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Generation of space with Π-shape steel frame set and its optimization

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ABSTRACT

This paper presents a novel approach to the generation of steel frame spaces through multi-objective optimization techniques. Inspired by the modular structure of stapler pins, the proposed method uses a cluster of these pins as a standard model module. These modules can be interconnected in multiple orientations—horizontally, vertically, parallel, or crosswise—allowing for the creation of flexible, complex spatial structures. By harnessing the inherent strength of each pin, the model supports the formation of diverse spatial configurations while maintaining structural integrity. The optimization process employs a genetic algorithm to refine and enhance structural, functional, and cost-related parameters, facilitating the generation of adaptable architectural spaces. This generative approach not only explores new possibilities for architectural design but also provides a sustainable solution for the construction of dynamic, multi-functional spaces.

Keywords: genetic algorithm, multi-objective optimization

1. Introduction

The COVID-19 pandemic has caused significant global disruption, leading to loss of life, economic hardships, and a reconsideration of societal structures. The urgency of vaccine development has underscored the need for rapid, effective responses to global health crises. As part of this effort, minimizing direct human contact and optimizing economic recovery have become central challenges. During the pandemic, many people across the world lost their lives, and the need for innovative solutions to ensure public health and continuity in critical sectors, such as construction, became evident. These challenges have emphasized the necessity of adaptable and resilient architecture, particularly in building methods that minimize physical interaction and ensure safety during emergencies [1].

The pandemic has highlighted the need for architecture to adapt its construction methods, with an emphasis on reducing physical interaction and ensuring safety during emergencies. One promising solution is the use of prefabricated steel structures, which offer substantial advantages for multi-story buildings, making them especially relevant for future developments such as residential buildings, schools, office spaces, and industrial plants. These structures are lightweight, reducing both material costs and construction complexity. Additionally, they allow for shorter construction periods, facilitating faster deployment, and their flexible layouts enable adaptable and scalable designs, ensuring greater efficiency and responsiveness to changing needs [2][3].

The integration of parametric design methods, which leverage computational tools to create innovative architectural forms, has become increasingly important in the design and construction industry. Generative design, in particular, has gained attention for its ability to explore new forms and structures by setting multiple optimization objectives. Programs such as Octopus and Wallacei have been developed to facilitate these generative processes, enabling architects and engineers to design buildings more efficiently by integrating multi-objective optimization techniques [4][5]. These computational tools are invaluable in optimizing performance across various domains, such as structural integrity, function, and cost [6].

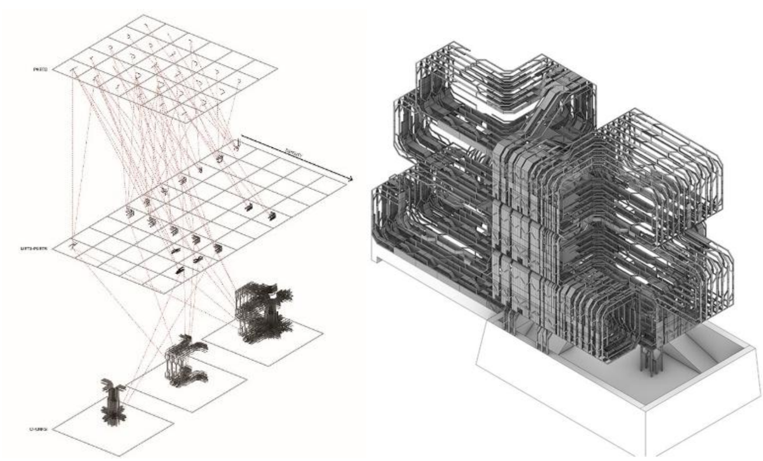
Multi-objective optimization involves defining a set of goals that span structural, functional, and cost-related objectives, which can be quantified and optimized using algorithms. In this study, the primary goals are structural optimization, focusing on minimizing structural displacement to enhance stability; functional optimization, aimed at creating flat, usable surfaces like seating areas to improve the functionality of spaces; and cost optimization, which seeks to reduce the length of rods used in constructing the frame, ultimately lowering material costs and increasing construction efficiency [7].

