Voxel-based Modular Architectural Design Strategy Toward Autonomous Architecture

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Rapid urbanization has led to resource shortages, necessitating sustainable approaches in the building industry. This research proposes a preliminary voxel-based modular-architectural design strategy (VMADS), focusing on reusable "H" blocks for component connections and construction. By integrating computational design and robotic fabrication, VMADS enhances precision and efficiency. The framework addresses discrete building theory, prefabrication, and autonomous architecture, emphasizing wood's anisotropic nature for structural integrity. Experimental results validated VMADS through digital simulations and physical tests, demonstrating its potential to create sustainable, reconfigurable structures and revolutionize construction practices.

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INTRODUCTION

In a process of rapid urbanization, increasing demands are being placed on social well-being and the construction of infrastructure. The process of urban growth and building construction consumes a large amount of energy, materials, water resources, and land resources, all while releasing greenhouse gases and carbon emissions, due to the increasing demand for material resources. These trends are causing a resource shortage in society, necessitating the promotion of a closed-loop material cycle to contribute to sustainability. In the building industry, designing products for reuse through modular systems and standardized components is critical. This research proposes a novel voxel-based modular-architectural design strategy (VMADS), focusing on component connections and construction for new architectural design and construction. Research has shown that the "H" block could be a suitable component for interlocking and combining into new structures, such as Furniture Installation and Architecture (FIA), resulting in a reproducible workflow for architects and designers in the industry.

In recent years, the architecture industry has increasingly adopted prefabrication methods as a sustainable alternative to traditional building techniques, offering significant environmental benefits (Cuadrado *et al*. 2016; Jiang *et al*. 2019; Hampson and Brandon 2004; Navaratnam *et al*. 2019). Prefabrication generally reduces resource and raw material waste, especially in the off-site assembly process, and it enhances safety for labor by reducing on-site burdens (Jaillon and Poon 2008; Jaillon *et al*. 2009). Cities are vital points within global sustainability policies, particularly highlighted in the 2030 Agenda (the UN

2030 Sustainable Development Goals), such as Goal 11 (sustainable cities and communities) and Goal 9 (industry, innovation, and infrastructure) (Kleinert and Horton 2016; Nitsenko *et al*. 2016; Koch and Ahmad 2018; Szopik-Depczynska *et al*. 2018; Yu *et al*. 2023). Both goals emphasize the importance of sustainable urban development and the architectural, engineering, and construction (AEC) industry as foundations for long-term economic growth.

Modular construction, particularly in low-rise buildings, is becoming more prevalent due to its advantages in speed, quality, and resource efficiency. Components such as building blocks are prefabricated off-site, transported, and assembled on-site, allowing for disassembly and reconfiguration, thus promoting material reuse and reducing waste (Jaillon and Poon 2014). This research introduces the preliminary voxel-based modular-architectural design strategy (VMADS), which integrates computational design and robotic fabrication to create new architectural possibilities. In this context, a voxel refers to a volumetric pixel, the smallest unit of a three-dimensional grid (Srihari 1981). VMADS proposes a flexible modular design using "H" block elements, enabling complex component packing in the voxel process and facilitating robotic construction and reconfiguration. The VMADS framework and autonomous architecture are explored during both the design and construction phases. Flexible digital technologies and computational methods are central to the design strategy, ensuring precise and efficient assembly during construction.

The primary modular components of the research include component design: flexible modular design of "H" block elements; a voxel-based component design system that allows for complex component packing in the voxel process; voxel-based modular design aggregation methodologies for pentomino connection and Soma cube connection; and construction technology, including robotic construction and other potential methods. The novel features of this research, including the "H" block and its applications in modular construction, are introduced early in the discussion to highlight the research's innovative contributions. The "H" block functions similarly to toy sets like "Legos," offering an interlocking mechanism for reusable building components. This paper's main method and workflow clarify the VMADS framework for architectural design and construction. The application of VMADS to various scale experiments, from furniture to installation, culminating in an architectural project that demonstrates the framework's real-world application.

EXPERIMENTAL

Method and Workflow

The goal of this work was to design a new component and apply it to the design of a prefabricated building. The workflow involves the Monoceros plugin (Subdigital, version 1.3.0.1, Bratislava, Slovakia) in Rhino, Grasshopper (Robert McNeel & Associates, version 7.34, Seattle, WA, USA), and the use of a UR3 robot (Universal Robots, UR3, Novi, USA) to simulate the assembly of the "H" blocks. The technological approach is divided into four parts: modular components design and prefabricated methods, component connection rules and methods, digital aggregation, and construction.

