Digital Processes for Wood Innovation Design

Fabio Bianconi, Marco Filippucci, and Giulia Pelliccia

Abstract The study reports the outcomes of a research activity focused on digitization techniques and in particular on the value of computational design, with the aim of implementing innovative product and process solutions resulting from an integrated design approach. The digitization paths focused on representative strategies for digital optimization of the architectural form of wooden houses as a function of context, based on research on generative modelling and evolutionary algorithms for multi-objective optimization applied to the architecture of wooden houses. With such an approach, centered on artificial intelligence or at least on augmented computational intelligence, it was possible to achieve a process of mass customization of meta-planning solutions of wooden architectures, based on the morphological and energetic selection of the best configurations, identified according to the context. These results were made accessible through a web-based configurator that provides the designer with initial configurations from which starting the real project. The studies are projected to the definition of a prototype of the "breathing house," characterized by its moisture-responsive wooden panels, with the identification of innovative solutions capable of reacting passively to changes in humidity according to the "natural intelligence" of the material, whose morphological transformation, empirically studied and digitally transcribed to identify performance solutions, generates well-being for living.

Keywords Meta-design · Energy optimization · Responsive architecture · Timber construction · Digital representation

United Nations' Sustainable Development Goals 9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster

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innovation · 11. Make cities and human settlements inclusive, safe, resilient and sustainable · 12. Ensure sustainable consumption and production patterns

1 Introduction

The digitization processes accompanying the recent industrial revolution, in the context of AEC (Architecture, Engineering and Construction), are based on representation: the design of form and enrichment through multiple information are amplified with the interactivity, modifiability and multimedia inherent in digital [1]. The goal is to make the information implicit in the form visible [2, 3]. The design is asked first and foremost for a total freedom but also for a full awareness, as validation tools for the construction phase, to the point of generating a digital clone that replicates reality to continuously derive information in the dynamic integration between hardware and software [4]. The built does not become an object in itself, but stands precisely through its digital replication in relation to its environment, through the processing of causal associations used to create predictions [5], in a cycle marked by data-information-knowledge [6]. Data, defined as the new oil [7], promotes the architecture's resilience.

Such processes result in multiubiquity [8] arising from enabling technologies [4, 9] that lead to a "Cyber-Physical Production System" [4, 10] inherent in the "Smart Factory" [11], which are bringing interesting substantial benefits in terms of digital production [12] and automation [13], but also in what concerns mass customization [14] and stimulating innovation [15]. This activates a digital thread [16] where design becomes a continuous process overlapping the built.

The field of research has thus increasingly shifted from the physical to the virtual space: the morphogenesis from which the model is originated, where the multiple information converges, changes the relationship between sign and image as well as the way of reading and interpreting reality, observing it from different points of view, analyzing it with integrated skills, studying its multiple variables and their mutual interaction. In Industry 4.0 [13], the new paradigm of digital tectonics is developing a new coincidence between virtual representations and their fabrication (Fig. 1), in what appears to be a true cultural revolution [17, 18], because "fabrication is not a modelling technique, but a new way of doing architecture" [19].

Profoundly affecting this transformation are the advances in computational design [20] and in particular parametric logics [21], all based on a different interpretation of the value of data: if the digital revolution has shifted the focus from models to visualization, then parametric design allows to reclaim the infinite potential of the model [1, 22] because data is not secondary but rather the main element that leads to form. "Through a well-designed system of rules, generative design systems have the capability of maintaining stylistic coherence and design identity while generating different designs" [23], rethinking relationships that are "intelligible because its members exhibit a common order resulting from the operation of the same generative principles" [24]. By varying parameters in defined but always open processes, the

