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Modular Robotic Prefabrication of Discrete Aggregations Driven by BIM and Computational Design

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Abstract

Discrete architecture is recognized as a computational design approach which uses computation to generate algorithmically combinable aggregations. It is therefore a promising innovation for increasing design process productivity through the adaptability of the aggregations it generates. In the built environment, discrete design is usually identified with the modular method. It is a construction process based on the aggregation of different modules assembled according to well-defined connections to ensure the building's integrity and functionality. It involves off-site manufacturing, and hence a controlled environment ensuring more predictability over weathering and change. But like in conventional construction practices, the fragmentation of modular construction processes hinders its productivity. As a result, this construction approach requires adequate technologies and communication tools to improve collaboration and productivity. This paper aims to address these requirements by adopting a BIM-driven computational approach to design processes and a robotic approach to prefabrication processes. It proposes a modular construction framework for design and production, and presents the results through a study adopting BIM-driven discrete design and robotic manufacturing.

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1. Introduction

In research, off-site manufacturing is presented as offering the potential to significantly improve the construction industry's performance and address many of its challenges [1]. Through volumetric modular design, this method of construction saves both time and money and develops affordable and efficient projects. In fact, a modular building can take on the characteristics of any architectural style if the factory manufacturing conditions are met [2]. This balance between constraints and design strategy that can be found using a specific computational design method called discrete architecture. The term "discrete" represents a notion that refers to individuality and separation. Opposite from this is the notion of continuity, based on unity and uniformity [3]. Thus, from a design point of view, this term defines the

change of the design strategy from a continuous architecture to a modular architecture. According to Tessmann and Rossi [4], discrete design involves modeling an aggregation of modules with reversible connections. These connections will then drive the aggregations defined according to the rules established by the designer. Therefore, these aggregations can be assembled, disassembled and reconfigured during their life-cycle. This concept could facilitate the design phase of modular projects, as this project phase is considered one of the major inhibitors to the adoption of off-site fabrication in construction [5]. Furthermore, by providing a wide range of digitally trackable iterations, this approach could be enabled by BIM tools through their ability to provide parametric design and planning functions. BIM frames this as a holistic construction management approach that covers the entire life-cycle of a construction project. This includes modeling, construction planning, cost estimating and post-construction facility management. The main characteristic of a BIM model is that it contains not only geometric information, but also material, resource, equipment, and fabrication data. Therefore, BIM-driven discrete design holds the potential to improve productivity throughout the building lifecycle, from design to operations and maintenance. It offers a promising alternative to modular robotic fabrication of complex shapes, and hence, the possibility to conceive ‘unthinkable architecture’ [6].

Automation of manufacturing processes using industrial robots has made its proofs in the automotive industry and is increasingly proving its potential application to construction. According to various studies, robotic manufacturing has been shown to be economically and environmentally efficient compared to conventionally built projects [7]. This manufacturing method is now technologically interoperable with construction design tools such as computational design and BIM tools. This marks a technological turning point, as it is now possible to link construction data in an embedded way to robotic arms for fabrication [8]. The present article addresses the conceptual combination of these different technological advances through a modular project realized adopting the developed framework. The off-site fabrication of the model is simulated in parallel in the same BIM environment with a reversible connection between the building data and the robotic manipulations. This development will facilitate technological interoperability between BIM and robotic manufacturing tools through algorithms-aided design, thus ensuring better management of information flow throughout the modular building life-cycle.

2. Proposed framework for modular robotic prefabrication of discrete aggregations driven by BIM and computational design

In the literature, the concurrent use of BIM and robotic manufacturing in modular construction lacks exploration [9]. This is primarily due to the parallel evolution of both the robotic and construction industries in terms of context, processes, tools, etc. [10]. This reality has motivated the research presented in this paper since such a lack of interoperability represents a significant barrier to automation in the construction industry. According to Poirier et al. [11], interoperability is defined as the ability to exchange information between two systems along technological, procedural, organizational, and contextual dimensions. This is a key aspect for the development of a fragmented construction industry since its economic impact is considerable [12].

