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АПЕРИОДИЧНА МОДУЛНОСТ В РАЗЛИЧНИ МАЩАБИ: ОТ МЕБЕЛЕН ПРОТОТИП ДО АРХИТЕКТУРНО ПРИЛОЖЕНИЕ

Парса Сохи

APERIODIC MODULARITY ACROSS SCALES FROM FURNITURE PROTOTYPE TO ARCHITECTURAL APPLICATION

Parsa Sohi [1]

Abstract:
This paper builds upon the research presented in the conference paper "A New Perspective on Modular Architecture" at DCB 2024, as well as the subsequently defended doctoral dissertation "Visual Complexity and Simplicity: Aperiodic Patterns and Geometry from Traditional Persian Architecture in the Context of Contemporary Modular Design." The study investigates the potential of aperiodic geometry to redefine modular design as a system of structured variation rather than repetitive standardization. Although modular construction offers significant advantages in terms of efficiency, prefabrication, and sustainability, its reliance on repetition often results in visual monotony and a loss of identity. Drawing on the geometric principles of traditional Persian architecture and contemporary aperiodic tiling systems, the research proposes an alternative architectural approach that preserves the benefits of modularity while introducing visual and spatial richness through non-repetitive structures.
The practical validity of this approach is demonstrated through the realization of the Aperiodic Mono-Tile Wine Table - a modular furniture system based on the recently discovered aperiodic Spectre tile. Fabricated using CNC technology and implemented in a real commercial environment, the prototype demonstrates how a single geometric module can generate multiple configurations while maintaining structural simplicity, adaptability, and visual coherence. Beyond its application in furniture design, the paper explores the scalability of aperiodic modular systems and their potential use in façade design, public spaces, and BIM-based design workflows. The findings suggest that aperiodic modularity can serve as a bridge between mathematical order, cultural continuity, and contemporary architectural practice, offering a viable alternative to both monotonous modular systems and formally uncontrolled complexity.

Keywords:
Modular Design, Aperiodic Geometry, Spectre Monotile, Modular Architecture, Computational Design, Digital Fabrication, Persian Geometric Patterns, Scalable Modular Systems

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1. INTRODUCTION

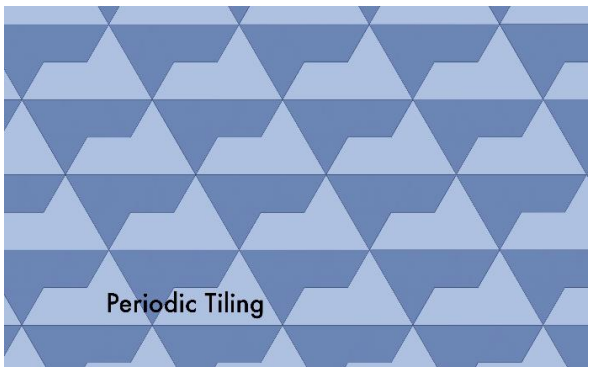
Modular architecture has become one of the most influential approaches in contemporary design and construction. Its advantages include reduced construction time, improved manufacturing precision, enhanced sustainability, and compatibility with industrialized building processes. However, despite these benefits, many modular systems continue to rely on repetitive arrangements that often produce visually monotonous environments. Throughout history, architecture has sought methods of balancing order and variation. Traditional Persian architecture offers particularly compelling examples of this balance through geometric systems that achieve remarkable visual complexity while adhering to strict mathematical principles, which are studied extensively in works by academics, like mathematician Syed Jan Abas and professor of architecture Keith Critchlow [1][2]. These patterns demonstrate that complexity can emerge from a limited set of geometric rules rather than from arbitrary formal manipulation.

The previous conference paper, New Perspective on Modular Architecture (2024) [3], introduced the possibility of integrating aperiodic geometric principles into modular design. The subsequent doctoral dissertation expanded this investigation through a detailed analysis of Persian geometric traditions and contemporary mathematical discoveries in aperiodic tiling [4].