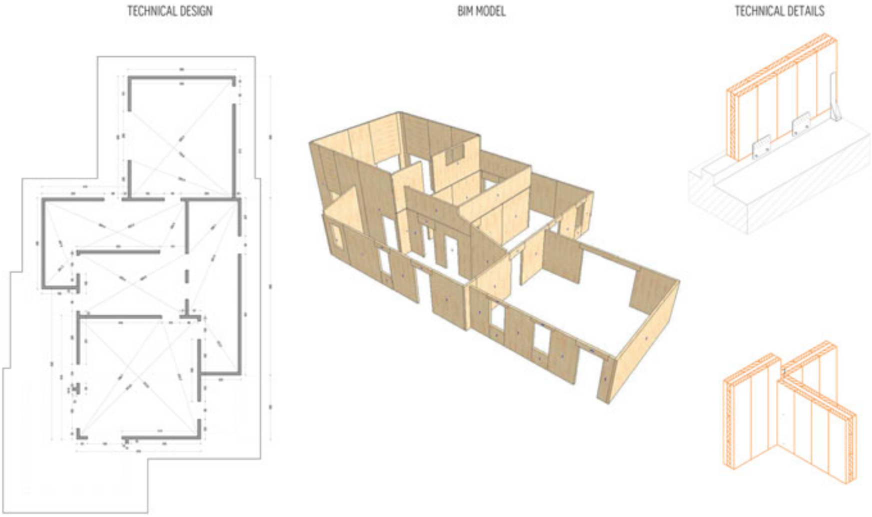

Fig. 1 Digital wood design and digital manufacturing

algorithm is a tool for configuring, rather than a static morphology, a generative pattern characterized by diversity.

Thus, a data-driven design [25] is developed where one relates to "complex systems" not by looking for simplifications or optimal solutions, rather by creating a combinatorial explosion [26], contrasting this Evolutionary Engineering marked by Multiscale Analysis [26–28] as an alternative to the "iterative and incremental" standard. Optimization strategies [29, 30] are structurally and environmentally optimized form-finding solutions [31] that enable the designer to visualize and evaluate thousands of design options and variants [32] through the materialization of the issue of architectural complexity [33], from the perspective of mass customization [34–43].

Representation is proposed in its definition of architecture and design as "*Lineamenta*" [44], understood according to Leon Battista Alberti's diction [45] as a system of signs. Artificial intelligence [46, 47] and in particular the logic of optimization inherent in evolutionary algorithms [48] acquires a central role in this relationship: computational design is enhanced thanks to the augmented intelligence of the digital [49–51], which finds perfect exemplification in wooden constructions, from design to realization.

Thus, in this context, wood emerges as a material that is absolutely congenial to digital logics, versatile, and fully adapted to contemporary needs for performance and customization (Fig. 2). Therefore, digital representation is added to the properties of matter and its Natural Intelligence (NI) [49–51]. Nature offers not forms but processes for thinking about form [52] and teaches how to create it [53, 54] in efficient structures [55, 56] explaining how the roles of design [57, 58] are truly adaptive and optimized [59]. NI defines paradigms that could be transposed not as "ignorant copying of forms"…but in the recognition "that biomimicry teaches that

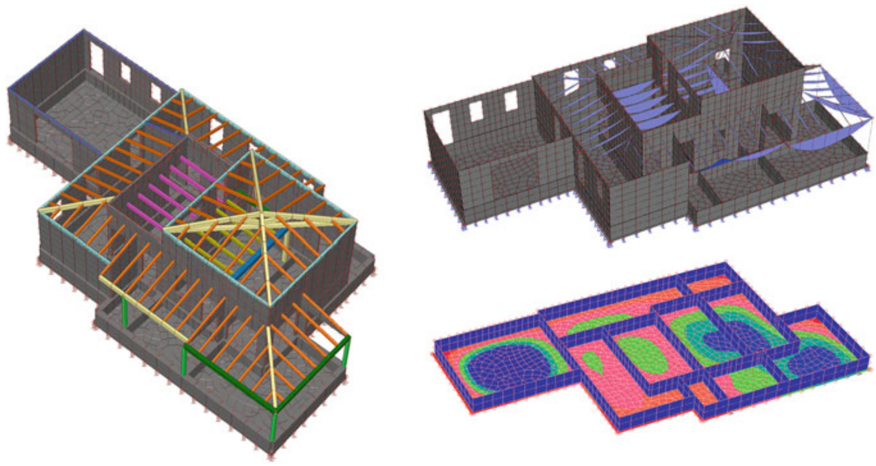

Fig. 2 Analysis and simulation in digital wood models

form is the most important parameter of all" [60], because at all levels it builds responsive and adaptive forms to preserve material and energy resources through the use of modular components combined with low-energy structural strategies [61].