Modular components design and prefabricated methods: This step proposed a letter "H"-shaped component which, by virtue of its left-right and center-symmetry properties, allows the "H" components to be tiled in the two-dimensional plane and interlocked in three-dimensional space. The prefabrication method includes both the use of a mold and the deletion of the smallest cube on the entire voxelized cube, and the interlocking of multiple “H” components to form a block by copying, rotating, and translating.

Components connection rules and methods: The connection rules are first defined according to the thickness of the geometry of the connected components. When the thickness of the geometry is one unit, the non-edge and corner positions are considered as two-dimensional planar connections; when the thickness of the geometry is greater than one unit, the whole is considered as a connection inside three-dimensional space. The connection method is based on the pentomino and Soma cube, and follows the Soma cube’s “Red”, “Yellow”, and “Green” rules for three-dimensional connections (Fig. 1). The colors are defined as follows, “Red” for required connection, “Yellow” for possible connection, and “Green” for no connection. Additionally, the research explores practical ways to bond pieces of wood together during the formation of “H” blocks, such as using adhesives, screws, or mortise and tenon joints.

Digital aggregation: After defining the connection rules and methods, the VMADS framework is considered for the design and construction of furniture, architectural components, pavilions, and architectural scales. Geometries of different scales are voxelized and each voxel is replaced with a different “H” block, ensuring that they can be connected by interlocking. The research uses digital simulations to optimize the assembly process, ensuring that the “H” blocks fit together accurately and efficiently. This process also involves the use of algorithms to automatically generate and fill the required “H” blocks in each voxel, reducing manual effort and enhancing precision.

Construction: The prefabrication and transportation of the module using “H” blocks involve both off-site and on-site processes. Off-site prefabrication includes mold pressing, cutting, and forming the discrete “H” components, which are then transported from the factory to the construction site. On-site construction involves robotic fabrication based on digital simulation results, where robots handle the transportation and masonry process. This approach ensures accurate and efficient assembly, minimizing human labor and reducing construction time. The research proposes a fully automated construction site where robots can autonomously handle tasks, thus enhancing efficiency and safety.

Pentomino and Soma Cube Connection Method

Pentomino - 2D (n × n) connection

A pentomino is a polygon formed in the plane by connecting five squares of equal size edge to edge. There are twelve different free pentominoes when the combinations after rotation and reflection are not considered as different shapes. Each of the twelve pentominoes satisfies the Conway criterion; thus each can lay down a plane (Rhoads 2003).

Using different pentominoes allows the formation of close-packed planes and planes with different porosity in two dimensions (Fig. 1). These close-packed planes can exist in different lengths and widths (*e.g.*, 6 × 10, 5 × 12, 4 × 15, and 3 × 20) for the same area (in multiples of 60 units) (Fletcher 1965). These planes can provide good paradigms on several flat surfaces of architectural components, such as floors, ceilings, complete walls, and even table and chair surfaces. Another type of plane exists with different porosity, which increases the richness of the internal and external extent of the plane, such as a regular outer boundary with a staggered inner boundary and a regular inner boundary with a staggered outer boundary, which can also exist simultaneously. The porosity can be demonstrated in sunken or raised floors and steps, walls containing casement windows, and openings.

Soma cube - 3D (n × n × n) connection

The Soma cube is a three-dimensional puzzle with seven blocks, made up of 27 cubes. Six of the blocks are made up of four cubes and one block is made up of three cubes. These blocks can be assembled in 240 ways to form a cube (3 × 3 × 3), and they are used as building blocks that can be assembled to achieve the required target formation (Peter-Orth 1985). Unlike the standard cube (3 × 3 × 3) combination of cubes, these blocks can also be connected into multiple two-dimensional or three-dimensional structures (Fig. 1) to achieve richer forms such as sofa, bench, tower, or pyramid.

