AN ADAPTIVE STRUCTURE PROTOTYPE DESIGN METHOD BASED ON DISCRETE MODULAR ASSEMBLY SYSTEM

XINYI HU[1], XIANG CHEN[2], YUE ZHU[3], CE LI[4], ZHE GUO[5]
[1,2,3,5]Hefei University of Technology
12019211923@mail.hfut.edu.cn, 0009-0006-9638-0360
22019211927@mail.hfut.edu.cn, 0009-0004-6524-3537
3assicapeter@gmail.com, 0009-0004-1149-1738
4marchlice@outlook.com, 0000-0002-6290-4297
5guogal@hotmail.com, 0000-0002-7660-0622

Abstract. This paper contributes to the research in the field of generative computational design of discrete assemblies and their implementations in constructing spatial structures in architecture. In the article, by proposing a standard tubular shape as the base unit, and then accomplishing type constraints, quantity integration, and cost control, we achieve an effective generation, optimization, and assembly strategy for discrete structures. Based on the principles of performance-oriented architecture and cost control, we utilize computational geometric generation and optimal design with simulated annealing and genetic algorithms to achieve a globally optimal solution by constraining the spatial voxel control mesh, which produces a discrete modular assembly system that not only has structural stability but also creates complex spatial forms. The method has the potential to optimize the digital generation and construction process, control implementation costs, and extend engineering applications.

Keywords. Computational Generative Design, Discrete Structures, Genetic Algorithm, Spatial Structures, Modular Construction

1. Introduction

Composite, intricate, and dense aggregate architectural spaces composed of discrete structures have attracted a great deal of attention from society in current architectural research. Inherent in these studies is the fact that by studying the components that make up the individual units and how their components are duplicated, discrete structures have been made available for a greater and wider range of applications in the field of architecture. The outstanding generative power of discrete structures and their component repetition in a special computational way have driven the development of heterogeneous digital components in architecture, involving design, construction, and fabrication.

Current research on architectural discrete structures often prioritizes aspects such as geometric design or stress analysis, while neglecting to adequately consider

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 271-280. © 2024 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

constraint conditions. Shape-oriented studies emphasize innovative design and aesthetic expression by exploring and optimizing the geometric forms of discrete structures to achieve architectural diversity and personalization. Conversely, stress-oriented research primarily focuses on the mechanical performance and stability of structures, optimizing stress distribution to ensure the safety and reliability of discrete structures during construction and use. However, these studies often overlook the impact of spatial constraints on structural design, resulting in the generation of discrete structure models with potentially irrational layouts and constructions that are disconnected from surrounding spatial conditions.

1.1. BACKGROUND

Discrete structures have exhibited remarkable adaptability and innovation in spatial design. For instance, Buckminster Fuller's Geodesic Dome utilizes a triangular mesh structure, enabling a balanced distribution of materials and high stability through the reuse of monolithic components (Fuller, 1954). Gilles Retsin's wooden pavilion for the Tallinn Architecture Biennale showcases the combination of discrete building blocks to form interlocking patterns, generating large beams and spans and suggesting potential for future expansion of discrete architecture (Retsin, 2017). Pottmann explored the design of shaped spaces using discrete mechanisms, proposing a new triangular mesh (Pottmann, 2010). Dellinger, Li, and Wang investigated the representation of smooth geometries using rough polygonal meshes and revealed the potential application of discrete mechanisms in curved buildings (Dellinger et al., 2023).

Discrete structures integrate design, computation, and construction systematically. Architects embrace digital discretization, data processing, materials, automation, manufacturing, and economical design models inspired by these structures. These approaches have significant advantages in building assembly, factory production, and the utilization of digital technology in architecture, robotic fabrication, and large-scale 3D printing. For example, Retsin's project Blokhut establishes a differentiated adaptive building system with prefabricated concrete components and customized 3D-printed parts, addressing challenges in traditional modular construction and enabling mass customization with reduced labor (Retsin, 2014).

With increasing automation in design and construction fields, digital materials associated with discrete structures gain importance as independent units, driving ongoing research. Fully automated construction requires reversible assembly and disassembly units. Digital materials, proposed by Gerschenfeld in mechanical engineering, are architectural objects with relative local positions that provide geometric constraints for assembly, eliminating the need for templates or tools (Gerschenfeld, 2012). In architecture, Gramazio Kohler pioneered the use of robots as serial assembly machines, demonstrated by the "programming wall" that stacks bricks (Gramazio & Kohler, 2006). Similarly, Sanchez's "Polyomino" research aimed to design smart bricks with identical units but different arrangements or patterns, enabling more efficient design strategies for complex forms (Sanchez, 2014).

