

Design Method Aided by MABS and Cloud Computing

Framework integrating: construction techniques, materials, and fabrication

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This paper presents a novel method based in Multi-Agent Based Simulation (MABS), Cloud Computing, and the combination of big data analytics and IoT. The method performs in two layers: it assists designers with information coming from previews of projects and surroundings, and, it automates some procedures according to parameters and interactions between agents. The first part of this paper briefly describes the state of the art and challenges of the real estate market. The second chapter highlight gaps and future challenges in design practice, and in the third chapter, it introduces the method. To conclude, in the last part, this concept is analyzed through a pilot project under development in our institution.

Keywords: Computational design, Multi-Agent-Based system, Robotic fabrication, Cyber-Physical Systems, Big Data, Internet of Things

INTRODUCTION

Industry 4.0 deals with a variety of emerging technologies, with a significant impact in information management and great potential to increase productivity in the manufacturing process. With the use of advanced computing, big data analysis, robotics, and digital manufacturing new horizons are envisioned, in which better and innovative processes have made the industry more efficient and able to meet demand with more personalized and sustainable products and services (Hemmerling, Cocchiarella 2017, p.40). From the combination of these technologies, among other things, Cyber-Physical Systems (CPS) and the Internet of Things (IoT) have an essential role in the efficient and digital fabrication of buildings in the near

future.

Concerning building efficiency, although not largely implemented, IoT is already a reality. Building automation, management systems, security, HVAC and lighting performance are some of the possible applications that, combined with CPS or digital twin can provide a platform to interpret data in real time and anticipate actions when necessary. However, the information gathered in a digital twin is not only an asset to optimize the project in itself and monitor the life cycle of a building. The information embedded is a valuable tool to analyze design decisions and fabrication processes, constituting a key element to assist and drive architects and engineers in a future open network (IoT + big data analytics).

A Multi-Agent Based System (MABS) can be described as the interaction between individual agents to reproduce phenomena or system, simulating “n” possible outcomes. Each agent receives a specific task and assumes relevant attributes and constraints. Through these interactions, between agent to agent and agent to environment, the model pursues a global equilibrium. MABS often adopt a bottom-up schema where agents compete and negotiate considering local rules in a complex scenario (Gilbert 2008).

1. PROBLEM

By 2050, around 70% percent of humankind will live in urban areas [3]. It means that, in the next decades, the demand for houses in urban centers will only grow. Analyzing profitability indicators for the construction industry, noticed that, in the 90s, the sector reached its peak and, from there on, it staggered or even declined (Rifkin 2018).

Looking into the german context, and comparing the disbalance between demand, license to build and completed constructions annually [7], the lack of efficiency in the construction sector becomes even more evident. Nevertheless, the waste of human resources is not the only factor. The construction sector is also one of the most polluting on earth [4]. Traditional techniques can be characterized by:

Project phase:

- Long time in the design phase, since every project is designed as an unique product.
- During the process, any change in the budget or/and the concept causes delays, rework, and additional costs.

Construction phase:

- Waste of resources by manufacturing on site (uncontrolled environment).
- Constant rework caused by unforeseen issues (delay).
- Hostile work environment (many accidents at work).

- Long periods of construction on site (higher labor costs).

Additionally, the regulations regarding work protection, as well as environmental protection, are getting more restricted every day. Consequently, the construction sector urgently needs to find new solutions to reduce its carbon footprint and increase its productivity.

To overcome these issues, we have been witnessing the progressive implementation of Building Information Modeling (BIM) in the industry. The American Committee of the National Information Model Standard Project defines BIM as “a digital representation of physical and functional characteristics of a facility... and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” [5]. And the U.S. Government General Services Administration defines BIM as “the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility” [6].

Although this growing implementation corresponds already to a significant advance to the design practice, the overall mentality throughout the industry persists the same. Object by object, part by part, designers create all information necessary to each project; that is, each project establishes a closed cycle in itself and the data extracted from them is used exclusively within its ecosystem.

