doi.org/10.62683/SINARG2025.115

Research paper

MOSAIC SAMPLING: GENERATIVE SCHEME FOR SPATIAL STRUCTURES DESIGN

Jelena Milošević[1], Maša Žujović[2], Milijana Živković[3], Marko Gavrilović[4], Andrej Josifovski[5]

Abstract

Because of their construction efficiency, regular tessellations are standardly applied in the design of discrete spatial structures. However, digital fabrication enables the application of intricate patterns that may be structurally even more rational, such as patterns based on isostatic (principal stress) lines, or the application of patterns inspired by nature. This study explores the potential use of ornamental patterns in the design of spatial structures' mesh geometry. A generative design tactic based on structural form-finding is suggested, wherein structural mesh geometry is created using mosaic samples. While computational form-finding is typically used in spatial structures design, the suggested design tactic is unique because it uses the sampling concept to define a generative system. In this context, sampling is an act of taking a fragment, or a sample, of one design and its implementation in different design solutions. Specifically, a series of mosaic designs were used to derive initial mesh geometry applied to the form-finding of spatial structures. Since form-finding directly links configuration with force in a closed loop, structurally rational designs are produced from the initial mesh patterns derived from mosaics. The effectiveness of the suggested approach was tested through design explorations. Further, the approach may also be extended to other patterns that are not conventionally used in the design of spatial structures.

Key words: *Generative Design, Form-finding, Spatial Structures, Structural Geometry, Sampling, Sampler, Pattern, Mesh, Mosaic*

[1] PhD, Assistant Professor, Univeristy of Belgrade – Faculty of Architecture, Serbia, jelena@arh.bg.ac.rs, ORCID 0000-0001-7293-8194
[2] MA, Research Assitant, Univeristy of Belgrade – Faculty of Architecture, Serbia, masa.zujovic@arh.bg.ac.rs, 0000-0001-6346-5102
[3] MA, Teaching Assistant, Univeristy of Belgrade – Faculty of Architecture, Serbia, milijana.zivkovic@arh.bg.ac.rs, 0009-0009-7191-417X
[4] MA, Research Assitant, Univeristy of Belgrade – Faculty of Architecture, Serbia, gavrilovic@arh.bg.ac.rs, 0009-0008-4427-2039
[5] PhD, Assistant Professor, Univeristy of Belgrade – Faculty of Architecture, Serbia, andrej@arh.bg.ac.rs, ORCID 0000-0002-7390-9579

1. INTRODUCTION

Application of digital technologies, transfer of knowledge and appropriation of methods, processes and procedures form other disciplines demarcate current architectural discourse, requiring our revision of conventional design processes and design tools. Implications are displacement of design process in the simulative and interactive environment, implementation of hybrid strategies and production of unconventional designs.

This paper presents the research on application of generative strategies in design of discrete spatial structures, grid shells, i.e., structural systems composed of linear elements [1]. Generative design in this paper is related with the discourse of structural performances, since spatial structures are form-active structural typology [2]. Since form of these structures are determined by stresses [3], the sustainable approach to their design is application of form-finding. Respectively, generating space structures represents process in which form emerges through modelling of their physical behavior by applying diverse modelling techniques. In contrast to the conventional designer-controlled process of shaping, forms that emerge from these self-organizing processes are influenced by the design of their boundaries. Instead of explicit decision of the designer, simulations of the influences and constraints manage modification of the model parameters and lead to the improvement of the geometry on the bases of feedback information.

Until the development of digital design and fabrication technologies [4, 5], regular tessellations were mainly used in the design of spatial structures because they were rational from both a design and construction perspective. Application of digital technologies opened opportunities for realization of unconventional spatial structures' mesh designs [6, 7, 8, 9].

The aim of this research is to define and apply generative design strategy based on the concept of sampling. Starting from the premise that mosaic, initially decorative patterns, could be applied for mesh topology of spatial structures, the task was to select patterns that have design potentials, to derive mashes for space structures form the selected mosaic patterns, and generate unconventional designs using form-finding. Additionally, this research contributes to the review of the relation between form and force, by analyzing correlation of mesh topology of equilibrium shapes and stiffness of the structure (deflections), and comparison of structural behavior. Exploration construct that manages this generative process, was implemented by application of computational tools.

This research demonstrates that, though form-finding processes follow precise rules and contain optimization by their natural description, they could be used as creative design tools in architecture. Furthermore, research demonstrates that application of mosaic patterns for construction of mesh topology offers range of possibilities and combination of design processes. Finally, study identifies impact of topology change onto structure's load paths so that these relations can be manipulated through design production.