In summary, discrete structures offer significant potential in terms of adaptation, construction efficiency, and the integration of digital technologies. They inspire innovative approaches to spatial design and hold promise for advancements in architecture, fabrication, and assembly processes.

1.2. CURRENT LIMITATIONS

The development of algorithms, such as genetic algorithms, particle swarm algorithms, and simulated annealing, has played a crucial role in optimizing discrete structures. However, existing research primarily focuses on unconstrained discrete structures, neglecting the formation and development of such structures under constrained conditions. Furthermore, although discrete prefabricated buildings have demonstrated improved construction efficiency and resource utilization, issues such as structural redundancy and reduced versatility demand further investigation. Excessive reliance on discrete components may result in unnecessary redundancy, impacting project economy and sustainability. Similarly, reduced versatility may limit the applicability of this construction method in different scenarios and applications.

1.3. RESEARCH AIM

This study focuses on addressing the challenges of complex discrete spatial structures through a bottom-up holistic structural design process. The key objective is to explore how the implementation of standardized unit modules, guided by type constraints, quantity consolidation, and cost control, can effectively facilitate the generation, optimization, and assembly strategies of discrete structures. These strategies play a crucial role in facilitating batch customization design and expediting modular construction.

2. Methodology

2.1. WORKFLOW

The research endeavor commences with the establishment of a fundamental spatial voxel control grid. This entails removing occluded voxels based on site restrictions and subsequently initiating form generation on the remaining voxels. To ensure geometric constraints, agent objects are employed, utilizing standardized bar elements and orthogonal connection node units.

The process of developing the component algorithm begins by defining parameters based on the geometric characteristics of the discretized orthogonal bar structure. The primary objective is to generate a reduced number of component schemes that satisfy the stability requirements of the connection structure. Components are classified into two categories: vertical supports and horizontal connections. Parameters are set as evolutionary conditions, taking into account the vertical stability and horizontal component density. This manifests practically as the quantity of vertical and horizontal bar elements connected to each orthogonal node.

Subsequently, based on the combination of genetic algorithm and simulated annealing, a hierarchical optimization method is established to develop a form optimization algorithm and perform parameter tuning. The optimization algorithm aims to refine the overall form of the structure, enhancing its structural performance.

Lastly, for the experimental phase, PVC, a readily accessible material, is selected as the constituent element for validating its adaptability and stability within various spatial contexts. The experimental investigation encompasses different types of spaces to evaluate the overall performance and feasibility of PVC as a construction material. The diagram showcasing the workflow of the study is presented below:

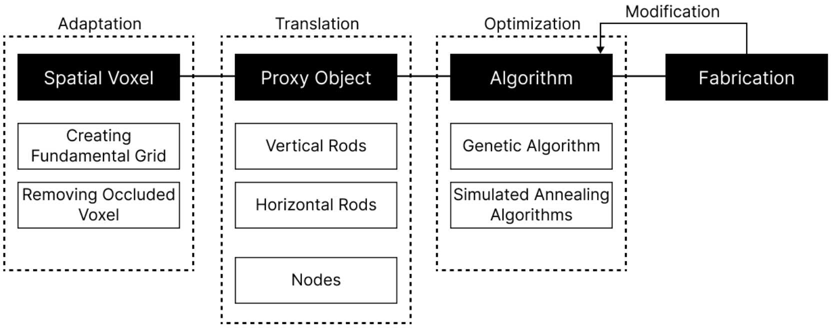

Figure 1. Research workflow

2.2. GENERATIVE DESIGN METHOD

2.2.1. Framework of adaptive discrete structure system

The research focuses on exploring the potential of spatial adaptability in discretized structures. It starts by abstracting the target space into voxels and retaining the voxels that are filled with discrete structural elements. The algorithm discussed in this study aims to optimize the structural design of discrete structures. It achieves this by extracting the structural framework from the voxels and optimizing it into a stable and reduced representation, taking the form of discretized bars and nodes as agent objects. The evaluation criteria for the algorithm are based on ensuring the stability of component connections within the structure and reducing the number of bars used.