In the field of urban design, multi-objective optimization has also proven effective, particularly in the planning of emergency settlements and refugee camps. Architects have employed algorithmic approaches to optimize the placement of shelters and the distribution of resources. Key objectives in these designs include minimizing the number of shelters that are inaccessible, reducing the overlap between functional areas such as water, sanitation, and hygiene (WASH) points, and minimizing the length of constructed piping systems, all of which contribute to more efficient and sustainable settlements [8][9].

Urban vegetation design, similarly, integrates environmental data to optimize factors like radiation gain, daylighting, and pedestrian walkability. These interconnected design objectives aim to improve both aesthetic and environmental efficiency. Likewise, architectural designs using multi-objective optimization involve diverse goals, such as energy efficiency, cost, and the spatial layout of buildings. Form-finding for architectural spaces must consider the geometric properties of buildings and adjust based on design goals, ensuring that the final form is functional, sustainable, and cost-effective [10][11].

Modular design is an innovative approach gaining traction in construction, particularly for spaces that demand flexibility and adaptability. Modular units, such as steel frames, are easy to connect and rearrange, allowing the creation of diverse spaces. This method is especially popular in both residential and commercial buildings due to its ability to enable quick, cost-effective construction while offering flexible layouts. Although some experiments have explored modular designs without multi-objective optimization, their potential for creating dynamic, adaptable buildings is evident. For example, steel-frame modules for dwellings offer a promising solution, enabling spaces to easily alter their structure and function, both indoors and outdoors, thus allowing buildings to evolve over time to meet changing needs. This approach has significantly contributed to the development of more responsive and flexible architectural designs, as demonstrated by the workflow and model in Figure 1a [12][13].

In China, an artist created a model of the city of Chongqing using stapler pins (Figure 1b). The artist chose stapler pins because they are easy to connect, allowing for the construction of various architectural forms such as high-rise buildings, avenues, towers, and bridges. The ability to control the number and arrangement of stapler pins made it an ideal material for creating modular city models. This technique highlights the potential of modular design in urban planning and architecture [14]. Recent research has further emphasized the potential of modular construction as a flexible and efficient solution for urban design. Wang and Zhang (2021) discuss advances in modular construction that contribute to its flexibility and efficiency in urban design, offering insights into how modular systems can be optimized for both adaptability and sustainability [15].



a) Shogo Suzuki; Digital Metabolism. Disruptive Arhitectures

b) Chongqing city model with stapler pins

Figure 1. Experiments for module designs

The handmade model with stapler pins, as depicted in Figure 2, provides an interesting contrast to the parametric models optimized through multi-objective algorithms. This model, constructed manually, was created before the parametric model utilizing Wallacei for multi-objective optimization, which is why it doesn't align with the Pareto Front solutions shown in Figure 6. The model, though not optimized, demonstrates the simplicity and potential of modular design using stapler pins, which are easy to connect and rearrange. Building on this concept, experiments suggest that using a genetic algorithm in conjunction with Wallacei could refine this design, optimizing it based on various objectives, such as structural stability, functionality, and cost. By applying multi-objective optimization, it is possible to enhance the efficiency of such modular designs, allowing for more dynamic, adaptable spaces that evolve in response to changing needs.

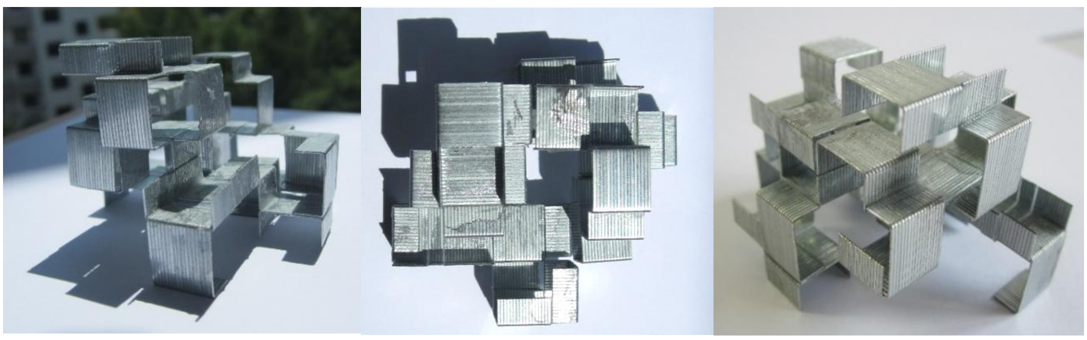


Figure 2. The handmade model with stapler pins

The images from Figure 2 are photos of a real model with stapler pins that followed the above experiments and were handmade. But this handmade model has been made before than the parameter model for multi-objective optimization, so it didn’t belong to the solutions of Pareto Front as Figure 6.

