

Parametric design strategies for the generation of creative designs

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As one of the emerging Computer-Aided Design (CAD) technologies for digital design and visualisation in the Architecture, Engineering and Construction (AEC) domain, parametric design potentially offers an innovative way of generating new design solutions. Despite this potential, design strategies associated with algorithmic scripting are not well understood. This paper provides a comprehensive understanding of individual design strategies supporting creative solutions in parametric design, using the combined application of protocol analysis and Consensual Assessment Technique (CAT). The article examines the generative and evolutionary aspects of parametric design that play an important role in the generation of creative designs. An in-depth analysis conceptualises designers' parametric design strategies into problem-forwarding strategy and solution-reflecting strategy. The solution-reflecting strategy focusing on the solution space of designing has potential to produce creative solutions by parametric design. A more in-depth understanding of parametric design strategies supports its effective adaptation to better serve the needs of digital design and visualisation in the AEC industry.

I. INTRODUCTION

How to most effectively utilise emerging Computer-Aided Design (CAD) technologies so as to better serve the needs of digital design in the Architecture, Engineering and Construction (AEC) domain has been a significant area of research. Recently, parametric design – one of the emerging CAD technologies – has attracted a strong interest from designers and design students alike specifically for the “creativity” it supports, as evidenced in the unique forms or styles it generates. Parametric design as a new approach to designing, the understanding of its unique method for generating design solutions and alternatives and the understanding of its impact on the design processes and design outcomes, is critical for its adaption in both design industries and design schools.

Parametric design allows designers to focus on formative and generative design using ‘advanced parametric applications [1]’ viz., Grasshopper™, CATIA™ and Generative Components™ through scripting. One main challenge for parametric design research is in understanding the relationships of applying the design skills with the scripting skills [2]. Capturing individual design strategies throughout the parametric design process is a way of understanding these relationships. The other important issue in parametric design research lies in understanding its potential and support for creativity, as creativity is fundamental to design. Many influential architects, e.g. Frank Gehry, FOA, Norman Foster, NOX, Peter Eisenman, UNStudio and Zaha Hadid [3-7], are using dynamic factors for design generation and fabrication [3], such as performative skins [8-9], supported in or related to parametric design in their practices. Some researchers [10-12] further argue that parametric design is fundamental to creativity through design exploration during the conceptual design phase, where variations can be generated by alternating design parameters, topological relationships [13], and rule algorithms. The scripting activities [14-16] in parametric design based on parameters and rules, also known as algorithmic activities, may allow for alternative design strategies different from the conventional design strategies and the “design productivity and exploration [16]” can potentially support creativity.

Nonetheless, our overall understanding of the generative and algorithmic strategies of parametric design and their role on creativity is limited. This paper will identify individual design strategies which can potentially support creative solutions in parametric design.

Creativity is a natural component of design [17]. Given the nature of design and creativity, the development of a scientific and systematic research framework might be controversial. Nevertheless, studies have shown that creativity could be studied in a relatively formal and scientific way, e.g. Consensual Assessment Technique (CAT) [18], which measures creativity of design products through experts’ evaluation of the design against defined

criteria. The CAT allows us to explore design strategies for the generation of designs through the level of creativity.

To connect parametric design and creativity, we adopted the concepts of divergent and convergent thinking, two critical factors in the creativity model, to understand parametric design. In parametric design divergent thinking generates a variety of solutions with the parameters as the “potential answer” to a question, while convergent thinking identifies the most appropriate solution as the “right answer” to a question with rules. Building on these understandings, this paper applies the Analysis-Synthesis-Evaluation model [19, 20] for the purpose of interpreting designers’ strategies during parametric design, both, in terms of the design problem and solution spaces, and to understand their relevance to design creativity.

The methodological approach to this study is to employ a multiple perspective approach through the combination of protocol analysis [20-23] and the CAT to explore design strategies applied by individual designers and their relevance to design creativity. This approach provides evidence for the verification of the understanding of each of the individual design strategies and their contribution to the development of creative solutions in parametric design. The levels of creativity measured by the CAT were used for the interpretations of the protocol analysis results. This paper highlights the result of protocol analysis in detail with four protocols. Protocol analysis as a design research method is limited in terms of the statistical significance of the results. Nevertheless, as will be demonstrated, it supports an in-depth exploration on the topic with significant amount of empirical evidence even with limited samples. A potential, conceptual model for parametric design strategies related to creative solutions has been proposed through descriptive and graphical analyses of the relationship between the design strategies used and their contribution to creative outcomes.