When considering corner connections to two-dimensional planes, this should be treated as a three-dimensional connection, as the depth and thickness factors cannot be ignored. Through rotating and flipping, it is possible to design three-dimensional shapes that start from the corners and lead to complete three-dimensional geometries, and gradually weaken the relationship of the boundaries of individual blocks and then move on to form- or function-driven geometries. With the “H” block, the boundaries of the cube itself are further reduced and the fragments made up of these discrete elements are combined into more continuous architectural components, making it possible to complete the design of the pavilion and the architecture. Additionally, two-dimensional connections and three-dimensional connections are allowed to exist simultaneously in the pavilion and in the voxels of single building components in larger scales to fill the gaps and fill overlays or overflows that often occur with Soma cube connections at the edge of the cube.

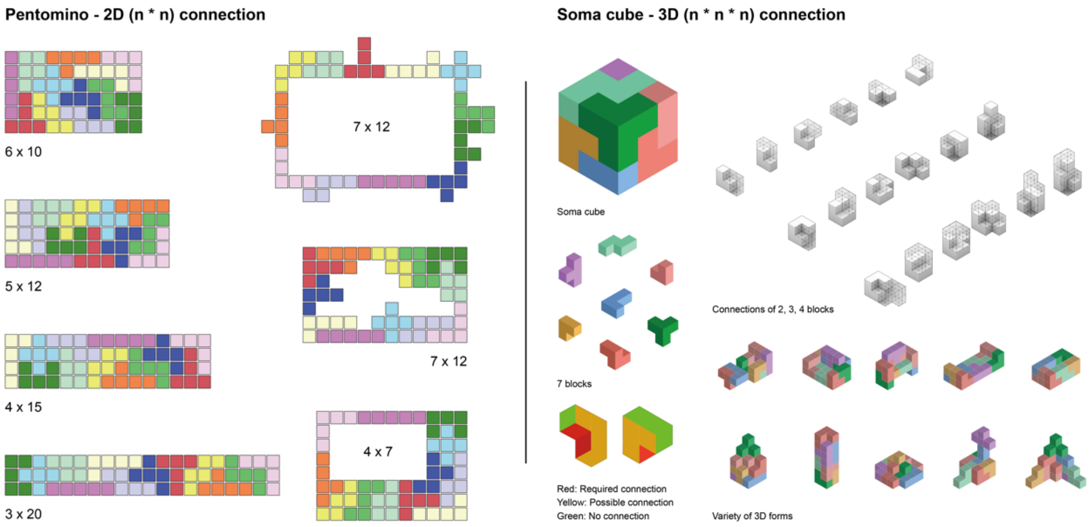

Fig. 1. Pentomino and Soma cube connection method

RESULTS AND DISCUSSION

Voxelized Components and Connecting to Blocks

“H” components to blocks

This paper presents a novel replicable discrete component, "H" component. By removing three adjacent smaller cubes in the middle of the top and bottom of the voxelized cube (3×3×3), a three-unit-thickness geometry (21 cubes) is obtained, and then a standard unit-thickness geometry (7 cubes) is obtained by cutting in three equal parts in the longitudinal direction, which is the base "H" component (Fig. 2). A single "H" component can also be seen as consisting of seven voxels, which is one method of production - the other is to use the mold directly for inversion, thus speeding up the production process and increasing the accuracy of the component. At the same time, the dimensions of each voxel in each "H" component will be defined for clearer follow-up research and design steps. Oversized voxel sizes, while better focused on large scale design and prefabrication, are almost impossible to apply to smaller scales. In contrast, the same is true for small voxel sizes. In this research, after several attempts, the size of a voxel was finally defined as 10 × 10 × 10 cm^3, so the boundary size of each base "H" component is 30 × 30 × 10 cm^3. At the same time, the existence of variants of the "H" form is allowed, that is, the width of each component is kept constant, and the number of voxels is increased from the vertical symmetry axis to the top and bottom symmetrically, thus adding two variants with a height of 50 and 70 cm, respectively.