2 The Research

Digitization has been the focus of the entire research project started in 2016 with the then wooden construction start-up Abitare+, in the aim of achieving innovative solutions that would characterize the quality of its offerings. The study is focused on digitization techniques and, in particular, on the value of computational design, with the aim of implementing innovative product and process solutions as the result of an integrated approach to design. The digitization paths addressed various issues, starting with the identification of representative strategies for digital optimization of the architectural form of wooden houses according to the context.

The research was developed at the Department of Civil and Environmental Engineering of the University of Perugia, a path that has found an important recognition in the "BIM&DIGITAL Awards 21" promoted by CLUST-ER BUILD and DIGITAL&BIM Italia. The award was intended to report as excellent the innovative path that through the new digital techniques of representation has led to the development of solutions for new generation wooden housing, capable of responding to the multiple performances and needs of living today. This collaboration was supported by funds from the 2014–2020 POR FESR of the Regione Umbria aimed at supporting the creation and consolidation of innovative start-ups with a high intensity of knowledge application. The sustainability of innovation processes is then strengthened by the support for research guaranteed by national regulations, which provides tax credit for a significant part of the investments made.

2.1 Meta-design and Mass Customization of Wooden Houses

One of the first approaches developed jointly with the company is based on computational design research to address the need to promote a design culture of wooden constructions. Indeed, the research is aimed at designers, who in the national context often face difficulties in designing wood constructions due to the absence of specific training: it is then intended to provide meta-planning solutions, a basis for then developing the project. Evolutionary principles have been applied aimed at informing the design and customization process in the early stage of design. The main goal is to design a comfortable house characterized by high energy performance taking maximum advantage of the passive use of sun and wind. For this purpose, a web-based interface has been developed allowing to explore the design alternatives of a specific construction model by visualizing and downloading a series of multimedia files.

The developed parametric process 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, constraints have been encoded in a way that each solution follows 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.

The integrated process proposed in this research has been entirely developed with Grasshopper, introducing in each phase of the project different add-ons for analysis, representation, and interoperability. 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. 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 (USGBC, 2013) (Fig. 3). In this research, due to time constraints, 15 generations of 100 individuals were evaluated with the climate data of Perugia,

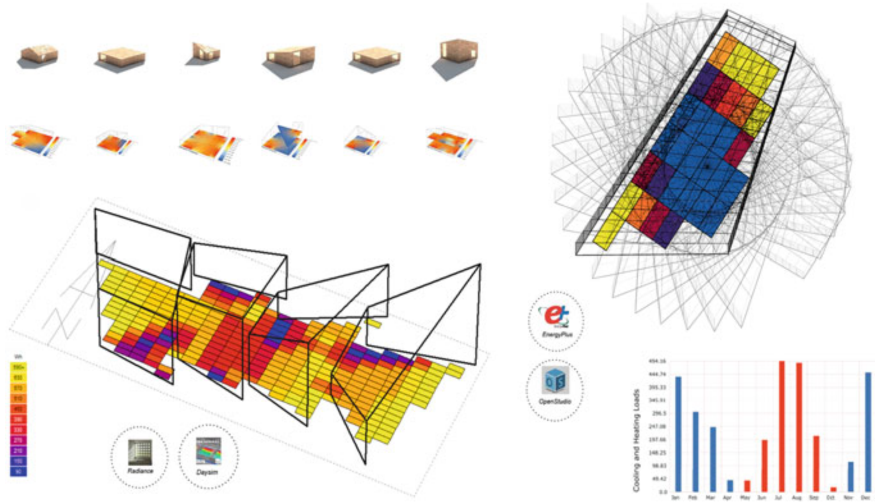

Fig. 3 Lighting, cooling and heating loads have been analyzed for the different geometric solutions through Honeybee for Grasshopper

Italy. Comparing the less and the most efficient solutions, taking into account that they have different areas, volumes, grazing rations, orientations, the results in saving on energy consumption per square meter was 380%, and saving on construction costs per square meter was 240%.

The proposed workflow highlights the centrality of the research approach, based on computational and collaborative strategies, as a link between design teams and modern construction companies. The analyzed solutions have then been represented in a web-based catalog through which the technology owned by modern construction companies can be shared with designers to achieve an integrated approach. Within a wider collaborative workflow, encompassing smart manufacturing principles and integrated design strategies, the research and development project focuses on the analysis and representation of data. As a result, design teams can take part in the process of mass-customization and start an integrated design process to optimize the product and achieve further design customizations.