From some experiments above, we thought that we could have tried to generate the model with stapler pins which come from the genetic algorithm and optimize with Wallacei.

2. Method

The experiment described in the document focuses on the generation of a modular steel frame structure using genetic algorithms and multi-objective optimization. The idea is to create a flexible, adaptable design that can serve as a multi-story building for various uses, such as offices or dwellings. This is achieved through a modular approach, where individual units (represented by stapler pins) are joined based on predefined genetic encoding, creating a steel frame structure. The experiment aims to optimize structural aspects such as stability, cost, and functionality using a genetic algorithm.

The "genes" refer to different joint styles for connecting these modules, with 49 distinct configurations available, forming the "DNA" of the design. These genes allow the algorithm to explore various combinations of joint styles, which ultimately influence the overall structure's behavior and properties. The goal is to optimize multiple objectives, such as structural stability, functionality, and cost, through the Wallacei plugin in Grasshopper, a tool used for multi-objective optimization. The setup involves defining parameters for the stapler pin module and its joints, with 49 joint types encoded as genes. These genes govern the connection of modules and help in exploring different configurations of the structure. The number of genes chosen influences the total volume and complexity of the building. A small number of genes is preferable in initial experiments to avoid computational complexity.

In the optimization phase, the model is evaluated against multiple objectives, such as minimizing structural displacement, creating a functional floor plan, and reducing material costs. The Wallacei tool is employed to identify the most optimized solutions by balancing these goals and selecting the best options from a Pareto front. Figure 3 illustrates the various configurations of two stapler pins and their joint connections, which serve as the fundamental building blocks for the modular steel structure. These joint configurations are encoded as "genes," enabling diverse combinations of connections in the model. Table 1 further details the encoding numbers and genotypes for the different connection methods between two stapler pins, showing how each gene corresponds to a specific joint style used in the modular assembly.

The entire process demonstrates how modular steel frame structures can be generated and optimized using genetic algorithms and multi-objective optimization techniques. The experiment serves as a foundation for more complex architectural designs that can be adjusted to different spatial requirements and functional needs. The ultimate aim is to make construction processes more efficient, flexible, and adaptable for future urban developments, particularly in response to needs like emergency settlements or remote construction.

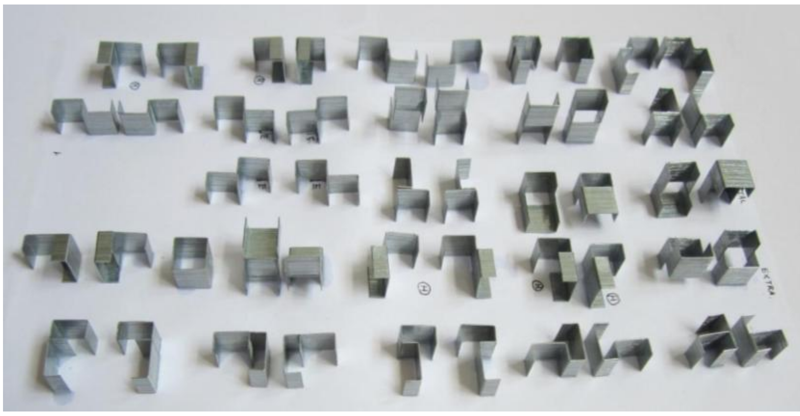
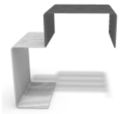
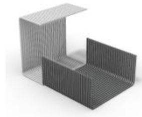
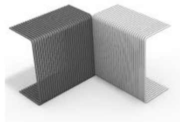
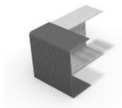
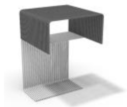
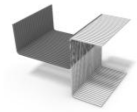
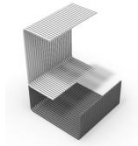
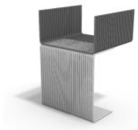
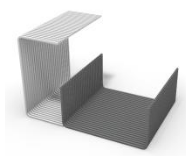


Figure 3. Models of two pins with their possible connections

Table 1. The encoding number and genotype for the connection method of two stapler pins