2. METHODOLOGY

2.1. Form-finding as medium for design of the discrete space structures

Form-finding could be defined as: *Finding shape of equilibrium forces within defined boundaries, and in relation to the defined stress state* [10]. Generally, it represents a method in which after setting certain geometric parameters, boundary condition, load and desirable stress and deflection constraints, starts a process of finding equilibrium shapes.

Development of form-finding methods is in relation with shape resistant structural typologies [11]. Deployment of lightweight structures, especially from the mid of XX century, in a certain way, provoked engineers to experiment. In that period Otto proposed design strategies inspired by nature [12]. Historical examples of Gaudi, Isler, Otto and others demonstrate that in order to design and test some of their innovative design solutions, they developed original form-finding methods.

Since 1960s the constraints manual experiments were replaced by more efficient, reliable, precise, and flexible computational simulations based on numerical methods. Design in computational environment, facilitated simultaneous analysis of diverse design demands, setting of large number of goals in form-finding processes, and explorations that are frequently on the interactive bases, implying change of the role of form-finding tools from problem-solvers to from-explorers.

The distinction between form-finding techniques could be made with respect to the medium on analogue and digital; or with respect to the concept on analytical (geometrical and mathematical), experimental (inverted chain models, tension and pneumatic membranes), and others (sculptural forms, simulation of the shells form nature). Generally, form-finding methods could be based on principle of the inverted chain, stress control concept or structural optimization.

In their simplest set-up form-finding methods both analogue and digital generate catenary curves or simple hanging forms. The hanging chain models are fascinating by their variety, structural performance, reduction to the minimal in terms of material use and resources and their peculiar aesthetics. Together these perimeters represent the common basis of a potential design or design concept and characterize its grade of sustainability.

Particle-Spring System (PS) is computational form-finding method applied in this work.

2.1.1. Particle-Spring System

Particle-Spring was applied for form-finding in the context of architecture by Kilian and Oschendorf in 2005 [13]. This system is initially developed for computer graphics [14]. Programs for animation use this technique, for animation of elasticity or plastic deformations of solids and creation of visually realistic preview of physical effects. In last decades it found application in modelling of physical performances of architectural systems. In this basis a number of conceptual design tools that enable experiments through simple digital models were developed.

Like in all dynamic equilibrium methods, in PS problem of dynamic equilibrium is reduced to static equilibrium problem (systems in the steady state), so obtained solution is equivalent to the static equilibrium. PS is Lagrangian based mesh method, i.e., the model is composed of the set of points that change their position.

PS system is composed of two elements: (1) dimensionless points in space – particles that are connected with (2) linear elastic rods – springs. Each spring has its rest length, i.e., span between two particles that it connects and stiffness that is assigned to the spring as the dampening factor. PS enables modelling variety of influences. Usually, in form-finding processes gravitational influences are modeled, or influences of the air pressure that replicate experiments with pneumatic models.

In the case of form-finding of equilibrium shapes due to the influences of self-weight (as in the case of this research), total mass of the system is modeled as concentrated mass in the particles. The value of the mass as well as initial non-equilibrium mash configuration are set at the beginning of the process. Influenced by the force particles start to move, mash starts to deform and oscillate. Because these displacements can quickly bring system in unstable state, in the case of modelling gravitational influences, it is necessary to specify dampening coefficients. After setting of oscillations resultant form represents approximate equilibrium shape of given system (Figure 1).

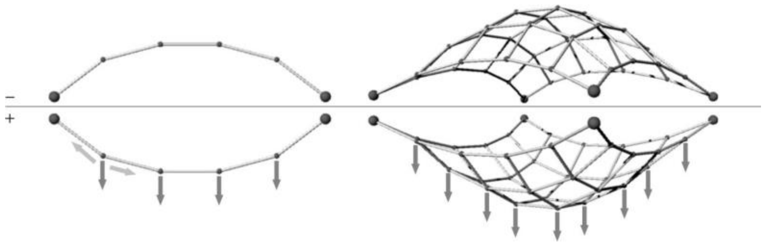


Figure 1. Particle-Spring setting into catenary form

Implementation of PS concept enabled creation various digital design environments. CADenary, created in 2002 on MIT in collaboration of several researchers, represents and example [15]. Its environment enables interactive three-dimensional visual research and dynamic simulations of catenary chains and meshes. Application of PS library in Processing programming language was also widespread option. Pikar developed Kangaroo Physiscs, plug-in for modeler Rhinoceros which is currently one of the most used tools in physically informed design processes.