2. MODULARITY BEYOND REPETITION

The modern understanding of modularity is largely associated with standardization, prefabrication, and mass production. As Architecture Professor Ryan E. Smith imply in his work, Modular systems typically employ identical units arranged through repetitive grids to simplify manufacturing and construction processes [5]. While repetition offers practical advantages, it frequently limits spatial diversity and visual engagement. Repetitive modular environments can appear uniform and predictable, reducing their capacity to respond to cultural, contextual, or experiential requirements.

The challenge therefore lies in preserving the efficiencies of modular construction while introducing greater diversity and adaptability. Taking a look at researches done by mathematicians Branko Grünbaum and Monique Senechal on Aperiodic geometry, it showcases that Aperiodicy offers a potential solution by enabling systems that remain modular while avoiding periodic repetition [6][7]. Unlike conventional modular arrangements, aperiodic systems generate structured variation. They maintain mathematical order while producing non-repeating compositions that create visual richness and spatial complexity.



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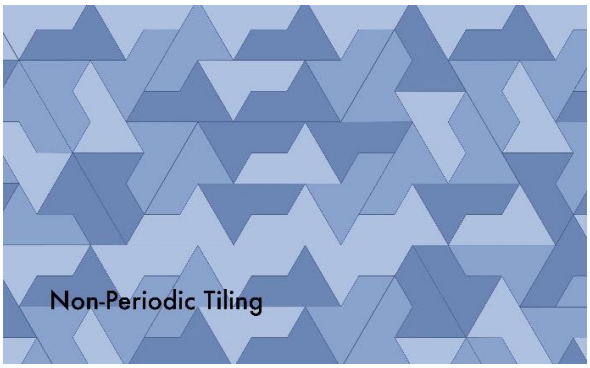


b)

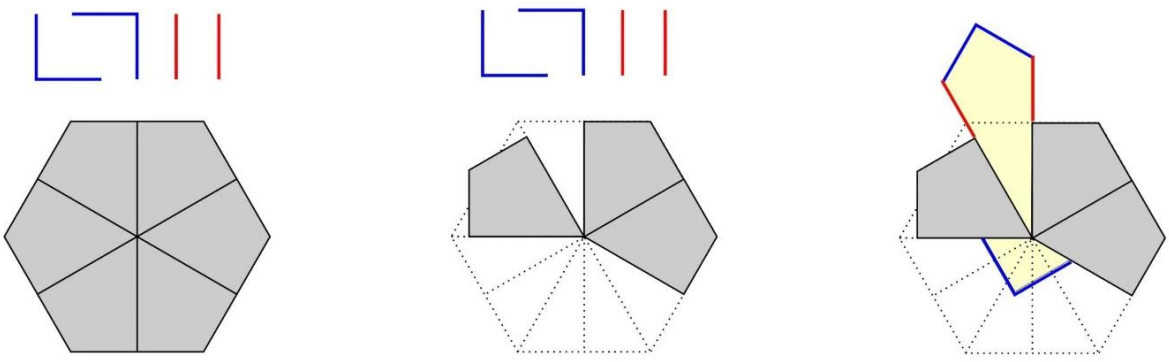
Figure 1. Comparison between conventional periodic modular systems (a) and non-periopdic/aperiodic modular arrangements (b) [8].

3. APERIODIC GEOMETRY AS A DESIGN FRAMEWORK

Aperiodic tilings occupy a unique position between complete regularity and apparent randomness. Although governed by strict geometric rules, they never repeat periodically across a surface [6][7]. The study of aperiodic tilings gained international recognition through the work of Roger Penrose during the 1970s [9]. Penrose demonstrated that two simple tile shapes could generate infinitely non-repeating patterns while maintaining local geometric consistency.

