# Inverse Models. Analog as Verification of the Digital

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*Abstract*

*The importance of representation as a space for model building has always been central to architectural practice. These models have served as a means of verifying ideas, according to a design approach that can be defined as "form-checking". With the digital transition, this relationship is reversed and models are increasingly identified by parameters and information providing analysis, forecasts and identifying solutions, in an approach that thus becomes "form-finding". If, however, the idea and form were initially "drawn" in the mind and on paper, today the idea and the figure remain in the mind, while the digital drawing finds the form according to the desired performance. The research presented here analyzes three case studies in which models stigmatize the relationships between ideation, verification and implementation. The first case study concerns the construction of the Ames room, an iconic theme of perception, created as a temporary pavilion, generated through generative algorithms, BIM models and digital fabrication. The second case study presents the creation of a test room, a model built to monitor in real-time and compare actual performance with data simulated by multi-objective algorithms. The third case study concerns experimental research on 3D printed wooden hygroscopic architectural elements, similar models that show the role of representation in the relationship between design, manufacturing and responsiveness.*

*Keywords: generative design, Ames room, digital fabrication, wooden pavilions, wood 3D printing.*

### *In Catilinam*

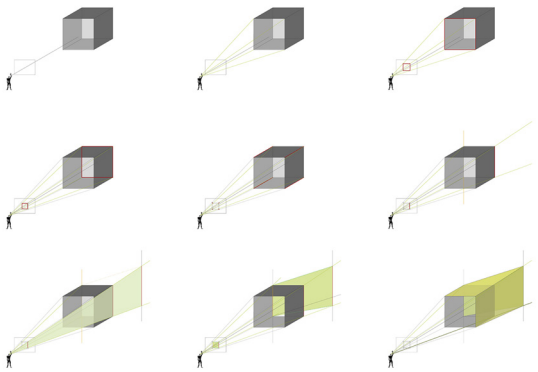
Representation as a field of research hyperbolically reflects the transformations activated by the digital transition [Hensel et al. 2006; Schumacher 2009] in the centrality of models [Bedoni et al. 1989; Migliari 2000; 2003], conquest of modern thought [Baudrillard 1981] as a theoretical construction, because, as Vasari writes, "the drawing is an apparent expression and declaration of the concept that one has in his soul, and of what has been imagined in the mind of others and fabricated in the idea" [Vasari 1568, p. 111]. Representing means fueling that necessary and continuous reference between reality and virtuality which is the basis of the model, a dynamic and continuous process where the materiality of analogue models has always played a fundamental role in refuting doubts and implicit 'allegations of falsity' attributed to the drawing, ascribed to the class of images. Analogue models have always had the task of 'verifying' the consequences of the loss of an inherent dimension in the drawing, due to the need to experience space, always understood as doubt and as conquest. Digital has emphasized distrust and distrust towards images, but the current role of Analogue models finds a new status in data-driven design [Bianconi et al. 2019b] and the centrality of performance [Oxman 2009; Hensel 2010].

With the digital transition, the selection and recomposition processes necessary for the knowledge process [Maturana et al. 1987; Popper 2002] converge in the representation of form, which presents itself as an effective