2.2. Sampling as exploration construct

Creation processes frequently use strategies of transpositions of creative elements, such as intertextuality or appropriation. Sampling represents act of taking a fragment, or sample, of one design and reusing it in creation of new design solution. Through originally related to the music, sampling strategy is used in this research for design exploration in architecture. In Killian (2006), design exploration is described as steering the design using the design explorer through a solution space, where the target of the design coevolves with the driver, the design and the design space itself.

Without intention for generalization, design exploration could be described as two stage process. In the first stage the task is to focus and define design problem, to abstract and create set of rules and constraints, and to turn them into exploration system. The task of second stage is to exercise exploration system according to the rules and constraints. Design exploration concept of sampling, outlined in the paper, follows this scenario.

Applied sampling strategy, enabled exploration of design potentials of mosaic pattern in construction of initial mesh topologies for form-finding of discrete space structures. In this constellation mosaic patterns represent samples that are transferred from decorative arts to the context of architecture (Figure. 2). The modes of transposition of patterns could be from literal copying of compositions to a more abstract derivation of principles and finding of systematic solutions. The aim is realization design solutions with describable structural performances and aesthetic attributes.

Sampling was implemented through definition of design explorer – sampler and application of design elements – samples.

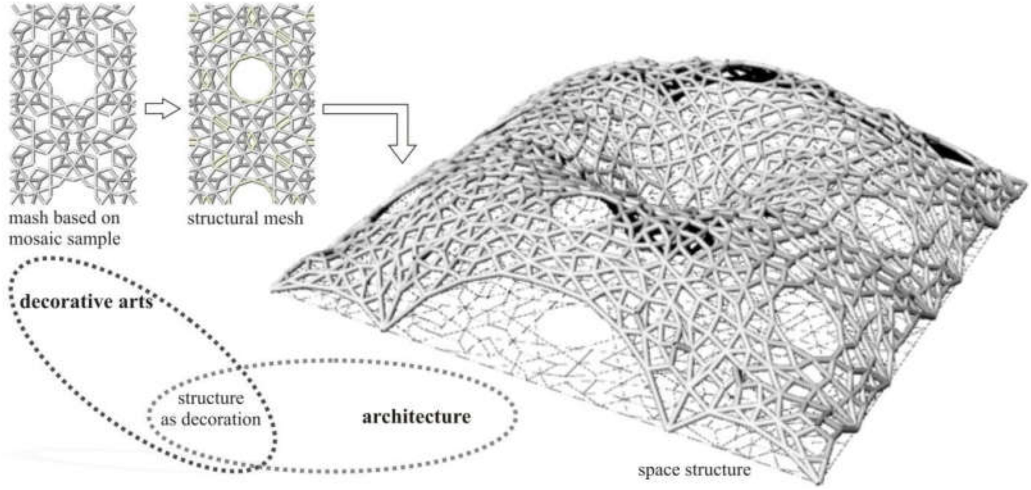


Figure 2. Sampling concept

2.2.1. Sampler

Sampler represents a computationally implemented design-driver. This design tool uses pattern samples in generation of mesh topology for form-finding of discrete space structures. In this work, mesh topologies are derived from the original patterns, but functionally of the sampler could be extended to modify original patterns in many different ways or to synthesize new ones.

Since the task of sampler is production of mesh topologies and form-finding, it is organized into a hierarchy of progressively more complicated data structure. At the bottom lay samples, individual patterns, at a particular rate and resolution. Samples may be arranged by defining rules of the repetition of the basic elements – polygons, allowing single or small number of elements to form tessellations. Parameters may be added to define how polygons are distributed in tessellations, as well as parameters that regulate change of the bar length and determine mesh density.

The sampler reproduces samples, as the first step of its algorithm. In the more developed version sampler could be synthesizer, a software that generates patterns algorithmically from mathematically described geometric elements. Sampler applies any of defined pattern samples and offer editing allowing designer to modify and process the design and apply a wide range of effects, which makes it a powerful and versatile design tool.

After generating mesh based on mosaic pattern the task is to conduct form-finding. Underlying form-finding techniques is particle-spring (PS), interactive computational method. As a result of this physics informed process emerges equilibrium form of space structure (Figure 3).

2.2.2. Samples

Samples represent patterns underlying generated mesh topologies. Samples are composed of regular or irregular polygons, and every tessellation could be decomposed on simple building blocks. Compositions could be: (1) *original samples* patterns co-opted from mosaics applied without modifications in design, (2) *re-samples*, custom patterns made by designer; (3) *synthesized samples*, computer generated artificial patters that resemble original.

