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A systematic shape rules repertoire in architectural design: A proof-of-concept

Abstract. The aim of this study was to identify, structure, and empirically validate a systematic repertoire of elementary form-transformation rules that accurately depicted sketch-based architectural design processes and can be directly implemented in computational environments. To address the lack of a systematically organised, detailed repertoire of shape transformation operations in architectural design research, 48 shape rules were developed through literature review and refined through empirical observation of sketching sessions conducted by two experienced architects. The rules were assigned to two operational categories (Plastic, Structural), one meta-category (Figurative), and 14 rule classes. Protocol analysis confirmed that the repertoire captured the full range of observed form manipulations across 23 sketches and 267 coded transformations, with high intra-coder reliability (Cohen's Kappa: 0.85-0.87), confirming the robustness and clarity of the proposed classification. Structural rules made up 74% of the observed transformations, highlighting the predominance of configurational exploration in early-stage design, whereas Plastic and Figurative rules accounted for 15% and 11%, respectively. Statistical analyses, including principal component analysis and hierarchical cluster analysis, showed a consistent bipartite structure across both designers: structural rules formed a distinct cluster, while plastic and figurative rules grouped, with PC1 explaining 97-99% of the total variance. The practical significance of this research lies in providing a transparent and reusable transformation framework that supports the analysis of architectural sketching behaviour and facilitates the development of rule-based computational design tools

Keywords: architectural sketching; form manipulation; shape grammar; protocol analysis; design cognition

INTRODUCTION

Studies in architectural design confirmed the enduring relevance of rule-based approaches for representing and generating architectural form. Among these, shape grammars remained a foundational paradigm for modelling the iterative transformations, through which architects explored and developed design alternatives. By explicitly encoding form manipulations as rule-based operations, shape grammars provided a formal bridge between design

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cognition, visual reasoning, and computational implementation. Parametric and computational implementations have demonstrated how rule-based systems can support early design exploration by systematically controlling transformations such as translation, rotation, scaling, and subdivision. For instance, A.F.P. Sondakh & A. Indraprastha (2023) proposed a parametric method combining shape grammar and generative components within a Grasshopper environment to guide spatial and functional reasoning during early-stage residential design. Similarly, X.-H. Xie *et al.* (2025) showed how parametric shape grammar rules implemented in Grasshopper environments enabled controlled, rule-driven form variation through explicit transformation operations.

Shape grammar approaches have also been applied to the analysis and generation of architectural form within specific spatial and cultural contexts. S. Çelik & Z. Şahin Çağli (2024) also applied shape grammar as an analytical and generative tool for facade design, identifying formation rules for detached houses on Ankara's Çınar Street through Boolean operations (join, intersect, differ) and transformation commands (rotate, mirror, shift, scale). Research demonstrated how extracted rules can be computationally implemented in CAD systems (AutoCAD, Showcase) to generate new facade designs for high-rise residences, while maintaining urban texture continuity. These bidirectional applications – analysing existing forms to extract rules, then applying those rules to generate new designs – exemplified the analytical and synthetic capabilities of shape grammar methodologies. It illustrated the capacity of grammars to encode complex formal logics, while remaining adaptable to contextual constraints. F.A. Linas & K. Chithra (2024) documented a wide diversity of shape grammar applications across architectural design, computational modelling, and spatial analysis. The authors also noted substantial variation in how transformation rules were defined, structured, and operationalised, limiting methodological consistency and comparability across studies. Parallel research streams have sought to expand the expressive power of grammar-based systems through bio-inspired models and hybrid computational pipelines. M. Kleiss *et al.* (2025) explored bio-inspired generative grammars for complex spatial configurations, while A. Plocharski *et al*. (2025) integrated grammar rules with machine learning techniques for façade generation. Although these approaches produced sophisticated generative outputs, it tended to embed transformation logic within complex computational workflows, making the underlying operations less explicit and more difficult to interpret or reuse.

S. Yiannoudes (2025) emphasised that, despite rapid advances in deep learning, rule-based form generation remained critical for maintaining transparency, interpretability, and designer control. Similarly, T. Berčič (2024) identified challenges in translating parametric and algorithmic innovations into standardised, interpretable transformation frameworks that aligned with architects' actual design practices, highlighting the importance of integrating shape grammars into parametric design tools to support systematic form manipulation. So, these works confirmed that rule-based transformation systems remained central to architectural design research. Also, it was revealed a persistent shortcoming: transformations were often defined at high levels of abstraction, tailored to specific domains, or embedded within opaque computational pipelines. What remained insufficiently addressed was the articulation of a fine-grained, systematically organised repertoire of elementary transformation operations that can accurately describe how architects manipulate form during design, while remaining directly implementable in computational systems. Despite advances in shape grammar methodologies and hybrid generative approaches (2023-2025), there was a lack of a systematically organised, fine-grained repertoire of shape transformation operations capable of accurately capturing designers' manipulations in a way that supported direct computational implementation. Broad categories such as "outline transformation" or "form modification" were insufficient for algorithmic mapping, whereas explicit operations – like rotation, translation, subdivision, bending, insertion, and replacement – can be directly translated into computational procedures.