support for orientation [Passini 1981; Sancar 1986; Meng et al. 2012; Bianconi et al. 2022] and memorization of information [Oxman et al. 2014], tool for visualizing logical connections [Jabi et al. 2013; Bianconi et al. 2019a] and the hierarchical relationships established between them [Bettetini et al. 1999, p. 75]. Representation thus becomes the field of existence of information [Mitchell 1995; Kolarevic 2001], due to the need for transdisciplinarity that this language offers for integrated planning [Labaco 2013], which feeds on the centrality of the connections that it brings to the current 'fifth industrial revolution', where the protagonism of artificial intelligence in information management is establishing itself [Bianconi, Filippucci 2019].
These concretizations reflect the canonical approach to the project, linked to the identification of design solutions aimed at generating forms, which are first verified through a series of criteria that weigh their performance. It is therefore a 'form-checking', which becomes more complex in the inclusion of the various project information, which must be specifically examined. Design increasingly becomes integrated, a condition that is enhanced by digital, always capable of including and connecting, with the form that lends itself to guaranteeing the existence of heterogeneous intertwining of entities, relationships and logics, identified by parameters and information, which can be interrogated from different disciplinary perspectives through calculations to offer analysis. In the variation of the possibilities of the parameters that are inherent in the model, the form can be read as one of the results, a process that can be seen as a substantial transformation of the design morphogenesis, however having the same statutory purpose of finding the best solutions. Digital is capable of making increasingly efficient calculations and it is thus possible to seek 'for the best' solutions aimed at optimizing even unthinkable performances [Menges 2009], not by deconstructing according to a single aspect [Jones 2009], but by combining in the organic and integrated vision of the project [Gruber et al. 2012] in a process that thus becomes one of 'form-finding' [Menges 2012; Adriaenssens et al. 2014].
If we then consider that where the boundaries between designing and producing are lost [Kolarevic 2004; Kolarevic et al. 2008] due to the new logics of digital manufacturing [Sheil 2005; Sakamoto et al. 2008; Corser 2010; Krieg et al. 2014; Austern et al. 2018] inherent in CAD/CAM systems [Sass et al. 2006; Chaszar et al. 2010; Sass 2012], in robotics [Menges 2012; 2013; Gramazio et al. 2014; McGee et al. 2014; Menges et al. 2017; Eversmann et al. 2017] and 3D printing [Correa et al. 2015; Le Duigou et al. 2016; Bianconi et al. 2019], it is understood that the accusation is not aimed at the 'modelling technique', but in the value of the new way of 'doing architecture' [Oxman et al. 2010, p. 24], a process characterized by a substantial hybridization between reality and virtuality.
The digital revolution consequently entails a profound renewal of the role of variation also of analogue models in an inversion between reality and virtuality which confuses temporal linearities: if previously the form was 'drawn' in the mind and on paper, with the models that served to test and materialize the multiple performances of what had to be built, today however in the computational design approach the idea and the figure remain in the mind, with the digital drawing that 'finds' the form due to the multiple performances sought, which they must be verified through the first prototype creations that anticipate what will be built. This thesis, in light of the pre-established hypotheses, finds verification in the experiments carried out by the writer, selected to highlight specific aspects in the 'defence' of representation.

*Fig. 1. Projective morphogenesis of one among the possible Ames rooms (graphic elaboration by the authors).*



## The model as perceptive experimentation: **the** Ames room

The first case study concerns the construction of the Ames room, which takes its name from the American psychologist and ophthalmologist [Behrens 1993] who proposed it in 1946 [Bamberger 2006]. It is an iconic

theme of perception, which was created as a temporary pavilion, generated through generative algorithms, BIM models and digital fabrication. The well-known case study is based on a spatial distortion that generates an illusory image, exploiting the value of the bias in perception and the lack of correspondence between the projected image and space. The reasons that led to tackling this research and, specifically, the creation of a built space, derive from the fact that the Ames room is experienced almost exclusively through images but not through the experience of space. The research therefore explored the morphological transformations starting from the visual pyramid of a canonically stereometric room: by limiting the point of view and varying the base of the pyramid, distorted spaces are formed, characterized by solid perspectives defined by divergent lines and inclined horizontal and vertical surfaces, which mislead observers in spatial assessments (fig. 1). The protracted form-finding approach is structured through generative modelling, using Grasshopper algorithms, to address spatial constraints and optimize the design for the exhibition context (fig. 2). This exploration revealed the different facets of architectural design, linking classical principles to computational design paradigms and highlighting the active role of the environment in the design process. Generative logic has integrated with BIM systems for wood design (SEMA), pushing the boundaries between design and implementation according to manufacturing processes (fig. 3). The analogue model of the architecture was created through the pavilion's platform-frame structure composed of *Oriented Strand Board* (OSB) panels, *Medium-Density Fiber* (MDF) panels and an external finish in micro-perforated black PVC (fig. 4). Among the design choices was a panel corresponding to the constrained point of view, creating a box that reveals the illusion only through the screen of a smartphone, showing how limited views adapt perception despite stereoscopic cues.
The creation of the Ames room, beyond its visual charm, shows a transformation of experience and thus became an opportunity for further experiments on the measurement of perception, using digital biosensors. The correlation between the eye-tracking data and the neural frequencies has provided insights into the behavior and emotional responses of the spectators to the epiphany of the illusion, which arises only from the constrained perspective, implemented by the smartphone: the data collected show the complexity of human perception [Palmer 1999] and how the appearance of the deceptive image captures the confused spatial exploration, the access key which in amazement activates an increase in attention in that process of knowledge which puts preconceptual images and models into crisis, according to a condition that has general validity for all analogue models of architecture.

