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Article

Comparing Designers' Problem-Solving Behavior in a Parametric Design Environment and a Geometric Modeling Environment

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Abstract: This paper presents the results of a protocol study which compares designers' behavior in a parametric design environment (PDE) and a geometric modeling environment (GME). An experiment was conducted in which seven designers were required to complete two architectural conceptual design tasks with similar complexity respectively in a PDE and GME. Protocol analysis is employed to compare the cognitive behavior of designers in these two environments. By analyzing the designers' actions, including shifting between "problem" and "solution" spaces, it was possible to compare their cognitive activities in PDEs and GMEs. Results of this research suggest that designers put similar effort into the design problem space and the solution space in PDE and GME and that interaction between these two spaces also appears similar in the two design environments. However, different Problem-Solution index values and discontinuity ratios are found across design stages of the two design environments.

Keywords: parametric design environments; geometric modeling environments; protocol analysis; problem and solution space; problem-solution index

1. Introduction

Parametric design has become increasingly prevalent in architectural design in recent years. Previous studies have argued that parametric tools advance design processes in a variety of ways [1–5]. However, there is a lack of empirical evidence supporting an understanding of designers' behavior in parametric design environments (PDE). As a relatively new design tool, the question of whether PDEs can assist the design process is therefore an important topic to explore. The overarching question that drives this research, therefore, asks: are parametric design environments more beneficial for designers' creative processes than traditional geometric modeling environments (GME)?

Research into the design process is a large and complex topic. One effective method of understanding the design process is by studying designers' cognitive activities in a real or simulated design environment. One of the recurring themes identified in past research using this method is the relationship between the "problem space" and "solution space" in the design process. Design, it is suggested, is a process that develops the formulation of a problem and ideas for a solution in parallel [6]. Therefore, this study starts by comparing designers' behavior in terms of their approach to design problems and solutions in both PDE and GME. In the study seven designers are asked to complete two different conceptual design tasks with similar complexity in both PDE and GME. Protocol analysis is then employed to study the designers' behavior in these environments. In this study we introduce two methods of measurement to quantitatively examine designers' cognitive behavior in PDEs and GMEs—the P/S index [7] and discontinuity ratio. By analyzing the interactions between the design problem and solution space, the designers' cognitive activities in PDE and GME are compared and discussed.

2. Background

2.1. Design Environments—PDE and GME

In the late 1990s, with the growth in importance of 3D digital tools in the design industry, architects began to identify a range of ways wherein these were superior to previous 2D computer aided design systems [8,9]. In the last decade a similar shift has begun to occur, with BIM and parametric software beginning to challenge the role played by 3D geometric modeling software in the AEC industry. Typical 3D geometric modeling tools used in architecture today include Archicad from Graphisoft, Revit from Autodesk, Rhino from McNeel, Maya and Sketchup. In the present study, for the purposes of comparison, Rhino was chosen as the traditional geometric modeling environment (GME).

Parametric design is a dynamic, rule-based process controlled by variations and parameters, in which multiple design solutions can be developed in parallel. According to Woodbury [10], it supports the creation, management and organization of complex digital design models. By changing the parameters of an object, particular instances can be altered or created from a potentially infinite range of possibilities [11]. The term "parameters" means factors which determine a series of variations. In architecture, parameters are usually defined as building parameters or environmental factors. In the architectural design industry, parametric design tools are utilized mainly on complex building form generation, multiple design solution optimization, as well as structural and sustainability control. Currently, typical parametric design software includes Generative Component from Bentley Corporation, Digital Project from Gehry Technology, Grasshopper from McNeel. Scripting tools include Processing based on the Java language, Rhino script and Python script, based on VB language from McNeel. In this study, Grasshopper was chosen as the parametric design environment. Grasshopper is both an advanced environment for facilitating conceptual design and its use is relatively widespread in the architectural profession.

The combination of Rhino and Grasshopper is also appropriate for the present study as the former offers advanced free-form making tools that will not lead to significant differences from the product produced in the Grasshopper environment. In addition, Grasshopper is an add-on in Rhino, which means that the two design environments are on the same platform. This combination ensures that the comparative goals of the experiment are both reasonable and achievable.

Previous studies on designers' behaviors in PDEs suggest that parametric tools advance design processes in a variety of ways. For instance, there is evidence that the generation of ideas is positively influenced in PDEs. Particularly, in Iordanova *et al.*'s [1] experiment on generative methods, ideas were shown to be generated rapidly while they also emerge simultaneously as variations. Moreover, Schnabel [2] shows that PDE is beneficial for generating unpredicted events and can be responsible for accommodating changes. However, researchers have typically studied design behavior in PDE mostly by observing students interactions in PDEs in design studios or workshops. Arguably, this approach cannot provide an in-depth understanding of designers' behaviors. This empirical gap will be addressed in the present study by adopting the method of protocol analysis. In 2012, Lee *et al.* [12] presented a pilot study using protocol analysis to evaluate creativity in the PDEs. Results of their study identified some conditions that potentially enhance creativity in the PDE. Using the same method, Chien and Yeh [5] explored "unexpected outcomes" in the PDE. However, without a basis for comparison, it is difficult to suggest how parametric tools enhance or hinder creativity in comparison with traditional design methods.

The present study is therefore a comparison between the two design environments and their impact on the design process. However, the seemingly obvious difference between parametric design and traditional geometric modeling tools is associated with the application of a rule-based algorithmic process. Yet, to a certain extent architectural design has always been a rule-based algorithmic process. But, as Ostwald [13] notes, such methods were often peripheral to the design process in previous eras, while today they have potentially become central or pivotal to the process. For example, in PDEs designers not only design by applying specialist knowledge, but also by defining and applying rules and their logical relationships using parameters. In contrast, in GMEs, the rules are present, but they are less significant or less central to the overarching process. Thus, in this study, discussion of the rule-based or algorithmic processes is used in a narrow technical sense to only refer to the generative engine in the PDE.

2.2. Design Problem and Solution Spaces

Design is not just a process of finding solutions to an initial given task, it is also about redefining/reframing the design problems that have been provided [14]. During the design process, designers continue redefining design problems and searching for solutions for the problems. Previous studies show that the expert design process also involves a close interaction between representations of problems and solutions [15]. Therefore, the notion of a design problem and solution space is one possible way to conceptualize the design process.