More recently, Craig Kaplan and collaborators discovered the “Hat” tile and subsequently the “Spectre” monotile, representing one of the most significant breakthroughs in tiling theory in recent decades [10]. These discoveries possess important implications for architecture. Rather than relying on multiple unique components, aperiodic systems can achieve diversity using a limited number of repeated manufacturing elements. Interestingly, similar principles can be observed in historical Persian architecture. Geometric compositions found in mosques, madrasas, and palaces demonstrate sophisticated approaches to organizing complexity through mathematical order. While not strictly aperiodic in the contemporary mathematical sense, these systems reveal a long-standing architectural interest in balancing unity and variation.

Figure 2. Geometric patterns from traditional Persian architecture (adapted from Abas & Salman [1] and Critchlow [2]) images by architecture photographer @ghasem.baneshi [11].



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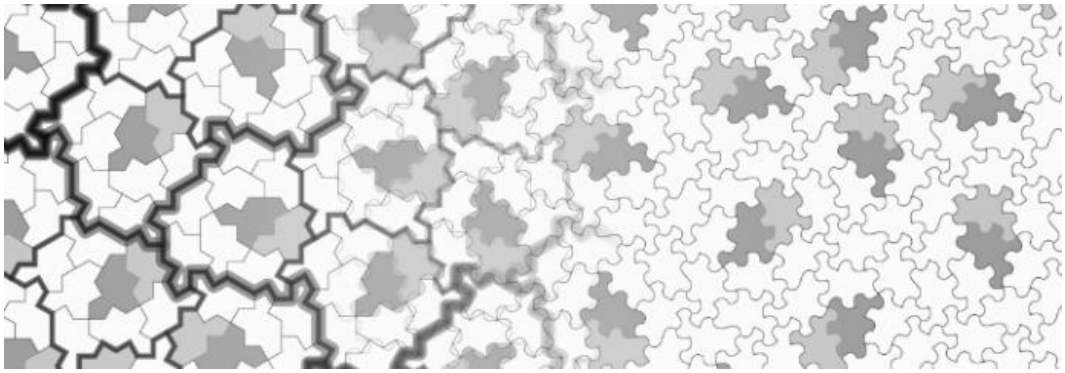


b)

Figure 3. Construction of the Spectre monotile (a) and example tessellation (b) Kaplan et al [10].

4. CASE STUDY: THE APERIODIC MONO-TILE WINE TABLE

4.1. Design Concept

To investigate the practical implications of aperiodic modularity, a furniture prototype titled the Aperiodic Mono-Tile Wine Table was designed and constructed. The project utilizes the Spectre monotile as its fundamental geometric unit [4]. The objective was to test whether a single module could generate multiple functional table configurations while maintaining visual coherence and manufacturing simplicity. Unlike conventional furniture systems that depend upon numerous unique parts, the proposed design relies on a singular geometric component capable of producing diverse arrangements.

4.2. Digital Modeling and Fabrication

The prototype was developed using simple modeling software and fabricated through CNC manufacturing processes. Digital fabrication allowed precise reproduction of the geometric module while maintaining production efficiency. The use of CNC technology demonstrates the compatibility of aperiodic modular systems with contemporary fabrication methods. Despite the visual complexity of the resulting configurations, manufacturing remains relatively straightforward due to the reliance on a single repeated component.