MATERIALS AND METHODS

Methodology of this study involved a focused sample of two experienced architects, deliberately selected to test whether the repertoire can successfully capture the full range of transformations observed in residential design activities. The transformation repertoire was developed through a two-stage process combining theoretical synthesis and empirical observation. Stage 1- literature synthesis: a systematic review of the literature on shape grammars, sketching, and design transformation was conducted to ensure alignment with modern research trends, including bio-inspired generative grammars, parametric extensions, and hybrid computational approaches, while seminal works were referenced for historical context. Transformation operations were extracted at a fine-grained, operational level, including rotation, translation, scaling, subdivision, aggregation, and deletion. Similar operations described with varying terminology were consolidated, while operations rarely observed in sketches were excluded. Stage 2 – empirical refinement: the preliminary rule set was iteratively refined through observation of two architects performing residential design tasks. Transformations not adequately captured by literature-derived rules led to additional categories, while redundant or indistinguishable rules were merged or removed. The final repertoire comprised 48 clearly defined shape rules, organised into 14 operational classes and grouped under three higher-level categories: plastic transformations: modify external appearance or outline (size, form, or texture); structural transformations: alter spatial or topological relationships; figurative transformations: affect representational visualisation without changing design outcomes.

This hierarchical structure enabled identification of recurring patterns, while preserving operational detail for computational implementation. By grounding the repertoire simultaneously in established theory and observed design behaviour, this approach balanced formal rigor with empirical validity. The resulting transformation system was sufficiently detailed to capture nuanced sketch-based manipulations, yet structured enough to support computational implementation and comparative analysis across designers and design tasks. Having developed the repertoire through literature synthesis, its content and structure were validated through empirical observation of design activities using protocol analysis. Protocol analysis enabled systematic capture of design behaviours through recordings of verbalisations and sketching activities. The think-aloud technique, in which participants vocalised their thoughts, while designing, was adopted. The analysis comprised three steps: data collection, protocol description (segmentation and coding), and data processing (Bouhelis & Arrouf, 2024). Three architects initially participated in the study, with two selected for analysis based on protocol completeness and verbalisation clarity. Both participants (Architect 1 and Architect 2) had over 20 years of professional experience in residential design and had completed multiple residential projects. This focused sample size aligned with proof-of-concept studies in design research and with the study's objective of testing the repertoire's descriptive adequacy rather than achieving statistical generalisation.

The experiment comprised two phases totalling 55 minutes. Participants designed a house for a plot within a residential subdivision, producing freehand sketches, while thinking aloud. Two video cameras captured the activity: one recording the designer's gestures and facial expressions, the other documenting sketch production and detailed manipulations. Video recordings allowed for detailed analysis of both verbal protocols and graphical transformations performed during the design process (Bouhelis & Arrouf, 2024). Following data collection, protocols were segmented into analysis units. Each sketch was treated as a distinct segment, as graphical outputs directly revealed shape rule applications. Video recordings and verbalisations aided rule identification. Sketches were sequenced chronologically and organised into transformation tables for pairwise comparison between successive sketches. Each sketch was compared with its predecessor to identify form transformations, which were then coded using the shape rules repertoire. The protocols were coded following a test-retest coding procedure with adjudication: the same coder performed initial coding, then recoded all protocols after completion, and finally compared the two versions to establish the final codification through adjudication of discrepancies. Intra-coder reliability was assessed using two measures: percentage agreement between coding rounds (Architect 1: 95%; Architect 2: 93%), and Cohen's Kappa coefficient calculated on the independent coding rounds before adjudication (Architect 1: k = 0.87; Architect 2: k = 0.85) (Table 1).

Table 1. Intra-coder reliability measures

Measure	Architect 1	Architect 2	Interpretation
Percentage agreement	95%	93%	Excellent (>90%)
Cohen's Kappa	0.87	0.85	Almost perfect

Source: based on J.R. Landis & G.G. Koch (1977)

To validate the structural coherence of the repertoire, both Principal Component Analysis (PCA) and hierarchical cluster analysis using Ward's method with Euclidean distance were performed on the coded protocols. These statistical methods tested whether the proposed three-category classification system (Plastic, Structural, and Figurative rules) corresponded to empirically observable patterns in how architects deployed shape transformations. The study received ethical approval from the laboratory's Scientific Council LEMPAU-2023-HRP-037 (Bouhelis & Arrouf, 2023). Also, the study was conducted in accordance with the norms of The Declaration of Helsinki (2013). All participants provided written consent and were informed of their right to withdraw at any time.

