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Article

A Rule-Based Parametric Workflow for Tessellation-Based 3D-Printed Textile Textures: A Haptic-Relevant Design Exploration

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Abstract: Quadrilateral-based continuous textile patterns are well suited to large-scale fabrication as rhythmic surface effects can be produced through repetition, translation and rotation. This paper presents a rule-based parametric design workflow for three-dimensional (3D)-printed textile textures based on tessellation patterns with continuous geometric properties that was developed through shape grammar principles and implemented in the Grasshopper visual programming environment. During testing, the workflow demonstrated how a square-based geometric primitive—defined here as a planar base unit with edge-to-edge continuity suitable for tessellation construction—can be systematically transformed into tessellated textile textures through parametric rules and form, forming a reproducible digital-to-physical pipeline from algorithmic generation to physical realisation. The square primitive was employed as an exemplar case due to its geometric clarity, while the underlying shape grammar rules and parametric operations were not restricted to a specific geometry and could have been extended to alternative planar primitives. The study focused on the integration of geometric rule definition, parametric variation and fabrication constraints within textile-integrated fused deposition modelling (FDM). Physical validation was therefore limited to printability, material feasibility and structural coherence using thermoplastic polyurethane (TPU) rather than empirical evaluation of tactile perception. Within this scope, haptic qualities were addressed as design-relevant dimensions embedded in geometric variation and fabrication parameters. Key parametric variables, which were defined through a set of explicitly structured geometric and fabrication parameters, provided a reproducible basis for future physical and perceptual evaluation. The contribution of this work lies in establishing a fabrication-aware, rule-based parametric workflow that bridges computational design logic and digital textile fabrication.

Keywords: Parametric Design; Rule-based Parametric Workffow; Computational Design; Digital Fabrication; 3D-Printed Textile Textures; Tessellation-based Patterns
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1 Introduction

1.1 Definition of Parametric Design and Rule-Based Computational Design Tools

As a computer-aided design (CAD) model, parametric design disrupts the traditional design process and provides a dynamic correlation between input parameters (variables) and geometric outputs [1–3]. In contrast to traditional manual drafting, which relies on fixed forms, parametric design enables models to evolve automatically based on predetermined constraint connectors and algorithm-based rules, thereby facilitating a high rate of iteration and allowing for the large-scale generation of variation [1, 4, 5].

Essentially, parametric design works with a parameter-constrained-solution mechanism. The geometries are computed and visualised by the system by defining important variables (dimensions, angles and material properties) and logical dependencies (i.e. geometric dependencies or fabrication constraints). This creates a dynamic and reconfigurable exploration area of designs where creativity and technical accuracy are encouraged [2, 3].

In contemporary discourse, this rule-based algorithmic nature of parametric design is increasingly situated within the

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broader category of computational design tools. Computational design environments, such as Grasshopper, embed executable logic, dependency propagation, constraint satisfaction and automated variation—properties which align with definitions of rule-based computational design systems such that generative rules act as a surrogate rule-execution mechanism that produces and evaluates alternatives before fabrication [6, 7]. In this framing, parametric modelling is not merely a modelling technique but a form of 'codified rule-based design logic' in which design intent is externalised into algorithmic decision structures that actively generate and transform geometry [1, 8].

From this perspective, parametric design can be understood as a rule-based computational paradigm for design—a human in-the-loop design system in which the author specifies rules and constraints, while the computational system executes, propagates and visualises the consequences at interactive speed. This establishes a hybrid design workflow in which rule-based generativity becomes the operational bridge between design cognition and machine-executed search in the design space [5, 6].

In the textile and fashion design field, parametric design has emerged as the key tool to attain the fusion of differentiation, structural effectiveness and functionality. Initial applications had been to two-dimensional pattern or pattern-making logics, in which repeatable surface patterns and size-adaptive panels were produced by using rule-based sets of parameters, the required re-drafting was minimised, and fit and form coherence was maintained [9]. Modern studies have extended these principles to three-dimensional (3D) textile fabrics and parts of a garment with the aid of digital fabrication and 3D modelling, and these technology-based algorithmic principles (such as tessellations, gradient fields and topology-driven pores) have been translated into physical structures, such as through additive manufacturing [10, 11]. More recent research also showed that parametric systems could create responsive textile artefacts by mapping geometric variables to body- or performance-related constraints, such as fabric fit, mobility or surface behaviour, to directly control spatial and structural variability on textile substrates [12].

By extending this human-in-the-loop paradigm to textiles, parametric design becomes the operative bridge between design cognition and fabrication by translating rule-sets into printer-aware geometric decisions. In this hybrid model, designers with non-programming backgrounds can control complex geometries (interlocked motifs or curved surface tessellation) by encoding design intent in an algorithmic form and showing their effects in experimental visual display before printing on a large scale. This accessibility, in combination with the process-sensitive principles of a printer on fabrics (such as adhesion, gap and thickness constraints), has led to a rapid uptake within both the fashion and technical textile sectors, where the textile behaviour and surface morphology of individual materials are critically required [10, 13]. In this study, the workflow was understood as an explicit externalisation of design intent into rule-based parametric relationships that can be systematically executed and evaluated by computational systems while retaining human authorship and decision-making throughout the process [1, 28].

1.2 Tessellation Patterns for Textile Applications

Tessellation, or tiling, is a process in which an area of two or three dimensions is covered by units (tiles) of geometry without any overlaps or gaps [14, 15]. Based on symmetry and periodicity, tessellation is commonly classified into periodic and aperiodic types: periodic tessellations repeat a fundamental unit at regular intervals across a surface, whereas aperiodic tessellations exhibit ordered patterns without translational repetition. In the recent literature on computational design and architecture, it was shown how such tiling systems can effectively act as mediators between geometry and fabrication with a generative connection between mathematical reasoning and physical practice [18]. These properties render tessellation very useful in textile design due to its modular adaptability, scalability and topological flexibility: Any tile can be considered an independent modular entity whose geometry, size or curvature can be locally adjusted and then assembled into a continuous whole, thereby allowing it to cover both planar and curved substrates [14, 16, 17].