## The model as verification of simulations: the test room

The second case study presents the creation of a test room, a model built to monitor in real-time and compare actual performance with simulated data through digital

*Fig. 2. Generative design and optimization of a possible Ames room (graphic elaboration by the authors).*

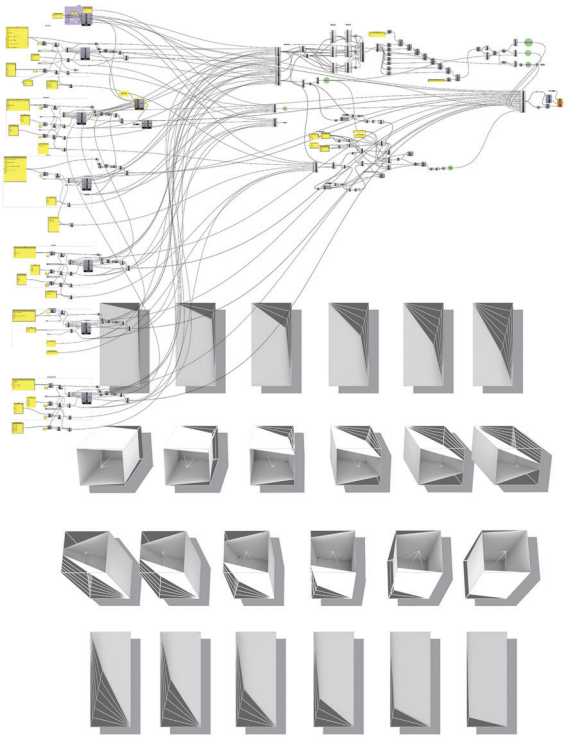
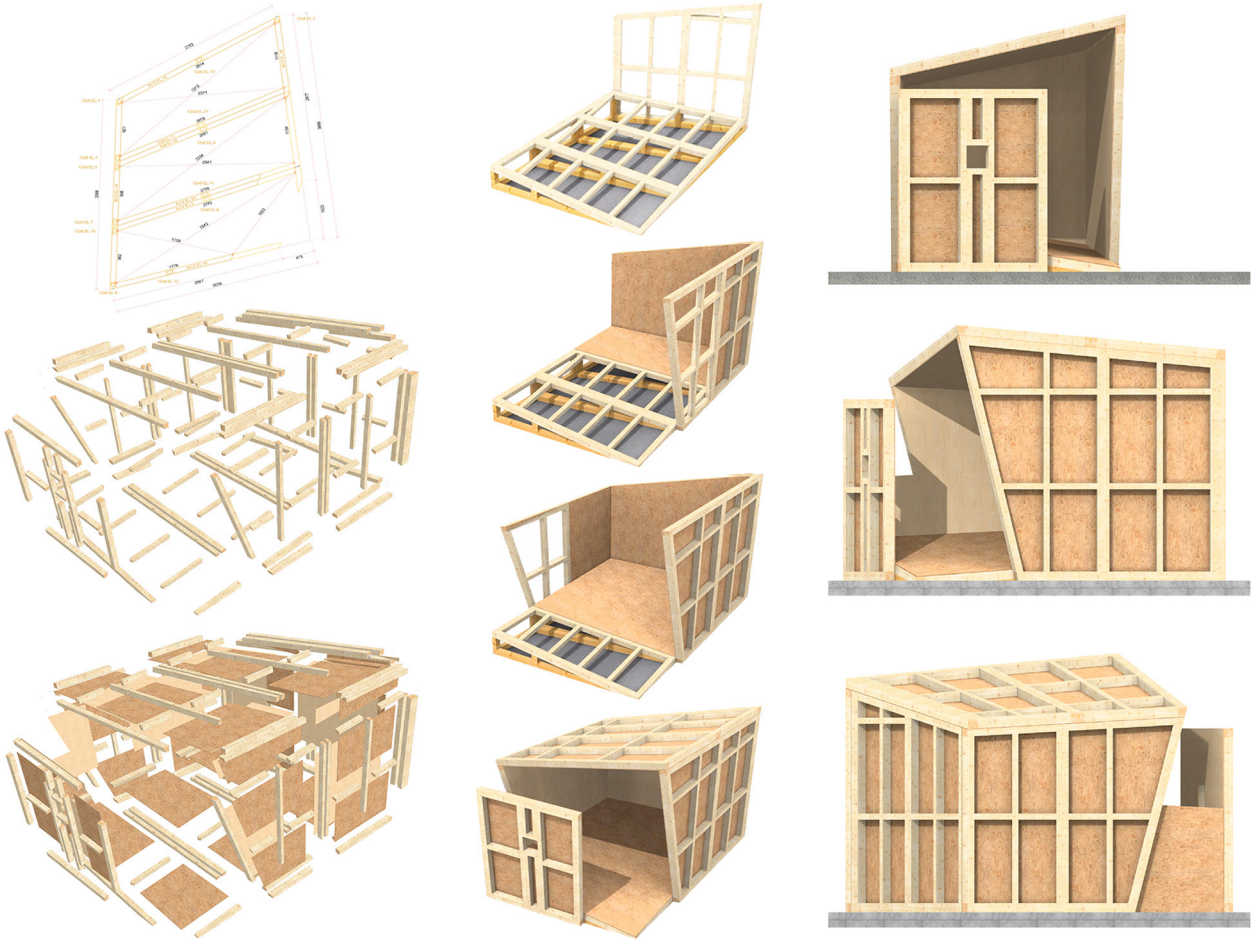


