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Parametric Generation Based Graphic Design and Spatial Expression Research

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ABSTRACT

Parametric design is nowadays a development hotspot in the field of design and graphic computing design. However, due to its existence need to have a little mathematical theory foundation and computer graphics software design foundation threshold exists, affecting designers and other enthusiasts on the threshold as well as the cost of learning. In this paper, we construct a complete set of development tool prototypes that can be adjusted and modified in any part of the complete traceable process from graphic design to spatial structural expression. This study explores the role of parametric design tool prototypes in the workflow and refines the strengths and weaknesses of parametric design in the past and summarizes the framework of the study on the production of graphic to spatial production workflow using parametric design development prototypes. It also summarizes a research framework for developing prototypes for graphic to spatial production using parametric design, providing design case studies and design methodology support for design tool innovation in the context of emerging technologies.

Keywords: Parametric design, Research framework, Design innovation, Digital and generative arts

INTRODUCTION

Under the wave of Industry 4.0, traditional production models struggle to adapt to evolving demands (Dandan et al., 2024). Parametric design and interaction, grounded in mathematical principles, have emerged as frontiers for exploring the intersection of visual arts and structural design. Originating from geometric design, parametric design transforms design elements into controllable parameters and establishes logical relationships between them, enabling the real-time optimization of solutions (Fang, 2016). As a computer-aided technology based on topological concepts, it represents an evolution of CAD. During the mid-to-late 20th century, parametric technology was mainly applied in complex systems engineering within aerospace and shipbuilding industries (Chiliang, 2014). As indicated in Table 1, the volume of published research papers on parametric design has shown an upward trend over the past five years, reflecting its establishment as a key focus for practice within the design discipline and a stable domain of academic output.

Table 1: Research on the growth rate of parametric design-based publications over the past five year.

Year	Growth Rate of Parametric Design Publications (%)
2019	Baseline(100%)
2020	0.15
2021	0.28
2022	0.42
2023	0.61
2024	0.85

Research on the Growth Rate of Parametric Design-Based Publications over the Past Five Years. The data in Table 1 shows a year-on-year increase from the 2019 baseline, with growth rates of 0.15, 0.13, 0.14, 0.19, and 0.24, respectively. Analysis of the data reveals an overall upward trend in the volume of parametric design-related publications, reflecting the technology's emergence as a focal point in design discipline practice and its role in sustaining relatively stable academic output. From the perspective of design products, the category of design includes two types. One is the material product, the other is the immaterial design (Yanzu and Fuya, 2011). This study examines three distinct design approaches—traditional craftsmanship, artificial intelligence-driven techniques, and parametric design technology—and summarizes their characteristics across six dimensions, as presented in Table 2.

Table 2: Comparison of current design workflows.

	Traditional Craftsmanship	AI Technology	Parametric Design Technology
Design Approach	Relies on artisan experience and manual operation	Generates numerous solutions via machine learning	Produces concrete forms through algorithmic parameter adjustment
Design Tools	Hand tools	Deep learning frameworks with AIGC tools	Parametric design software
Production Efficiency	Weeks to years per piece	Minute-level solution generation	Hours-level form iteration
Current Applications	Art customization, intangible cultural heritage preservation	AI-generated content	Complex engineering, product customization
Key Advantages	Customizability, artistic creativity	Efficiency, flexibility, low cost	Customizability, traceability, efficiency, flexibility

Continued

Table 2: Continued

	Traditional Craftsmanship	AI Technology	Parametric Design Technology
Existing Challenges	Lengthy production cycles, standardization difficulties, inability to meet mass demand	High data dependency, lack of emotional expression, absence of cultural concepts in generative AI	High complexity in rule-setting, steep technical barriers

The product design innovation method based on parametric design thinking makes up for the deficiencies of designers in traditional design methods, thereby enabling the design of more divergent and feasible optimization schemes (XiKun et al., 2023). This study aims to explore the geometric composition of patterns through parametric design, offering innovative perspectives for motif development while revealing cultural core drivers. To validate the sustainability of this design philosophy, the research employs a three-dimensional analytical framework—comprising data analysis, parametric path reconstruction, questionnaire surveys and analysis, and output diversity—for comparative testing to verify the accuracy of design outcomes.