RESULTS AND DISCUSSION

Analysis of the empirical data confirmed that architects' shape transformations can be systematically captured using the proposed repertoire of 48 rules, organised into a hierarchical system comprising two operational categories (Plastic and Structural), a meta-category (Figurative), and fourteen classes of operative rules. The theoretical grounding and empirical validation of each category have been presented, followed by an examination of the statistical patterns that emerged from their deployment across designers and design tasks. Plastic shape rules related to the first strategy identified by F.D.K. Ching (2007) as a "slug". This strategy was defined as transformation by "metamorphosis" or "plastic transformation" (Wetzel *et al.*, 2006). The term "plastic" pertained to the external appearance and outline of an element or a form, to the set of lines, shapes, or colours. Plastic shape rules were most commonly utilised to refine and enhance architectural forms (Prats *et al.*, 2009). For instance, bending a volume's outline or changing its proportions were plastic transformations that modified appearance, while maintaining overall organisation. This category of shape rules was decomposed into four different classes. These classes describe shape transformations that affected the visual properties of a form or an element as: conformation, size, colour, and texture. The second strategy, corresponded to what F.D.K. Ching (2007) metaphorically likened to a "lobster"

(Fig. 1). It was the process of producing forms through adjustment and combination. The term “structure” referred to the “internal constitution” and the “internal relations” within the architectural form, as well as the relationships among shapes and elements – specifically geometrical and topological relations (Borie *et al.*, 2006). These transformations were termed “structural transformations” or “transformations by composition”.

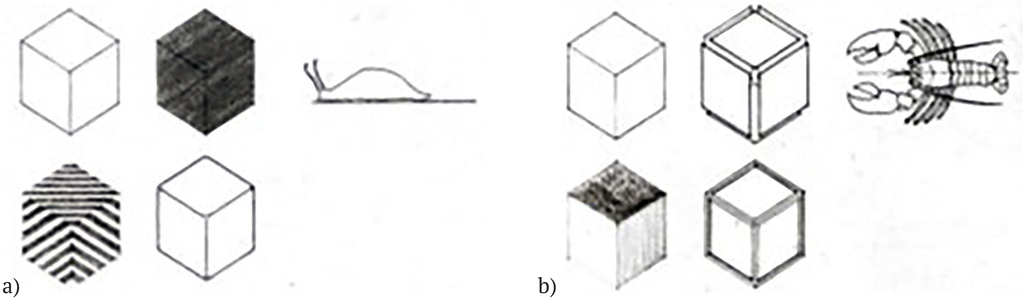


Figure 1. Examples of plastic form in architecture
Note: a - architectural form “lobster”; b – architectural form “slug”
Source: based on F.D.K. Ching (2007)

Structural transformations were primarily used to explore different spatial relationships between elements and to investigate the variety of solutions concerning the organisation, the layout, and the composition of a design. Structural shape rules were more likely to result in significant changes in shape compared to plastic transformations (Prats *et al.*, 2009). For example, adding a new volume to an existing configuration, or rotating an element, changes the overall design organisation and spatial relationships. A. Borie *et al.* (2006) noted that it included three classes of shape rules, namely: topological relations (position), geometrical relations (orientation), and constitution. The category of figurative shape rules occupied a distinct theoretical position within the repertoire, functioning as a meta-category rather than as a third equivalent category alongside plastic and structural rules. This distinction stemmed from a fundamental ontological difference: while plastic and structural rules directly transformed the architectural form itself, figurative rules operated at a representational level, transforming how the form was visualised, explored, and evaluated without modifying the design solution itself. This meta-categorical status was justified by several observations: first, figurative rules exhibited an asymmetric relationship with transformational rules. Plastic and structural transformations can be visualised through various representational modes (e.g., a structural change can be examined through plans, sections, or 3D views), but changes in representation do not produce formal transformations. Rather, it facilitated the application of transformational rules by enabling designers to select the most appropriate view for exploring or evaluating specific aspects of their design. Second, figurative rules served a mediating function between the designer and the design artifact. They do not generate new design alternatives but rather provide different perspectives on existing solutions, supporting the cognitive processes of form exploration and evaluation.

For instance, switching from a plan view to a section (a figurative transformation) does not alter the building but revealed spatial relationships that may inform subsequent structural or plastic transformations. Figurative rules were primarily utilised to enable designers exploring and visualising the shape transformations they perform. Their role was thus to test and detail visually-figured solutions generated by architects. This meta-category concerned transformations of the type of representation, the change of the rule’s space or object, the change of the rule’s space or floor (de Biasi, 2000), the point of view (Prats *et al.*, 2009), the direction of view, the size of the sketch, and finally its level of complexity (Rodgers *et al.*, 2000). This meta-categorical conceptualisation had methodological implications for protocol analysis. The frequency and sequencing of figurative rules can reveal designers’ exploration strategies: a high rate of view changes may indicate complex spatial reasoning, while the temporal relationship between figurative and transformational rules can illuminate how designers prepared, executed, and verified their form manipulations. This hierarchical structure – with figurative rules at a meta-level supporting plastic and structural transformations at the operational level – provided a more nuanced understanding of the sketching process and offered a conceptual framework for both design process analysis and computer-aided-design tools development. Figure 2 summarised the final structure of the repertoire. The repertoire encompassed both elementary and composite transformations identified in residential architectural sketching tasks. Table 2 presented the distribution of these transformations across operational classes and higher-level manipulation categories, as observed throughout the experimental work. Notably, Plastic and Figurative transformations prevailed during later compositional stages, while Structural transformations emerged predominantly in early exploratory design phases.