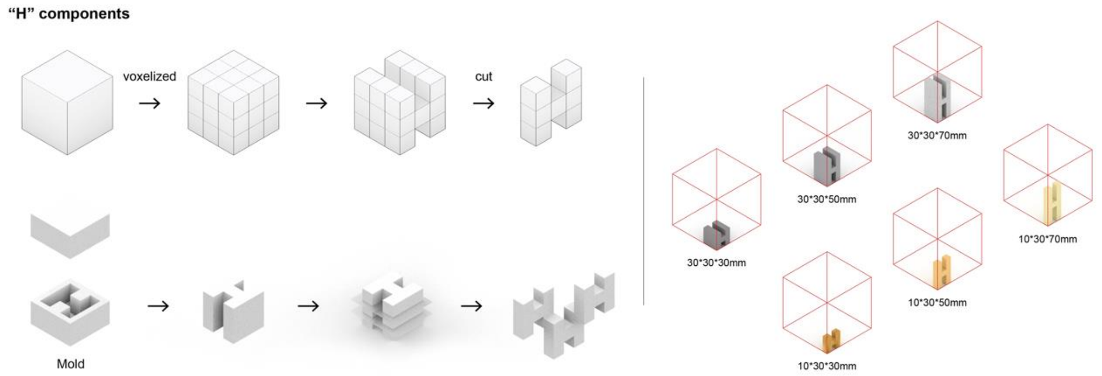

Fig. 2. "H" components

Due to the self-interlocking feature caused by its symmetry, the research next focused on the problem of connections with more than one "H" component. Without considering the material characteristics of the geometry, identical parts by rotating, flipping, and mirroring will not be counted, as well as ensuring that no void is allowed between all connected surfaces (similar to Soma cube's connection rules). In total, there are four different connection possibilities between two components of the same size to form a single "H" block, corresponding to close-packing (the first one), corner connection (the second and third ones), and extension (the fourth one). Attempts were made to connect the three components on this basis, and the complexity of the connections and stacking increased as the number increased.

Voxel connections using pentomino and Soma cube connection method

It seems meaningless to consider only the number of components connected, and after inspiration from pentomino, it is worthwhile to start with three sizes of "H" components on close-packed planes in two dimensions. The research explored several different layouts, each presenting a different degree of dispersion of the components in the plane. Figure 3A is an approximately completely close-packed proposal, and Fig. 3B and Fig. 3C are planes with one flat side of the inner and outer edges of the plane containing porosity, respectively. The case where both the inner and outer edges are irregular is not discussed here because of low practicality. Figure 3D shows a plane where the inner porosity is shifted and scaled. After the two-dimensional connections begin to take shape, connections in three dimensions starting from the edges and corners will be considered. The connection rules between the different fragments of the Soma cube are provided here as a reference and are applied to form some geometry whose features are familiar to the public. Seven geometry proposals (Figs. 3E to Fig. 3K) are implemented by defining the required, possible, and unconnected surfaces of the components surface after rotating, flipping, and mirroring in the xyz axis. Figures 3E through 3G are attempts to approximate the shape of chairs, benches, and tables. At the same time, designs on a larger scale are also proposed, such as Figs. 3H through 3K, for attempts at floor, ceiling, wall, and stair shapes.

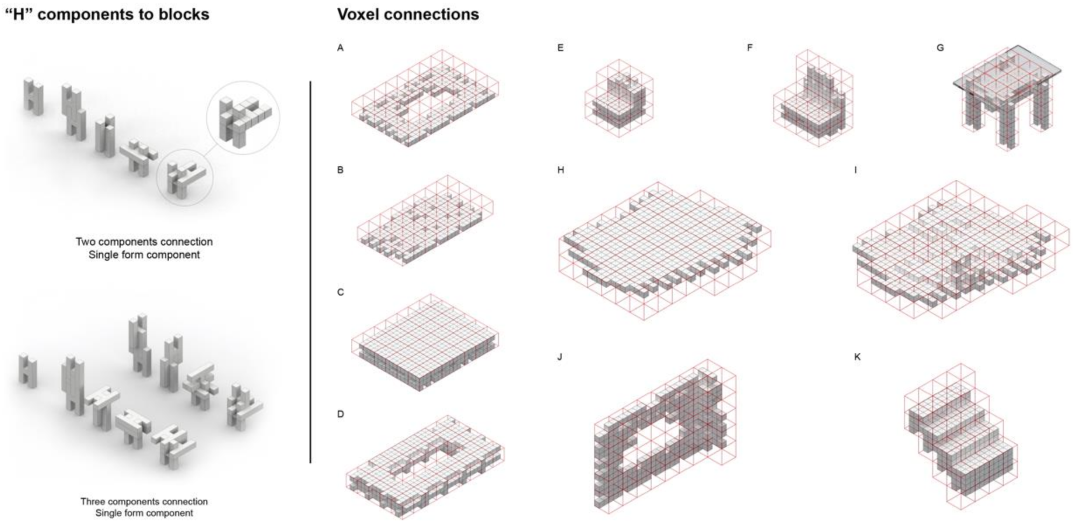

Fig. 3. “H” components to blocks, and Voxel connections using pentomino and Soma cube connection method

VMADS Applications in Incremental Scale

Furniture scale design

The VMADS framework proposed in this paper used “H” block substitution into different scales of voxelized geometry. It is essential to consider the material properties, particularly when designing figurative objects, as function cannot be discussed separately from material. In subsequent research, digital simulations will be performed using “H” blocks made of wood, one of the most widely used building materials, often oriented in the longitudinal direction due to the anisotropy of wood (Brémaud *et al*. 2011).