The elements of the developed framework (Figure 1) are categorized according to the environment of production and management of information during the design and execution phases. The design phase is divided in two since it includes the architectural design and its simultaneous programming for robotic manufacturing. Such a task requires a computational design environment that involves programming in order to simultaneously develop the design and act as a post processor for robotic manufacturing [13]. With its integration in a BIM environment, it is possible to incorporate information in the various components of the modular building, facilitating their identification and their manufacturing [14]. BIM, in the collaborative context, also enables cloud-based collaboration to centralize project information and streamline its flow between the diverse stakeholders. It serves as an information continuity system linking design and production processes in order to minimize information loss [15]. Indeed, information accuracy is crucial in the context of robotic manufacturing. Through manipulations such as CNC milling, welding, or assembly, industrial robots must guarantee unequivocal accuracy to ensure the efficiency and safety of the manufacturing process. The end effector and the robot categories are also defined with computational design tools; they will allow to define the tool path and prepare the manufacturing script. This will allow the robotic arm in place to perform the

instructed commands and provide feedback on the completed manufacturing step, remaining time, system warnings, etc [16]. This framework is developed taking into consideration the technological interoperability of the tools used. It represents a specific development of the "tightly coupled" approach which is based on data exchange through the APIs of the software used [8]. Revit is taken as an example of BIM modeling software and this approach is performed using the Rhino.Inside.Revit plugin. Therefore, the script involving robotic manufacturing is developed in Rhinoceros whereas Grasshopper is used for the generation of discrete aggregations through plugins like Wasp or Monoceros.

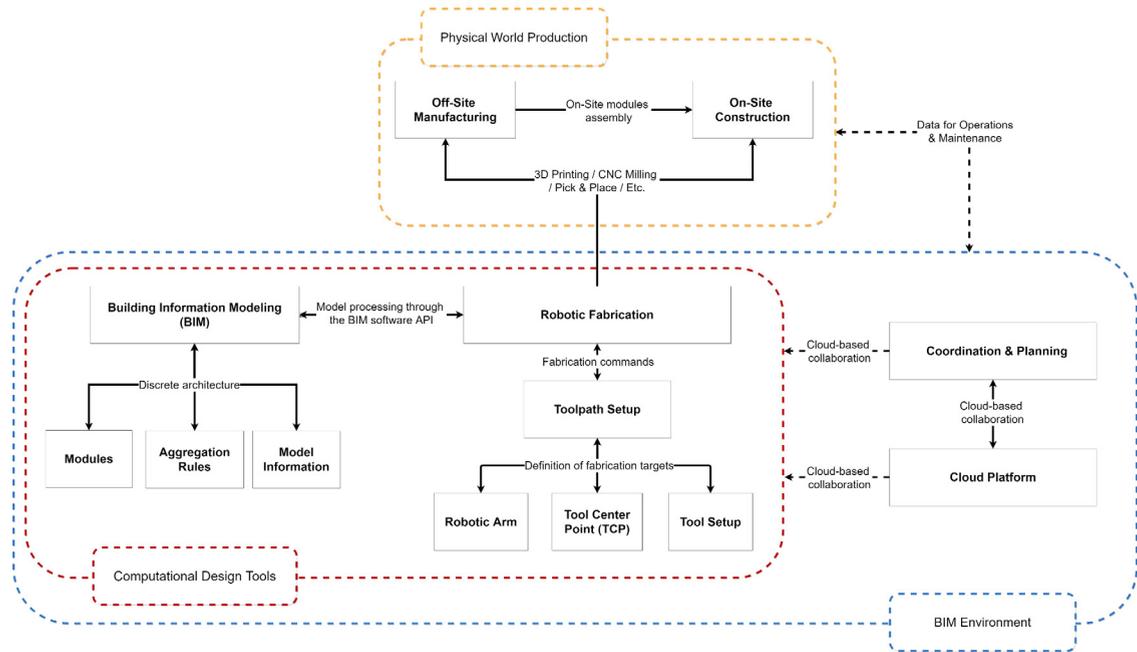


Fig. 1. Proposed framework for the use of discrete architecture and robotic manufacturing for modular construction driven by BIM and computational design