The overall structure of the algorithm follows a hierarchical optimization approach. It begins with an optimization screening using a genetic algorithm, followed by further optimization using a simulated annealing algorithm. The algorithm employs eight variables to represent and encode the quantity and distribution of connection nodes and the number of bars connected to each node. Based on given conditions, the algorithm evaluates and scores the nodes and bars through addition and subtraction, selecting the highest-scoring solution for further optimization. The initial population of the genetic algorithm is based on the structural framework lines and nodes derived from the voxel representation of the input system. The algorithm undergoes a process of genetic evolution by randomly removing lines.

To ensure vertical stability, the algorithm imposes constraints on the number of nodes in the same plane and the area enclosed by the nodes. Horizontal stability is achieved by controlling the number of bars connected to the same node and their distribution in the horizontal direction (x and y directions). The termination condition of the algorithm is determined based on the convergence of the genetic algorithm results.

2.2.2. *Voxel division of structural fit space*

Voxels are tools widely used in the digital representation of space on a three-dimensional grid, and they find extensive applications in the design of prefabricated structures and discretized spatial environments. In this study, we adopted cubes as the fundamental voxel units. Eventually, these voxels will be replaced by agent units, namely connection points and struts. Due to the importance of structural stability, the voxel aggregates obtained through fitting should exhibit the characteristic of connecting voxel boundaries.

We defined the spatial adaptation object as the units representing the given space minus the obstacle units and the units required for human activities. After inputting the given space, we fit the given space and the designated space using voxels of specified dimensions. Subsequently, we determined the presence of an intersection between interfering voxels and the voxels representing the designated space, removing any interfering voxels accordingly. The remaining voxels constitute the fitted representation of our spatial adaptation object. Depending on the specific spatial scenarios, the size of the fitting voxels and the approach to handle interfering spaces can be adjusted to achieve the agent object's filling of the target voxels. The process is shown in the following diagram:

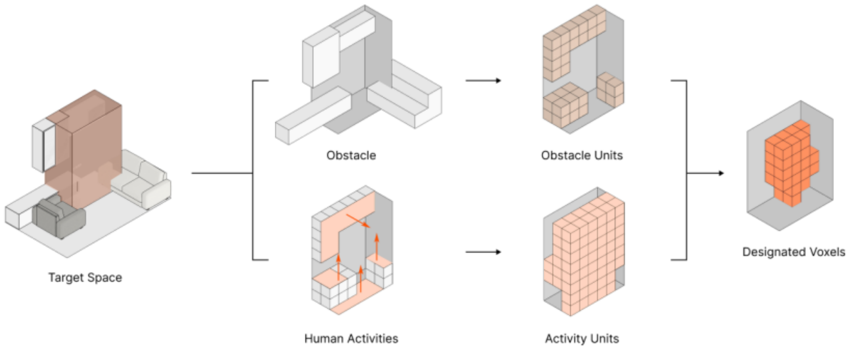

Figure 2. Obtaining designated voxels

2.2.3. *Discrete components agent mechanism*

The agent objects in this study consist of orthogonal elements, namely bar members and connection nodes. We adopted a bottom-up construction and design approach, examining the geometric properties of the target structure and summarizing the conditions for shape generation as algorithm parameters. Starting from the bar members, we derived geometric prototypes. We divided the discrete components into planar and vertical parts, with mutual constraints and influences between them. The vertical components were generated by controlling their planar layout, while the horizontal members connected the vertical assemblies through spatial vertices.

The distribution of the vertical bar members in the plane can be seen as a requirement for the distribution of connection nodes in the horizontal plane, which should satisfy the following characteristics: 1. Let the number of points in the wth layer be Nw, and the number of grids in the wth layer is Mw. It should satisfy $1 <= Mw < 4$, Nw = Mw + 1; Mw >= 4, Nw = Mw. 2. In each layer, the enclosed area formed by all the nodes should be as large as possible. Figure 3 illustrates some of the possible node layouts that can occur in a 2x2 plane.