2. RELATED RESEARCH

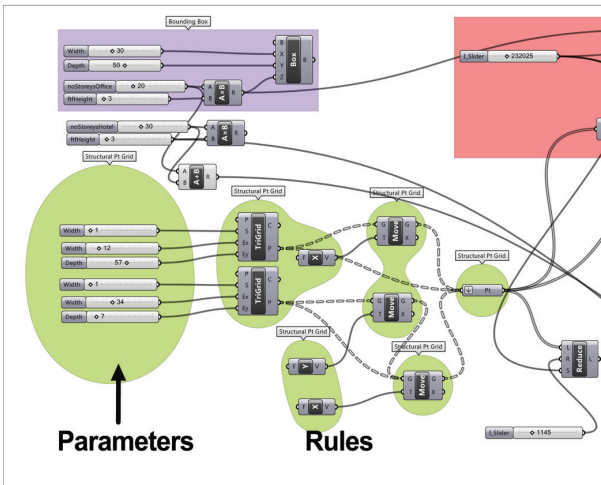
2.1. Parametric design

Cardenas [24] explained that the notion of parameter is usually related to factors defining a range of variations. While it originates in mathematics, parameters currently refer to design variations in the design domain. Parametric design can offer variations that generate multiple ideas [10, 12], indicating divergent thinking with the potential of evoking creativity. With parameters, designers can express and explore varying ideas beyond being constrained by their own sketching skills, traditionally associated with ideation. Making variations is the key to pursuing creativity as well as extending the boundaries of knowledge [3, 25]. However, there is potential risk in using parametric design as the variations may be too abstract and only viable virtually [26].

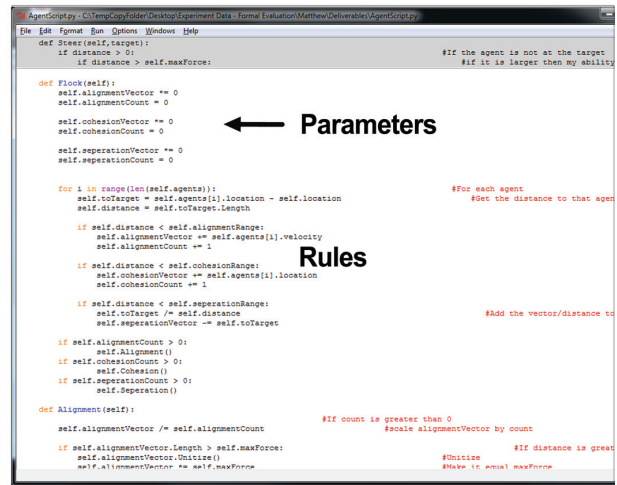
“Rules”, the other feature in parametric design when considering creativity, are about convergence of Knowledge. The “rules” define relations

among geometric elements and configure the parameter attributes. These “rules” can be related to specific knowledge. Knowledge is being one of the important factors eliciting both personal and design creativity. Encoded architectural knowledge, linked to “rules” such as structure, climate and composition, provides a new way of design thinking and exploration also drawing on architectural expertise [8, 9, 12]. Design parameters, when using the supportive “rules”, can achieve an appropriate product as a design outcome. The coding scheme for our protocol study and the evaluation criteria for CAT, presented in Section 3, were designed to capture the characteristics of ‘parameters’ and ‘rules’ in Figure 1, as they support convergent and divergent thinking in parametric design.

▼ Figure 1: Examples of parameters and rules in two different parametric design environments



(a) Graphical algorithm editor (Grasshopper)



(b) Text-based algorithm editor (Python)

Paramedic design could also potentially contribute to the development of a new methodology for architectural design and research, highlighting a wide range of impact from design optimisation [1] to design innovation in terms of complexity and emergence of forms [46]. For example, its support of extensive productivity and design exploration has enabled the investigation of “responsive and performative environments [8-9, 46]”. Hagen and Roller [47] further categorized the research approaches emerged from parametric design as the constructive, the numerical, and the knowledge-based. In particular, the knowledge-based approach emphasised here uses rule-based variants and reasoning. Rule-based design as a computational design method has been foundational in the practice and research of design computing. Overall, parametric design could support for exploring critical architectural issues and design innovation [48] pertaining to performance, sustainability, adaptability and creativity, while understanding parametric, numerical and

mathematical logics and reasoning will potentially contribute to conducting, extending and re-interpreting “architectural design and research [49, 50]”.

2.2. Measuring creativity

The cognitive approach to design research has been crucial for the comprehensive understanding of design process [27], while it tends to downplay social contexts or personality. CAT, a confluence approach, has growing acceptance in creativity research as it considers multiple components rather than considering one component as encompassing the whole phenomenon [28] of creativity. The study, reported in this paper, applied both cognitive and confluence approaches to the measurement of creativity.

The cognitive process and creativity have received significant attention in design research. Dacey and Lennon [29] described early creativity models of the mental process as “associationism”, Gestalt, and cognitive-developmental approaches. The theories argue that creative cognition is more than problem solving, and stress that selective and evaluative processes are important parts of the creative process. Cognitive process models play an important role in understanding creativity across various domains including the design domain. One of the most reliable methods for investigating cognitive design activities is protocol analysis, as it effectively transforms the qualitative segments during design processes for quantitative measurements.