Tessellation provides additional creative and functional options when it is coupled with 3D printing technologies. To be more specific, in contrast to other conventional approaches to finishing, like embroidery or screen printing, 3D printing permits the direct fabrication of volumetric textures on fabric substrates, which results in physical relief, control of units and high-interfacial bonding of polymer and fibre. As an example, the localisation of layer height and toolpath paths can create quantifiable layers of relief on surfaces which instruct fabrics to flex better or be perceived differently. The most recent experiments demonstrate how different 3D-printed geometric configurations integrated with textiles influence the drape behaviour and bending response of composite textile structures [19]. Likewise, every single tessellated module may be fabricated with either rigid polylactic acid (PLA)(dimensional stability) or flexible thermoplastic polyurethane (TPU)(elasticity) to build heterogeneous textures and gradient shifts throughout the textile function [10]. Mechanical interlocking bonds are also created by the direct deposition of molten filament on woven or knitted substrates without undermining the softness or stretch. It has been demonstrated through systematic studies that adhesion performance is determined by polymer and textile weave as well as process parameters, including extrusion temperature and the print speed [13, 20].

In our framework, tessellation is treated as a rule-based geometric organisation: Families of local rules (alignment, edge continuity and curvature control) map directly onto global pattern behaviour and subsequent material performance when printed on textiles [1, 6]. In this study, therefore, tessellation was chosen as the central geometric construct to investigate 3D-printed textiles with parameters. Its parametric nature of organisation is innate to the algorithmic logic of rule-based organisation and thus to manipulation with computational rules as opposed to manual repetition. Moreover, tessellation has long been studied in architecture and material science, but it has not been studied in additive manufacturing using textiles, in which factors like fabric flexibility, drape and deformation create unique design and technical challenges [18]. Due to its modular redundancy, tessellation also offers higher reliability of manufacture than free-form or non-structured geometries: Failures in the parts do not spread over the surface, minimise failures of printing or improve manufacturing efficiency [19]. This study, which was achieved through the integration of tessellation as a part of a parametric process, connected geometric reasoning and material making by converting digitally computed decorative motions into structurally and adaptively produced materials in the form of 3D textile fabrics and 3D printing.

1.3 Parametric Tools for Fabrication-Aware Texture Design

To design the haptic variations, we needed a controlled approach that varied properties within the same family of shapes for testing and evaluation. For this, we opted to use Grasshopper, a node-based interface that enables designers to create and edit design logic in real time and convert algorithmic thought to a visual and understandable workflow with no knowledge of code needed.

We interpreted Grasshopper, a visual programming environment within Rhino, as a rule-based parametric design environment in the sense that it embeds computational capabilities (rule execution, dependency propagation and constraint satisfaction) to support generative design at interactive speeds. Components act as operators in a graph that propagates parameter changes, thereby enabling rapid search of a design space authored by the designer's rules [1, 3]. In practical terms, every operation node acts as a discrete logic unit and performs certain transformations, such as rotation, scaling or subdivision, that maintain the relational dependencies of inputs and outputs. When one variable is changed, the results automatically cascade throughout the network thereby updating connected geometries and maintaining global coherence. For tessellation-based pattern development, this enables geometric rules—for example, the alignment of units or continuity across edges—to be encoded once and then dynamically tested across hundreds of iterations with immediate visual feedback on both aesthetic composition and structural feasibility. In this light, Grasshopper functions not as a static modeller but as a dynamic parametric modelling environment—a live system in which computation supports designer decision-making through real-time rule execution and geometric updates.

Controlled randomness and algorithmic variation are also key features of Grasshopper. Components such as 'random', 'noise', and 'graph mapper' can be used to generate non-uniform tessellation patterns. By connecting Perlin noise—a gradient-based procedural noise function commonly used to generate smooth, continuous variation—with parameters such as tile size or rotation, designers can create gradient-based transitions across textile surfaces to introduce controlled variation and visual diversity [8, 10]. Real-time visualisation and an iterative workflow further enhance design efficiency by allowing parameters such as tile rotation, spacing or layer height to be adjusted interactively with immediate feedback in Rhino [3].

By combining the parametric design model with slicing or toolpath-simulation software, such as Cura or Slicer, can cause possible fabrication problems, such as overhangs or adhesion failures, that must be detected and removed before printing [21]. However, Grasshopper is time efficient because it uses algorithmic automation. Activities like tile copying, pattern shifting and edge trimming can be performed in the space of several seconds thanks to such components as 'array' and 'boundary surface', which significantly decrease the influence of human error and achieve geometric consistency of various large-scale tessellations [22, 23]. Lastly, the platform allows the designing of complex geometries and interdisciplinary integration. Tessellation geometry can be used to optimise performance requirements by locally increasing thickness in high-strain regions or varying pore sizes to regulate light and thermal behaviour. Such performance-driven adaptations are enabled by linking design parameters with analytical tools integrated within parametric workflows, including Karamba3D, a structural analysis tool for evaluating stress distribution and deformation in parametric geometries, and Ladybug, an environmental analysis plugin used to simulate solar exposure, daylight performance, and thermal behaviour [7, 10]. This adaptability based on data can be particularly useful in regard to technical textiles, through which material behaviour, flexibility and aesthetics need to co-evolve within a computation framework.

In general, Grasshopper is both a modelling environment and a parametric modelling system, and it can be used to lead to rapid iteration, real-time feedback and 3D-printer-aware control of the design of the structurally coherent visual dynamics of 3D-printed textile textures.

1.4 Haptic Considerations in Parametric 3D-Printed Textile Design

This study related to haptic textiles. Haptic textiles play a critical role in expanding the scope of parametric 3D-printed textile design by offering a multisensory dimension that moves beyond visual aesthetics and structural optimisation to embrace embodied interaction and user experience. While parametric and tessellation-based methodologies have enabled designers to generate structurally coherent, fabrication-aware textile geometries, the consideration of haptic aspects foregrounds the tactile and experiential qualities of textile surfaces. Touch is a primary mode through which textile materials are perceived, and tactile attributes, such as softness, friction, elasticity and surface texture, influence comfort as well as the perception of and interaction with textile artefacts.