No	Encoding number of gene	Genotype	No	Encoding number of gene	Genotype	No	Encoding number of gene	Genotype
1	1		6	12		11	31	
2	2		7	16		12	35	
3	3		8	21		13	39	
4	6		9	25		14	46	
5	9		10	30		15	49	

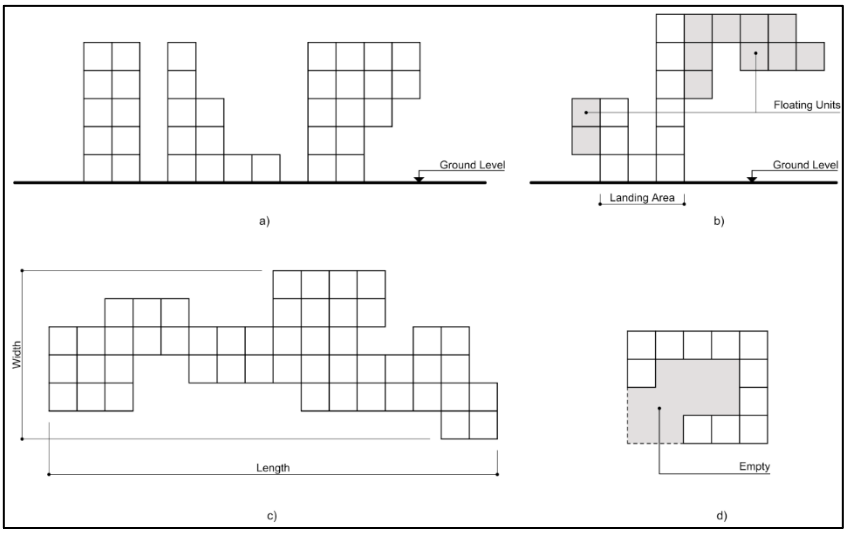


Figure 4. Some goals for multi objectives. a): the fewer upper units, the more stable the total units, and it sounds like an improper fraction and a proper one. b): this goal is for counting the floating units

In this study, multi-objective optimization was employed to evaluate the modular steel frame structure model against six specific goals, identified based on prior experimental trends. These goals include stability considerations, such as minimizing the number of upper units to enhance structural stability, managing floating units to prevent instability, and controlling the height and length of the structure to maintain balance and fit within the designated site. Stability goals also extend to the integrity of the structure, ensuring that all necessary components, like floors, ceilings, and walls, are in place, preventing wasted space and resources. Furthermore, the model addresses the reduction of empty spaces in floor plans, which can decrease architectural density and diminish the solidity of the building. Figure 4 illustrates these goals, where (a) emphasizes that fewer upper units contribute to greater stability, and (b) focuses on counting floating units. The Wallacei tool, integrated with Grasshopper plugins like Galapagos, was utilized to optimize these multi-objective goals. The tool's performance allows for the selection of the most optimized solutions, thus refining the model's structural design. This approach is particularly valuable for creating adaptable, modular spaces that meet both functional and structural requirements, paving the way for further research into space connectivity, structural joints, and building functions.

3. Result and Discussion

In this study, the genes were generated using Galapagos, a plugin for Grasshopper, and utilized to form a complete model consisting of interconnected units. The genes were initially random, enabling the framing of the problem as one aimed at optimizing solutions for multiple objectives. These genes acted as the foundation for generating the structure's mass, as illustrated in Figure 5, which depicts models with various stapler pin configurations.