Kruger and Cross [16] divided different design approaches into "problem driven" and "solution driven". Problem-driven design refers to the way designers focus on the problem and use information to solve the problem. Solution-driven design describes the way designers focus on generating solutions, and use this information to develop a final resolution of the central issues in a design. For example, Kruger and Cross [16] studied the design processes of nine product designers and their results show that most adopted either a solution-driven or a problem-driven design paradigm. The solution-driven designs expressed high level creativity but low overall quality. The problem–driven design approach was, on the contrary, low in creativity and high in overall quality. Significantly, in this study Kruger and Cross used an S/P index to quantify the two kinds of design numerically and to measure the difference between a solution-driven and a problem-driven approach. This index was developed by Jiang *et al.* [7] in a study comparing the design approaches of industrial design and mechanical engineering students. The P-S index (problem-solution index) is the ratio of problem related issues/processes to solution related issues/processes. Their study applies the FBS model [17] as a coding scheme, and they also divided the FBS issue and processes into problem/solution related issues/processes, which makes the method formalized: using P-S index, it is possible to identify the bias of the design process as either problem-or solution-centered, quantitatively over time.

Besides examining the proportion of problem and solution spaces inhabited over a period of time, another related concept which has been considered is the potential co-evolution of the design problem space and the solution space [6,18]; a representation of the interaction between the two design approaches ("spaces"). The main concept of co-evolution is that designers formulate design problems and explore ideas for solutions to these problems together; design is therefore an interactive process which involves the analysis, synthesis and evaluation of design problems and solutions [15,19]. Maher and Poon [18] and Dorst and Cross [6] conceptualize co-evolution models to demonstrate designers' movements between problem-solving and solution-finding processes. Later, Kim and Maher [20] applied the concept of co-evolution in their protocol study comparing designers' spatial cognition in tangible user interfaces (TUI) and graphical user interfaces (GUI) in design environments. Their results show that designers in TUIs have more interaction between design problem and solution spaces. Such studies also suggest that the co-evolution of a design problem and solution process has a close relationship with the occurrence of design creativity. A recent protocol study conducted by Helms and Goel [21] examined the co-evolution processes of an inter-disciplinary class of students. Their results suggest that there is an "evaluation-pruning" function in the early design stage and that analogical strategies are important for generating problems at a similar time.

3. Research Methods

This study employs protocol analysis to compare the cognitive behavior of designers in PDEs and GMEs. Protocol analysis is a method that is widely used for cognitive studies into designers' behavior during the design process [22,23]. This method has also been applied across a variety of design environments [24,25]. Importantly, protocol analysis of this type deals with a relatively small number of samples, but it enables an in-depth exploration of the samples. Thus, a study of the cognitive behavior of seven designers is both reasonable and in keeping with past research in this field because of the quality and depth of information that is recorded and analyzed. However, for this reason we also cannot generalize the results of this research to describe the actions or behaviors of a much larger population of designers. Nevertheless, from such studies important patterns which are repeated by designers could be used to provide a heightened level of understanding of the design process.

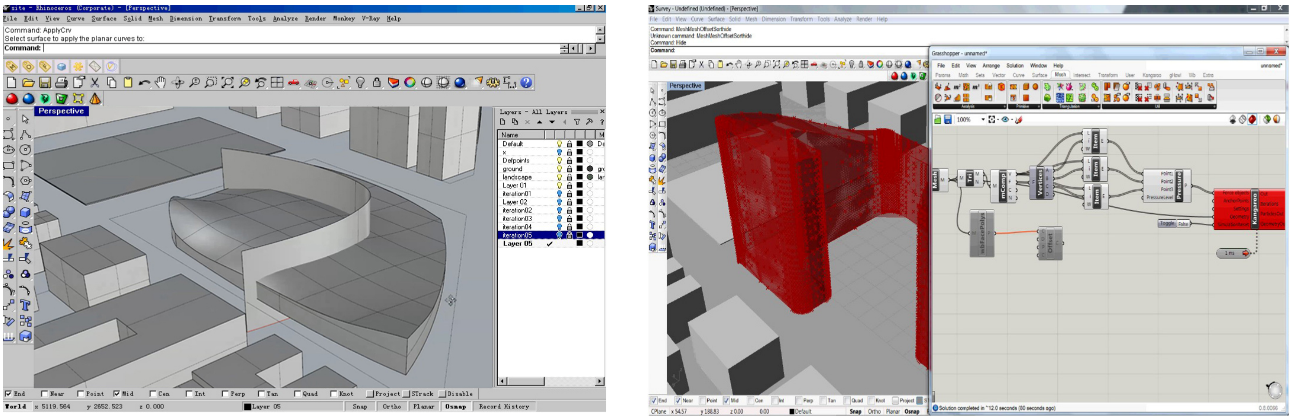
The general procedure undertaken for protocol analysis of this type is that data (in this case, video-recordings of designers' actions and behaviors in particular design environments) is collected from the experiment and transcribed and segmented using a set of rules or protocols. A customized coding scheme is then applied to each category's segments. Through statistical analysis of this data the character of designers' behavior can be identified and compared.

3.1. Design Experiment

In devising the present experiment, each designer was required to complete two different design tasks with similar levels of complexity in a PDE and in a GME. Seven designers participated in the experiment, each of whom are professional architects with an average eight years of experience on architectural design, and no less than 2 years on parametric design.