The “confluence” approach regards creativity as the confluence or convergence of domain-relevant knowledge and abilities, creativity-relevant skills, intrinsic motivation, and the social environment [18, 30]. Amabile [18] proposed the Consensual Assessment Technique (CAT) as a means of measuring both artistic and verbal creativity. The CAT, an expert panel assessment, has been used widely in research fields, including education, arts, business, advertisement, etc. It has been valuable in the measurement of the levels of creativity evident in design products.

The cognitive approach and the confluence approach in isolation have limitations in exploring design creativity, but through the application of both approaches, we believe it is possible to overcome these limitations. This is achieved through the cognitive approach’s ability to evaluate creative activities in the design process and to identify design strategies that designers adopt. Whereas the confluence approach is able to be customised to measure the level of creativity of design products and it facilitates the interpretation of the results of the cognitive approach.

2.3. Design strategy

Design strategies relate to both design quality and creativity [31]. Strategies containing information relating to how the final goal is achieved [32]. Design strategies define sub-goals, which limit the possible operation. That is, design

strategy is linked to personal preference and habits of the designer and contributes to defining designers' thinking processes.

Design strategy can be studied in terms of the problem-solving process [31-32]. Ho [33] employed protocol analysis for the purpose of identifying how problem decomposition strategy and working-forward/backward strategy are used to differentiate between expert and novice designers. Lindström [34] presented process criteria in rubrics to help students to develop and assess their own work. His criteria included investigative work, inventiveness, ability to use models, and capacity for self-assessment. Also the rubrics, with the imbedded criteria, are useful for the purpose of better understanding the difference between the strategies used by experts and novices in their pursuit of inventiveness, e.g. experts often establish sub-problems or reformulate problems, whilst novices do not employ this approach.

Ahmed et al. [35] identified that experts use design strategies, whilst novices use trial and error as their design method (backward reasoning). Kruger and Cross [31] supported the concept of a problem or solution driven design strategy, they identified that a solution driven strategy produces lower solution quality but higher creativity while a problem driven design strategy provides the best balance between quality and creativity.

3. RESEARCH METHOD

3.1. Protocol analysis

Protocol analysis [20-23] has been effective in better understanding the design activity through the study of the protocols involved in the activity, through researchers asking participant designers to verbalise their thoughts and actions whilst involved in the activity of designing. This enables the designers' cognitive behaviour during the design process to be "captured". The method has been used extensively in design research to develop understandings of design cognition. Due to the large volume of data produced and the complexity of the procedure, usually protocol studies involve relatively small number of subjects. Protocol analysis is considered to provide a more in-depth understanding of the design activity than other cognitive research techniques such as interviews with designers, observations and case studies, reflection and theorising, and simulation trials [36]. Verbalisation can result in the identification of concurrent or retrospective protocols. Even though the validity of concurrent and retrospective protocols is subject to some debate among researchers [37], Gero and Tang [38] indicate that there are similarities between the two techniques in terms of the process-oriented aspects of the design process. However, a concurrent protocol, so-called "think-aloud", might interfere with the design process and inhibiting the designer in expressing the thoughts aloud, whilst a retrospective protocol might result in details being omitted or even recalled incorrectly. While noting these difficulties, we

adopted think-aloud verbalisations for the initial protocols and enhanced this by the inclusion of a post-experiment interview in this study. The interview verifies the protocols retrospectively by asking the designer to watch the recorded video and elaborate on their thinking whilst involved in their design process.

In protocol analysis, a predetermined coding scheme is essential and must be devised specifically for the purpose of the design study. There is considerable literature reporting on research that adopts 'Analysis–Synthesis–Evaluation' as a design method [19]. McNeill et al. [20] employed this method in the micro strategy coding scheme: analysis of the problem, synthesis of a candidate solution, evaluation of a candidate solution, and other activities. Based on this model, our coding scheme contained three categories: analysis, synthesis, and evaluation. In order to capture the programming (scripting) activities, the coding scheme included the two sub categories of geometry and algorithm.

'Analysis' decomposes a problem into sub problems [19, 33], the coding scheme, shown in Table 1, enabled us to identify the introduction of new ideas (An-Initial Goal), new geometric ideas (An-Geometry SubGoal), and new algorithmic ideas as an extension of a previous idea (An-Algorithm SubGoal). These cognitive activities belong to the conceptual level of Suwa's definition [23].

'Synthesis' refers to the re-composition of sub problems into different forms [33]. We deal with two sub-levels of this aspect through differentiating between 'physical', including geometric and algorithmic activities, and the 'generative level'. The distinction between the two sub-levels allows the capture of the generative aspect of parametric design, which differs from the synthesis of a solution. Through this process we were able to distinguish physical depiction from generative synthesis, which is thought to better support creativity in parametric design. The generative synthesis (Sy_g in Table 1) is defined as an activity that makes generation or variation through parametric modelling environments. This includes the activities of executing the generation process and finding an appropriate solution through inputs of a range of parameters.

