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Understanding Cognitive Activities in Parametric Design

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Abstract. Parametric design offers a new paradigm in the field of Computer-Aided Design; a paradigm focused on the potential for producing design variations. However, despite this potential, the cognitive activities associated with parametric design are not well understood. The authors of this paper present a formal method for capturing cognitive activities via protocol analysis. To support the interpretation of this method, this paper evaluates creativity implicit in design products by way of a consensual assessment technique. The findings identify two cognitive activities ('making generation' and 'changing existing parameters') as potential critical to divergent thinking and the restructuring of design components. These activities facilitate the generative aspects of parametric design. The paper concludes with a discussion of three cognitive levels (physical, perceptual and conceptual) that support an understanding of cognitive activities in parametric design.

Keywords: Parametric design, CAD, Cognitive activity, Protocol analysis, Consensual assessment technique.

1 Introduction

Parametric design is frequently praised for offering a new approach to design generation [1]. Despite this, the cognitive activities that occur during parametric design have not been adequately studied in the Computer-Aided Design (CAD) field. In particular, there is a general lack of empirical evidence of cognitive activities in parametric design.

Parametric design could be understood as the action of considering alternatives that fit within certain controls or limits. Parametric design is a new algorithmic approach to formal generation using parameters and rules. Unlike traditional digital design environments, parametric design approaches support the design process through the effortless production of design variations [2], that conform to the required parameters and rules.

By using parameters, designer is able to express and explore varying ideas without being limited by their own drawing and modelling skills [3]. In this system, making variations is the key to extending the boundaries of knowledge [4]. Rules define the relations between geometric elements [5] and configure the parameter attributes.

Rules can also address design factors such as user needs, functional requirements and structural demands [6]. Oxman [7] explain that parameters and rules can result in parametric formations which enable topological variations.

Previous studies by the present authors [8, 9] have argued that parametric design environments can better support divergent thinking than the conventional CAD tools. They facilitate processes for the restructuring of components [10] and the regulation of elements into comprehensive solutions [11], which enhance problem solving activities. To further the research, this paper presents a modified coding scheme focusing on explorations of cognitive activities in parametric design and highlighting three cognitive levels: physical, perceptual (geometric versus algorithmic activities) and conceptual (problem-finding, solution-generation and solution-evaluation). Section 2 in the paper explores the related literature and then presents research techniques including protocol analysis and consensual assessment technique (CAT). The results of expert assessments and protocol analyses are presented in Section 3. Finally, Section 4 concludes the current study by outlining directions for future work.

2 Research background

2.1 Parametric activities

Designing could be understood as both problem solving activity [12] and a cognitive process. In the design domain, process and cognition are core themes [13], and much of the research undertaken in this field is aimed at enhancing our understanding of design creativity. For example, past research observes that flexible and intuitive sketching activities have advantages over CAD tools in terms of creativity [10, 14]. However, Ibrahim and Rahimian [15] illustrate that both sketching and conventional CAD tools have limitations in supporting problem-solving activities during the conceptual design phase. Sketching has limitations in constructing complex designs and conventional CAD tools can hinder creativity due to their inflexibility.

Bilda and Demirkan [14] argue that digital design techniques need to provide interactive imagery so as to allow the designer to perceive visio-spatial features and organizational relations, and thereby generate alternative solutions. Other researchers go further, arguing that such techniques need to also consider the management of part-whole relationships, design hierarchies, topology-geometry relationships, well-structured or ill-structured problems, and restructuring of problem parameters [11]. Recent research efforts have shown these characteristics are evident in parametric design.

Advances in parametric digital design techniques are also providing an increasing capacity to encode the generative process and evaluate the generated product. Such techniques can therefore more intuitively support design exploration whilst maintaining flexibility [9, 16]. Recent research has illustrated that some parametric design tools provide intuitive restructuring and flexible regulating environments, thereby allowing interactions that can engage higher levels of complexity [16]. This paper highlights these parametric activities.

2.2 Research techniques

This study adopts two research techniques: (a) a consensual assessment technique (CAT) for design products, and (b) protocol analysis for exploring cognitive design activities.