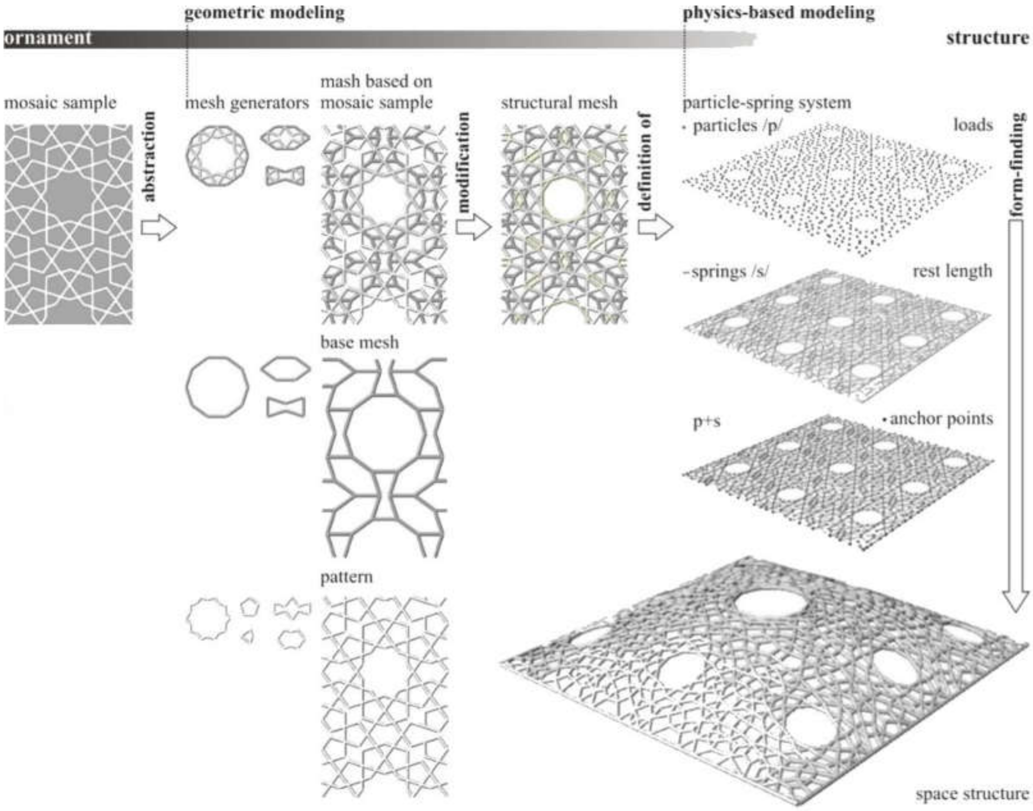


Figure 3. Flowchart of the process

Samples can be edited. Sampler should facilitate creation of costume elements, in order to enable for the designer to manipulate elements to match other part of the composition. Manipulation of elements is to extend range of their applicability. For example, to meet structural demands certain patterns must be modified by introduction of additional elements.

3. RESULTS

Previous methodology was applied to explore structures created form different mesh topologies for the same boundary conditions – supports and loads. Conventional regular mesh patterns, irregular mosaic patterns, and their combinations are applied for production of designs. Besides mesh topology, PS system require definition of spring stiffness and geometric lengths. Changing the parameters of the system influences the geometric shape outcomes as well as force distribution.

Generally, design exploration could be realized through the variation of the supports, loads (masses of the nodes), the length and strength of the springs, topology of the mesh and related discretization of load. Starting from the rectangular base 10x10m, defined supports along edges, and self-weight load case, the task was to monitor what happens with structure's form for different mash topologies.

To test correlation between form and mesh topology in self-organizing equilibrium structures variations of mesh topologies for the same hanging model surface were applied. The range of exploration covers regular tessellations, and irregular derived from mosaic patterns. The overview and the comparison of the results as well as the possibility of targeted selection are exploited as the basis for creative applications.

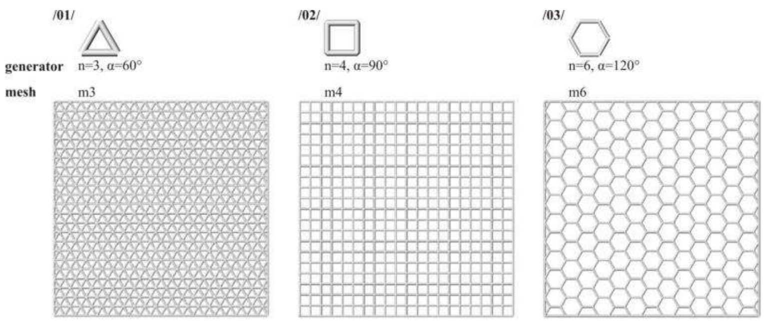
Modeling of structural was realized by application of PS system. First step in modeling of the system is definition of initial configuration. Initial configuration is described by the set of particles and rods/springs that connect them. In the next step points in which system is fixed are determined. Because the length of the spring cannot be anticipated, for the practical reasons identical loads are assigned to all nodes, in spite of the fact that varying the rest length of the spring imply that assignment of the identical values for the mass to each particle is wrong (i.e., particles that connect longer elements should be more loaded because they represent self-weight of the bigger part of the structure).