Wood’s anisotropic nature means that its mechanical properties, such as strength and stiffness, vary depending on the direction of the grain. This characteristic is crucial when designing and assembling “H” blocks, as it influences the overall structural integrity and performance of the assembled furniture. For example, wood is typically stronger and stiffer along the grain (longitudinal direction) compared to across the grain (radial and tangential directions). Understanding these directional properties ensures that the “H” blocks are designed and oriented to maximize their load-bearing capacity and durability.

The research started with the design of furniture scales for the interior of the building, including attempts at a wooden chair, sofa, and table, and included an assembly test - taking the example of a small “H” block stool made up of four components (Fig. 4). The test is performed by bending 5-mm-thick recycled corrugated cardboard to create a single "H" component and assembling four of them. The final completed assembly can bear the weight of an adult, but it also can be used to place some necessities and decorations.

Use "H" components to build a stool

1. Cutting corrugated cardboard
2. Stick cardboard
3. Fix cardboard
4. Waiting for the glue to dry

Fig. 4. Furniture scale design and the assembly test- take a stool as an example

Architectural components and the pavilion automated assembly design

As the design is extended to the scale of the building, it is necessary to consider the components that form a building, such as beams, columns, floors, ceilings, walls, stairs; these are the most basic architectural components (Fig. 5).

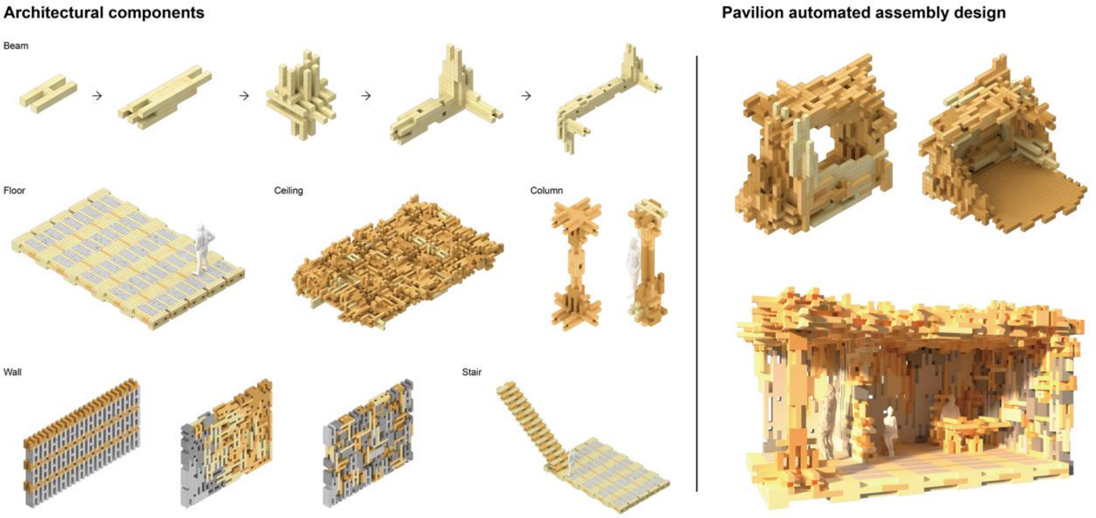

Fig. 5. Architectural components and the pavilion automated assembly design

The research first tried the process of joining into beams with some corner connections reserved at the end to connect with other architectural components when combined into larger volumes. Attempts at floor, ceiling, column, wall, and stairs were also started, and then the pavilion design based on this type of architectural component will also be proposed. However, as the volume increases, the manual replacement of “H” blocks will be more tedious. The research proposes a digital aggregation approach that uses algorithms to automatically fill the required “H” blocks in each voxel. Additionally, the furniture is arranged in the interior to measure the practicality of the space.