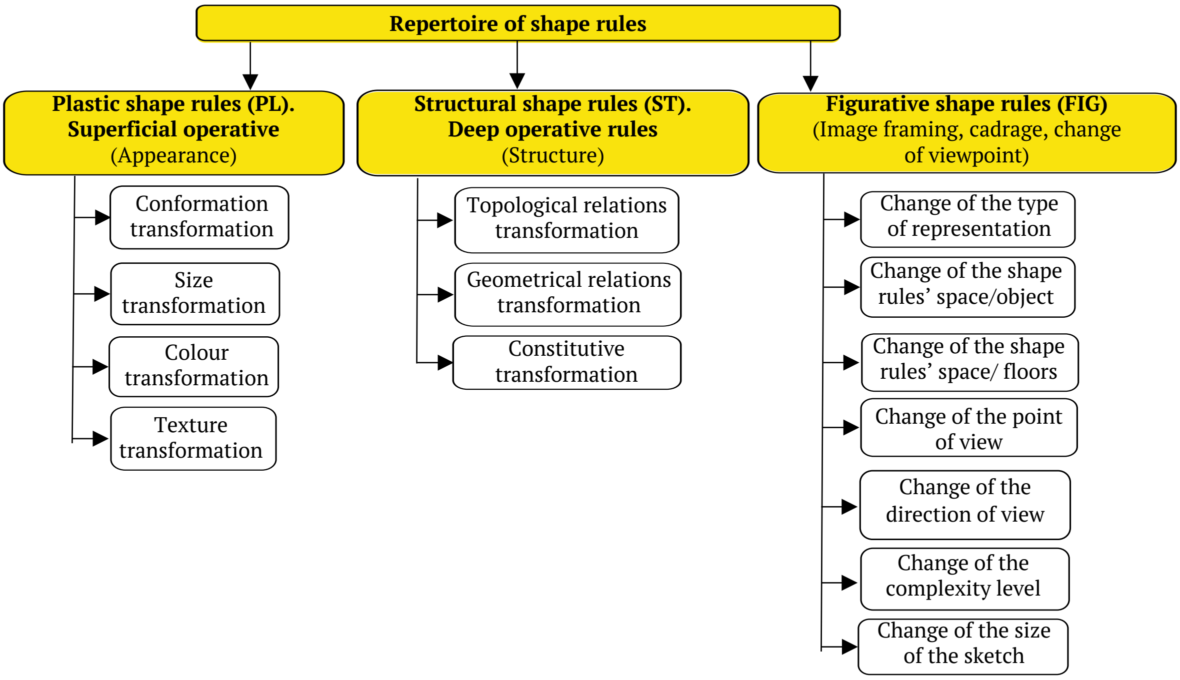
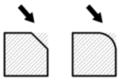
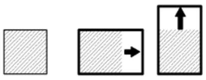
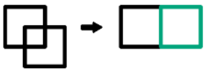
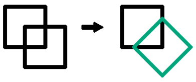
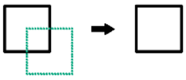


Figure 2. Global structure of the shape rules' repertoire

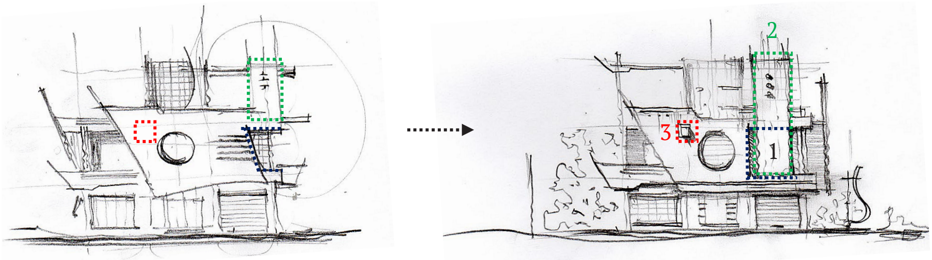
Source: developed by the authors

Table 2. The final constitution of the repertoire of shape rules

Categories of shape rules	Classes of shape rules	Examples	Illustrations
Plastic (PL)	Conformation transformation	Truncate, bend, push, fold, pierce, twist, pinch	
	Size transformation	Change length/width/depth	
	Colour transformation	Change colour	
	Texture transformation	Change texture	
Structural (ST)	Topological relations transformation	Change position	
	Geometrical relations transformation	Rotate, reflexion	
	Constitutive transformation	Add, delete, split, combine	
Figurative (FIG)	Change of: Type of representation Shape rules' space/object Shape rules' space/floors Point of view Direction of view Complexity level Size of the sketch	Change representation type, extend sketch, change floor	

Source: developed by the authors

Sequential analysis of sketches revealed consistent patterns in rule deployment. Across both participants, Structural rules accounted for 74% of observed transformations, Plastic rules 15%, and Figurative rules 11%, reflecting the dominance of structural reorganisation in initial residential designs. Plastic transformations were frequently combined with Structural rules, producing compound manipulations without altering the hierarchy of operations. Figurative transformations were primarily applied for clarifying design intent or adjusting visual readability. Figure 3 illustrated selected transformations from Architect 1, showing examples of Plastic (scaling), Structural (translation and aggregation), and Figurative (sketch overlay and annotation) rules applied to successive sketches. This figure demonstrated how the repertoire provided a consistent, operational framework for mapping observed design behaviours.