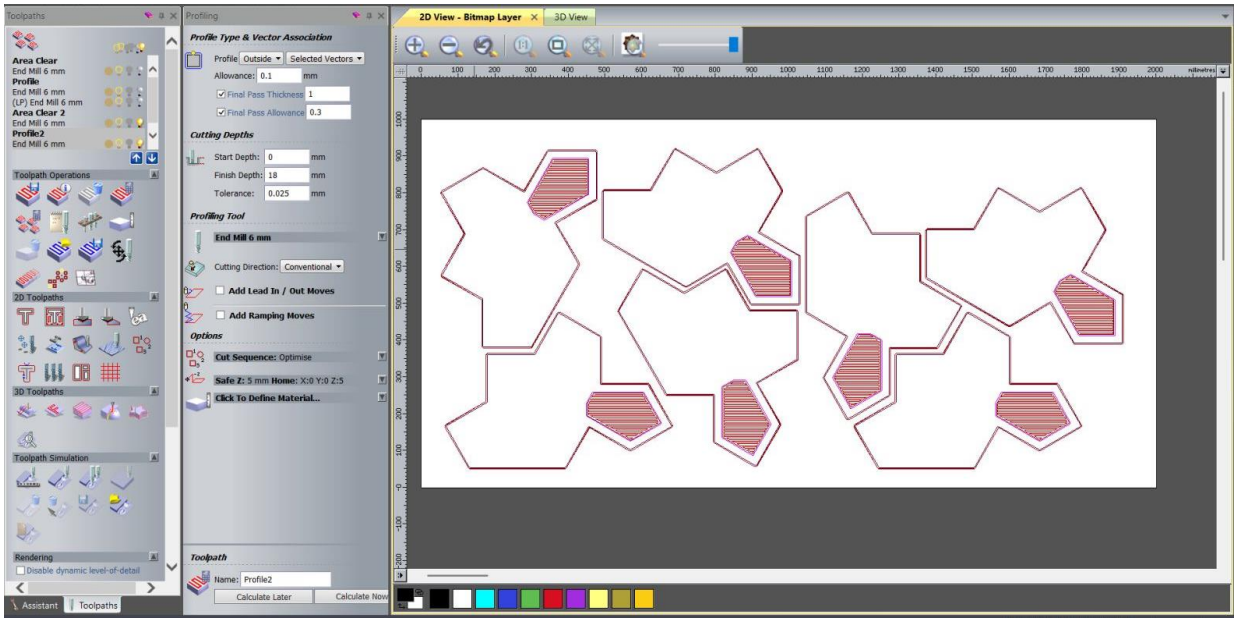


Figure 4. Digital model of the Aperiodic Mono-Tile Wine Table (Author’s image) [4].

Figure 5. CNC fabrication process and assembly components (Author’s image) [4].

4.3. Commercial Interior Application

The completed prototype was implemented within a functioning commercial interior environment.

The realized project demonstrated several advantages:

- **Visual diversity generated from a single module.**
- **Adaptability to different spatial requirements.**
- **Efficient fabrication and assembly.**
- **Strong visual identity derived from geometric complexity.**

The prototype confirms that aperiodic modular systems can successfully bridge the gap between mathematical theory and practical design implementation.

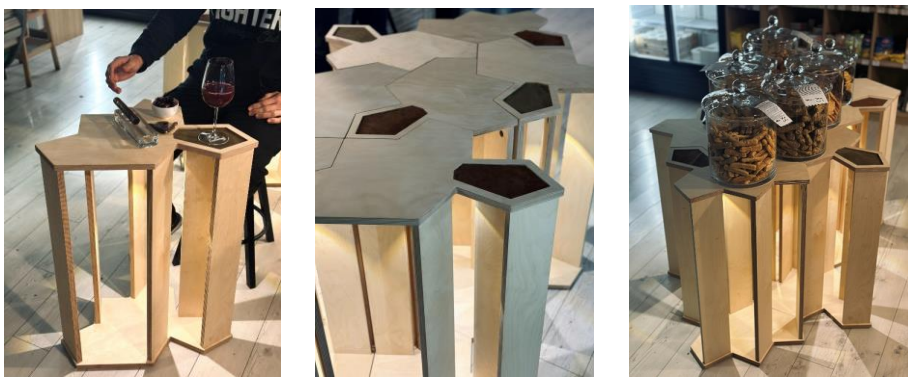


Figure 6. Installed prototype within commercial interior (Author’s image) [4].

