DISCRETE CONTINUITIES: GENERATIVE DESIGN EXPLORATIONS OF SPATIAL STRUCTURES IN ARCHITECTURE

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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. Works and research on discrete architecture and architectural ontology suggest that the considerable promise for a complex, open-ended, adaptable architecture could be a digital form of assembly based on parts. In this study, the topic of compositions made of discrete elements is researched through the perspective of the creative process. Respectively, the paper explores the possibility of using generative systems based on graph grammar formalism in the creation of adaptable spatial configurations in an architectural context. We tested this approach through design research in which a computational generative system was used as an embedded system for formal explorations. Starting from the specification of discrete elements/modules and their inherent attributes, then the definition of the composition rules and constraints, we applied graph grammar formation procedure which, by a random selection of the modules and rules on each iteration of the additive process, generated a variety of complex spatial structures. The emergent discrete continuities exhibit new and unanticipated detail, materiality, structure, functionality, and aesthetics inherent to the design process augmented by human-machine interaction. The structural performance of these structures was evaluated using software based on the Finite Element Method (FEM), while the constructability was tested through the construction of small-scale prototypes. This theme enabled us to study specific design methodology, as well as to investigate the potentials of digitally intelligent architecture.

Keywords: generative design, architectural design, spatial structures, discrete architecture, discrete automata

INTRODUCTION

Formation of composite, intricate, dense aggregations/ agglomerations/ assemblages/ compositions/ structures made of aggregates/ bits/ components/ cells/ elements/ modules/ parts/ units is currently subject of interest in diverse architectural research [1, 2, 3]. Inherent to these studies is the analysis of principles and relations underlying these arrangements. The generative capacity of these rules and their computational implementations progress the idea of heterogeneous digital assemblies in architecture, from the perspective of design, construction, and fabrication. Curved lines and continuous surfaces, exploited by the architects of the first digital turn [4], were both technical and aesthetical achievements enabled by digital technologies. However, problems with speed, structural performance, multi-materiality, tectonics, and reversibility of continuous fabrication processes renewed interest in prefabrication and assembly methods of material systems made of discrete objects [5, 6]. Currently, architects of the second digital turn [7] practice design models that appropriate computational digital discrete, digital data processing, digital materials, digital automation, fabrication, and economy

In architecture, diverse authors study aggregative architecture, jamming-based architecture, mereological compositions, and discrete architecture. Studies of aggregates as an architectural material system can be traced back to the research in the context of form-finding initially done by Otto at the Institute for Lightweight Structures at the University of Stuttgart and later in Diploma Unit 4 at the Architectural Association London and GSD Rice University, as well as in other studies [8, 9, 10, 11, 12, 13] . In these studies, of so-called design granulates individual particle is synthetically designed to meet specific architectural performance.

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1 G. Retsin (Ed.), *Discrete: Reappraising the Digital in Architecture*, NJ, USA, 2019.

2 S. Tibbits (Ed.), *Autonomous Assembly: Designing for a New Era of Collective Construction*, USA, 2018.

3 Lab-eds. Available online: https://lab-eds.org

4 M. Carpo (Ed.), *The digital turn in architecture 1992–2012*, NJ, USA, 2012.

5 D. Koehler et R. Navasaityte, "Mereological Tectonics: The Figure and its Figuration". In: *Proceedings of 77th Annual Convention and Expo 2016 TxA Emerging Design + Technology Conference*, San Antonio, Texas, USA, 3–4 November 2016, TX, USA, 2016.

6 MIT MediaLab, Center for Bits and Atoms. Available online: https://www.media.mit.edu/graduate-program/center-for-bits-and-atoms/

7 M. Carpo, *The second digital turn: Design beyond intelligence*, Cambridge, MA, USA, 2017.

8 S. Gabeta, et F. Otto, Experimente/Experiments, Form-Kraft-Masse 5/Form-Force-Mass 5. Mitteilungen des Instituts für leichte Flächentragwerke (IL) Universität Stuttgart Nr. 25/Information of the Institute for Lightweight Structures (IL) University of Stuttgart Nr. 25, Stuttgart, Germany, 1990.

9 M. Hensel, Michael et Menges, Achim. "Aggregates". In *Versatility and Vicissitude, Performance in Morpho-ecological* Design; Hensel, M.; Menges, A., Eds.; Wiley: NJ, USA, 2008; 80–87.

10 M. Hensel, et A. Menges, "Materialsysteme 05: Aggregate". In: *Arch+, Form Follows Performance: Zur Wechselwirkung von Material, Struktur, Umwelt*, No. 188, M. Hensel, M.; Menges, A., Eds.; Achen, Germany, 2008; 76–85.

11 K. Dierichs, F. Fleissner et A. Menges, "Aggregate Structures: Material and Machine Computation of Designed Granular Substances". In: *Material Computation-Higher integration in morphogenetic design*; A. Menges, (Ed.); NJ, USA, 2012; 74–81.

12 K. Dierichs, F. Fleissner et A. Menges, "Functionally Graded Aggregate Structures – Digital Additive Manufacturing with Designed Granulates". in: *Proceedings of the 32nd Conference of the Association for Computer Aided Design* (ACADIA), San Francisco, USA, 18–21 October 2012, 295–304.

13 K. Dierichs et A. Menges, "Aggregate architecture: Simulation models for synthetic non-convex granulates". In: ACADIA 2013 Adaptive Architecture, 2013, 301–310.

Unlike research into material systems, Koehler [14] applied mereology as a design method that facilitates exploration of impact of the digital practice on architectural compositions. For Koehler and Navasaityte [15], mereology is a conceptual paradigm for designing an architectural object not through a reference to its content or form but through the resonance of its parts. Moreover, for Koehler and Navasaityte mereological approach represents the evolution of the two main ideas emerging from the digital taught in architecture: the algorithmic [16] and the parametric [17]. The convergence and development of both approaches promote assembly patterns that become a relation between different stages of an internal and external organization. Their architectural research practice demonstrates a range of possible exciting outcomes based on applying mereological relations [18].

Furthermore, discrete architecture [19] is related to the computational understanding of the discrete parts/bits/pieces that are scalable, accessible, and versatile as digital data. Discrete architecture takes advantage of the digital economy and automation to democratize the production and increase access, recognizing potential economic, social, and cultural implications [20]. Works and research on the discrete architecture and architectural ontology [21, 22, 23, 24] suggests that the considerable promise for a complex, open-ended, adaptable architecture could be a digital form of assembly based on parts. Current pioneering design experiments that embrace unconventional methodologies, investigation of robotic manufacturing, and large-scale 3D printing indicate exciting possibilities for architectural use of digital technologies. Research by The Center for Bits and Atoms at MIT, Boston, demonstrates that robotic assembler and hierarchical assembly procedures allow an enormous up-scaling of structural dimensions by retaining the ordinary part-to-whole relation between strut, beam, truss, and space truss [25].