Architectural scale design proposal

The last part is the design attempt of architectural scale. In contrast to a pavilion, which often contains multiple spaces with different functions within a building, the research uses a two-floor residential space of 12 × 16 × 8 m^3 containing a living room, an activity room, a kitchen, a study, a master bedroom, and two secondary bedrooms. The design defines the floors on which they are located (Fig. 6).

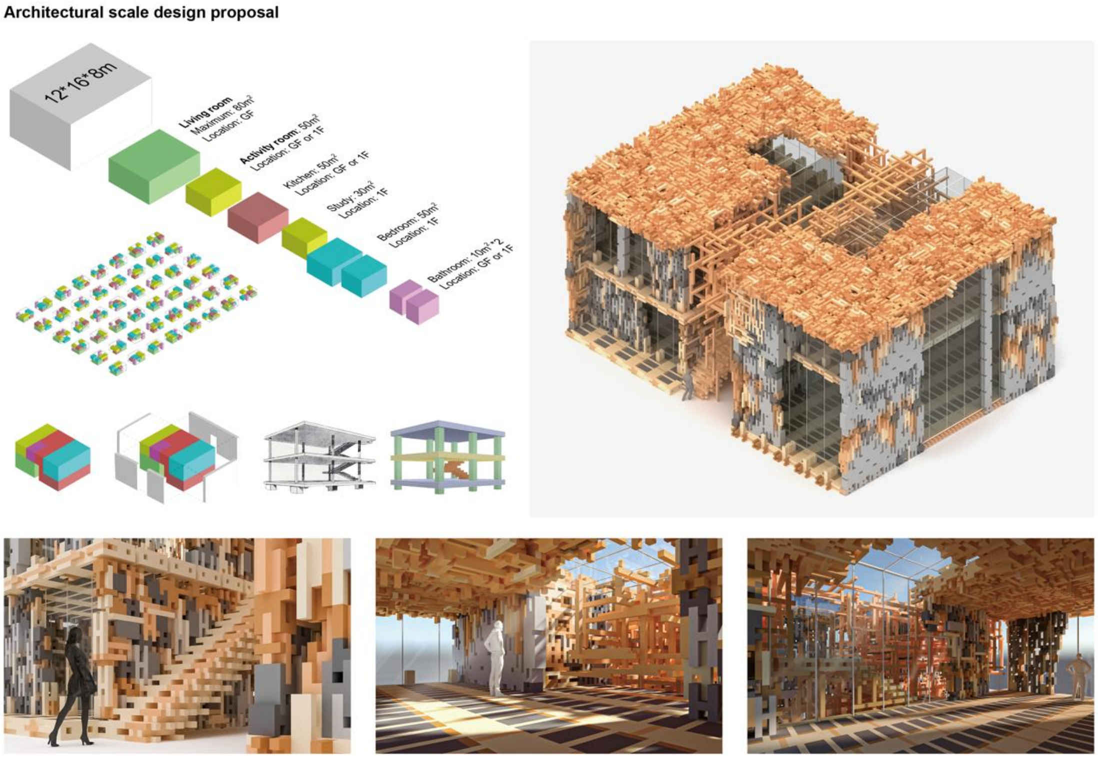

Fig. 6. Architectural scale design proposal

Step 1: Using algorithms to automatically generate 48 combinations of scenarios within the boundaries in which they are located and select the one that best fits the pedestrian flow lines for subsequent exploration.

Step 2: The geometry of the proposal is voxelized, with each voxel unit corresponding to the size of the voxel composed of a single "H" block, and the four vertical faces are mapped, that is, the complete wall and the wall containing the holes for windows and doors.

Step 3: To base the spatial arrangement and connections on the underlying floor structure, an open floor plan design is introduced here, Dom-Ino House by Le Corbusier (1914). Its architectural framework is completely independent of the plan, thus allowing freedom to design the interior configuration. In addition to walls, this step considers floors, columns, ceilings, and stairs as necessary components, which are discussed and refined.

Step 4: The "H" block is replaced inside the voxel by an optimized voxelized geometry. The addition of glass in the holes and wooden strips in the transitional areas between spaces as decoration enhances the water resistance and richness of the building.