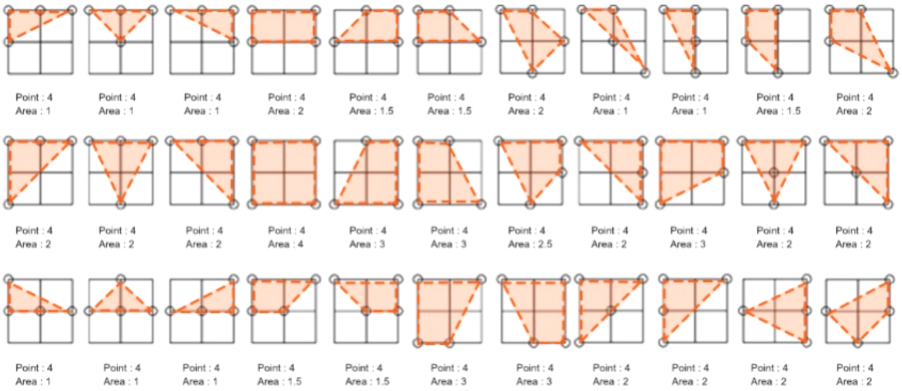

Figure 3. Node layouts in a 2×2 plane

The horizontal bar members primarily serve to resist lateral forces in the overall structure and play a crucial role in the functionality of the structure, providing support and accommodating functions such as suspending. We stipulated that each node should be connected by at least two bar members in any direction. Finally, considering component simplification, we specified that the total number of bar members should be minimized. To validate the above conditions, we conducted a morphology experiment on a 2x2 plane. The generated structure results are shown in Figure 4, which align with our expectations.

Figure 4. Structure generation on a 2×2 plane

2.2.4. Structural optimization algorithms

Genetic algorithms and simulated annealing algorithms are frequently employed in the domain of structural optimization due to their suitability for complex combinatorial optimization problems and their inherent adaptability and robustness. Genetic algorithms facilitate solution evolution by leveraging genetic operations among individuals within a population, thereby progressively enhancing solution quality. In contrast, simulated annealing gradually diminishes search randomness through the acceptance of "inferior" solutions based on a predetermined probability, akin to an annealing process, with the ultimate objective of converging toward the optimal solution. In this study, we integrated both algorithms for morphological optimization.

By employing the voxel acquisition method described in section 2.2.2, we input the voxels into the generative algorithm. The algorithm uniformly sets the edge length of each voxel to one unit and randomly removes boundary lines and nodes of all input voxels. Through continuous optimization based on the evolutionary conditions of the genetic algorithm, we ultimately select the solution with the highest score. The evolutionary conditions of the genetic algorithm are determined based on the geometric conditions derived in section 2.2.3. The number of parameters in the genetic algorithm is determined by the number of voxel boundary lines, and it must satisfy the condition that the number of parameters is greater than the number of extracted voxel boundary lines. The iteration count for both the genetic algorithm and the simulated annealing algorithm is controlled by observing the convergence of results. Subsequently, we optimize the selected solution using the simulated annealing algorithm. The evaluation conditions for the simulated annealing algorithm are the same as those for the genetic algorithm.

Figure 5 presents the results of a genetic algorithm experiment and the subsequent results after iteration using the simulated annealing algorithm. It is evident from the results that the simulated annealing algorithm significantly improves upon the results obtained from the genetic algorithm. This indicates that the structural prototype has achieved adaptability to the given space and satisfies the requirement of reducing the number of components.

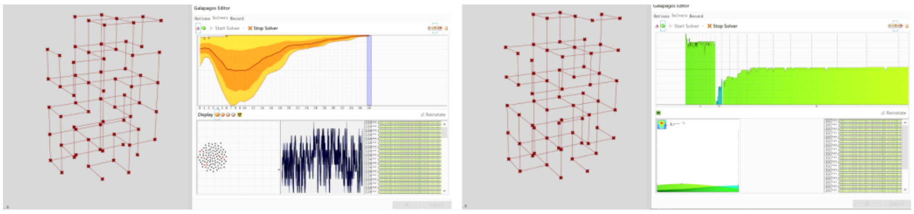

Figure 5. Results of genetic algorithm and simulated annealing algorithm

2.3. APPLICATION STRATEGY

The structure prototype finds its primary application in the process of interior design, specifically in utilizing and integrating irregular and scattered spaces. Based on discrete modeling and simulated annealing algorithms, it offers a flexible way to connect the spatial logic of entire interior designs into a cohesive whole. Beyond its inherent adaptability and minimal support requirements, this prototype caters to diverse spatial functional needs such as exhibition, storage, partitioning, and decoration.