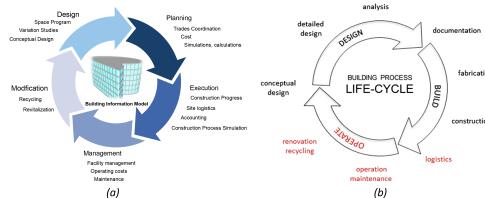
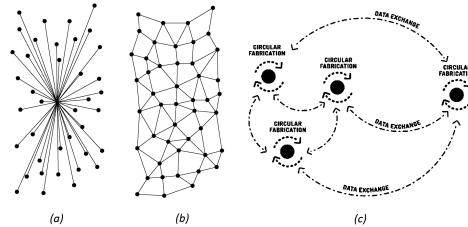


Figure 1
BIM Life-Cycle (a)
(Borrmann, König,
Koch and Beetz
2015, p.4) (b)
(Hemmerling,
Cocchiarella 2017,
p.40)

Comparing the model above with the organizational model suggested by the 4th industrial revolution (see

figures 2b and 2c) it is clear that we are still using the previous model of centralizing characteristics (see figure 2a), where the learning process acquired in each project is transferred to the next empirically, and not shared with the network.

Figure 2
Centralization vs
Distributed [1] [2]



2. HYPOTHESIS

At this point, we can conclude that it is not only necessary to have better software and better machines. The benefit comes when the model is capable of pulling and filtering information in a continuous optimization process, where the adaption occurs when agents learn from each other or change strategies as they gain experience.

Rather than an additive process, the interaction between agents should follow conditional and non-linear methods, the parts and the interaction between them must be studied simultaneously. According to Holland (2000, apud Baharlou and Menges 2013), "One procedural approach, is to organize such complexity through a computational framework that incorporates its elements, rules, and interactions... The proper generative computational framework includes both mechanisms to generate possibilities and constraints to limit the range of possibilities".

Therefore, this new model implies a questioning of traditional design methods. To open the possibilities for "n" design solutions, performance and shape must be intrinsically connected, and thus, domains and parameters should precede form.

It is also essential to acknowledge the need for a profound change in the concept of ownership embedded in each project. As mentioned earlier, the foundations of the digital revolution are anchored in

the way it manages and cross-references information. Moreover, the exponential improvements to gathering and filter information, aligned with new production techniques, allows the implementation of mass customization.

Applying these concepts to the construction sector, it is necessary to integrate the whole industry in a lateral network between architects, engineers, city planners, construction companies, and city governors. Thus, from a shared database, it will be possible to improve efficiency in the design and construction processes exponentially, constantly targeting the needs of society as well as optimizing marginal costs and waste of resources. In other words, to consolidate this framework, new communication channels between the smart Building reports (massive IoT implementation category), industry, city regulations, and society, are needed.

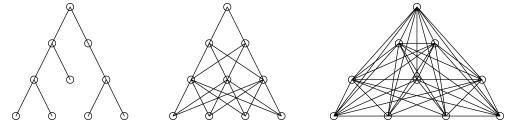


Figure 3
Cross-references
information
between parts and
whole

3. METHODOLOGY

3.1. Concept

Based in highly constrained construction techniques, materials, and fabrication, a methodology of parametric design arose from current research in the constructionLab at TH-OWL. A framework to build models that integrate: design; structural performance; fabrication files, and construction drawings.

The method is based in Multi-Agent Based Simulation (MABS), Cloud Computing, and the combination of big data analytics and IoT. According to Drogoul, Vanbergue, and Meurisse (2002), in MABS systems, the design process relies on the different roles involved (in our case: Architects, Engineers, and Computer Scientists), and its versatility supports the simulation of complex systems. Cloud computing, in turn, delivers the necessary on-demand computing resources to simulate the models in real-time and "by defining sets of higher level functions (e.g., an Appli-

cation Programming Interface (API) that provide interfaces to several expert-level BPS software..." (Nembrini, Samberger and Labelle 2014), it is possible to extend the framework capabilities.