The experiment environment was a computer installed with Rhino and Grasshopper. During the experiment, designers' activities and their verbalization (narrative) were audio and video-recorded by a screen capture program; the recorded data forms the basis of the protocol analysis. There were two design sessions: one session using Rhino (GME) (Figure 1a) and another using Rhino and Grasshopper (PDE) (Figure 1b). Designers were given 40 min for each design session. Task 1 is a concept design for a community center and Task 2 is a similar study of a shopping center, with both containing some specific functional requirements (see Appendix). These functional requirements are the main difference between the two tasks. In all other ways the two designs were similar, including the site provided, the building size, and the extent of concept development. A pre-modeled site was provided to the designers for each task. Because the present study is focused on exploring designers' behavior at the conceptual design stage, they are required to only consider concept generation, simple site planning and general functional zones. No detailed plan layout is required. Both tasks focus on conceptual design in general to enable the design process to be completed in a relatively short time period and captured and analyzed using the adopted method. In order to avoid the bias that can be potentially be caused by using the same brief in the two different design environments, the study uses two different design briefs that share the same levels of complexity. The tasks are both open and general enough to provide designers with the freedom to enable various possible design strategies to be applied during parametric design. As a result, designers may exhibit different ways of approaching parametric design, which are similar to the actual practices of parametric design and can be beneficial for us to generalize findings. The design sessions and tasks are randomly matched among different designers. During the experiment designers were not allowed to physically sketch, ensuring that almost all of their actions happened within the computer. This ensured that the design environment was purely within either PDE or GME. In this way the research method minimized the impact of other variables except for the difference between the two different design environments.

Figure 1. (**a**) Geometric modeling environment (GME), and (**b**) Parametric design environment (PDE).



(**a**) (**b**)

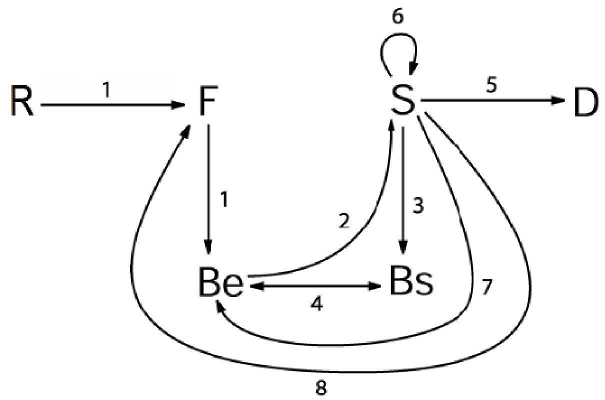
3.2. Coding Scheme—FBS Model

After collecting the protocol data from each design experiment, a particular coding scheme was applied to categorize the data, enabling a detailed study of the design process in the chosen design environment(s). This section presents the coding scheme used, which is based on the established FBS ontology [17] and modified specifically for the purpose of encoding design processes in PDEs and GMEs.

Since its publication, Gero's FBS model [17] has been applied in many cognitive studies [24,26,27]. Its advocates argue that it is potentially able to capture most of the meaningful design processes [24] and transitions between design issues are clearly classified into eight categories. Gero and Kan [28] applied the FBS ontology to a study of software designers' behavior, suggesting that the method was effective for encoding programming or rule-based activities across different design disciplines. Given that the PDE enables scripting and programming activities, this strongly suggests that the FBS scheme is able to encode both geometric modeling and rule-based algorithmic activities effectively. In this study it is introduced as a conceptual foundation for developing the coding scheme for protocol analysis.

The FBS model (shown in Figure 2) contains three classes of variables: Function (F), Behavior (B) and Structure (S). Function (F) represents the design intentions or purposes; behavior (B) represents how the structure of an artifact achieves its functions, either derived (Bs) or expected from (Be) structure; and structure (S) represents the components that make up an artifact and their relationships. The model is strengthened by two external design issues; requirements (R) and descriptions (D). The first of these represents requirements from outside the design and the second, description, means the documentation of the design. Figure 3 shows the eight design processes—formulation, analysis, evaluation, synthesis, description, and reformulation I, II, III. Among the eight design processes, the three types of reformulation are suggested to be the dominant processes that potentially capture innovative or creative aspects of designing by introducing new variables or a new direction [29]. In the present study, we adopt the FBS model as our coding scheme, including all the design variables except description (D), because in PDE and GME, the description process rarely occurs.

Figure 2. FBS model [17].



3.3. Problem-Solution Division in FBS Ontology

This paper adopts the problem and solution division identified in the FBS model [7]. Furthermore, regarding FBS issues, problem-related issues include design consideration about requirements, Function (F), and expected behavior (Be). While solution-related issues involve design considerations about structure (S) and behavior derived from structure (Bs). According to the design processes indicated in the FBS model, design process transition with problem/solution related issues is categorized as a problem/solution-focused design process (as shown in Table 1).

Table 1. Mapping FBS design issues and processes onto problem and solution spaces [7].

Problem/Solution Space	Design Issue	Design Process
Reasoning about problem	Requirement (R) Function (F) Expected behavior (Be)	1 Formulation 7 Reformulation II 8 Reformulation III
Reasoning about solution	Behavior derived from structure (Bs) Structure (S)	2 Synthesis 3 Analysis 4 Evaluation 6 Reformulation I

4. Results

From observation of the experiment, the designers each showed a clear ability to understand the design brief and operate the software. The time limit meant that all design outcomes were resolved to a similar level although some designers stopped at the building mass or a façade design. However, they all considered the site planning as well as the building function in more detail, providing a considered response to the conceptual design brief. In both PDEs and GMEs, designers started by reading the brief and inspecting the site model provided. During the design process, they also revisited the design brief. The design brief provided details concerning functional constraints and site conditions. It was up to designers to decide how many of these conditions to consider. As usual in architectural design, different designers have their own design strategies: some designers preferred to start from functional analysis, thinking through site conditions and road and traffic information before drawing diagrams of the site to explore these relationships. Other designers focused on geometric modeling as the priority.

Through direct observation we found that in the PDE designers tended to build a "correct" parametric relationship system rather than building a "correct" model. Thus, the whole system concept seems to be determined at the beginning of design stage. Designers in the PDE were not completely sure about what would come out after they made a piece of script, and thus there were multiple "Aha" moments. For example, several times designers stated that "this looks good" or "it starts to look interesting", when referring to their evaluation of the designs in a PDE. Designers in the PDE switched between the script interface (Grasshopper) and the geometry interface (Rhino) frequently. They tended to go back to examine the model after they changed a parameter or parametric relationship, or went back to check their previous definition using the script interface. This inspection of a previous model or script definition can be defined as a kind of perceptual activity, which is connected to the accumulation of generated intentions.