'Evaluation' refers to testing the performance of new structures [19, 33]. The code Ev-Geometry, attributed to evaluating primitives or existing geometries, identifies the geometric cognitive activity. Two other codes in the algorithm level reveal the algorithmic activities, which are related to evaluating existing parameters and rules as specific activities in parametric design. The codes in the algorithm level may refer to evaluating the problem, which belongs to 'Analysis', the algorithm level regarded as the activities of evaluating both problem and solution spaces of parametric design. These sequences of coded segments (i) identify cognitive patterns revealing insights into creativity in parametric designing. These findings then (ii) relate to the results of the CAT evaluation of the design products; so as to (iii)

▼ Table 1: Coding scheme for studying design strategy in parametric design

derive relationships between these two sets of results focusing on the designer's strategy and/or preference.

Category	Code	Description	Sub-code
Analysis (An)	An	Introduce new ideas (or goals) based on a given design brief	An-Initial Goal
		Introduce new geometric ideas extended from a previous idea	An-Geometry Sub Goal
		Introduce new algorithmic ideas extended from a previous idea	An-Algorithm Sub Goal
Synthesis (Sy) Physical (p)	Sy_p	Create directly geometries	Sy-Geometry
		Change existing geometries	Sy-Change
		Create initial parameters	Sy-Parameter
		Change existing parameters	Sy-Change Parameter
		Create initial rules	Sy-Rule
		Change existing rules	Sy-Change Rule
Generative (g)	Sy_g	Make generation (or variation)	Sy-Generation
Evaluation (Ev)			
Geometry (g)	Ev_g	Evaluate primitives or existing geometries	Ev-Geometry
Algorithm (a)	Ev_a	Evaluate existing parameters	Ev-Parameter
		Evaluate existing rules	Ev-Rule

3.2. Consensual assessment technique

The various versions of CAT as an expert panel assessment [18] had several dimensions of criteria including creativity, technical, and aesthetic dimensions. The common criteria of the CAT procedure for measuring creativity of design products include novelty, value, and aesthetics. Pektas [39] utilised two criteria (creativity and technical quality) in his application of the CAT for the purpose of revealing the relationship between design students' cognitive styles and design performance in digital media. Chulvi et al. [40] applied three aspects of the criteria: novelty, utility and creativity to broaden the understanding of the activity. The study reported here involved the use of four criteria: *novelty*, *usefulness*, *complexity*, and *aesthetics*.

Novelty can be interpreted as 'Originality (of idea)' and its 'Evolution', referring to the degree to which the design itself demonstrates a novel idea [18]. *Usefulness* refers to the degree to which the design shows the quality of practical application. *Complexity* refers to the degree to which the design shows the level of complexity of the design. *Complexity* relating to the context of parametric design is a criterion to evaluate technical quality. *Aesthetics* refers to the degree to which the design is aesthetically appealing [18].

4. RESEARCH EXPERIMENTS AND DESIGN OUTCOMES

Four postgraduate architectural students, two with over five years' parametric design experience (S1, S3) and two with only one year of experience (S2, S4), were recruited for this study. They were given one hour to undertake a given design task using parametric modelling tools. Each of

their design activity was recorded using the think-aloud method of protocol analysis for collecting their design protocols. The design brief, shown in Table 2, involved the conceptual design of a high-rise building.

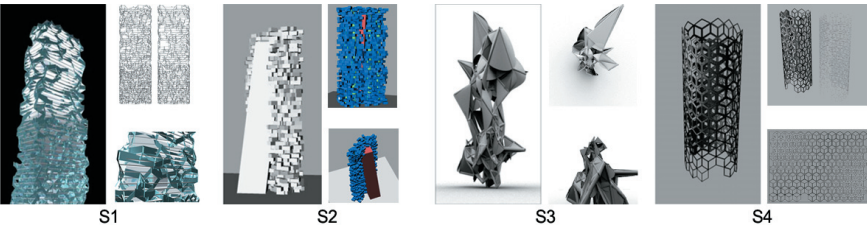
Each design session was video-recorded using two cameras, one providing a view of the student’s overall activities and the other recording the computer screen. Before the experiment, the researcher explained the design brief and undertook a ‘practice-run’ of think-aloud verbalisations with each participant. The completed designs as computational design models were collected.