Also, hosted in a web application, the system allows not only its extension but also the simultaneous work of several models, and the straight communication with a database, scalable and integrated, provides practical information in all design stages.

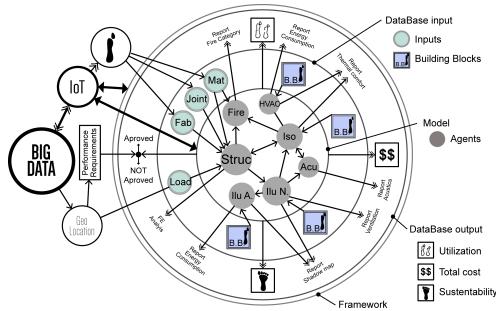


Figure 4
The framework architecture

3.2. Strategy

Parametric design, in theory, can compute the model of an entire building within a cell, originating families. By varying the values (parameters) that influence the model, it creates a unique project (Beesley, Williamson and Woodbury 2006). With this strategy, the framework "presents the problem and solution of each pattern in such a way that it is possible to judge and modify it, without losing the essence that is central to it." (Alexander 1977)

As a result, the adoption of technology in the design process has surpassed literal descriptive formalist approaches, evolving into a bottom-up method that integrates with versatile analysis tools for structure, thermodynamics, light, and acoustics, and evaluates the behavior of the system in interaction with the simulated environment (Menges 2008, p.196).

Furthermore, using "programming language, instead of drawing, it also matches the nature of the nonlinear design process made of refinements where each step compromises the project as a whole" (Ox-

man 2006, apud Labelle, Nembrini, Huang 2010). From this local and global intercommunication, two hierarchical layers work in a feedback loop:

The top layer provides a local domain of solutions for each agent, assisting designers to make informed choices. "At this layer, the aim is not necessary to get the best-fitted solution, but to do a probe in the surroundings of the bench-marked ones to explore qualities that when put together would then suggest architectural relations that needed to be best evaluated from a designer perspective" (Mena 2018).

And the bottom layer automates agents, highly dependent on performance behaviors. According to its data structure (internal mechanisms and constraints), and from the first design manipulation, these agents interact between each other, targeting an equilibrium in a global domain and consequently, narrow down their initial local domain.

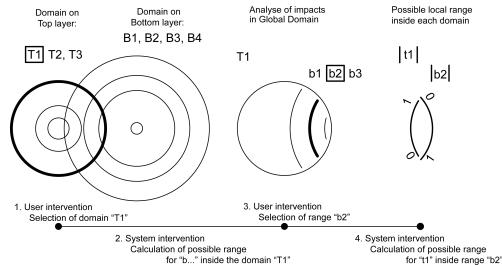


Figure 5
Formal representation of the simulation between Top and Bottom Layers (Agents "T" and "B")

As more frameworks are developed in the network, the range of typologies and construction systems available to designers increases. Nevertheless, protocols are needed and should cover three main points:

1. Information security - although it works within an open network, the information generated must be provided anonymously. Blockchain technology suggests the use of a decentralized database that combined with highly secure cryptography, becomes - in theory -, one of the safest solutions (Mougayar 2016).
2. Standardization of metric units of measurement (physical and temporal), providing reli-

able and comparable indicators.

3. Standardization of modeling technology. In this regard, IFC proves to be the most appropriate tool to be used [5].

Figure 6
Multiobjective
Optimization

3.3. Design Method:

First, it is crucial to formulate the problem (objective functions), specifying intentions and boundary conditions. Drogoul, Vanbergue, and Meurisse (2002) define it as the Target Model, and call the experts in this phase as “Thematically”. In this phase, the characteristics to be taken into consideration are: Typology, construction technique, fabrication methods, materials, local resources, and even cultural aspects.