As revealed in this study, designers can exhibit different approaches when applying parametric design. Some of them define and apply rule relationships as the dominant way to explore and progress design concepts, others mainly use rules to generate geometries only. For example, one designer applied the sunlight analysis of the given site model for area planning, which reflects a relatively high-level conceptual parametric thinking. Another designer generated random points to make a variable façade, which mainly aims for an innovative form. As this study focuses on conceptual design in the PDE in general, there are different levels of approaches which are similar to the actual practices of parametric design and can be beneficial for generalizing the findings.

Two rounds of segmentation (the division of protocols into individual units based on FBS notions) and coding were conducted after the experiment was completed. The coding was conducted by one researcher with a time interval of two weeks between the two rounds of coding. Thereafter an arbitration session (to make decisions on any disagreements between codes) was carried out to produce the final protocol. The agreement between the two rounds of coding was 84.35% and the final arbitrated results were 91.95%. The high level of agreement suggests the reliability of the coding results. Table 2 provides the general information of coding coverage. The numbers shown in the table are the average of the seven protocols. The average overall segments are respectively 240 in the PDE and 223 in the GME. Designers also spend more time in the PDE session (47.4 min) than in the GME (43.0 min). The design speed is very similar in the two design environments. Over 91.97% of segments can be coded as FBS codes. Non-codes include communication, and software management.

Table 2. General coding information.

Design Environments	Time (min)	Number of Segments	Coded Percentage (%)	Speed (Segments/min)
GME	43.0	223	91.97	4.78
PDE	47.4	240	92.45	4.68

4.1. Design Issue and Design Process Distribution

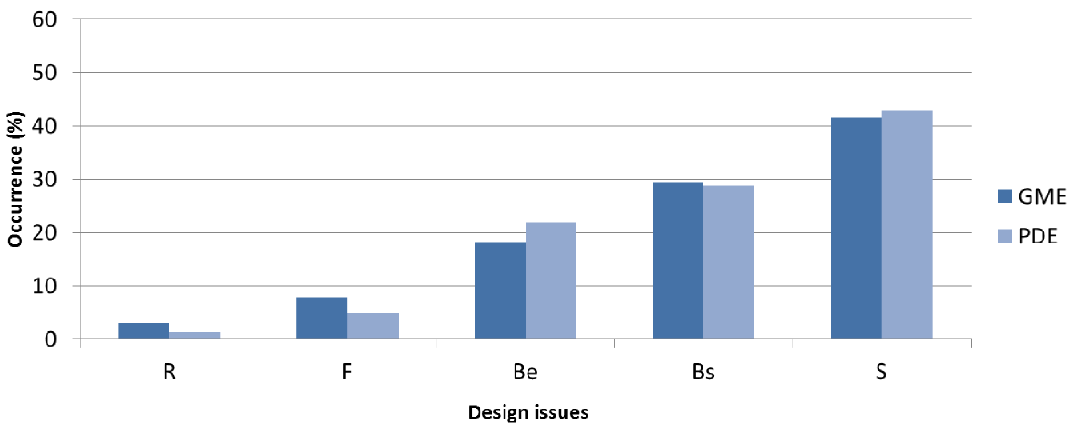
In the following analysis, in order to focus on the differences between the PDE and the GME, all of the values are the average of the seven sets of protocols. In Figures 3 and 4, we normalize the vertical axis as a percentage of the total design issues/processes occupied in overall coded segments (non-coded segments are not counted in this analysis). The distribution of FBS design issues is shown in

Table 3 and Figure 3. The two design environments produce similar design issues distributions except for Requirement (R) and Function (F). More cognitive effort is expended on the structure design issue than any others in both environments. This is followed by behavior from structure (Bs), expected behavior (Be), function (F), and the least effort is expended on requirements (R). From the results it can be inferred that among the overall distribution of design issues, only Requirement (R) (T = 2.0, p = 0.093), and Function (F) (T = 2.07, p = 0.084) is significantly affected by the method used (* $p < 0.1$). The higher percentage of R and F in the GME than the PDE may because that within similar timeframe, designers allocate part of their effort to the designing of rule relationship in the PDE.

Table 3. Design issue distributions in GME and PDE.

Participants	Problem Space						Solution Space			
	R		F		Be		Bs		S	
	GME	PDE	GME	PDE	GME	PDE	GME	PDE	GME	PDE
Designer A	2.44	1.79	11.71	4.02	18.05	13.39	26.83	28.13	40.98	52.68
Designer B	1.67	1.15	7.50	3.45	12.92	20.69	37.08	39.08	40.83	35.63
Designer C	2.96	1.99	3.70	1.49	13.33	5.97	31.11	37.31	48.89	53.23
Designer D	2.17	0.82	4.35	3.29	22.61	25.10	31.74	30.04	39.13	40.74
Designer E	2.98	1.29	9.79	4.29	18.30	24.89	30.64	25.75	38.30	43.78
Designer F	0.47	0.39	6.05	9.41	12.56	27.84	25.58	22.35	55.81	40.00
Designer G	8.94	2.25	11.17	9.01	30.17	35.59	22.91	18.92	26.82	34.68
Mean	3.09	1.38	7.75	4.99	18.28	21.93	29.41	28.80	41.54	3.09
SD	2.72	0.66	3.22	3.01	6.40	9.74	4.69	7.40	9.05	7.49
T	2.0		2.07		−1.25		0.41		−0.408	
p	0.093		0.084		0.257		0.696		0.697	

Figure 3. Design issue distribution in GME *vs.* PDE.