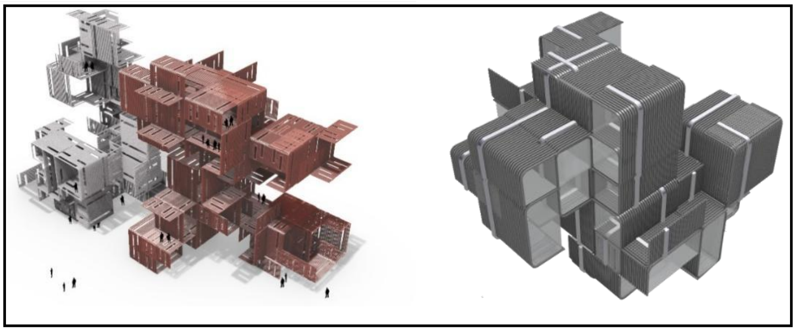
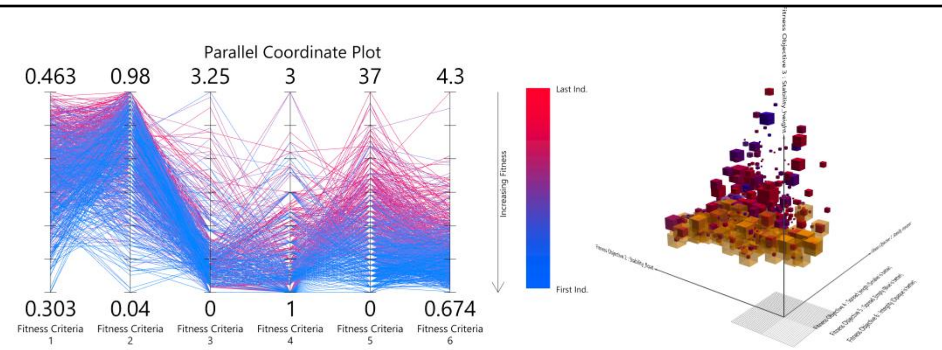


Figure 5. The whole models with different stapler pins

In the optimization phase, Wallacei was employed to execute a multi-objective optimization process. The generation size for Wallacei was set to 50, with 100 iterations, yielding a population size of 5000 solutions. This configuration was constrained by computational limitations. If more time and computational power were available, we could have further refined the optimization process, targeting better solutions across six distinct objectives. The simulation produced 139 solutions in the Pareto Front, as shown in Figure 6. To identify the most optimal solution, we used the Wallacei Diamond Fitness Chart operator. For example, Generation 97, Individual 38 was selected. This selection process, however, was based on a manual visual inspection, which may not be the most effective approach. Future improvements could involve developing a more systematic and data-driven selection method for choosing solutions from the Pareto Front.

Figures 5 and 6a provide a visual representation of the complete models and the Parallel Coordinate Plot of the 139 Pareto Front solutions, respectively. Figure 6b displays the phenotypic characteristics of these solutions, further illustrating the diversity of the generated solutions. While the current solution selection method was sufficient for this study, we recognize the need for more advanced techniques that would facilitate a more accurate and efficient selection process in future iterations of this research.



a. The Parallel Coordinate Plot and Objective Space of 139 solutions of the Pareto Front

b. The phenotypes of 139 solutions of Pareto Front

Figure 6. 139 solutions of Pareto Front from the simulation

In this study, several challenges are encountered that require further examination, such as the adhesion of steel components used to create the basic units and the method for joining two units according to their genotype, as shown in Figure 7. These issues also prompt discussions regarding the type of architectural space this model favors. The methods explored could ultimately support the remote construction of buildings using digital tools. However, this paper does not delve into the specifics of the structural joint connections because the focus is now shifting to enhance the model's capability to integrate architectural functions. We believe that addressing these challenges in future research is crucial.