The study carried out with this framework is based on a project prepared for a modular design competition. It consists in the prefabrication of a modular residential building manufactured through subtractive wood fabrication and assembly manipulations. This building is designed to be built in Montreal and is based on a discrete aggregation of volumic modules. The modeling process is developed in Grasshopper with a BIM schema provided by Rhino.Inside.Revit, and the robotic manufacturing script is prepared in the same environment. BIM usage explained in this study is for multidisciplinary collaboration and data consistency in a construction project. Further in this article, we describe the framework in its design and operation phases, followed by a discussion of the results and concluding statements.

3. Discrete architecture driven by BIM and computational design for modular construction

The productivity enhancement offered by computational design has marked a "computational shift" in building design. It has revolutionized traditional design processes that were heavily based on manual drawing and calculation tasks. Indeed, design computation aims to explore, develop and implement digital models of design drawings (CAD), analysis (CAE) and manufacturing (CAM) into the design process [17]. It operates essentially with discrete data to enable working with complex shapes and complicated design tasks to redefine the entire architecture production chain [6]. In the design context, discrete aggregation tools were developed to open new design perspectives computationally based on adaptability and functionality [18]. Through Wasp, the aggregation of modules is conceived as reversible discrete assemblies [19]. Modules can be predefined hierarchically, which means that they can contain information

with several design levels. They are assembled either according to their possible connections, or to the aggregation rules set by the user. As shown in Figure 2, the modules used in this study are divided into two categories. First, there are core modules that can either be parallelepipedal or cubic and can include a kitchen, a living room and a work space. Second, there are two types of functional modules that are both cubic and constitute either a bedroom, a bathroom with a corridor, or another type of use. When configuring these modules, it is sufficient to define their aggregation in their volumetric form for the massing to be achieved. This design strategy is enhanced with BIM tools as each floor, column, beam and other building element is recognized and mapped according to their unique families. Such a use of BIM allows the acquisition of structured information for each module. This information will be valuable for the documentation of the project and for the management of the building information throughout its life-cycle.



Fig. 2. The hierarchy of selected external modules used for the project aggregation

According to Yuan et al. [15], a computational design methodology specific to modular construction could potentially improve the adoption of modularity in construction and optimize the design phase of projects. This article could constitute an interesting technological advancement in off-site construction. For example, using the modules already predefined in our context and a field-driven design technique [20], discrete architecture allows to generate different modular aggregation proposals (presented in Figure 3). This aggregation process, coupled with more structural and functional rules, has the potential to be an innovative technique for the modular massing design phase.