Furthermore, as design and construction fields are becoming more automated digital materials [26] that are treated as a set of independent units and have discrete representation in the design process and physical output, robotic assembly is only

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[14] D. Koehler. *The mereological City: A reading of the works of Ludwig Hilberseimer*. Transcript, New York, USA, 2016.

[15] *Ibid.* 5.

[16] K. Terzidis, *Algorithmic Architecture*, Burlington, MA, USA, 2006.

[17] Patrik Schumacher.com, Texts, “Parametricism as Style – Parametricity Manifesto”. Available online: https://www.patrikschumacher.com/Texts/Parametricism%20as%20Style.htm

[18] *Ibid.* 3.

[19] *Ibid.* 1.

[20] *Ibid.* 1.

[21] G. Retsin, “Discrete and Digital: A Discrete Paradigm for Design and Production”. In: *Proceedings of the 77th Annual Convention and Expo 2016 TxA Emerging Design + Technology Conference*, San Antonio, Texas, USA, 3–4 November 2016, San Antonio, TX, USA, 2016.

[22] G. Retsin, “Discrete Assembly and Digital Materials in Architecture”. In: *Complexity & Simplicity*, Proceedings of 34th eCAADe Conference – Volume 1, Univeristy of Oulu, Finland, 22–26 August 2016, 143–151.

[23] G. Retsin, *et al*. “Discrete Computation for Additive Manufacturing”. In *Fabricate 2017*; Menges, Achim., Sheil, B., Glynn, R., Skavara, M. (Eds). London, UK, 2017; 178–183.

[24] Unit19: The Bartlett School of Architecture, ULC. Available online: http://unit-19.net

[25] *Ibid.* 6.

[26] N. Gershenfeld, “How to Make Almost Anything: The Digital Fabrication Revolution”. *For. Aff.* 2012, *91(6)*, 43–57.

feasible and scalable in the context of digital material and discrete computation [27]. Reversibility of assembling and disassembling units [28], the robotic assembly's execution requires specific features of units as demonstrated by the students' work at the Bartlett – INT, cores led by Retsin and Jimenez Garcia. Studies oriented on the new design, materialization, construction, or fabrication advantages resulting from overlapping digital possibilities and assembly modes [29, 30, 31, 32, 33, 34, 35], suggest that these approaches could be applied in the broad context of architectural design from the definition of principles and concepts to the development and fabrication of explicit buildings. Discrete, combinatorial, reversible systems supported by high technologies open new opportunities for a digital architecture beyond standardization and modular coordination. Despite the attention of the subject, further studies focusing on diverse design approaches, frameworks, models, processes, and tools that better meet the specificity of the architectural production are needed.

This study aims to describe and evaluate generative design methodology based on the mereological approach in which complicity between parts articulates the whole. The assessment was carried out in the context of the specific task. In this action-oriented design research, the assignments were to define design exploration framework – generative procedure and tool that will correspond to the set objectivate of the study and perform design exploration to evaluate the effectiveness of this approach through the production of artifacts. Respectively, study focuses specific design situations that will enable us to examine building ontologies based on shaping the tension between architecture and its parts. Design experiment in this research is oriented on the influence of compositional operations on the design of macro architectonic compositions. The objective of design research was to study discrete spatial structures that achieve heterogeneity and differentiation through serial replication of identical components. These structures, at the same time, possess formal complexity and fabrication sustainability facilitated by repetition.

This research contributes to the explorations in generative design, and in specific application of discrete assemblies in design of architectonic structures. In this approach, the definition and implementation of a design strategy and custom tools represent part of the creative process. Contrary to conventional practice, the goal moves from creating a design using top-down approach to a definition of a more objective bottom-up design strategy that meets the need for design problem-solving. The suggested approach enables to avoid preconceived solutions and psychological inertia attributed to a designer's finite experience. Symbiotic human-machine interaction facilitates the exploration of performances and the emergence of unexpected

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27 G. Retsin et M. Jimenez Garcia, "Discrete computational methods for robotic additive manufacturing". In: *ACADIA 2016 Posthuman Frontiers*; 2016, 332–341.

28 N. Gershenfeld, et al. "Macrofabrication with Digital Materials: Robotic Assembly". *AD* 2015, *85(5)*, 122–127.

29 *Ibid.* 3.

30 N. Leach, D. Turnbull et C. Williams (Eds). *Digital Tectonics*, NJ, USA, 2005.

31 F. Gramazio et M. Kohler, *Digital Materiality in Architecture*, Baden, Germany, 2008.

32 A. Menges, et S.Ahlquist, *Computational Design Thinking*; NJ, USA, 2011.

33 S. Brell-Cokcan, et J. Braumann, (Eds.). *Rob|Arch 2012: Robotic Fabrication in Architecture, Art and Design*, Reprint of the original 1st ed. 2013, New York, USA, 2016.

34 G. Retsin, *et al*. (Eds). *Robotic building: Architecture in the age of automation*, Munich, Germany, 2019.

35 J. Willmann, *et al*. (Eds) *Robotic Fabrication in Architecture, Art and Design 2018: Foreword by Sigrid Brell-Çokcan and Johannes Braumann, Association for Robots in Architecture*, New York, USA, 2019.

discrete formations. On the other hand, while the applied design research method is generally speculative, reflective, and critical in learning general lessons from specific cases, the process itself represents experience, regardless of the achievements, as it may be re-used for the new tasks.

METHOD

In this paper research by design method was applied to explore concept of digital discrete spatial structures. Where digital is related to the ability to represent discrete values and the models of the composition of distinct values or figures [36]. This approach is not strange to architecture, which is basically a compositional discipline that deals with arrangements and assemblies. Applied generative design procedure underlying form exploration enables production of architectonic structures not by dealing with its form or function but by replicating its parts/components. The focus was on analyzing possible part-whole relationships and their character (e.g., geometrical, physical, material, functional). The procedure acts as a meta-model for generating digital assemblies, providing a digital description of a compositional whole.

Components and Patterns

Two features describe the generative design problem:

- components, and
- patterns.

Components are forms, abstract representations of fundamental parts/units/modules. The process of component description includes establishing the analogies between the components used to create the model and elements of a potential future architectural object they represent. Components are geometrical entities (e.g., 2D or 3D mesh elements) representing abstractions of building's structural elements. Patterns are composition rules that define possible component transformations, i.e., how modules can be connected. Composition rules consist of two parts separated by an underscore, where the left-hand side of the underscore denotes component (i.e., its name) and the plane of the connection (defined by its origin and x-axis), while on the right-hand side, the component that will be connected and its connection plane are specified. The connection planes are markers that locate and orient components. Composition rules describe a relation between components, and they could be related to the component shape, properties, role, or express certain desirable and undesirable connections, interactions, conditions, situations, restrictions, and others. In the generative process, the composition rule has a role in producing a composition and directing design explorations towards feasible solutions.