*Fig. 3. Drawings for Ames room digital fabrication (graphic elaboration by the authors).*

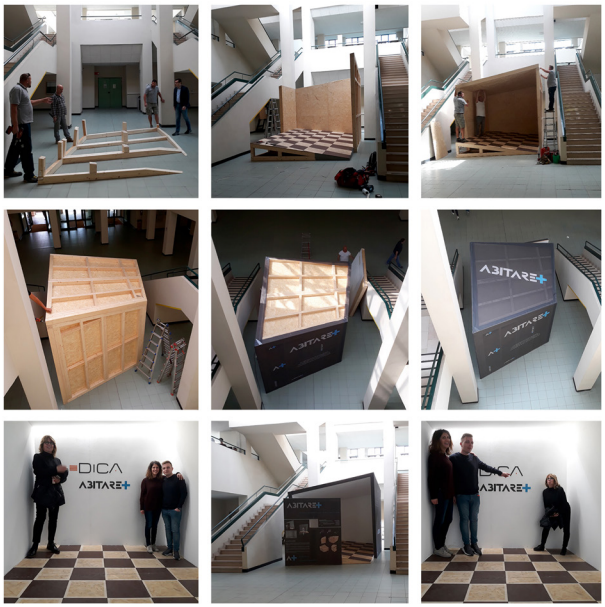


optimization processes defined by multi-objective algorithms. The research set itself the task of innovating wooden buildings to increase their performance, seeking meta-design solutions aimed at designers, who encounter difficulties due to the lack of specialized training in wooden buildings [Bianconi et al. 2023]. Using Octopus evolutionary optimization algorithms in Grasshopper, the solutions identified were shared by developing a web interface to explore and choose alternatives based on the imposed conditions. Extending the principles of mass customization [Benros et al. 2009] to architectural elements, the research has explored the optimization of perimeter walls, examining, in particular, the Platform-Frame and X-Lam construction systems [Bianconi et al. 2019b]. Algorithms were then developed to analyze and combine the data to obtain diversified wall solutions, taking into account costs and energy performance [Seccaroni et al. 2019] (fig. 5), simulations that identified combinations of wall elements with significantly better performance than the standard ones used, with lower costs (fig. 6).
Digital simulations, in the attractiveness of these results, offered a structural revolution of the products, which before being implemented required its validation in the face of an implicit prejudice on the value of the digital representation. To ensure the quality of digitally optimized solutions, a temporary wooden test room with a Platform-Frame structure was built equipped with a heat pump, thin-film photovoltaic panels, humidity-sensitive wooden panels, sensors and probes (fig. 7). Monitoring and measurements were conducted to compare simulated and actual performance, through the creation of a real-time monitoring system and digital twin in the BIM environment [Bianconi et al. 2021], with data demonstrating the full reliability of what had been digitally designed (fig. 8).
The test room is a paradigm of contemporary research, an analogue model of architecture, built in scale, which makes visible not what is in the mind, but what remains internal to the design ecology of virtual space, where data seem to have their existence which we want to be sure that corresponds to the simulated reality.

## The model for material programming: 4D printing of hygro-responsive actuators

The third case study concerns experimental research on hygroscopic architectural elements in wood, similar models that show the role of representation in the relationship between creation, programming and optimization of their responsiveness, derived from the meso-scale of the material and constructed through additive printing that thus includes the design of the fourth dimension (fig. 9). By exploring solutions with digital simulations, the potential of intelligent materials such as wood, known for its hygroscopic properties, was highlighted, which instead of being contrasted as happens with plywood panels, was supported to activate responses to humidity variations. The study was therefore inspired by nature by replicating the hygroscopic behavior of pine cones to create an artificial composite for the hygrometric well-being of internal environments. The principles have extended to the 4D printing of wood-based composites, introducing a fourth-time dimension to adapt to environmental humidity. The research involved natural ventilation principles, which integrate air conditioning systems and regulate humidity through bioclimatic principles, and biomimicry [Benyus 1997; Vincent et al. 2006] is exploited here to create responsive passive actuators.

*Fig. 4. Execution and installation of the Ames room for the experience verification (graphic elaboration by the authors).*



Over the past decade, 3D printing, especially *Fused Deposition Modeling* (FDM) technology, has emerged as a promising avenue for developing materials with complex architectures, including smart materials and various sensors [Mustapha et al. 2021]. To improve building performance sustainably, key priorities include achieving low embodied energy, minimizing energy consumption during operation and reducing the environmental impact of new technical applications. The search for intelligent and autonomous environmental solutions, based on real-time data, has led to the study of natural sensors, which exhibit passive behavior in response to specific stimuli, such as the passive expansion and contraction of hygroscopic materials following variations in environmental humidity [Dawson et al. 1997; Elbaum et al. 2014; Elbaum 2018; Correa et al. 2020].
The adaptive behavior of these elements is based on their material architecture, which is designed, programmed and simulated through computational design and visual scripting tools, and then manufactured directly via 3D printing, which therefore allows for the creation of similar models (fig. 10). Leveraging wood as a biomimetic template for 3D printed composites means amplifying the shape deformation characteristics of wood to create responsive structures. Biomimetic principles inspired by the opening of pine cone scales are transferred to engineered artificial structures, resulting in double-layered structures with a pre-programmed response to changes in humidity (fig. 11). These solutions are conceived and calculated in the virtual sphere of digital computation and concretized in similar models necessary to verify the actual simulated behavior (fig. 12). The fabrication of this actuator was

*Fig. 5. Performance morphogenesis of timber frame wall system (graphic elaboration by the authors).*