Sketch 3 **Sketch 4**

Figure 3. Example of coding process: transformations from Sketch 3 to Sketch 4 required 36 shape rules (Architect 1)
Source: developed by the authors

To validate the content of the repertoire, the identified shape rules were applied to the sketches produced by the two subjects. Two parameters were then observed: their "completeness", and their "relevance". "Completeness" meant the rules captured all the transformations performed by the architects, while "relevance" meant it was all involved. Following the coding procedure, sketches were analysed using the shape rules repertoire. The coding of the segments was recorded for each subject in an "objects/attribute" table. Table 3 represented the objects, and the categories of shape rules serve as attributes.

Table 3. An excerpt of the quantification table of the protocols of Architect 2

Segments	Categories of shape rules Plastic (PL)	 Structural (ST)	 Figurative (FIG)
Sketch 2	0	5	0
Sketch 3	1	5	1
Sketch 4	0	1	1

Source: developed by the authors

Across both subjects, a total of 23 sketches were produced, yielding 267 coded shape transformations (Table 4). Two temporal references guided the coding: the immediately preceding sketch (chronological reference) and the sketch containing the element before modification (referential sketch). For example, if an element was added in Sketch 5, modified in Sketch 7, and deleted in Sketch 10, the referential sketch for the deletion in Sketch 10 was Sketch 5 (where the element was created), not Sketch 7 or Sketch 9. This approach ensured accurate tracking of element lifecycles throughout the design process. Structural rules were most frequent (74%, n = 198), followed by plastic rules (15%, n = 40) and figurative rules (11%, n = 29). This distribution reflected the exploratory nature of early-stage design, where organisational decisions (Structural) dominated over refinement (Plastic) and representational adjustments (Figurative). The similarity in rule distribution between subjects (Architect 1: 73% ST, 15% PL, 12% FIG; Architect 2: 79% ST, 17% PL, 4% FIG), suggested consistency in how architects deploy shape rules during early-stage design, though the small sample size (n = 2) limited generalisability.

Table 4. Descriptive statistics of the outputs of the coding process of the two Architect's

Descriptive statistics	Architect 1	Architect 2	Total
Total number of sketches	19	4	23
Total number of shape rules	219	48	267
Plastic shape rules (PL) Count percentage	n = 32 15%	n = 8 17%	n = 40 15%
Structural shape rules (ST) Count percentage	n = 160 73%	n = 38 79%	n = 198 74%

Table 4. Continued

Descriptive statistics	Architect 1	Architect 2	Total
Figurative shape rules (FIG) Count percentage	n = 27 12%	n = 2 4%	n = 29 11%
Mean of shape rules/sketch	11.53	12	11.60

Source: developed by the authors

The description and codification demonstrated that shape rules, categories, and classes within the repertoire were fully utilised to describe and codify the shape transformations executed by the participating architects. Moreover, the repertoire supported all operations performed by the subjects in this proof-of-concept. Consequently, it can be asserted that all shape rules were necessary and sufficient for a complete description of the form manipulation and generation process observed within the architectural design activity of the two participating architects. Preliminary saturation was considered to have been reached under the following conditions: 1) all observed shape transformations could be coded using the existing repertoire without requiring new rule creation; 2) the two operational categories (Plastic, Structural) and the meta-category (Figurative) consistently captured all transformation types across participants; and 3) no unclassifiable transformations emerged from the protocol analysis. While preliminary saturation was achieved within this exploratory sample, demonstrating the internal coherence and applicability of the repertoire, theoretical saturation would require validation across a larger, more diverse population of architects with varying experience levels, design styles, and task types. The current repertoire should be considered as providing coverage for the observed design activities in this proof-of-concept, establishing a foundation for future validation studies rather than claiming universal completeness at this stage. PCA was performed on the coded protocols from both architects, extracting components that explained 100% of total variance in both cases. The first principal component (PC1) accounted for 97.64% of variance for Architect 1 and 99.58% for Architect 2, indicating a highly unidimensional structure where virtually all discrimination occurs along a single dimension. Figure 4 presented biplots of the first two components (PC1: horizontal and PC2: vertical) for each architect.