2.2 Multi-objective Optimization of Architectural Elements

The logic of mass customization applied to architectural morphogenesis can be similarly applied to the design of building elements. Focusing on the envelope as an essential element of buildings, the research examines perimeter walls by analyzing them from the point of view of both winter and summer behavior and verifying the absence of the of interstitial condensation. Two building systems, Platform-Frame and X-Lam, were analyzed with the aim of optimizing, through the creation of special algorithms, their stratigraphy in order to provide the company with a set of diversified solutions that take into account both cost and energy performance [62, 63].

The combination between the thicknesses and types of materials that compose the wall is the basis of the analysis. Large amounts of data can thus be analyzed and combined and to get solutions that simultaneously present the best values of the parameters chosen as inputs, returning the required outputs. By varying the parameters, the outputs describe the summer and winter behavior of the wall through thermal transmittance U, periodic thermal transmittance Y_{ie}, decrement factor f and time shift φ, according to UNI EN ISO 13786:2018 [64] in addition to the verification of interstitial condensation by Glaser diagram according to UNI EN ISO 13788:2013 [65]. The total cost was then used as a benchmark for comparison with the optimized packages. The stratigraphy optimization process was conducted using Octopus, which allows evolutionary principles to be applied to parametric modelling in order to optimize specific parameters [66, 67]. In the two cases considered, Octopus calculated about 5.000 possible solutions; among them, only those belonging to the Pareto Front [68] were selected. Packages were then divided according to performance, as defined by DM 26/6/2009 "National guidelines for energy certification of buildings" [69]: excellent performance ($\varphi > 12$ h, $f > 0.15$) and good performance ($10 < \varphi < 12$ h, $0.15 < f < 0.30$). Depending on the final cost, the most suitable walls were identified, narrowing down to those with a lower or slightly higher cost than the standard reference package (Fig. 4).

Through the proposed optimization and selection method, it was possible to obtain walls with significantly better performance than the standard ones, even at a lower cost. For Platform-Frame, in particular, a stratigraphy can be obtained with excellent

Fig. 4 The optimization process through Octopus for Grasshopper combines materials and thicknesses while maximizing time shift and minimizing thermal transmittance, decrement factor and costs

performance with a saving of 0.7% and one with good performance with a saving of 3.8%. For X-Lam, on the other hand, an excellent stratigraphy can be obtained with a saving of 1% and a good one saving 13% of the costs as compared to the standard wall. If, instead, the improvement in energy performance is considered without limiting the cost, Platform-Frame can be improved up to 20% in transmittance and 31% in time shift, and for X-Lam up to 28% in transmittance and 22% in time shift. Thus, the parametric design and muti-parametric optimization tools proved to be, once again, essential to process a large amount of data and select the best performing solutions according to specific needs.

Experiments in digital form-finding are linked to BIM modelling, aimed at defining digital manufacturing processes. The construction is linked to representation through BIM interchange models that define the characteristics of the envelope and structural elements, which in turn find information from the algorithms developed in generative modelling.

2.3 The Breathing House

Alongside digital simulations carried out to achieve the ultimate goal of improving the energy consumption of wooden buildings, solutions can also be found in exploiting the properties of the materials themselves. This is the case, for example, of technological smart materials, which have the ability to react to a particular stimulus and change some of their properties to adapt to the external conditions [70, 71]. Smart materials also include natural materials such as wood, which is a sustainable, easily available and low-cost solution [72]. In fact, thanks to its hygroscopic properties, wood expands and shrinks as ambient humidity changes. One can therefore think of exploiting these properties for the control of hygrometric well-being in indoor environments [73, 74].