Design Brief (Conceptual design of a high-rise building)
You are asked to provide a conceptual design of a high-rise building. This is a form generation task focusing on creative ideas for the three dimensional shape of a high-rise building. The building will have two main functional programs: office and hotel.
The followings should be considered as part of the design process:
Maximum total floor area is 2,500 square metres.
The building should have over 40 storeys and it will be designated as a regional landmark.
Basic structural design can be represented in the conceptual design. (e.g. columns in the exterior or interior of the building)
You can reflect on design transformation forces using external data.
You should consider Novelty (e.g. originality, complexity, and evolution), Value (e.g. function, usefulness, and understandable form), and Aesthetics (e.g. aesthetic form and style) for the conceptual design.
A new creative architectural vision depends on you. At this early design phase, no site or construction constraints have been stipulated, with a client seeking a highly creative outcome as a priority.
Deliverable: Design representation(s) of the high-rise building that should satisfy the brief; and produce (1) three-dimensional model(s); (2) three rendered or captured images showing the strength of your design, to clearly represent the conceptual design. They should be saved on your desktop.
Timeline: One hour

◀ Table 2: Design brief

A panel consisting of seven expert judges provided assessment of the four outputs. Each design was presented as a collage of images on A4 size paper with all design products being similarly scaled for consistency of evaluation (See Figure 2). The judges assessed designs using three evaluation frameworks, consisting of (i) independent non-criteria based assessment of creativity, (ii) comparative non-criteria based assessment of creativity, and (iii) criteria-based assessment of creativity using - novelty, usefulness, complexity, and aesthetics. Each assessment task used a seven-point Likert scale (where 1 is the lowest and 7 the highest).

► Figure 2: Four design outcomes generated by the participants



4.1. Consensual assessment of the four designs

The results in Tables 3, 4 and 5 indicate the level of creativity of S3’s design was assessed as being consistently the highest across all evaluations, with the exception of a criterion (usefulness) in Table 5, where S1’s design has the highest score for the level of usefulness.

Table 3 shows the (i) independent non-criteria based assessment of creativity by the seven judges. On a scale from 1 to 7, the judges scoring each design’s level of creativity, S3’s design received the highest score, while S4’s design the lowest in the level of creativity. Table 4 shows the results of (ii) comparative non-criteria based assessment of creativity. Also judged were (a) the most creative and (b) the least creative models, also (c) its criteria assessing the level of creativity of the design models relative to one another. Six judges identify S1’s design as the most creative relative to the criteria and most judges assessed S2 and S4’s designs as the least creative.

Table 5 shows the results of (iii) criteria-based assessment of creativity using - *novelty*, *usefulness*, *complexity*, and *aesthetics*. The results are also similar to the scores for *novelty* and *complexity*. Overall, the results show that the level of creativity exhibited in S3’s design was assessed as the highest and S1’s design achieved the second highest overall score but had the highest result for usefulness. This evaluation therefore regards S1 and S3’s design overall as the most creative products.

► Table 3: Independent non-criteria based assessment of creativity

Protocol	Judge1	Judge2	Judge3	Judge4	Judge5	Judge6	Judge7	Mean	SD
S1	5	5	2	5	3	5	2	3.86	1.46
S2	5	5	1	4	1	6	5	3.86	2.04
S3	6	7	5	7	5	6	4	5.71	1.11
S4	4	2	2	4	1	3	5	3.00	1.41

► Table 4: Comparative non-criteria based assessment of creativity

	Judge1	Judge2	Judge3	Judge4	Judge5	Judge6	Judge7
(a) most creative	S3	S3	S3	S3	S3	S3	S4
(b) least creative	S4	S4	S2	S2 or S4	S2 or S4	S4	S1
(c) judges' criteria	complexity, form, repeating elements, direction	usual-unusual, simple-complex (skin), Interesting	-	novelty of the form, aesthetics, organisation, structure of the basic models	response to criteria, synthesis of objectives	visualisation, complexity, conceptualisation of brief	aesthetics, clarity, simplicity

	Judge1	Judge2	Judge3	Judge4	Judge5	Judge6	Judge7	Mean	SD
Novelty									
S1	6	7	4	5	4	4	1	4.43	1.90
S2	6	5	3	4	1	5	5	4.14	1.68
S3	7	7	7	7	6	6	6	6.57	0.53
S4	4	2	2	3	2	1	2	2.29	0.95
Usefulness									
S1	5	7	3	5	3	4	5	4.57	1.40
S2	4	5	3	4	2	6	7	4.43	1.72
S3	6	7	2	7	4	2	2	4.29	2.36
S4	4	3	3	4	4	4	6	4.00	1.00
Complexity									
S1	3	6	3	5	5	6	5	4.71	1.25
S2	4	5	4	3	4	4	3	3.86	0.69
S3	5	7	6	7	7	7	6	6.43	0.79
S4	3	2	2	4	2	1	3	2.43	0.98
Aesthetics									
S1	5	7	1	5	3	3	1	3.57	2.23
S2	2	2	1	2	1	4	3	2.14	1.07
S3	3	2	5	6	5	7	4	4.57	1.72
S4	6	1	4	4	4	1	5	3.57	1.90

◀ Table 5: Criteria-based assessment of creativity

4.2. Protocol analysis results

The average value of the number of segments of the four protocols is 297.8 (S1: 220, S2: 319, S3: 364, S4: 287). Over 90% of each protocol was encoded using the coding scheme, regardless of the two types of applications: graphical algorithm editor (Grasshopper) and text-based algorithm editor (Maya Script Editor and Python). This implies that our coding scheme enabled effective encoding of the protocol data. Only S1 completed the design within one hour (48 min), whilst the others took approximately one and a half hours. The overrun in time was caused by the need for additional trouble-shooting processes required by participants S2, S3 and S4. Parametric design tools also require the user to wait for the design to be generated, e.g. in S3's protocols there were 17 segments of 'waiting', contributing to the need for extra time.