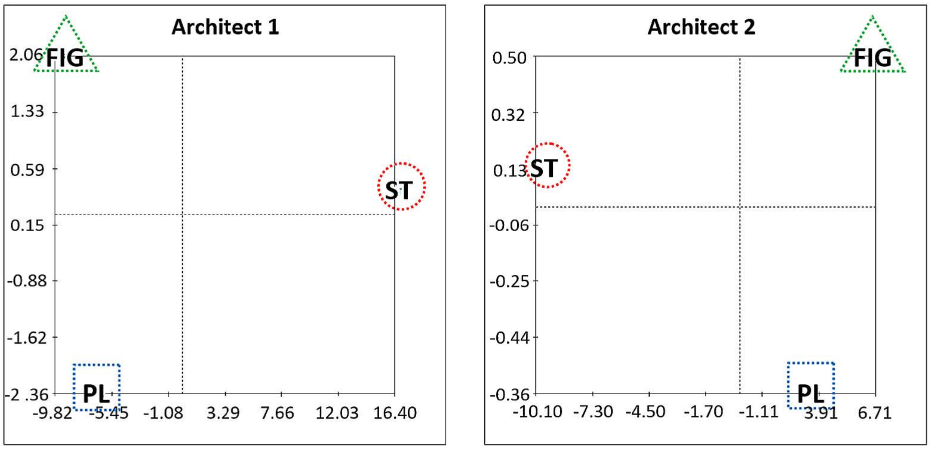


Figure 4. Factor analysis biplots

Note: green triangles – Figurative rules (FIG), red circles – Structural rules (ST), blue rectangles – Plastic rules (PL). Axes represent principal components with percentage of variance explained

Source: developed by the authors

The analysis revealed clear differentiation among the three rule categories along PC1, though with opposite orientations between subjects – a common and interpretatively neutral feature of PCA. Both architects showed a consistent bipartite structure: ST formed an isolated cluster at one extreme of PC1, while PL and FIG rules clustered together at the opposite extreme. This consistent pattern demonstrated the distinctiveness of each rule category, and the closer functional association between Plastic and Figurative rules relative to structural rules – supporting the hierarchical classification system. Figure 5 provided comparative overlays that highlighted the structural consistency across subjects. Shape rule categories (ST, PL, FIG) projected on first two components for Architect 1 (top left) and Architect 2 (top right). Bottom panels showed comparative overlays (black = reference; red/blue = subject-specific). U1 explained 97.64%/99.58% of variance; U2 explained 2.36%/0.42%.

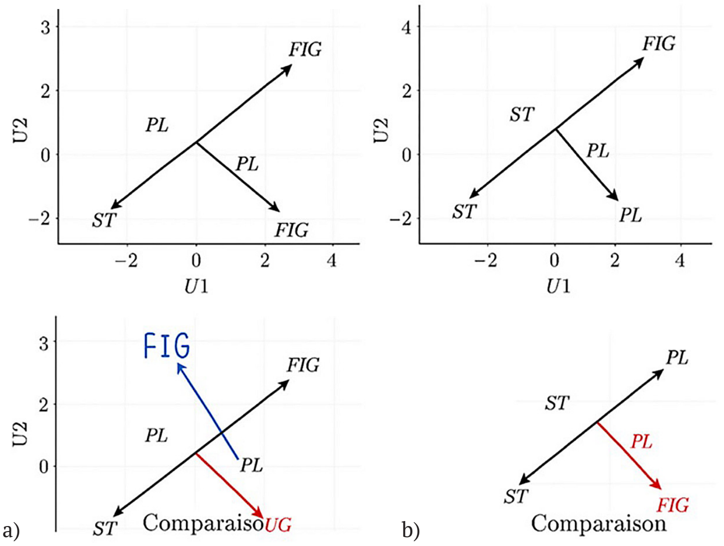


Figure 5. Principal component analysis biplots
Note: a – shape rule categories for Architect 1; b – shape rule categories for Architect 2
Source: developed by the authors

This classification was further validated by hierarchical cluster analysis using Ward's method with Euclidean distance, illustrated in the graphs in Figure 6. The dendrograms revealed a consistent bipartite structure across both architects. Structural rules (ST) formed an isolated cluster, separating at a linkage distance of approximately 23.7 for Architect 1 and 5.6 for Architect 2. In contrast, Plastic (PL) and Figurative (FIG) rules clustered together, suggesting functional similarity despite their ontological difference. This clustering pattern supported the conceptualisation of figurative rules as a meta-category that operated in parallel with plastic rules during vertical transformations (refinement and detailing), while structural rules drove lateral transformations (exploration of alternative configurations). The consistency of this pattern across both participants strengthened the validity of the three-level classification system.

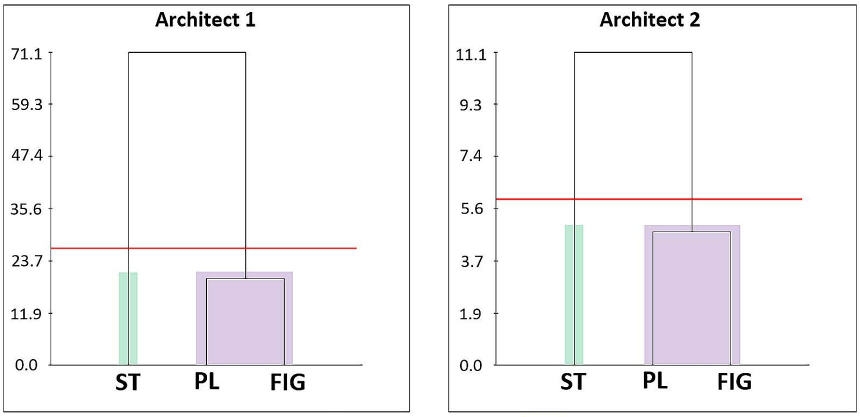


Figure 6. Hierarchical cluster analysis dendrograms for Architect 1 and Architect 2
Note: green colour – Structural rules (ST), purple colour – Plastic rules (PL) + Figurative rules (FIG). Red line indicates clustering threshold
Source: developed by the authors