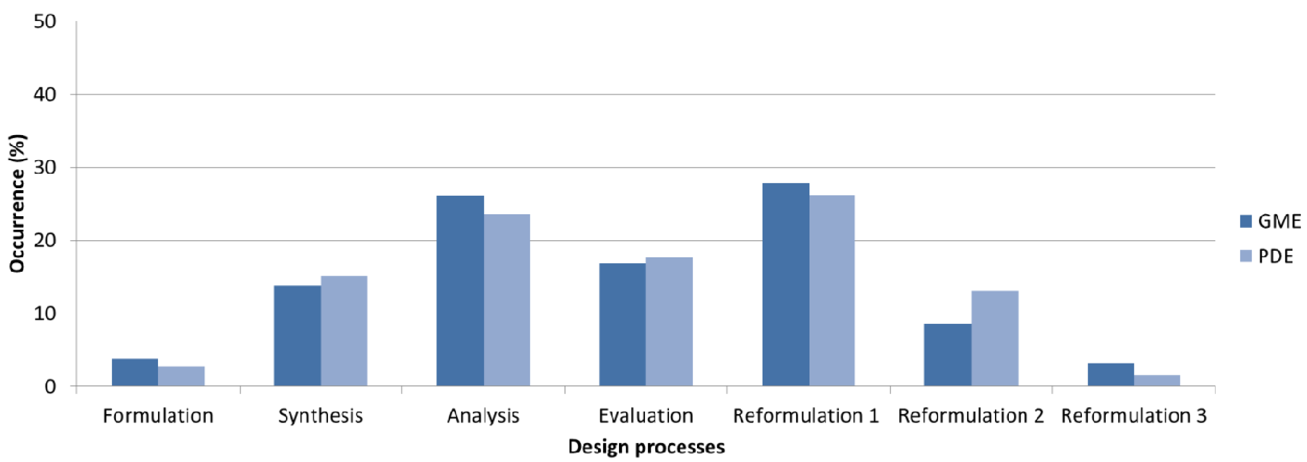


The syntactic design processes in the two design environments are plotted in Table 4 and Figure 4. In this study there are no significant differences in design processes between GME and PDE except the reformulation II process (T = −2.233, p = 0.067 < 0.1): the other types of design processes are very similar between the GME and PDE. More cognitive effort is expended on the analysis and reformulation I process. This is followed by evaluation, synthesis, reformulation II, and the least effort is expended on formulation and reformulation III. From the statistical analysis of design issues and syntactic design processes, there are few significant differences between the PDE and GME. We can infer that designers' thinking at FBS level does not change by the method used. One of the potential reasons is that designers' high-level thinking is more related to individual approaches to designing, which do not necessarily change in the different design environments. However this is a complex issue that deserves further exploration. A future study will further sub-divide the samples according to their approaches to parametric design and re-conduct the analysis to explore the similarities and differences.

Table 4. Syntactic design processes distributions in the GME and PDE.

Participants		Problem Space				Solution Space		
		Formulation	Reformulation II	Reformulation III	Synthesis	Analysis	Evaluation	Reformulation I
Designer A	GME	6.1	6.8	7.6	15.9	26.5	16.7	20.5
	PDE	2.6	7.7	0	11.6	29.7	9.7	38.7
Designer B	GME	1.5	8.1	4.4	10.4	37	15.6	23
	PDE	0	15.9	0.9	14	30.8	29	9.3
Designer C	GME	2.4	7.1	1.2	8.3	27.4	11.9	41.7
	PDE	0.8	4.8	0	3.2	41.9	12.1	37.1
Designer D	GME	2.6	12.3	1.3	19.5	24.7	19.5	20.1
	PDE	1.2	11.4	1.2	15.7	16.9	23.5	30.1
Designer E	GME	3.5	9.9	2.1	14.2	22	20.6	27.7
	PDE	3.1	16.1	1.9	19.1	19.8	14.8	25.3
Designer F	GME	1.3	6	2.7	9.3	28.7	9.3	42.7
	PDE	4.1	18.1	5.3	19.9	13.5	17	22.2
Designer G	GME	9.1	10.1	3	18.2	16.2	24.2	19.2
	PDE	7.5	17.7	1.4	22.4	12.9	17.7	20.4
Mean	GME	3.8	8.6	3.2	13.7	26.1	16.8	27.8
	PDE	2.8	13.1	1.5	15.1	23.6	17.7	26.2
SD	GME	2.84	2.24	2.23	4.44	6.38	5.13	10.20
	PDE	2.53	5.23	1.81	6.43	10.80	6.65	10.22
T		1.41	–2.233	1.368	–0.643	0.687	–0.287	0.338
p		0.207	0.067*	0.220	0.544	0.518	0.784	0.747

Figure 4. Design process distribution in GME *vs.* PDE.



4.2. Problem-Solution Index

The problem-solution (P-S) index indicates the ratio of the number of design problem related issues/processes to the number of design solution related issue/processes, as shown in Equations (1) [7] and (2) [30]. The value of P-S index can be used to understand if designers' behavior is problem-focused or solution-focused in style. According to Jiang *et al.* [7], if the P-S index > 1, the design is classified as problem-driven style; when it is <1, it is solution-driven design style.

$$\text{P-S index (design issue)} = \frac{\sum Problem\ related\ issues}{\sum Solution\ related\ issues} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \quad (1)$$

$$\text{P-S index (syntactic process)} = \frac{\sum Problem\ related\ processes}{\sum Solution\ related\ processes} = \frac{\sum(1,7,8)}{\sum(2,3,4,6)} \quad (2)$$

Figure 5 shows the sequential design issue P-S index [calculated using Equation (1)] in the PDE and the GME. The horizontal axis records the whole design session, divided into ten sub-sessions, each with an equal number of segments. In the following description, we define the "early design stage" as the period from 1 to 3.3 on the horizontal axis, the "mid-design stage" as from 3.4 to 6.6, and the "end design stage" as between 6.7 and 10. The descriptors are thus time-based, rather than a direct indicator of the degree to which a design has been developed or completed. Both environments show a similar decreasing trend towards the end of the design session. Thus, a similar degree of effort is invested in on both the problem and solution spaces in PDEs and GMEs. From Figure 5, we found designers progress into a solution-driven process (P-S index < 1) quicker in a PDE. The index starts with a higher value in the PDE, which lasts for a short time, and is followed by a period that is higher in the GME. Thus, during the early stage, designers spent more effort in the problem space of the GME. The possible reason for this is that designers have to consider the rule algorithm design at the early design stage, which occupies a greater cognitive load. From the mid design stage, designers focus more in the problem space in the PDE. This may be because designers constantly redefine the problem space by setting up algorithmic sub-goals in the PDE.