Research in design psychology and emotional design has suggested that tactile sensations influence affective perception, with material textures contributing to sensations such as comfort, stimulation or discomfort [24, 25]. From this perspective, incorporating haptic-related considerations into parametric 3D-printed textiles is relevant to the development of textile surfaces that are more responsive to user perception and interaction thereby complementing structural and fabrication-driven design objectives.

The convergence of parametric control, additive manufacturing and haptic-oriented design opens a design space in which tactile qualities can be explored through controlled geometric variation. Parametric variables, such as unit curvature, density, protrusion height and pattern rhythm, can be systematically adjusted to produce surface configurations with differing tactile-related characteristics. When combined with future tactile evaluation approaches, such as user studies or sensor-based methods, these parametric variations may support the more systematic investigation of relationships between geometric configuration and user perception, thus providing a conceptual basis for perception-oriented textile design.

Haptic textiles are therefore positioned as a relevant research direction not only for fashion applications but also for broader design contexts, such as well-being-oriented products, therapeutic garments and adaptive textile systems, in which tactile experience plays an important role in comfort and interaction [26]. Embedding haptic considerations within parametric workflows also supports the exploration of alternatives to conventional textile finishing processes by enabling surface variation to be achieved through geometry rather than additional material treatments.

The integration of haptic-related design considerations enriches parametric textile design with a human-centred dimension aligned with emerging priorities related to user experience and sensorial sustainability [27]. By framing tactile aspects as design-relevant parameters rather than validated perceptual outcomes, haptic textiles extend parametric 3D-printed textile research beyond purely geometric and fabrication concerns while remaining grounded within the scope of computational design exploration. The present study did not conduct empirical tactile or emotional evaluation; references to haptic and emotional dimensions are intended to motivate geometric exploration and future research directions rather than to report validated perceptual outcomes.

1.5 Research Aim, Methodological Approach and Outcomes

Although several earlier studies[10–13, 19, 20] investigated the integration of parametric design and 3D printing into textile settings, the vast majority were carried out with a view to the generation of ornamental surfaces or surface visualisation without achieving a systematic methodology that ties together the definition of geometric rules, parametric variation and the fabrication of a structure. In most instances, parametric design has been treated mainly as a visual modelling tool and not as a reproducible design system with a distinct separation between computational logic and material realisation. In addition, tessellation as a rule-based morphological platform of textile-integrated 3D printing is relatively underexplored despite extensive studies[14–18] on tessellation in the architectural and material science domains.

For the focus of this research—haptic-relevant geometric variation—we explored parametric variations to explore the different types of surface texture variation. To achieve this objective, we proposed a generative rule-based workflow that merged shape grammar (SG) with parametric control in Grasshopper to create a reproducible, fabrication-aware pipeline from digital rules to physical textile textures [1, 6, 28]. This workflow integrated algorithmic logic with visual programming to allow the design logic to be both human authored and machine executed. To address the gap identified in previous studies—the lack of a reproducible, fabrication-aware methodology that integrates rule definition, parametric variation, and physical textile fabrication—the current research created an all-inclusive, example-grounded framework that combined SG and parametric design logic in Grasshopper to create a visualised design-to-fabrication process of 3D-printed textile textures. This paper is based on a case study of the geometric transformation of a square primitive and tracing its development from a two-dimensional base unit to a complex tessellated surface. Grammar-based rules, which included rotation, scaling, translation and mirroring, were used in this process to study how sets of rules that have structure can motivate pattern morphology and surface rhythm. These algorithmically produced motifs were then additively printed onto textile substrates, thereby realising textile logic as physically fabricated, three-dimensional structures.

Methodologically, the system works as a closed-loop framework that leads to four partly overlapping stages: the definition of geometric primitives and parameter initialisation, shape deduction and unit generation via SG rules, tessellation mapping and texture reconstruction via parametric modelling and validation and model export of final printability controlled by the fused deposition modelling (FDM) constraints. Every step was implemented in the visual programming environment of Grasshopper, which allows users without knowledge of code to visually manipulate parameters and view geometric operations live.

FDM was chosen for the study due to its low cost, availability and suitability for flexible surfaces, whereas TPU was chosen because of its elasticity and trustworthy holding capacity to the textile fibres. The result of this study was a designer-friendly workflow capable of being reproduced with high fidelity that acts as a bridge between the computer-based form generation and a real object. The study showed that SG-based parametric design can perform as both a creative and technical approach to building tessellation-based textile structures, thereby providing a fresh paradigm of algorithmic design and 3D printing in textile practice. The workflow demonstrated how digitally encoded rules, simulation and fabrication can be orchestrated to accelerate responsible material exploration in textiles [13, 21].

2 Method

2.1 Research Framework

SG [28] is a design method that generates new forms through rule-based transformations of symbolic shapes. This study adopted a case study approach that integrated SG theory with parametric design logic to construct a visualised workflow for generating 3D-printed textile textures. The research framework (see Figure 1) was organised into four consecutive phases that created a closed-loop process and related the concepts of geometric design to the phase of physical fabrication via 3D printing. The individual stages were executed inside the Grasshopper visual programming environment, which allows manipulation of parameters in real time and provides instant visual feedback and a user-friendly design interface.