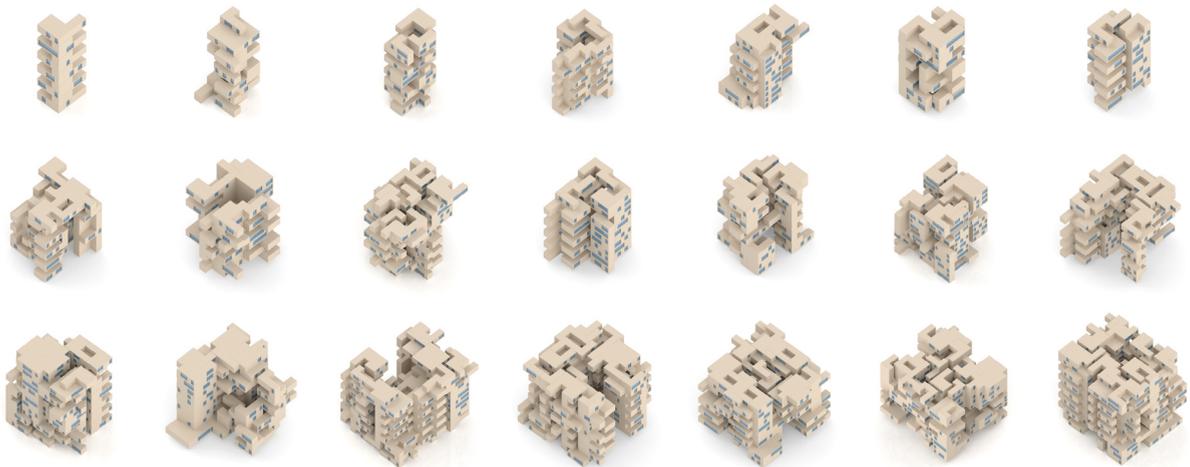


Fig. 3. Sample of preliminary iterations obtained during the massing design of the project

To ensure more control over these aggregations, we took into consideration the limitations of the above-mentioned competition and the contextual analysis of the construction site. The code regulations regarding modular construction were also taken into consideration to determine the number of floors and the size of the modules. To date, a completely modular construction in Quebec must not exceed five floors, and the modules to be transported must not exceed 15 m [21]. If exceeded, there is a penalty of being confronted with the use of exceptional convoys. The chosen site and the

regulations put in place constrain our modular building to exploit only three facades as it has a five-story building at its back. We therefore opted for a configuration that combines the complexity of aggregation with the simplicity of massing - proposing a solution with three non-uniform facades with cantilevered balconies. The plumbing aspect was a key consideration for this project. We respected the rule that one toilet must be superposed over another, and connected to a main cubic module of the apartment on the kitchen side. This is to minimize the dispersion of the piping through the floors of the building and between the compartments of each apartment. An analysis of exposure to solar radiation was also conducted on the building with the Ladybug tools. This allowed to determine the optimal width of the windows as well as the appropriate offset of their shades to minimize exposure with the help of the evolutionary algorithm of Galapagos. The solar radiation analysis also informed the design of a canopy, which will allow the use of the building's roof as a cafeteria. This canopy transforms into a staircase to connect the various sections of the building's roof and will be robotically manufactured. With this specific aggregation approach, the strategy is to maintain controlled connections guided by the functional needs of a building. The results of this design study are illustrated in Figure 4, which shows the final rendering of the different building facets, its various floor plans and its exposure to radiation.