Figure 5. Sequential design issue P-S index in the PDE *vs.* GME.

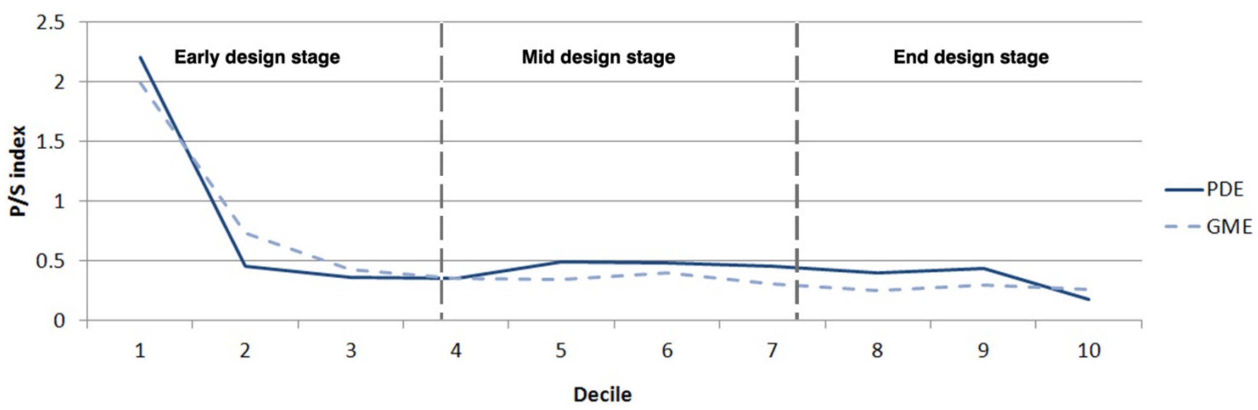
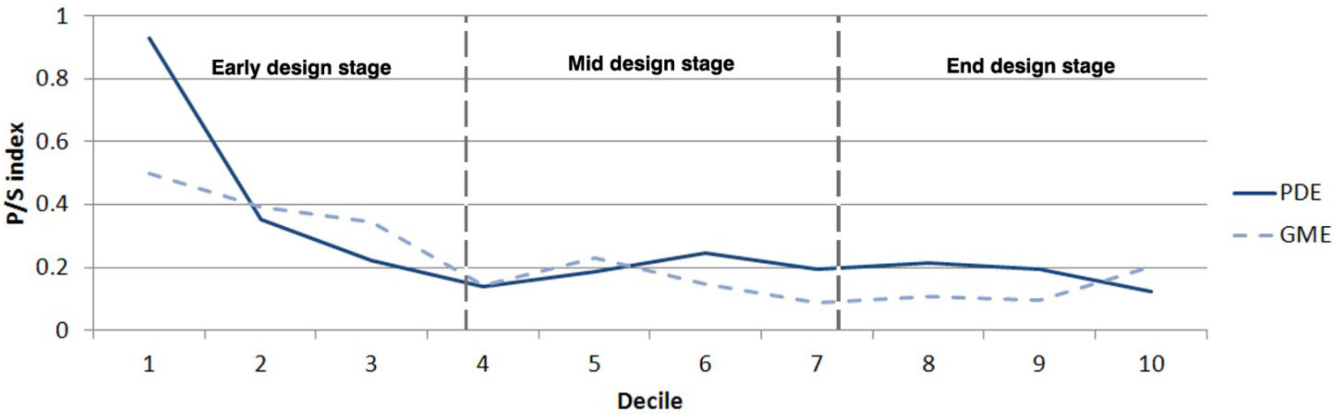


Figure 6 shows the syntactic design process P-S index [calculated using Equation (2)] in the PDE and GME. Just as design issues P-S index, it too shows a decreasing trend in both design environments. The main differences appear at the beginning of the design session, which in the PDE starts with a higher index value but decreases quicker than in GME.

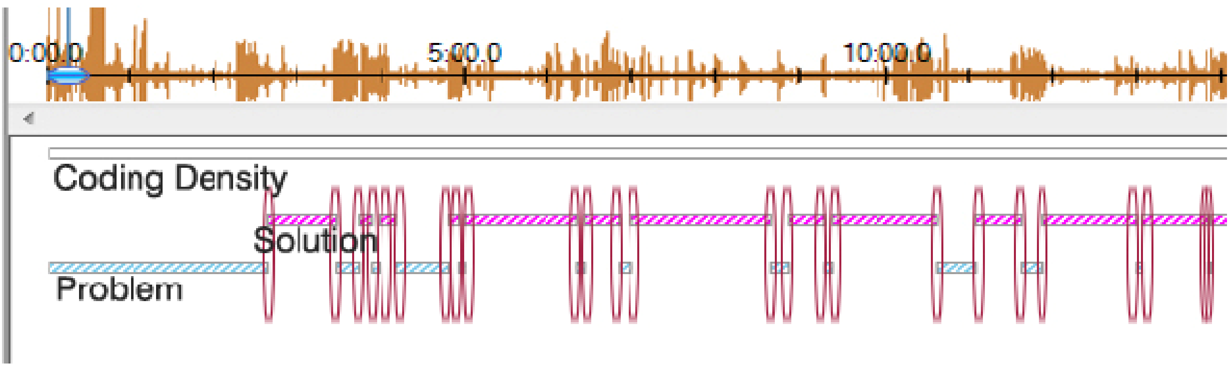
Figure 6. Sequential design process P-S index in the PDE *vs.* GME.



4.3. Co-Evolution of Problem and Solution in the PDE and GME

Using P-S index, we can identify whether the design process tends to be problem-focused or solution-focused. However, the interaction between problem space and solution space cannot be revealed in this way. Creative design might be demonstrated in terms of the co-evolution of problem and solution spaces [6]. The transition between design problem space and solution space is examined by calculating the discontinuity ratio of designers' processes. A higher discontinuity ratio indicates a higher frequency of interaction between design problem and solution spaces. Figure 7 is a section of an interactive graph which illustrates the co-evolution of one designer's cognitive activities between the design problem and solution spaces. Each red ellipse indicates a transition.

