AUTCON.2009.12.005
Popovic Larsen O (2003) Conceptual structural design: bridging the gap between architects and engineers. Thomas Telford, London
Popovic Larsen O (2008) Reciprocal frame architecture. Architectural Press, Oxford
Popper KR (1957) The poverty of historicism. Beacon Press, Boston, pp 123–124
Pottmann H, Huang Q, Deng B, Schiftner A, Kilian M, Guibas L et al (2010) Geodesic patterns. ACM Trans Graph 29(4):1. https://doi.org/10.1145/1778765.1778780
Pugh A (1976a) An introduction to tensegrity. University of California Press. Retrieved from https://books.google.it/books?id=McEOfJu3NQAC&dq=A.+Pugh.+An+Introduction+to+Tensegrity.+University+of+California+Press,+1976.&lr=&hl=it&source=gbs_navlinks_s
Pugh A (1976b) Polyhedra: a visual approach. University of California Press, Berkeley
Rajanen M, Iivari N (2015) Power, empowerment and open source usability. In: Proceedings of the 33rd annual ACM conference on human factors in computing systems—CHI '15, pp 3413–3422. https://doi.org/10.1145/2702123.2702441
Ramachandran VS (1990) Visual perception in people and machines. In: Blake A, Troscianko T (eds) AI and the eye. Wiley, London
Ratti C, Claudel M (2015) Open source architecture. Thames & Hudson, New York
Rechenberg I (1965) Cybernetic solution path of an experimental problem. Royal AircraftEstablishment, Ministry of Aviation, Farnborough Hants
Reichert S, Menges A, Correa D (2015) Meteorosensitive architecture: biomimetic building skins based on materially embedded and hygroscopically enabled responsiveness. Comput Aided Des 60:50–69. https://doi.org/10.1016/J.CAD.2014.02.010
Renner G, Ekárt A (2003) Genetic algorithms in computer aided design. Comput Aided Des 35(8):709–726. https://doi.org/10.1016/S0010-4485(03)00003-4
Reyssat E, Mahadevan L (2009) Hygromorphs: from pine cones to biomimetic bilayers. J R Soc Interface 6(39):951–957. https://doi.org/10.1098/rsif.2009.0184
Richard R-B (2005) Industrialised building systems: reproduction before automation and robotics. Autom Constr 14(4):442–451. https://doi.org/10.1016/J.AUTCON.2004.09.009
Riether G, Wit AJ (2016) Underwood Pavilion. A parametric tensegrity structure. In: Adriaenssens S, Gramazio F, Kohler M, Menges A, Pauly M (eds) Advances in architectural geometry 2016. Vdf Hochschulverlag AG an der ETH Zürich, pp 114–203
Rippmann M, Block P (2011) Digital stereotomy: Voussoir geometry for freeform masonry-like vaults informed by structural and fabrication constraints. In: Proceedings of the IABSE-IASS symposium 2011. IABSE, Boston
Roudsari MS, Pak M (2013). Ladybug: a parametric environmental plugin for Grasshopper to help designers create an environmentally-conscious design. In: Proceedings of the 13th international IBPSA conference. Lyon, pp 3128–3135
Rüggeberg M, Burgert I (2015) Bio-inspired wooden actuators for large scale applications. PLoS ONE 10(4):e0120718. https://doi.org/10.1371/journal.pone.0120718
Runeson S (1988) The distorted room illusion, equivalent configurations, and the specificity of static optic arrays. J Exp Psychol Hum Percept Perform 14(2):295–304. https://doi.org/10.1037/0096-1523.14.2.295
Rutten D (2013) Galapagos: on the logic and limitations of generic solvers. Architectural Des 83(2):132–135. https://doi.org/10.1002/ad.1568
Sadao S (1996) Fuller on tensegrity. Int J Space Struct 11(1–2):37–42. https://doi.org/10.1177/026635119601-206

Saint Aubin JP (1994) es enjeux architecturaux de la didactique stéréotomique de Desargues. In: Dhombres JG, Sakarovitch J (eds) Desargues en son temps. Librairie scientifique A. Blanchard, Paris