Once having all agents denominated, it is necessary to turn from macro towards micro decisions elucidating individual constraints (local domain) and relations between building blocks (global domain). According to Menges (2008, p.196), “the underlying logic of computation strongly suggests such an alternative, in which the geometric rigor and simulation capability of computational modeling can be deployed to integrate manufacturing constraints, assembly logic, and material characteristics in the definition of material and construction systems.”

Finally, having the Domain Model as a guideline, the computational modeling of the agents begins. Starting from free-hand sketches, “designers write shape-describing code, abstractly creating and modifying objects through geometrical transformations”(Nembrini 2014). Here, to amplify the perception of system behavior, it is prudent to use not only parametric tools and 3d visualization, but also physical prototypes.

The aim goal at this phase is to translate the Domain Model in a Design Model that consists of a parametric model to be eventually implemented or optimized by a computer scientist (See figure 9).

As each agent will be responsible for different tasks in a complex and interdependent system such as the components of a building, the optimization process (minimization/maximization) becomes difficult or even impossible (Cagan, Grossmann and

Hooker 1997). Therefore, defining the hierarchy and the optimization strategy implemented in the negotiation between agents should also consider feasible region solutions.

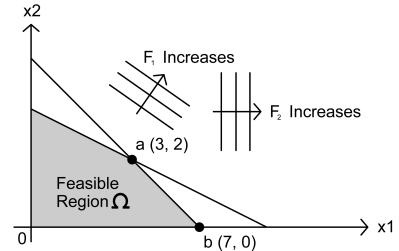
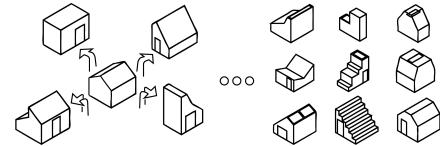


Figure 7
Interface:
Hypothetical array
of solutions

4. CASE STUDY

4.1. Interface



Although not fully implemented, the modeling interface will be initialized in the shape of a “primitive house”; then, using drag and drop commands, the designer can manipulate the envelope as he or she wishes. At this stage, no internal divisions and intermediary supports are possible, which limits the total size of the house. Additionally, the opening’s building blocks (doors and windows) are fixed, requesting (like other agents) further development. Regarding the cladding, as a variety of wall assemblies are under investigation, the system will become resilient for different climates. Insulation, rainscreens, heating systems, and shading devices could all be incorporated into the system and regulated through the thermodynamics, light, and acoustics agents.

The diagram below highlights the agents integrated into the current study, so far. Next, we disclose its application and results.