The consensual assessment technique [17] is a common approach for measuring the creativity implicit in design products. It is based on the assumption that the combined assessment of experts in a field is capable of the measurement of the creativity of an artefact. A basic requirement of an expert panel assessment is that its members are familiar with the design domain and the techniques for producing the design [17]. Evaluation Criteria are often comprised of three categories: novelty, value and aesthetics. Based on these categories, a number of subscales can then be derived. In CPSS, Christiaans [18] used a large number of bipolar subscales for this purpose; 70 in total. However, such a large number of criteria would be time-consuming and even confusing for assessors. For this reason, this paper uses four criteria: *Novelty*, *Usefulness*, *Complexity*, and *Aesthetic attractiveness*. The first two criteria are relatively straight forward, whereas the third, ‘complexity’ refers to the degree to which the product shows the level of intricacy of the design [17]. This is specifically relevant to the complex forms often produced in parametric design. The final criterion, attractiveness refers to the degree to which the design is aesthetically appealing [17]. The evaluation of the parametric design products using these criteria can then be correlated to the cognitive results from protocol analysis for our research.

Protocol analysis has been widely used to explore cognitive activities. Since Dorst’s study [19], protocol analysis, as a significant cognitive research technique, has become a popular method in the design domain. The experiment presented here investigated the cognitive activities of the parametric design process using protocol analysis. To obtain design protocols, participants were instructed to verbalise their thoughts and actions while designing. Verbalization can result in concurrent or retrospective protocols. The research adopts think-aloud verbalisations for the initial protocols enhanced by a post-experiment designer interview. This interview aims to capture and verify the protocols retrospectively by asking the designer to review and elaborate on their recorded performance during the design process.

2.3 Coding scheme

A coding scheme for exploring cognitive activities is essential to undertake protocol analysis. It should be devised in such a way as to be suitable for the purpose and contexts of the design environments; in this case, parametric design environments.

The coding scheme we have adopted, as shown in Table 1, has three levels: physical, perceptual and conceptual. These levels are inspired by Suwa’s cognitive coding scheme [20] and then revised to make them more suitable for parametric design. The coding scheme developed by Gero and Neill [21] was valuable for characterising the conceptual level of parametric design and it is used to support the coding scheme. Designing in parametric environments involves activities at both the geometric and algorithmic modes, which therefore are used to further detail the physical and percep-

tual levels in the coding scheme. For example, the algorithm category of ‘physical level’ includes ‘A-Parameter’ and ‘A-Rule’.

The physical level represents generative activities in parametric design. It refers to the physical actions [20]. ‘Geometry’ category represents the modelling activities for generating the digital geometries, while ‘algorithm’ category represents generative algorithms, which describe the ‘parameter’ and ‘rule’ as well as the ‘reference’. The reference is regarded as an internal guideline [22] to transform data (e.g. structure, climate, sun, wind, etc.) for design considerations.

The perception level represents the activities related to visual imagery in the design process. This level also has the two categories of geometry and algorithm. The perception level may be understood in terms of the notion of incubation in Wallas’s creative stage model [23], which might facilitate creativity.

The conceptual level consists of three categories of actions – problem-finding, solution-generating, and solution-evaluating – which are adopted from Gero and Neill [21]. While cognitive activities of the conceptual level can be largely interpreted as problem-solving processes, Dacey and Lennon [24] claim that creative cognition is more than problem solving; selection and evaluation processes are equally important as parts of an integrated process for supporting design creativity. They are reflected in the development of our coding scheme. The solution-generating action is essential to capture the generative aspect of parametric design. Making variations is to extend the boundaries of the designer’s existing knowledge and the state space of possible solutions [4] which is also the key to pursuing creativity.

Table 1. The coding scheme for exploring the parametric design process

Level	Category	Subclasses	Description
Physical	Geometry	G-Geometry G-Change	create geometries without an algorithm change existing geometries (by drag-and-drop)
	Algorithm	A-Parameter A-Change Parameter A-Rule A-Change Rule A-Reference	create initial parameters change existing parameters create initial rules change existing rules retrieve or get references
Perceptual	Geometry	P-Geometry	attend to existing geometries
	Algorithm	P-Algorithm	attend to existing algorithms
Conceptual	Problem-finding	F-Initial Goal	introduce new ideas (or goals) based on a given design brief
		F-Geometry Sub Goal	introduce new geometric ideas extended from a previous idea
		F-Algorithm Sub Goal	introduce new algorithmic ideas extended from a previous idea
	Solution-generating	G-Generation	make generation (or variation)
	Solution-evaluating	E-Geometry	evaluate primitives or existing geometries
		E-Parameter	evaluate existing parameters
		E-Rule E-Reference	evaluate existing rules evaluate existing references

3 Results

The design experiments involved four architectural designers who each have experience in parametric design. Participants were given one hour to undertake a design task, but they could continue if more time was required. The design task was a simple form generation activity (see appendix).