By employing discrete modeling and simulated annealing, this prototype optimizes spaces in multiple dimensions, surpassing traditional constraints. It expands vertically without disturbing existing items on the floor, maintaining their natural arrangement. To meet diverse user needs and consider adaptability in various scenarios, we conducted finite element analysis and structural optimization. We selected four different variants, each corresponding to different usage scenarios and encompassing various structures such as cantilevers, supports, and suspensions, aiming for comprehensive coverage in structural type analysis. Analysis revealed potential structural vulnerabilities, primarily at cantilever or suspension nodes lacking support below, transmitting risks to adjoining components based on their connection methods. As shown in Figure 6, we conducted finite element analysis and deformation simulations and adjusted the materials of vulnerable points and surrounding components, replacing the initial 75mm diameter, 400mm long PVC pipes with high-strength recycled paper tubes and TPE pipes. Simulations indicated that using lighter materials at weak structural points significantly reduced potential vulnerabilities.

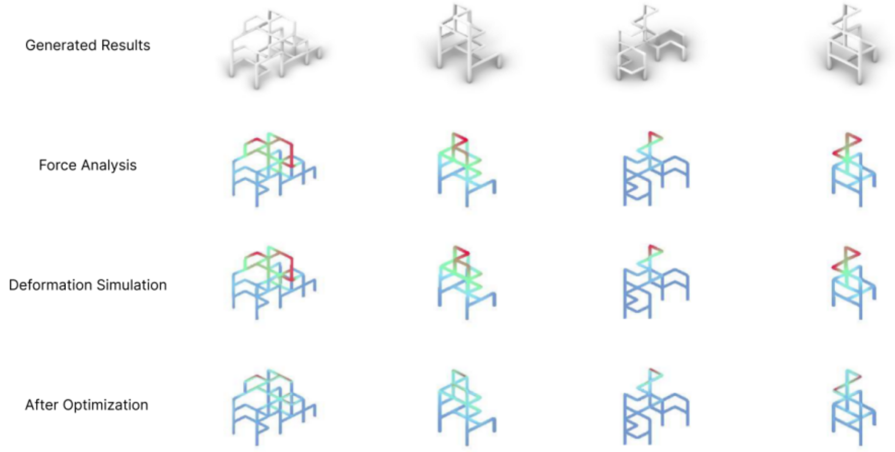

Figure 6. Structural finite element analysis simulation and optimization

The prototype adapts seamlessly when encountering obstacles during expansion and ensures optimal utilization of irregular spaces while maintaining the original design style. Its algorithmic adjustments offer a new solution for optimizing and integrating irregular indoor spaces.

3. Empirical Applications

3.1. DISCRETE COMPONENTS ATTRIBUTES

We used rigid PVC pipes and corresponding connectors as the actual validation scheme for the prototype's PVC pipes, known for their diverse sizes, affordability, and wide availability, were our primary choice. Inner diameter 75mm, 3mm wall thickness PVC pipes, each 400mm long, were defined as standard components. We also utilized various connectors (inner diameter 78mm) like double street elbows, and triple connectors, and supplemented them with materials such as hemp ropes, wooden boards, and felt fabric for functional construction.

3.2. JOINT CONSTRUCTION

The connection nodes, a key innovation, were designed based on industrially produced PVC pipe connectors. Traditional PVC connectors were used directly for standard component connections, allowing easy insertion based on the quantity at each node. Additionally, for functional modules, a special set of connectors was developed using cut PVC components, Velcro straps, and 20mm long cut PVC pipes (inner diameter 75mm, 3mm wall thickness). These connectors provided ease of loading, clamping, and functionality for complex scenarios, with Velcro straps enabling easy disassembly.

3.3. FABRICATION PROCESSING

Before constructing a full-scale model, we validated the skeletal structure and load-bearing capacity of the structure using scaled models. As Figure 7 dedicated, we utilized 20mm inner diameter, 2mm wall thickness PVC pipes as standard components for the validation phase. After creating two sets of models and feeding the data back to the development phase, we confirmed that the spatial form and material effects met the requirements for a one-to-one model, prompting us to proceed with assembling a larger-scale model.