A typical example of hygroscopic behavior is showed by pine cones, whose scales bend due to the different reaction to moisture of the two tissues from which they are composed (fibres and sclereids) [75–78]. It is therefore possible to replicate these properties by making an artificial composite that takes advantage of the hygroscopicity and anisotropy of wood (active layer) combined with a material that does not react to moisture or has a lower hygroscopic expansion coefficient (passive layer). A single layer of wood will always show some degree of shrinkage/expansion proportionally to changes in moisture; by coupling it with a material that does not undergo deformation, its response can be pre-programmed in order to achieve the desired configuration at a given moisture content, and from a simple dimensional change will result in bending [79, 80]. The carried tests on various specimens with different configurations and characteristics were used to create a prototype of a modular ceiling panel which is pre-programmed to bend for relative humidity other than 40% (Fig. 5). Double-layered wood panels react passively to changes in humidity and, therefore they can be considered as low-cost, low environmental impact and technological

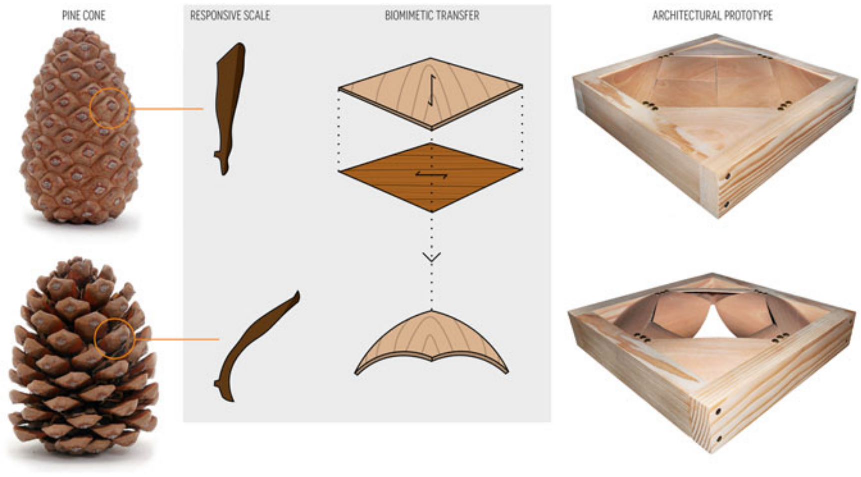

Fig. 5 The biomimetic transfer of properties from the pine cone to an artificial prototype can be used in responsive architectures to passively react to humidity variations

elements that may be able to improve indoor hygrometric comfort without additional energy consumption. In particular, it is intended to propose a model of natural ventilation, complementary to the use of air conditioning systems, especially for the regulation of humidity, which is thus regulated thanks to bioclimatic principles that exploit the convective motions of warm and humid air and the chimney effect.

These principles and goals have since been transferred to the field of 4D printing [81–83] of wood-based filaments, joining the 3 dimensions in space with a fourth dimension, time which allows the composite to adapt to environmental humidity. Additive printing allows a total customization, making it possible to design the hygroscopic deformations. Using the commercially available filament LAYWOOD, composed of 40% recycled wood powder and 60% PLA (polylactic acid) [84], the direction of expansion of the composite is drawn by the deposition of the filament itself, which can then follow the desired pattern and result in complex deformations. Various printing properties radically affect the result obtained, from layer height to infill, feed rate to z-offset with respect to the printing plane, and so on. By varying these parameters, different curvatures and curvature velocities can be obtained for the same design (Fig. 6).

The production of multiple specimens to compare the hygroscopic deformations, both in natural and printed wood, and the research aim of applying these composites to the improvement of indoor well-being then led to the creation of a test room where these panels and optimized solutions for wood walls could be tested.

Fig. 6 Different curvatures and velocity of curvature of similar 3D printed specimens with different printing properties

2.4 The Wooden Test Room

Digitally optimized solutions as well as the idea of a "breathing house" involve multiple aspects that need to be analyzed but also verified. For this need, a temporary wooden test room was built at the Engineering Pole of the University of Perugia.

This structure was developed on a single level with Platform-Frame structure, of about 20 m^2 and average height 2.4 m, characterized by a glazed opening in the south direction. On the roof, about 15 m^2 of thin-film photovoltaic panels with a storage battery are needed for the heat pump, to cool and heat, simulating the winter and summer indoor thermo-hygrometric conditions typical of a residential environment. The north-facing wall is removable and can be replaced with other walls characterized by different stratigraphies.