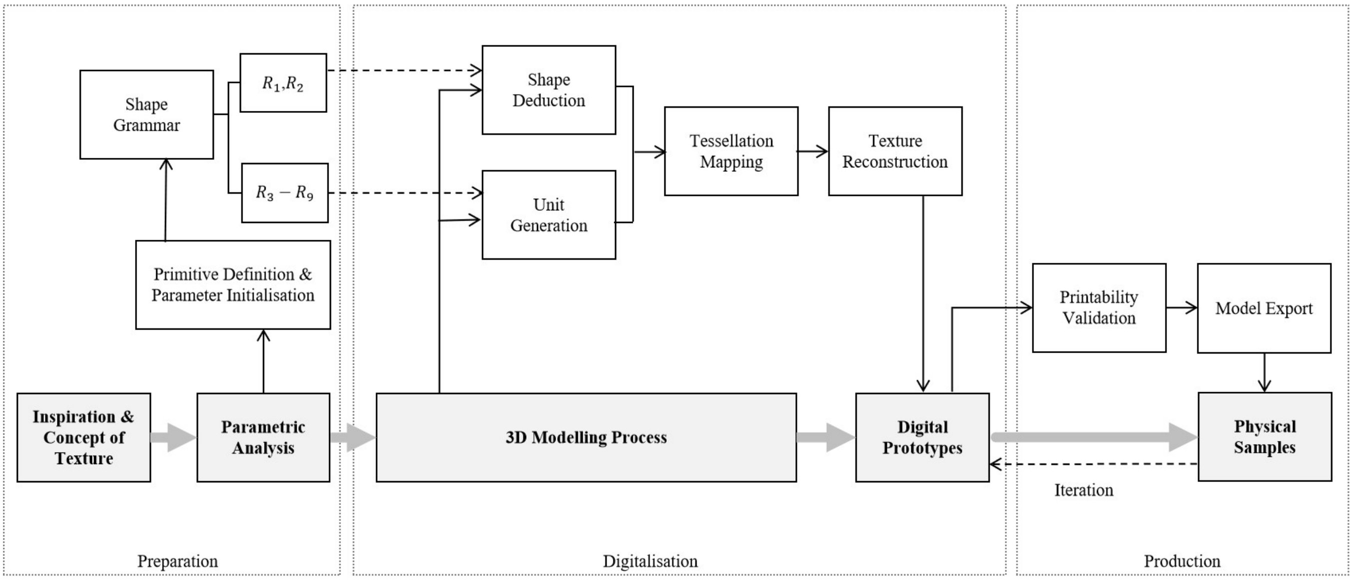


Figure 1: Research framework of 3D-Printed textile texture generation based on parametric tessellation design.

The workflow was designed specifically to serve textile and fashion designers who do not have a background in algorithmic modelling and who can work with computational design thinking using the available visual tools instead of the actual operation of the code.

The framework externalises rule-based parametric logic (rule execution and exploration of parameter spaces) while retaining human agency for goal setting and evaluation [1, 6]. Specifically, the research design had four consecutive steps: (1) primitive definition and parameter initialisation, (2) shape deduction and unit generation, (3) tessellation mapping and texture reconstruction and (4) printability validation and model export. These processes complete a closed-loop process that links a digital geometry to a physical fabrication. Introduced in Grasshopper, the framework enables designers to manipulate the parameters visually and immediately render the results, thus creating a smooth flow of computation logic and actual textile textures.

The square primitive was employed as an exemplar geometric archetype due to its topological clarity and tessellation stability to allow the rule-based logic of the workflow to be transparently demonstrated rather than restricting the applicability of the system. The SG rules and parametric operations defined in this study were geometry agnostic and can be directly applied to other planar primitives, such as triangles or hexagons, without modification to the underlying workflow.

The initial step involved defining the underlying geometric primitive and modulating its parameters (i.e. translation, rotation and scaling) along interactive sliders in Grasshopper to allow the flexible exploration of possible shape variations. The second stage applied SG rules to form and optimise motif units to allow the systematic development of form by generative and derivative sequence. These motifs were mapped in the third phase on a two-dimensional lattice to create continuous tessellated textures with variable space and alignment to guarantee visual coherence and printability. The last phase measured the manufacturability of the produced textures based on basic FDM printing constraints and sent the verified models to be produced. Figure 1 presents an overview of the overall parametric workflow from digital design to physical printing.

2.2 Shape Grammar(SG) System

We formalised SG as the core rule-based generative system of the workflow. SG provides a formalised structure for generating new shapes through rule-based transformations. The system can be represented as a four-element tuple:

$$SG = <S, L, R, I> \quad (1)$$

where,

S represents a finite set of initial shapes (e.g.basic geometric primitives, such as triangles, quadrilaterals or polygons),

L denotes a finite set of symbolic labels that define geometric relationships and transformations,

R is a finite set of inference rules that determine how shapes evolve over successive iterations and

I refers to the initial configuration of the primitive shape.

The rule set was defined as

$$\text{RuleSet } R = \{R_1, R_2, R_3, \ldots, R_9\} \quad (2)$$

Each rule denoted a specific geometrical operation applied during design evolution. According to their operational logic, the rules were categorised into two broad groups: generative rules and derivative rules.

1. Generative rules distort or substitute local areas of the original form and bring in structural diversity. They consist of two basic operations: replacement and addition.
2. Derivative rules apply geometric changes to the preexisting forms without changing their character of design identity. These consist of seven basic operations: scaling, mirroring, repetition, rotation, skewing, screening and Bézier curve transformation.

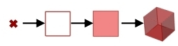
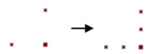
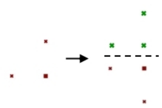
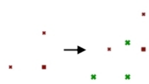
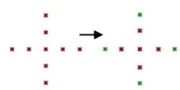
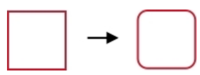
The combination of these rules functions as a genetic metamorphosis in which one generation includes the formal ’DNA’ of a former shape but adds controlled morphological distinctions. Formalisation of such rules enables systematic building, encoding and visualisation in the Grasshopper environment. The rules are parameterised and embedded as programmable components, which allows an opportunity to dynamically manipulate and provide real-time feedback throughout the generative process. Within this workflow, SG operates as a rule-based parametric framework wherein rule execution and dependency propagation support the systematic evaluation of spatial outcomes and refinement of geometry through iterative feedback. This process transforms Grasshopper from a passive modelling interface into an active parametric modelling environment that bridges computational design logic and human decision-making. The rule set was defined in detail, with relevant mathematical, functional and illustrative diagrams describing their geometric effects, and it is summarised in Table 1 .

2.3 Base Unit Definition and Parametric Variables

The definition of the base unit also provides the geometrical basis for the tessellation pattern and its further conversion to printable 3D textures, thereby serving as the geometrical basis of the parametric system, in which geometric behaviour emerges through the interaction between encoded rules and parametric transformations. This step, which is a sequential grouping of two-dimensional (2D) and 3D forms of monomers, is the design unit in the parametric framework, as indicated in Figure 2.