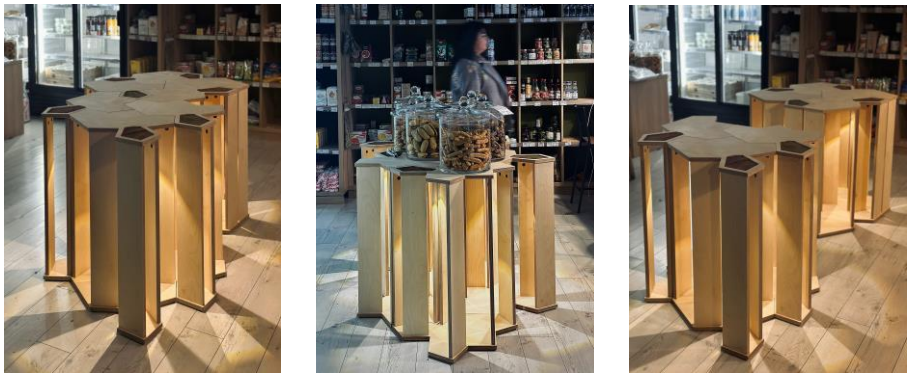


Figure 7. Alternative configurations generated from the same module (Author’s image) [4].

5. SCALABILITY ACROSS ARCHITECTURAL SCALES

The successful implementation of the furniture prototype suggests broader architectural applications.

5.1. Façade Systems

Aperiodic modular façades can create visually dynamic building envelopes while utilizing a limited set of prefabricated components. Similar principles can be observed in contemporary parametric façade systems such as Federation Square in Melbourne, Australia, by LAB architecture studio, which utilizes the “pinwheel” tiling, where modular panels generate complex visual effects while remaining rationalized for fabrication [12].

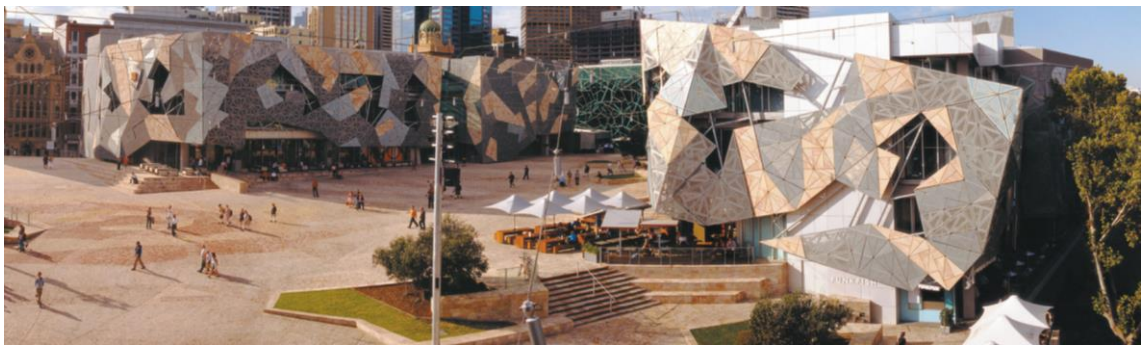


Figure 8. Federation Square, Melbourne, Australia, illustrating non-repetitive modular façade articulation [12].

5.3. Public Space Design

The application of aperiodic geometries can extend beyond building envelopes and modular housing systems into the design of public spaces, landscape interventions, and urban installations. In these contexts, non-repetitive geometric systems offer opportunities for creating visually rich environments that maintain coherence without relying on conventional repetition. A notable example is the Design District Event Space by Aranda\Lasch in Miami. The project incorporates a geometric surface pattern generated through rotational transformationsof a single module [13]. Another relevant precedent is the Penrose Tile paving installation at the Simons Center for Geometry and Physics, Stony Brook University which employs Roger Penrose’s aperiodic tiling system [14].