To demonstrate effectiveness of suggested approach several example patterns were selected. We started from regular patterns, composed of triangular, quadrilateral, and hexagonal polygons (Figure 4a). These patterns frequently represent underlying of base mesh in mosaic design. In the structural design these meshes are commonly applied.

Semi-regular pattern composed of triangular, quadrilateral, and hexagonal polygons that represents base mash, mosaic tessellation composed of irregular polygons and their composition were examined in this work (Figure 4b). Since these patterns does not represent conventional mesh in structural design, to produce mashes that meet structural demands modification were performed (Figure 4c).

After setting all model parameters, program generates flexible geometry, which deforms in order to take its equilibrium position. The obtained form represents schematic preview of the real structure. Of all parameters that determine equilibrium form and that could be varied such as position of the supports, number of nodes, number of geometric segments, length of spring elements, in this research we tested influence of the load path.

The generative system was implemented by application of Kangaroo Physiscs plug-in for Grasshopper, a visual programming editor for Rhinoceros modeler. Results of design explorations are for regular patterns are presented in Figure 5 and mosaic patterns in Figure 6a and modified mosaic patterns in Figure 6b.



(a)

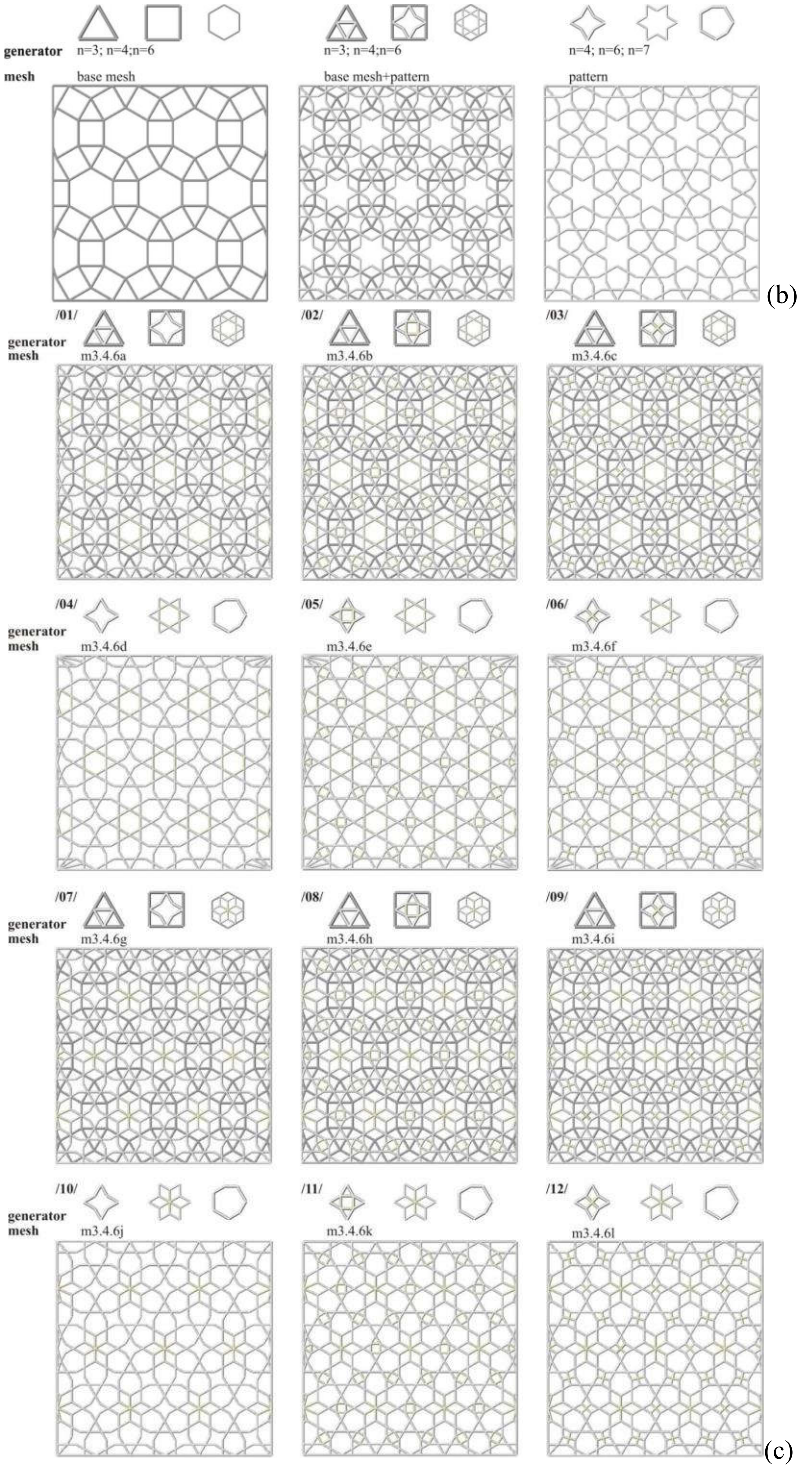


Figure 4. Samples made of regular (a) and irregular polygons (b,c)

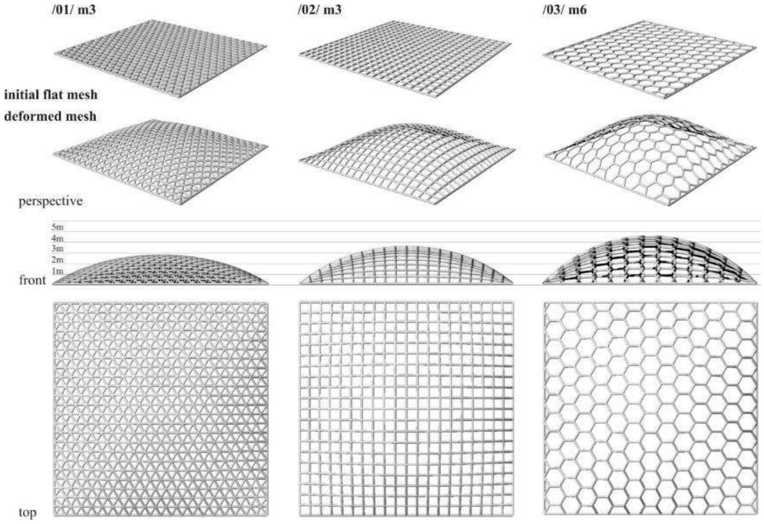
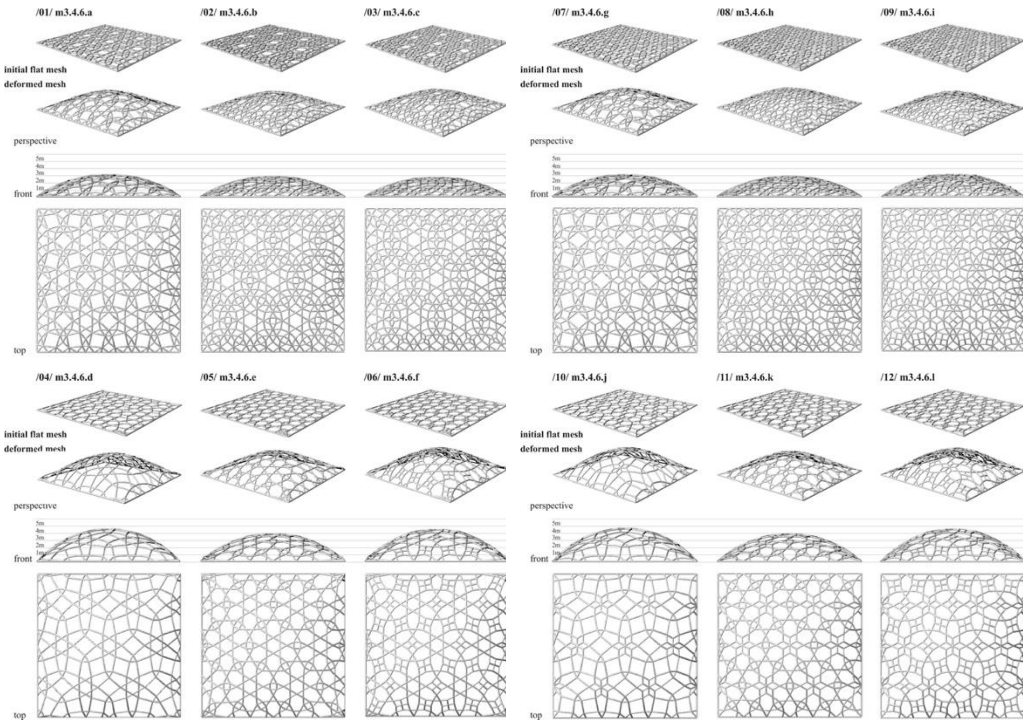