Finally, the highly unidimensional structure revealed by PCA (PC1 explaining 97-99% of variance) suggested that a single underlying dimension – interpreted here as a lateral-vertical transformation continuum – captured most of the variation in rule deployment. This parsimony was significant in relation to contemporary computational design research. In machine learning-based generation, X. Zhuang *et al.* (2025) emphasised that overly complex models can reduce transparency and control. Results of this research suggested that a relatively simple operational continuum may be sufficient for capturing the dominant structure of transformation behaviour in early design, supporting the feasibility of interpretable computational tools.

Table 5. Summary of empirical patterns and theoretical interpretations

Pattern	Finding	Interpretation
Bipartite structure (PCA + cluster)	ST isolated; PL + FIG together	Two operational modes: exploration vs. refinement
Rule clustering	PL ≈ FIG despite ontological difference	Representational refinement coupled with plastic transformation
Frequency distribution	74% ST, 15% PL, 11% FIG	Early-stage design dominated by configurational exploration
Dimensionality	PC1: 97-99% variance	Lateral–vertical continuum sufficient

Source: developed by the authors

So, this study identified the shape transformations performed by architects during the form manipulation and generation phase of architectural design activity, and proposed a systematic framework capable of capturing them. To achieve this, research on grammar-based generation, performance-driven form exploration, and AI-assisted design workflows was gathered and compared, providing a contemporary basis for understanding how design rules can be formalised and operationalised during early-stage architectural design. S. Jang *et al.* (2025) highlighted that contemporary AI-based systems increasingly depended on data quality, evaluation protocols, and methodological transparency. While such systems can generate highly coherent formal outputs, they often lacked explicit interpretability in terms of step-wise transformation logic. Similarly, Y. Huang *et al.* (2025) argued that generative AI workflows reshaped design practice but still struggle to represent design reasoning as a sequence of explicit and meaningful operations. In this context, this work contributed a complementary approach: rather than replacing design operations with black-box generation, it formalised and classified the transformations themselves, preserving interpretability and aligning with human-centred computational design. The contributions of this study in relation to existing research were multifaceted. A primary contribution was the identification and definition of 48 distinct shape rules, enabling a detailed and operational description of shape manipulation and transformation actions carried out by architects in early design. Unlike many contemporary generative frameworks that focused on producing optimised outcomes or increasing output diversity, this study foregrounded fine-grained transformation semantics, providing an explicit inventory of micro-operations that can be directly mapped to computational procedures.

A.A.C. Al-Hashim & C. Alalouch (2025) demonstrated how shape grammar can support early design learning by structuring creativity through explicit rule systems. Their contribution confirmed the educational value of grammars, yet their focus remained primarily on pedagogy rather than on constructing a comprehensive and systematically classified repertoire of transformation rules. In contrast, this study contributed a more detailed operational taxonomy intended for both analytical and computational implementation. At the level of performance-driven design, L. Chen *et al.* (2025) proposed a design-grammar-based framework for high-rise office towers in early-stage design, integrating grammar generation with performance objectives. It was equally, what had been performed by S.M. Elgohary *et al.* (2023), who introduced a performative-driven form-finding framework that combined shape grammar with evolutionary genetic algorithms to generate building forms optimised for energy performance. Applied to the Sakan Masr prototype housing project in Cairo, this methodology implemented shape operations through addition and subtraction rules, while encoding environmental variables – including spatial daylight autonomy (SDA) and annual sunlight exposure (ASE) – as fitness functions. These works supported the idea that grammars can be integrated into optimisation workflows. However, such approaches often treat grammar rules as design constraints or generative heuristics rather than as an empirically grounded repertoire of transformations observed in actual designer activity. This study complemented performance-driven grammar research by supplying the missing layer of explicit transformation granularity, which can strengthen the interpretability and implementability of performance-based generative systems.

X. Zhuang *et al.* (2025) reviewed advancements and challenges in machine learning for generative architectural design, noting that modern research must balance automation with designer control and interpretability. Overall, studies confirmed that grammar-based and AI-assisted generative approaches were rapidly expanding. However, this work addressed a persistent gap: the lack of a systematically organised, fine-grained repertoire of shape transformations grounded in empirical observation of designers' operations. This contribution was particularly relevant for interpretability, pedagogy, and tool development. Beyond these conceptual contributions, the empirical analyses revealed several patterns that warrant theoretical interpretation. First, the bipartite structure observed in both PCA and cluster analysis – with structural rules forming an isolated cluster and plastic-figurative rules grouping together – suggested that early-stage architectural design was dominated by two distinct operational modes.