RELATED WORK

In the early 1990s, pioneering architectural institutions and design teams began exploring parametric design, exemplified by practices such as Foreign Office Architects (FOA) in the Netherlands, the Architectural Association (AA) in the UK, and architects including Greg Lynn, Frank Gehry, and Zaha Hadid. China's adoption of parametric technology commenced later, though academic institutions—notably Tsinghua University, Tongji University, and South China University of Technology—spearheaded its domestic development. In professional practice, Beijing-based MAD Architects, led by Ma Yansong, produced signature works including the Absolute Towers (Mississauga, Canada), Ordos Museum, Harbin Opera House, and Haikou Cloudscape Library.

The involvement of parametric techniques in the design process and the development of "parametric design" took place in the field of architectural design (Liuzhuang, 2016). Over time, parametric design has transitioned beyond being a subject of debate and controversy, permeating diverse realms of artistic design. Although the technology holds potential for elevating recognition of cultural products, it has yet to foster public engagement with design and cultural narratives. Developing experience-centric solutions with enhanced visual language and enriched cultural depth has thus emerged as a critical industry focus.

METHODOLOGY

Research Methodology

This study highlights parametric tools (e.g., Touch Designer, Grasshopper, Blender) using node-based modules for efficient data flow. Open-source ecosystems enhance accessibility, supporting data-intensive research and iterative workflows. While parametric design streamlines pattern transformation, current applications focus primarily on product design, with limited 2D-to-3D conversion. Consequently, this research integrates social sciences with parametric methodologies to develop a cross-disciplinary theoretical framework (Figure 1) addressing:

Figure 1: Theoretical framework and blueprint for parametric design.

1. Technical: Grasshopper-based 2D/3D conversion;
2. Cognitive: Semiotic and aesthetic dimensions;
3. Generative: Kinetic-algorithmic synthesis.
4. Assess prototype system usability through interdisciplinary synthesis to advance media integration and design expression.

Table 3: Schematic diagram of the study route.

Stage	Focus	Methodology
Research on Pain Points	Difficulties in expanding the use of tools and parametric tools to enhance design expression in pattern design and spatial design	Software Difficulty Test Questionnaire
Prototyping based on parametric design cases	Comparison of visual tension and richness of detail with content produced by conventional design tool techniques	Prototype control

Continued

Table 3: Continued

Stage	Focus	Methodology
Prototype evaluation	Mapping in terms of resolution, fineness, degree of model conformity to expectations, aesthetics and semiotics	Comparative assessment
Summarizing and concluding	Feasibility and summarizing the direction of future modifications through consultation	User research

Data and Methodology

This parametric design study engages four domains using Grasshopper-generated Penrose tessellation components. The system employs two primary shapes—kites (1: φ) and darts (φ: 1)—adhering to the golden ratio ($\varphi \approx 1.618$) with strict rotation rules (e.g., 36°/72°).

Algorithmic Workflow:

1. Decomposition: Recursive subdivision of base shapes (e.g., rhombi) into kites/darts.
2. Scaling: φ-based iterative refinement of sub-patterns.
3. Alignment: Edge-matching constraints enforcing aperiodicity.

Grasshopper Implementation:

1. Formula input via Expression components for parametric scaling.
2. Recursive subdivision using Anemone plugin: golden ratio (φ) scaling/rotation per iteration.
3. Vector/Transform components for tile orientation (e.g., 36° rotation via Transform Rotation).

A hexagonal centroid-diffusion framework generated 12 parametric texture styles (Figure 2), enabling spatial-image comparisons through parametric spatial composition.