Sakamoto T, Ferré A (2008) From control to design: parametric/algorithmic architecture. Actar-D, New York

Salvador F, De Holan PM, Piller F (2009) Cracking the code of mass customization. MIT Sloan Manag Rev 50(3):71–79

Salvatore M (2012) La stereotomia scientifica in Amédée François Frézier. Prodromi della geometria descrittiva nella scienza del taglio delle pietre. Università degli Studi di Firenze

Sanabria SL (1989) From gothic to renaissance stereotomy: The design methods of Philibert de l'Orme and Alonso de Vandelvira. Technol Cult 30(2):266. https://doi.org/10.2307/3105105

Sanjurjo Alvarez A (2010) La Vis-de-Saint-Gilles: analyse du modèle dans les traités de coupe des pierres et de son influence sur les traités espagnols de l'âge moderne. In: Carvais R, Guillerme A, Nègre J, Valérie Sakarovitch (eds) Édifice & Artifice. Histoires Constructives. Editions Picard, Paris, pp 679–689

Sass L (2006) A Wood Frame grammar: a generative system for digital fabrication. Int J Architectural Comput 4(1):51–67. https://doi.org/10.1260/147807706777008920

Sass L (2012) Direct building manufacturing of homes with digital fabrication. In: Gu N, Wan X (eds) Computational design methods and technologies: applications in CAD, CAM, and CAE education. IGI Global, New York

Sass L, Botha M (2006) The instant house: a model of design production with digital fabrication. Int J Architectural Comput 4(4):109–123. https://doi.org/10.1260/147807706779399015

Sass L, Oxman R (2006) Materializing design: the implications of rapid prototyping in digital design. Des Stud 27(3):325–355. https://doi.org/10.1016/J.DESTUD.2005.11.009

Scheurer F (2010) Materialising complexity. Architectural Des 80(4):86–93. https://doi.org/10.1002/ad.1111

Schlaich M (2004) The Messeturm in rostock: a tensegrity tower. J Int Assoc Shell Spatial Struct 42(2):93–98

Schumacher P (2011) The autopoiesis of architecture: a new framework for architecture. Wiley, West Sessex

Seike K (1986) The art of Japanese Joinery. Weatherhill, Tankosha

Self M, Vercruysse E (2017) Infinite variations, radical strategies. In: Menges A, Sheil B, Glynn R, Skavara M (eds) Fabricate 2017 conference proceedings. UCL Press, London, pp 30–35

Sheil B (2005) Design through making: an introduction. Architectural Des 75(4):5–12. https://doi.org/10.1002/ad.97

Skelton RE, de Oliveira MC (2009) Tensegrity systems. Springer Science & Business Media, London

Skelton RE, Adhikari R, Pinaud JP, Chan W, Helton JW (2002) An introduction to the mechanics of tensegrity structures. In: Proceedings of the 40th IEEE conference on decision and control (Cat. No.01CH37228), vol 5, pp 4254–4259. IEEE, Orlando. https://doi.org/10.1109/CDC.2001.980861

Snelson K (1996) Snelson on the tensegrity invention. Int J Space Struct 11(1–2):43–48. https://doi.org/10.1177/026635119601-207

Snelson K (2012) The art of tensegrity. Int J Space Struct 27(2–3):71–80. https://doi.org/10.1260/0266-3511.27.2-3.71

Solomon J, Vouga E, Wardetzky M, Grinspun E (2012) Flexible developable surfaces. Comput Graph Forum 31(5):1567–1576. https://doi.org/10.1111/j.1467-8659.2012.03162.x

Son S, Fitriani H, Kim JT, Go S, Kim S (2017) Mathematical algorithms of patterns for free-form panels. In: Proceedings of the 2nd world congress on civil, structural, and environmental engineering (CSEE'17), vol 101, pp 2371–5294. CSENM,Barcelona. https://doi.org/10.11159/icsenm17.101

Song K, Yeom E, Seo S-J, Kim K, Kim H, Lim J-H, Joon Lee S (2015) Journey of water in pine cones. Sci Rep 5(1):9963. https://doi.org/10.1038/srep09963