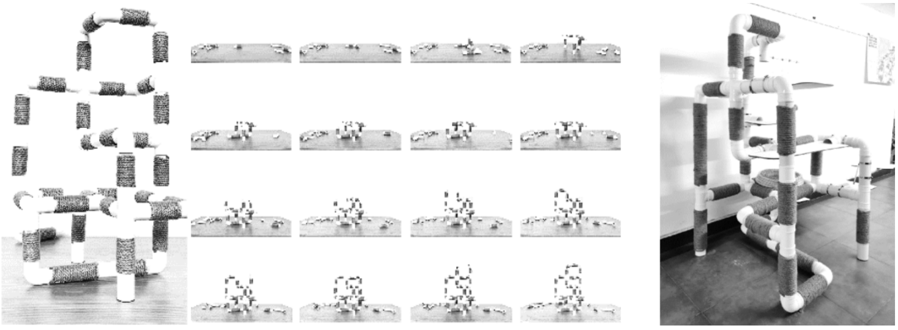

Figure 7. Scale model and 1 : 1model

The assembly process followed a bottom-up logic, first pre-mounting some connection nodes onto 400mm PVC standard pipes, then connecting standard components with nodes to meet assembly requirements on the X-Y plane. Using the remaining holes on the connectors, we performed model assembly in the Z-axis direction. Figure 7 showcases the successful construction of a 1:1 model during the validation phase.

4. Conclusion

In view of specific spatial constraints, a discrete structural design method is proposed. The method utilizes computational generation and optimization for the design of structures. It focuses on generating, deriving, and selecting discrete structurally generated unitary modular components for different spatial forms and mechanical constraints, ultimately generating multiple relatively optimal solutions. This approach has the potential to optimize current digital generation and construction processes, control the cost of implementing complex spatial forms, and further extend the engineering applications of structural prototypes. This research enables computational generation and optimal design of discrete structures based on standard tubular cells through a combination of algorithms and constraints. Within the framework of a spatial voxel control grid, a global optimal solution for the discrete structure is established by the automated generation of constraints and algorithms using a simulated annealing algorithm and a genetic algorithm. This approach effectively simplifies and improves the adaptability of the structure by evaluating the density of discrete cells, eliminating redundant and irrational structural components.

In the study, scaled construction experiments were also conducted using standard PVC pipes as empirical objects to verify the reliability of the constraint-based form generation and optimization method. The experimental results show that the algorithm of automatic generation by the restricted space produces a discrete modular assembly system that achieves structural stability and well adapts to the constraints. These results provide strong support for the application of discrete structures in construction, especially in the automated generation of structural design and cost optimization, and provide an innovative approach for future assembly and factory construction.

References

F. Scheurer: 2005, Turning the Design Process Downside-Up - Self-organization in Real-world Architecture. In: B. Martens, A. Brown (Eds.), *Computer Aided Architectural Design Futures*, Springer, Dordrecht, Vienna, 2005, pp. 269-278

Guo, Z.F. and Li, B: 2017, Evolutionary approach for spatial architecture layout design enhanced by an agent-based topology finding system, *Frontiers of Architectural Research*, 6(1), 53-62

Retsin, Gilles :2016, Discrete Assembly and Digital Materials in Architecture. In: Herneoja, Aulikki; Toni Österlund, and Piia Markkanen (eds.), *Complexity & Simplicity - Proceedings of the 34th eCAADe Conference - Volume 1*, University of Oulu, Oulu, Finland, 22-26 August 2016, pp. 143-151.

Nan, Cristina and Rossi, Andrea : Discrete Circular Scaffolding A reflection on discrete systems in construction. In: Dokonal, W, Hirschberg, U and Wurzer, G (eds.), *Digital Design Reconsidered - Proceedings of the 41st Conference on Education and Research in Computer Aided Architectural Design in Europe (eCAADe 2023) - Volume 1*, Graz, 20-22 September 2023, pp. 559–568

Rossi, A; Tessmann, O: 2017, Collaborative Assembly of Digital Materials. *ACADIA 2017: DISCIPLINES & DISRUPTION [Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)* ISBN 978-0-692-96506-1] Cambridge, MA 2-4 November, 2017), pp. 512- 521

Retsin, G. (2015). Discrete Assemblage as Design and Fabrication Strategy. *TxA Emerging Design + Technology,* ED15_3_discreteassemblage.

Dellinger, F., Li, X., & Wang, H. (2023). Discrete orthogonal structures. *Applied Geometry, TU Wien, Vienna, Austria*; College of Civil Engineering, Tongji University, Shanghai, PR China; Visual Computing Center, KAUST, Thuwal, Saudi Arabia. Article history: Received 18 May 2023, Accepted 30 May 2023, Available online 8 June 2023.

Milošević, J. Ž., Nenadović, A. S., Žujović, M. S., Živković, M. D., Zimović, I. A., & Gavrilović, M. M. (2021). Discrete Continuities: Generative Design Explorations of Spatial Structures in Architecture. University of Belgrade – Faculty of Architecture, Belgrade, Serbia.