A panel of three design experts, each with a minimum of five years professional and/or academic architectural teaching experience, assessed the final design models. The design models were presented as a collage of images (A4 size paper) and assessed using a seven-point Likert scale (where 1 is the lowest and 7 is the highest).

Two (G1 and G2) of the four designers utilised Grasshopper, as the graphical algorithmic editor, whilst the other two (T1 and T2) used Python and Maya script editor, hereafter the text-based editor. One of the participants is a university lecturer (G1) and another participant is an expert Python user (T1). Both of them have had over five years' experience. G1 and T1 therefore can be regarded as expert designers in this study. G2 and T2 were postgraduate architectural students at the time of the experiments, with only one-year experience in parametric design.

3.1 Expert panel assessment

Expert judges were asked to assess the outcome of the design tasks using three different evaluation forms: (i) independent non-criteria based assessment of creativity, using the expert's own set of criteria and assessing each of the parametric model without comparing to each other, (ii) comparative non-criteria based assessment of creativity, again using the expert's own set of criteria but assessing the parametric models by comparing to each other, and finally (iii) criteria-based assessment of creativity, using the given four criteria of Novelty, Usefulness, Complexity and Aesthetic attractiveness.

The values shown in Table 2 are the average scores of the judges' assessments. The results show that the level of creativity exhibited in T1's model is assessed by the expert panel as being the highest. G1's model achieves the second highest scores and has an equal score with T1's regarding *Usefulness*. By contrast, G2 and T2's model has the lowest creativity score.

Table 2. Assessment scores of the parametric design models

	Non-criteria assessment	Comparative assessment	Novelty	Usefulness	Complexity	Aesthetic attractiveness	Mean
G1	4.0	-	5.7	5.0	4.0	4.3	4.8
G2	3.7	Lowest (1)	4.7	4.0	4.3	1.6	3.7
T1	6.0	Highest	7.0	5.0	6.0	3.3	5.3
T2	2.7	Lowest (2)	2.7	3.3	2.3	3.7	3.0
Mean	4.1	-	5.0	4.3	4.1	3.2	4.2
SD	1.4	-	2.1	0.9	1.5	1.5	1.1

3.2 Protocol analysis

The protocols of each recorded video were directly transcribed using NVivo 9 and automatically segmented into smaller episodes. A coder segmented and encoded each protocol twice with over three-month interval.

The average value of the number of segments was 297.8 (G1: 220, G2: 319, T1: 364, T2: 288). Over 90% of each protocol was encoded through the coding scheme. Only G1 completed his design within one hour (48 min), whilst the others took approximately one and a half hour (1 h 33 min, 1 h 42 min, and 1 h 34 min). These over-timed design sessions may have been caused by many additional trouble-shooting processes undertaken by the three designers G2, T1 and T2. Parametric design often requires user to wait for the design to be generated. For example, in T1's protocol there were 17 segments of 'waiting'.

Table 3 shows the coding results describing the percentage of the frequency weighted by time duration of each code. On average, the coverage of 'physical' accounts for 45.3% (geometry: 5.5%, algorithm: 39.8%); 'perceptual' accounts for 6.2%; 'conceptual' accounts for 48.5% (problem-finding: 11%, solution-generating: 5.5%, solution-evaluating: 32%). Solution-evaluating dominates in the conceptual level. The following sections will discuss the protocol analysis results further, from three cognitive levels (physical, perceptual and conceptual), in terms of creativity.

Table 3. The percentage of coding results

Level	Category	Subclass	G1	G2	T1	T2	Mean	SD
Physical	Geometry	G-Geometry	2.0	6.4	0.0	1.3	2.4	2.8
		G-Change	0.5	8.8	0.0	3.0	3.1	4.0
	Algorithm	A-Parameter	4.9	3.0	0.1	2.9	2.7	2.0
		A-Change Parameter	10.0	1.6	4.7	1.0	4.3	4.1
		A-Rule	24.7	16.5	20.0	19.0	20.0	3.5
		A-Change Rule	6.0	2.9	12.2	26.9	12.0	10.3
		A-Reference	0.0	0.0	0.2	2.8	0.8	1.3
Perceptual	Geometry	P-Geometry	2.8	1.0	1.8	0.4	1.5	1.0
	Algorithm	P-Algorithm	3.2	2.8	4.0	8.6	4.7	2.6
Conceptual	Problem-finding	F-Initial Goal	3.0	1.4	0.2	1.1	1.4	1.2
		F-Geometry Sub Goal	7.0	10.7	2.5	2.3	5.6	4.0
		F-Algorithm Sub goal	4.1	6.4	4.4	1.0	4.0	2.2
	Solution-generating	G-Generation	4.0	1.9	13.0	3.0	5.5	5.1
	Solution-evaluating	E-Geometry	19.4	18.1	17.3	8.8	15.9	4.9
		E-Parameter	0.8	0.0	0.0	0.0	0.2	0.4
		E-Rule	7.6	18.5	19.5	17.9	15.9	5.5
		E-Reference	0.0	0.0	0.1	0.0	0.0	0.1
	Sum		100	100	100	100	100	-