A representation scheme is a crucial part of this design framework. It is important to establish a good correlation between the components used in design exploration and elements of the future architectural object/structure. The component representation should reflect the main properties and characters of the real-world entities, and the level of abstraction should be chosen concerning scale complexity or other essential design features. Respectively, it is vital to appropriately represent aspects of the project task or architectural design concept by reducing them to the elemental components and the composition patterns. Previously could be achieved through the study of components' shape, size, proportion, role, content, or purpose, and

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[36] *Ibid.* 5.

possible connections and relations between components, and between components and composition is the first step in this design framework.

Design Domain

Design domain represents constrained space in which solutions are generated. The design domain's role is to narrow, and to a certain extent, control a set of alternative solutions and direct design explorations to meaningful or feasible solutions. It is preferable to define the design domain parametrically to facilitate its more straightforward and fast changes by manipulating parameters. These design domain modifications could further manage design exploration towards more sustainable solutions by updating search boundaries or other constraints. A definition of a design domain could include:

- composition quantity,
- composition boundary, and
- composition field.

The composition quantity is a maximal number of elements in the aggregation, assigned as discrete values or a continuous range of integer values set between the lower and upper limit. The composition quantity could be used, for example, to control dimensions or area of the building by limiting a total number of elements. Composition boundary represents a geometry (e.g., plane or volume) that constraints aggregation growth (e.g., from one side of the plane, in or outside the volume). The design domain boundary could be used to introduce the location constraints (e.g., the geometry of a lot, terrain, maximal length, length, width or height of a building, wholes in a building). The field is the design domain that constraints composition to predefined custom scalar filed. The field-driven composition can also be used to inform the generation process with diverse kinds of objective information obtained as the results of a structural form-finding and optimization [37], performance analysis (e.g., structural, environmental). A definition of a design domain could include multiple constraints and variables, in which case the final solution space is the area where each of the boundaries overlaps. Also, a design domain definition should be carefully chosen and balanced between introducing all relevant information, which will lead to possible results and excessive restrictions that could considerably limit design exploration.

Generative system

The composition procedure has a task to autonomously produce a set of solutions, possible compositions, based on a predefined setup (components, patterns, and design constraints). The creation of the procedure implies computational implementation of an algorithmic definition of the chosen concept. The method underlying tool could be based on shape grammars, a generative compositional system for

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[37] A. Rossi, et O.Tessmann, "Designing with Digital Materials". In: *Protocols, Flows, and Glitches*: Proceedings of the 22nd Annual Conference of the Association for Computer-Aided Architectural Design Research in Asia; Janssen, P., Loh, P., Raonic, A., Schnabel, M. A., (Eds).,Suzhou, China, 2017, 37–42.

producing geometric shapes [38, 39] with diverse architectural applications [40, 41]. In this research, we used the concept of graph grammar proposed for self-assembly robotics [42]. The application of this concept in architecture for designing with repetitive modules was proposed by Rossi [43]. Generally, graph grammar is a technique of algorithmic generating new graphs from the original. The procedure is applied for generating discrete compositions represented as 3D digital models. Herein, the graphs are components, computational abstractions of structural elements, while the transformations are conducted by applying composition rules on the components. Graph rewriting rules are string regulated graph grammars. Usually, a graph rewriting system consists of a set of graphs rewriting rules of form $CL|nL\_CR|nR$, with L being the left-hand side and R called the right-hand side of the rule. C represents the component's name in both the left-hand and right-hand side of the syntactic statement, while n is the number representing connection id. Respectively, the generation engine in this procedure selects and processes previously defined composition instructions, i.e., one rule is randomly selected and executed from the predefined set in each step. The selected rule performs the transformation, which implies positioning two components in space (i.e., their geometries) relatively to their connections.

Graph grammar aggregation procedure allows the generating of compositions from the combination of different components by adding them iteratively. This mechanism facilitates an autonomous generation process, and the outcomes have an emergent property and complexity depending on the number of components and the character of the model-related parameters. The procedure is implemented as an open-source program Wasp, mainly developed by Rossi [44], offers a platform for design exploration of mereological relations and discrete compositions/design, and digital materials. This software was developed for an architectural application and implement aggregation procedures that facilitate the generation of diverse compositions/structures. The program operates as a component for Grasshopper [45], a graphical editor for commercial CAD systems Rhinoceros [46]. Design exploration of discrete systems could also be done by application of graph-based growth models to fill pre-modeled shapes with components and that this concept is implemented in Fox [47], anther open-source plug-in for Grasshopper. These two programs were applied for implementation of an autonomous production system that could be considered a generation engine that drives form exploration and produces designs.

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[38] G. Stiny, et J. Gips, "Shape grammars and the generative specification of painting and sculpture". In: *Information Processing 71*, Amsterdam, Holland, 1972, 1460–1465.

[39] G. Stiny, "Introduction to shape and shape grammars". *Env. and Plan. B: Planning and Design, 7(3)* , 1980, 343–351.

[40] W. Mitchell, *The Logic of Architecture*, London, UK, 1990.

[41] A. McKay, et al. "Spatial grammar implementation: From theory to useable software". *AI EDAM* 2012, *26(02)*, 2012, 143–159.

[42] E. Klavins, R. Ghrist, et D. Lipsky, "Graph grammars for self-assembling robotic systems". *In: Proceedings of the 2004 IEEE International Conference on Robotics and Automation, ICRA 2004; IEEE: New Orleans, LA, USA, 26 April – 1 May 2004, 5293–5300.*

[43] *Ibid.* 37.

[44] Food4Rhino, Wasp. Available online: https://www.food4rhino.com/app/wasp

[45] Grasshopper – Algorithmic Modeling for Rhino. Available online: https://www.grasshopper3d.com