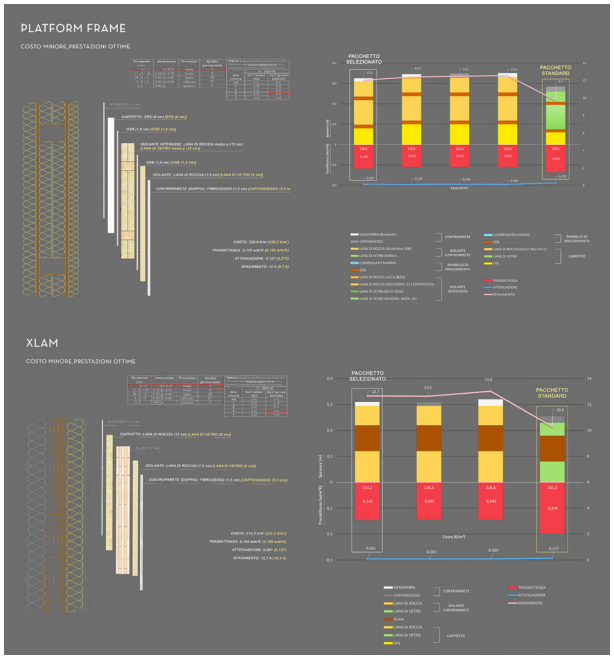



*Fig. 6. Generative design and multiobjective optimization of timber frame wall