Table 5 shows the frequency weighted by time (calculated by the time of the duration of each coded protocol). This allows the determination of the time devoted to each component of the design strategy as well as time devoted to each level of design thinking for each participant. On average the range of coverage is 'Synthesis' - 50.8% (physical: 45.3%, conceptual: 5.9%); 'Evaluation' - 32.0% (geometry: 15.9%, algorithm: 16.1%); and 'Analysis' - 11.0% being the smallest component.

The number of coded segments of S4's protocol was the highest and the 'analysis' of S4 was relatively low. This participant, a junior student, had a tendency to solve the problem through introducing small ideas or

variations. This is consistent with the procedure of a novice's problem-solving process [33, 37] indicating that a novice designer may lack problem analysis or scoping skills or strategies. S3, identified as an experienced designer, struggled with trial and error (novice's backward reasoning as defined by Ahmed et al. [35]). However, S3's generative synthesis was significantly higher than the other three participants.

S1 and S2 contributed relatively higher percentages of their time to the 'analysis' activity. Both S1 and S2 utilised Grasshopper as the graphical algorithm editor, whilst the others (S3 and S4) used text-based algorithm editors. The graphical editor tends to involve more 'An-Initial Goal' and 'An-Geometry Sub Goal' activities for problem-finding compared to the text-based editors. Especially, S1, rated as an experienced designer applied strategic rules from the initial states of the problem, which can be identified as a working-forward search strategy [33].

One interesting finding related to S3's performance, which demonstrates a high level of both 'synthesis' (generative level) and 'evaluation' (algorithm level) activities. S3's approach may have provided an advantage in generating creative design variations, because these activities are related to both the problem and solution spaces in the "co-evolution process [41, 42]".

► Table 5: The percentages of coding results for each protocol

Category	S1	S2	S3	S4	Mean	SD
Analysis	14.1	18.5	7.1	4.4	11.03	6.45
Synthesis						
Physical level	48.1	39.2	37.2	56.9	45.35	9.04
Generative level	4.0	1.9	13.0	3.0	5.48	5.09
Evaluation						
Geometry level	19.4	18.1	17.3	8.8	15.90	4.81
Algorithm level	8.4	18.5	19.6	17.9	16.10	5.18
Sum	94.0	96.2	94.2	91.0	93.85	2.14

4.3. Parametric design strategies

The encoded data was visualised to facilitate the exploration of design strategies over time. Figure 3 illustrates the five levels of design thinking – Ev_a: Evaluation (algorithm level), Ev_g: Evaluation (geometry level), Sy_g: Synthesis (generative level), Sy_p: Synthesis (physical level), and An: Analysis – in sequence in order to compare the changes over time.

While Sy_p and Ev_g were the dominant activities over time, occurrences of both the An and Sy_g codes differ more significantly between all four participants. The Sy_g – generative synthesis – within the protocol of S3 occurred at regular intervals throughout the time period. The analysis codes also appear regularly in the protocols of S1 and S3. The problem space in our coding scheme is based on 'analysis', whilst the solution space highlights 'synthesis (generative level)'. Based on this understanding, it can be observed that S3 used design strategy highlighting both the problem and the solution spaces. S3's design strategy may have

enhanced creativity in parametric design, when considering the high scores S3's design received in the CAT assessment.

The An and Sy_g codes do not happen regularly in the protocols of S2 and S4, which may be a feature of the novice's problem-solving in parametric design. The Sy_g codes only appear towards the end of S2's protocol, while the A_n code rarely happens in the protocol of S4. S4's protocol highlights Sy_p and Ev_a codes. These features have not enhanced creativity in the case of the participants, when considering the relatively lower scores achieved by S2's and S4's designs in the CAT assessment.

S1's protocol shows the regular use of 'analysis' with a small number of activities encoded as making generation (Sy_g) compared to S3. As the problem space in this study is based on 'analysis', while the solution space relates to the generative aspects of parametric design. These features imply that S1 adopted a problem-driven strategy rather than a solution-driven strategy to produce the design.