Monomers in the 2D domain include triangles, squares, pentagons, hexagons and circles, and these are the basic primitives used in tessellation. The planar units also find particular

Table 1: Deduction Rules of the Shape Grammar System

Category	Rule Name	Mathematical Expression	Geometric Interpretation	Graphic Description
Generative	Replacement (R_1)	$TS = S'$; $S = \{\diamond, \Delta, \square\}$; $S' = \{O, \Delta, \star\}$	Replace one shape element with another to form a new configuration.	
Derivative	Addition (R_2)	$TS = S + S'$; $TS = \{\diamond, \triangle, \square\}$; $S = \{\diamond, \triangle\}$; $CapS' = \{\square\}$	Add a new geometric element to the existing shape; this increases the structural complexity.	
	Scaling (R_3)	$TS = \lambda S = \begin{bmatrix} \lambda_x & 0 & 0 \\ 0 & \lambda_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$	Scale shape S by factors λ_x and λ_y along the X and Y axis. $\lambda > 1$: enlargement; $0 < \lambda < 1$: reduction. Uniform if $\lambda_x = \lambda_y$; non-uniform if $\lambda_x \neq \lambda_y$.	
	Mirroring (R_4)	$TS = KS = \begin{bmatrix} K_x & 0 & 0 \\ 0 & K_y & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$	Reflect shape S about the axis or line. $K_x = -1, K_y = 1$: mirror over the Y axis; $K_x = 1, K_y = -1$: mirror over the X axis.	
	Repetition (R_5)	$TS = (N+M)S = \begin{bmatrix} N+1 & 0 & 0 \\ 0 & N+1 & 0 \\ M_x & M_y & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$	N: replication count ($N \geq 0, N \in \mathbb{Z}$); M_x, M_y: translation displacements of replicated shapes.	
	Rotation (R_6)	$TS = RS = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$	Rotate the shape by angle θ around the origin (counter-clockwise).	
	Skewing (R_7)	$TS = HS = \begin{bmatrix} 0 & H_y & 0 \\ H_x & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$	H_x: horizontal skew coefficient; H_y: vertical skew coefficient.	
	Screening (R_8)	$S' = \{s_i \in S \mid (x_i, y_i) \in \Omega\}$	From a set of shapes $S = \{s_1, s_2 \ldots s_n\}$, select those whose coordinates fall within the defined region. Used for range-based or condition-based shape filtering.	
	Bézier (R_9)	$B(t) = P_0(1-t)^3 + 3P_1(1-t)^2 t + 3P_2(1-t)t^2 + P_3 t^3, \quad t \in [0,1]$	P_0, P_1, P_2, P_3: control points defining a cubic Bézier curve; adjusting any point changes the curve shape.	

importance in pattern making as their edge connection and angular compatibility permit continuity of their edges when repeated, translated and rotated across an extended textile surface. In the framework of 3D-printed textiles, these 2D primitives serve as structural seeds which characterise the logic of geometry according to the continuity of patterns and connectivity through modules.

To convert the tessellated patterns to 3D printing, every 2D unit is extruded, lofted or hollowed to create a 3D subunit. This transformation holds the planar connectivity necessary for tessellation and brings in volumetric properties to introduce tactile-relevant surface variation and material integrity. The resulting 3D forms can be categorised into three groups, namely extruded solids, lofted or faceted volumes and hollow or perforated geometries. They offer different tactile-relevant and visual characteristics appropriate to 3D flexible textile integration.

In practice, this phase is realised in Grasshopper, where important parameters—some of them being location (translation), size (scaling) and orientation (rotation)—are parameterised along interactive sliders. These parameters dynamically create evolving configurations that create a continuous motif seed chain, which is the basis of the tessellation pattern. This parametric responsiveness is achieved as Grasshopper executes rule-based parametric input and updates geometric outputs in real time. An important point in this step is visual rule checking, whereby the designer monitors constant changes of patterns in the parametric viewport of Grasshopper. This works as an effective transfer of the formal logic of SG into a visual language of design, which is interactive. In comparison to purely symbolic grammars [28], with this integration, there is instant recognition of spatial rhythm, and aesthetic/functional judgment can be made through iterative application of the rules.

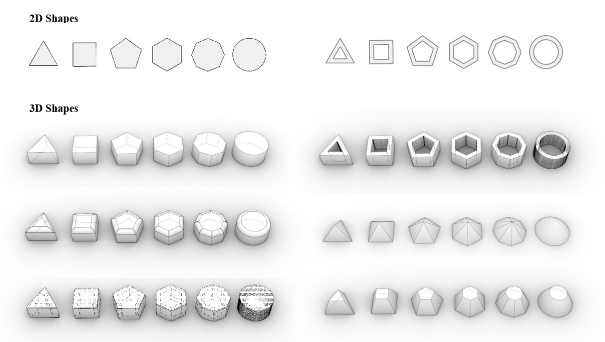


Figure 2: Classification of 2D and 3D monomer shapes used for base unit definition.

2.4 Tessellation Pattern Construction

The construction phase of the tessellation pattern converts the parametric specifications made in the other steps to a distinctly comprehensible and reproducible surface texture, thereby functioning as a rule-based parametric process through which encoded rules are executed iteratively to generate and refine geometric outcomes. It starts with two points of reference, which serve as geometric calibration points, after which a chain of shape transformations takes place. As shown in Figure 3, the pattern is built up by repeated applications of the rules of SG, thus leading to the introduction of controlled variations in position, rotation and quantity of units. This iteration of deductions turns simple line alignments into swirling, complicated structures, which eventually develop into interlinked, tessellated networks.

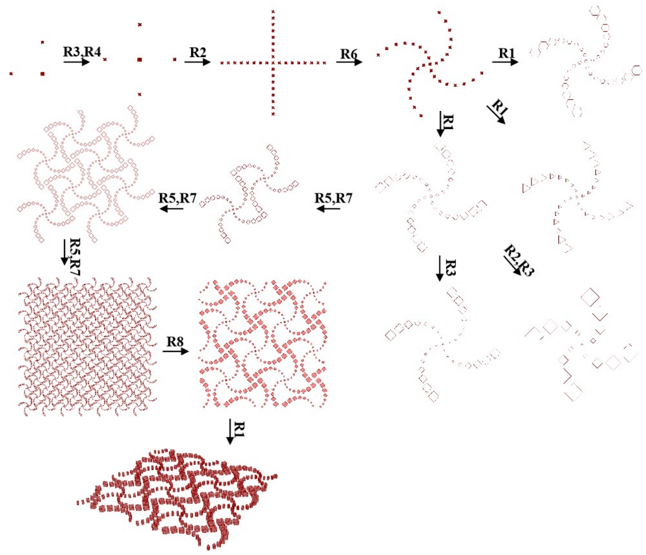


Figure 3: Evolution process from point-based origin to tessellated pattern through rule iteration.