Prefabrication and Automation Construction

With the gradual growth in the number of prefabricated buildings and maturing technology, as well as the onsite single-task automation, this research proposes a possibility to enhance the automation of construction (Fig. 7). The first part is the offsite prefabrication of the discrete "H" component, which includes the previously mentioned steps from mold pressing, cutting, and forming, and then transporting it from the factory to the site. The second part is onsite robotic fabrication, which uses robots in complex field environments to complete the process from transportation to masonry automated fabrication with constant attention.

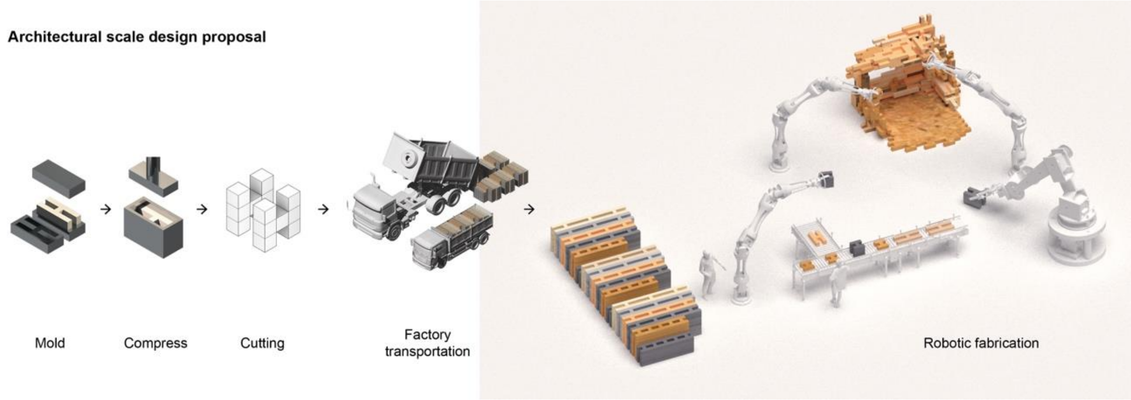

Fig. 7. Offsite prefabrication and onsite robotic fabrication

DISCUSSION

Wood Recycling in the Circular Economy

Wood is a bio-based material that is seen as a non-renewable resource due to its growing life cycle. Brick, brick-making method, and the entire process consumes land resources, labor costs, labor force, and time. Further, its mechanism is stable during the construction and demolition processes. With the support of the UN Sustainable Development Goals 11 and 12 (United Nations, 2023), reusing and recycling the material will reduce the waste of raw materials, improve environmental impacts, and respond to the Circular Economy (CE) for sustainable development.

VMADS (Voxel-based Modular-Architectural Design Strategy)

For component reconfiguration in architectural design and assembly, the component must be disassembled so that it can enter a new life cycle. The author has provided a computer-aided design and aggregation process through a programmable digital aggregation platform, which enhances the possibility of these components entering a new cycle. The VMADS project, the author's theory based on the Soma cube and pentomino logic, can be combined into a design platform, generated, and automated in the future. Furthermore, it should be more applicable in other projects in the step of structure generation and assessment method. Thus, the structure generation and optimization method should be considered together.

Robotic Construction and AR-assisted Assembly Methods

Automation in construction, and AR-assisted assembly make design and construction easier. Robotics, which is automation for complicated assembly projects, saves energy and replaces repetitive missions and labor force issues. This can help alleviate the scarce labor resources in society. In the future, a comprehensive workflow should be developed, focusing on reclamation systems for components and blocks (recording, classification) and architectural construction applications. Close relationships should be made among the materials, components, design, construction, and their related technologies, adapting to the real requirements of stakeholders, architects, and designers.

CONCLUSIONS

1. The research developed a flexible "H"-shaped interlocking component, summarizing a SOMA cube and prominent connecting system. Making a bench as an example, from voxelization to aggregation to assembly, this applied research collaborated with computer-aided and robotic technologies in the autonomous architecture and prefabrication method fields.
2. Prefabrication using "H" components demonstrates substantial environmental benefits, particularly through off-site assembly processes that minimize resource and raw material waste. This method also improves labor safety and reduces on-site construction burdens.
3. The VMADS (Voxel-based Modular-Architectural Design Strategy) framework significantly advances sustainable construction by integrating computational design and robotic fabrication, enhancing efficiency, reducing material waste, and improving construction accuracy and safety.
4. The incorporation of automated construction methods within the preliminary VMADS framework addresses labor shortages, streamlines construction processes, and supports sustainable development goals by promoting resilient infrastructure and innovative design strategies.

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