▼ Figure 3: Patterns of different levels of design thinking (Ev_a: Evaluation (Algorithm), Ev_g: Evaluation (Geometry), Sy_g: Synthesis (Generative), Sy_p: Synthesis (Physical), and An: Analysis)

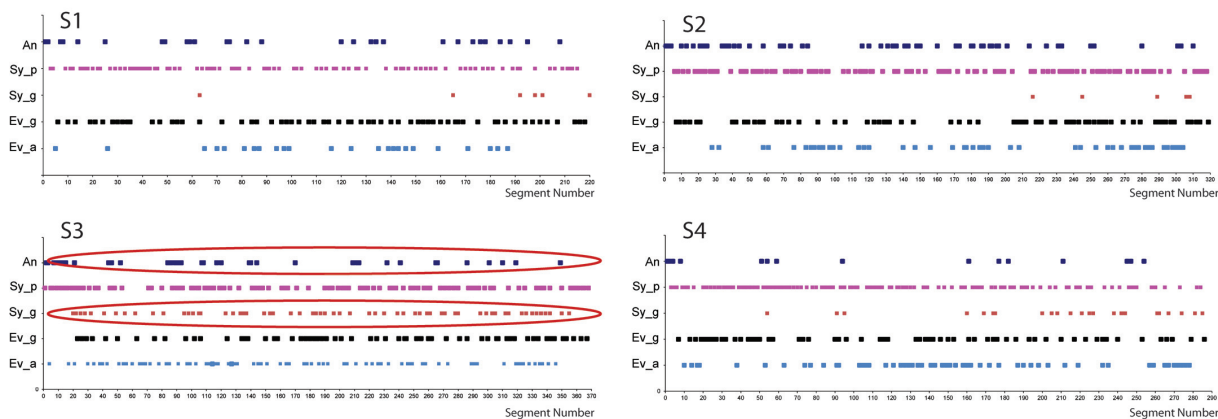
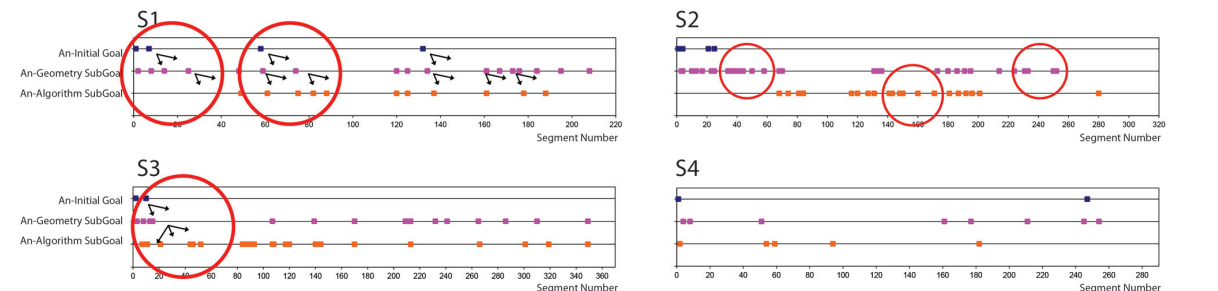


Figure 4 shows the three cognitive activities of 'analysis' over time. It enables the investigation of problem decomposition strategies in detail. 'An-Initial Goal' refers to explicitly introducing the main problem, while the other two codes introducing sub goals deal with sub problems. A closer

▼ Figure 4: Three cognitive activities of 'analysis' over time



examination of Figure 4 reveals that only S1 produces 'An-Initial Goal' at the beginning, middle and end of the protocol. S1 also sequentially decomposes the problem into geometric sub problems and then algorithmic sub problems. This is consistent with the "explicit problem-decomposing strategy [33]". This strategy is probably in line with Kruger and Cross' problem-driven strategy [31] that produces good results in terms of both overall solution quality and creativity.

The above observations using the CAT assessment consistently show that the level of usefulness of S1's design is higher than the scores of S3's design. S1's other scores are also similarly higher, while S2's design received the lowest scores. That is, both the problem-decomposing strategy and the problem-driven strategy may facilitate the generation of creative solutions.

Figure 4 shows that S2 and S4 tend to use an implicit problem-decomposing strategy, a strategy often adopted by novices. S2 produces 'An-Initial Goal' at the beginning but does not sequentially relate to the geometric and algorithmic sub problems. Rather, he often stopped to solve each problem as it emerged. This implies that his lack of Ho's working-forward search strategy. S4 produces 'An-Initial Goal' at the beginning and end of the protocol but rarely deals with sub problems. There is no critical pattern identified related to solving problems. This implies that the participant performs unsystematically and adopts the working backward search strategy. By contrast, S1 and S3 explicitly decompose the initial problem into both geometric and algorithmic sub problems. Furthermore, as revealed in Figure 3, S3 regularly uses the generative synthesis (Sy_g). S3 uses a design strategy relating to both the problem and the solution, but the generation of solutions often directly links to sub problems as shown in Figure 3 (see also sequential sub problems in Figure 4). These observations imply that S3 adopts a solution-driven strategy in the design and reflective processes [43].