[46] Rhinoceros. Available online: https://www.rhino3d.com

[47] Food4Rhino, Fox. Available online: https://www.food4rhino.com/app/fox

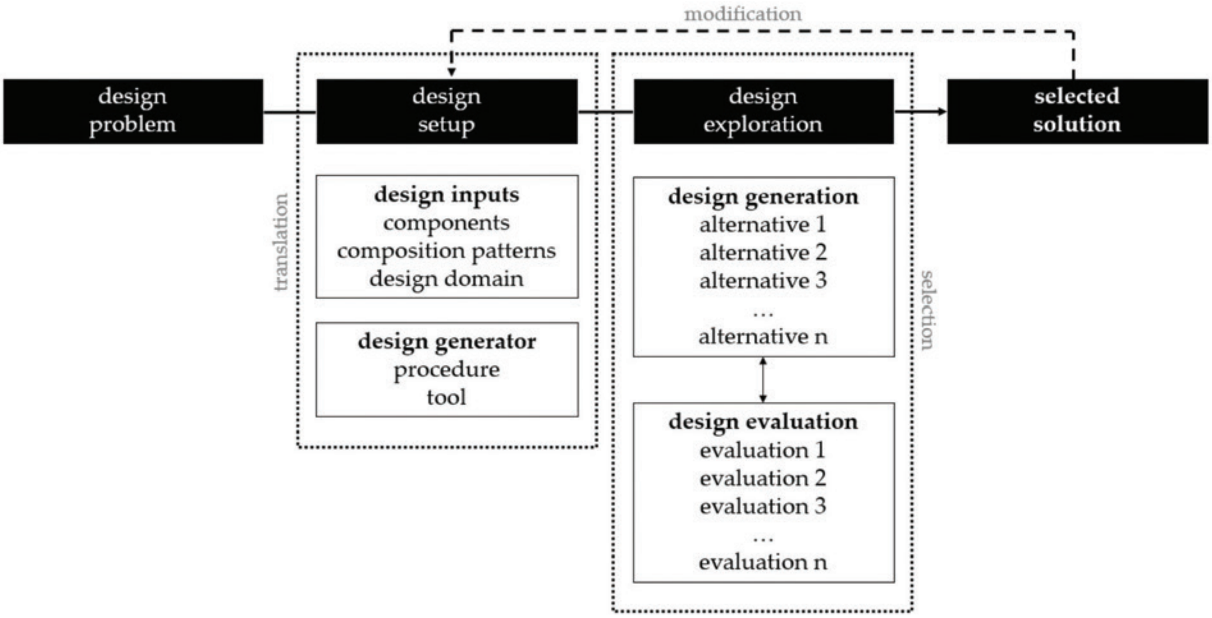

Fig. 1

Design Exploration

The design exploration is done by combining geometric representation and abstract graph information of individual components and applying different procedures for modular composition. It is additionally managed by manipulation of the parameters and design constraints. The rapid generation of the set of design proposals by design explorer enables testing, comprehension, and evaluation of their qualities, aesthetics, performances, and selection of the one for further elaboration. The comparison and evaluation of the design solutions could be subjective, based on authors preferences, or more objective, driven by the results and conclusions of diverse analysis (e.g., structural, environmental) in the case when certain measurable attributes of a solution could be used to describe design problem and objectives. Also, constraints imposed by the demands of fabrication could be introduced both in generation and evaluation process. The inclusion of performance-driven aspects to guide designers' decisions directs design process towards more sustainable solutions and increases efficiency of design and construction process. The process of evaluating solutions could be further automated by using optimization algorithms (e.g., evolutionary algorithms, genetic algorithms, neural networks).

Computer-generated compositions are produced based on an algorithmically determined system of rules (program instructions). In this process, the author allows the computational system to generate a series of alternative designs while maintaining the role of determining the rules. Although compositions emerge through the autonomous assembly process, the design relies on computer-designer collaboration. The Assembly process is bottom-up, but it can be combined with a top-down modeling strategy, enabling designers to control and direct the exploration process. Respectively, the author's preferences and control are included in every step of the design process, from the setup (definition of components, composition patterns, and design domain) to the selection of the final solutions. The author is in power to navigate the exploration process by modifying setup parameters and constraints, and thus interactively explore solutions. Although results emerge in controlled processes, they are not predetermined, leaving room for the unexpected.

The overview of the framework is illustrated in Fig. 1.

RESULTS AND DISCUSSION

Implementing the proposed framework was performed as a part of the larger design research project that investigates applications of generative design methods in architecture. The effectiveness of the proposed design framework has been tested in a learning environment focusing conceptual stage of architectural design process. Besides the thematic framework, the brief included specification of design location and program – an additional facility for research and education, within the complex of the Scientific-Technological park in Belgrade, Serbia. The brief's flexibility allowed examining diverse concepts and, consequently, the versatility of the framework and its adjustability to application in design exploration of different types of component-composition relations.

Following the general framework and previous objectives, the design process was performed through the following activities:

- definition of the design exploration construct (components, composition rules, domain, procedure, tool),
- design exploration, and
- design evaluation (FEM and construction of small-scale prototype).

Design Exploration Construct Development

After analyzing the context and expression of the design intentions and concept, the following step was to translate them into data and instructions of the algorithmically determined generative system (components, composition rules, and design constraints). As a medium for translating abstract design intention into an architectonic concept, physical models were used because they are receptive to designers, who need a flexible, intuitive, and interactive medium to test their ideas at the beginning of the design process. The physical models' role was to enable us to investigate possible rules underlying discrete compositions (bottom-up approach), intuitive formal studies, and expression of design intent (top-down approach). Respectively, the task was to produce different structures by repeating discrete elements. The preparation step for the model studies included developing a production strategy involving selecting materials for elements and joining that can adequately represent module and explore the part-whole relationship. Modeling was based on the trial-and-error method. The outcomes were a range of architectonic structures that expressed the initial design concept in terms of certain qualities of discrete elements and possible composition principles (Fig. 2).

Experiments with physical models were useful mediums for communication of initial design patterns. Formations obtained in this way were highly dependent on the materials selected to represent elements and techniques used for their connection. Elements were custom-made or ready-made, and connections enabled relatively fast assembly and disassembly in the iterative form-finding process. Form manipulations were carried out by changing the distribution and number of elements. The research through this medium can have certain advantages over formal studies in the digital environment since physical models have a real character, and their flexibility facilitates adaptation of elements and detection of solution's weaknesses/advantages. Promising research towards digital modeling advancements is Project DisCo [48], which applies spatial design of compositions from modular building blocks into Virtual Reality (VR), allowing designers a more interactive and intuitive approach.

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[48] Project DisCo. Available online: https://project-disco.com/