system (graphic elaboration by the authors).*

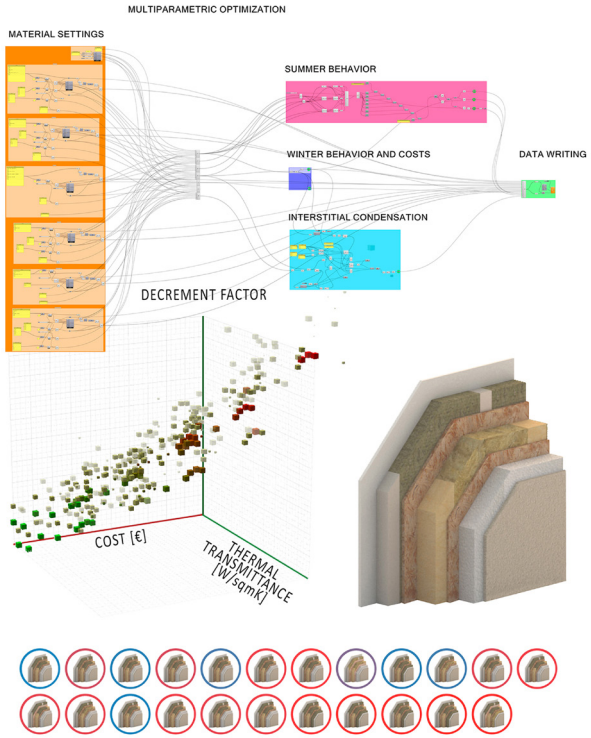
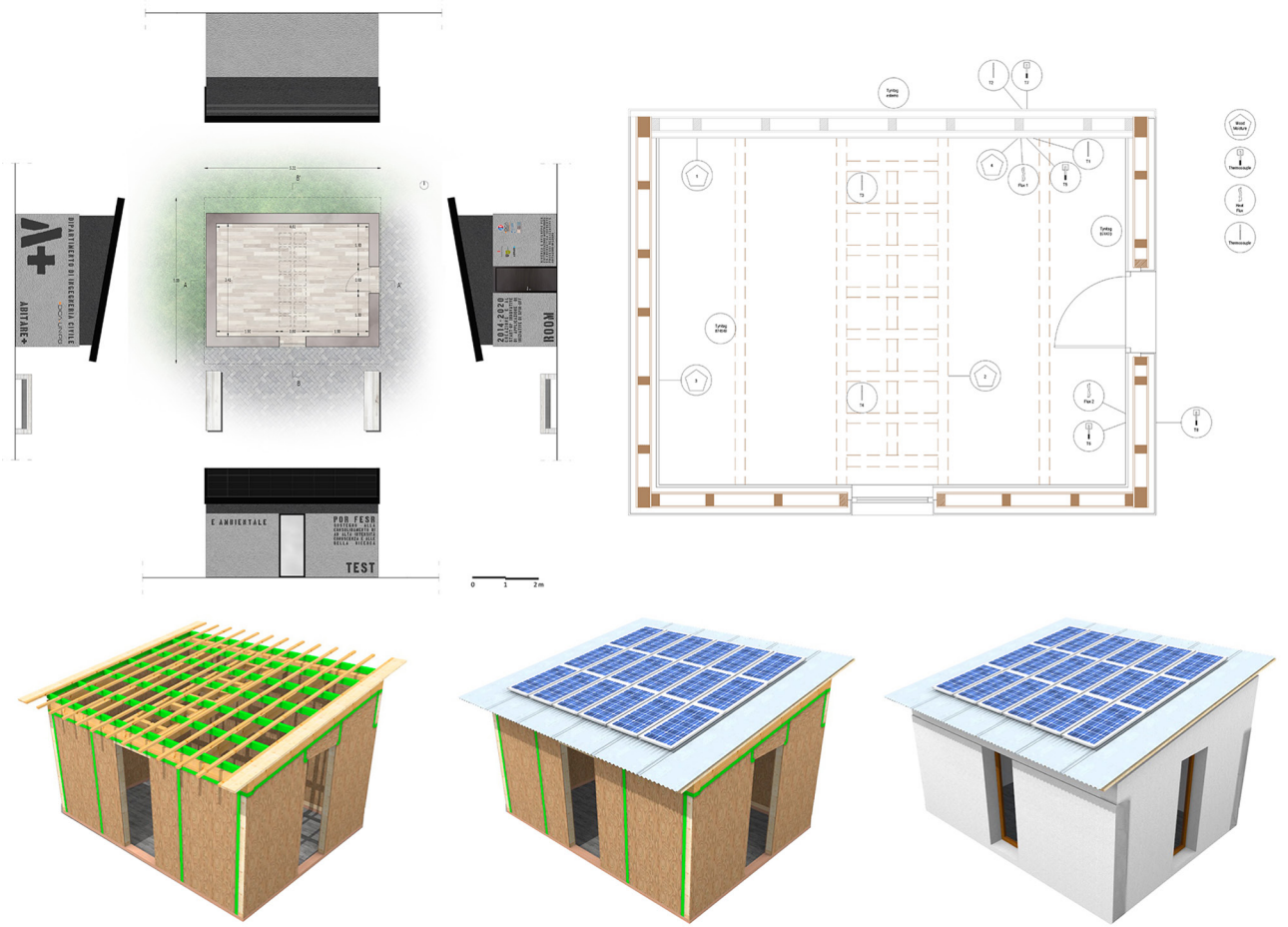