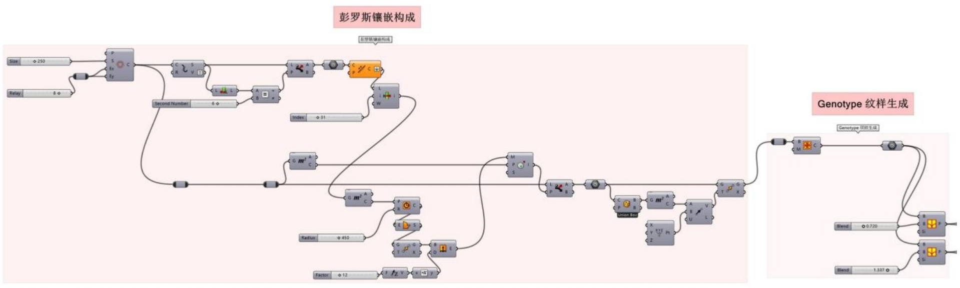

Figure 2: Parametric toolset prototype and math toolset demonstration.

Building on this, researchers established tiling relationships between supplementary images and a central centroid image to generate patterns, enabling on-demand polyhedral assemblies for graphic applications. Penrose tessellation—an aperiodic tiling method—demonstrated single-to-composite transformations (Figure 3).

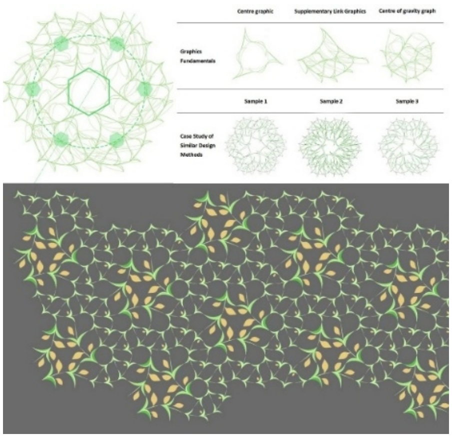

Figure 3: Schematic based on multiparty continuous and combinatorial graphical relationships and Schematic of a case with irregular tiling.

Adjusting connector thickness, height parameters, and node count enables rapid development of:

1. Spatial visualization products;
2. 3D deconstructive rendering of planar patterns;
3. Parametric stylization for digital media/games.

The study establishes a fully traceable workflow where data adjustments instantly modify models. Genotype principles automate complex designs through dataflow-driven logic, establishing a workflow: planar framework → continuous assembly → parametric linking → spatial modelling (Figure 4). Precisely controlling curve radii through function-parameter relationships materializes 2D graphics into 3D spatial forms with volumetric attributes (Figure 5).

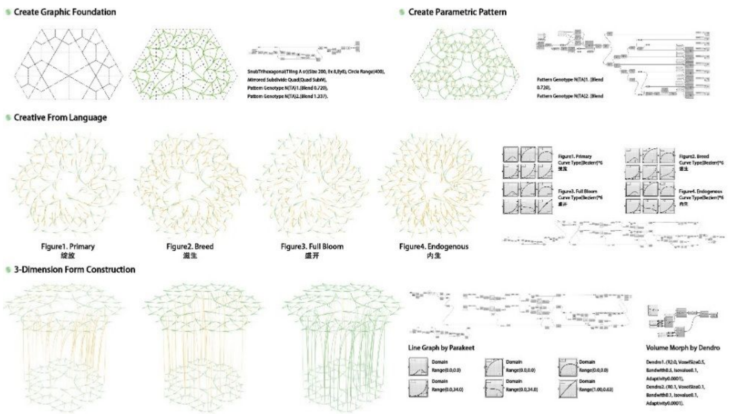

Figure 4: Decomposition diagram based on parametric prototyping tools.