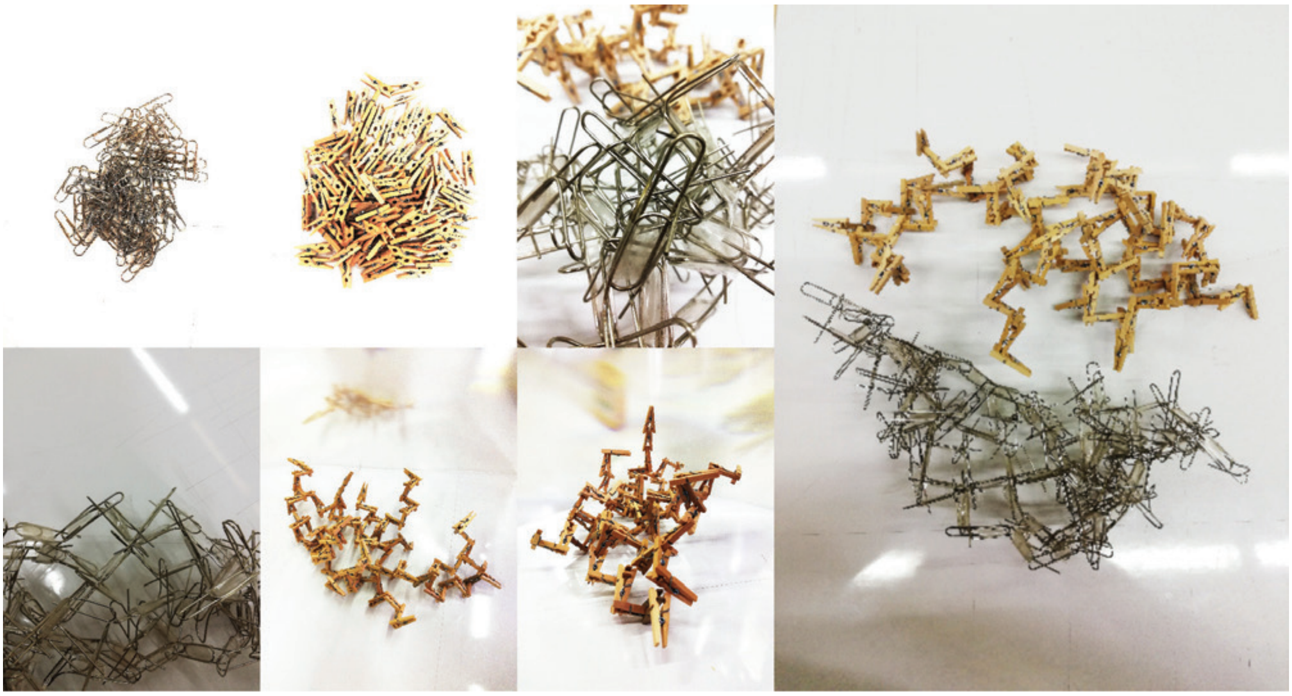

Fig. 2

Application of physical models did not determine the final geometry, but rather for its approximation and studying of the representation scheme that was further elaborated and applied in a computational environment. Respectively, the following step was the definition of algorithms and their implementation, which involved creating Grasshopper definitions for autonomous productions of compositions. For constructing definitions, we applied Wasp's [49] and Fox [50] components. The developed codes (GH definitions) include components that enable generating architectonic structures from one or multiple elements, based on predefined rules, by applying stochastic, field-driven, or graph-grammar aggregation. The basic algorithm must include components that define elements, composition rules, aggregation, and visualization, while the constraints could be used optionally to introduce more control in the composition growth.

The mesh geometry applied for the component's representation can be drawn in Rhinoceros. Each component must include topological information on connections. The set of connections determines the module's topological graph, which is then used to define the composition possibilities with other modules. The rules are instructing which connections are allowed to be made during composition. The rules could be generated from parts names and connection ids or text springs. There is also an automated rule generator that creates rules between connections of the same type (if no grammar is provided), or between connections of different types, according to the specific grammar rules. Automated rule generation creates versatility; however, sometimes, it can produce spatial solutions that are hard to interpret architecturally, so, in order to introduce more control to the form-finding process, in some instances, it is more convenient to specify rules that will limit undesirable connections. Rule definition, along with the specification of the number of elements in the composition, regulates the generation process.

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[49] *Ibid.* 44.

[50] *Ibid.* 47.

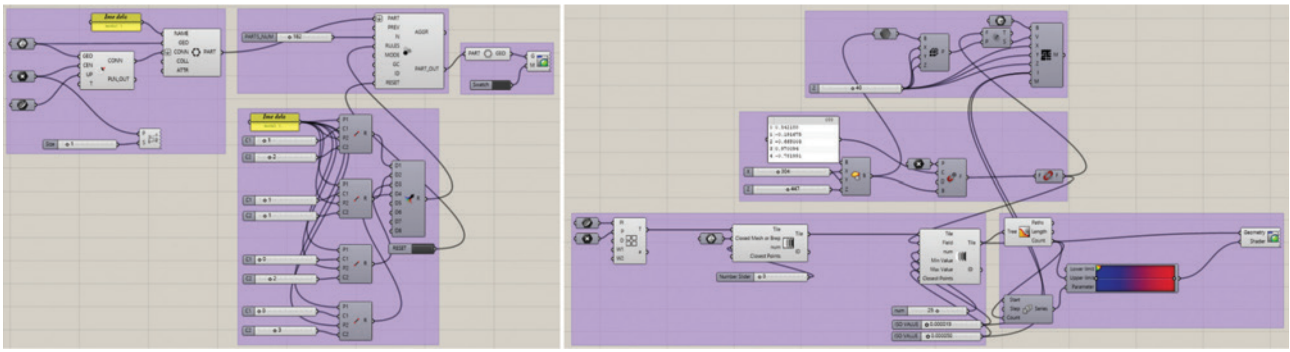
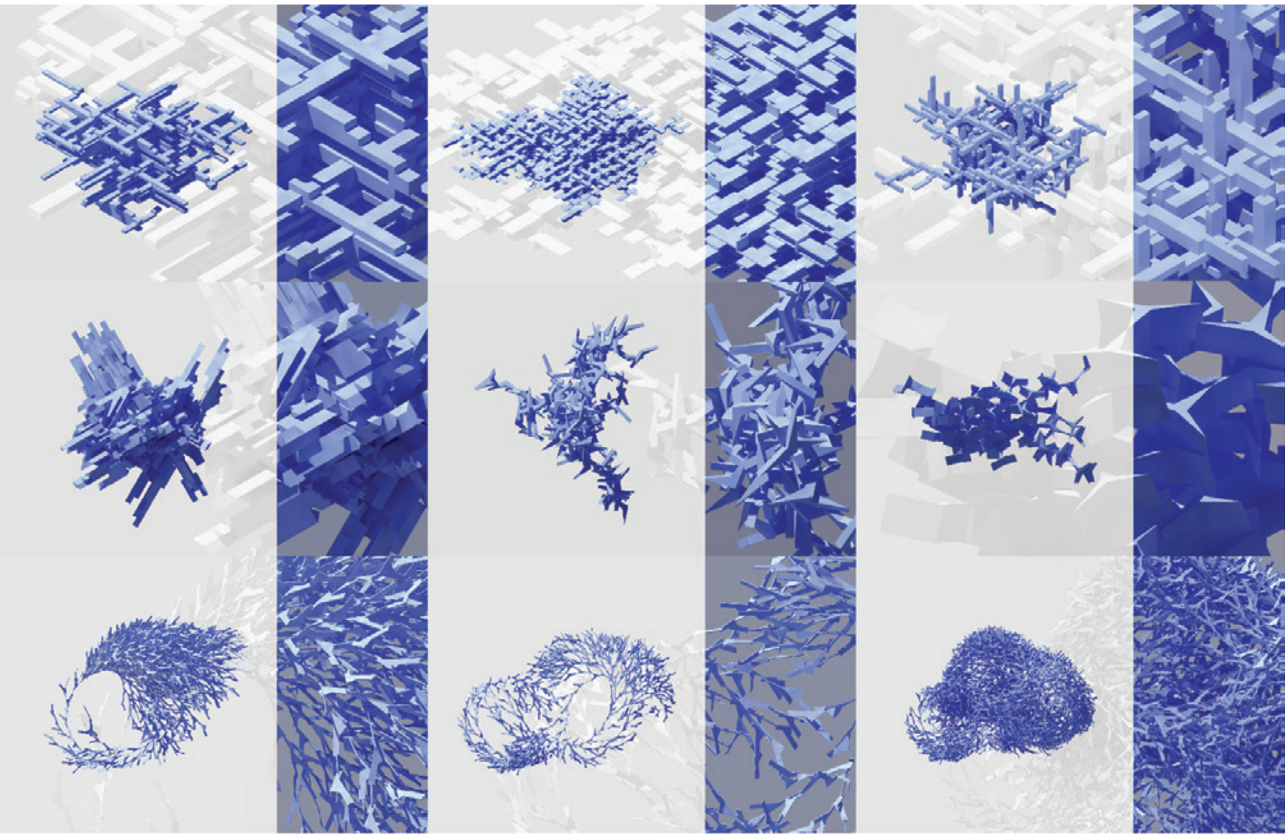