*Fig. 7. Drawings for test room digital fabrication (graphic elaboration by the authors).*



achieved through an additive manufacturing process, called 4D printing [Tibbits 2014] since the time dimension constitutes a crucial aspect in defining the shape and final configuration of the printed analogue models. Through visual scripting algorithms, representation is the first player in the programming of *Stimulus Responsive Materials* (SRMs) but also in 4D printing, a data-driven process that aims to offer solutions to improve interior environments with low-cost and cost-effective renewable materials with minimum operating conditions [Bianconiet al. 2023]. The representation thus manages to draw time in its simulations but also to include it and materialize it in the material, in its forms and in the future behavior of what is drawn through computational design machines. It is thus possible to create similar models that appear canonical, purely material, but profoundly innovative as they are the result of a design that directly influences their physical behavior and spatial configuration.

## Conclusions

The article presented allowed us to explore in depth the crucial role of representation in contemporary architecture. The transition from traditional analogue models to the centrality of digital models is analyzed through a lens that embraces the history of art, design theory and the evolution of technologies. Through the transformations activated by the digital transition, the centrality of models in modern thought emerges and underlines the critical role of representation as a theoretical construction. Verification through analogue models in the context of digital images, often the subject of mistrust, is fundamental in this context.
The three case studies highlight how analogue models continue to play a fundamental role in the context of digital architecture. While the Ames room constitutes a tangible verification of the perspective deception created digitally through an analogue model, the test room demonstrates the importance of validating simulations through a physical model. Digital representation also takes on a further crucial role in the programming of responsive materials, in which the analogue model is fundamental for verifying the actual digitally simulated behavior. The research presented here demonstrates how analogue models are key witnesses of the process of cultural transformation that is affecting architecture. First of all, the Ames room highlights how the need for concretization is implemented in a model that is not just a reduction but, by digital manufacturing, is what leads to the built, which is a precise concretization of a family of solutions, of a reality that has incomparable potential in digital. The second case study highlights more the distrust towards the digital, which, in its autonomy as a model, needs the analogue as a verification space, inverting the primordial representations that were used to verify the drawings with their dimensional loss. The third case study highlights how in the dichotomy between virtual and real the difference between the analogue model and construction is lost, with digital manufacturing generating forms programmed to have their simulated vitality. The initial concretizations are tests transformed into smart solutions inherent in the natural intelligence, that is transcribed into a design of time, inherent in the realization as well as in the response to stimuli.
Design shows itself as the deep soul of architecture: just as the score for music remains beyond execution, so