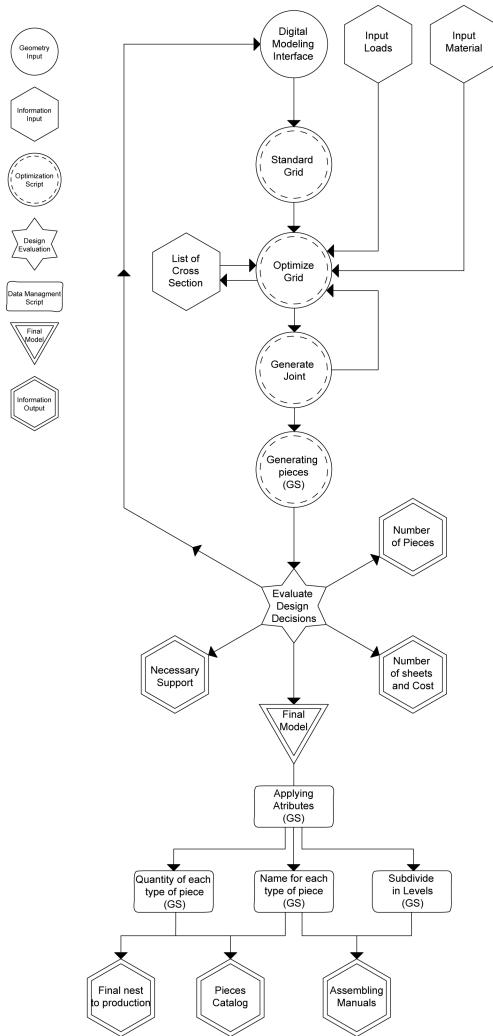


Figure 8
Diagram of structural agent procedures

ing into account that the majority of CNCs available in the market have only three axes, we decide to restrict the design solutions by using only manufacturing strategies feasible for this type of machine. Following the same principle, wood panels were adopted as a structural material. Besides being renewable and recyclable, they are easily found throughout the territory, which allows the manufacturing of the pieces near the construction area, promoting the local market and reducing transportation costs.



Figure 9
Big data analytics to assist design decisions

Finally, the research group defines that the assembly process should occur without the need for any machines or tools, and the solution should contemplate the possibility to assemble and disassemble the house several times.

4.3. Domain Model

At this level, examining the building's fundamental components, the central issues which underlie the study became clear, and from the essential element responsible for connecting the parts (the joint), the cardinal rules that drive the structural generative system were formulated.

By limiting horizontal and vertical orientations, complex angular connections and extra fasteners are eliminated. Despite having no diagonal members, the vertical parts are offset in each layer, providing lateral bracing that resists shear forces.

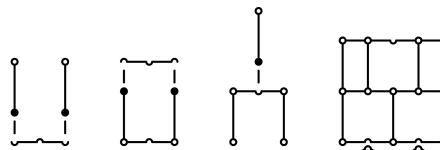


Figure 10
Assembly steps: cardinal rules

4.2. Target Model

Considering the local tradition in wood construction, the growth of human flow and the lack of affordable dwellings in Germany, the study case presented in this paper targets tiny houses as typology. Next, tak-

Figure 11
From the
fabrication to the
assembly

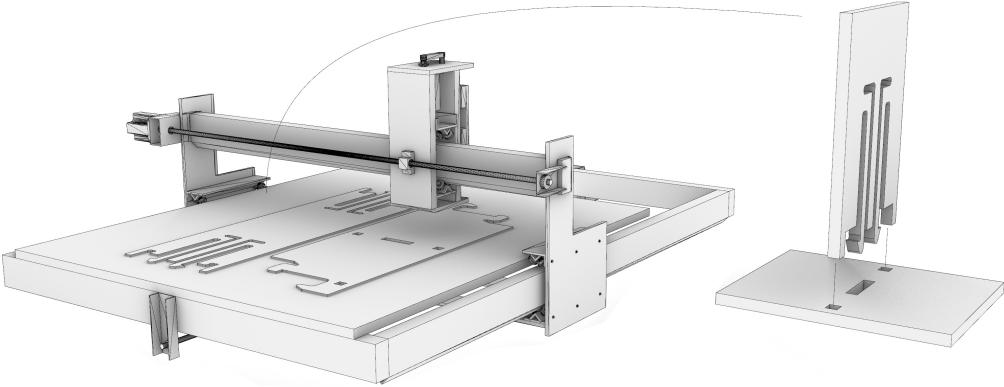
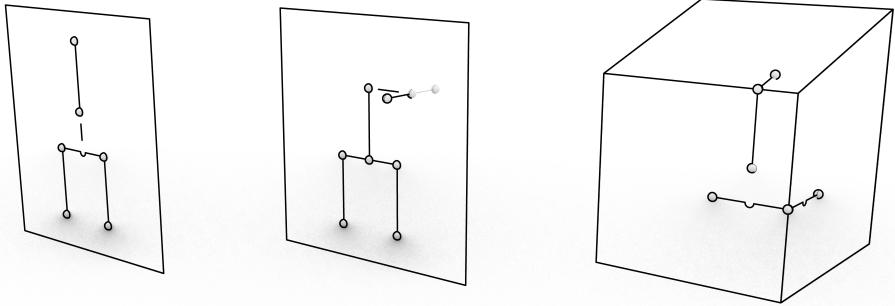


Figure 12
Main joint,
secondary
connection and
transition between
planes





To facilitate handling the parts during the construction, the length of elements is limited. Vertical elements vary from 0.5 to 1.5 meters, and horizontal members can grow up to 2.0 meters. As a result, the loads acting on the structure are transferred through a series of small-scale framing layers.