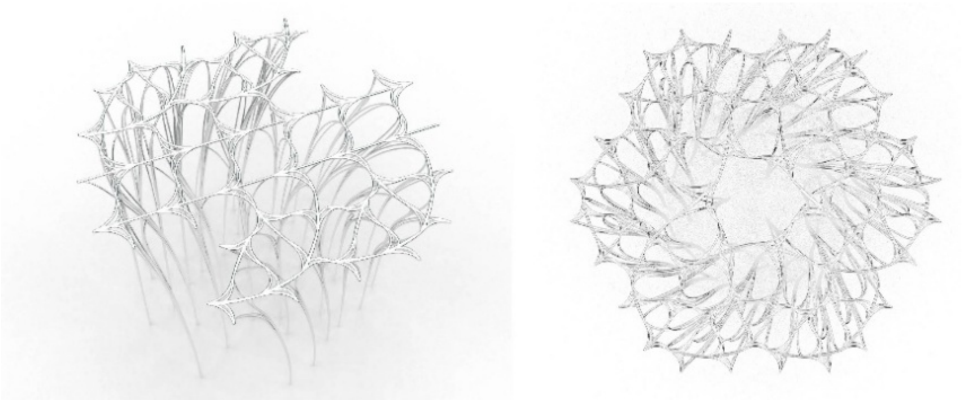

Figure 5: Results map of design outputs based on parametric prototyping tools.

Data Conclusions

To assess prototype usability and visual perception, this study conducted an in-person survey and one-day exhibition with undergraduate design students. Fifty participants from Product/Industrial Design backgrounds were divided into five groups (three to four members each). Each group developed distinct thematic patterns/models for presentation (Figure 6).

Figure 6: Schematic diagram of user testing of the prototype system.

Prior to the project, we trained the control group participants in the use of parametric prototyping to generate patterns and models, including:

1. How to configure and deploy the operating environment for parametric design tools and software.

2. How to use the above parameterized module prototype to test the generation effect.
3. How to collect new data and adjust the data to optimize the model.
4. Summarize the limitations of prototyping tools.

Summarizing the limitations of the prototyping tool, after the above training, the students collected the datasets from their groups, retrained the AI prototypes, and finally selected the outputs that were suitable for processing to be presented as the results for comparison with the hand-drawn graph-transformation modeling group. During this process, the authors of this paper will be involved in answering questions that arise when using the prototyping tool but will not be involved or interfere in the production of the final work. To explore the advantages and disadvantages of utilizing efficiency and production in relation to traditional design and drawing, visitors were invited to fill out a questionnaire (24 valid questionnaires were received).

Table 4: Statistical data on the time spent by each control group in different sessions.

	Average Time Spent on Pre-Pattern sketches(Unit: Minutes)	Convert CAD to Vector Drawing	Model Building	Model Optimization	Model Rendering
Traditional workflow	45mins	10mis	92mins	12mins	44mins
Parametric Design Prototyping Group	16mins	2mins	118mins	24mins	external renderer

Prototype Limitations

Thirty design experts meeting two criteria—professional training and modelling tool experience—assessed workflow plausibility using 5-point Likert scales across four dimensions: colour, form, detail, and production rationality (higher scores indicating better quality). As summarized in Table 5, the method generates relatively efficient design sequences.

Table 5: When examining the workflow steps, what factors made the evaluator feel that there were problems?

Options	Distribution
Documentation and toolkit need to be improved	9/37.5%
Toolkit titles and content visualization need to be improved	11/45.8%
Content richness needs to be improved	18/75%
A little difficult to get started	14/58.3%
The type is prone to bugs and errors	6/25%

RESULTS AND ANALYSIS

Prototype Development and Design Outputs

Graphic design represents an established, self-contained visual system (Wei, 2022). To advance knowledge in this field, qualitative methods were employed to examine designers' cognitive processes through two phases (Table 6): mathematical deconstruction of drawing principles, and interdisciplinary development of parametric tools.

Table 6: When examining the workflow steps, what factors made the evaluator feel that there were problems?