The broader potential of these approaches can be observed in speculative and conceptual projects. The proposal 20 Bridges for Central Park by Aranda\Lasch explores organizational principles derived from crystallization and aggregation processes [15]. Although it does not use a strict aperiodic tiling system, it shares key conceptual ground with aperiodic geometry: both generate complex spatial organizations from simple local rules rather than predefined global forms. In the bridge proposal, complexity emerges through growth, accumulation, and interaction of basic elements, producing variation, hierarchy, and adaptability - qualities also found in aperiodic systems, where repeated rule application yields diverse configurations from minimal modules, sometimes even a single one, as in monotiles like the Spectre. This parallel is significant architecturally because it shows how a simple generative framework can produce many unique outcomes without increasing geometric or material complexity. Combined with aperiodic modular systems, such principles could enable a single module to generate diverse bridges, pavilions, and installations while maintaining a coherent logic, preserving the efficiency of modular construction while enhancing spatial richness.

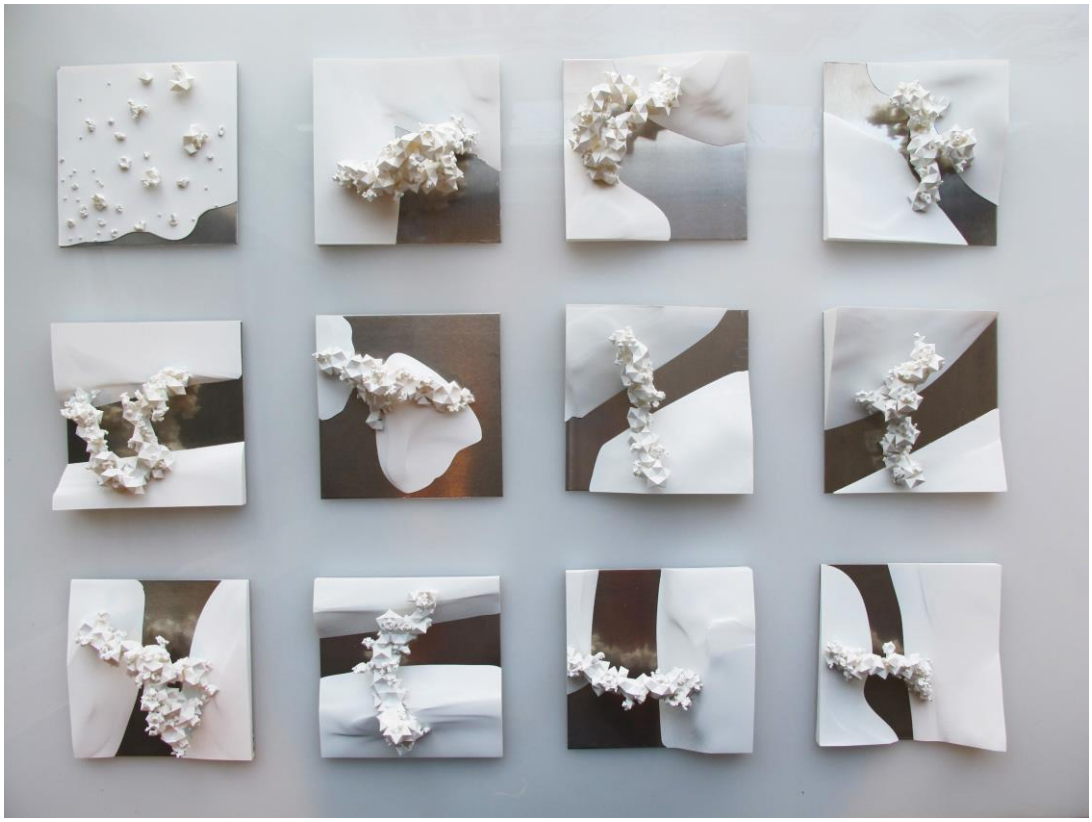
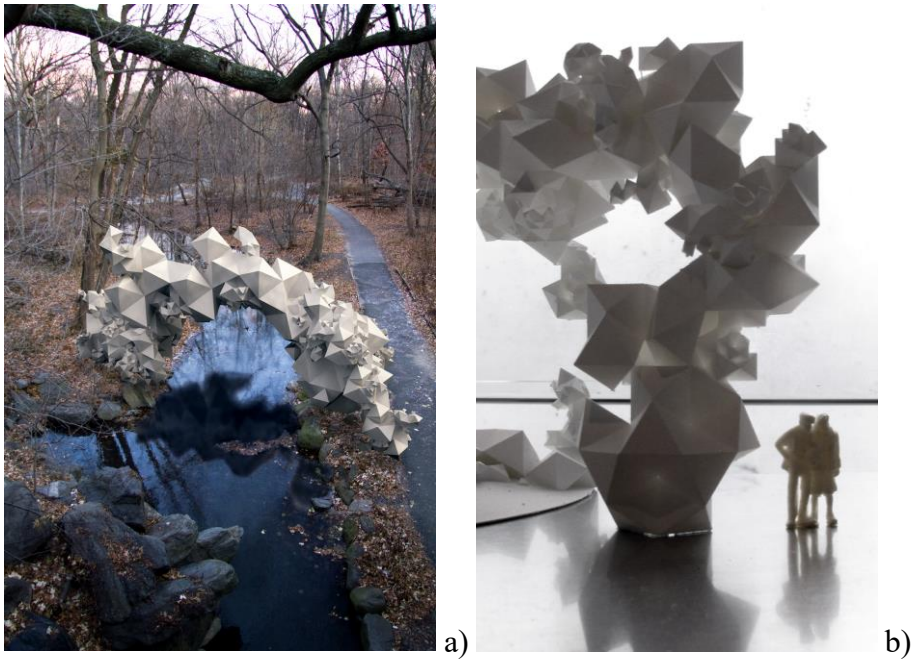