This generative logic is systematically encoded within a procedural algorithm implemented in Grasshopper (see Figure 4). The stages are point generation, curve filling, unit instantiating, array transformation and boundary condition control. Every unit in the Grasshopper flow defines a specific phase of geometrical computation in that the main structure is set by the 'point series' module and the orientation and proportional relationships between units are controlled by rotate and scale units and accurately repeated by the 'array' and 'boundary trim' units. This procedural implementation facilitates algorithmic precision as well as visual flexibility to provide the designer with a way of intuitively controlling the values of the parameters, including rotation angles, unit spacing and the count of arrays, via interactive sliders.

Figure 5 shows the comparative results of the influence of important variables on the generated tessellations in this study:

1. Figure 5(a) compares the patterns of the various numbers of square monomers that were used (6, 8 and 10). Further addition of units leads to visual rhythm and complexity to create a denser and more continuous network without compromising geometric continuity.
2. Figure 5(b) depicts the effect of rotation angle (82°, 72°, 36°, 48° and 7°). The medium levels of the rotation produced more evenly distributed spatial configurations in the directional flow and spatial harmony, but extreme figures resulted in a distortion or uneven concentration in the pattern field.
3. Figure 5(c) studies the geometry of the monomers by replacing the triangles, squares and hexagons. The findings indicated that all three retained edge connectivity, but the

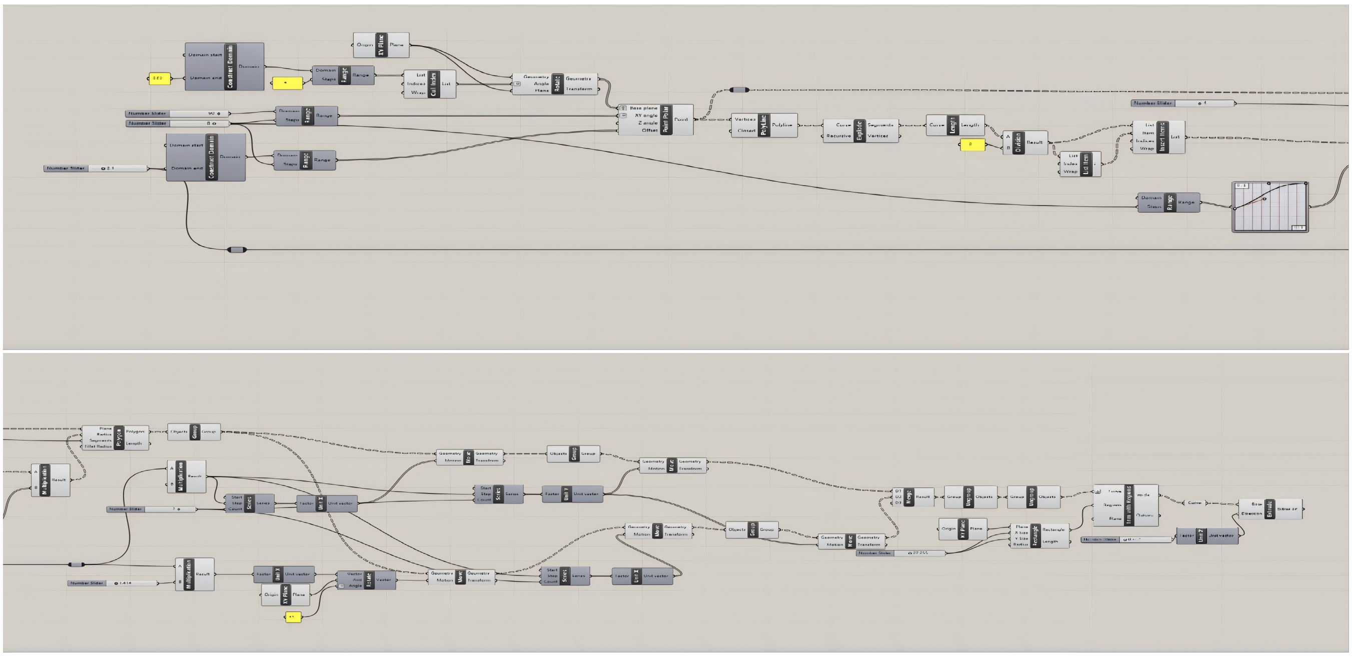


Figure 4: Grasshopper parametric flowchart illustrating the tessellation generation process.

square monomer attained the most stable surface coverage and aesthetic continuity. Hence, it was particularly suitable under the constraints examined in this study.

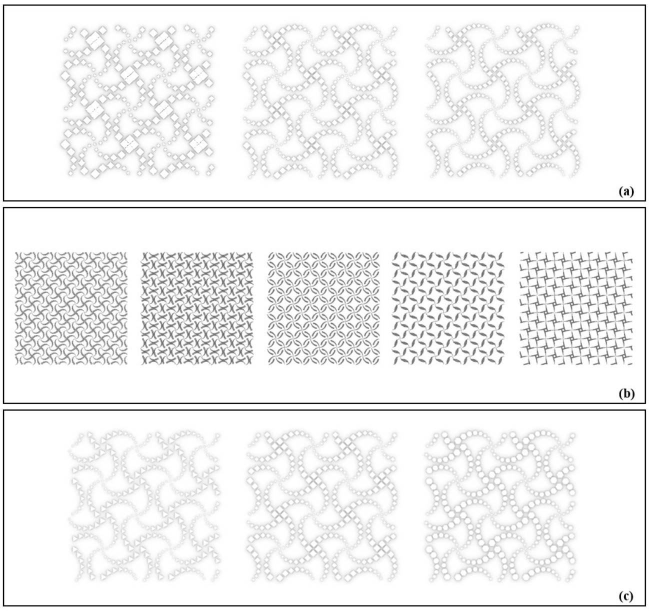


Figure 5: Comparative analysis of generated tessellation results: (a) unit number variation, (b) rotation angle variation, and (c) monomer geometry variation.