The peculiarity of this Platform-Frame test room is that the monitored north-facing wall is removable for testing with different stratigraphies chosen from the various solutions optimized by the algorithm in the simulation phase. Monitoring was carried out through heat flux sensors, thermocouples, humidity and temperature probes during the summer period (Fig. 7). The acquired data were used for the determination of the in situ thermal transmittance to be compared with the one simulated by the algorithm, referring to UNI ISO 9869 [85], according to which it is possible to obtain the thermal resistance from the ratio of the summation of the surface temperature difference between outside and inside and the summation of heat fluxes.

Moisture-responsive wooden panels made of beech and larch wood were installed at the ceiling of the test room. Thanks to the convective motions of moist air rising toward the false ceiling, which causes the panels to bend due to the difference in humidity, air flows inside a cavity and is carried outside by exploiting the chimney effect.

Measurements were made on an optimized wall that best combines the most popular insulation materials on the market. Thermal transmittance was then calculated from the acquisitions, and considering the 10% uncertainty rate of the direct measurement, due to multiple factors, as well as the fact that the stated values of the

Fig. 7 The test room has been designed and built to experiment in reality what had been digitally simulated, concerning in particular the responsive false ceiling and the optimized timber walls

thermal conductivities of the insulating materials also exhibit percentages of variability, it was concluded that the actual behavior is similar to that obtained from the simulations. The information is then returned from the built to the digital in the final section of the study, in order to build a real-time monitoring system of what is happening within the test room and integrate that data into the model, creating a digital twin in the BIM environment [86].

The test room certainly represents one of the clearest paradigms of a contemporary way of doing research, a space set up to transfer innovation to the market in which Abitare+ presents itself by offering innovative and performing solutions. At the end of this first part of the research it is interesting to highlight that the data acquired confirmed the reliability of the calculations made by the algorithm, with a small percentage of error due to field measurements.

2.5 Representation and Communication of the Optimized Models

One of the key aspects of the research was the collection of data and its representation through ways that are accessible to everyone: the algorithms created have their own complexity and specificity so that even the company's engineers cannot manage the information. In fact, during optimization processes, a huge amount of data comes into play, and visualizing this data is crucial for understanding, comparing and sharing the results of the approach carried out.

In this context, the combination of data visualization became an effective way to enhance the decision-making process [87] 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 [88]. The aim is to create an open source design [89–91] as meta-project for adaptable and mass customized housing [92]. The user interface developed in this research 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.

For both the meta-planning solutions of the houses and the multi-objective optimizations of the walls, the same representative action was carried out, which allows the selection of parameter ranges for the different elements that characterize their geometry (Fig. 8). At the strategic level, the company then decided to make public the results of the mass customization of the houses while leaving for internal use the dynamic catalogs of the wall element combinations, which become a performance enhancement to the solutions of each house as a result of the executive design, in terms also of production, which the company refines at the end of the design phase.

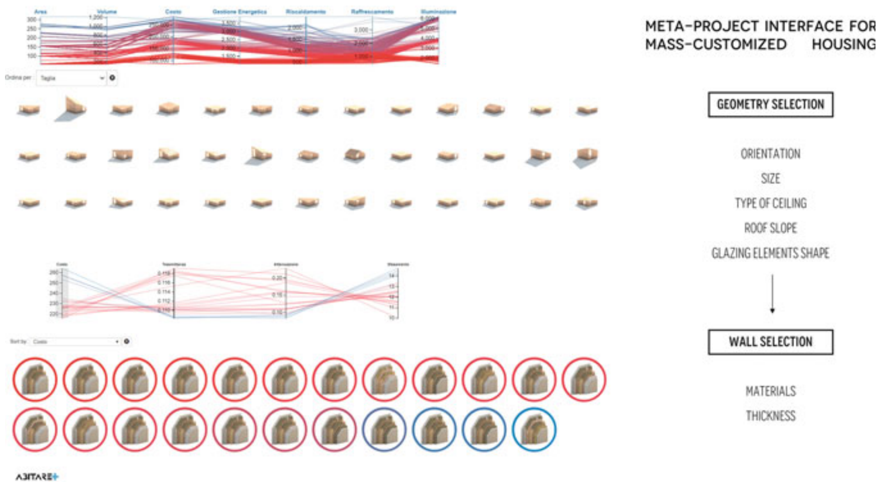

Fig. 8 The web interface allows the users to select the optimal solutions, choosing the best geometries and walls depending on their performance requirements or budget

2.6 Representation and Communication of the Environmental Simulations

The data, analysis and the whole logic of performance and efficiency that is demanded of buildings today does not meet the needs of living. The design of the home must be communicated comprehensively to both engineers and clients. Technical drawings and renderings, which are the main tools for communicating design, do not guarantee customization, which instead is inherent in digital language.