Figure 7. Co-evolution of the problem and solution space.



The discontinuity ratio is the ratio of transition times to overall number of segments [see Equation (3)]. This ratio represents the frequency of transition between the problem and solution spaces in a certain design period.

$$\text{Discontinuity ratio} = \frac{\sum Transition\ times}{\sum overall\ segments\ number} \times 100\% \qquad (3)$$

Figure 8 is an example of coding, demonstrating the discontinuity transition between the design problem and solution spaces. Each red curve represents a transition. There are 10 segments in this piece of example coding, so the discontinuity ratio would be 5/10 × 100% = 50%.

Figure 8. Example of the discontinuity transition between the design problem and solution spaces.

42	So this circle needs to be bigger	Be	Problem
43	Pan on the rhino interface	Bs	Solution
44	(Measure the radius of the circle) so that actually 7.8	Bs	Solution
45	(change parameters) so I will make this 40	S	Solution
46	Cool, say my radius is 40	Bs	Solution
47	Now in terms of height	S	Solution
48	I want to take a unit	Be	Problem
49	So I want to move it 10 m	S	Solution
50	I want to make it three stories	F	Problem
51	So 15 m	S	Solution

Figure 9 shows the comparison of the discontinuity ratios in both the PDE and GME across the early, mid and end design stages. The vertical axis is the average of the seven participants' discontinuity ratios. From the figure, we can see that over the whole design session, there are similar discontinuity transitions in both the GME and PDE. At the beginning of the design session, the PDE shows more discontinuity transition. The reason for this is possibly that in the beginning, designers consider the algorithm structure and knowledge based design function together, which requires them to keep shifting between the two design spaces. While in the middle and end, designers tend to focus more on form generation in the PDE and there is relatively less need for them to return to and revise the problem space.

Figure 10 demonstrates a more dynamic comparison of the discontinuity ratio in the PDE and the GME. The horizontal axis is the whole design session divided into ten sub-sessions with an equal number of segments. The discontinuity ratio is flat in the GME, which means designers keep a stable rate of transition between problem and solution spaces in the whole design session, while in the PDE the transition rate varies dramatically: the value being high at the beginning and then decreasing for a period of time and, at the end of the design session, rising once more and then drops off. During sub-sessions 6–8, there is an observable higher discontinuity ratio in the PDE, which potentially indicates a period when designers actively engage in the co-evolution process.

Figure 9. Discontinuity ratio comparison of the PDE *vs.* GME at different design stages.

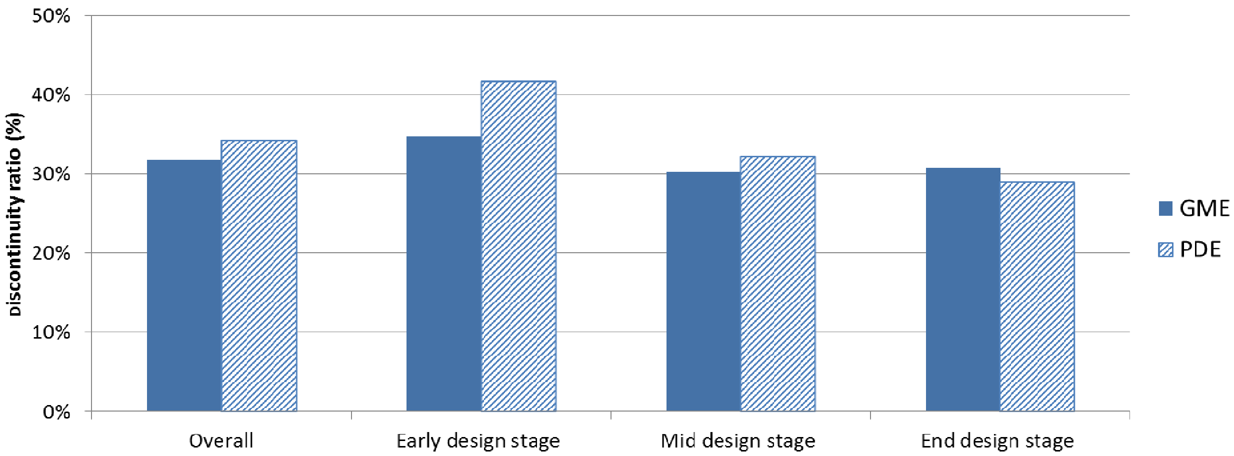
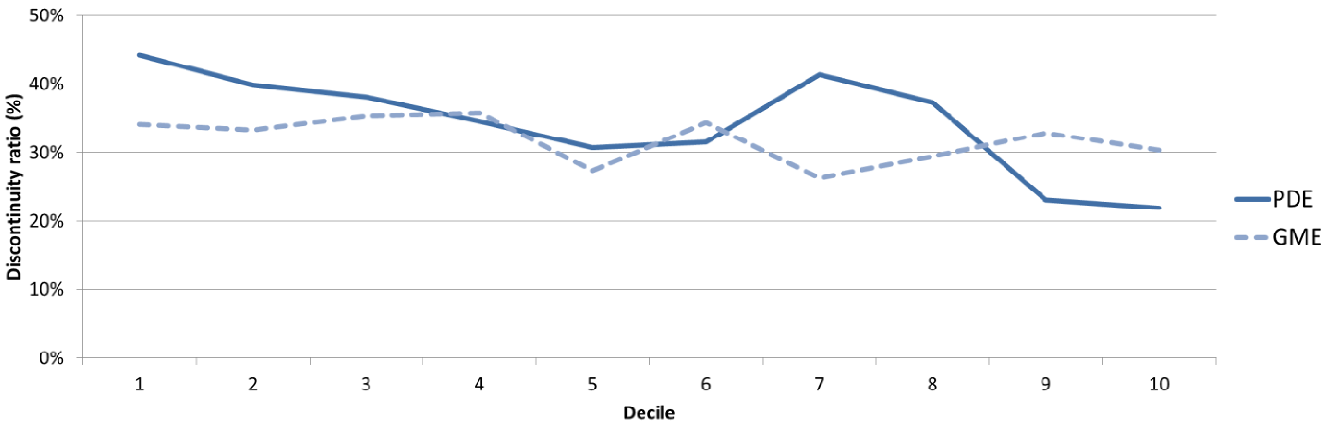


Figure 10. Discontinuity ratio of problem and solution space in the PDE *vs.* GME.