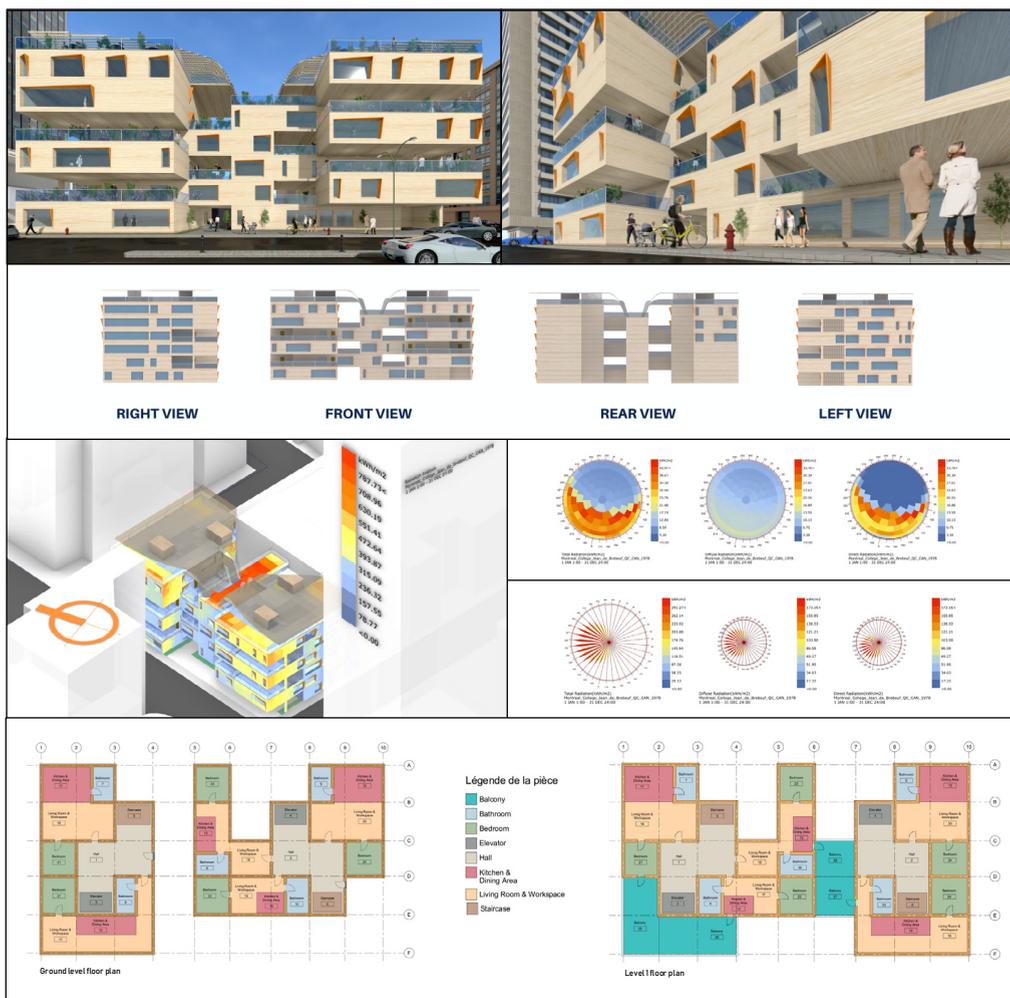


Fig. 4. Final rendering of the different facets of the building, analysis of its radiation exposure and illustration of its floor plans

Discrete architecture driven by BIM and computational design is a paradigm shift for the design phase in modular construction. Such a design process demonstrates the potential behind delivering detailed and documented designs in

the preliminary phases of projects with a reduced timeline. In fact, it results in an automated architectural design that is both efficient and mass produced [19]. It reallocates the distribution of efforts, placing more emphasis on functional design and reduces redundant processes like clash detection. With their interoperability, BIM and computational design eliminate the need for multiple entries of duplicate data and facilitates automation. This combinatory potential constitutes an innovative approach that incites rethinking the production chain of contemporary architecture, opening the door to mass customization in construction.

In the context of the developed framework (Figure 1), the result of the established modeling is simultaneously processed for off-site manufacturing. This step will be performed by robotic arm cells appropriately equipped to perform cutting and assembly operations. They will be technologically interoperable with the computational design tools used since they will be programmed in these same environments. In this way, computational design tools will act as post processors for industrial robots and will provide the link between design and robotic control. This will provide a parametric aspect to robotic programming and will lead to a modular robotic prefabrication of discrete aggregations driven by BIM and computational design.

4. Robotic manufacturing in discrete architecture driven by BIM and computational design

Construction automation, as defined by Cousineau and Miura [22], is the application of industrial automation principles to construction. This industrial automation is applicable to the construction of buildings, structures, and any other project related to the built environment. The use of this terminology is frequently linked to robotics. With nearly 1.5 million robotic arms installed in 2014, this technology has therefore become the largest commercial application of robotics, making it the most related to the automation term [17,23]. Unlike hard automation, robotics provide flexibility in manufacturing processes. It is a technology capable of adapting to design changes while ensuring accuracy, reliability and low operating costs [24]. According to Stumm et al. [14], off-site construction is one of the most promising methods for facilitating the adoption of robotic technologies for fabrication. With repetitive processes and a controlled environment, the incorporation of robotics for modular manufacturing represents a promising development. This automation perspective has the potential to save time and costs, provide a safer working environment, reduce waste, and improve project performances [25]. But this integration faces many challenges, particularly in terms of technological interoperability between design and robotic tools [5].