Fig. 3

The constraints could be represented by 2D plane geometry, limiting the composition growth to space on its selected side (positive or negative), 3D volume represented by mesh geometry, limiting the growth inside or outside the body, or iso-surface. The boundary constraint could be imposed as hard or soft. In the first case, the entire component must be within the boundary, while only its center is in the second. Aggregation procedures are composed of strategies for selecting simple composition rules, defined as an instruction to orient one component over another component's selected connection. Visualization of the results (a set of information) of these additive composition processes based on randomization represents emergent composition geometry. Custom GH definitions using Wasp or Fox components were developed (Fig. 3) to conduct design explorations (Fig. 4).

Fig. 4



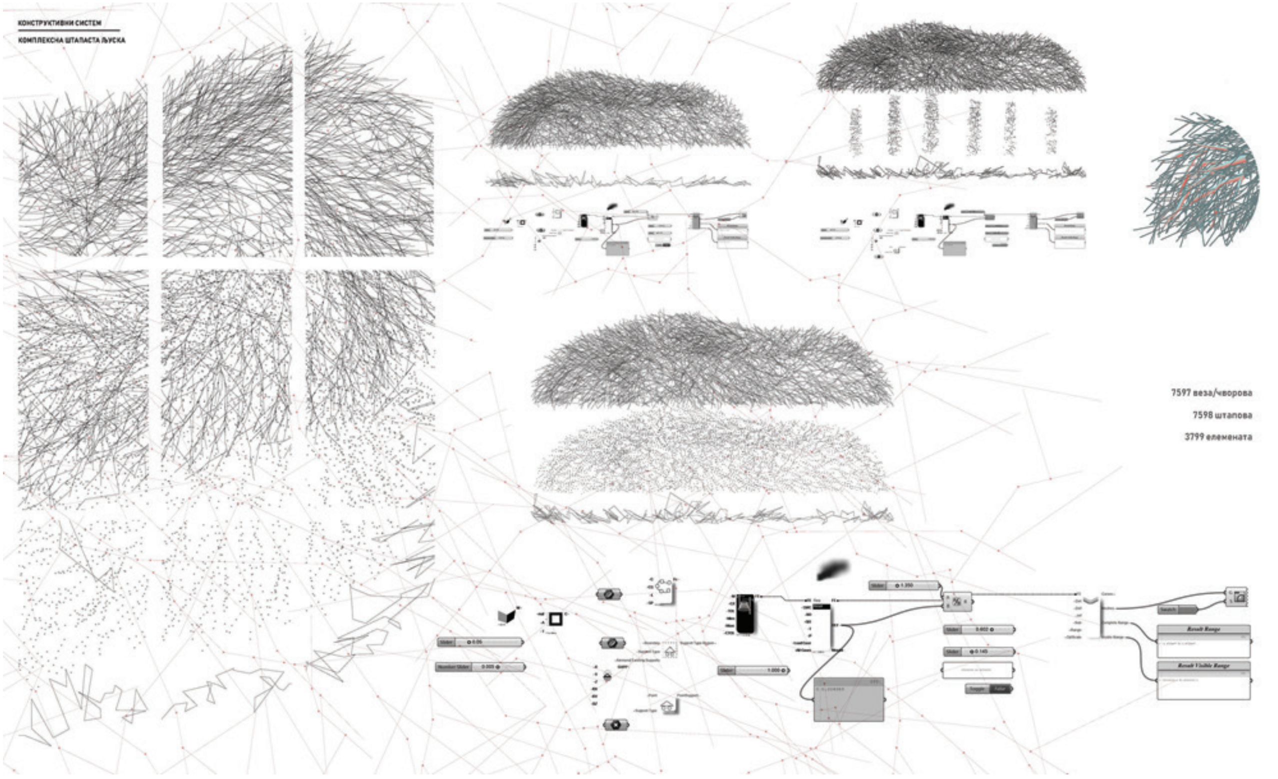


Fig. 5

Design Evaluation

The design was evaluated using FEM; this method is standardly applied to analyze performances in the design of spatial structures [51, 52]. A custom GH definition was created for the structural analysis using Millipede [53], Grasshopper plug-in for structural analysis and optimization. This plug-in enables linear elastic analysis of frame and shell elements in 3d or 2d plate elements for in-plane forces and 3d volumetric elements. The GH definition for structural analysis contains segments of conventional FEM algorithm – preprocessing, processing, and postprocessing. In preprocessing finite element mesh, boundary conditions, cross-sections, and material properties are defined. The analysis was conducted for the self-weight of structures made of linear elements with rectangular cross-sections. The results of the linear elastic analysis conducted by the solver are numerical values of deflections (but also bending moments and stresses values) and diverse options for visualizations of results. Based on structural analysis, results informed modifications and improvement of the proposal in the iterative design process (Fig. 5).

The construction of a small-scale prototype enabled us to evaluate the architectural qualities of the selected design proposal and verify, to a certain extent, structural efficiency and construction approach. A 90 x 60 cm segment of the spatial structure was constructed with 461 identical parts, each measuring 8.5 cm in length and laser cut from carboard (Fig. 6). The digital model and custom GH definition were applied for considerations of construction strategy and the model preparation, and the ele-

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[51] M. Nestorovic, P. Nestorovic, J. Milosevic, "Performance Based Approach in Design of Freeform Space Structures". In: *Facta Universitatis, Series: Architecture and Civil Engineering*, vol. 15, no. 2, 2017, 153 – 166.

[52] J. Milosevic et Dj. Nedeljkovic "Computational Design and Analysis of Tensegrity Structures", In: *Serbian Architectural Journal – SAJ*, vol. 9, no. 1, 2017, 1 – 20.