Figure 5. Result from form-finding for different topologies for the same plan, based on conventional regular meshes



(a) (b)

Figure 6. Result from form-finding for different topologies for the same plan, based on mosaic samples

4. DISCUSSION

Construction of the physical based models represents essential part of the design of spatial structures. Within this paper we investigated application of the computational methods in design. In this approach we replace the absolute goals of optimization with interactive, iterative approach which means use of same underlying algorithms. Such approach allows designers to selectively deviate from optimal solutions and explore design variations, found through discovery rather than precise analysis. Applied design approach enables designers to conduct explorations that overcome exclusively aspect of visualization. This research illustrates opportunities of form-finding techniques in design of equilibrium shapes, with the note that it is not simple to predict behavior of the real structure on the basis of the obtained results.

The starting topology and geometry represent the main interface for specifying the final form. Regular grids are often a starting point, or randomized triangulated meshes when using standard mash approach such as Delaunay triangulation. Due to their simple repetitive geometry and constant node valence, the most common default mashes are the quad grids. But they are not particularly well suited for form-finding. Take, for instance the case of an equally spaced rectangular grid, fixed at its four corner points, with an equal load distribution assumed using particles of equal mass. The mesh distorts extremely as it moves towards an equilibrium state.

Different mesh topologies, iterative re-mashing strategies, as well as iterative parameter adjustments could account for the possible deformations of the geometric mesh during the form-finding process. This does require a more complex set-up. Alternatively, one can set a topology and geometry close to the expected and result to reduce this deformation. Still, changing the mesh topology has a major impact on the resultant form, and so steering the design through topological variation is a regularly the most influential of all steering methods.

In comparison to the linear chains, structural behavior of the mesh is more complex. There is no one unique load path, multiple paths between supports and loads are possible, and no single determined solution exists. With the increasing mesh density, the behavior of the structure approximates that of the shell. The load paths in the spatial structure are very much dependent on the topology of the mesh and the geometry of the individual members. By changing of the topology, a singular dominant load paths could be avoided.

In the PS system the performance and dimension of a structure is integrally connected with its topology. Deformations of the spring could vary in dependence of it position in the mesh, so at the end of form-finding, mesh that was composed of elements that initially had equal length becomes mesh with elements of diverse lengths. Springs near supports frequently have larger deformations, which represents consequence of that all forces act in the particles that are hanged on the supports and could be corrected by increasing the stiffness of the springs.

In his research Isler find out that the 90% of the loads in his shells are traveling into the supports in the corners of his shells. The edge supports receive only a fraction of the weight. This is due to the varied stiffness of the shell areas and subsequent variant resistance to loading [16]. The optimization of compression-only structures does not guarantee evenly distributed loads. In his research Kilian explored influence of the topology in form-finding centenary forms [15]. Previous research demonstrate that change of the topology considerably influences efficiency of form.

This research demonstrates that mesh topology has a substantial effect on the form of the structure and on the distribution of forces within it. The mesh topology fundamentally influences the performance of the structure. Implying that optimization of the structure should not be restricted to finding of the most efficient form for a given topology, but to finding the most optimal topology for a given load case as well. Novel topology can challenge the starting conditions.

Topology studies may be a way to steer the design towards desired results with topologies reflecting the expected flow of force more closely. A change in the topology can have significant impact onto load paths in a structure. Therefore, the design cannot stop at optimizing geometry but has to address the optimization of topology as well. This could lead to introduction of topology-finding of structure in addition to form-finding.

5. CONCLUSION

Within this research we applied sampling concept in form-finding. We also examine influence of the topology on the resulting global structural form. Application of proposed strategy opens up infinite range of possibilities in creating of space structures with new architectural qualities like shown in case studies and experiments, leading to larger issues of goals for design intent rather than structural performance alone.

Computational form-finding techniques are usually conceived to simulate behavior of physical models. Advantages of current and emerging digital technologies expanded interest of the designers for unconventional space structures. The goal of proposed design strategy is to use computational methods to achieve more integrative design solutions, and to extend the canon of forms established through conventional analytical techniques.