3.3 Physical activities

Algorithmic activities are dominant in the physical level for each protocol as shown in Table 3 and Figure 1. ‘A-Rule’ and ‘A-Change Rule’ in Table 3 are dominant activities in parametric design. This suggests that the algorithmic representation is a preferred medium for progressing design in parametric design. There is some other differentiation among participants in the coding results as shown in Table 3. For example, G1, G2 and T1 often made new rules (A-Rule) rather than changed existing ones (A-Change Rule), while T2 tended toward changing existing rules. This indicates that there are differences in approaches to conducting parametric design.

As discussed above, G1 and T1 are regarded as expert designers with more design and programming experiences than G2 and T2. G2 and T2 had only one-year experience in parametric design at the time of the experiments. Table 3 shows that the frequency coverage of ‘A-Change Parameter’ was significantly higher in both G1’s and T1’s protocols. These results imply that experts had an advantage regarding the generative aspects of parametric design. Figure 1 also shows that the coverage percentage of geometric activities more often occurred in novices’ protocols. The geometric activities may hinder the generative processes in parametric design, which are possibly related to creativity.

Fig. 1. The coverage percentage of algorithmic and geometric activities in the physical and perceptual level

3.4 Perceptual activities

Perception is based on the activities related to visual imagery undertaken during the design process. Our pilot study [9] demonstrated that the perception of existing geometries and algorithms produced unique patterns of perception in the different designers’ protocols, captured by the perceptual activities coded by ‘P-Geometry’ and ‘P-Algorithm’. It also claimed that occurrence of the ‘P-Geometry’ code (perceiving or attending to existing geometries) that is consistent with the results of the product-based evaluation of creativity.

Figure 1 shows that expert designers (G1 and T1) – their models received relatively high creativity score from the expert panel – generally had higher frequency coverage of the geometric perception than novices. Perceiving geometries may play a more significant role than the perception of – or attendance to – existing algorithms. In traditional modelling environments, the encoding of perception refers to the actions of attending to visuo-spatial features of depicted elements [20]. To formulate mental imagery during parametric design processes, sensing visual cues is also an essential part of creative problem solving processes.

Whilst this study highlights the significance of algorithmic activities and perception of topological scripts or codes (also reported by other researchers as significant, designers continue to rely on the perception and exploration of design ideas using the 3D view. While current parametric tools may assist creative thinking at the algorithmic level [16], perceiving geometries – an activity traditionally reported as significant to design cognition – continues to be a critical part of creativity in parametric design.

3.5 Conceptual activities

The conceptual level in our coding scheme enables the exploration of the designers' cognitive activities in both the problem space (through the 'Problem-finding' code) and the solution space (through the 'Solution-generating' and 'Solution-evaluating' codes). Figure 2 show the coverage percentage of main cognitive activities in the conceptual level. Even though G2 and T1 had the similar coverage of the conceptual level, each coverage percentage of main cognitive activities has a differentiation. For example, T1's protocol produced relatively a large amount of 'G-Generation' and a small amount of 'F-Geometry Sub Goal', while G2's protocol had a lack of 'G-Generation' but produced relatively a large amount of 'F-Geometry Sub Goal'. G2 may conduct more geometry-based activities. Expert panel assessment results indicate that T1's model had the highest creativity and novice designers' (T2 and G2) models had the lowest creativity scores overall. This implies that 'G-Generation' is one of potential activities to creativity in parametric design.

The frequency coverage of 'Problem-finding' in our protocol analysis shows that designers who use the graphical algorithm editor adopt a problem driven process (G1: 14.8% and G2: 18.5%), in order to progress parametric design. That is, G1's and G2's cognitive activities occurred largely in the problem space.