With the proposed framework (Figure 1), it is possible to employ robotic manufacturing tools natively in BIM environments. This type of system allows access to a tightly coupled approach where the information related to the building is centralized and the manufacturing process is integrated [8]. With a BIM-driven discrete design as a method, the information related to the established aggregation of modules is structured with visual programming tools. These tools will allow the control of the robotic arms available to perform the necessary operations, varying between 3D printing, CNC milling, and Pick-and-Place, among others. This allows the user to simultaneously adapt the robotic toolpath to geometry changes, and then simulate the results in a similar environment [26]. Once the design and programming process is set, the manufacturing commands are generated and then transferred to the robotic arms in real time. In this study, the robotic manufacturing process is integrated into a BIM environment to allow collaboration with other project stakeholders. This is done to demonstrate the effectiveness of the proposed framework for multidisciplinary collaboration within a discrete design process. The model and robotic commands coordination within the design team was done with a connected design platform named Speckle. It is a cloud-based open-source platform focused on the technological interoperability of different software. It provides real-time collaboration, data management, versioning and automation of various workflows in the AEC industry [27,28]. As shown in Figure 5, elements that will incorporate plumbing systems are manufactured by a robotic cell. These collaborative robots prepare the piping locations by CNC milling and then assemble them by automatic screwdrivers according to the Mechanical Electrical and Plumbing (MEP) model. Since both design and robotic programming are performed in the same environment, building blocks that will incorporate the plumbing components are directly nested separately in the digital robotic cell. This will allow the simulation of the manufacturing process and generate the fabrication commands for the robotic arm. A robotic program that will take into consideration the routing of the pipes according to the parameters (diameter, slope, category, etc.) included in the BIM model.

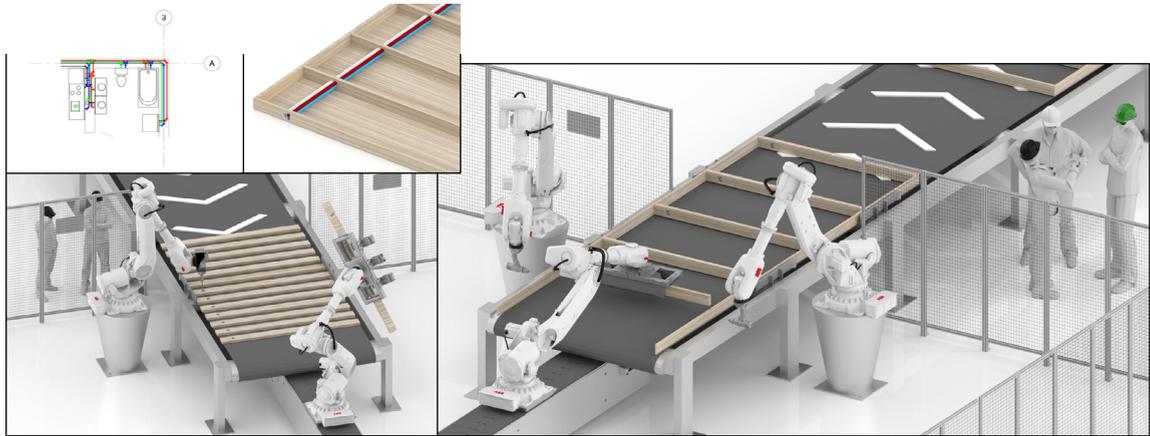


Fig. 5. Robotic manufacturing and assembly of the elements that will incorporate plumbing systems based on the BIM model

With the automation of modular manufacturing practices, a BIM-driven discrete design approach defines a feedback loop between manufacturing and design processes. It allows for the development of strategies for the manufacturing of adaptive and permutable components. These components can be assembled by robotic arms to form modules that will be transported to the construction site, where they will be assembled. This method of construction will allow the modules to be re-configured if the building serves a different function than the one initially planned [29]. Therefore, the notion of digital material intervenes since it links the material and digital world by offering a reversible and programmable manufacturing process [30]. This terminology could nevertheless be contested with the argument that materials are analogue, and cannot be recognized as being digital [31]. However, it could still be defended depending on the context in which it is used [19,29,32]. Figure 6 shows the canopy that is placed on the roof of the building. It is composed of wooden parts interlocked in a male-female system to ensure their stability. This canopy is multifunctional as it simultaneously provides sun protection for the cafeteria and a passageway between the different roof compartments. Finally, the parts to be manufactured are parametrically identified and optimally nested on the wooden plate to minimize manufacturing waste and to generate their documentation with BIM tools.