The experience conducted is projected in the logic of the serious game [93–96], aimed at gathering information on the impact of simulations. In fact, the interaction between the user and the model is monitored by an analysis of the sensations related to the different configurations: in the interactive experience, sensors applied to the fingers are able to assess the galvanic skin response (GSR) [97–100] to pick up variations in its micro-sensation, including, for example, involvement and stress. This information, after the interactive visit, is cross-referenced with data collected "in game" regarding the user's location and point of view to understand what events triggered the changes recorded by the sensors.

In order to create a process of relations and communication between the user and the company, an immersive model was then created with the Unreal Engine graphics engine of a dwelling chosen from the optimized ones that is made interactive and customizable according to the client's needs.

Starting from the catalog shapes, transformed into a design, materials were applied and the interior of the building was enriched with furniture. In addition, some geometric variations to the morphology of the house were reproduced to create different configurations of the spaces to be made available later during the immersive experience. Thus, all the functions necessary for the different types of variations were programmed, as well as those that allow the user to move through the space, others for recording all the actions, movements and points in the scene on which the user focused most, the functions necessary to allow the execution of the experience with a VR visor and the logic related to the graphical interface. Finally, some numerical data and interactive graphs were included that adapt following the user's choices and describe the impact they have on some parameters related to the house (such as energy costs, construction costs, comfort parameters), with the aim of providing awareness of the effects of decisions (Fig. 9).

3 Conclusions

Wood constructions reverse some conceptions linked to the building processes proper to our architectural culture, which is deeply tied to craftsmanship. This issue concerns the transition between architecture and fabrication: concepts such as smart manufacturing [101], robotic fabrication [102] virtual prototyping [103], automatic rule-based design [104] and virtual building design [105] are rapidly reshaping the relationship

Fig. 9 Starting from the design, the project can be 3D modelled and reproduced through virtual reality before the construction, to show the results and help in the decision-making phase

between architecture and construction, where we are increasingly seeing a direct transition from design to fabrication thanks to digitization and robotics [106].

Wood is naturally connected to the intelligence of biology [72]. It is a renewable resource [107] with an aesthetic value, workability, flexible, relatively light, versatility, low thermal conductivity, but it presents also undesirable characteristics for its sizing limits and deformations, anisotropy, hygroscopicity and degradation. Through its engineering aimed at the homogenization of its characteristics, wood represents a performing solution that integrates fabrication as a generative paradigm into the design process [108]. For these conditions, wood represents one of the most important field of application of parametric design [109–113] where "non-standard timber structures can be efficiently aggregated from a multitude of single timber members to foster highly versatile timber constructions" [114]. In hybridization and integration of digital wood design, the innovative tools involve a transformation of paradigm and form, connections and limits.

The processes of digitization and the value of digital techniques of representation are increasingly being contextualized in the innovations implemented in relation to the issues of contemporary building, many of which may find optimal solutions in wood. As a natural, sustainable, inexpensive, and extremely versatile material, wood is well suited not only for use as a material in construction, but also for experimenting with generative design and digital fabrication solutions.

The presented research ranges from multi-objective optimization of forms and construction details, to empirical research on responsive panels, and finally focus on forms of sharing and communicating the obtained results. The presented path thus describes the collaborative process implemented that has created a development of products, processes and services to meet the need for innovation that characterizes the new Industry 4.0 applied to architecture. The data and experiments are enriched with dynamic simulations in immersive reality, with the interactive variation of possible morphological and perceptual configurations, which can be used by the company to show the client the impact of the final project, reinforcing the full involvement of the end user, designer and/or owner, in the choices thus made aware of their impacts.

Representation presents itself as the field of existence of research: from design to construction, and beyond into the digital twin, drawing understood as a model is enhanced by the logics of digital. The transdisciplinary language of representation, open to different knowledges based on form, suited to bring out the underlying relationships, presents itself as the lifeblood of Industry 4.0 and the contemporary logics of doing architecture.

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