Fig. 2. The coverage percentage of main cognitive activities in the conceptual level

Design strategies based on a problem driven process can result in the best balance between quality and creativity [25]. The results of the expert panel assessment for G1 tend to support this position. However, also adopting a problem driven process, G2's model received the lowest creativity score from the panel. This implies personal aspects also play an important role in supporting creativity in parametric design. G2, the other novice designer, had the highest frequency coverage of 'Problem-finding' (18.5%). This implies that problem-finding activities alone may not necessarily have a positive effect on creativity in parametric design. Creativity in parametric design may not only depend on 'Problem-finding', but generative activities including 'A-Change Parameter' and 'G-Generation'

T1 is regarded as adopting a solution driven process for progressing parametric design, as T1's protocol had the most frequency coverage of 'Solution-generating' and 'Solution-evaluating' (36.9% altogether). The frequency coverage of 'G-Generation' for T1 was also the highest (13%). T1's protocol had the second highest frequency coverage of 'A-Change Parameter' (4.7%). Complementing the solution driven process, 'G-Generation' and 'A-Change Parameter' may have enabled T1 to generating design variations, because these features are related to divergent thinking and the restructuring of design components [10]. T1's model had the highest creativity score as assessed by the expert panel in Table 2. This is consistent with Kruger and Cross's results [25], indicating design strategies adopting a solution driven process can lead to outcomes with higher creativity.

Fig. 3. The normalized coverage of the cognitive levels over time

The summed coverage data in each 20-segment interval was visualized using the normalized coverage value (normalized $A = (A - \text{mean})/SD$) [26] to facilitate the exploration of cognitive activities over time. Figure 2 shows the normalized coverage of the cognitive levels over time. The graphs in Figure 3 describe that the normalized coverage of evaluation activities has a relatively high value in the middle of each timeframe of T1 and T2' protocol, whilst the activities in G1 and G2's protocol often occurred later in the design process. Activities coded as 'G-Generation' in G1 and G2's protocol often occurred later in the design process. By contrast, T1 and T2 produced 'G-Generation' repeatedly over time. Figure 3 also reveals that cognitive activities in the 'Problem-finding' category different patterns within each timeframe.

Two designers (G1 and G2) utilised Grasshopper, as the graphical algorithm editor, whilst the others (T1 and T2) used text-based algorithm editors. 'A-Change Rule' and 'P-Algorithm' in Table 3 occurred dominantly in the text-based algorithm editors. The text-based editors tended to produce more algorithmic activities in the physical representation level than the graphical editor. These results show that parametric design processes can vary when adopting the problem versus solution driven process as well as the geometric versus algorithmic approaches.

4 Conclusion

This paper has presented the results of a protocol study that investigates the cognitive activities that occur during a parametric design process, and with a focus on creativity. Whereas past studies have focused on the importance of performative modeling and optimisation in parametric design, this paper highlights its cognitive activities which include generative and parametric activities.

Our discussion has been structured around three cognitive levels: physical, perceptual and conceptual. In this way it provides a more in-depth understanding of cognitive activities in parametric design. ‘G-Generation’ and ‘A-Change Parameter’ are potential parametric activities enabling divergent thinking and the restructuring of design components. They also facilitate a solution-driven process leading to outcomes with higher creativity. Although this early study is limited to the small number of participants, this study has provided the much needed empirical evidence and a starting point to better understand cognitive activities in parametric design.

Future research will adopt larger sample sizes and/or more comprehensive techniques. Sample size – from only two participants [27] up to twelve designers (six experts and six novices) – has always been a contentious issue in protocol studies, because such studies produce very large data sets. An appropriate number of participants should be carefully considered for future studies. Our future work will require an even more in-depth analysis to explore a wide variety of aspects of the protocols. Some method of graphical analysis, like linkography, might also be used. The graphical analysis will allow us to better facilitate the exploration of sequential patterns of cognitive activities in parametric design.

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Appendix: 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 design task to consider the creative form of the high-rise building. The high-rise building will have two main functional areas: Office and hotel.

The followings can be considered:

- Maximum total floor area is 2,500 square metres (50m x 50m).
- The high-rise building will 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 at the exterior or interior of the building)
- You can reflect transformations of 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, elegance, and well-transformation) 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 quality 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). In order for you to clearly represent the conceptual design, (2) three rendered or captured images showing the strength of your design should be saved on your desktop. (Timeline: One hour)