Design Dimension	Genotype Design	Penrose Mosaic
Core value	Data flow control and parameterized logic reuse	Nonperiodic aesthetics and mathematical algorithm generation
Applicable scenarios	Structural optimization, modular design, dynamically tuned data flow control and parametric logic reuse	Decorative patterns, lightweight construction, artistic skins
Tool support	Anemone, Lunchbox, Path Mapper	Customized scripts, golden ratio calculations, rotation matrices
Strengths combined case	Dynamic parameterization and mass production adaptation of Penrose patterns	Unification of performance optimization and aesthetic expression for acyclic structures

Developing beginner-oriented parametric tools requires understanding both technical characteristics and learning challenges. Through literature review and expert interviews, we identified two core aspects. The technical foundation includes, Hierarchical dataflow control via tree structures; Real-time parametric adjustments (e.g., Number Slider); Modular logic encapsulation (Clusters); Plugin integration (Anemone/Lunchbox); Automated solution filtering (Cull Pattern/Dispatch); Computational optimization (Flatten/Proximity 3D); Shape: Sequential scaling of similar forms; Colour: Contextual relationship adjustments; Composition: Centre-to-periphery sequencing; Hierarchy: Primary elements before details; Aperiodic patterns: Mathematical textures for decorative applications; Proportional systems: φ-based recursive division.

The principles outlined above may present potential conflicts, with no single principle holding absolute priority. To identify the primary challenges faced by beginners learning parametric design component creation, we conducted semi-structured interviews with ten novice users. Analysis of the interview findings revealed the main difficulties encountered when learning this tool for designing graphics and transforming spatial expressions. It includes Inaccurate shape data adjustment (45%); Inconsistent colour palette (32%); Difficulty in grasping specific functions of functional groups (52%);

Graph transformation spatial expression is prone to bugs but complex to adjust and debug (19.6%).

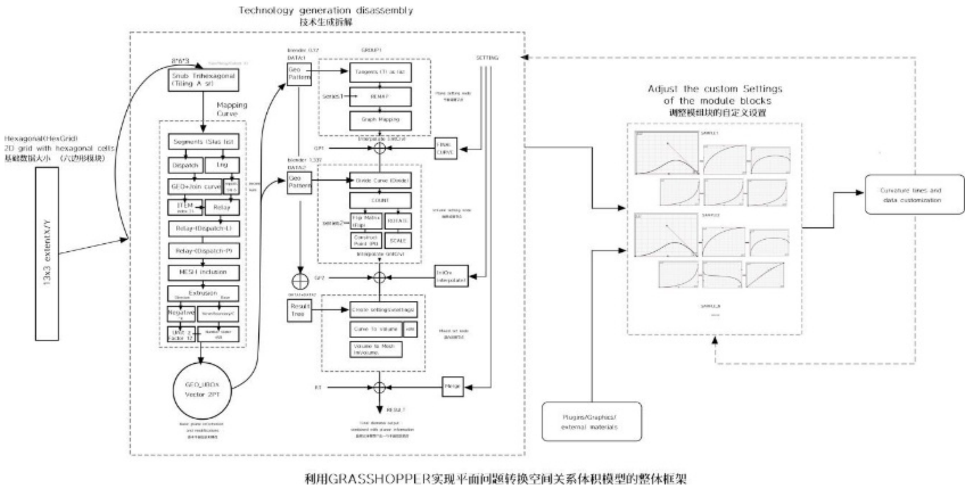

Figure 7: An overall framework for transforming spatially relative volume models for planar problems using grasshopper.

Comparative Questionnaire Results Analysis

To evaluate the usefulness and potential issues of parameter generation for beginners, we invited 10 novice designers to use our prototype system for design support. Semi-structured interviews were then conducted. When asked about the usefulness of parametric design steps for learning, 80% of beginners found them helpful. When asked about missing information in parametric drawing steps, beginners highlighted three main issues:

1. Unclear modification beyond templates, requiring more mathematical knowledge and software proficiency;
2. Insufficient guidance on modeling principles and fine-tuning model transformations;
3. Excessively high drawing detail requirements, though potentially directly related to traditional graphic conceptualization and planar design.

Analysis and Evaluation

Building on prior research and leveraging a comprehensive battery toolset, the combined advantages of Genotype and Penrose tessellation yield the following insights:

1. Innovative design possibilities: Integrating Genotype with Penrose tessellation enables flexible yet aesthetically rigorous outcomes;
2. Automated efficiency and precision: Grasshopper scripts generate Penrose tessellation to eliminate manual assembly errors.
3. Cross-disciplinary potential: Genotype provides the technical framework, whereas Penrose tessellation energizes high-end product design (e.g., luxury goods, smart home devices).