In this research we used several patterns, to illustrate effectiveness of proposed design approach. Further development of the design strategy concept proposed in this paper is towards expanding vocabulary of patterns and development of computational tools. The expansion of the pattern vocabulary could be achieved by development of the comprehensive library/repository of patterns and generation of synthetic samples.

Sampling is not restricted to application of pre-existing patterns. Genetic coding could be applied for creation of artificial patterns and construction of dynamical complex generative system with a capacity to produce endless variations. Creating artificial DNA of mosaics could represent basis for generation of practically infinite number of different patterns. Like any morphogenetic process, it is based on a software to produce non-repeatable designs. From the rang of synthesized patterns the selection of design configuration could be done in order to both fit aesthetical and structural performance criteria.

The use of sampling could be controversial, because it opens the question of originality. While some may argue that sampling lacks originality, others may view it as a form of innovation. In any event, it is worthwhile to conduct additional research on how design might change as a result of applying different approaches and transferring design elements.

ACKNOWLEDGMENTS

This research was funded by the Ministry of Education, Science and Technological Development of the Republic Serbia, grant number 451-03-68/2020-14/200090. The research was done under the research units of the University of Belgrade – Faculty of Architecture, Laboratory for Innovative Structures in Architecture (LISA).

REFERENCES

[1] Otto Frei, Schauer Eda, Hennicke Jurgen, Hasegawa Takeshi: **IL 10-Gridshells**, *Institute for Lightweight Structures, University of Stuttgart*, 1974.

[2] Engel Heino, **Structure Systems**, 3rd ed. *Hatje Cantz*, 2007.

[3] Allen Ashley Batts and Leary Mark: **Self-Compassion, Stress, and Coping**, *Social and Personality Psychology Compass*, vol. 4, no. 2, pp. 107–118, Feb. 2010, doi: 10.1111/j.1751-9004.2009.00246.x.

[4] Kolarevic Branko, Ed., **Architecture in the digital age: design and manufacturing**. New York, *NY: Spon Press*, 2003.

[5] Willmann Jan, Block Philippe, Hutter Marco, Byrne Kendra, and Schork Tim: **Robotic Fabrication in Architecture, Art and Design 2018: Foreword by Sigrid Brell-Çokcan and Johannes Braumann**. Association for Robots in Architecture. *Springer International Publishing*, 2018.

[6] Adriaenssens Sigrid, Ney Laurent, Bodarwe Eric, and Williams Chris: **Dutch Maritime Museum: Form-finding of an irregular faceted skeletal shell – Part b**, 2009.

[7] Adriaenssens Sigrid, **Ney Laurent, Chapter two: Shaping Forces**, in *Shell Structures for Architecture: Form Finding and Optimization*, Routledge, 2014.

[8] Schling Eike, Hitrec Denis, Schikore Jonas, and Barthel Rainer: **Design and Construction of the Asymptotic Pavilion**, *VIII International Conference on Textile Composites and Inflatable Structures,* 2017

[9] Tracy Kenneth, Jandaghimeibodi Mahdi, Aleem Sara, Gupta Rahil, and Tan Ying Yi, **AVM Pavilion: A Bio-inspired Integrative Design Project**, in *Computer-Aided Architectural Design. Design Imperatives: The Future is Now*, D. Gerber, E. Pantazis, B. Bogosian, A. Nahmad, and C. Miltiadis, Eds., Singapore: Springer Singapore, 2022, pp. 494–512.

[10] Bletzinger Kai-Uwe, **Form Finding and Morphogenesis**, in *Fifty Years of Progress for Shell and Spatial Structures: In Celebration of the 50th Anniversary Jubilee of the IASS (1959-2009)*, International Association for Shell and Spatial Structures (IASS), 2011.

[11] Bechthold Martin, **Innovative Surface Structures: Technology and Applications**. *Taylor & Francis*, 2008.

[12] Otto Frei and Rasch Bodo, **Finding Form: Towards an Architecture of the Minimal**. *Edition Axel Menges.*, 1996.

[13] Kilian Axel and Ochsendorf John, ***Particle-spring systems for structural form finding***, *IASS*, vol. 46, no. 147, pp. 77–84, 2005.

[14] Reas Casey and Fry Ben, **Processing: A Programming Handbook for Visual Designers and Artists**. in Working paper series (*National Bureau of Economic Research*). NBER, 2007.

[15] Kilian Axel, **Design Exploration through Bidirectional Modeling of Constraints**, *Massachusetts Institute of Technology*, 2006.

[16] Chilton John and Isler Heinz, **Heinz Isler: the engineer's contribution to contemporary architecture**. in Engineer's Contribution to Architecture Series. *Thomas Telford*, 2000.