Stephan S, Klimke H (2004) The making of a tensegrity tower. In: IASS 2004 symposium, international association for shell and spatial structures. Editions de l'Espérou, Montpellier

Svilans T, Poinet P, Tamke M, Ramsgaard Thomsen M (2018) A multi-scalar approach for the modelling and fabrication of free-form glue-laminated timber structures. In: Humanizing digital reality. Springer, Singapore, pp 247–257. https://doi.org/10.1007/978-981-10-6611-5_22

Tachi T (2012) Interactive freeform design of tensegrity. In: Hesselgren L, Sharma S, Wallner J, Baldassini N, Bompas P, Raynaud J (eds) Proceedings of the advances in architectural geometry conference. Springer, Wien, pp 259–268. https://doi.org/10.1007/978-3-7091-1251-9

Tamborero L (2006) The "Vis Saint-Gilles", symbol of compromise between practice and science. In: Proceedings of the second international congress on construction history. Construction History Society, Cambridge, pp 3025–3040

Tamke M, Thomsen MR (2009) Digital wood craft. CAAD Futures

Teghtsoonian M (1965) The judgment of size. Am J Psychol 78(3):392. https://doi.org/10.2307/1420573

Thompson DW (1917) On growth and form. Cambridge University Press, Cambridge

Thönnissen U (2014) A form-finding instrument for reciprocal structures. Nexus Netw J 16(1):89–107. https://doi.org/10.1007/s00004-014-0172-1

Thönnissen U, Werenfels N (2011) Reciprocal frames—teaching experiences. Int J Space Struct 26(4):369–371. https://doi.org/10.1260/0266-3511.26.4.369

Tibert G (2008) Advances in the optimization and form-finding of tensegrity structures. In: Proceedings of the 6th international conference on computation of shell & spatial structures. Internet-First University Press, Stockholm

Tibert AG, Pellegrino S (2011) Review of form-finding methods for tensegrity structures. Int J Space Struct 26(3):241–255. https://doi.org/10.1260/0266-3511.26.3.241

Tran TM (2002) Reverse displacement analysis for tensegrity structures. University of Florida. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.15.2315&rep=rep1&type=pdf

Trevisan C (2011) Per la storia della stereotomia: geometrie, metodi e construzioni. Aracne, Roma

Tsigkari M, Angelos C, Joyce SC, Davis A, Feng S, Aish F (2013) Integrated design in the simulation process. In: Proceedings of the symposium on simulation for architecture & urban design. Society for Computer Simulation International, San Diego

Turan M (2009) Reconstructing the balloon frame: a study in the history of architectonics. METU J 2(26):175–209. https://doi.org/10.4305/METU.JFA.2009.2.10

Turrin M, von Buelow P, Stouffs R (2011) Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms. Adv Eng Inform 25(4):656–675. https://doi.org/10.1016/J.AEI.2011.07.009

Ugolev BN (2014) Wood as a natural smart material. Wood Sci Technol 48(3):553–568. https://doi.org/10.1007/s00226-013-0611-2

Vailati C, Bachtiar E, Hass P, Burgert I, Rüggeberg M (2018) An autonomous shading system based on coupled wood bilayer elements. Energy Build 158:1013–1022. https://doi.org/10.1016/J.ENBUILD.2017.10.042

Van Telgen MV, Snijder H, Habraken APH, Beetz J (2013) Parametric design and calculation of circular and elliptical tensegrity domes. In: IASS 2013 Wroclaw: 'Beyond the Limits of Man'—structural morphology. International Association for Shell and Spatial Structures (IASS), Eindhoven, pp 1–8

Vassart N, Motro R (1999) Multiparametered formfinding method: application to tensegrity systems. Int J Space Struct 14(2):147–154. https://doi.org/10.1260/0266351991494768

Vattam S, Helms ME, Goel AK (2007) Biologically-inspired innovation in engineering design: a cognitive study, Atlanta. Retrieved from http://hdl.handle.net/1853/14346