The Joint: The idea of the cutting operations was to perform every cut in the XY plane, limiting the milling to 90° degrees and allowing engravements only in the surface of the plates. Horizontal beams receive pre-cut slots that locate the vertical members, eliminating the need for any guesswork or imprecise on-site measuring. Both ends of the vertical columns are milled with a clipping mechanism that slides into the horizontal member and locks securely into place.

4.5. Design Model

Assembly Procedure: After the initial prototypes, we began the investigation of the assembly movements and sequences. To avoid collisions and make the transition between planes, a secondary connection was included. Unlike the main joint, where the assembly vector follows the plane, in the secondary connection the vector is perpendicular to it, so the chronological order of assembly must be respected. Furthermore, the elements that touch neighboring planes, whether vertical, horizontal or inclined, function as transitional elements between planes, incorporating 3-nodes instead of 2.

Optimization: The finite elements that constitute the structure of each plane have an original subdivision of one by one meter. As geometric changes are made or load parameters are applied, the structural agent recalculates geometry dependent loads, deformation, and stress in each finite element and node. Next, an optimality criteria approach finds the solution. Using the pre-dimensioned clip, the agent can include or eliminate members, increasing or decreasing the spacing between vertical and horizontal parts to reduce the stress at the critical node until it matches with the joint's capacity.

Like the grid, the cross-section is initialized with standard dimensions, and in case of no solution

Figure 13
Photographic record of the assembly.

during the finite element optimization method, the structural agents request the next cross-section in a sorted list (see figure 15a).

Considering that the agent seeks to maximize structural stiffness, the spacing between the parts can result in a very dense mesh, which would lead to an excessive amount of parts and waste of material. To prevent this situation, the agent responsible for the rationalization of manufacturing and the agent responsible for calculating the overall cost request a new simulation. Using the next cross-section in line the system calculates a distinct, more spaced grid, and the agents compare both solutions using a conditional operation as follows:

pseudo code

```

sortList_cS = [n1, n2, n3, n4, n*]
cS = sortList_cS[n1]
#calculating material volume
vol1_mat
vol2_mat
vol*_mat
...
while sortList_cS.index(cS) <= len(
↳ sortList_cS):
    if (vol1_mat > vol2_mat):
        vol1_mat = vol2_mat
        vol2_mat = vol*_mat

    elif (vol1_mat < vol2_mat):
        return vol1_mat
    else:
        print ("Consider changes in
↳ the design")
        return vol*_mat

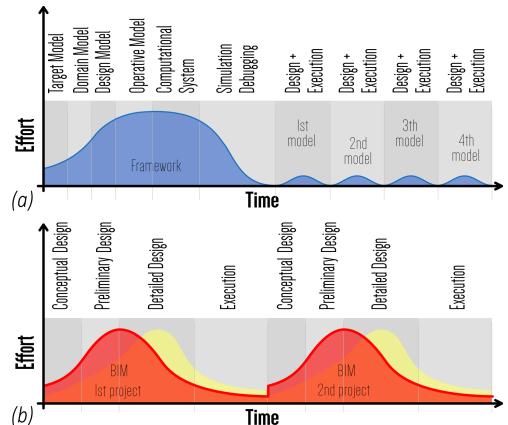
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Outcome.: After a successful simulation, the result is a collection of documents, including (see figure 15b):

1. Cyber-Physical System that, on the one hand, monitors the life cycle of the building, and, on the other, sends information to the framework agents.
2. CAD file containing all parts of the model properly labeled with their assembly names and locations.

3. G-CODE and nested file with such pieces organized through an algorithm that distributes the parts in clusters of useful dimensions for cutting.
4. Technical drawings, showing the construction procedures and chronological order of assembly.
5. Spreadsheets including a discrete list of parts; the specifications and amount of material; unitary and global costs.
6. Simulation reports coming from the analysis tools for structure, and later on, thermodynamics, light, and acoustics.

Figure 14
Function Effort/
Time

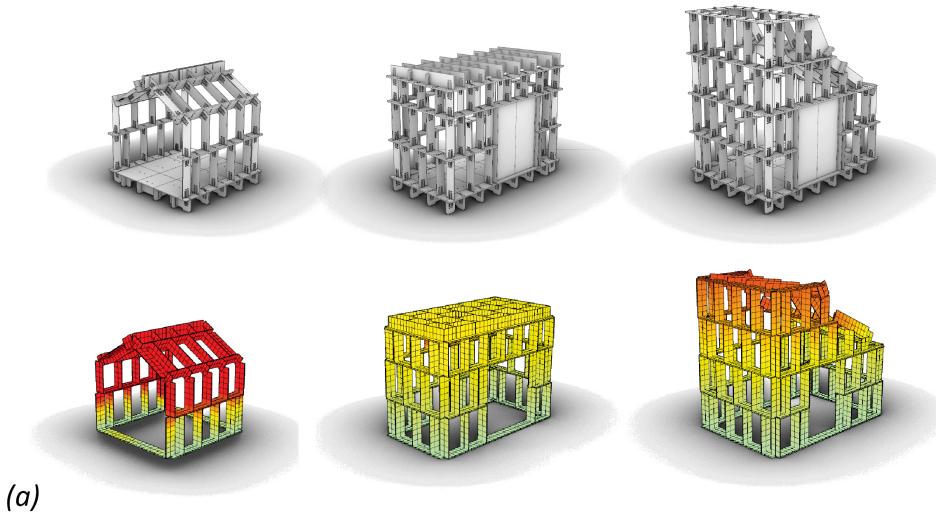


5. CONCLUSIONS

This paper has presented a novel design method where the automation of production is embedded in optimization procedures and parametric design works with design assistance tools supported by data mining. The implications of this method are demonstrated through a case study. The analysis and tests prove consistency between virtual simulations, fabrication, and physical model. Also, it shows a rationalization of material resource and structural architecture.

Taking the agent responsible for the structure

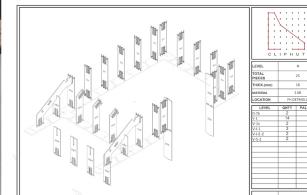
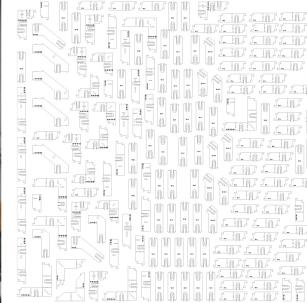
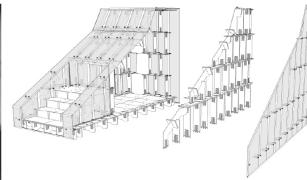
Figure 15
 (a) FE Analysis (b)
 Outcome



(a)



(b)



as a parameter, once the application was finished the function effort/time to generate a new model will stay almost flat (see figure 14a). Overlapping it with the popular graphic that compares BIM and traditional methods (see figure 14b), we can theorize the advantages of using such a framework within the scope of mass customization.

It is known that there are many plugins and tools at disposal, but no initiatives to formalize a method and a semantic. Understanding the difficulties in traditional processes is the way to locate the gaps during the design and construction processes. Acting in this way, not only relevance is attributed to the use of the method, but it also opens spaces for an interdisciplinary field that can contribute to close gaps between designers, society, and industry.

Although the research is still in its early stages, which implies the combination of many agents to have a fully automated framework, the results achieved so far show the guidelines for future investigations into the topic. Some of the consequences of this implementation may lead in a different direction, further expanding our perception of industry 4.0.

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