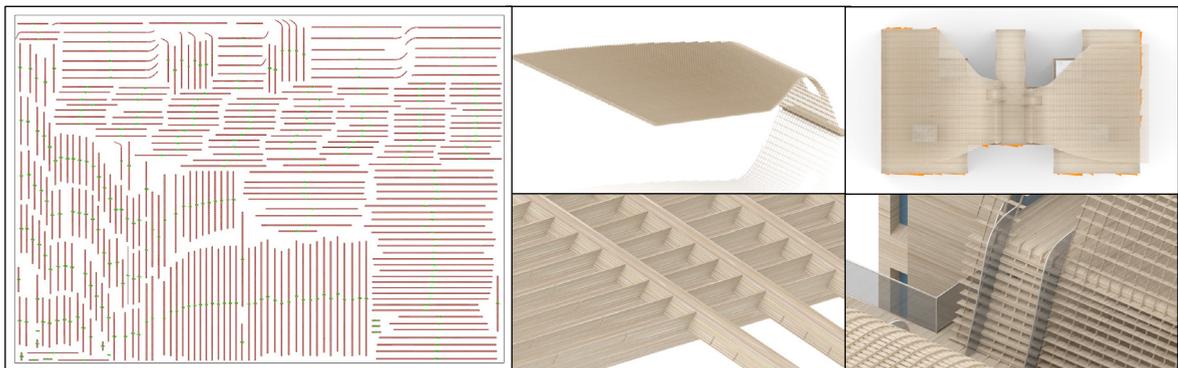


Fig. 6. Illustration of the canopy placed on the roof of the building (right) and nesting of its different components (left)

The use of BIM processes integrating computational design tools to design, collaborate and manufacture modules off-site, favors the development of a workflow centralizing information. This workflow allows the distribution of products with a reduced timeline and an enhanced quality. The interoperability between both robotic and BIM-driven discrete design tools provides instant adaptability of robotic toolpaths. In fact, by acting as a powerful design tool for adaptability to change through computing, robots can adapt to change. Initiated with the various categories of

computational design, this workflow will facilitate the fabrication of free-form project designs that have remained a considerable problem in conventional off-site fabrication [2]. Indeed, one of the main advantages of robotic arms compared to conventional digital manufacturing methods is their ability to operate with different degrees of freedom. Such an ability allows them to manufacture freeform and complex shapes, and to ensure operational flexibility through simple tool changes. Figure 7 illustrates the fabrication and assembly of the canopy components placed on the roof of the building (see Figure 6) using a robotic arm cell.

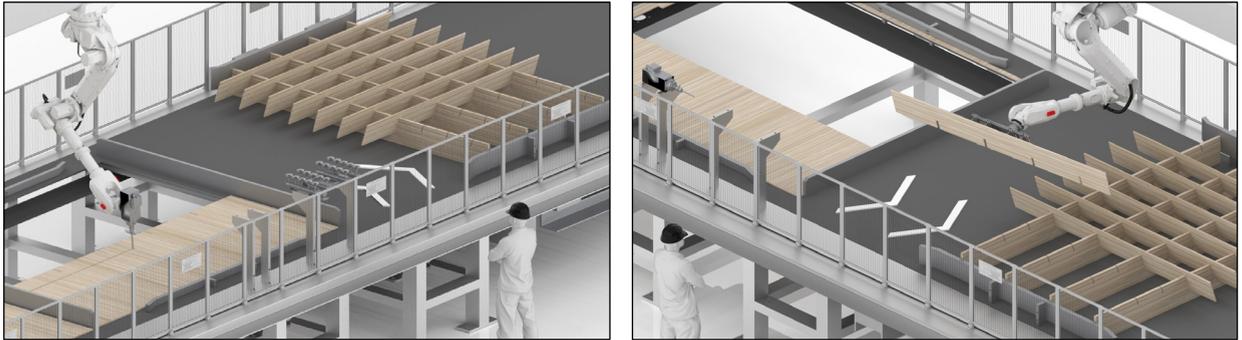


Fig. 7. Manufacturing and assembly of the canopy elements with a robotic arm cell equipped with a tool changer