Through repetition and alignment of the motifs with their controlled offsets, a continuous and non overlapping tessellated pattern was created. This step was applied in Grasshopper by the combination of array components and a boundary condition constraint to make the edges flow seamlessly. The result of the design was a full-scale modular tile that could be infinitely extended over a textile surface without geometrical distortion.

This tessellation generation step is an example of the SG rule recursion, and it shows how geometric logic can be integrated into a parameter-based CAD system to give rise to structurally consistent but formally diverse patterns. The lattice translation algorithm was implemented in Grasshopper, and it can replicate and position repeated patterns with an interval (Δ x, Δ y) equivalent to the size of the bounding box of the unit in both directions (non overlapping fusion and perpetual connection). To further improve manufacturability, inter unit spacing parameter (g, 1–5 mm) is dynamically controlled by a connectivity control unit to control the flow of materials in 3D printing to avoid texture deformation.

This design philosophy aligns with the work of Burry and Burry [4], who state that through computational control of geometric relationships, complex and stable morphologies can be achieved. In this sense, the tessellation generation process operates as a form of rule-based geometric organisation, in which geometric outputs are assessed and refined through rule-based iteration and the parametric nature of the workflow. The tessellation process can be seen as a means of creating surfaces as well as an experimental system that uses this parametric system to explore the aesthetic rhythm, structural consistency and physical versatility of 3D-printed textiles.

2.5 Printability Evaluation and Model Export

The final stage of the workflow focused on evaluating the printability and fabrication feasibility of the tessellated geometries that were developed within a textile-integrated FDM process, thereby closing the feedback loop between digital modelling and material execution. At this stage, geometric constraints were systematically evaluated and adjusted to ensure fabrication feasibility. This step ensured that the digitally generated patterns could be reliably produced on flexible textile substrates while maintaining an appropriate balance between structural integrity, flexibility and adhesion.

The FDM printing technique was selected for this study because it is cost-effective, accessible and highly flexible in experimental applications of textiles. In comparison with high-end multi-material systems, like PolyJet printing, which offer high resolution but require the use of expensive proprietary resins as well as rigid build platforms that are expensive and difficult to obtain, FDM is a more viable and cost-effective option. It permits direct deposition onto flexible substrates (which is required for textile integration) and allows fine control of process conditions, such as nozzle temperature, layer height and extrusion speed, which supports iterative testing and the optimisation of adhesion.

Three major geometric and material constraints were imposed by using the typical guidelines of FDM design [29, 30]:

1. Minimum thickness (t $\geq$ 2 mm) to prevent filament breakage and ensure continuous material flow.
2. Minimum gap (g $\geq$ 1 mm) to avoid material accumulation and maintain textile flexibility.
3. Curvature radius (r $\geq$ 1 mm) to minimise stress concentration and improve print accuracy.

After computational verification, the models were processed and prepared for fabrication then exported either as Stereolithography file format (.stl) or as G-code toolpaths, which define machine-readable instructions controlling the motion and operation of the 3D printer. The printing process followed a layer-textile-layer strategy. First, an initial adhesion layer (approximately 1 mm thick) was printed. The textile substrate was then positioned on top of this layer, after which printing resumed to generate the tessellated texture. This approach enhanced the mechanical interlocking between the printed polymer and textile fibres and resulted in consistent and uniform bonding across the samples (Figure 6).

During material testing for this study, the textile skin permeability of a number of thermoplastics, such as PLA, acrylonitrile butadiene styrene (ABS) and TPU, was tested. PLA was very stiff but was prone to cracking during bending, whereas ABS had moderate toughness/low adhesion with a higher melting point. TPU had better elasticity, strength and bonding between layers, which made it the most suitable for flexible substrates. The samples printed with TPU demonstrated good adhesion, toughness and surface compliance, thus confirming its suitability for embedded textile-polymer fabrics.

The stage of sample fabrication validated the relevance of the proposed digital-physical workflow by demonstrating that computationally generated tessellation models can be translated into practical 3D-printed textile textures using accessible fabrication technologies. Algorithmically defined geometric rules were verified and refined through fabrication constraints, thereby illustrating how parametric accuracy and controlled manufacturing processes support reproducible and fabrication-aware textile design.

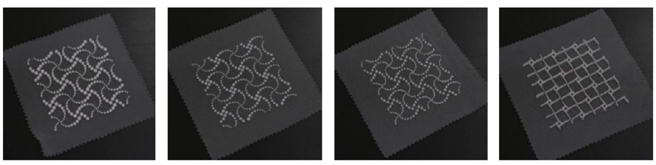


Figure 6: Final 3D-printed textile samples fabricated using TPU via FDM printing.

3 Results

This study showed that the proposed SG-based parametric model effectively enables the fabrication of geometric logic on textiles through 3D printing. It demonstrated how rule-based parametric workflows can translate rule-based algorithms into tangible textile structures, thereby bridging rule-based parametric modelling and material fabrication. The emerging process of parametric control, geometric transformation and manufacturability expressed through the successive cycles of a digital-to-physical workflow can be traced through the iterative transformation process of a primitive definition to a physical object.

The geometric transformation at the first step started with two reference points that characterised the square primitive of the base. The primitive became an interconnected modular system through a series of applications of SG: translation, rotation, scaling and mirroring of the primitive. With each new iteration, there was a progressive amount of complexity, which resulted in a tight tessellation repeating pattern that retained structural integrity and visual rhythm (Figure 3). This iterative, rule-based evolution demonstrated how systematic parametric variation generates diverse and fabrication-feasible design configurations, in which minor parametric shifts produce multiple design possibilities. This transformation can be seen as a demonstration of the generative ability of the system, through which a wide range of visually different and fabrication-enabled structures were generated by use of simple geometric inputs.