*Fig. 8. Execution and installation of the test room for simulated performance verification graphic (graphic elaboration by the authors).*

*Fig. 9. Programmed morphogenesis of the hygro-responsivity of wooden actuators made by additive printing (graphic elaboration by the authors).*

*Fig. 10. Generative design and kinematic optimization of the programmed hygro-responsivity of wooden actuators made by additive printing (graphic elaboration by the authors).*

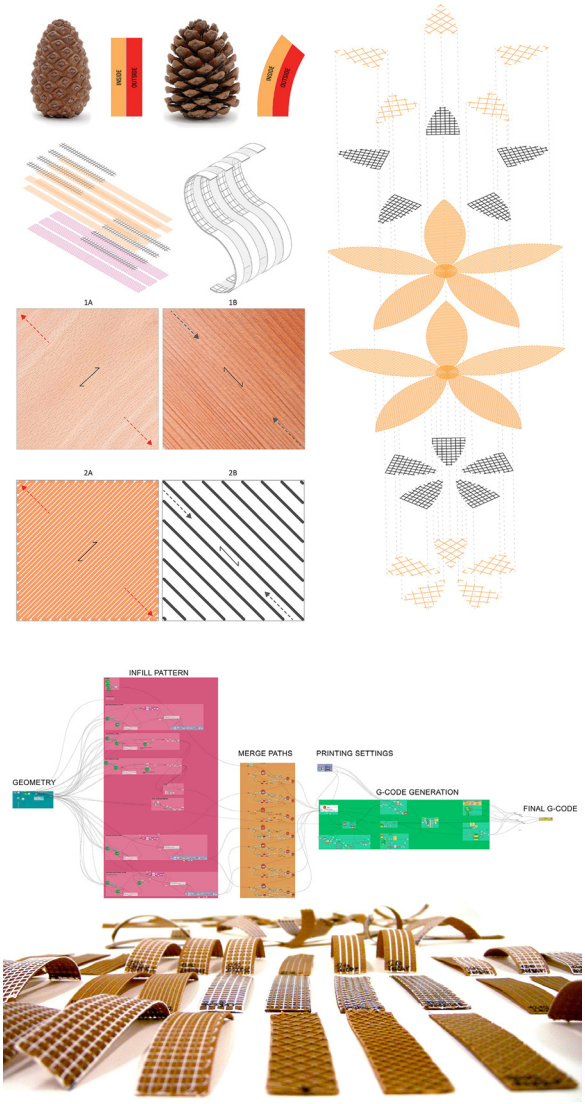



*Fig. 11. Drawings for digital fabrication of the wooden actuators made by additive printing (graphic elaboration by the authors).*

*Fig. 12. Execution and installation of the wooden actuators made by additive printing for verification of the hygro-responsivity and kinematics (graphic elaboration by the authors).*

representation is the place where what remains ethereal and blurry in ideas takes shape. The analogue models of architecture have always been moments of checks, similar to when someone reads a musical score and plays some key passages to concretize what he feels without hearing. The scale factor that has characterized their realizations has always been fundamental, with digital emphasizing this loss of measure. This condition is at the origin of the current value of models, so marked by a spatial atopicity that leads to autonomy that generates as much suspicion as the world of ideas. In computational design, the possible universes of infinite combinations highlight how representation is capable of accepting increasingly complex challenges, but equally, even though virtual universes are built, its statutory role of projecting itself towards creation, towards construction, towards architecture.

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