Figure 9. Variety of structures from 20 Bridges for Central Park, Aranda\Lasch [15].



a) b)

Figure 10. Render (a) and physical model (b) from 20 Bridges for Central Park, Aranda\Lasch [15].

In computational design, parametric and algorithmic tools extend this logic by encoding rules, growth patterns, and assembly constraints into workflows that generate and evaluate numerous configurations from a single element. Aperiodic geometry thus becomes a design strategy rather than only a formal system, enabling scalable, adaptable architectural systems that balance efficiency, diversity, and spatial complexity.

5.4. BIM and Computational Workflows

The integration of BIM platforms and parametric design tools provides new opportunities for implementing aperiodic systems at architectural scales. These computational workflows allow non-periodic geometries to be treated not as abstract mathematical constructs, but as constructible and data-driven design systems embedded within standard architectural practice.

Tools such as Grasshopper and Dynamo enable the generation, modification, and documentation of complex geometric arrangements while maintaining full coordination with BIM environments. This integration is particularly relevant for aperiodic systems, as it allows rule-based patterns to be translated into parametric definitions that can be controlled, tested, and optimized in real time. As demonstrated in foundational work on tilings and geometry by Grünbaum and Shephard, aperiodic and non-periodic structures can be rigorously described through local matching rules rather than global repetition [6]. Building on this mathematical foundation, Senechal’s research on quasicrystals further highlights how ordered complexity can emerge from deterministic systems without translational symmetry [7]. Within a Computational Workflow context, these principles enable architects to embed aperiodic logic directly into design models, where each component can carry geometric, relational, and material information. Instead of treating complexity as a post-rationalized formal outcome, it becomes an inherent property of the computational model. This allows for automated coordination between geometry, structure, and fabrication data, ensuring that even highly irregular assemblies remain constructible and efficient. As a result, aperiodic systems can be incorporated into computational design workflows not as exceptional geometries, but as scalable and rule-based frameworks. This positions BIM and parametric tools as key mediators between mathematical theory and

architectural practice, translating proven geometric principles into adaptable and buildable design strategies.