Results if this research indicated that early design transformations were structured and interpretable, and that computational systems may benefit from explicitly representing these two operational modes. Also, the clustering of plastic and figurative rules together, despite their ontological difference (transformative vs. representational), revealed a functional similarity in how architects deployed them during refinement. This was consistent with the observation that AI-based workflows often excel at producing refined visual outputs but struggle to distinguish representational operations from transformational ones. S. Yiannoudes (2025) highlighted that deep learning models can generate convincing architectural imagery, yet it frequently blur the distinction between "form transformation" and "representation enhancement". Empirical pattern of this study supported the need for a meta-category of figurative rules, clarifying that representational actions were not secondary but structurally integrated into early design refinement. The predominance of structural rules (74% of total transformations) in early-stage design task aligned with the configurational nature of conceptual design. This finding complemented grammar-based performance workflows such as L. Chen *et al.* (2025), where early-stage generation of tower forms was primarily concerned with organisational logic before detailed refinement. Results of this study provided empirical support for this sequencing: designers prioritise structural transformations during early exploration, while Plastic and Figurative rules became more prominent during later refinement. The repertoire directly enhanced design pedagogy. While A.A.C. Al-Hashim & C. Alalouch (2025) demonstrated that grammars can structure creativity and guide early design learning, and D. El-Mahdy (2022) showed how they can be used to improve learning through practice, repertoire of this research built on these contributions by offering a richer, more detailed inventory of transformational actions that can be explicitly taught, thereby helping students to expand their operational design vocabulary. Finally, the repertoire may also support generative morphology workflows by offering a general and systematically organised set of transformations that can be adapted to diverse morphological contexts.

CONCLUSIONS

This study addressed a fundamental gap in design research by developing a comprehensive, empirically validated repertoire for systematically categorising shape transformations in architectural design. The research successfully demonstrated the feasibility of encoding all observed form manipulations using 48 shape rules organised into two operational categories (Plastic, Structural), a meta-category (Figurative), and 14 rule classes. Empirical validation through protocol analysis of two architects' residential design tasks confirmed that the repertoire accurately captured the full range of form manipulations observed during early-stage sketching. The repertoire's structural coherence was validated through statistical analysis revealing a bipartite pattern supporting the theoretical distinction between lateral and vertical transformations. Principal Component Analysis showed PC1 explaining 97.64%/99.58% of variance across subjects, demonstrating clear differentiation among rule categories. Hierarchical cluster analysis confirmed consistent structural patterns: structural rules forming isolated clusters, while plastic and figurative rules grouped together, validating the three-category classification system. The distribution of rule use (74% Structural, 15% Plastic, 11% Figurative) reflected the exploratory nature of early-stage design and showed consistency across both subjects. The results demonstrated that architects' shape transformations can be systematically described, providing a reproducible framework for both descriptive and computational applications, with potential for three complementary domains: analysing sketching activity to uncover cognitive processes, developing pedagogical tools to enhance design education, and creating computational systems to support early-stage design exploration. Small sample size (n = 2 architects) limited the generalisability of findings, and while sufficient to test the viability and internal coherence of the repertoire, it cannot establish universal applicability across all architects, design contexts, or architectural styles. Beyond these limitations, the findings suggested that the repertoire can be integrated into a computational tool. Future research aims to develop a computer-assisted-design software based on the obtained repertoire to support designers and architects during the process of form generation and manipulation.

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CONFLICT OF INTEREST

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Систематичний репертуар правил трансформації форм у архітектурному дизайні: концептуальне доведення

Анотація. Метою цього дослідження було виявлення, структуризація та емпірична перевірка систематичного репертуару елементарних правил трансформації форм, що точно відображають процеси архітектурного дизайну на основі ескізів та можуть бути безпосередньо впроваджені в обчислювальні середовища. Для вирішення проблеми відсутності систематизованого та детального репертуару операцій трансформації форм у дослідженнях архітектурного дизайну було розроблено 48 правил трансформації форм через огляд літератури та уточнено за допомогою емпіричних спостережень за сесіями малювання, проведеними двома досвідченими архітекторами. Правила були розподілені на дві операційні категорії (пластичні, структурні), одну мета-категорію (фігуративні) та 14 класів правил. Протокольний аналіз підтвердив, що репертуар охоплював увесь спектр спостережуваних маніпуляцій з формами через 23 ескізи та 267 закодованих трансформацій, з високою внутрішньою узгодженістю кодерів (Каппа Когена: 0,85-0,87), що підтвердило надійність та чіткість запропонованої класифікації. Структурні правила становили 74 % спостережуваних трансформацій, підкреслюючи домінування конфігураційного дослідження на ранніх етапах проєктування, тоді як пластичні та фігуративні правила складали 15 % і 11 % відповідно. Статистичні аналізи, включаючи аналіз головних компонент та ієрархічний кластерний аналіз, показали послідовну дводольну структуру у обох дизайнерів: структурні правила утворювали окремий кластер, в той час як пластичні та фігуративні правила групувалися, при цьому PC1 пояснював 97-99 % загальної дисперсії. Практичне значення цього дослідження полягає в наданні прозорої та багаторазової платформи трансформацій, який підтримує аналіз поведінки при архітектурному малюванні та сприяє розвитку засобів обчислювального проєктування на основі правил

Ключові слова: архітектурне малювання; маніпуляція формами; граматика форм; протокольний аналіз; пізнання в дизайні