5. Discussion

According to literature, the contribution of discrete architecture will have a significant impact on modular design [3,4,20,30,33]. A design phase that is not yet sufficiently mastered in industry with a cost that remains more expensive than conventional design [2,9]. However, discrete architecture used through computational design tools is insufficient on its own to produce modular buildings. The adoption of BIM, which is fundamentally contrary to the notion of discontinuity, has the potential to perform a key role in the adoption of these innovative technologies in construction [34]. This provides the opportunity to move from a classic discrete design to one that is conducive to manufacturing and assembly on the site. With the proposed framework (Figure 1), it is possible to ensure an automatic integrated building-related information flow during two main phases of the modular construction. Namely, from the automation of the design process through the BIM-driven discrete design, to the automation of its production phase with robotic arms. It is a process that has ensured the intrinsic programming of the design and its manufacturing, while ensuring its flexibility and adaptability to possible changes. Such a framework would facilitate the digital shift of the construction industry through the controlled environment it provides and the adaptability of the operations on which it is based. But the combination of these conceptualizations is not without flaws since it is costly in terms of data consumption. Discrete design associated with robotic manufacturing in the same environment consume a lot of computational power. This excessive consumption remains an aspect that generally causes a considerable loss of time during the design and programming process. Moreover, this process is based on discretization and separation. These notions influence the stakeholders since the other dimensions of interoperability in the context of the developed framework (i.e. organizational, procedural and contextual) are not as developed as the technological aspect. Collaboration on the cloud using data-intensive models is also not as effective as expected and requires further development. This proves that automation is highly dependent on information management and justifies the use of a BIM environment in the developed framework to drive technological innovations. Therefore, the combined use of discrete architecture algorithms and robotic arms in construction is a technological association that holds a promising future for modular construction in the AEC industry.

6. Conclusion

As defined by Retsin [3], discreteness in architecture is associated with the notion of individuality. It is not linked to continuity, but with what is separate from other components. Such fundamentals are contrary to the notions of BIM,

which relies on the continuity of processes to address the AEC industry's fragmentation [35]. By bringing these concepts together, this article demonstrates the use of computational design to develop modular structures with a BIM-driven discrete design approach. This is done to provide an automated manufacturing process, that will be carried out by robotic arms. This article proposes a framework that enables the use of these different concepts, apparently distinct in their foundations but deeply linked in their application within construction projects. This approach is illustrated by a modular residential project designed with discrete architecture concepts and robotically prefabricated offsite.

The results of this article clearly demonstrate that the developed framework offers the potential to have an accelerated design phase based on centralized information through a BIM model. It disrupts conventional design concepts by shifting the paradigm from a whole to an assembly of parts, and combines those parts into a whole that is driven by BIM. Therefore, it presents the intrinsic connection between continuity and discontinuity in the design processes of architecture and manufacturing. By adopting the tightly coupled approach of Anane [8], it is possible to gain access to the potential of BIM-driven computational design functionalities. These functionalities include discrete design, cloud collaboration, project documentation and robotic manufacturing. This provides the possibility to improve the construction industry's productivity and automate its processes on both the conceptual and real-world levels. It provides an innovative framework for modular manufacturing and contributes to its democratization among designers. Additionally, it opens the door to many research topics such as mass customization, robotic production cells for construction, and discrete automation. Although this approach is certainly not void of shortcomings, it is an innovative development contributing to the automation in construction processes.

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