A practical implementation of these principles can be observed in community-developed definitions within Grasshopper, where Penrose tilings are generated through recursive, rule-based subdivision and assembly logic. In the referenced McNeel forum discussion, various Grasshopper users demonstrate how the tiling can be constructed by encoding Penrose matching rules into a parametric definition rather than manually drafting geometry. The approaches typically start from an initial seed configuration and then apply iterative subdivision or growth rules that control tile orientation, adjacency, and scaling. Through repeated cycles, the system maintains local edge-matching constraints while producing a non-periodic global configuration, allowing users to adjust recursion depth, seed selection, and geometric parameters in real time. These implementations, developed and shared by contributors within the McNeel Grasshopper community, illustrate how aperiodic tiling systems can be embedded directly into computational workflows, translating local matching rules into constructible geometric systems consistent with BIM-integrated design approaches McNeel Discourse Penrose Tiling Grasshopper Example [16].

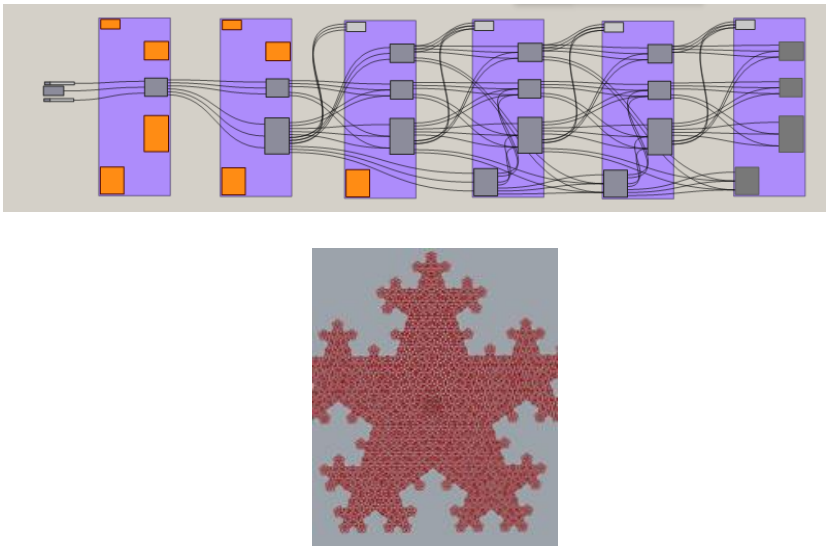


Figure 11. Screenshots from generated Penrose tiling in Grasshopper by Bob Mackay [16].

6. DISCUSSION

The research demonstrates that aperiodic geometry offers a viable alternative to conventional modular design approaches. Rather than viewing modularity as synonymous with repetition, the findings suggest that modular systems can generate diversity through mathematically structured variation. The Spectre monotile illustrates how a single geometric element can produce a broad range of spatial and visual outcomes without increasing manufacturing complexity. Furthermore, the study establishes meaningful connections between contemporary mathematical discoveries and historical architectural traditions. The relationship between Persian geometric principles and modern aperiodic systems suggests new possibilities for integrating cultural heritage into technologically advanced design methodologies.

7. CONCLUSION

This research extends previous works into modular architecture by demonstrating the practical application of aperiodic geometry through a realized furniture prototype and exploring its potential architectural scalability. The Aperiodic Mono-Tile Wine Table validates the hypothesis that modular efficiency and visual complexity need not be mutually exclusive.

Through the use of a single Spectre-based module, the project achieves adaptability, non-repetitive composition, and fabrication efficiency simultaneously. Combining mathematical rigor, cultural continuity, digital fabrication, and computational design methodologies, aperiodic systems offer an alternative path beyond both repetitive modular standardization and formally uncontrolled complexity.

Future research may focus on full-scale architectural implementation, performance evaluation, and the integration of aperiodic modular systems into contemporary BIM-based construction workflows.

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