Vierlinger R (2013) A framework for flexible search and optimization in parametric design. In: Rethinking prototyping—proceedings of the design modelling symposium. Berlin. Retrieved from https://www.researchgate.net/profile/Robert_Vierlinger/publication/283073197_A_Framework_for_Flexible_Search_and_Optimization_in_Parametric_Design/links/5628c83308ae04c2aeaeb6cb.pdf

Vierlinger R (2015) Towards ai drawing agents. In: Ramsgaard Thomsen M, Tamke M, Gengnagel F, Faircloth C, Scheurer B (eds) Modelling behaviour. Springer International Publishing, Cham, pp 357–369. https://doi.org/10.1007/978-3-319-24208-8_30

Vierlinger R, Bollinger K (2014) Accommodating change in parametric design. In: Proceedings of ACADIA 2014. Association for Computer-Aided Design in Architecture, Los Angeles

Vierlinger R, Zimmel C (2015) Octopus. Retrieved 27 Aug 2018, from https://www.grasshopper3d.com/group/octopus?groupUrl=octopus&id=2985220%3AGroup%3A742529&page=3

Vincent J (2009) Biomimetic patterns in architectural design. Architectural Des 79(6):74–81. https://doi.org/10.1002/ad.982

Vogel JM, Teghtsoonian M (1972) The effects of perspective alterations on apparent size and distance scales. Percept Psychophys 11(4):294–298. https://doi.org/10.3758/BF03210382

Wang B (2004) Free-standing tension structures: from tensegrity systems to cable-strut systems. Spon Press

Weber S (2005) The success of open source. Harvard University Press, Cambridge

Weinand Y (2016) Advanced timber structures: architectural designs and digital dimensioning. Birkhäuser, Basel

Wester T (2002) Nature teaching structures. Int J Space Struct 17(2–3):135–147. https://doi.org/10.1260/026635102320321789

Wikipedia (2015) The poverty of historicism (2002nd ed.). Routledge, London

Willis D, Woodward T (2010) Diminishing difficulty: mass customisation and the digital production of architecture. In Corser R (ed) Fabricating architecture: selected readings in digital design and manufacturing. Princeton Architectural Press, pp 184–208

Willmann J, Gramazio F, Kohler M (2017) New paradigms of the automatic: robotic timber construction in architecture. In: Menges A, Schwinn T, Krieg OD (eds) Advancing wood architecture. A computational approach. Routledge, London, pp 13–28. https://doi.org/10.4324/9781315678825-11

Wood DM, Correa D, Krieg OD, Menges A (2016) Material computation—4D timber construction: towards building-scale hygroscopic actuated, self-constructing timber surfaces. Int J Architectural Comput 14(1):49–62. https://doi.org/10.1177/1478077115625522

Wood D, Vailati C, Menges A, Rüggeberg M (2018) Hygroscopically actuated wood elements for weather responsive and self-forming building parts—facilitating upscaling and complex shape changes. Constr Build Mater 165:782–791. https://doi.org/10.1016/J.CONBUILDMAT.2017.12.134

Woodbury R (2010) Elements of parametric design. Routledge, London

Zarrinmehr S, Akleman E, Ettehad M, Kalantar N, Borhani A (2017) Kerfing with generalized 2D meander-patterns: conversion of planar rigid panels into locally-flexible panels with stiffness control. In: Çagdas G, Özkar M, Gül LF, Gürer E (eds) Future Trajectories of computation in design. Cenkler Matbaa, Istanbul, pp 276–293

Zhang L, Maurin B, Motro R (2006) Form-finding of nonregular tensegrity systems. J Struct Eng 132(9):1435–1440. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:9(1435)

Zipkin P (2001) The limits of mass customization. MIT Sloan Manag Rev 42(3):81–87. https://doi.org/ISSN: 1532-9194

Zitzler E, Laumanns M, Thiele L, Zitzler E (2001) SPEA2: Improving the strength pareto evolutionary algorithm. Zurigo. https://doi.org/10.3929/ethz-a-004284029

Zwerger K (1997) Wood and wood joints: building traditions of Europe, Japan and China. Birkhäuser, Basel