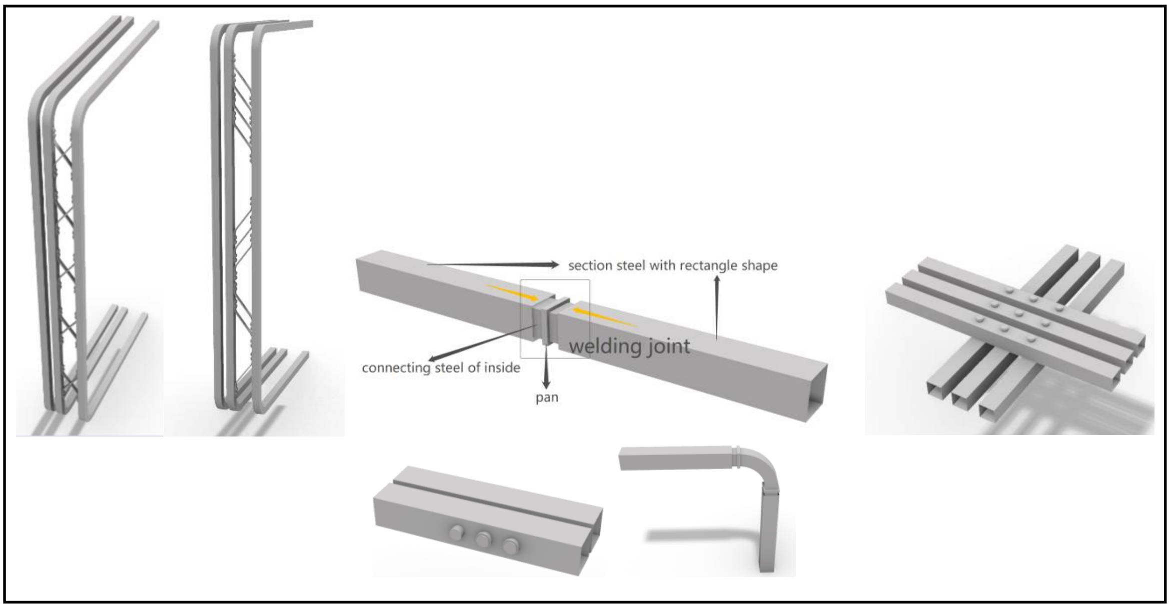


Figure 7. The joint connections for steel components

Regarding the manufacturing and on-site building process, another key issue is the allocation of space according to architectural functions. Although this aspect was not directly addressed in the current study, we propose a structural method for dividing space, as illustrated in Figure 8. This steel pipe structure allows for flexible interior space arrangements, making it easy to adapt spaces to different purposes. Figure 9 depicts the final model, featuring a solution from Generation 97//Ind.38, which could be scaled to resemble various types of buildings, such as office towers or residential dwellings. The scale of the stapler pin was set to 6 meters for this model but adjusting this dimension would result in different architectural forms. Further experiments should focus on specifying the required scale for different types of buildings.

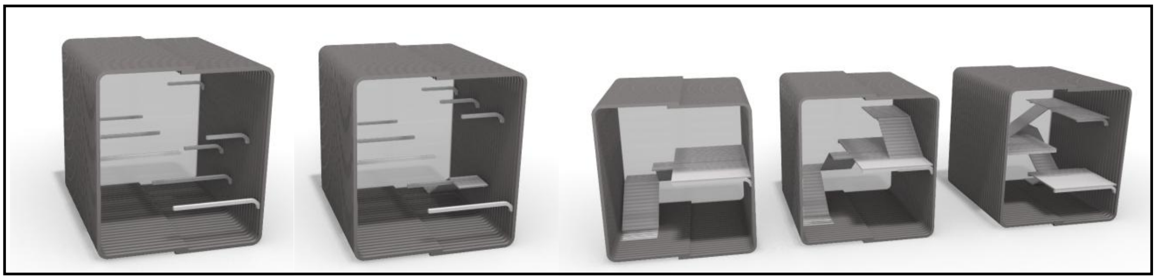


Figure 8. Setting carcass to put the floors on, and installing the components like floors and stairs

Figure 9. The model of Generation 97//Ind.38

This paper offers a model optimized through multi-objective algorithms that demonstrate its potential for creating flexible, modular architectural spaces. While structural and functional divisions of space remain unresolved, future work should address these critical issues, focusing on architectural functions and connections between spaces to improve the overall model.

5. Conclusion

To explore new architectural forms, we developed a model that utilized the NSGA2 algorithm for multi-objective optimization. Through this experiment, we achieved three key outcomes: the creation of a steel pipe structure resembling stapler pins as modular components, the ability to generate diverse architectural spaces based on the number of rooms or modules, and the potential to optimize these models for a variety of objectives. This approach enables the generation of a wide array of architectural forms and offers valuable insights into the optimization of architectural designs. Furthermore, by integrating floors onto the stapler pins, the model provides a flexible interior structure that can be easily adjusted.

The model also incorporates functional elements, such as pipes, which allow for the installation of necessary utilities like wiring and water supply pipes, expanding its practical application. While this experiment primarily focused on the generation of architectural space, we acknowledge that it did not fully address the functional connections between spaces or the division of these spaces according to architectural needs. Future research should focus on solving these architectural functional challenges to improve the model's adaptability and functionality. Looking forward, the next step involves utilizing this model for the design of dwellings or office buildings, particularly in contexts where non-contact construction and remote control are essential. This method holds significant potential for revolutionizing construction practices, enabling more flexible, efficient, and adaptable architectural solutions.

5. Conflict of Interest

The authors declare no conflict of interest related to this research. All the data and findings presented in this paper are the result of the authors' independent work and have not been influenced by any financial, personal, or professional interests.

6. Acknowledgment

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