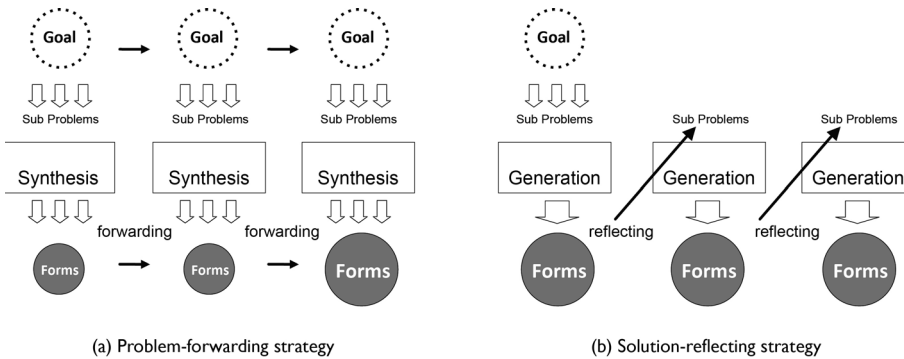
With the coding results in Table 5 and the above graphical analysis, we propose two parametric design strategies (problem-forwarding strategy and solution-reflecting strategy) and illustrate them in Figure 5. The problem-forwarding strategy, a problem-driven strategy, focuses on 'analysis' and explicitly decomposes the initial problem into both geometric and then algorithmic sub problems. S1's problem-decomposing strategy, with the working forward search strategy, results in a sequential analytic-synthesis procedure to achieve a final design solution. It shows the strong inventiveness [34] as an expert design process. It is also followed sequentially by a number of activities encoded as making generation (or variation).

The solution-reflecting strategy, a solution-driven strategy, highlighting the generation of variations has potential for enhancing parametric design. S3's design outcome (using the solution-reflecting strategy) received the highest score from the judges in terms of creativity. This is consistent with

Kruger and Cross' results that a solution-driven strategy produces higher creativity scores. In order to achieve a comprehensive solution, the solution-reflecting strategy often continues to both making variations and reflecting the variations recursively (Figure 5).

Of course, designers probably use both parametric design strategies to make creative solutions, but each individual strategy may be more effective in achieving different qualities in the outcomes.

▼ Figure 5: Two parametric design strategies



5. DISCUSSION AND CONCLUSION

This study aimed to explore how to effectively adopt parametric design – an emerging CAD technology, as a new design environment for the AEC domain – for producing creative solutions through different design strategies. Programming or scripting is no longer an exclusive domain of a particular discipline [2]. This is evident in parametric design because designers use both geometric and algorithmic approaches to develop the design solution. The scripting activities via parameters and rules produced the specific patterns of parametric designing, which enabled us to capture individual design strategies. Thus, it is possible to report on the exploration of the subjects' design strategies in parametric design based on the three levels of design thinking: 'Analysis', 'Synthesis', and 'Evaluation'.

Our coding scheme enables the capture of design strategies that support the co-evolution of problem and solution spaces. Correlating the results of the CAT assessment and the results of the protocol study, it implies that 'analysis' and 'synthesis (generative level)' are positively related to the generation of creative outcomes in parametric design. Further we categorise the particular designers' design strategies into two: problem-forwarding strategy and solution-reflecting strategy. The problem-forwarding strategy and the solution-reflecting strategy are supported by the dominant usage of rules and parameters, respectively. To effectively adopt parametric design to both practice and education, both strategies should be carefully considered as support for creativity.

The problem-forwarding strategy is a kind of problem-driven strategy. The sequential design process has been described in much literature, but the model highlights the relationships between geometric and algorithmic activities. For example, designers need to associate algorithmic ideas with geometric problems as extensions from a previous idea. The solution-reflecting strategy is a kind of solution-driven strategy that is particularly effective for the generation of creative outcomes in parametric design. The text-based scripting environments, such as Maya Script Editor and Python may require trouble-shooting processes regardless of their expertise. At the early stages of design education, designers are often limited by their ability of mastering the design tools [39]. That is, cognitive process may be influenced by a variety of factors such as personal experiences and design environments. However, even though S3's protocol exhibits features of both novices' and experts' behaviour, this designer's solution-reflecting strategy may have resulted in the highest score of the CAT assessment in terms of creativity. This may be because the solution-reflecting strategy often causes "unexpectedness" [44], which can be interpreted as novelty.

Finally in terms of the generalisation of the findings, limited sample size has always been a debatable issue in protocol analysis because protocol studies produce very large data sets, which therefore limit the number of subjects being studied. For example, Ho [33] used only two participants' protocols to capture individual strategies in great detail rather than focusing on the generalisation. Nonetheless, our future study will continue the exploration with more subjects to adopt the analysis of variance (ANOVA) to reveal the differences between experimental groups, such as experts and novices, for statistical significance [45]. Whilst the authors acknowledge the small sample size in the current study, our results reveal some unique characteristics of parametric design in the forms of two parametric design strategies. These two design strategies will allow both professional designers and design students alike to adopt and explore these strategies for creativity in parametric design.

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