[53] Grasshopper Docs, Millipede. Available online: https://grasshopperdocs.com/addons/millipede.html

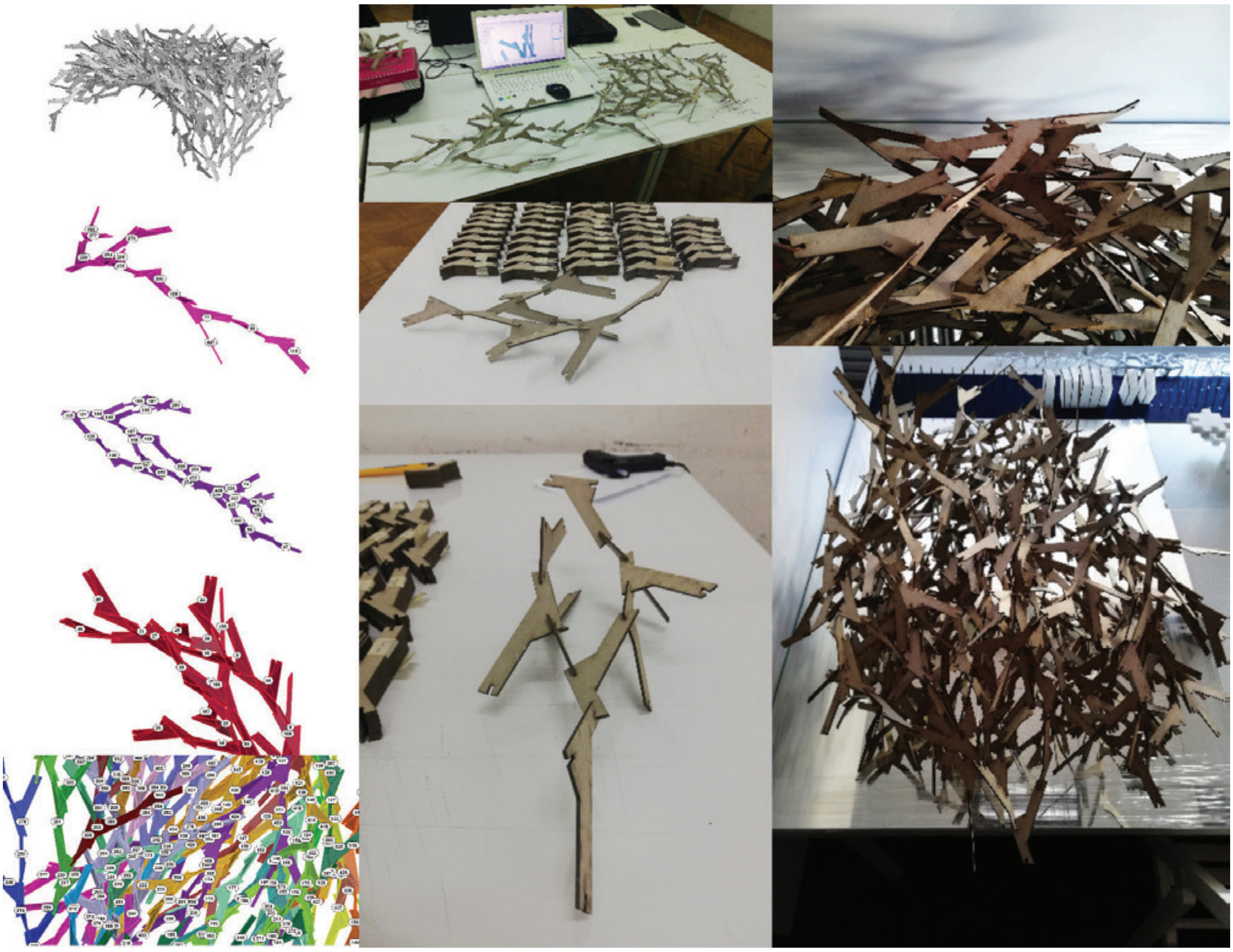
Fig. 6

ments were assembled manually. Although modularity introduced effectiveness in the construction process, further research in automation of this process is needed to increase productivity.

DISCUSSION

The presented design research has two types of results:

- process – the digital design framework, and
- products – form explorer and discrete compositions.

We can make an analogy between these outcomes and concepts used in Object-oriented design (OOD). Respectively, the process could correspond to the *object-oriented design strategy*, form explorer is equivalent to the *objectile*, while the composition is an actual artifact and matches the *object*. Furthermore, listed research outcomes have a different degree of usability. While the process is an experience that can be re-used in another design situation, form explorer (*objectile*) should be re-cycled and adopted to a different problem, and compositions (*objects*) are integral to the particular design (re)search.

Allocation of autonomous computational systems in the creation process and different types of results introduce, correspondingly, a possibility for multi-level authorship in design research, discussed by Carpo [54]. In contrast to the conven-

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[54] *Ibid.* 7.

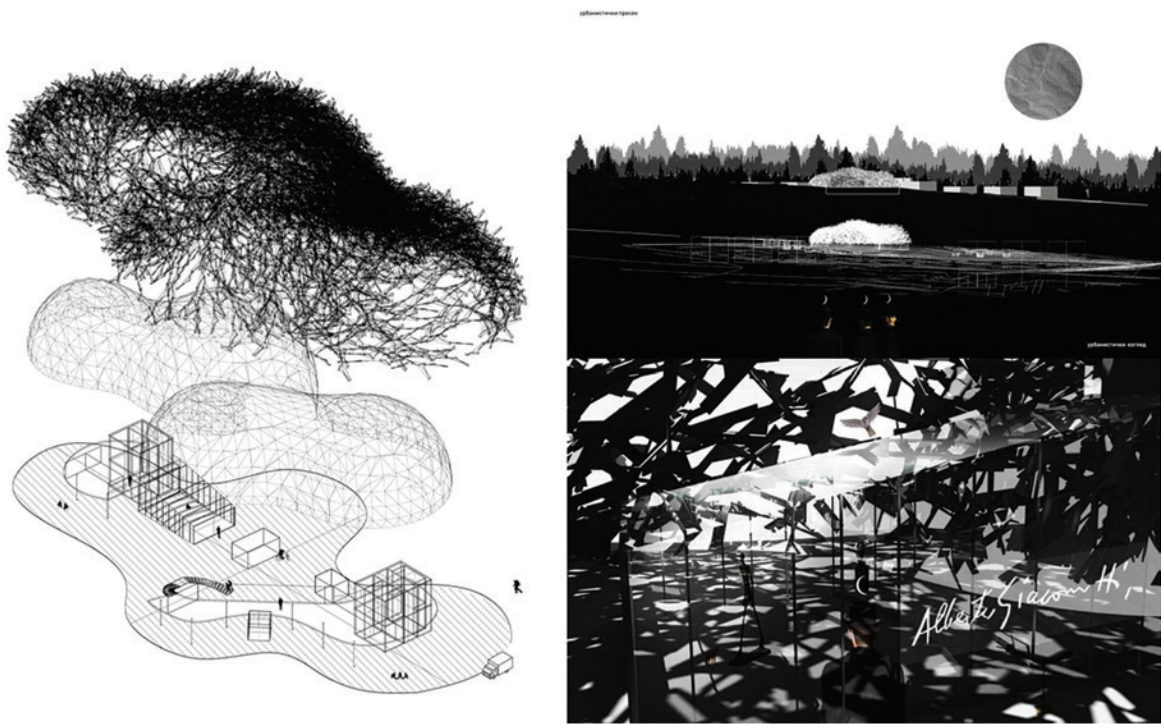

Fig. 7

tional approach in which the relationship between the subject (designer) and the object (artifact) is mostly direct, the process of generative design requires creating a generative mechanism that mediates the object's creation. In other words, it is possible to recognize authorship on the level of design research strategy proposal, then on the level of production of the exploratory system (e.g., algorithm or code), and on the level of design/artifact produced by manipulating code parameters.