DISCUSSION

The application of digital technology in the field of cultural heritage protection is becoming increasingly in-depth. It provides channels for sharing, dialogue, cooperation and collective action to achieve social transformation (Fei, 2025). Responses to digital skill development should prioritize human-centred approaches (Xiaojuan & Yuanyuan, 2024). Consequently, we developed an applied research framework to facilitate the transition from 2D patterns to 3D spatial conversion through parametric generation (Figure 8).

Section 3 details a Grasshopper-based arithmetic tool employing mathematical foundations to drive aesthetically inspired designs, enhancing detail and visual tension. Questionnaire and field studies revealed that while users found the parametric process novel and exciting, they preferred more interactive formats and richer feature sets. Section 4 evaluates prototypes via case studies and functional component simplification. User experiments confirmed the tool's usability with clear classification and traceability methods, yet interviews indicated demands for enhanced guidance post-beginner stage.

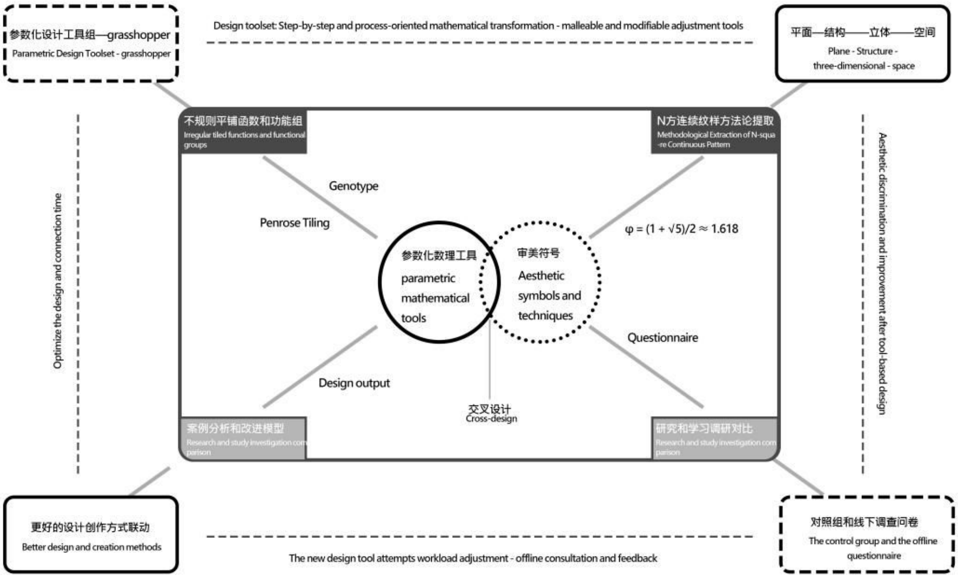

Figure 8: Parametric design and aesthetic symbolism research framework diagram.

CONCLUSION

In the ever-changing world of globalization, culture is constantly evolving (Drache and Froese, 2006). Enriching design expression through emerging technologies and methodologies is a universal cultural challenge. Parametrically generated patterns and spatial design are evolving from technical tools into cross-disciplinary innovation paradigms (Jincheng, 2014). Their core strength lies in transcending static boundaries of traditional design, achieving dynamic equilibrium among form, function, and culture through algorithmic logic (Yan and Zhuo, 2019). As intelligent technologies and sustainability principles advance, parametric design will deepen dialogues between art/engineering and tradition/innovation, redefining design's essence—from "creating forms" to "organizing systems."

This study explores parametric technology's potential in expanding technical boundaries and visual expression through pattern design. We analyzed challenges in prototyping and learning processes, validating advantages through participatory experiences. Interviews and analysis identified optimizable areas for intelligent tools in enhancing design efficiency and expressiveness, leading to actionable recommendations. Finally, we proposed a parametric design experience framework leveraging mathematical toolkits. This research provides tools, methodologies, and theoretical references for future design and cultural studies.

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