5. Discussion and Conclusions

Researches into the design process suggests that designers constantly return to the design problem space to reformulate the problem [31]. With the interaction or evolution between design problem space and solution space, the design is progressed and a "satisfactory" solution [32] is expected to be identified. This paper presents the results of a comparison of designers' behavior in the PDE and GME. We examine their cognitive behavior from the perspective of design problem and solution spaces. Two measurement methods are used in this study. The first is the P-S index which examines the proportion of design problem and solution issues/processes. The second method measures the discontinuity ratio in order to study the co-evolution process in PDEs and GMEs. The discontinuity ratio reveals the frequency of transition between problem and solution spaces, an event which is beneficial for the emergence of design creativity [6]. The measurement of discontinuity ratio compliments the P-S index to provide a more complete understanding of the designers' cognitive activities in the PDE.

Considering the interaction between designers and the design environments, designers switched between the geometry interface and the scripting interface frequently in the PDE. Parametric design basically progresses by defining and changing logical parametric relationships, reflecting a designers' concept and intention. This feature adds an extra layer of reasoning over the more traditional way of design thinking in the GME. The two types of interfaces facilitate the exchange of design information effectively. During the parametric design process, the designer shifts between the two types of interfaces, which potentially provoke more frequent interactions between designers and computers. The designers' intention is defined by a response/reflection to the instant feedback through the execution of an action [33,34]. During the parametric design process, designers get inspirations from what they see on the screen; at the same time, they reflect on what they see and what they do by taking action through making rules. Schön describes this process as "seeing-moving-seeing" [33]—in the PDE the designer sees what is on the screen, adjusts model and script in relation to it, and sees what they have produced, a process which informs further design. The whole process is circular and recursive, continuously building up the design problem and solution spaces in order to inform and progress the design.

From our observation and analysis, designers put similar effort into design problem space and solution space in the PDE and GME. Designers exhibited problem-driven design tactics at the early design stage of both the GME and PDE, when they tended to start with analysis of the design brief. The main differences are found at the early stage wherein designers focused more on problem space in the GME, and they stepped into a solution-driven process earlier in the PDE. One of the possible reasons is that within the same time frame, designers allocated parts of their effort to solve the rule algorithm problem. Since solution-driven design is suggested to be beneficial for design creativity [16], we can infer that PDE may have potential benefit for the inspiration of design creativity.

From calculating the discontinuity ratio between design problem space and design solution space, the overall discontinuity ratio (indicating the design cognitive transition between problem and solution spaces) is similar in the PDE and the GME. However, different discontinuity ratios are found across design stages: in the early design stage, there are significantly more transitions in the PDE than in the GME, which indicates a good co-evolution design process in the early design stage of the PDE. Scholars have suggested that most of the important design decisions are made at the early design stage [35], and that early solution conjectures are beneficial for solution exploration [36]. Therefore, the frequency of interaction in the PDE at the early design stage creates more opportunity to generate an in-depth design solution within the same time frame. The analysis results will assist us to better understand designers' problem-solving processes in the PDE and GME.

Conflicts of Interest

The authors declare no conflict of interest.

Appendix: Design Brief

1. Brief 1: **Community Center**

This community center is designed for nearby residents to have social activities together. The main functional areas inside the building are activity room, classrooms, meeting rooms.

Issues to consider:

- For site design, consider the traffic route, parking area, and outdoor activity space.

- For the building design, consider the entrance and façade; focus on conceptual design and do not consider detailed layout.
- Area: Building area is around 6000 m^2, one or two stories.

2. Brief 2: **Shopping Center**

The main functional areas are main shopping area and leisure area including café and restaurant (1000 m^2).

Issues to consider:

- The two functional areas can be combined in a single building or separately.
- For site design, consider the traffic route and parking area.
- For the building design, consider the entrance and façade; focus on conceptual design and do not consider detailed layout.
- Area: Building area is around 6000 m^2 one or two stories.

Requirements:

The focus of the design task is conceptual design including form generation of the building and a simple site design. Do not worry about the detailed functions or layout.

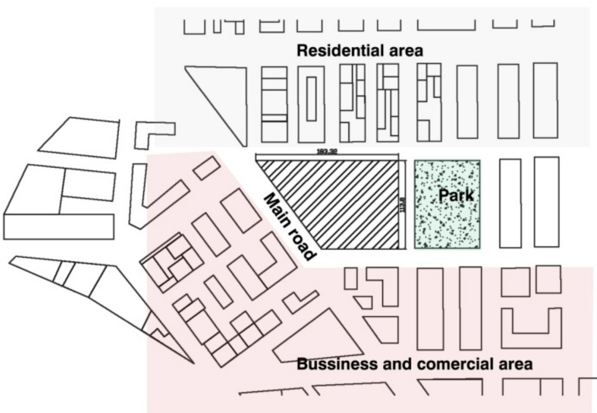
You are expected to aim to complete the design in 40 min, but you can continue for an additional 20 min if required.

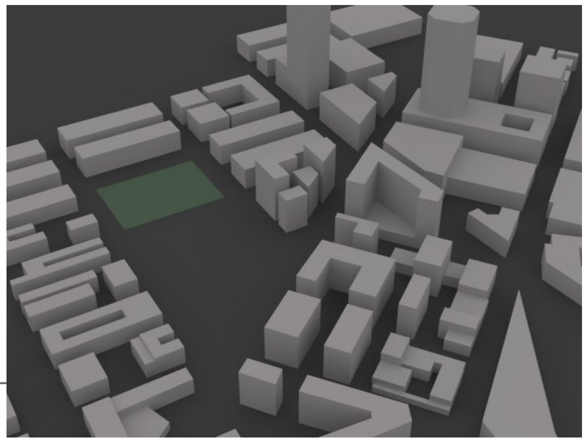
Outcomes:

A 3D model

Two rendered images of the completed design to show the strength of your design.

The following site plan and model are provided for you to complete the task:





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