This evolution was implemented as a Grasshopper workflow (Figure 4). Within the parametric interface, sliders controlling position, size and orientation enabled the real-time variation of geometric outputs. This allows designers to visually observe pattern changes as parameters are adjusted, thus supporting intuitive exploration during the design process. The parametric-geometric relationship establishes a clear connection between computational rules and spatial form and enables abstract SG operations to be examined through visual feedback.

The influence of key parametric variables on pattern formation and surface continuity was examined through comparative configurations (Figure 5). Variations in the number of units indicated that increased density enhanced surface continuity while requiring careful adjustment of inter unit spacing to preserve geometric clarity. Changes in the rotation angle affected the directional flow of the texture, with moderate angles producing more balanced configurations and extreme values resulting in distortion or uneven concentration. Comparisons between triangular, square and hexagonal base units showed that all geometries retained edge connectivity; however, under the fabrication constraints examined in this study, the square arrangement exhibited greater stability and resulted in smoother transitions across the textile plane. To support surface continuity and reduce abrupt geometric transitions, a lattice translation algorithm was used to repeat and position the units of motifs with intervals corresponding to their respective bounding box size. Boundary-conscious arraying guaranteed continued non overlapping and infinite repeatability, whereas a connectivity control parameter controlled the distance between repeated motifs. This minimisation of the material flow streamlined the FDM printing process and prevented over-extrusion or warping. It also provided aesthetic coherence as well as structural integrity to the printed textures (Figure 5(c)).

The digital models were also verified against three major FDM constraints in the printability validation stage: minimum texture thickness (t ≥2 mm), minimum inter unit gap (g ≥1 mm) and edge curvature radius (r ≥1 mm). The designs that conformed to these requirements had a smooth extrusion, precise deposition and good adhesion to the textile substrates. TPU performed better in the material trials in terms of both flexibility and bonding than PLA and ABS, which were vulnerable to being brittle and weakly adhesive, respectively. The FDM technique, which used a layering-fabric-layering approach, improved the bonding capabilities further between the printed texture and the textile ground. The resultant physical samples (Figure 6) verified that it was feasible to laminate complicated tessellated structures on soft materials such that the framework was able to mediate between digital accuracy and material performance in the final product.

Altogether, the findings of this study confirmed the underlying assumption that a strategic combination of SG and parametric control can be used to produce textile textures in tessellated form that are geometrically consistent and feasible to produce in real life. The system demonstrated how rule-based parametric design can move beyond digital simulation to material innovation and form a reproducible pathway for digital fabrication and prototyping in textile design. The structure of the framework is modular and reproducible, which makes it a flexible starting point in which to explore additional issues related to computationally generated 3D-printed textiles. This finding contributes to the broader discourse of computational textile design and digital fabrication by showing how computational design frameworks can support the development of textile prototypes.

4 Discussion

The results of this paper showed that a SG-based parametric model can serve as a good way to close the gap between computational design logic and textile-integrated 3D printing for the design of surface and structural variations. As a rule-based parametric framework, it supports design exploration and fabrication-aware refinement by linking parametric variation with geometric verification and printability constraints across the workflow. The scientific case study, which started as a basic square primitive and evolved into a sophisticated tessellated structure, established that rule-based parametric modelling offered creative freedom as well as geometric control in a single workflow. The capacity to encode the shape rules enabled the tessellated patterns to develop in a predictable way and, at the same time, to have variety in design. This integration enabled the expression of the abstract geometrical principles in physical material forms, which could confirm the possibility of parametric grammar as a design-to-fabrication strategy.

The findings also indicated that parameter coupling is an essential element to enable the balance of texture morphologies. The number of units, the degree of rotation and the geometry were demonstrated to affect the density, rhythm and continuity throughout the textile surface. The coherent transitions were obtained at moderate parametric settings, and the irregular spacing and distortion were observed in extreme parametric values. The integration of manufacturability considerations, which included minimum thickness, gap and curvature radius, into the Grasshopper workflow was important because every resulting geometry was printable under FDM conditions. Applying TPU as the main material used in printing was especially successful because it has elasticity and adhesion properties that are durable; this choice therefore supported the appropriateness of flexible thermoplastics as an additive manufacturing material for the textile industry.

From a geometric perspective, tessellation provides a robust structural framework for computational textile design. Its modularity, scalability and capacity for seamless repetition align well with the layer-by-layer logic of FDM printing. When combined with SG and parametric control, tessellation enables a closed-loop design workflow that supports iterative refinement, real-time visual feedback and physical validation. This approach helps reduce the disconnect between digitally generated designs and material realisation, which has been a long-standing challenge in computational textile research.

This study contributes to both computational design and textile fabrication practice in several ways. First, it presents a designer-oriented parametric workflow that integrates SG within a visual programming environment, thereby making algorithmic form generation accessible to designers without advanced programming expertise. Second, it embeds manufacturability constraints directly into the generative process, thus reducing trial and error during fabrication. Third, it establishes a reproducible system of parameter mapping that enables systematic comparison across design iterations. Finally, it demonstrates the potential of tessellation-based pattern systems to integrate geometric variation and structural consistency within a unified parametric framework.

Despite its contributions, this study had limitations. The workflow was demonstrated through a single exemplar case using a square primitive that was selected for geometric clarity and tessellation stability; however, the underlying SG rules and parametric operations were geometry agnostic and transferable to other planar primitives. In terms of fabrication scope, the material trials focused on FDM printing with PLA, ABS and TPU and did not include other additive manufacturing methods, such as PolyJet, selective laser sintering (SLS) or multi-material extrusion. In addition, this work emphasised geometric and fabrication validation, while mechanical testing and user-centred evaluation (e.g. tensile behaviour, flexibility retention and tactile perception) were beyond its scope.

Our future work will focus on extending the parametric framework through systematic geometric analysis and expanded fabrication testing. Further studies may explore additional geometric archetypes, alternative material systems and quantitative evaluation methods to examine mechanical behaviour and tactile-related surface characteristics. These extensions of the research could strengthen the empirical grounding of the framework while preserving its rule-based and designer-centred nature.

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Author Contributions

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Conflict of Interest

All the authors declare that they have no conflict of interest.

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