This study demonstrates that proposed framework could be a suitable method for synthesizing architectonic structures. Applied generative procedure facilitate production of diverse outcomes expressing geometrical relations between discrete components. The geometric output is flexible in its variation, sizes, number of units. Architectural qualities are accomplished through the friction and overlap of compositional elements and the aesthetics of jamming (Fig. 7). Furthermore, the method can be applied to investigate diverse relations (structural, formal, functional) and implemented to produce formation at different scales (from material, through architecture to urbanism).

CONCLUSIONS

The exploitation of the computer's capability to process large amounts of information opens opportunities for developing different design strategies. This research reviews the generative design framework for design of complex discrete architectural structures. Presented approach should not be solely perceived as a means to intensify form and create aesthetics of jamming, but as a problem-solving design strategy, which could increase efficiency and detail. Also, this approach relies on designer-computer interaction to drive parametric digital modeling. Designers define processes and design constraints, built tools, and explicitly select designs out of the range of solutions that emerged in the shape exploration performed by the computational tool. On the other hand, the computational tool augments the designer's performance and finds solutions beyond his/her perception or experience.

There are various directions for further research. Additional studies on part-to-whole relations and compositions could be done. For example, research focused on the inclusion of qualities based on objective external information (such as physical or material) that could affect the configuration. This approach is beyond components derived from abstract archetypes [55] and towards customized components that adapt to local tolerances and other unpredictability. The computational procedure could also be further developed by integrating geometrical and topological information with data from performance simulations (e.g., environmental) into a coherent information model. This combined model would comprehensively render formation behavior and reduce the need for abstract concepts of ordering and arranging. Additionally, optimization algorithms could be used to automate evaluation and search for solutions [56]. Finally, additional work on the sustainability of the mereological approach should be carried out regarding the new relations in architectural design and construction driven by automation [57]. Structures made of autonomous modules and repeated non-redundant processes of composition have the potential to increase the efficiency and economy of the fabrication, transport, and construction time.

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ILLUSTRATIONS

1: Overview of the design framework.
Преглед оквира дизајна.
2: Research of a part-to-whole relation using physical models.
Истраживање односа делова и целине коришћењем физичких модела.
3: An example of a costume Grasshopper definition that facilitates generation of spatial structures.
Пример дефиниције костима у апликацији Grasshopper којим се олакшава генерисање просторних структура.
4: Examples of generated spatial structures.
Примери генерисаних просторних структура.
5: Structural performance evaluation.
Процена структурних перформанси.
6: Construction of a small-scale prototype.
Конструкција прототипа малих димензија.
7: Conceptual architectural design visuals – exploded axonometric, ambience renders
Визуелни прикази идејног архитектонског дизајна – разложени аксонометријски, амбијентални рендери

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[55] *Ibid.* 16.

[56] J. Mukkavaara et M. Sandberg, "Architectural Design Exploration Using Generative Design: Framework Development and Case Study of a Residential Block". *Buildings* 2020, *10*, 0201.

[57] A. Andia et T. Spiegelhalter, *Post-parametric Automation in Design and Construction*, Norwood, MA, USA, 2014.

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ABBREVIATIONS

CAD – Computer Aided Design
FEM – Finite Element Method
VR – Virtual Reality
GH – Grasshopper
2D – two dimensions
3D – three dimensions

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ДИСКРЕТНИ КОНТИНУИТЕТИ: ГЕНЕРАТИВНА ИСТРАЖИВАЊА КРОЗ ПРОЈЕКАТ ПРОСТОРНИХ СТРУКТУРА У АРХИТЕКТУРИ

Резиме: Изазови са којима се архитектонско пројектовање суочава у дигиталној ери подразумевају повећање комплексности пројеката и захтевима за примену за ефикасних пројектантских методама и алата. Овај рад доприноси истраживањима у области генеративног рачунског пројектовања дискретних склопова и њиховој примени у изградњи просторних структура у архитектури. Дискретна архитектура је приступ који се односи на рачунарско манипулисање дискретним елементима архитектонских објекта који су репрезентовани у форми вишезначних, адаптибилних и скалабилних дигиталних података. Дискретна архитектура користи предности дигиталне економије и аутоматизације како би допринела демократизацији производње и повећању доступности, препознајући потенцијалне економске, социјалне и културне импликације. Истраживања и пројекти орјентисани на тему дискретне архитектуре и архитектонске онтологије указују на потенцијале које нуде комплексне, прилагодљиве архитектоничне структуре који настају као резултат дигиталног склапања елемената. У оквиру овог рада, тема композиција од дискретних елемената истражује кроз креативни процес. С тим у вези, рад испитује могућност употребе генеративних система заснованих на формализму граматике графова у стварању прилагодљивих просторних конфигурација у архитектонском контексту. Приступ је тестиран коришћењем методе истраживања кроз пројекат у коме се рачунски генеративни систем користи као уграђени систем за истраживања форме просторних структура. Као генеративна процедура у истраживању се користи граматика графа. У овој процедури полазећи од спецификације дискретних елемената / модула и њихових атрибута, затим дефиниције правила и ограничења њихове композиције, стохастички алгоритам случајним одабиром модула и правила на свакој итерацији адитивног процеса генерише различите просторне структуре. Просторне структуре од дискретних елемената генерисане на овај начин поседују особину емергенције, континуитета, али и нови ниво материјалности, детаља, структуре, функционалности и естетике који су својствени процесу пројектовања који је заснован на интеракцији дизајнера и рачунара. Структурне перформансе композиција оцењене су помоћу софтвера заснованог на Методи коначних елемената (МКЕ), такође конструкција је у одређеној мери проверена и кроз израду прототипа у малој размери. Предметно истраживање је омогућило проверу специфичне пројектантске методологије, као и испитивање потенцијала дигитално интелигентне архитектуре.

Кључне речи: генеративни дизајн, архитектонско пројектовање, просторне структуре, дискретна архитектура, дискретни аутомат